Numerical simulation of a giant-hail-bearing Mediterranean supercell in the Adriatic Sea

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ABSTRACT

On 10 July 2019, a giant hail-bearing supercell hit the Adriatic coast of central Italy. Hailstones with maximum diameter of 15 cm were recorded over the city of Pescara at around 10:40 UTC. The aim of this study was to understand the main synoptic and mesoscale features responsible for the triggering and the development of the supercell using the WRF model, forced with GFS and IFS data. In addition, the HAILCAST module of WRF was used to simulate some hailstorm characteristics, in particular the average hailstone diameter. Specifically, the work was organized in three parts: first, a brief synoptic description; next, the trajectory of the supercell and the dynamic and thermodynamic characteristics of the environment where it developed were analyzed; in the last part, the focus was on the simulation of reflectivity and mean hail diameter. Model simulations proved to be in a good agreement with radar and satellite observations, so that the HAILCAST module produced results reliable, for the simulation of this severe hailstorm.

KEYWORDS: Mediterranean supercell, hail, WRF, HAILCAST

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1. INTRODUCTION

Hail forecasting is very difficult due to the complexity of the formation and growth processes of hailstones (e.g., Rasmussen and Heymsfield, 1987; Dennis and Kumjian, 2017; Martius et al. 2018). Also considering that hailstorms occurs on a very small spatial and temporal scale.

The lack of sufficiently detailed ground-level hail observations makes it difficult to analyze single event, to establish a climatology of hail, and, when available, to validate the numerical or subjective forecasts (Manzato et al.,2020).

Climate change manifests itself in terms of an increase in the frequency and/or intensity of extreme events over most areas of the world (*IPCC,2012; Gleeson et al.,2020*). The Mediterranean regions, in particular, represent a hotspot for climate change, as an increase in the intensity of heavy rainfall and intense cyclone is predicted, as reported in the IPCC-AR6 (International Panel for Climate Change-Sixth Assessment Report; https://www.ipcc.ch/report/ar6/wg1/).

On 10 July 2019, a hail-bearing supercell hit the central part of western (Italian) coastline of the Adriatic Sea. This supercell was catalogued in the European Severe Weather Database (ESWD) as s severe convective event, with hailstone sizes up to 14 cm observed at the surface (Montopoli et al.).

The aim of the present study is to evaluate the dynamic and thermodynamic characteristics of the environment where the supercell developed, using numerical simulations with the Weather Research and Forecasting (WRF) model [13]. For the simulation of the hailstones, in particular of the hail size, the HAILCAST [1] module is employed. The model outputs will be compared with the observations available. Specifically, the trajectory of the supercell and mesoscale fields will be analyzed, at various altitudes. Attention will also be given to the thermodynamic conditions.

The paper is organized as follows. Section 2 describes the model setup and the data available. Synoptic conditions are reported in Section 3, while numerical model outputs are described in Section 4. Conclusions are drawn in Section 5.

2. MODEL SETUP AND DATA

The WRF Model is used to simulate the synoptic and mesoscale environment where the hailstorm developed. The optional WRF-HAILCAST module is activated to simulate the hail growth and the hailstone mean and maximum diameter.

Numerical simulations are implemented over three nested domains, with grid spacings of 16, 4 and 1 km, respectively (As visible in Fig 2.1). The number of grid points is respectively 150 x 120, 217 x 161, 321 x 261, and 41 vertical hybrid levels. The following parametrization are employed: the WSM6 microphysics scheme (Hong and Lim, 2006), the RRTM longwave (Mlawer et al., 1997) and Dudhia (1989) shortwave radiation, the Unified Noah land-surface model (Tewari et al.,2004), the YSU boundary layer (Hong et al., 2006), the Kain–Fritsch cumulus scheme (Kain, 2004) is active for the domains at 16 and 4 km grid spacing, while for the inner domain at 1 km, an explicit treatment of convection is employed. The HAILCAST module was only applied to the inner domain. HAILCAST consists of a one-dimensional, time-dependent hail growth model, receiving information about the updraft from the prognostic model, in this study the WRF Model. A full description of WRF-HAILCAST is provided in [1].

The starting time for the simulations is 00:00 UTC on 10 July and it covers 15 hours.

Global Forecasting System (GFS) and European Centre for Medium-range Weather Forecast–Integrated Forecasting System (ECMWF-IFS) forecasts are both used to force the model as initial and boundary conditions every 3 hours.

The hailstones collected at the surface were up to 14 cm large and affected, in particular, the city-of Pescara at around 10:40 UTC, as visible from radar images (Montopoli et al.,2021). Fig 2.2 shows the supercell as seen from the Sentinel satellite (false color image), on July 10, 2019 around 10:00 UTC, (photo: Sentinel/Copernicus EU), which shows the deep convection near the Adriatic coast of Italy. The location of the supercell is better represented in fig. 2.3, where the time sequence of the nearby dual-polarization Doppler weather radar located at Mt. Il Monte (lon = 14.6208◦, lat = 41.9394◦, alt . =710 m) shows the supercell moving from 09 to 11 UTC along the Adriatic coast and passing near Pescara between 10 and 11 UTC. The radar output variable show here is the constant altitude plan position indicator (CAPPI) of the equivalent reflectivity factor at horizontal polarization (Z_{HH}). The size of the hailstones that fell to the ground was up to 14/15 cm from 10 to 11 UTC (Montopoli et al., 2021) (Fig. 2.4).

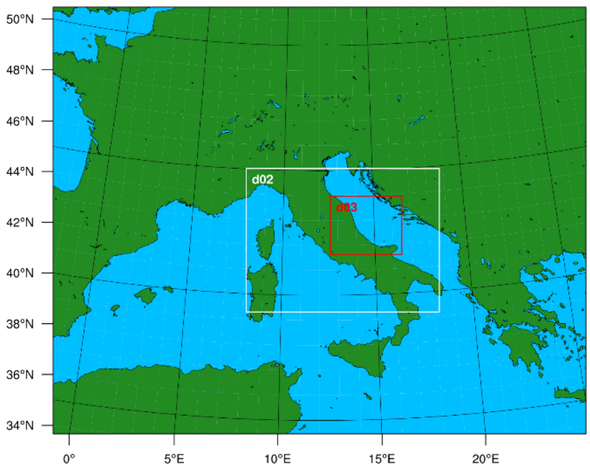

Fig 2.1 view of the three nested domains on which the simulations were implemented.

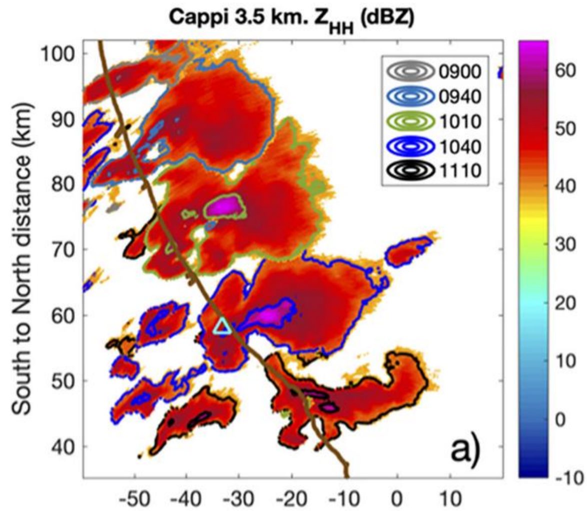

Fig 2.3 Time sequence of radar ZHH from 09 to 11 UTC.

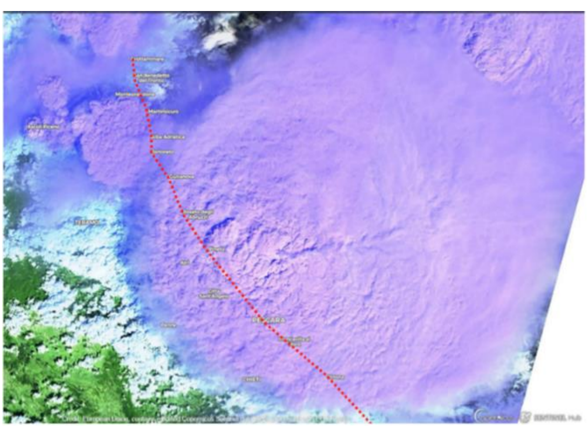

Fig 2.2 View of the supercell as seen by the Sentinel satellite (false color image), on July 10, 2019 around 10:00 UTC, (photo: Sentinel/Copernicus EU).

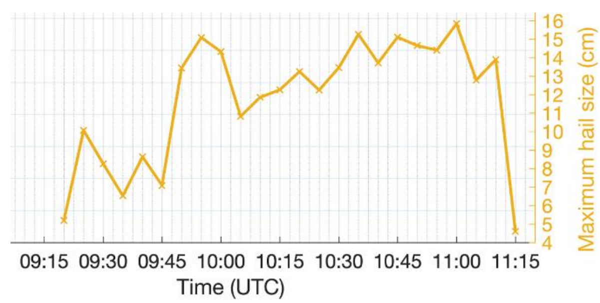

Fig 2.4 Maximum hailstones size observation on the city of Pescara

3. SYNOPTIC DESCRIPTION

Between 6 and 11 July 2019, a 6-day severe weather outbreak developed across the entire northern and central Mediterranean region spreading into the Alpine region and the Balkans. The long-lasting outbreak was caused by a trough from Eastern Europe that affected the central Mediterranean region (Fig. 3.1). The area under consideration was located on the eastern side of the trough axis.

Weather conditions were particularly harsh in Italy and Greece due to the low-level intrusion of relatively cold and dry air on the northern Adriatic Sea (Fig. 3.2), moving from North to

South. A convergence line was apparent, generated by the interaction between cool northeasterly winds ("bora") and the moist and warm southwesterlies from inland (see Fig. 3.2). Figure 3.2 shows the 850 hPa temperature, with cold air masses extending from Eastern Europe toward the central Mediterranean and warmer air over the southern Mediterranean. The interaction with the complex orography and the sea surface, generated several storm structures (supercell and intense squall lines) along the eastern Italian coast, from the morning to the late afternoon. (Montopoli et al., 2021).

Figure 3.3 shows the jet stream at 300 hPa at 00:00 UTC, with maxima around 120-130 km/h. Pescara is located near the left exit of the jet stream branch positioned over Southern Italy, but not far from the rear right entrance of the branch positioned over Eastern Europe. These two areas are those with the greatest upper-level divergence and therefore are favorable to strong convection.

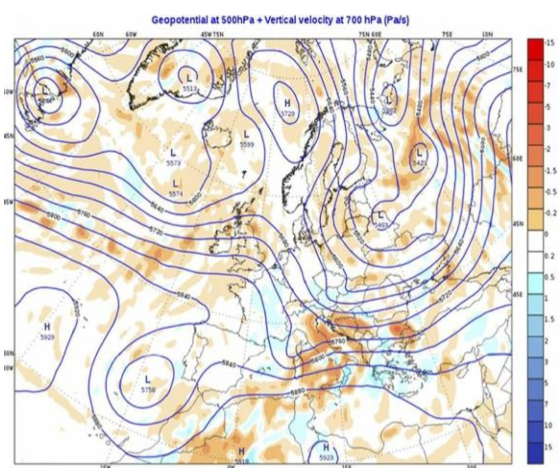

Fig 3.1 Geopotential height at 500 hPa and vertical velocity (in Pa/s) map. ECMWF model output at 06:00 UTC.

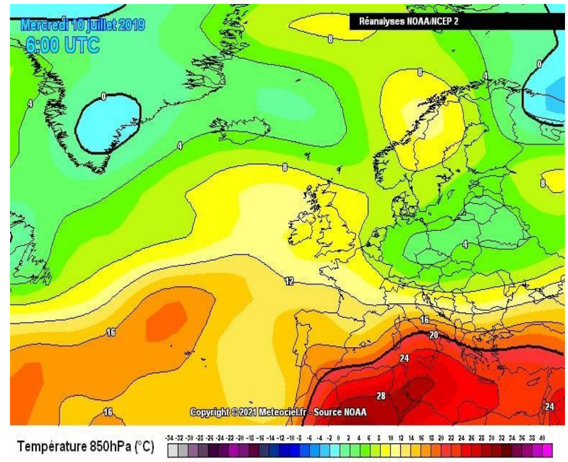

Fig 3.2 Temperature at 850 hPa map (Meteociel.fr, source NOAA).

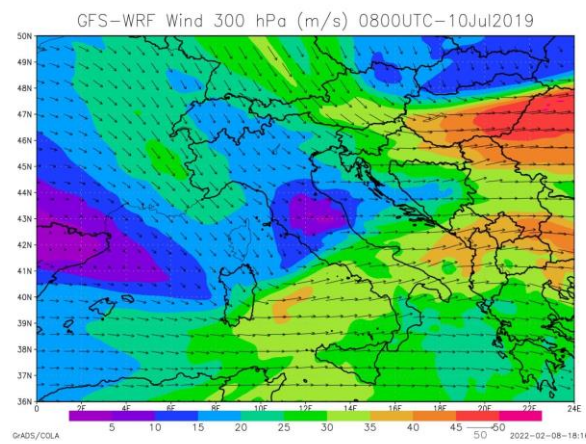

Fig 3.3 Jet stream map at 300 hPa, at 0800UTC from GFS data.

4. RESULTS AND DISCUSSION

4.1 Supercell development

To identify the presence of the supercell, updraft helicity between 2 km and 5 km and windstorm relative velocity are considered.

Updraft helicity is defined as the vertical integral of the product of vertical velocity and vertical vorticity between two levels. It is defined as:

$$UH = \int_{z1}^{z2} w \ \zeta \ dz \quad (1)$$

where z1 and z2 are the extremes of layer over which UH is calculated, w is vertical velocity and ζ is the vertical component of vorticity.

It is commonly used as a proxy for mid-level rotation in simulated supercells. Figure 4.1 shows the updraft helicity between 2 km and 5 km obtained from GFS and IFS data. From 08:30 until 10:30 UTC, a UH core with values above 1000 $m^2 s^{-2}$ can be seen, moving along the Adriatic coast towards the southeast. A comparison between the two simulations shows that the model run forced with the GFS data seems to reproduce the case study better; in fact, the supercell is closer to the observed track, near the Adriatic coast of Italy; the model run forced with the IFS data simulated the supercell farther from the coast, over the Adriatic Sea. Hence, the simulations with GFS data will be used in this study to analyze hereafter the environment in which the supercell developed and its characteristics.

4.2 Mesoscale environment

To understand the environmental conditions in which the supercell developed, we first analyze the wind and thermal profiles in the area where it developed.

The winds at 1000 hPa, 850 hPa, 700 hPa and 500 hPa, are shown in Fig 4.2 at 08 UTC, when convection was still in its early stage. The maps identify a strong vertical wind shear over the Adriatic Italian regions: in the northern part, it is mainly directional shear, due to rotation from northeasterlies (bora, in the lowest 1500 m) to northwesterlies (in the upper levels). On the other side, in the central regions the shear is mainly due to wind speed, which strongly increases with height due to the presence of the jet stream axis.

Some instability parameters are shown in Fig. 4.3 and 4.4. All of these parameters, i.e. LCL (Lifting Condensation Level), LFC (Level of Free Convection), CAPE (Convective Available Potential Energy) and CIN (Convective Inhibition), show the presence of a region with favorable conditions for convective development near the Adriatic coast. The extent of this area extend from the open sea to the whole central Adriatic coast. Therefore, a supercell could develop in the area due to the combination of large wind shear, high CAPE (above 2000 J/kg), low CIN (less than 10 J/kg), and low LFC and LCL (around 300-500 m). This means that a weak uplift was necessary to trigger convection, and that an intense updraft can be generated.

These considerations are supported by the sounding simulated in Pescara at 09 UTC, representative of the environment that the supercell encounters in its southward movement, and by the hodograph at the same point (Fig 4.5).

The unstable profile is mainly due to the steep lapse rate (greater than 7/8 K/km) between 700 hPa and 500 hPa, which represents an indication of the strong instability at medium altitudes. Steep lapse rates are also present above, so that the “fat” CAPE favors vertical motions extending at very high altitudes (level of neutral equilibrium at about 200 hPa). As a consequence, CAPE is very high in the Hail Growth Zone, the layer between -10°C and -30°C which represents the area most efficient in the growth of hail, favoring the formation of large hail. Other favorable indications for hail formation are the high humidity in the PBL, close to saturation, and the wet bulb zero level, which is low as it can be estimated from the soundings at about 700 hPa. Also, the value of the significant hail parameter (https://www.spc.noaa.gov/exper/mesoanalysis/help/help_sigh.html) is 1.6, well above 1, which is the threshold that indicates a favorable environment for significant hail.

On the other hand, the hodograph clearly shows the rotation and intensification of the wind with altitude: from the east at low levels, it becomes from from the west at upper levels, with a profile like what is usually observed in severe convection environments (Markowski and Richardson, 2011).

The map of potential temperature at 1000 hPa (Fig. 4.6) shows that the area where the supercell develops at the border of warm air, followed by the arrival of cold air behind. The cold front had plausibly the role of triggering the convective system since it provides the uplift necessary to overcome the limited inhibition.

Finally, the dew point temperature map (Fig. 4.7) shows that, especially at low-levels, a band of high humidity crosses the central Adriatic, approximately corresponding to the area where the value of CAPE are high.

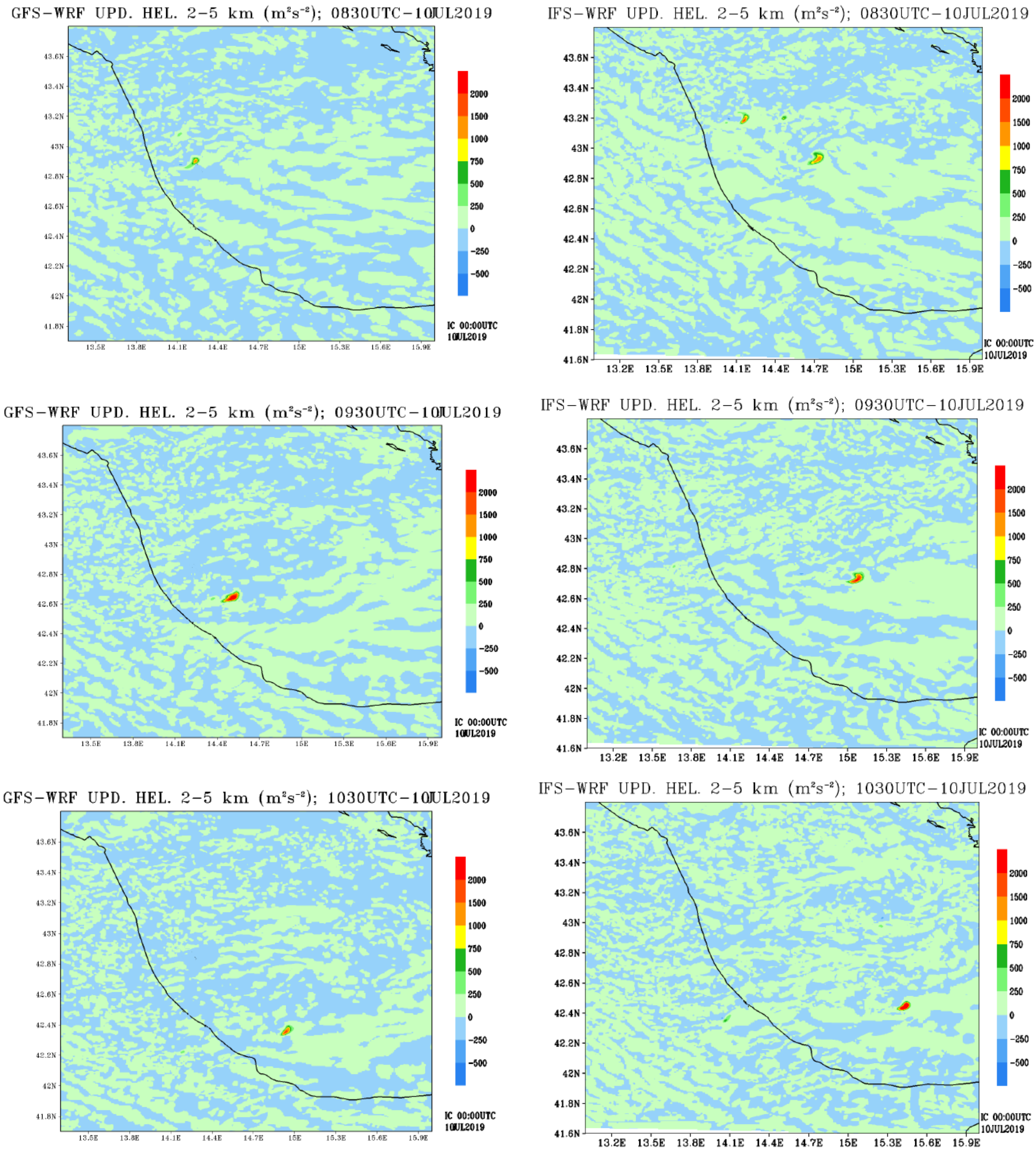

Fig. 4.1 Updraft helicity between km and 5 km and from 08:30 to 10:30 obtained from IFS and GFS data

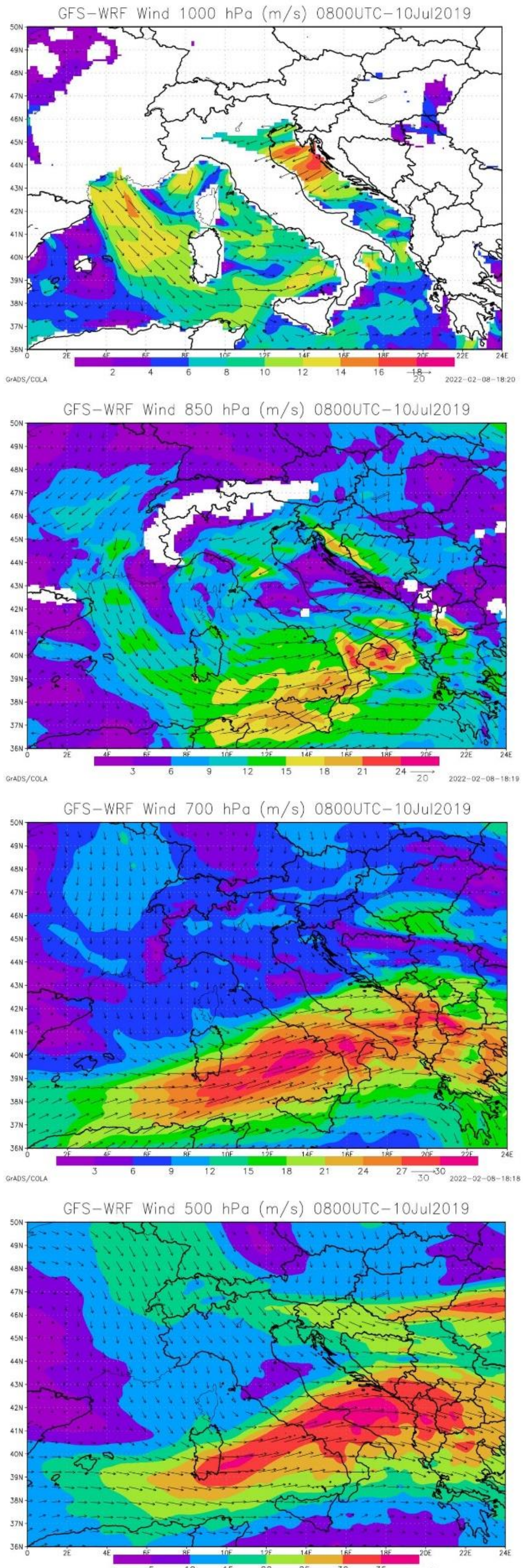

FIG. 4.2 Wind maps at 1000 hPa, 850 hPa, 700 hPa and 500 hPa at 08 UTC from GFS data.

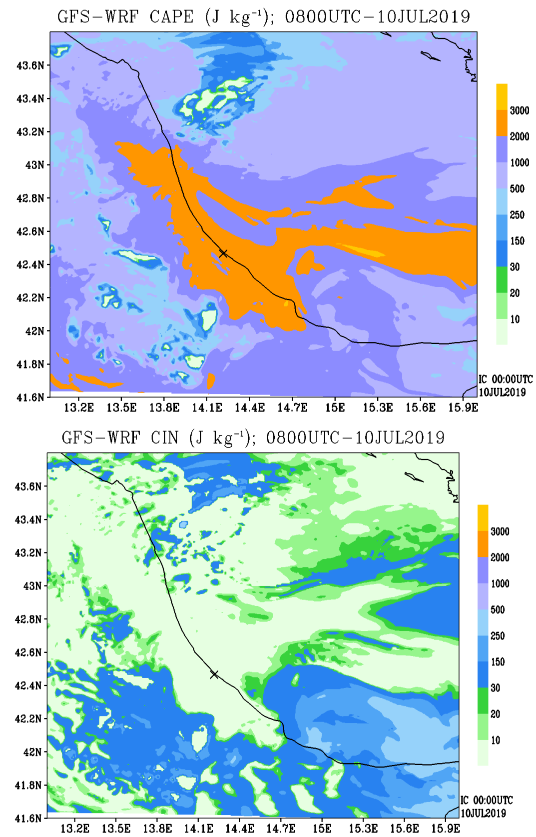

Fig 4.3 CAPE and CIN maps at 08:00

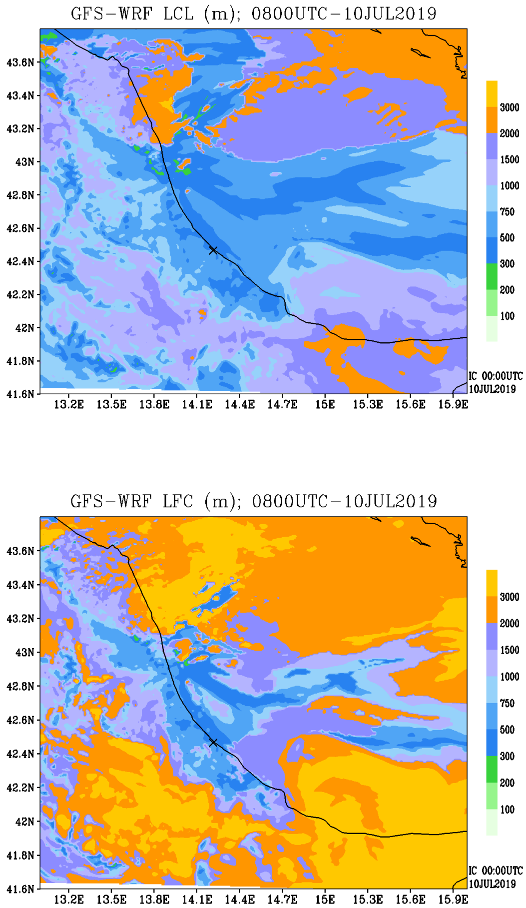

Fig 4.4 LFC and LCL maps at 08:00

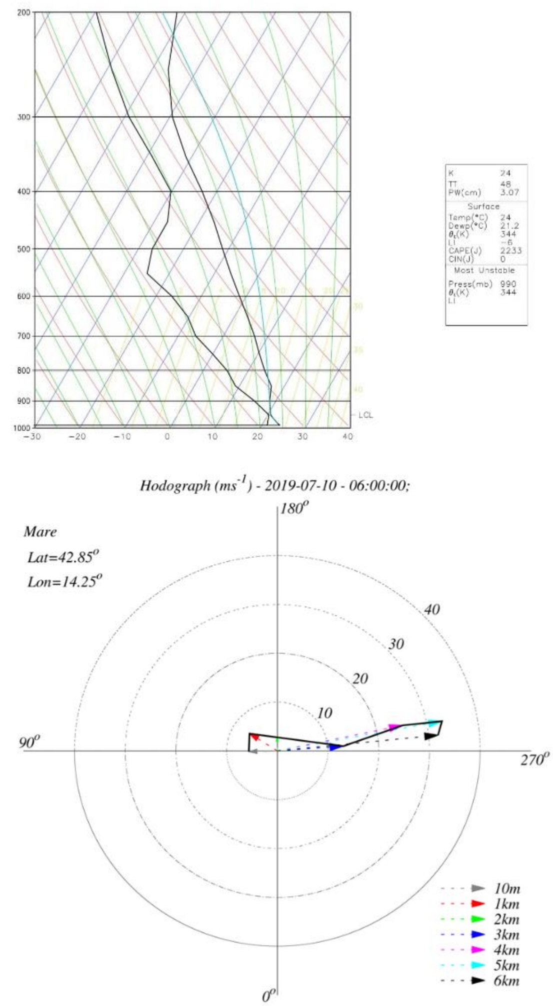

Fig 4.5 Sounding and hodograph at 09:00 over the town of Pescara

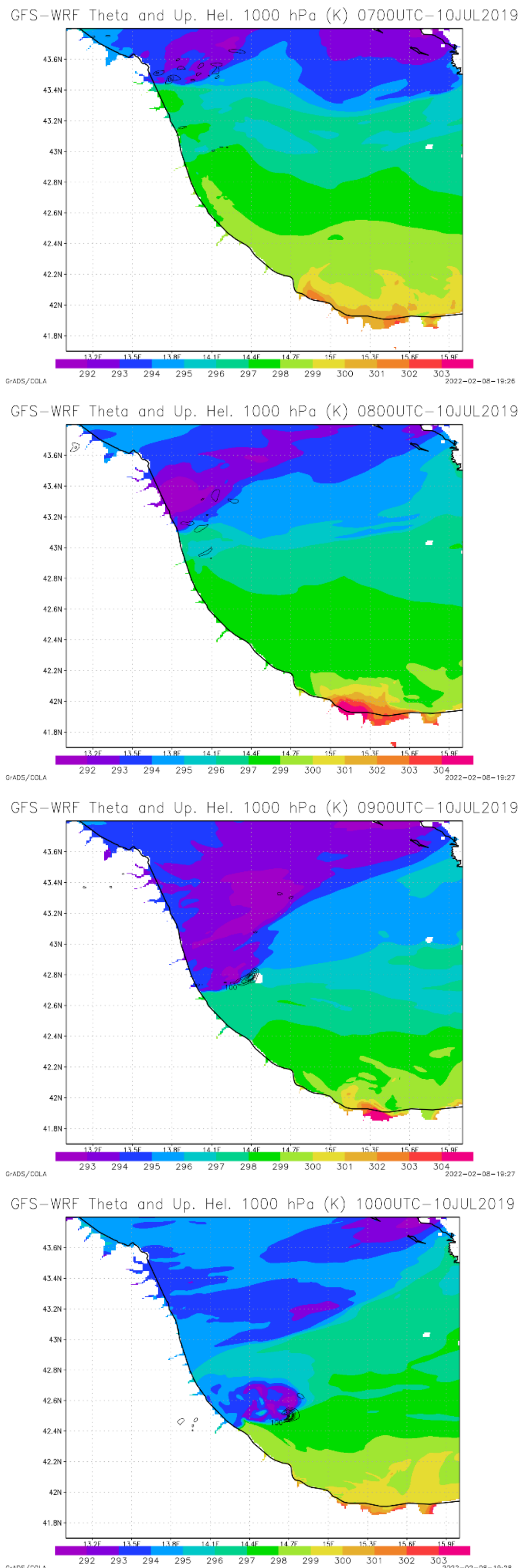

Fig 4.6 Potential temperature at 1000 hPa, from 07 UTC to 10 UTC, using GFS data.

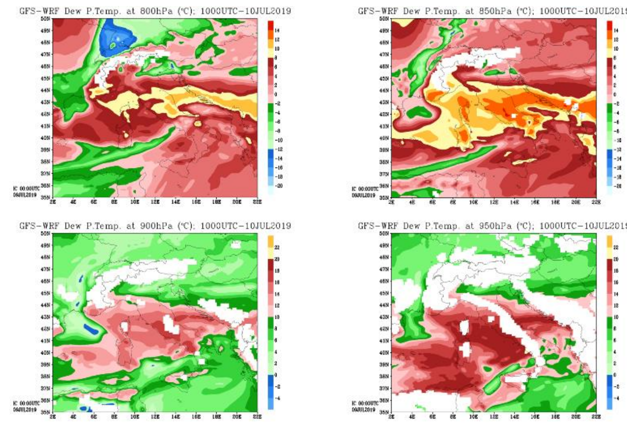

Fig 4.7 Dew Point Temperature at various altitudes, using GFS data

4.3 Hailcast fields

Finally, the reflectivity at 650 hPa (about 3.5 km) and mean hail size fields produced by the HAILCAST module of WRF model, forced from both IFS and GFS data (IFS-WRF and GFS-WRF respectively), are shown. These will be compared with the radar and satellite observations.

Figures 4.8 and 4.9 show the maps of reflectivity at 650 hPa and mean hail diameter obtained by the GFS-WRF and IFS-WRF simulations respectively. From the comparison with the observation, emerges that, the IFS-WRF model run identifies the supercell a bit too far from the coast (as discussed above), although high values are present also over the city of Pescara, possibly due to a weaker cell developed near the coast (apparent also in the updraft helicity map at 1030 UTC). On the other hand, the GFS-WRF model run, places the cell closer to the Adriatic coast, and seems to better reproduce the case study (cfr. with Fig. 2.2).. Finally, observations show that the maximum diameter of hail fallen on the city of Pescara has also reached 15 or 16 cm. This figure matches well with the values predicted by both the WRF model runs using the HAILCAST module, both in terms of diameter (simulated hailstones are of order of 10 cm) and time (transit over Pescara is simulated at around 1000 UTC).

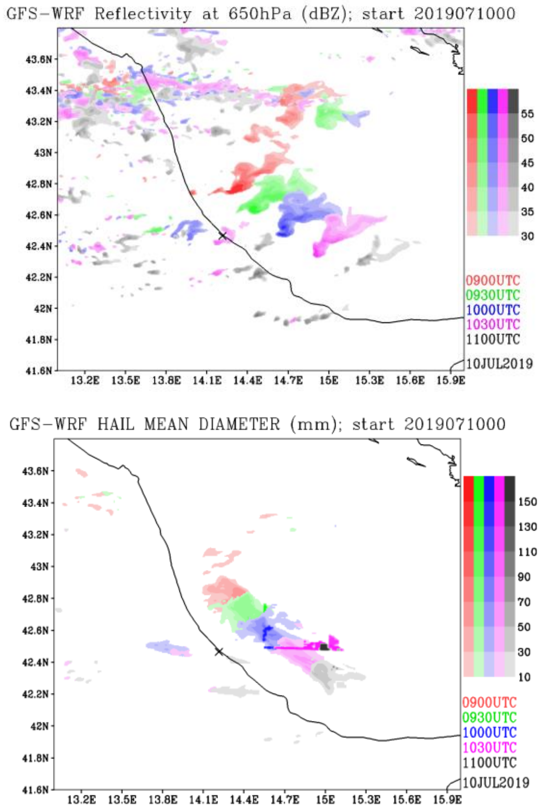

Fig 4.8 Reflectivity and hail mean diameter according to the GFS-WRF run.

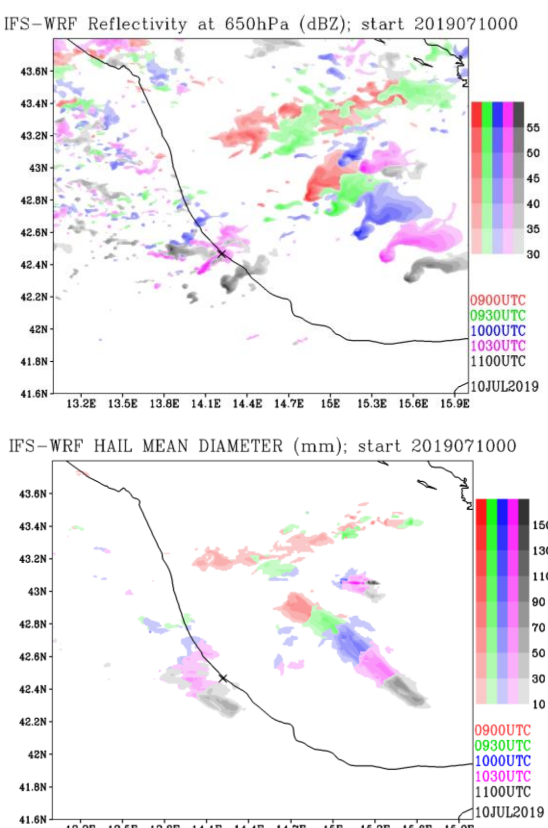

Fig. 4.9 Reflectivity and hail mean diameter according to the IFS-WRF run.

5. CONCLUSIONS

The aim of this work was to simulate the supercell that, on 10 July 2019, generated hail up to 15 cm in diameter close to the Adriatic coast of Italy and the city of Pescara. Using numerical simulations with the WRF model, various parameters of instability, wind and temperature fields, were analyzed also using soundings and hodographs. The analysis of these fields confirmed both that the environment was favorable for the development of the supercell and that the supercell is well reproduced by the model.

The hail diameter was also simulated using WRF HAILCAST module. These simulations are in agreement with the satellite and radar observations, and with the surface reports, both in terms of mean diameter and time of occurrence. As for the position of the supercell, the GFS-WRF run reproduced the event better than the IFS-WRF run, since it placed the cell closer to the Adriatic coast.

The results of this case study are therefore encouraging in terms of the ability of the WRF HAILCAST module to simulate hail events, which is at forefront of weather forecasting research.

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