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Numerical simulation of Crotone flood: Storm evolution(*)

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Summary. — A nested-grid primitive equation model (RAMS, version 4.3) is used to simulate a high-precipitation (HP) storm which occurred in Calabria, southern Italy. Storm produced intense rainfall over the city of Crotone, in the central Ionian coast of Calabrian peninsula, during the morning of 14 October 1996. Precipitation spell lasted for two hours, was highly localized and rainfall rates were intense ($>$ 60 mm/h). The aim of this paper is to reproduce precipitation measured by raingauges and to highlight local and synoptic conditions that determined the storm, in order to acquire insight into the convective environment that produced the event. Four telescoping nested grids allow to simulate scales ranging from the synoptic scale down to the high-precipitation storm. All convection in the simulation is initiated by resolving explicitly vertical motion and subsequent condensation-latent heating from the model microphysics; no warm bubbles are used to start or trigger the storm. The model is able to well simulate measured precipitation both in terms of total precipitation and rain intensity. Also the position of the major spell is acceptable.

PACS `92.60.Gn` – Winds and their effects.
PACS `92.60.Jq` – Water in the atmosphere (humidity, clouds, evaporation, precipitation).

1. – Introduction

During the morning of 14 October 1996 a severe storm produced intense rainfall over Crotone, a city located in the central Ionian side of Calabria peninsula (fig. 1).

The event was determined by a severe storm that produced very intense rainfall ($>$ 60 mm/h) over the city. The presence of large asphalt areas and the nearby sea inhibited water drainage and determined damages to properties. In addition six people were killed by the flood. The storm lasted for two hours producing about 150 mm of

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(*) The authors of this paper have agreed to not receive the proofs for correction.

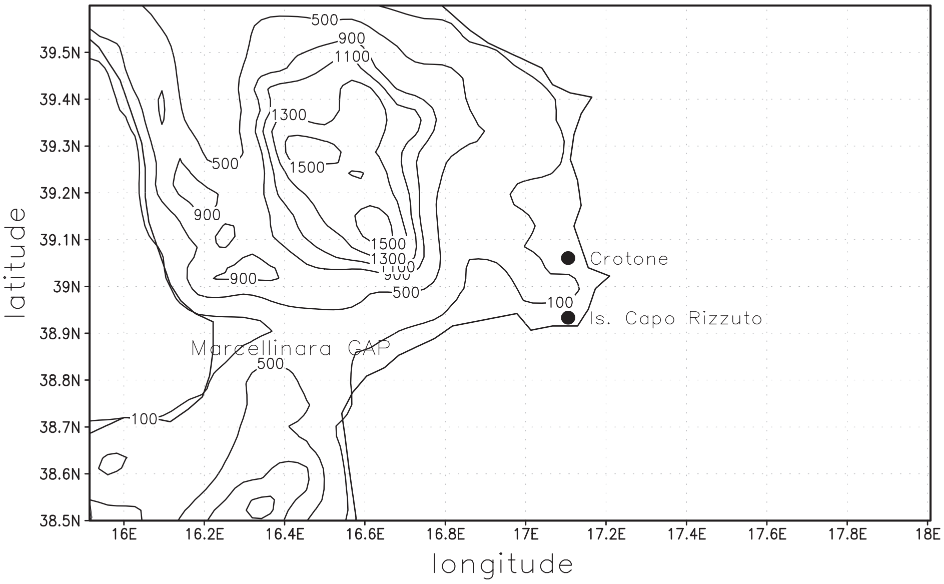

Fig. 1. – Orography of central Calabria averaged over 3 km^2.

precipitation and can be classified as a "flash flood". High localized precipitation spell and high rainfall rates show the convective nature of the storm investigated.

Several papers on convective storms have demonstrated that their nature and structure depend on a large number of environmental factors, including vertical wind shear, buoyancy, mesoscale forcing and nearby convection [1-3]. We simplify the problem limiting these factors to two basic ingredients: CAPE (Convective Available Potential Energy) and vertical wind shear. On the basis of the values of these two parameters classification scheme helps to classify convective storms. Three basic types can be defined: the isolated, short-lived (< 40 min) cell; the multicell storm that consists of many short- or long-lived cells; the supercell storm consisting of organized long-lived (> 60 min) cells. The term of supercell was first introduced by Browning [4] in reference to storms that exhibit evidence of strong rotation when viewed with time-lapse photography and, recently, supercells have been defined as storms that have persistent spatial correlation between updraft center and vorticity center. The conceptual model of a classic supercell, introduced by Browning, has little changed in the last 20 years: most of the precipitation falls downwind from the main storm updraft, which lies above the intersection of the forward flank and the rear flank gust front. A quantitative definition of supercell is given in Moller [5].

From a synoptic point of view this rainstorm was completely different from other precipitation events that produced damages over Calabria and highlights a different route to severe weather. In this country intense and abundant rainfalls are, usually, related to deep low-pressure pattern in the South-Central Mediterranean basin (usually over Sicily or between Sicily and Sardinia islands [6]). This baric situation determines advection of warm maritime unstable air over Calabria that interacts with complex orography of the peninsula and with the warm central Mediterranean sea. These interactions determine air masses uplift, convection development and storm reinforcement thanks to water vapor exchange between the meteorological system and the warm Mediterranean sea [7]. During Crotone flood, however, synoptic situation was favorable to ordinary cells/supercell development, *i.e.* large CAPE (Convective Available Potential Energy) and strong vertical shear.

In this paper we use Regional Atmospheric Modeling System (RAMS) to study the storm. After an introduction on large-scale conditions and raingauges data we introduce model configuration, then results of a simulation and conclusions are derived.

2. – Synoptic overview and measurements

In this section we report synoptic scale conditions, derived from ECMWF analysis, and measurements available from meteorological stations. These refer to raingauge data available from a stations subset of the network of the Istituto Mareografico ed Idrografico-Dipartimento di Catanzaro and to data collected at Crotone ground station belonging to Italian Air Force. Last dataset will be used also to evaluate model output in the grid point nearest to Crotone station.

Figure 2a shows sea level pressure and wind field at 00:00 UTC, 14 October, *i.e.* about nine hours before precipitation spot over Crotone. Winds are plotted on the $z^* = 23$ m surface, in the terrain following coordinate system used by RAMS [8]. Map evidences the presence of a low-pressure system above Balearic Islands and West Europe. Wind vectors show advection of humid marine air toward the Ionian side of Calabria. Wind direction remained almost unchanged during twelve hours preceding the storm, while surface wind intensity increased from $2.5\,\text{m s}^{-1}$ to $4.5\,\text{m s}^{-1}$ over the flooded area. Advection of unstable air from central Mediterranean basin toward Ionian Calabrian coast is confirmed by the increase of dewpoint temperature. In correspondence of Crotone station, RAMS model simulates a dewpoint raise from 15°C to 17.5°C, during the twelve hours preceding the event, that compares well with measurements at Crotone Italian Air Force station, reporting an increase from 15°C to 18°C.

Figure 2b shows geopotential height and wind field at 500 hPa surface and at same time of fig. 2a. Figure 2b shows the presence of a ridge extending from Africa to central Mediterranean basin. By this time, wind shear averaged over Calabria is about 15 ms^{-1} in the lowest 5700 m and wind vector rotates clockwise with height. During the whole event, *i.e.* from 12:00 UTC of 13 October to 12:00 UTC of 14 October, wind shear remained almost constant.

This synoptic situation favours development of ordinary cells/supercells if a well-localized strong updraft is present. Indeed, if high CAPE values and strong vertical shear are realized, both the tilting of the updraft and the storm rotation induced by the tilting of low-levels streamwise vorticity by the updraft enhance storm intensity and increase its longevity.

Vertical sounding over Calabria is not made and a direct measure of CAPE is not available, so we used ECMWF analysis and our simulation to plot logP-Tskew diagrams to infer CAPE during 24 hours preceding the flood, in correspondence of Crotone meteorological station. Figures 3a and b show two soundings at 12:00 UTC of 13 October and 06:00 UTC of 14 October, respectively. Solid thick line is temperature sounding, dot-dashed line is dew point sounding, thin solid line is the adiabatic parcel ascent. CAPE raised from 400 J kg^{-1} at 12:00 UTC of 13 October to 1300 J kg^{-1} at 06:00 UTC of 14 October. From fig. 3 a clockwise rotation of wind with height and an increase of dew point temperature at middle and lower tropospheric levels are also evident. This is related to advection of humid marine air from South and to the passage of a cloud system before

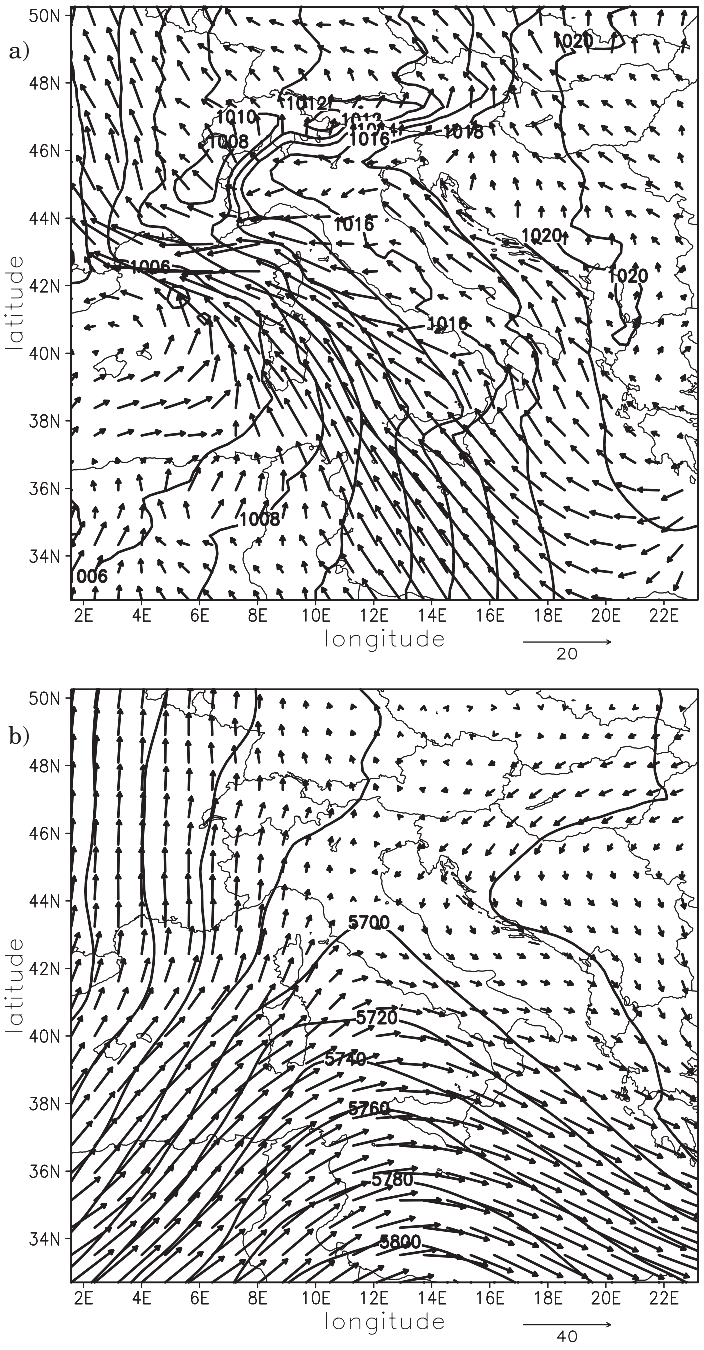

Fig. 2. – a) Sea surface pressure and wind vectors at 00:00 UTC of 14 October 1996 derived from ECMWF analysis. Figure also reports the first grid used in the simulation. b) As in a) but for geopotential height and wind vectors on 500 hPa surface.

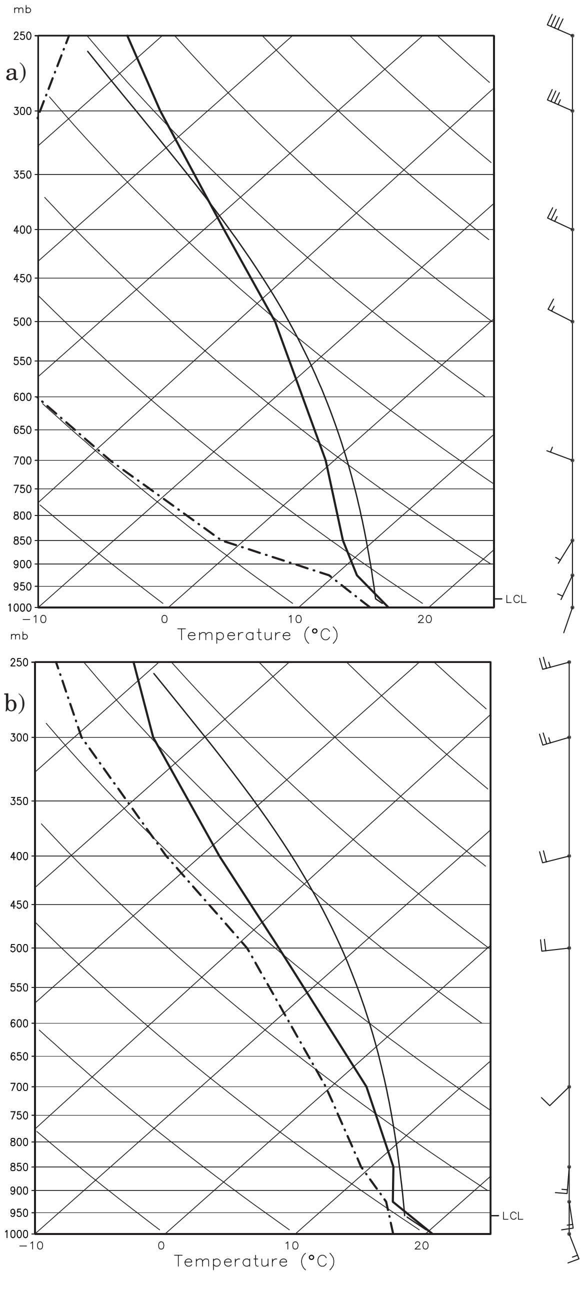

Fig. 3. – a) Vertical sounding in correspondence of Crotone station derived from ECMWF analysis on 12:00 UTC of 13 October. b) As in a) but for 06:00 UTC of 14 October.

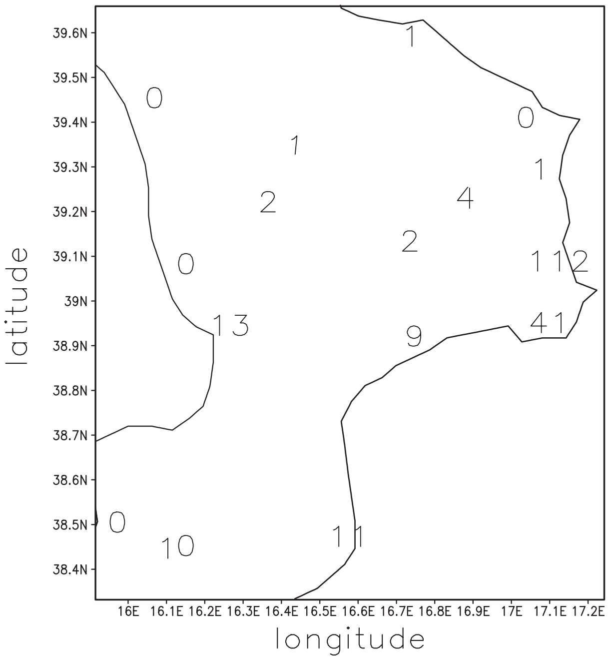

Fig. 4. – Rainfall measured by a stations subset of Istituto Mareografico ed Idrografico-Dipartimento di Catanzaro.

main storm (see below). Temperature gradient between 700 hPa and 300 hPa raised from 6.8°C/km to 7.4°C/km increasing instability. From Crotone "sounding" CAPE it follows that, regardless to the storm type, severe weather can occur because, owing to high CAPE value, updraft is strong.

In fig. 4 we report measurements made by a subset of raingauges of Istituto Mareografico ed Idrografico-Dipartimento di Catanzaro network. Numbers represent the precipitation cumulated at stations from 12:00 UTC of 13 October to 12:00 UTC of 14 October. This figure highlights precipitation spot that characterized the flood. All stations, if we exclude Crotone and Isola di Capo Rizzuto, received little or no rain mainly fallen during the passage of a cloud system before the storm. To complete this analysis, we say that Crotone ground station of Italian Air Force, located 5 km far from the previous cited station, recorded 147 mm. About 95% of the precipitation fallen over Crotone was measured in two hours, between 09:00 and 11:00 UTC.

We conclude this section showing the METEOSAT infrared image at 12:00 UTC of 14 October (fig. 5), *i.e.* two hours after the precipitation spell over Crotone. It is evident the convective cell that produced the flood and the large anvil extending from Calabria toward Balkans along wind direction at high levels (*i.e.* from NW to SE). Image illustrates also the presence of a cloud system, associated with a front, over Balkans displaced in the N-W, S-E direction. This produced light rain during its passage over Calabria but it contributed to main storm development. Indeed, in our simulation, middle atmosphere was humidified by the passage of the front because of the evaporation of the falling rain that it produced. This is corroborated by the ECMWF analysis too (see fig. 3). As a consequence the entrainment of ambient air by the storm was characterized by rather

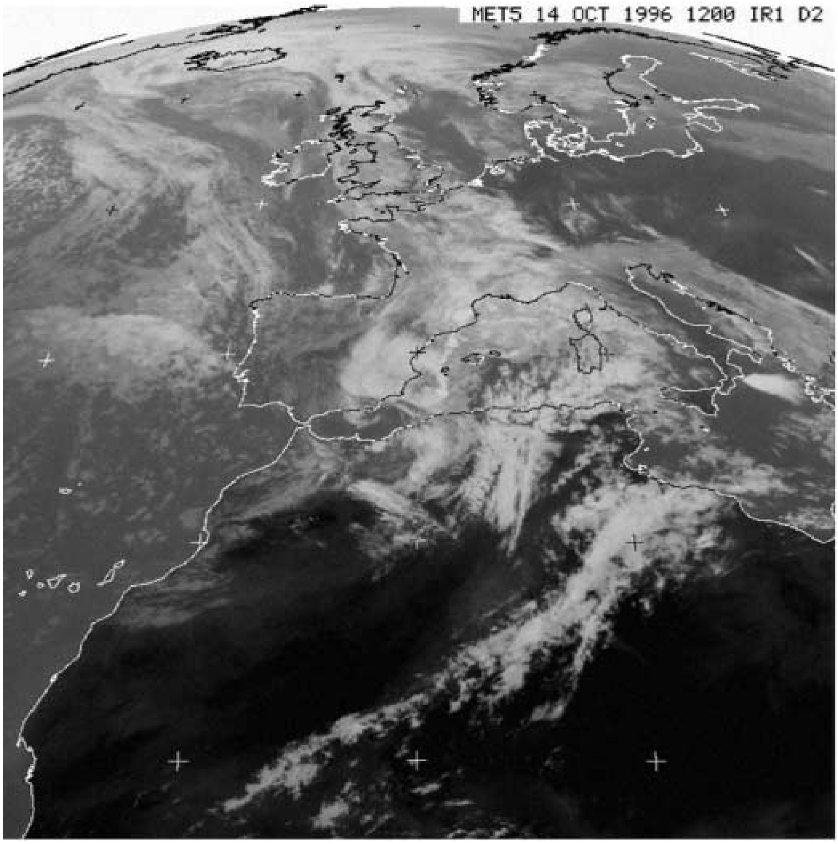

Fig. 5. – Meteosat image, infrared channel, at 12:00 UTC of 14 October. Both main storm and cloud system over Balkans are evident.

humid air both at low and mid levels due to air advection from central Mediterranean basin and to the passage of the cloud system, respectively.

3. – Model configuration

Regional Atmospheric Modeling System (RAMS) version 4.3 is used to simulate the storm. In this section we just describe outstanding aspects of interest to our purposes. A complete discussion can be found in Pielke [9].

Table I. – *Summary of grid configuration used in the simulation*

Grid number	Horizontal resolution	Grid points x, y
Grid 1	30 km	70 × 70 points
Grid 2	7.5 km	66 × 62 points
Grid 3	2.5 km	77 × 65 points
Grid 4	833 m	89 × 59 points

Condensed water species are represented with a single-bulk moment microphysics parameterization [10]. Mixing ratio of rain, snow, aggregates, hail and graupel are computed by solving predictive equations for each hydrometeor. Cloud water is computed as a residual.

Soil model uses a multilayer parameterization in which heat and moisture are exchanged vertically between different soil layers and atmosphere [11]. Vegetation cover is classified using 18 different categories. Each class has its own value of roughness, albedo, leaf area index, displacement, and root parameters.

RAMS convective precipitation is parametrized following Molinari and Corsetti [12] who proposed a simplified form of Kuo scheme that accounts for updraft and downdraft. In the simulation reported in this paper, convective scheme is activated for grid one only but, because it decreases CAPE, it may inhibit explicit convection on finest grids too, even though it is not applied there.

Topography on all four grids is generated using USGS 30 second dataset. Sea surface temperature is provided by 1° monthly mean temperature values, the NCAR SST dataset. Vegetation type and land percentage are provided by the USGS 30 second land use dataset.

Two-way interactive grid nesting is used to enhance resolution in the area of interest [8]. Initial and boundary conditions are derived from 0.5° ECMWF analysis and updated every 6 hours. In our simulation, the use of synoptic data and telescoping nested grids provides inhomogeneities necessary to initiate convection and no warm bubbles or "bogus soundings" are used.

Simulation starts the 13th of October 1996, at 00:00 UTC, and lasts 36 hours. The most intense precipitation spell occurred during the morning of 14 October.

In the simulation presented here, a total of four grids were used. Grid 1 is able to represent the evolution of synoptic scale features. Grid 2 well represents the interaction of large-scale flow with Calabrian orography and this interaction usually provides routes to initiate convection. Grids 3-4 allow to follow the evolution of the storm. Table I gives a grids configuration summary. For Crotone case study several numerical experiments were performed to assess grids number needed for useful simulation. Using the largest two grids of table I only, the event is not reproduced at all because model resolution is poor compared to storm characteristics. Using three grids, performance is enhanced, but simulation of rainfall amount is in better agreement with measurements using four grids. In addition, storm circulation and convective cells are more clear adding grid number four. We also performed few simulations using five grids (down to 300 m resolution), but no significant improvements were obtained. In addition, use of grid five increases computing time, due to large number of grid points needed to cover storm volume, so we decided to use four grids, as shown in table I.

4. – Results

Simulation starts at 12:00 UTC of 13 October and during first eighteen hours of run only light rain is simulated due to the passage of the previously mentioned cloud system (sect. **2**). Nevertheless precipitation humidified middle troposheric levels leaving favorable conditions to sustain convection.

Around 06:00 UTC of 14 October the flow at low levels intensifies producing a steep rise in dew point temperature. The interaction between air masses and local orography triggers convection. Indeed orography plays an important role in perturbing atmospheric

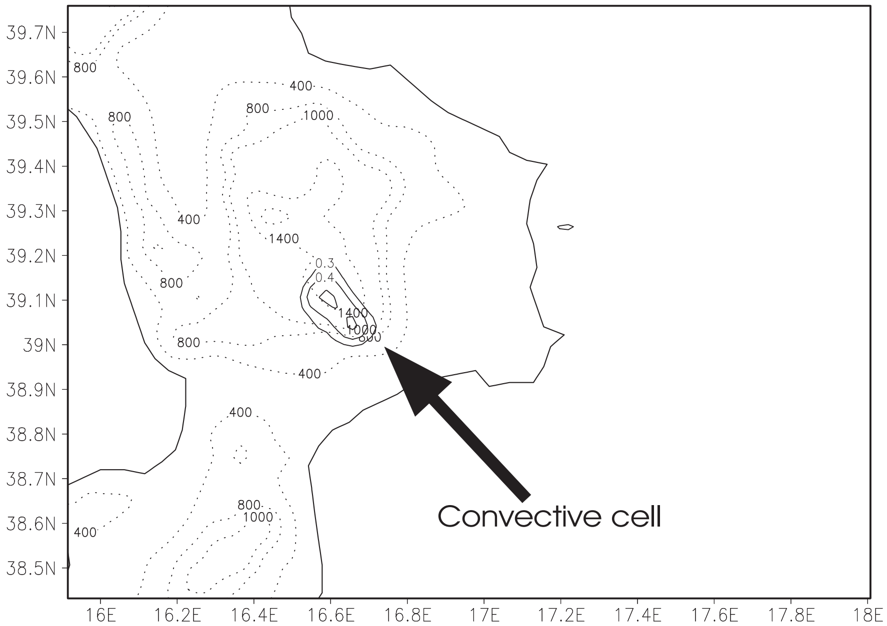

Fig. 6. – Rain on $z^* = 23$ m surface at 07:30 UTC of 14 October. Main cell that produced Crotone flood is initiated by orographic ascent.

flow and influences a wide scale of mesoscale phenomena [13]. Due to the peculiar geomorphology of Calabria several routes to convection can be realized. In particular air masses uplift is one mechanism because topography forces air to ascend triggering convection, if suitable conditions for its development are met [14, 15]. Convergence, also induced by orographic flow modification, is another mechanism, mainly in the presence of moisture gradient in the horizontal plane [16]. An interesting case study of precipitation induced by orographic uplift and consequent flow modification is given in Cosma [17]. In this paper one shows a successful simulation of characteristics and repetitive structures observed by radar measurements in Cévennes, in the Central Massif area, France. A close inspection of RAMS output fields suggests that the storm develops by the former mechanism. Indeed, flow at low and middle levels is from S-W to N-E and simulated thunderstorm starts on the west side of the peninsula, by orographic uplift, then moves to the east side, following those currents, leaving a precipitation swath just North of Marcellinara gap (fig. 9a). Figure 6 shows rain, superimposed to topography contour, at 07:30 UTC on $z^* = 23$ m surface. Topography contours range from 400 m to 1600 m and rain contours are from 0.3 g/kg to 0.5 g/kg. At this same time, other precipitation cells are present in the domain, but their rain content on $z^* = 23$ m surface is less than 0.3 g/kg, so they do not appear in the figure. The cell of fig. 6 has reached orographic ascent top and is the most active cell of the domain. So orographic ascent is the mechanism that triggers convection in our simulation, while, as discussed in sect. **2**, large-scale conditions evolve in a way that favours convection development and maintenance. We can say that orography determines where convective cell is initiated, while large-scale conditions determine when.

By 08:00 UTC the same storm of fig. 6 assumes the typical shape of an intense

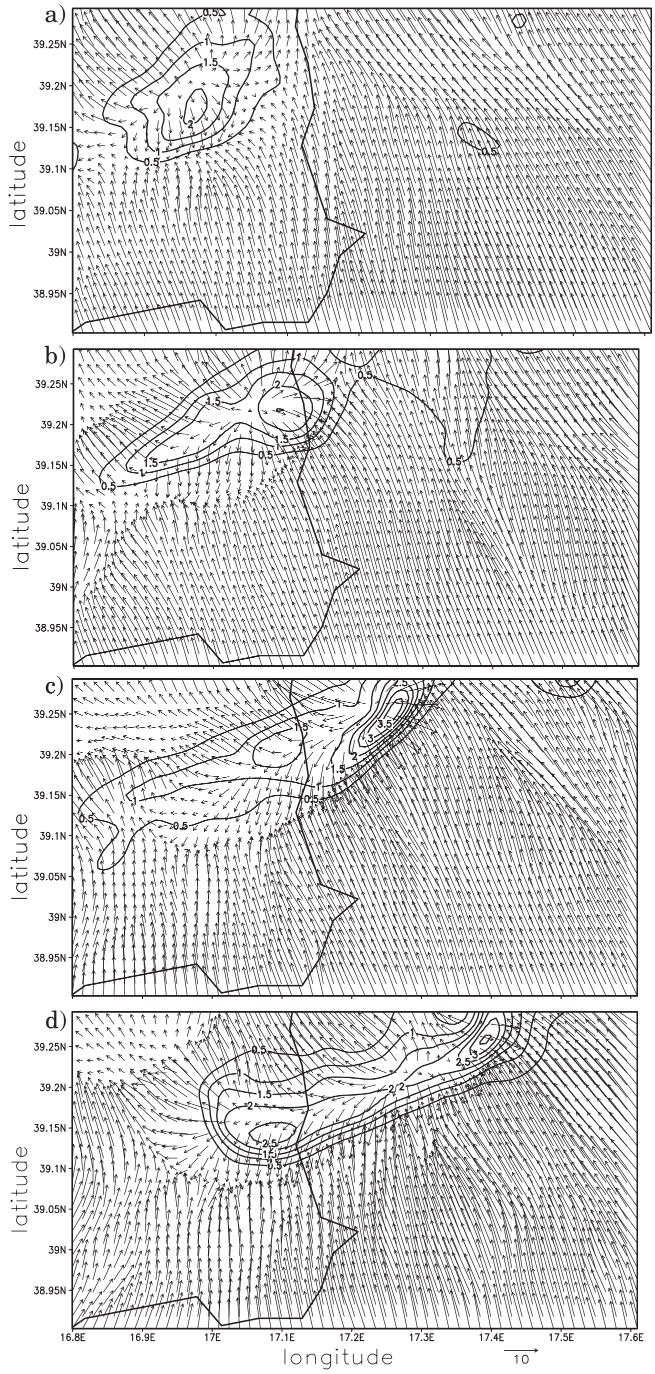

Fig. 7. – Total condensate and wind field on $z^* = 23$ m surface in terrain following coordinate system used by RAMS. The condensate field is shown every half hour starting at 08:00 UTC and ending at 09:30 UTC.

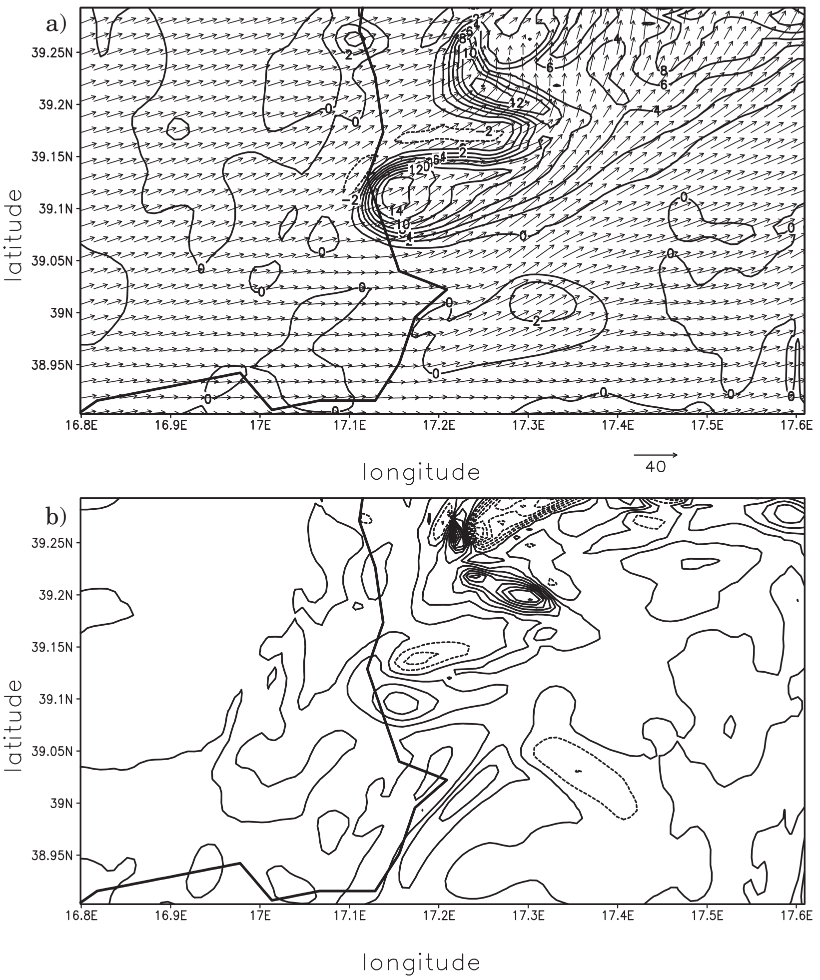

Fig. 8. – a) Wind vector and vertical velocity (ms^{-1}) on 5800 m surface. b) As in a) but for relative vorticity (s^{-1}). Vorticity contour interval is 0.001 s^{-1}. Contours from $-0.004\mathrm{s}^{-1}$ to 0.005 s^{-1}.

thunderstorm (in terms of vertical velocity, total condensate, rain-rate). Figure 7 shows time evolution of total condensate and wind field, for grid four, every 30 minutes, starting from 08:00 UTC on $z^* = 23$ m. Total condensate is given by the sum of hydrometeor concentrations simulated by RAMS and, at this elevation, it is essentially falling rain. This quantity is helpful to localize main updraft centers and storm movement. Figure 7 represents the time period characterized by the intense storm that produced the flash flood. Fine resolution of grid four, 833 m, is enough to reproduce storm structure and in fig. 7a both gust front and intense horizontal velocities are evident.

After 08:00 UTC, storm moves north-eastwards along tropospheric winds at about 6000 m and by 08:30 UTC main core reaches the coastline (fig. 7b). In addition a second cell forms in the west side of the storm, aided by the outflow coming from the biggest one. This mechanism is typical of multicell storms.

By 09:00 UTC (fig. 7c) condensate at $z = 23$ m surface assumes an elongated comma shape pattern that is a typical evolution of this kind of storm [18, 19, 2] and splits into two main cells having more than 3.5 g/kg condensate. During following 15 minutes, the storm assumes a more curved comma shape pattern and westernmost cell disappears. Nevertheless a new, more intense convective core, become dominant. This second cell forms nearly at the same position of the core shown in fig. 7a. This position is favorable to cells formation because the outflow from the main storm must rise above the orography (fig. 1). In addition, this same position is favourable to storm development induced by orographic uplift forced by mid-level flow because it is just downwind of the main orographic feature, as shown in fig. 6.

By 09:30 UTC (fig. 7d) rainstorm has a well-developed comma shape and it is formed by two main cells with a condensate content greater than 3 g kg^{-1}. By 10:00 UTC the storm moves south-eastwards over the sea.

It has been known for several years that severe storms, and in particular supercells, travel to the right of low and middle levels. In our simulation we found that the storm moved first to E then to S-E (fig. 7). The environmental wind field at low tropospheric levels is directed from S to N while at middle levels it is from SW to NE. So, the propagation of the storm is to the right of low- and middle-levels winds. Relative motion of the winds at these levels toward the storm flank is responsible of the characteristics organization and structure of this kind of storm.

Figures 8a and b show vertical velocity and relative vorticity at 10:00 UTC of 14 October. Updraft velocity is greater than $14\,\mathrm{ms}^{-1}$ and the high correlation betwen storm updraft and vorticity centers is evident. This correlation is well simulated for all cells shown in fig. 7.

All simulated updrafts, corresponding to precipitation cells shown in fig. 7, have a lifetime from 30 minutes up to 1 hour. In particular the updraft shown in fig. 8a, having a vertical velocity of 14 ms^{-1} is the same cell shown in fig. 7c at position (17.1 E, 39.2 N) and has a lifetime greater than 1 hour.

Total precipitation accumulated at ground and its intensity at the position (17.15 E, 39.12 N) are shown in figs. 9a and b, respectively. Figure 9a is in good agreement with fig. 4 and fig. 9b confirms the high intensity of the storm. In particular between 08:00 UTC and 10:00 UTC about 100 mm rainfall is simulated by RAMS. The maximum simulated intensity, 60 mm/h, is between 09:00 UTC and 10:00 UTC. Crotone station of Italian Air Force measured about 10 mm before 09:00 UTC, then 140 mm were recorded between 09:00 UTC and 11:00 UTC confirming simulation results. Crotone station of Italian Air Force is about 5 km south of the (17.15 E, 39.12 N) position, so there is a slight mislocation of the precipitation swath.

We conclude our discussion about rainstorm showing the comparison between model simulated temperature, at the same position of fig. 9b, and measurements at Crotone station of Italian Air Force, reported in fig. 10. There is a general agreement between the curves and temperature decrease is associated with the passage of the gust front (mesofront) that generates from the adiabatic saturated descent of air masses. The comparison shows a short time lag between simulated and measured temperature, neverthless the model is able to catch temperature decrease. This evidences that RAMS model well describes the mesofront of Crotone flood.

To the extent that our simulation can describe convective characteristics of the flood, we use the suggestion of Browing and Weisman to classify the event [20, 2]. Following these authors we divide the cells spectrum into two classes: ordinary cells and supercells. Multicell storm, as the one simulated in this paper, can be made up of a combination

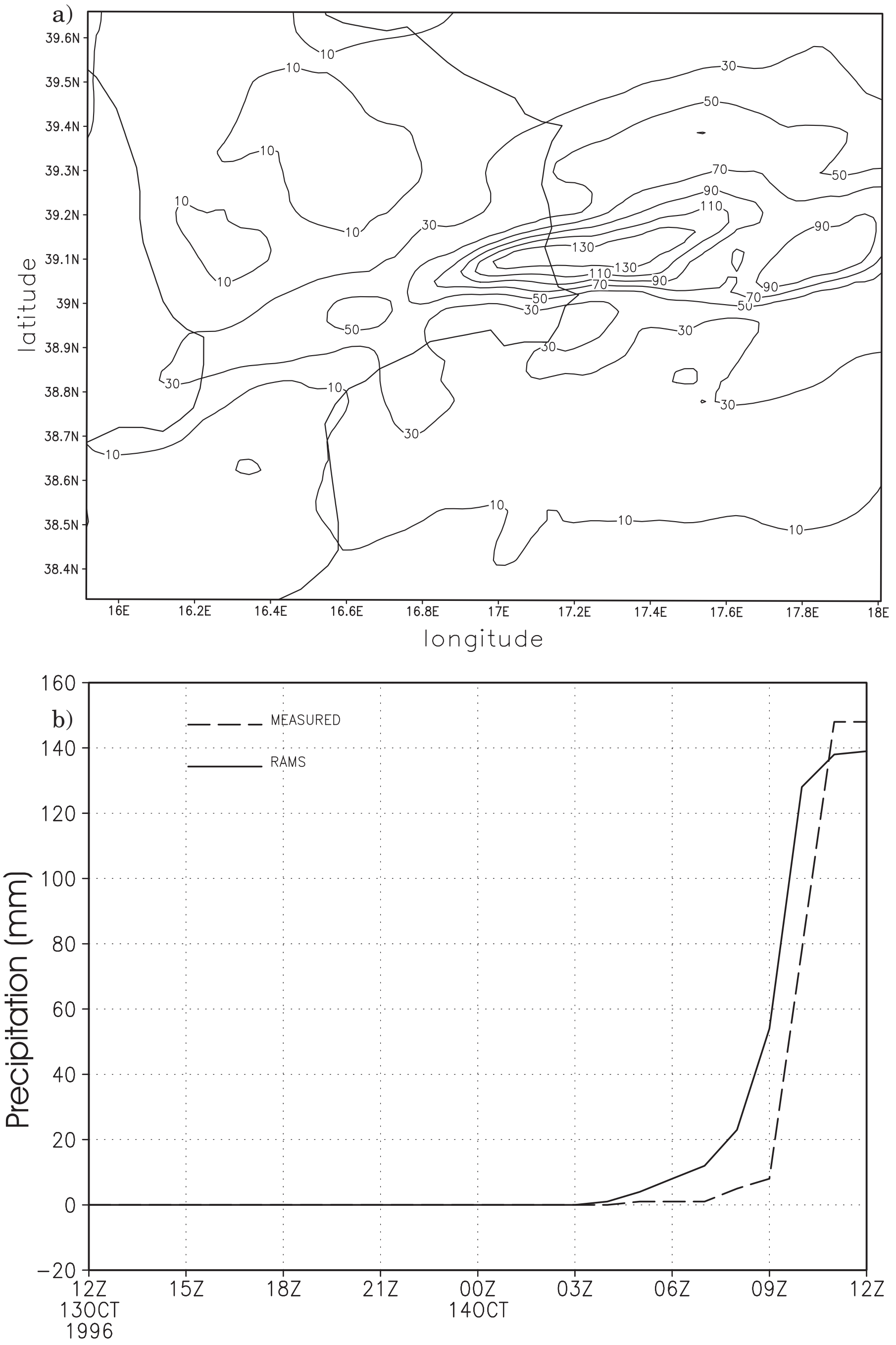

Fig. 9. – a) Total precipitation (mm) cumulated by RAMS during the event. b) Total precipitation (mm) cumulated by RAMS during the event at the position (17.15 E, 39.12 N). We also show measured precipitation at Crotone Italian Air Force station for comparison.

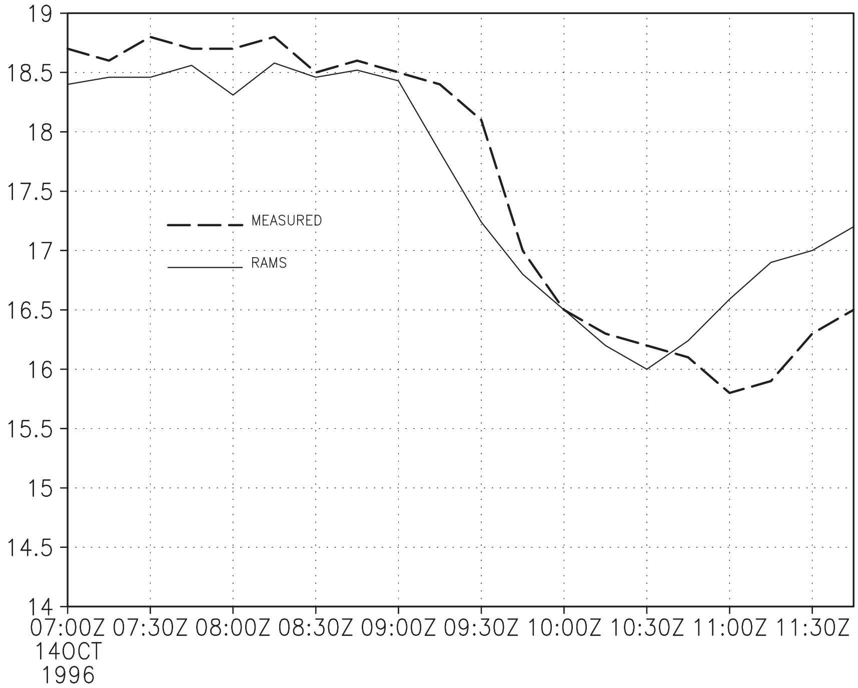

Fig. 10. – Comparison between simulated (solid line) and measured (dashed line) temperature in correspondence of Crotone Italian Air Force meteorological station.

of them. The basis for differentiating among these classes are their dynamic distinction: lifetime, storm propagation, correlation between vorticity centers and updrafts, Bounded Weak Echo Region (BWER), dynamic structure. In this context the multiple cell nature takes on only a secondary significance with respect to the dynamic structure of the cells. Our simulation of Crotone flood developed several cells during its total lifetime and some of them resemble, at a first inspection, supercells. Indeed, lifetime, storm movement, correlation between updraft and vorticity centers are typical of supercells. Neverthless, a closer inspection of the simulated fields did not reveal the presence of the BWER and two other typical dynamic aspects of supercells. In particular, in these kind of storm, most of the precipitation falls downwind from the main updraft that is not the case of our simulation; in addition, we were unable to simulate a complete rotation around the updraft in the classical sense even in a more resolved simulation that used a fifth grid having 300 m resolution. For these reasons we conclude that, even if some of the simulated cells can have, at a first inspection, supercell characteristics, the storm resemble a quite organized multicellular one, without supercells.

5. – Conclusions

In this paper we simulated the evolution of a multicell storm that produced damages to properties and killed six people in the city of Crotone, and we compared model output with available measurements. Results can be summarized as follows.

1) Storm originated in highly favorable conditions to severe weather development

because of high CAPE and vertical shear intensity. The passage of a front humidified middle tropospheric levels and low-level flow from south injected warm humid marine air through the flanking line of the storm. Convection was initiated by the interaction of large-scale flow with the complex Calabrian orography, by orographic uplift. No warm bubbles or bogus sounding were used to initiate the storm. Once started, it moved eastwards then south-eastwards, to the right of the mean low-levels and middle-levels winds.

2) Synoptic pattern occurred during Crotone flood is completely different from typical synoptic conditions recorded during heavy precipitation events in Calabria and it represents a second route to severe weather.

3) Intense convective storms are associated with large winds, strong vertical shear, high CAPE, mesofront and intense precipitation. All these features are both simulated by RAMS and measured at Crotone station of Italian Air Force or inferred by ECMWF analysis. Even if we cannot confirm the behaviour of every single cell and even the convective nature of the storm, due to lack of measurements, results are realistic in terms of precipitation amount, intensity and distribution, and in the simulation of mesofront.

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