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Analysis of the development mechanisms of a large-hail storm event on the Adriatic Sea

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ABSTRACT

A severe weather event is analyzed in terms of cell development, dynamics, and thermodynamics. The Mediterranean region is sporadically affected by severe weather events causing damage and injuries. An unusual and severe weather event hit Italy on July 9–10, 2019 causing heavy damage. The meteorological structure was characterized by a trough entering the eastern Mediterranean area from northeastern Europe affecting Italy and the Balkans with cold-air advection over the Adriatic Sea. On the morning of 10 July 2019, a supercell developed along the coast north of Pescara (central Italy), producing intense rainfall (130 mm/3 h) and a heavy hailstorm with hailstones larger than 10 cm in diameter. In this work, the dynamics and thermodynamics for triggering and maintenance of the supercell are investigated using the numerical model WRF (Weather Research and Forecasting system), satellite, radar-data, soundings, and ground observations. In the companion paper, the role of SST and orography was investigated assessing that the SST spatial representation, its anomaly distribution and the topography play a key role in triggering the supercell (Ricchi et al., 2023). In this paper, high spatial and temporal-resolution model simulations and observations are used to investigate the characteristics of the supercell by analyzing both its horizontal and vertical structure. The hailstone characteristics are assessed by using the HAILCAST parameterization in which its performance and reliability are discussed.

1. Introduction

Severe weather events driven by intense convective cells are frequently observed in the Mediterranean area, in particular during May, June and July, with higher occurrence over coastal and sea areas, with a peak from 9 to 12UTC (Galanaki et al., 2018).

Climate change is expected to increase the severity of intense thunderstorms. Using climate models Kahraman et al. (2021) showed that an increase in the activity of severe thunderstorms, particularly along the coast, is expected in the coming decades. The Mediterranean region will be one of the most affected areas, specifically Italy. Taszarek et al. (2020), using lightning strikes from the National Lightning Detection Network, Arrival Time Difference long-range lightning detection network, and severe weather reports from the European Severe Weather Database (ESWD) and Storm Prediction Center (SPC) Storm Data, confirmed the finding obtained by Punge and Kunz (2016) using ERA-interim reanalysis, that hailstorm frequency has increased over northern Italy, by >1000 cases between 2020 and 2010.

Occasionally, Italy is affected by thunderstorms which can take on extreme characteristics, sometimes characterized by hail. Recently, Italy was hit by several hailstorms causing severe damage: 1) in September 2015, a hailstorm hit Naples, and in particular its coastal area, which caused extensive damage to boats both in the harbor and over open sea (Marra et al., 2017); 2) on June 10, 2019, a hailstorm hit Pescara

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(Montopoli et al., 2021; Tiesi et al., 2022) producing damage to cars and injuries; 3) on July 13, 2021, a hailstorm hit Mantua forcing airplane flights to land, 4) on July 26, 2021, in the same area, a hailstorm associated with a windstorm occurred along a highway crossing the Po Valley, so that severe car accidents were reported, together with agricultural and infrastructure damage. The hailstone size for these events was approximately 10 cm, whereas for the Pescara case, hail size reached up to or was larger of about 14 cm.

The estimation of hail size at the ground is still a challenge. Typically, the hail data at the ground comes from heterogeneous information: (i) regional hail pad networks are sporadically used and, if available, the hail events are generally under-sampled or completely missed; (ii) damage claims to insurance companies could be of some help to map the hail events at the ground, but their utility is limited to regions with high-insurance density; (iii) remote-sensing data are widely used as proxy to identify hail (eg. Laviola et al., 2020); in particular, weather radars, thanks to the detectable signatures in their data, can identify the presence of hail and hail formation processes (Montopoli et al., 2021), can identify and locate hailstorms and give some indirect indications (eg. Skripniková and Řezáčová, 2014, Kunz and Kugel, 2015 and Capozzi et al., 2017) for statistical hail occurrences (Fluck et al., 2021); (iv) local news from newspapers and digital media; (v) crowd-based initiatives with direct and timely qualitative information of ground effects of hail. Therefore, due to the local scale of hail-affected areas and the lack of widespread, standardized, and accurate hail-observing systems, operated with temporal continuity, hailstorms are not always captured accurately and comprehensively, limiting a reliable hail frequency characterization (Mohr et al., 2015). The most intense hail events are generated by intense storm systems, called “supercells”. Supercell storms are a unique class of severe convective storms, characterized by a long life (up to several hours), a motion that deviates from the mean winds and a quasi-steady rotating updraft, which persists for a period much longer than it takes an air parcel to rise from the base of the updraft to its summit, often much longer than 10–20 min (American Meteorological Society glossary; Rotunno, 1993). Supercells are usually responsible for local heavy precipitation and flash-floods, gusty winds, large hail and even tornadoes. In this work, according to Púčik et al. (2019), we refer to large hail for hailstones with a diameter larger than 2 cm, very large hail for hailstones with diameter larger than 5 cm and giant hail for diameters larger than 10 cm. Supercells can be caused by numerous trigger mechanisms, and can develop with various atmospheric configurations, especially in mid-latitude areas, such as the Mediterranean Sea basin. The mechanisms of thunderstorm and supercell formation over the Italian basin, are multiple and complex, and the various areas, formation processes, and atmospheric regimes drastically affect the predictability of these phenomena; improving the knowledge and prediction of supercell events is of strong societal and scientific interest (Miglietta and Davolio, 2022). In this complex context, one must differentiate forecast simulations, which by their nature can have low predictability, from hindcast simulations, which allow for greater model tuning, and the choice of the best numerical schemes suitable for the study of the individual event. This model tuning implies that the numerical approaches used, may not be generalizable, nor applicable to all contexts.

In particular, in the coastal area, Sea Surface Temperature (SST) plays an important role in these phenomena (Meroni et al., 2018; Miglietta et al., 2017; Ricchi et al., 2021), strongly influencing the predictability and the intensity of the supercells (Miglietta et al., 2017), especially during summer and at the beginning of autumn.

In this study, the physical mechanisms triggering the storm and producing the giant hail event that occurred from 06UTC to 13UTC of July 10, 2019 along the central Adriatic Italian coast, are investigated by means of numerical analysis, radar, radiosounding and satellite data. This supercell event was cataloged in the European Severe Weather Database (ESWD) (Dotzek et al., 2009) as the main convective event in Italy during 2019, with hailstone sizes of about 10-14 cm at the surface and 130 mm/3 h of rain. Ricchi et al. (2023) identified the SST and the topography as the key mechanisms for the triggering and maintenance of this phenomenon.

The exceptional nature of the analyzed event is more evident considering the climatology of the area affected (Webb and Elsom, 2015, Baldi et al., 2014), which indicates an expected maximum hail diameter equal to or slightly >2 cm with a frequency of 0.71 events/yr (0.3 event/yr for hail diameter >2 cm).

In this work, the aim is to document the supercell characteristics, the dynamics and thermodynamics producing the hailstorm and the structure of the hailstone event itself, with particular attention to the predictability of giant hail production using the HAILCAST algorithm. The numerical configuration is based on the “best run” approach of Ricchi et al. (2023), using “Enhanced topography “ and Sea Surface Temperature from the GOS-CNR (Buongiorno Nardelli et al., 2013) dataset. The main novelty of this work lies in the investigation and definition of this exceptional storm using 3D model output and observations with high spatial and temporal resolution of the order of 1 km and tens of minutes.

The manuscript is structured as follow: in section 2 observation and numerical model characteristics are discussed; the meteorological characteristics of the event are presented in section 3; the analysis of the horizontal and the vertical structure of the cell using radar data are discussed in section 4; the hail-storm simulation result is discussed in section 5; the conclusions are given in section 6.

2. Data and methods

To investigate the structure of the storm, several data are used, including radar, satellite images, surface weather data and radiosondes.

2.1. Remote and in-situ observations

In this work, data from the Italian radar network are used to track the storm evolution and characterize some structural and dynamical aspects of the analyzed supercells. In particular, the two radars located on Mt. Il Monte (lon = 14.6208°, lat = 41.9394°, alt. =710 m) and Mt. Serano (lon = 12.80017°, lat = 42.86594°, alt. = 1446 m) simultaneously observed the development of the supercell on an area of the order of 100 km every 5 min at kilometer scale, thus allowing an in-cloud wind reconstruction (Montopoli et al., 2021). Storm track was also seen by a local radar network managed by Abruzzo and Marche Region Civil Protection that consists of four weather radars located at the sites of Mt. Midia, Cepagatti, Tortoreto (Barbieri et al., 2022) and Cingoli (Iocca et al., 2023).

Satellite data are used to investigate the event both at synoptic and local scales. Satellite data from the Rapid Scan High Rate SEVIRI Level 1.5 Image Data - MSG dataset (Aminou et al., 2003) updated every 15 min, in the channel of Visible, Infrared and High Resolution Visible (HRV), are used in the area around the Abruzzo region from latitude 42°N to 43.6°N and longitude from 13.6 to 15.2°E. Moreover, to study the morphological characteristics and to identify the important structures of the storm cell, the Cloud Top Height satellite data product from SEVIRI/MSG (MSGCLTH) dataset available at https://www.eumetsat.int/ is used. Finally, the brightness-temperature data at the top of the cloud and height of the cloud top, both remotely sensed by the SEVIRI satellite, are used to define the top of the supercell.

The network of meteorological stations managed by the Regional Environmental Agencies of central Italian regions are used to study the dynamics at ground level during the event. The nearby radio-soundings from Zadar and Pratica di Mare are also used: 1) to explore the structure of the atmosphere some hours before the event; 2) to investigate the role of the tropopause folding in the storm evolution; 3) to characterize the characteristic of the atmosphere in the areas adjacent to the supercell.

2.2. *Numerical model and experimental design*

The Weather Research and Forecasting (WRF-ARW) numerical model version 4.0.2 (Skamarock and Klemp, 1992) is used for this study. The model configuration, producing the best results in terms of location, intensity, and timing of the storm in Ricchi et al. (2023), using the SST GOS-HR at 1 km and improved topography (GOS-TOPOENANCHED), is used in this investigation. Hence, the following configuration is used: two two-way nested (Fig. 1) domains, with the outer domain enclosing Italy at 3-km grid spacing centered at 41.916°N, 12.47°E and the nested grid centered over central Italy, including several central Italian regions at 1 km grid spacing. One hundred and ten vertical levels are used with the first level at 15 m above the ground to help reproduce the physical processes occurring in the PBL. The output frequency is set to 10 min to allow a correct analysis of the developing cell.

The following parameterization are used: the Mellor-Yamada-Janich (MYJ; Janjić, 1994) is used for the Planetary Boundary Layer (PBL); the RTMM (Mlawer et al., 1997) and Dudhia (Dudhia, 1989) schemes have been chosen for the longwave and shortwave radiation; in order to estimate hail hydrometeors the Milbrandt (Milbrandt and Yau, 2005) double-moment microphysics, which implements 6 classes of hydrometeors (Cloud, Rain, Graupel, Ice, Hail, Snow) is used; the cumulus convection is explicitly computed on both domains (Table 1, Ricchi et al., 2023). ECMWF data analyses and 3-hourly forecast (IFS, Morcrette et al., 2009) at 9-km resolution (using all vertical levels) starting at 12UTC on July 08, 2019 are used to initialize the simulations and to update the boundary conditions. As in Ricchi et al. (2023), the high-resolution Sea Surface Temperature GOS-CNR field (Buongiorno Nardelli et al., 2013) and the improved topography are used. Finally, the hail-diameter prediction module (Hailcast model; Adams-Selin and Ziegler (2016) is used to forecast the hailstones dimensions for this localized hailstorm.

HAILCAST is the module used in this study to forecast hail; it was developed by Brimelow and Reuter, 2009,Adams-Selin and Ziegler, 2016 and then updated by Adams-Selin et al. (2019). With the aim of testing the ability of HAILCAST to predict severe events developing in complex regions such as the Mediterranean area, it was used for simulating this event. WRF HAILCAST is a 1-D model and computes the maximum size of the hail in the air column, which may not have the same size of the hail reaching the ground. Hence, this is a limitation for this module aside from the fact that the smoothness and wetness of the surface of hail are accounted for in the forecast. Using the data collected during an observation and calibration campaign for HAILCAST in the USA, Adams-Selin and Ziegler (2016) found that the seeds present in the initial phase of the storm are very important for predicting large hail (> 50 mm).

3. Case study: hailstorm on July 10, 2019

On July 10, 2019 a hailstorm occurred in central Italy. Before the supercell development, the meteorological structure was characterized by an upper-level trough with the axis tilted NE-SW over northern Italy consistent with westerly wind in central and southern Italy and northeasterly wind in northeastern Italy (Figs. 2a and c). At the surface, a pressure minimum was located south of Pescara consistent with the local advection of cooler air from the Balkans (Fig. 2c). Moreover, because of the large geopotential gradient at upper levels, strong wind was also present in the mid-troposphere (Fig. 2a). At 10.00 UTC, as the supercell developed, a local pressure minimum was observed at the surface north of Pescara allowing for convergence to occur. In the meantime, the upper-level trough moved slightly southward enhancing the NE-SW tilt of the trough axis. This resulted in an enhancement of the cooler and dryer northeasterly advection associated with the bora jet traveling southward as described in Ricchi et al. (2023).

Moreover, a sea surface temperature anomaly characterized this event. A thunderstorm structure developed along the north coast of Pescara, causing heavy rainfall between 09 UTC and 11 UTC. A 3-hourly accumulated rainfall of 130 mm/3 h was recorded at Pescara Porto with maximum rainfall reaching 110 mm/h between 10:30 UTC and 11:30 UTC (Fig. 6b in Ricchi et al., 2023). Moreover, an intense hailstorm hit the city of Pescara with giant hailstones reaching 10–14 cm in diameter (Tiesi et al., 2022, Online image and video).

In summary, as stated by Ricchi et al. (2023) the evolution of this storm was driven by the interaction of different air masses in the area of

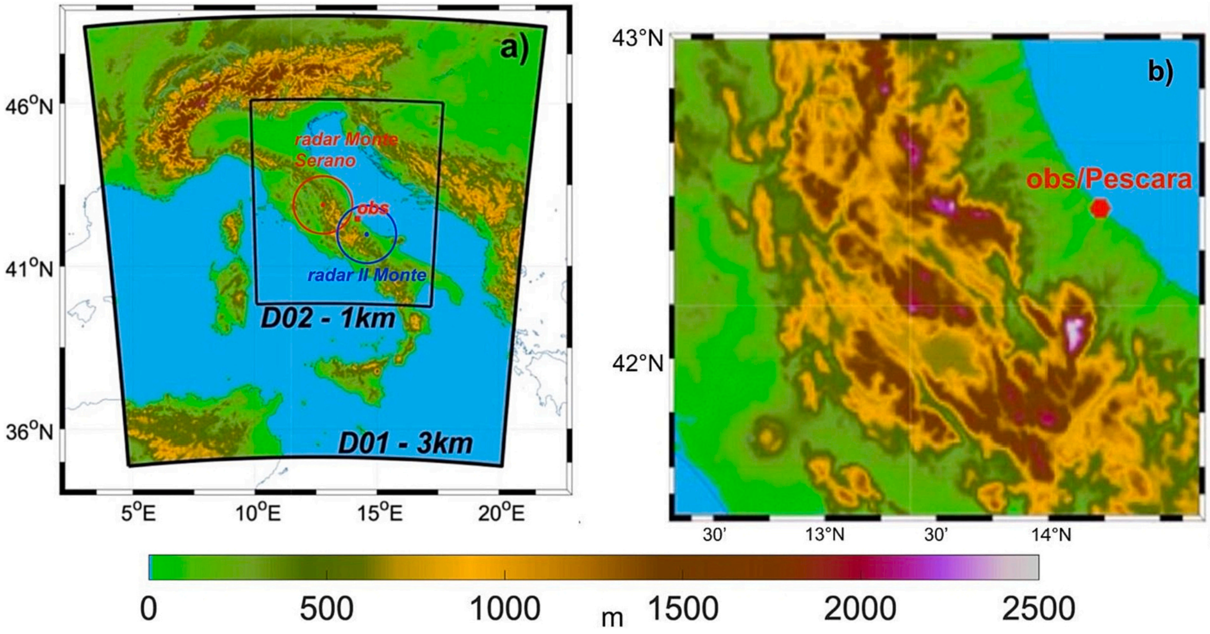

Fig. 1. Domain configuration, red dot is the Pescara station location. In panel a) Domain 1- at 3-km spacing, and domain 2 at 1-km grid spacing; b) windowed-in region of interest to show the complex topography that characterizes the studied area. Red circle Monte Serano radar area (100 km radius in red) and blue circle Il Monte radar (100 km radius in blue) described in Montopoli et al., 2021. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

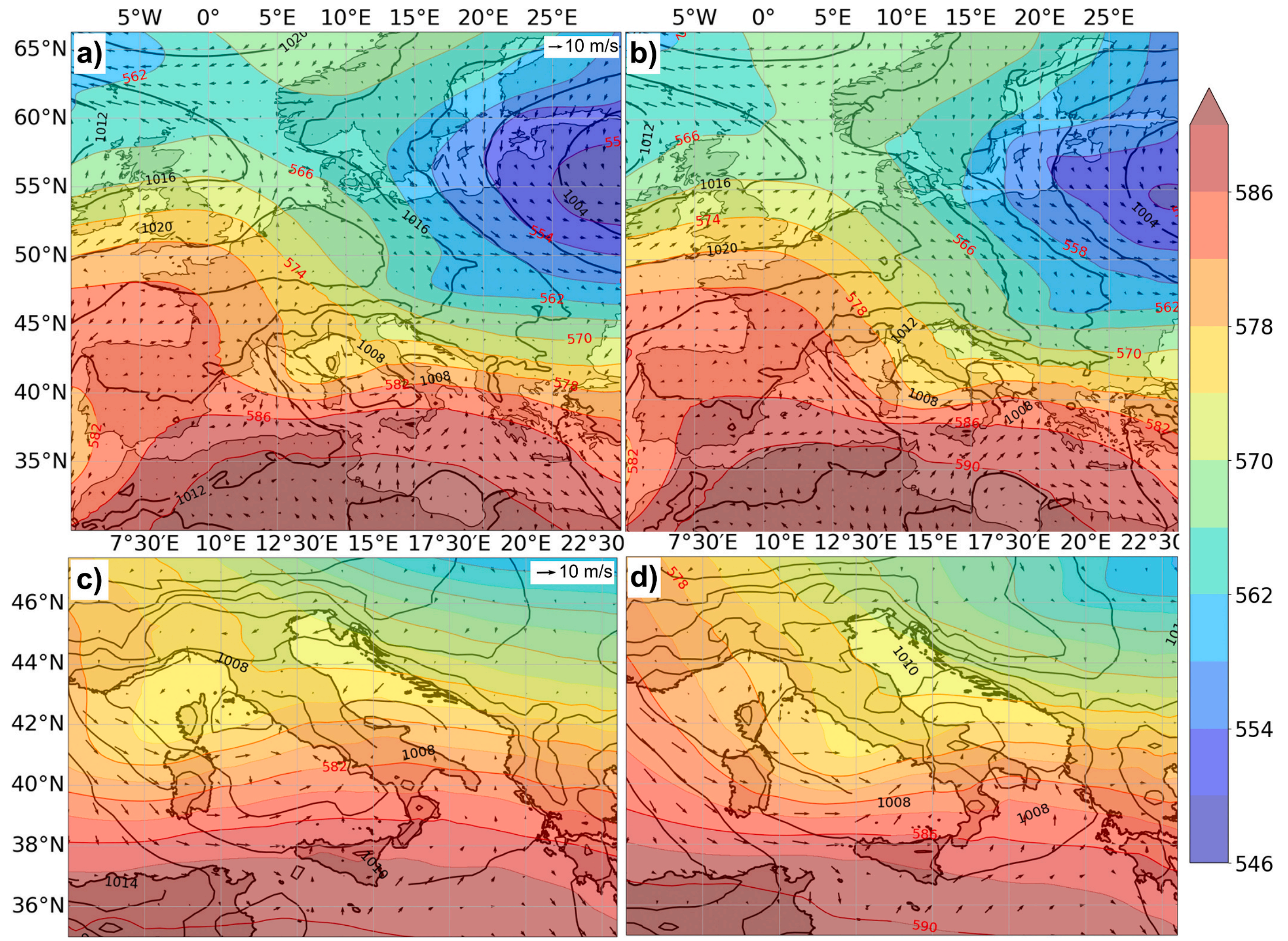

Fig. 2. 500 hPa (dam, shaded) and mslp (hpa, solid lines) wind at 10 m (vectors) at 06UTC (a) and 10UTC (b). Panels c) and d) as in a) and b) respectively, but windowed-in over Italy. The two selected times are referred to before and after the development of the supercell.

its formation:

i) the convergence between the mass of mild low-level air from southeast and cold Bora dry air masses from Northeast, along the coast of Pescara, which determined conditions of potential instability;
ii) the entrance of cold and dry air masses at mid and upper-level, from the northwest (the hinterland of the Apennines).

4. Analysis of the cell: radar and model simulation

Based on Ricchi et al. (2023), where the WRF model's ability to reproduce the storm was established, the following analysis aims to investigate the structure of the supercell and the physical processes producing its local intensification.

For this study, model outputs every 10 min, between 10:10 and 10:30 UTC (the time when the supercell moves near the Pescara area, according to the radar data), are analyzed because of the highly localized and fast-moving intense cell.

The 3.5 km Constant Altitude Plan Position Indicator (CAPPI) radar data show (Fig. 3a) that the storm rapidly evolves in the "Developing Stage" between 9:40 UTC and 10:30 UTC, moving rapidly southward along the central Adriatic sea coast. This development follows the evolution of the relatively cold air that moves along the Adriatic coast. In this phase, a small, but well-structured thunderstorm cell develops in the prefrontal area, near the Abruzzo coast. The "mature stage" of the storm occurs around 9:30–09:45 UTC, as the storm is embedded in the pre-frontal convective structure near Pescara (Fig. 3a). In the mature stage, the storm takes on CAPPI values higher than 60 dBZ and an elongated shape, perpendicular to the coast (Fig. 3b). Several typical supercell radar features are evident. The hook echo (F1) caused by the rotating updraft, which is also clearly visible in the bounded weak echo region (F6) area in panel c, that captures some falling precipitation to form a reflectivity factor depression; the forward (F2) and rear flank (F3) which are the main and wide region of heavy precipitation, including hail; the V-shaped notch signature which is the obstruction caused by upper-level winds that are then forced to be deflected around the core of the storm (F4), and the three body scatter signature (F5) which is a multiple scattering mechanism among radar signal, large hail aloft and the Earth surface that makes the radar-return incorrectly located, and in particular further away in range. In this mature supercell phase, the interaction among the mass of dry, cold air associated with Bora jets, arriving from north Adriatic Sea, and the mild, unstable air from the south, associated with the cyclonic circulation, and dry air masses, at mid and upper-level, arriving from Appenines, takes place (Figs. 8g-h in Ricchi et al., 2023). The "Dissipating Stage" occurs around 10:40 UTC in Pescara (first dissipating stage). Later, the storm regenerates between Pescara and the Gargano region, with more widespread rainfall, an enlarged rainfall area with values of CAPPI below 50dBZ.

The time evolution of the storm reproduced by GOSTOPOENANCHED run agrees with the radar observation, as the comparison between Figs. 4c-e, Figs. 4h-m, and Figs. 5d,f clearly shows.

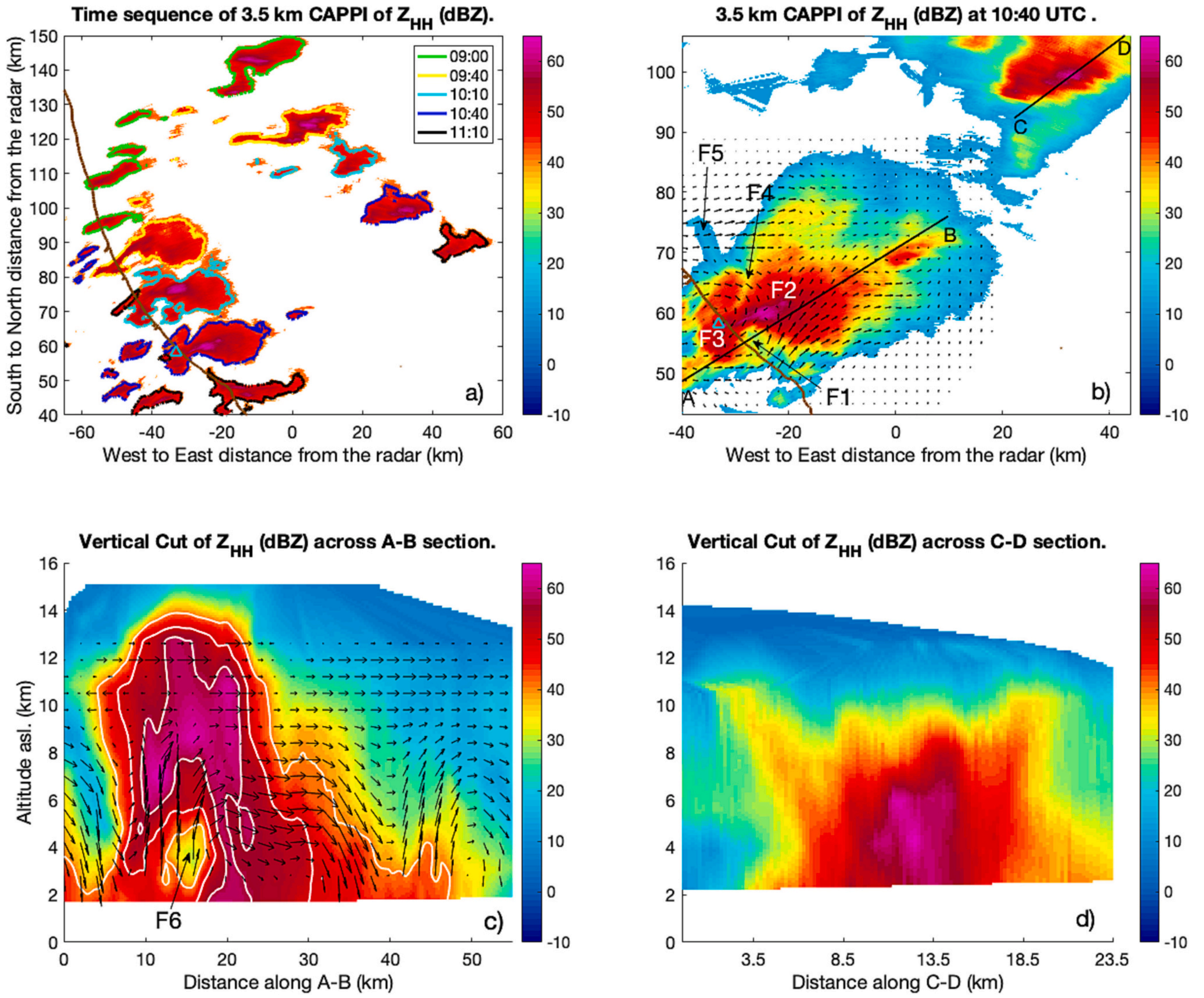

Fig. 3. (a) Time evolution of the supercell between 9:00 and 11:10 UTC on 10 July 2019 in terms of Constant Amplitude Plan Position Indicator (CAPPI) at 3.5 km altitude. In this panel, values below 40 dBZ are removed for ease of visualization. (b) Windowed-in graph of the supercell before the dissipation phase at 10:40 UTC, with dual-Doppler wind retrieval (Montopoli et al., 2021). (c)-(d) Cross-sections along transects A-B and C—D shown in panel b). Note: radar wind retrieval is performed within a common coverage area of Il Monte and Mt. Serano radars used in the study which limits the applicability of the wind retrieval to the main supercell only.

Indeed, the WRF model simulation reproduces a prefrontal cell at 9:00 UTC and the mature stage occurs between 9:50 UTC and 10:30 UTC, highlighting a very small time disagreement with the radar observations. Also, the GOS-TOPOENANCHED run develops the cell with an elongated shape perpendicular to the coast during the phase of maximum intensity (10:00–10:10UTC). As shown (Figs. 3a-b and Figs. 4a-e), there is a cyclonic circulation associated with a reduction of the reflectivity intruding ahead of the cell system; in fact, the simulation is able to reproduce (Figs. 5d,f) a rotation/convergence of winds at 3000 m height, but smoother than that observed, likely because of the coarser resolution of the simulations compared to the radar data. The Fig. 3 panels c-d show radar vertical cross section across selected transects. They will be discussed in the next section.

4.1. Horizontal structure of the supercell

As previously described, the phase of maximum intensity of the storm around 10:00–10:30 UTC is correctly reproduced by the model, therefore in what follows the meteorological parameters simulated by the model are analyzed every 10 min in the same time range. Figs. 5a-c show the structure of the rainfall and hail at the ground (accumulated every 10 min), and helicity. In this phase (at 10:10 UTC) the structure changes rapidly: initially, two cells are present with light solid precipitation (ice, hail, graupel, snow), rain in the rear of the cell, and high helicity in the front. Similar to that observed for other supercells (Qiao et al., 2018), this structure is associated with strong wind-shear in the first 3000 m (Ricchi et al., 2023) (not shown), and SRH values higher than 500 m^2s^{-2} (Fig. 5l), strongly suggesting a developing supercell. In the area between the maximum helicity and the cell (on land), low wind speed at all altitudes, and a rapid counterclockwise rotation is found, suggesting the formation of a mesocyclonic structure (as will be shown later in Fig. 8). In this phase, the maximum radar reflectivity (Fig. 5d) is approximately 50 dBZ, in agreement with the observations at 09:40 (Fig. 3a gray contours); the two cells, initially separated, start to merge. Merging is a transient phase, because in the following hours, the storm cell splits into two cells. Laterally and behind the storm cell, a cold region at 3000 m height (Fig. 5g), and a warm, moist inflow from the sea are observed. The absolute vorticity at 3000 m and the refelctivity (Fig. 5l) show two convective cells, joined dynamically in two cylinders with positive-negative vorticity, guided by the vertical wind shear

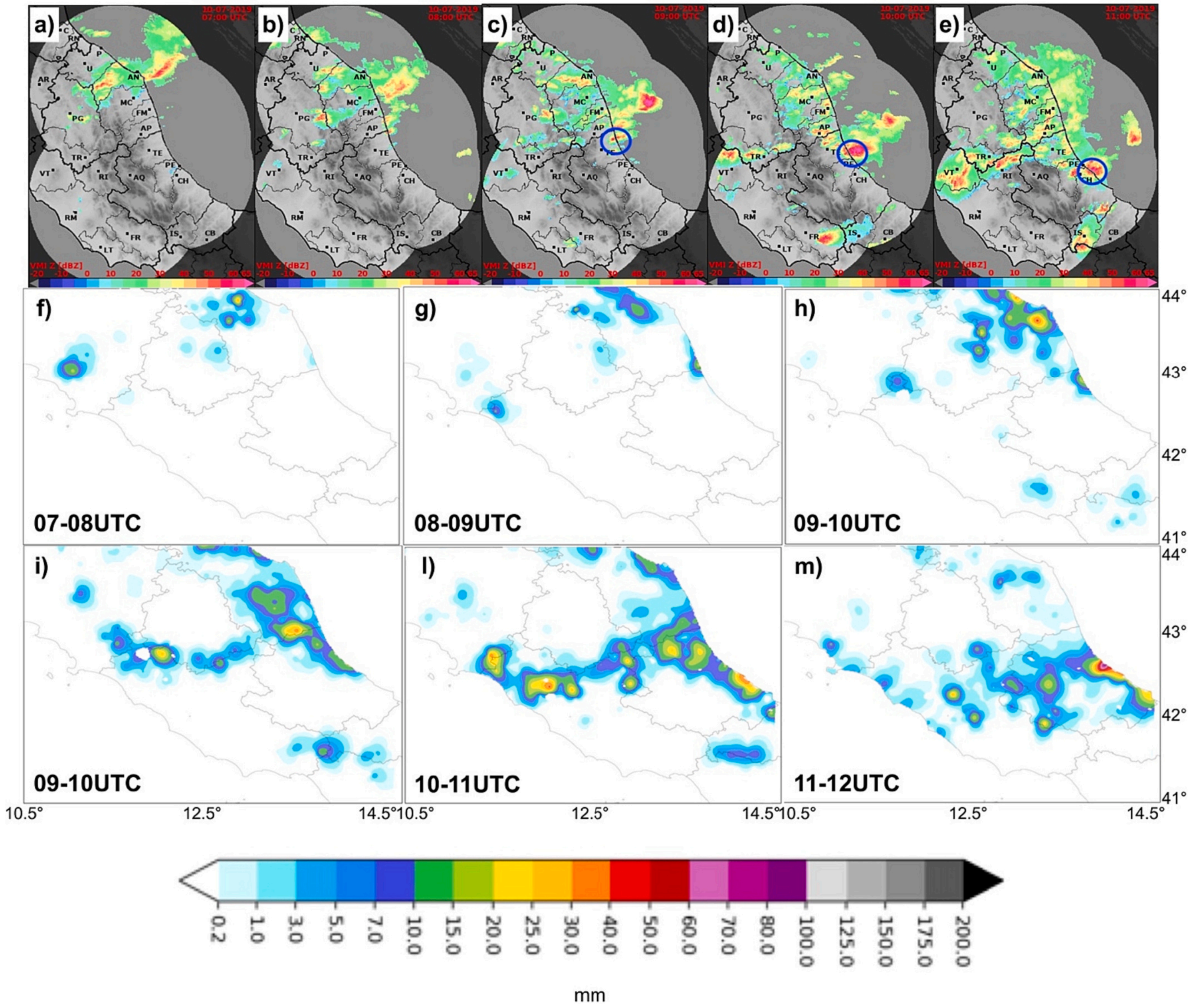

Fig. 4. Panels a-e show the radar reflectivity for the storm-evolution at 07 UTC (a), 08 UTC (b), 09 UTC (c), 10 UTC (d), 11UTC (e) taken by Abruzzo and Marche local radar network. Panels f-m show the hourly accumulated rain (mm/h), recorded by Regional Environmental Agencies weather station network and downloaded by DEWETRA data portal. Rain data are interpolated hourly, over the same grid used for numerical simulation at 1-km horizontal grid spacing.

(Ricchi et al., 2023). At 10:20 UTC (Fig. 5b) the structure shows the maximum intensity at the ground: precipitation exceeding 40 mm in 10 min and still two main lobes are simulated in an elongated structure perpendicular to the coast. Moreover, the accumulated hail reaches 8 mm in 10 min; the wind at 3000 m shows a slight rotation and the reflectivity hook that starts to form (Fig. 5e), with rotation of the winds in the vicinity of the hook (cf. with radar observations in Fig. 3b). The reflectivity near the hook exceeds 65 dBZ and the interaction of the three air masses (as described in Ricchi et al., 2023) starts to become more intense: the inflow from offshore, the prefrontal area, with the dry, cold air from the land, and the warmer and unstable air mass along the coast from the southeast (Fig. 5h). In this phase, the structure of the absolute vorticity begins to change into two separate vortex structures, clearly related to the mature stage of the supercell (splitting) and the rotating updraft within the structure starts to develop. In the last phase, at 10:30 UTC (Figs. 5c,f,i,n), the mesocyclone is mature, showing heavy precipitation all over the area, but smaller dBZ values and less-intense Θ_e gradients, especially near the convergence area. The cell is in its mature stage, in which two vortex structures (two rotating updrafts), and a central/rear area with heavy rainfall are formed (as will be discussed in the next section). The characteristics highlighted by this analysis suggest the formation of a double-core storm supercell, formed by the cells splitting.

4.2. Vertical structure analysis

- -SEVIRI and WRF: Cloud top and brightness temperature.

The cloud-top retrieved by the sensor SEVIRI onboard the MSG satellite and the simulated vertical velocity are analyzed. Note that the SEVERI data are available every 15 min, whereas the WRF simulation output is every 10 min, therefore there is a small mismatch between the two in the following analysis. With the aim of studying the upper part of the supercell, and its peculiar characteristics, the brightness temperature at, and the height of, the cloud top, remotely sensed by the sensor SEVIRI (https://www.eumetsat.int/seviri) and simulated from WRF are analyzed. Furthermore, to validate the model results, in particular the cloud top altitude, the Zadar and Pratica di mare radio soundings