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:	Exploring high resolution modelling of extreme convective events in the Mediterranean Region with WRF model
Computer Project Account:	spitsara
Principal Investigator(s):	Paolina Bongioannini Cerlini[1] ; Miriam Saraceni[2]
Affiliation:	1 University of Perugia, Dep.t of Physics and Geology; 2 Norwegian University of Science and Technology, Dep.t of Civil and Environmental Engineering;
Name of ECMWF scientist(s) collaborating to the project (if applicable)	
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
High Performance Computing Facility	(units)			20.000.000	2,506,214
Data storage capacity	(Gbytes)			50 TB	2T

Summary of project objectives (10 lines max)

The objectives of the project are related to exploring the use of simulations at different resolutions to understand which type of convective extreme events are more susceptible to the increase of horizontal resolution and why. While this focus has remained, the research was expanded to the possibility of implementing data assimilation with observations from satellites and ground-based meteorological network, mainly because the project is embedded in a collaboration with the regional authorities of Umbria (central Italy) regarding weather forecasting. The new added objective is: Can data assimilation improve forecasts of different types of extreme convective events?

This has been explored given the same set of observed events originally explored plus one new event:

1. Ianos cyclone (15th –21st of September 2020),
2. the Umbria Mesoscale Convective System (23rd of August 2021)
3. the Umbria flood (11th –14th of November 2012)
4. the Marche flood (15th -18th of September 2022)

This will help to develop a framework coupling a convection permitting model with the IFS analyses to interrogate Mediterranean convective extremes. Another connected goal is to disentangle the roles of self-aggregation, CAPE and moisture-convergence feedback in driving extremes. Our final goal is to produce best-practice guidelines for an operational sub-kilometer ensemble system for Mediterranean feedback prediction. Release open data, reproducible workflows and insights to accelerate European convective-scale research, specifically in our region.

Summary of problems encountered (10 lines max)

The first critical aspect of the work was related to chosen model, gSAM, to carry out the simulations. Indeed, gSAM has proved to be very difficult to adapt for modelling “real” cases. Since it is in its early development stage, gSAM lacked a part of code to successfully achieve the initialization of a “real” case, and in addition the version we planned to use had bugs especially on the surface scheme. Furthermore, in the same version we found that gSAM short-wave/surface-flux restart bug hampers flux-based data assimilation, which becomes important for the new project objectives. Therefore, it was decided to change model and carry out the simulations with the WRF model. The WRF model was chosen because of its easy initialization from reanalysis and other data types and because it allows data assimilation with a specific scheme, WRFDA. In fact, the preliminary simulations carried out with WRF were presented last year in the previous report. A second critical issue was found on the type of initialization chosen. The initialization data chosen was the reanalysis of ERA5. Starting with the first case study chosen, Ianos cyclone, it was realized that the ERA5 resolution was not sufficient to be able to initiate convection from the cyclogenesis phase of the cyclone, i.e., September 15th, 2020. This was found for both the 27-km simulation, the 9-km simulation and the 3-km simulation, which were made with the dynamic downscaling of ERA5 reanalyses. The convection and cyclone were only able to form from already initiated cyclone on September 16 and September 17 of 2020. For this reason, we have decided to change the data for the initialization, as will be discussed below. The results we present here were all initialized directly from IFS analysis at 9 km for all cases and then a set of nested simulations were carried out from 9 km for the Mediterranean basin to 1 km over the specific event area. We have already seen great improvements in the Ianos simulation, in line with what demonstrated in Pantillon et al. (2024) when increasing simulation resolution from 10 km to 2 km.

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

To solve the initialization problems and to continue the research on data assimilation as well, we have already redone the simulations of the cases study considered with the initialization with the operational analysis of IFS at 9 km. This way we were able to carry out simulations at 9, 3, and 1 km. As mentioned, before we have also extended the same simulation set to at least one other observed convective extreme event in Central Italy, the Marche and Emilia Romagna flooding event of September 2022. Some discussions regarded the possibility of discarding the nesting procedure in the simulations to compare directly high-resolution simulations with the lower ones without considering the large to small scale energy transmission. This is one of the plans for the continuation of the project. We are still considering data assimilation for these cases. In the case of Ianos cyclone, the planned data assimilation will specifically involve the assimilation of Sea Surface Temperature (SST) satellite data (from the ESA CCI product), while in the case of the two mesoscale convective systems, the data assimilation will involve the assimilation of 2m temperature, precipitation, and soil moisture data observed from meteorological networks in central Italy, as the one in the Umbria region.

List of publications/reports from the project with complete references

None

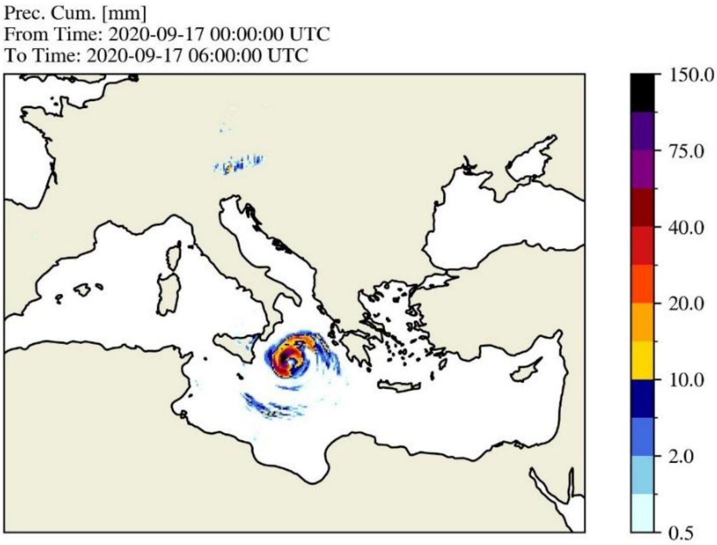
Summary of results

We carried out three different simulations as mentioned of Ianos cyclone, where we enable the change in resolution from 9 km to 3 km to 1 km, within the same initialization date through IFS analysis. The starting and end dates we chose are reported below for each event:

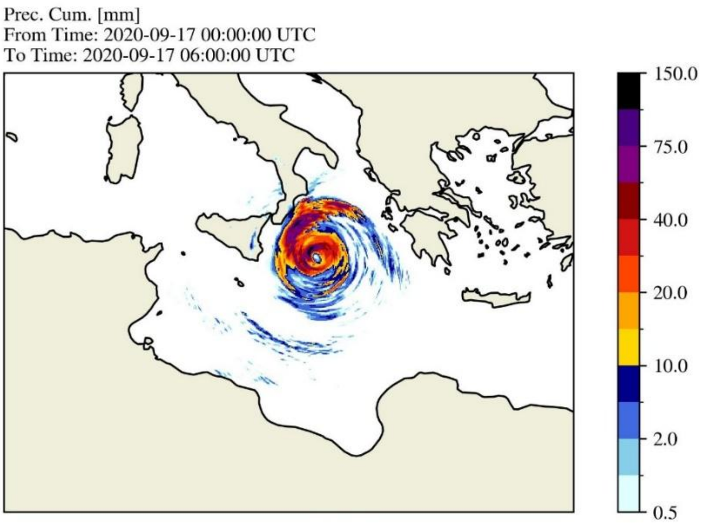
1. Ianos cyclone (16th –21st of September 2020),
2. the Umbria Mesoscale Convective System (22nd – 24th of August 2021)
3. the Umbria flood (11th –15th of November 2012)
4. the Marche/Emilia Romagna flood (15th -18th of September 2022)

All simulations were initialized at 00 UTC. We report in the following the differences between the accumulated rainfall in the three nested simulations for each event as summary of the simulations results.

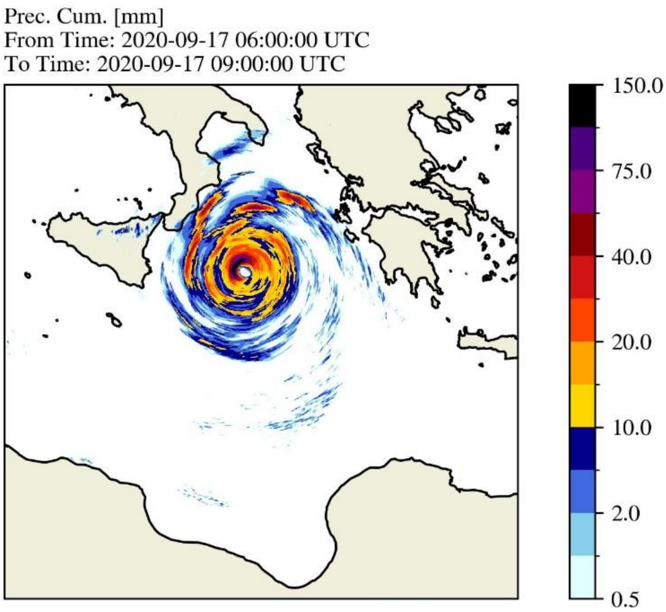
1) Ianos cyclone (17th of September 2020 06 UTC)



(a) 9 km

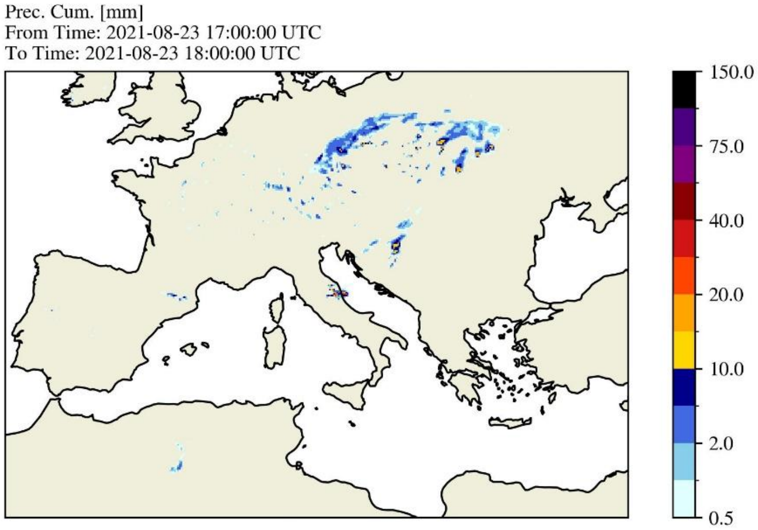


(b) 3 km

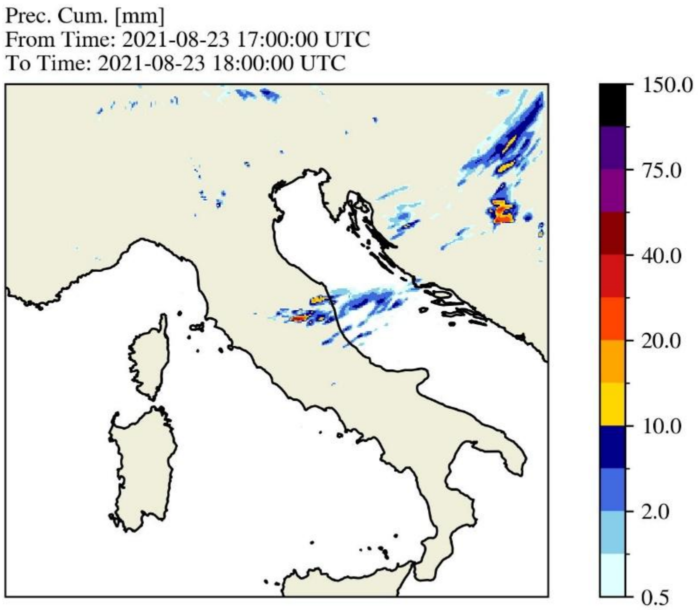


(c) 1 km

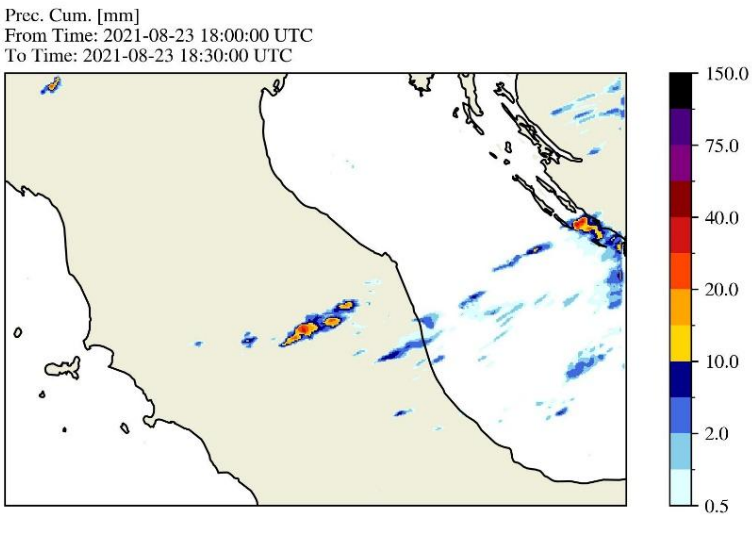
2) the Umbria Mesoscale Convective System (23rd of August 2021 18 UTC)



(a) 9 km

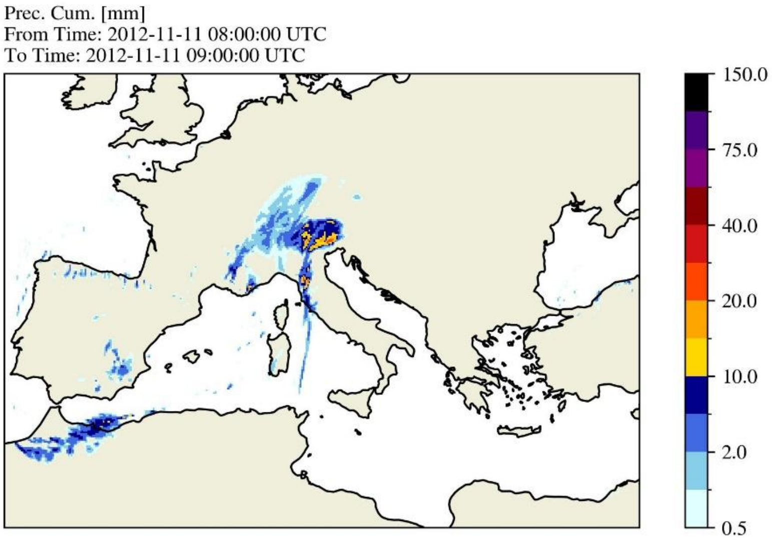


(b) 3 km

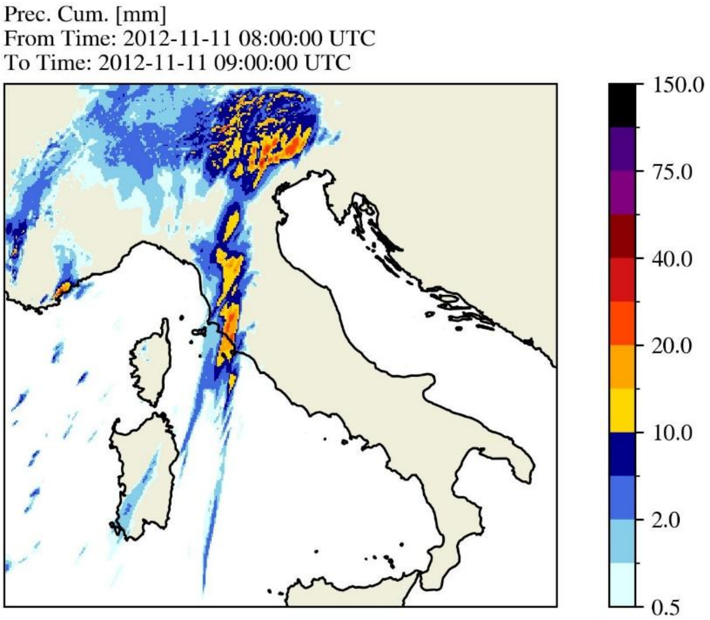


(c) 1 km

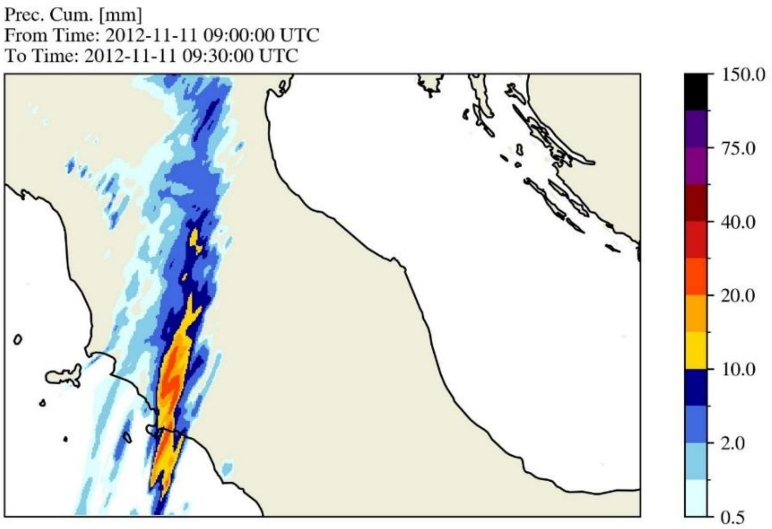
3) the Umbria flood (11th of November 2012 09 UTC)



(a) 9 km

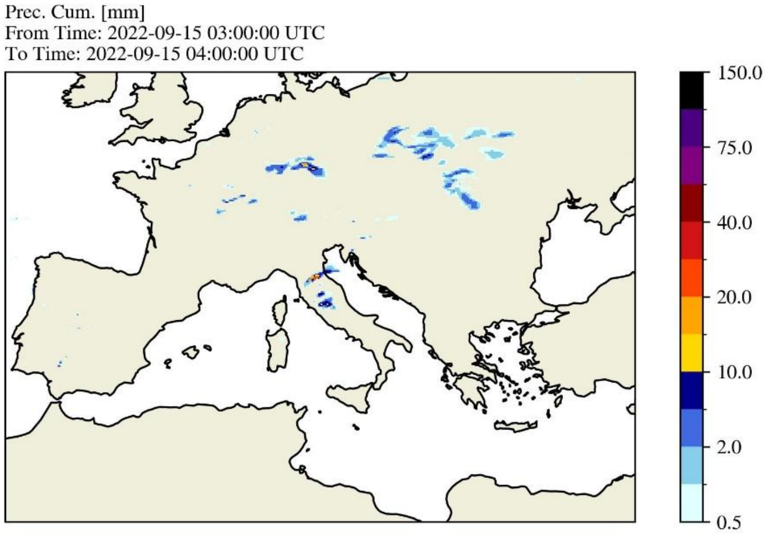


(b) 3 km

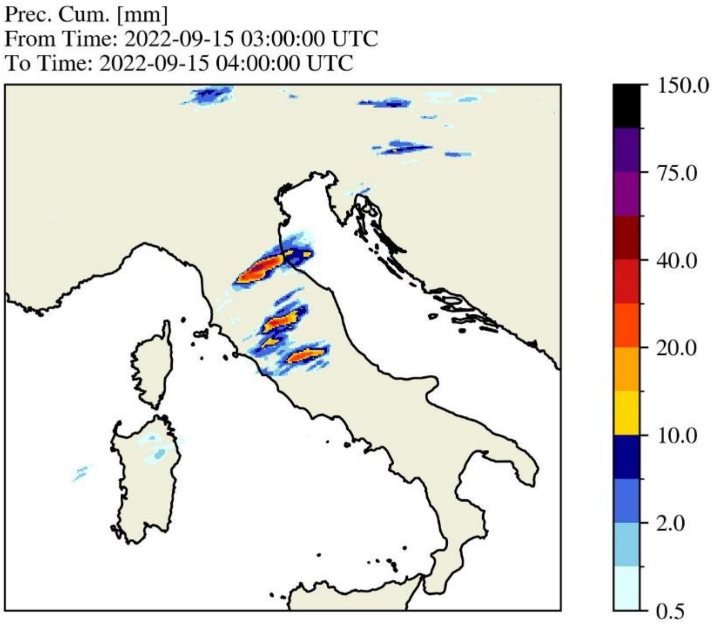


(1) km

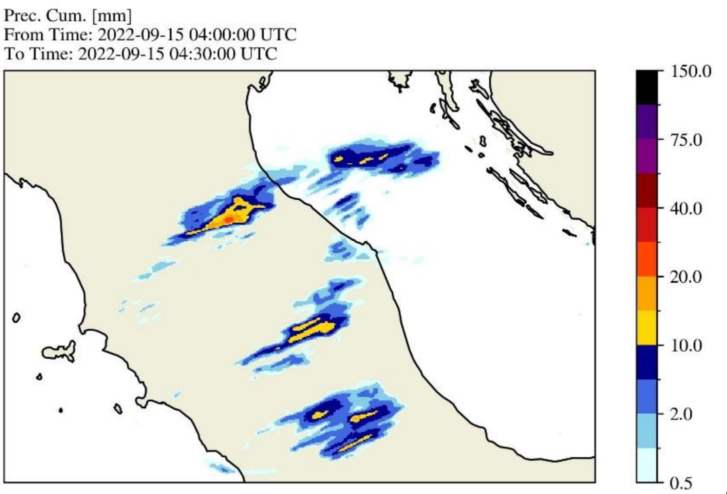
4) the Marche and Emilia Romagna flood (15th of September 2022 04 UTC)



(a) 9 km

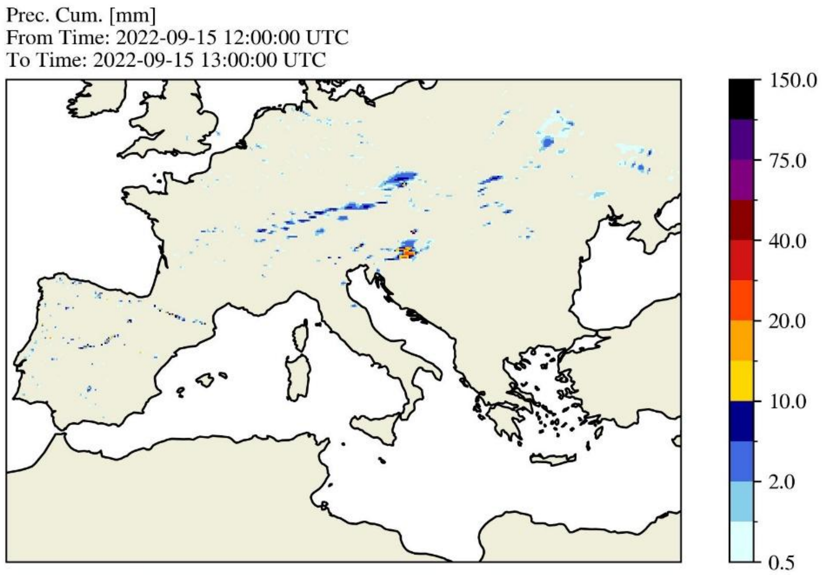


(b) 3 km

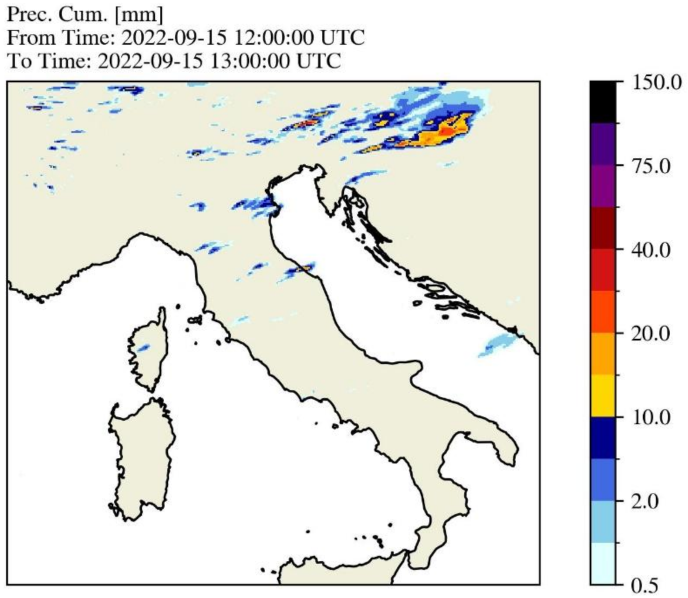


(c) 1 km

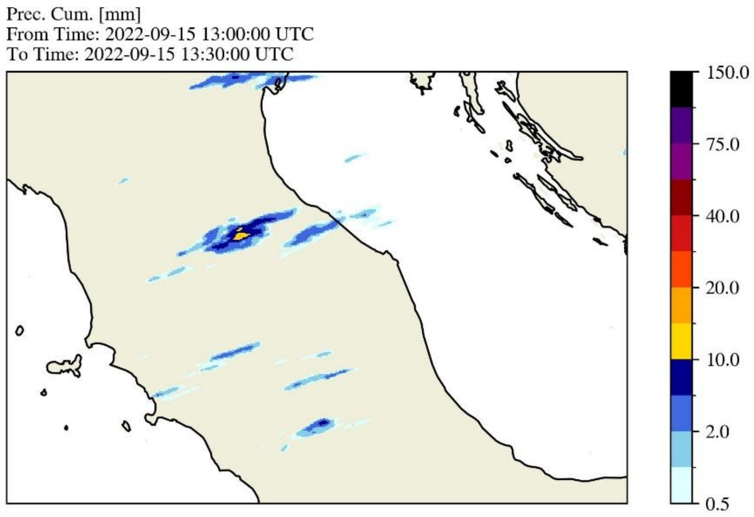
5) the Marche and Emilia Romagna flood (15th of September 2022 13 UTC)



(a) 9 km



(b) 3 km



(c) 1 km

Here, we briefly summarise some preliminary results from the analysis of these four different events. The cyclogenesis of Ianos took place in mid-September 2020 over anomalously warm waters of the Gulf of Sidra, locally exceeding 28 °C (Lagouvardos et al. 2022). On 13 September, a convective cluster was present to the south of Sicily associated with a cut-off low, while a separated surface low was present over Libya (Saraceni et al. 2024, Saraceni et al. 2025). On 14 September, the convective cluster and the surface low approached each other, and on 15 September, the two structures merged. On 16 September, the cyclone moved northward and deepened, while the convection redeveloped. Finally, on 17 September, the cyclone attained its mature phase, exhibited tropical features and turned eastward (Figures (a), (b) and (c for Ianos cyclones). On 18 September, the cyclone made landfall over Greece and was still associated with deep convection. Later, the cyclone bifurcated southward and weakened quickly.

Medicane Ianos exhibits some pronounced sensitivity to variations in horizontal resolution. At the coarsest resolution, the model identifies the cyclonic structure in the southern Ionian Sea, but the distribution of accumulated rainfall appears partially fragmented and unorganized. The definition of the cyclone's eye is weak, and the peak precipitation values are distributed over a large area. A sharp qualitative leap is observed in the representation of the system's dynamics. The spiral structure becomes sharply delineated, featuring a well-defined symmetric circulation around a precipitation-free central eye. Accumulated rainfall rates increase significantly (red and purple bands between 40 and over 75~mm), uniformly wrapping around the core and approaching the coasts of Ionic Calabria and the Peloponnese. Upon reaching the 1 km scale, the model explicitly resolves the deep convective bands of the eyewall. The eye of the cyclone narrows its geometric section, increasing the consistency of the baric gradient, and the maximum accumulated precipitation further intensifies along the edge of the storm wall, confirming the crucial importance of this resolution for the correct representation of the event's cyclogenesis. However, the improvement from the 3 km simulation to the 1 km simulation is partial, and there is an actual decrease in precipitation.

The case of the Umbria Mesoscale Convective System (MCS of the 23rd of August 2021, 18 UTC, as reported in Figures (a), (b), and (c) for this event) that struck central Italy (Rapporto Evento 2021 from civil protection) highlights the model's ability to localize the most intense thunderstorm cores at higher resolution. The phenomenon, which was particularly intense and long-lived, is attributable to a stationary synoptic-scale configuration (Rapporto Evento 2021 from civil protection). In this setup, a flow of cool Atlantic air originating from Northern Europe clashed with a weaker circulation of African origin flowing along the central-western Mediterranean. The stationarity of the convergence line allowed the storm system to constantly replenish its energy and moisture, causing it to persist violently over a limited area for an extended period.

Based on the analysis of radar imagery from the national network, the storm system was composed of a series of aligned, essentially stationary precipitation cores moving in a West-East direction. Satellite imagery shows a structure typical of a "Mesoscale Convective System" (MCS) defined as a "V-Shape," whose cloud top reached the tropopause (approximately 13 km)—an indicator of the extreme intensity of the updrafts that developed within the various cells. The 9 km resolution simulation displays a very extensive macroscale phenomenological pattern covering central Europe and the Balkan peninsula.

Over central Italy, however, the convective activity is displaced, underestimated, or confined to very weak signals below 2~mm. At higher resolution, a mesoscale instability line arranged diagonally emerges clearly, with well-defined thunderstorm cells yielding accumulated precipitation between 20 and 40~mm (up to higher local peaks); and at the maximum resolution, the internal geographical details of the MCS are fully isolated.

It is possible to distinguish the internal multicell structure of the system, with the most organized cores (localized accumulations exceeding 40-75~mm) aligned corresponding to the internal orographic and coastal areas. Figure c) is also more closely corresponding to the observed precipitation (RADAR (Centro Funzionale Umbria) and Meteosat (HRV+IR10.8) (EUMETSAT/Aeronautica Militare) reported in Figure 4 of the Rapporto Evento 2021 from civil protection). For this case, the benefit of using a simulation at 1 km of resolution is clearly shown.

The Umbria flood (11th of November 2012 09 UTC, as reported in Figures (a), (b), and (c) for this event) was characterized by a humid and persistent flow blocked by the Apennine ridge (Rapporto Evento 2012 from civil protection). The synoptic situation on 11 November 2012 showed the presence of an extensive and deep trough stretching from the Norwegian Sea to the Middle Atlas, placing the polar jet's ascending branch over the western Mediterranean, with the jet streak's right entrance over the Tyrrhenian Sea. This led, in the hours that followed, to the development of a ‘warm conveyor flow’ over southern Italy and the Adriatic, immediately followed, on its western flank, by a cold front. This configuration was the driving force behind the convective activity, which developed over the Tyrrhenian Sea in a south-north direction. The main phenomena were ‘V-shaped’ convective structures which, starting from the sea, moved towards the mainland. During the afternoon, a series of thunderstorm systems, continuously fueled by the advection of warm, humid air over the Tyrrhenian Sea, developed from the sea and affected Umbria with intense and persistent rainfall. By evening, a closed low-pressure system could be seen. This created a baroclinic band along the western Mediterranean's northern coasts, reaching into northern Italy and Eastern Europe. While upper-level flow aligned with this band, low-level warm air advection persisted from the south, pushed by the slow-moving low over northern Algeria. This led, on Monday, 12 November, to the formation of a stable and well-fed convergence line over the northern Tyrrhenian Sea, extending in a west-east direction from northern Sardinia. Until late in the evening, a series of V-shaped convective systems, which could be grouped within the context of a single, extremely long-lived mesoscale convective system (MCS), brought widespread, intense, and persistent rainfall to Tuscany, northern Lazio, and Umbria. On 12 November, this produced a stable, well-fed convergence line across the northern Tyrrhenian Sea, running west-east from northern Sardinia. A long-lived MCS made up of successive V-shaped systems brought heavy, persistent rain and intense lightning to Tuscany, northern Lazio, and Umbria into the late evening. Overnight, the low-pressure center shifted further east, breaking the balance sustaining the convergence zone and cutting off the system's energy supply, which dissipated into scattered storms by early Tuesday (13 November, 6 UTC).

The simulation at 9 km captures the massive weather front associated with the Mediterranean cyclogenesis ascending from the Tyrrhenian Sea toward Northeast Italy and the orographic Alps. The accumulation shows widespread precipitation but is spatially overly smoothed, failing to localize the orographic maxima in central Italy. Once again, narrowing the domain to 3 km allows for a better focus on the orographic forcing effect. The front organizes into a narrow and intense longitudinal precipitation band parallel to the Tyrrhenian coast and the Apennines, highlighting concentrated accumulations exceeding 40~mm. The precipitation pattern at 1 km presents defined and aligned convective structures driven by the orography of the Umbria region. More precisely, precipitation ground accumulations align closer with observed precipitation (RADAR (Centro Funzionale Umbria) and Meteosat (HRV+IR10.8) (EUMETSAT/Aeronautica Militare) reported in Figure 4 of the Rapporto Evento 2012 from civil protection).

The final case study, the flood event of the Marche/Emilia Romagna (15th of September 2022, as reported in Figures (a), (b), and (c) for this event), was a catastrophic autumn flood suffered by the Adriatic side of the Apennines (Rapporto evento Marche ed Emilia Romagna 2022).

This was a convective mesoscale system generated by low pressure over the Atlantic and high pressure over northern Africa, which resulted in the formation of a stationary, self-healing thunderstorm as it transited from West to East over the north of the Tyrrhenian Sea. This typology of the storm is called “V-shaped” because of its geometry. The synoptic situation was dominated by a large area of low pressure centred over Scandinavia, which was channeling a warm and humid south-westerly flow towards the central Mediterranean, fed by a trough over Spain and an intense jet stream over the central Tyrrhenian Sea. On 15 September, convective systems – triggered by the contrast between cool Atlantic air and warmer North African air – developed over the Tyrrhenian coast (Sardinia, Corsica, Tuscany) before moving eastwards. On 16 September, the weather systems started to weaken, but more localised precipitation was present in both regions.

In the lowest resolution simulation, widespread instability activity is visible over central Europe. Over the Italian peninsula, the precipitation signal associated with the violent convective self-aggregating system (a V-shaped storm) is almost absent or confined to small, isolated clusters near the Adriatic coasts. At 3 km resolution, the model successfully triggers and organizes the convective system, especially in the Emilia-Romagna ridge. Three or four distinct cell structures oriented from Southwest to Northeast clearly emerge, with sudden and severe precipitation accumulations locally exceeding 40-75~mm. Extending the calculation to 1 km enhances the stationarity of the cells. The precipitation peaks increase in intensity and concentrate geographically along the critical river basins between the Marche and Emilia-Romagna regions, resolving the interaction between the convergence of the moist marine flow and the Apennine topography. Unfortunately, the event convection was sustained only up to the 15th afternoon, then decaded and re-emerged at the end of the 16th of September in Southern Italy. Indeed, all the simulations are not able to sustain the aggregated convection of the night of the 15th on the coast of the Marche region (as shown by the second section of Figure (a), (b), and (c) for the 15th of September 2022 at 13). This might be due to the lack of SST assimilation in the simulations, given that the re-ignition of the convection in this event also came from the presence of higher-than-normal surface temperatures of the Adriatic Sea in the summer of 2022. Furthermore, the cold pool representation (possibly too weak cold pools), in the Apennines and at the border between the coast and the land might have impacted negatively the maintenance of convection in the simulation. These two aspects will be further explored in the future.

What emerges from these four cases proves that going to higher resolution with WRF improves the convection representation only for mesoscale convective events rather than cyclones in the region. While the intensity of precipitation can be captured already at 3 km in most cases, the real improvement is in the spatial distribution of the latter and more specifically the convective cells alignment with the large-scale flow.

The benefit of reducing the horizontal grid spacing from 10 km with parameterised convection to convection-permitting 2 km to further improve the Ianos cyclone track and intensity was already found in Pantillon et al. (2024). Higher resolution enhances convective activity, which improves the phasing of the cyclone with an upper-level jet and its subsequent intensification and evolution. The 10 numerical frameworks show robust agreement but also reveal model specifics that should be taken into consideration, such as the need for a parameterisation of deep convection even at 2 km horizontal grid spacing in some models. However, we are showing that an additional reduction toward 1 km does not affect the simulation further.

Regarding the simulation of MSCs, Prein et al. (2021), for instance, by performing mid-latitude idealized ensemble MCSs simulations, found similar results where, even if they found significant improvements in precipitation, movement, cold pools, and cloud properties when transitioning from 12 km to 4 km of horizontal resolution; decreasing beyond 4 km resulted anyway in improvements for up- and downdraft sizes, average vertical mass fluxes, and cloud top height and temperature. This aspect will be explored and deepened in the next steps of the project.

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Report sull'evento meteorologico avverso del 15 al 17 settembre 2022. A cura del Centro funzionale delle Marche, pubblicato settembre 2022

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