Atmospheric Research 100 (2011) 586–602

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmos

Mechanisms for convection development in a long-lasting heavy precipitation event over southeastern Italy

D. Mastrangelo [a,⁎,1], K. Horvath [b], A. Riccio [c], M.M. Miglietta [d]

[a] Department of Environmental Sciences, Parthenope University of Naples, Centro Direzionale Isola C4, 80143, Naples, Italy
[b] Meteorological and Hydrological Service, Gric 3, 10000, Zagreb, Croatia
[c] Department of Applied Science, Parthenope University of Naples, Centro Direzionale Isola C4, 80143, Naples, Italy
[d] Institute of Atmospheric Sciences and Climate, ISAC - CNR, Strada Provinciale km 1.200, 73100, Lecce, Italy

ARTICLE INFO

Article history:
Received 15 February 2010
Received in revised form 7 October 2010
Accepted 8 October 2010

Keywords:
Heavy precipitation
Low-level jet stream
WRF model

ABSTRACT

Observational data and outputs from the Weather Research and Forecasting (WRF) model are used to investigate a heavy precipitation event that occurred on 12 and 13 November 2004 in Apulia and Basilicata, southeastern Italy. The event lasted for more than 24 h and featured two large rainfall peaks, with values up to 250 mm in one day, recorded in two different phases over two distinct areas.

The analysis indicates that a low-level jet stream (LLJS) induced by the large-scale pattern maintained a convectively unstable environment and advected moist air masses at very low levels throughout the event. During the first phase, the orography provided the lifting mechanism to develop convection. During the second phase, the convergence developed in the low levels was sufficient to maintain a quasi-stationary linear mesoscale convective system over the nearly flat terrain of Salento peninsula.

High-resolution numerical outputs highlight that the shift of precipitation from the first to the second maximum was caused by the passage of a weak mesoscale cyclone and of an upper level short-wave trough. The delay in the modeled evolution of these subsynoptic features is considered responsible of the incorrect timing of the simulated precipitation.

The study provides further evidence of the close relationship between the occurrence of a moist and unstable southerly LLJS and heavy precipitation over the Italian Ionian regions.

1. Introduction

Deep moist convection results from the interaction of processes acting on different space–time scales (Doswell, 1987). When a moist and conditionally unstable troposphere and a mesoscale mechanism able to lift the unstable air mass are in place at the same time, deep moist convection is expected to develop (Doswell et al., 1996) and heavy precipitation to occur. Due to the short life cycle of single convective cells, heavy precipitation is recorded, especially when different cells generate and organize into a mesoscale convective system (MCS). In particular, the slow motion and the peculiar organizational structure of MCSs (Doswell et al., 1996; Schumacher and Johnson, 2005) are the main features favoring the repeated passage of different cells over the same area; consequently, high rainfall amounts may be produced.

Over the Mediterranean Basin, an environment favorable to convectively driven heavy precipitation events develops especially during late summer and autumn (Doswell et al., 1998; Romero et al., 1998). During this period of the year, the relatively high sea surface temperature supplies heat and

⁎ Corresponding author. Parthenope University of Naples, Department of Environmental Sciences, Centro Direzionale Isola C4, 80143, Italy. Tel.: +39 081 547 6575; fax: +39 081 547 6515.
E-mail addresses: mastrangelo@uniparthenope.it, d.mastrangelo@isac.cnr.it (D. Mastrangelo).
[1] Present address: Institute of Atmospheric Sciences and Climate, ISAC–CNR, Via P. Gobetti 101, 40129, Bologna, Italy. Tel: +39 051 639 9600, Fax: +39 051 639 9658.

0169-8095/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.atmosres.2010.10.010

moisture contributing to reduce the low-level static stability; moreover, synoptic-scale disturbances, associated with potential vorticity (PV) streamers elongated in meridional direction, start to move across the basin because of the weakening of the summer anticyclone subsidence (Martius et al., 2006). The occurrence of PV streamers promotes heavy precipitation by inducing subsynoptic upward motion and by enhancing the southerly moist flow on the advancing forward flank (Massacand et al., 1998).

Additionally, the synoptic environment can indirectly favor convection by forcing the onset of a low-level jet stream (LLJS); for instance, a low-level cyclogenesis induced by a persistent upper level large-scale disturbance may cause the formation of a LLJS through the enhancement of the surface pressure gradient (Homar et al., 2002). A LLJS sustains heavy rainfall by quickly and efficiently transporting moisture toward the affected area, especially when it comes from the southern portion of the Mediterranean Basin (e.g., Romero et al., 2000; Nuissier et al., 2008).

Also the complex orographic structure of many Mediterranean coastal regions favors heavy precipitation. Orographic obstacles may mechanically force upward motion on the upstream side of the mountains, promoting condensation and then precipitation (Miglietta and Buzzi, 2001) or may deviate the low-level flow and favor the persistence of convergence in confined zones (Buzzi and Foschini, 2000; Miglietta and Buzzi, 2004). Both the mechanisms may increase the precipitation amount and the risk of floods (Ducrocq et al., 2008).

The Ionian Italian region has been proven to be one of the Mediterranean areas more affected by heavy precipitation events (Federico et al., 2008; Miglietta and Regano, 2008). This region is characterized by an almost-arc-shaped topography with elevated (about 2000 m high) and steep mountains on the western boundary, along Calabria and southwestern Basilicata, by coastal plains bordered inland by small ridges (up to 700–800 m high) on central Basilicata and central Apulia, and by the flat and narrow Salento Peninsula on the east (Fig. 1). Also, it is located in the middle of the Mediterranean and is exposed to warm and humid southerly flows. The interaction of such flows with the tall and steep mountain ranges of Calabria can easily lead to deep convection (Federico et al., 2003; Moscatello et al., 2008) but also the lower orography of central Apulia can initiate deep convection under favorable conditions (Miglietta and Regano, 2008).

The rainfall episode presented in this work is a high-impact meteorological event associated with a wide Atlantic mid-tropospheric trough spanning the western and central Mediterranean Basin during the period 12–15 November 2004. Horvath et al. (2006, hereafter HF06) analyzed the first stages of this period characterized by the generation of a deep low-level cyclone over the northern Africa and the forecast sensitivity to the upper level PV anomaly (Horvath and Ivančan-Picek, 2009). Here, we analyze through observations and numerical simulations the heavy precipitation event affecting Basilicata and Apulia during 12 and 13 November 2004. Rain gauges recorded two distinct precipitation maxima in different phases of the event, with amounts larger than 200 mm recorded in both phases. Damages to road and crops were reported as a consequence of flooding.

The purpose of the paper is to identify the main synoptic and mesoscale features responsible for the generation of convection, as a contribution to understand the factors controlling the occurrence of hazardous heavy precipitation events over the Ionian Italian region.

A description of the case study is provided through the analysis of the synoptic evolution in Section 2 and of the available observations in Section 3, the numerical model setup and outputs are discussed in Section 4, the main mesoscale features leading to convection and precipitation are analyzed in Section 5, and finally, summary and conclusions are presented in Section 6.

2. Synoptic evolution

Reanalysis data provided by the European Centre for Medium-Range Weather Forecast (ECMWF; Fig. 2) show that at 12 UTC 12 November (Fig. 2a), about at the beginning of the precipitation event, the 500-hPa synoptic pattern in Europe and the Mediterranean Basin was dominated by a cutoff low centered over the western Mediterranean, embedded in a preexisting positively tilted trough. A very moist 700-hPa airstream affected the Italian peninsula. At the surface (Fig. 2b), the Azores high, positioned to the west of France, and a weaker anticyclone over Eastern Europe surrounded a wide area of relatively low pressure covering northwestern Africa, western and central Mediterranean, with a minimum of 1000 hPa centered to the south of the Atlas mountains. At the same time, a southerly LLJS was elongated from Libya toward southern Italy.

In the following 24 h (Fig. 2d and f), the southerly LLJS extended northward advecting low-level warm air to the Ionian regions. At 00 UTC 13 November, the 500-hPa cutoff low narrowed (Fig. 2c) and moved southeastward; as a result, the currents aloft the study area veered to the southwest. As shown in HF06, an upper level PV maximum above the Atlas mountain range interacted with a low-level thermal anomaly already present in the lee, causing the deepening of the surface cyclone. Downstream of the cutoff low, a weak short-wave trough (SWT) developed on the forward flank of a 320-K PV anomaly and approached southern Italy, moving from southwest to northeast between the main trough and the ridge. At low levels (Fig. 2d), a weak minimum formed over the Tyrrhenian Sea, although the pressure over southern Italy did not substantially change. The PV anomaly was co-located with the weak Tyrrhenian surface minimum (Fig. 2d) and with 700-hPa dry air mass (Fig. 2c).

During 13 November, the surface cyclone deepened and moved over Tunisia, reaching the Mediterranean Sea at about 12 UTC (Fig. 2f). The induced cyclonic circulation approached the Ionian Sea, replacing the LLJS that narrowed and shifted east–northeastward to the southern Adriatic. On 14 November, the cyclone moved toward the southern Adriatic causing a major long-lasting extreme Bora event with hurricane force gusts (Horvath and Ivančan-Picek, 2009) and slowly dissipated over the Balkan region during the subsequent day.

3. Observational analysis

The simultaneous occurrence of three ingredients—moisture, instability, and lift—generally leads to deep moist convection (Johns and Doswell, 1992; Doswell et al., 1996). The observational data are shown to relate precipitation to the

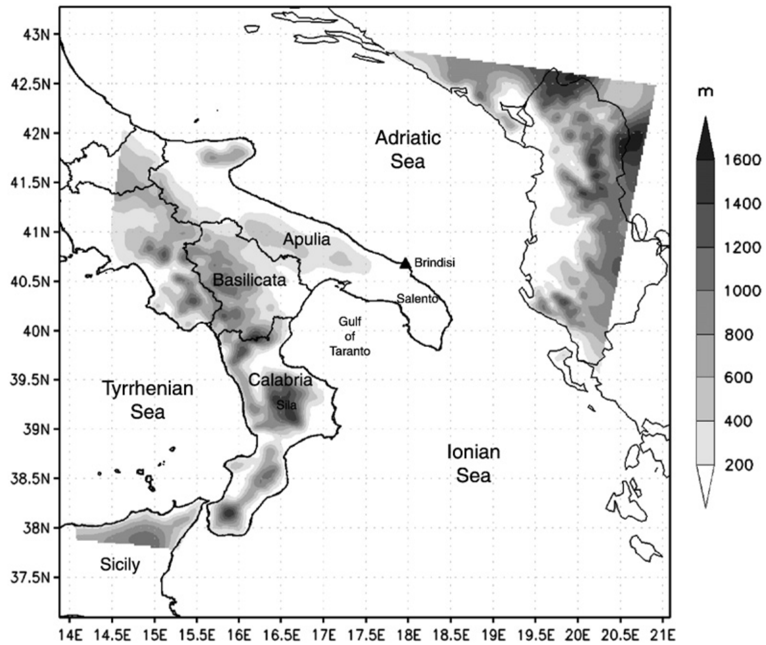

Fig. 1. Map of the Italian Ionian regions showing the orography as modeled on the WRF inner domain (m, shaded as in legend) and the geographic features mentioned in the text. The Brindisi rawinsonde site is indicated by a black triangle.

various processes that contributed to bringing the ingredients into place.

The precipitation occurring on 12 and 13 November 2004 is described through hourly rain gauge data recorded at 45 locations in Apulia and Basilicata. Satellite images are also used to identify the precipitating systems in relation with the synoptic circulation and to highlight their main features, especially over the sea, where no other observational data were available. Moreover, sounding data measured at Brindisi, close to the study area (Fig. 1), are shown to provide information on the vertical profiles of the troposphere.

The phase of heavy rainfall associated with deep convection lasted about 26 h, from 14 UTC 12 November until 16 UTC 13 November. As two distinct rainfall maxima were identified in the observations, the event was subdivided into two phases.

3.1. First phase

The first phase occupied the second half of 12 November and produced the largest precipitation amount along localized Ionian coastal areas of southern Basilicata and the adjacent Apulia territory (Fig. 3a). Over these zones, precipitation started at about 14 UTC 12 November. The two most intense precipitation peaks were observed at 17 UTC and 23 UTC, the latter producing the highest rain rate of the event, which generated 103 mm in a two-hour period.

At 12 UTC 12 November, the Brindisi sounding (Fig. 4a) depicted a slightly unstable atmosphere, as the convective available potential energy (CAPE) was about 114 J kg^{-1}; however, a low-level inversion produced a convective inhibition (CIN) of 116 J kg^{-1}. Since Brindisi is located about 100 km east of the area where the largest rainfall was recorded (cf. Figs. 1 and 3a), the thermodynamic profile characteristics are not completely representative of the pre-convective environment over the studied area. However, the sounding featured a deep moist atmospheric layer, from the surface to approximately 500 hPa, and precipitable water exceeding 30 mm, highlighting the role of the mid-tropospheric south–southwesterly circulation in advecting moisture toward the region.

A wide cloud system, located over Sicily and Calabria at 12 UTC, approached the study area from southwest in the subsequent hours. At 16 UTC (Fig. 5a), convection affected different areas of southern Italy and the Tyrrhenian Sea. However, rain gauge data indicated that the most intense precipitation occurred only in a limited area (shown in Fig. 3a). Afterwards, the whole cloud system continued to move northeastward. Convection disappeared over surrounding regions and concentrated mainly on the Ionian area, extending from the reliefs of central Calabria towards southern Apulia, as shown by the location of the crosses (Fig. 5b and c). This intense mesoscale convective system yielded the second intense rainy spell (Fig. 6a). As a result, on 12 November, the rain gauge at Marina di Ginosa recorded 248 mm, whereas, in spite of the widespread and persistent cloud cover, much lower amounts were observed in the surrounding zones (Fig. 3a). Specifically, a sharp precipitation gradient was found immediately northwest of the maximum, while large precipitation amounts with a peak of more than 90 mm extended farther to the north–northeast. This hilly zone is located north of the flat area affected by the largest rainfall amount, and resulted downstream of the mid-tropospheric winds.

3.2. Second phase

During the early hours of 13 November, precipitation weakened and started to shift eastward, over the Salento peninsula. Fig. 4b shows the Brindisi sounding taken at 00

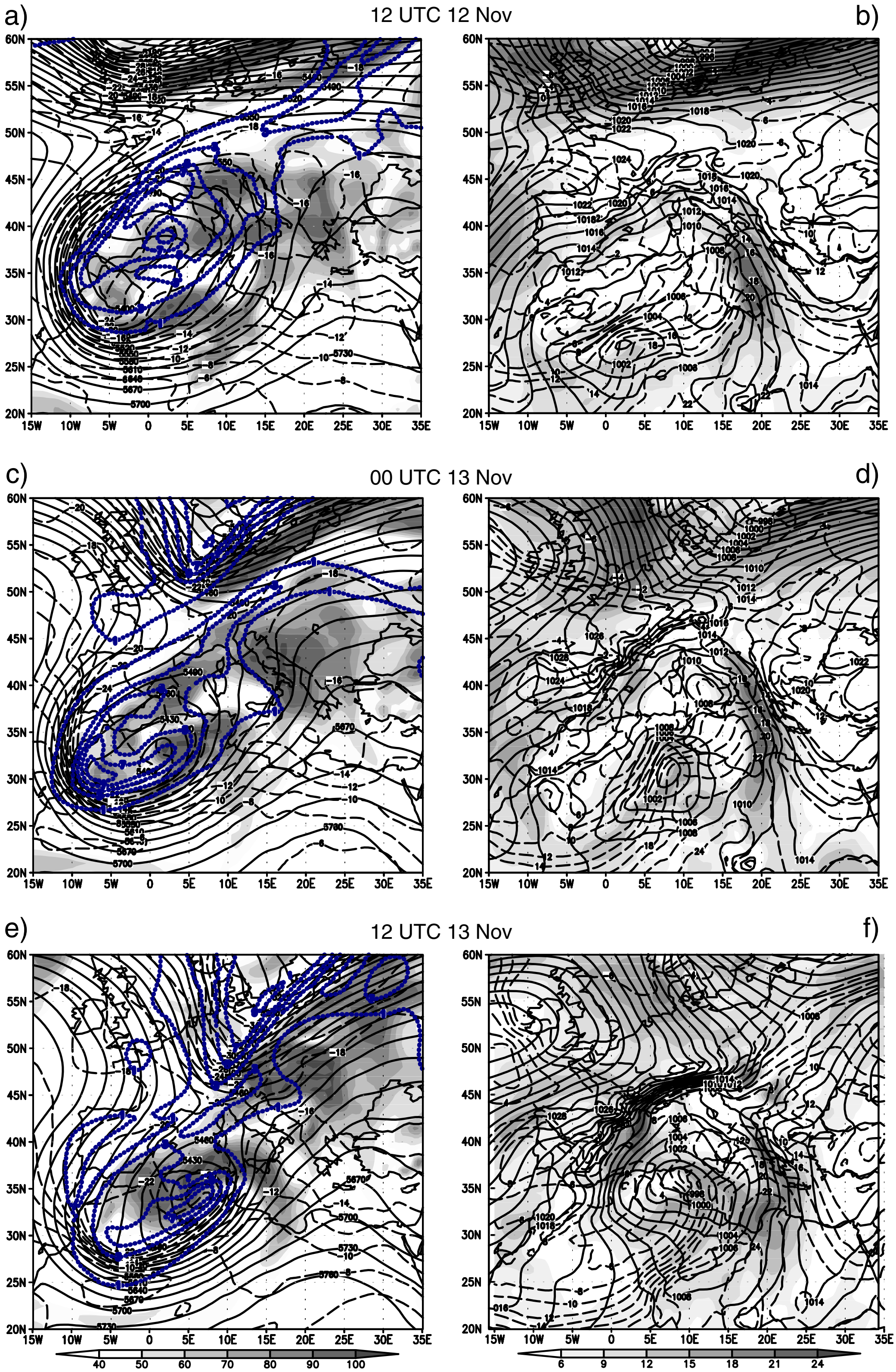

Fig. 2. ECMWF reanalysis fields. Left-hand side panels: 500-hPa geopotential height (solid contours, every 30 m) and temperature (dashed contours, every 2 C), 320-K potential vorticity (blue dotted contours, PVU; 1 PVU = 10^{-6} K m^2 kg^{-1} s^{-1}), and 700-hPa relative humidity (shaded as in legend) at (a) 12 UTC 12 November 2004, (c) 00 UTC, and (e) 12 UTC 13 November 2004. Right-hand side panels: 925-hPa wind speed (shaded as in legend), mean sea-level pressure (solid contours, every 2 hPa), and 850-hPa temperature (dashed contours, every 2 C) at (b) 12 UTC 12 November 2004, (d) 00 UTC, and (f) 12 UTC 13 November 2004.

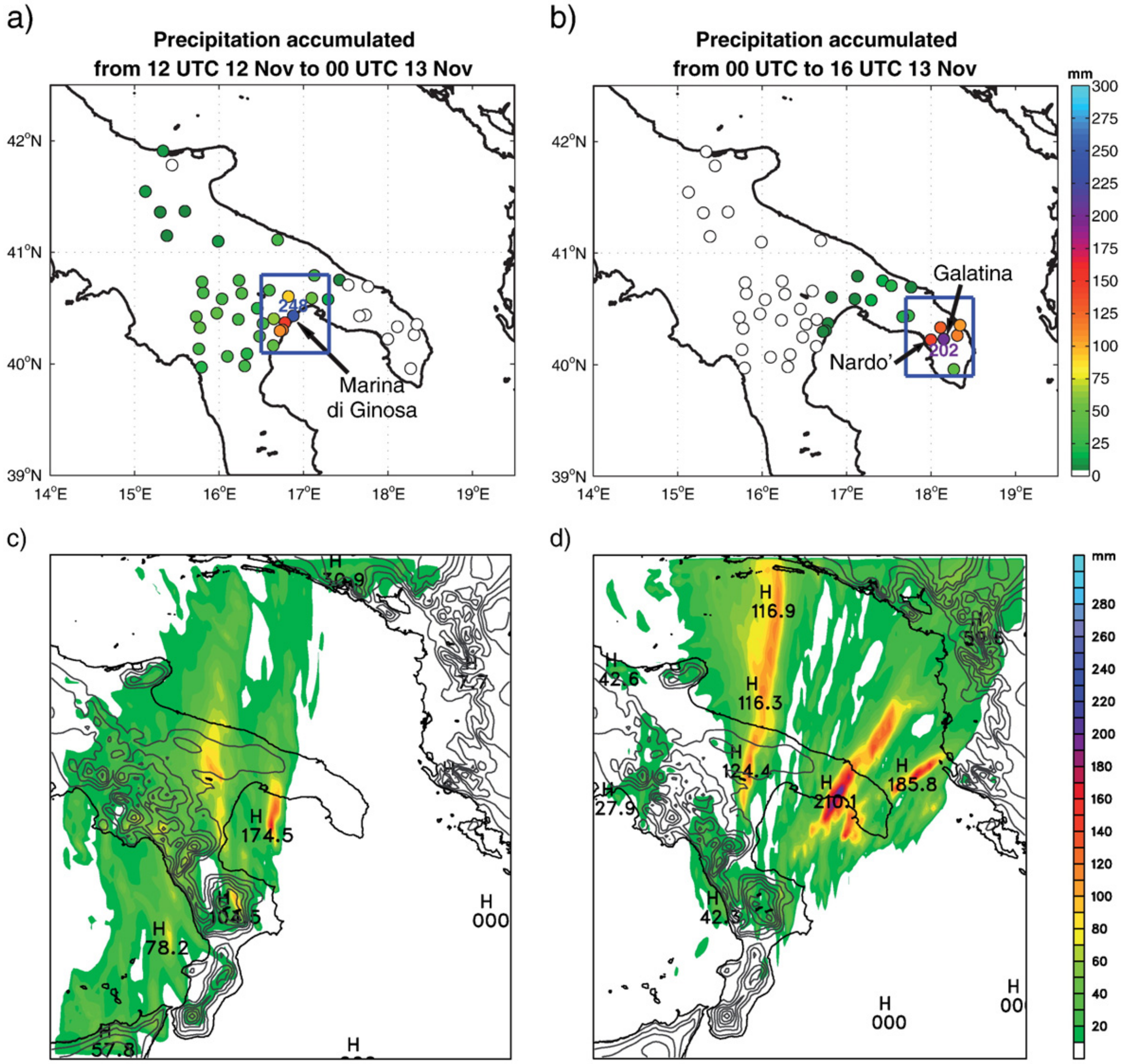

Fig. 3. Observed (top panels) and modeled (bottom panels) precipitation (mm, shaded as in legend) during the first phase of the event, from 12 UTC 12 November 2004 to 00 UTC 13 November 2004, and the second phase, from 00 UTC to 16 UTC 13 November 2004. Data from Marina di Ginosa and Galatina refer to 24-h accumulation.

UTC. The saturated and nearly saturated layers above 700 hPa were associated with the MCS covering the Ionian area (see Fig. 5d). Comparison with the sounding taken 12 h earlier (Fig. 4a) shows that, in agreement with reanalysis data (Fig. 2d), the LLJS reached Salento. Winds strengthened throughout the troposphere and the highest intensity, almost 31 m s^{-1}, was observed at 875 hPa. From the surface to this level, the atmosphere was potentially unstable ($\partial\theta_e/\partial z<0$, with θ_e indicating equivalent potential temperature and z the vertical coordinate) as a consequence of the thermodynamic properties of the LLJS, i.e., the almost saturated relatively warm air close to the surface and the drier air immediately above. This is a consequence of the fact that the LLJS developed over the northern African mainland, where the air was initially dry, and subsequently moved northward over the sea so that the sea surface fluxes could moisten the very lowest layers.

At 03 UTC 13 November, moderate precipitation—rain rate larger than 5 mm h^{-1}—reached the central part of Salento and persisted until 09 UTC (Fig. 6b), when the highest hourly peak of 37 mm was recorded at the rain gauge station of Nardò, to the western side of the narrow area affected by the strongest precipitation (Fig. 3b). The sequence of satellite images for this period (Fig. 5d–f) shows that the MCS shifted eastward while its main axis slightly rotated clockwise until 04 UTC, causing the observed precipitation shift. At this time, the cloud shield was oriented from southwest to northeast and its most active core was organized along a line. The linear structure persisted for about six hours. During this period, the tip of the MCS, which had previously moved from the central

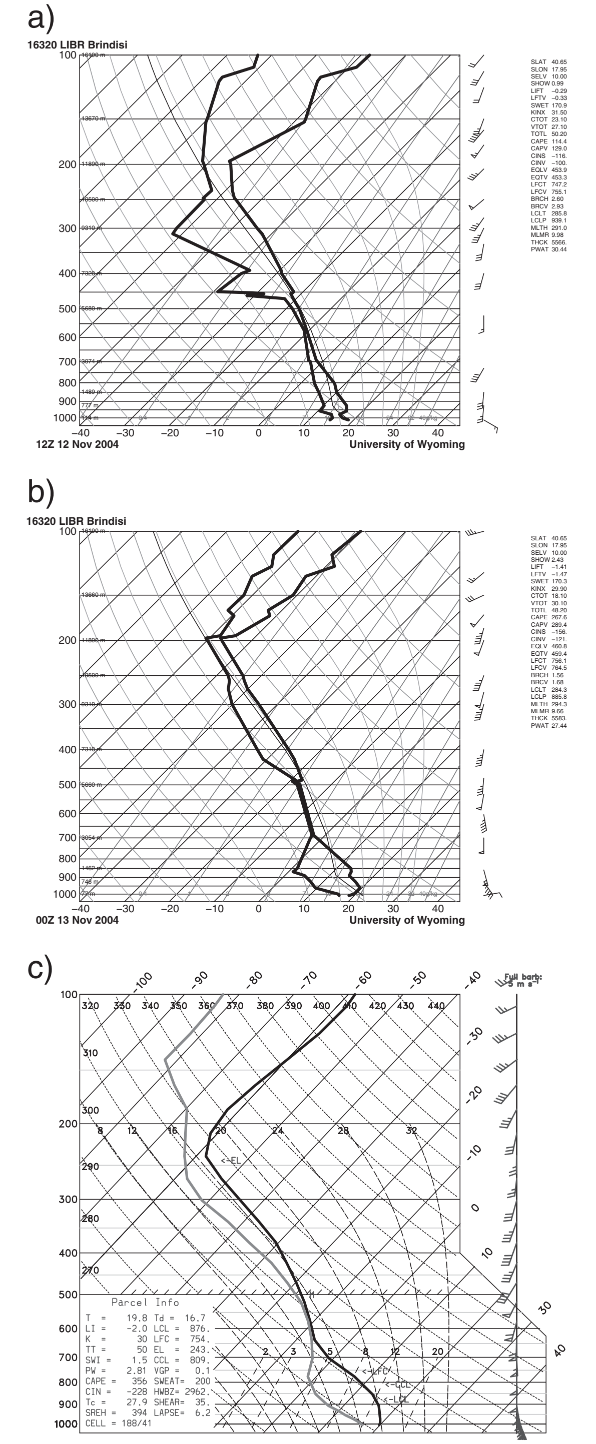

Fig. 4. Skew T-log p diagram showing thermodynamic sounding observed at (a) 12 UTC 12 November 2004, (b) 00 UTC 13 November 2004, and (c) modeled on the WRF outer domain at 00 UTC 13 November 2004, in Brindisi (see Fig. 1 for location). Source of observed soundings: http://weather.uwyo.edu/upperair/sounding.html.

Calabria reliefs to the sea just off the Calabria Ionian coast, remained nearly stationary indicating the occurrence of a convection-regenerating process.

The comparison between satellite images (Fig. 5d and e) and the synoptic situation at 00 UTC 13 November (Fig. 2c) shows that this second phase corresponded with the passage of the SWT and, as already described in Section 2, was associated with dry air at mid-tropospheric levels, coinciding with the absence of major cloud systems, especially over the southern Tyrrhenian Sea. Moreover, the cloud pattern close to the coast of Croatia at 08 UTC 13 November (Fig. 5f) suggests the presence of a vortex over the central Adriatic Sea.

During this phase, the LLJS impinged almost perpendicularly on the linear MCS. The latter is a feature typical of linear MCSs; for instance, Parker and Johnson (2000) analyzed 56 cases of linear MCS in the United States, demonstrating that, at low levels, the wind component perpendicular to the convective line is greater than the parallel component and always directed against the convective-line motion.

From about 10 UTC, the convective line disaggregated and, following the whole synoptic system, definitively shifted east–northeastward (Fig. 5g and h), producing discontinuous precipitation over central and southern Salento, still with an hourly peak of 43 mm observed at 14 UTC (Fig. 6b). In conclusion, the quasi-stationary convective line was the main precipitation feature of the second phase of the event and resulted in a maximum amount of 145 mm accumulating at Nardò from 00 UTC to 16 UTC 13 November and 202 mm at Galatina airport on 13 November (Fig. 3b).

This event shared many of the processes observed in other Mediterranean heavy precipitation episodes (Lin et al., 2001; Buzzi et al., 2005): the presence of an upper-level trough and/or a cutoff low, the passage of a SWT and the development of heavy precipitation in the region between the main trough and the ridge east of it, the warm and moist LLJS occurring in advance of a surface cyclone, the conditional or potential unstable environment, and the presence of a complex orographic pattern.

The WRF model was used to investigate how the observed low and upper level processes interacted to generate convection and intense precipitation. Numerical outputs are discussed in the next sections.

4. Numerical outputs

4.1. Model setup

The WRF model, version 2.2, was used to simulate the 12–13 November 2004 event. The model solves a set of fully compressible, Euler nonhydrostatic equations describing the evolution of six basic prognostic variables and is formulated using a terrain-following vertical coordinate and Arakawa C-type horizontal grid.

The model was implemented on two domains nested with a two-way nesting technique. Thirty unequally spaced vertical levels were defined for the present study, while the top of the box was set to the constant pressure surface of 50 hPa. The outer domain was centered at 39°N, 5°E and made up of 215×137 grid points, with grid spacing of 16 km, covering the central and western Mediterranean Basin and northwestern Africa. The inner domain was centered over southern Italy and the Ionian Sea and was made up of 128×148 grid points with grid spacing of 4 km. Recent studies on severe convective weather forecasting experiments have documented that such grid spacing is sufficiently fine to ensure a successful reproduction of convection, its mesoscale

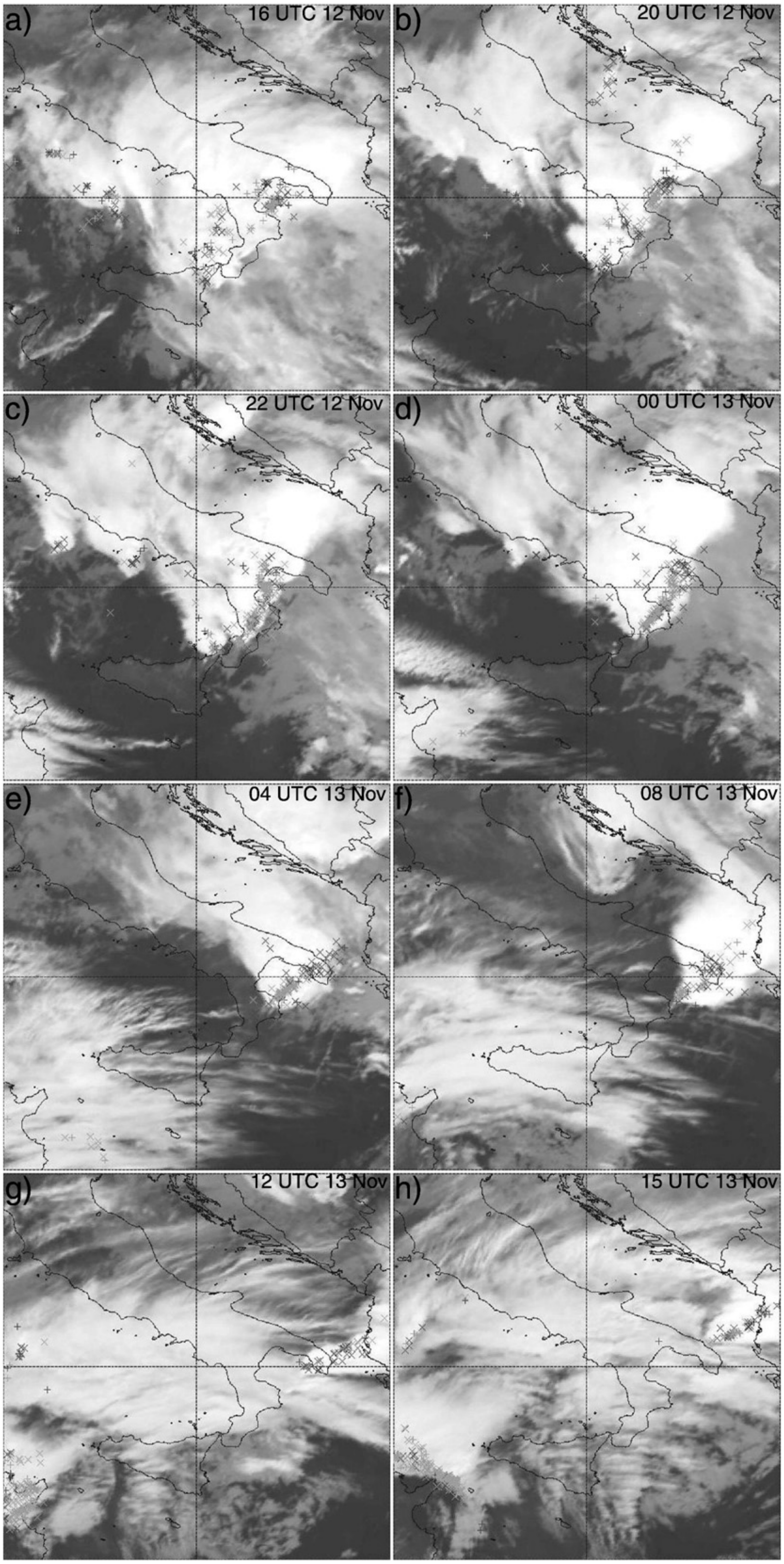

Fig. 5. Meteosat infrared images at (a) 16 UTC, (b) 20 UTC, and (c) 22 UTC 12 November 2004; (d) 00 UTC, (e) 04 UTC, (f) 08 UTC, (g) 12 UTC, and (h) 15 UTC 13 November 2004. Crosses indicate the location of lightning strikes recorded in the previous 15 minutes.

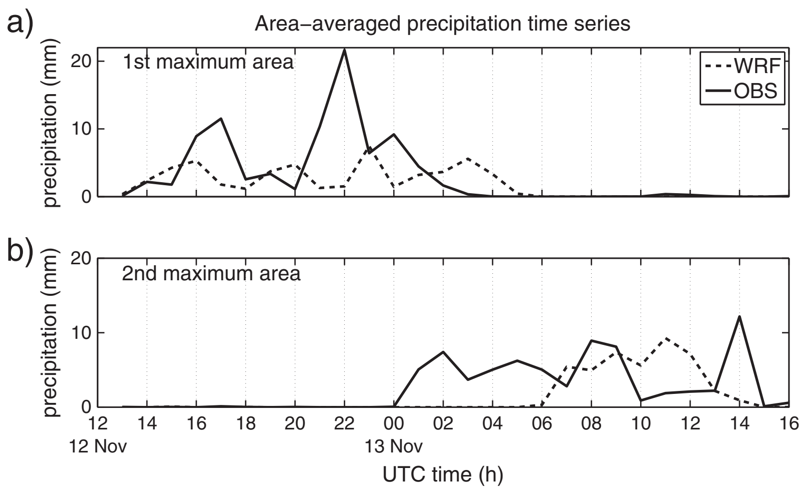

Fig. 6. Time series of hourly observed (mm, solid line) and modeled precipitation (mm, dashed line) from 12 UTC 12 November to 16 UTC November 2004, for (a) the first and (b) second rainfall maximum area. Modeled hourly precipitation has been averaged over the two areas depicted in Fig. 3a and b; observed hourly precipitation results from the average of the rain-gauge stations included in the same areas.

organization, and associated precipitation (Done et al., 2004; Weisman et al., 2008; Kain et al., 2008; Schwartz et al., 2009, 2010) with no active convective parameterization scheme. Thus, the Kain (2004) cumulus parameterization scheme was used only on the outer domain.

Among the other parameterization schemes available in WRF, we used on both domains: the Rapid Radiative Transfer Model (RRTM) for long-wave radiation based on Mlawer et al. (1997), the Dudhia (1989) scheme for short-wave radiation, the Yonsei University (YSU) scheme for the boundary layer (Hong and Pan, 1996), a five-layer thermal diffusion soil scheme (Skamarock et al., 2005), and the Thompson et al. (2004) microphysics.

The simulation was initialized at 00 UTC 12 November 2004 and integrated for 72 h. Initial and boundary conditions were provided by the ECMWF forecast with grid spacing of 0.5 deg latitude × 0.5 deg longitude. The boundary conditions, including sea surface temperature field, were updated every six hours.

4.2. Model verification

The outer domain outputs are compared with ECMWF reanalysis to verify that the model correctly reproduces the large-scale evolution of the event.

The comparison of Figs. 7c and 2c shows that at 00 UTC 13 November, the overall synoptic configuration is well simulated, although some shortcomings affect the depth of the cutoff low over northern Africa, as well as the position of the PV anomaly and 700-hPa dry air over the Tyrrhenian Sea. The latter two features are reproduced to the southwest with respect to the reanalysis data (cf. the 1-PVU isolines near the Tyrrhenian coast), revealing that the observed northeastward shift of the upper level disturbance is simulated with a delay of a couple of hours. A delay in the timing of the synoptic evolution was also detected in simulations performed in HF06 using the MM5 model, suggesting that the large-scale initial and boundary conditions are probably responsible for this behavior.

The mean sea level pressure, the 925-hPa θ_e and wind vectors are depicted in Fig. 7d for the same hour. The modeled pressure field adequately simulates the location and intensity of the main cyclone (1000 hPa) over Tunisia and of the weak cyclone (1008 hPa) over the Tyrrhenian Sea (cf. Fig. 2d). At this time, the LLJS reached the Italian Ionian regions and the southern Adriatic with a wind speed maximum of about 30 m s^{-1} over the southern Ionian Sea. The θ_e field shows maximum values on the western side of the Ionian basin. The north–south high-θ_e band is located on the western flank of the LLJS, is associated with moister air and, as evidenced in the next section, also corresponds to the area with higher CAPE.

To evaluate the ability of the model to properly simulate the thermodynamic properties of the atmosphere close to the area of interest, the modeled Brindisi sounding is compared to the profile observed at 00 UTC 13 November (Fig. 4b and c). The model simulates well the whole profile and, in particular, the dryer air overlying the moist surface layer, the nearly saturated layer between around 700 and 500 hPa, the slightly unstable atmosphere and the level of free convection (LFC) quite far from the surface (~750 hPa). The modeled wind profile shows a rotation with increasing height from south–southeast to west–southwest, similar to the observed sounding, and the presence of intense wind speeds, with a maximum greater than 26 m s^{-1}, in a deep layer from around 900 to 600 hPa.

Precipitation amounts simulated on the inner domain and accumulated on each of the two phases of the event are shown in Fig. 3. During the first phase (Fig. 3c), from 12 UTC 12 November to 00 UTC 13 November, the overall pattern is correctly reproduced. The largest amounts are modeled over part of the Ionian areas of Apulia and Basilicata, whereas, in accordance with observations, no precipitation is reproduced over most of the Salentine Peninsula. In addition, weaker precipitation affects the rest of Apulia and the inner areas of

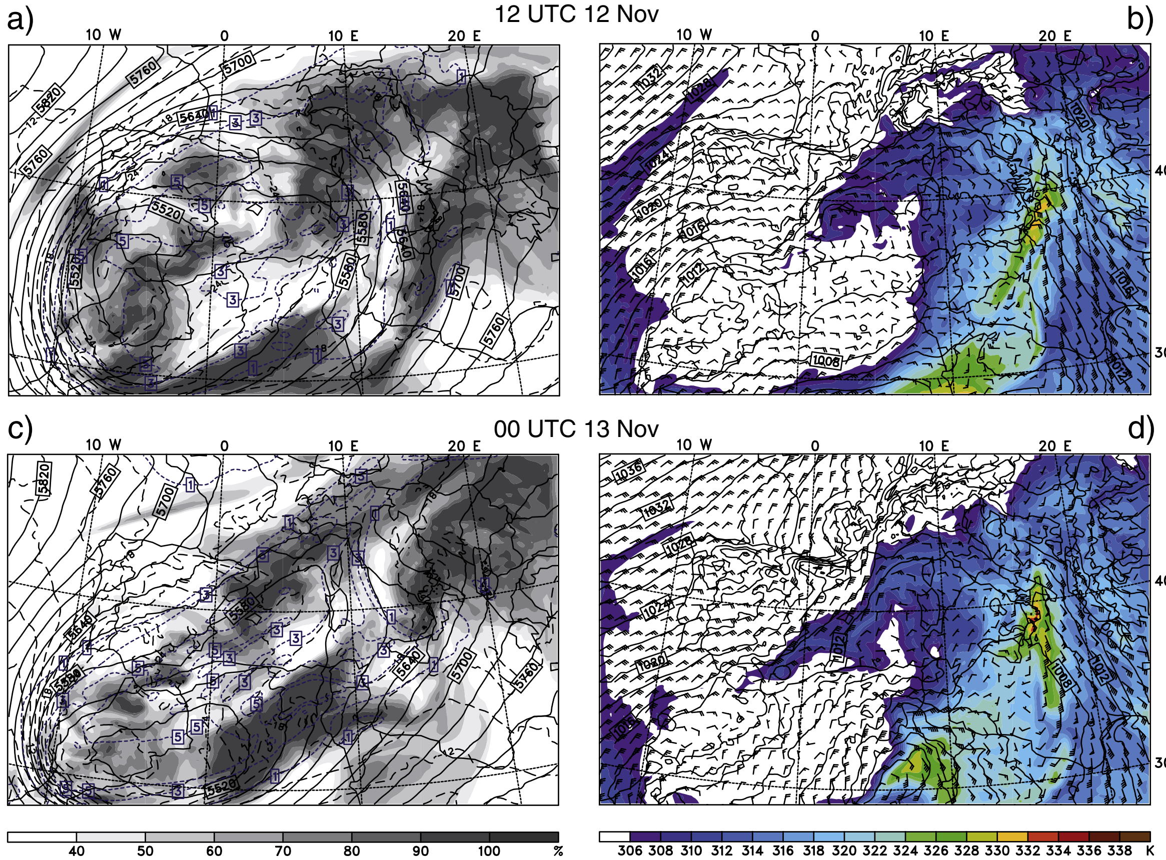

Fig. 7. WRF outer domain. Left-hand side panels: 500-hPa geopotential height (solid contours, every 30 m) and temperature (dashed contours, every 2 C), 320-K potential vorticity (PVU, blue dotted contours), and 700-hPa relative humidity (shaded as in legend) at (a) 12 UTC 12 November 2004, (c) 00 UTC 13 November 2004. Right-hand side panels: mean sea-level pressure (contours, every 2 hPa), 925-hPa wind vectors (one full barb = 5 m s^{-1}), and equivalent potential temperature (shaded as in legend) at (b) 12 UTC 12 November 2004, (d) 00 UTC 13 November 2004.

Basilicata, while some overestimated peaks are reproduced close to the Tyrrhenian coast of Basilicata. Finally, the model identifies two distinct bands elongated from south to north: one rain band along central Apulia, comparable with the observations, and an additional narrow band over the northern Ionian Sea with an absolute precipitation maximum of 174 mm. Due to the lack of data over maritime areas, this amount cannot be directly verified. Nonetheless, the timing and position of the band agrees well with the convective activity visible in satellite data shown in Fig. 5a–c.

The time series of observed and modeled precipitation, averaged over the areas depicted in Fig. 3a and b, reveal that the model realistically predicts the beginning of the rainy spell but overestimates its duration (Fig. 6a). In fact, during 12 November the model predicts a maximum of 110 mm in an elongated precipitation band (Fig. 3c) and still simulates a peak in the same area in the first hours of 13 November (Fig. 3d), persisting a little longer compared to observations. The modeled maximum of about 235 mm is located about 50 km to the northwest of the observed maximum, and slightly underestimates it.

The modeled pattern of the second phase of the event (Fig. 3d), 01–16 UTC 13 November 2004, adequately reproduces the main features of observed precipitation, although the rainy spell begins a few hours later (Fig. 6b), confirming the delay in the modeled evolution of the event discussed above and already evidenced in Fig. 6a.

The largest amount is simulated along a narrow band crossing the Salento Peninsula, located just some tens of kilometers northwest of the observed precipitation band. The maximum amount of 210 mm simulated close to Nardò station overestimates the maximum observed at that station over the same time period (145 mm), although it is very close to the precipitation amount of 202 mm in 24 hours recorded in Galatina (~10 km far) on 13 November. A secondary precipitation line is located to the southeast and is due to a further shift of the main convective line still producing residual precipitation. Both precipitation bands show a southwest–northeast orientation that compares well with satellite data and rain-gauge observations.

Therefore, the model is able to reproduce correctly the atmospheric environment at 00 UTC 13 November and the corresponding precipitation features. Thus, the numerical outputs can be exploited to obtain more information on the evolution of the air masses affecting the Ionian regions during the precipitation phases.

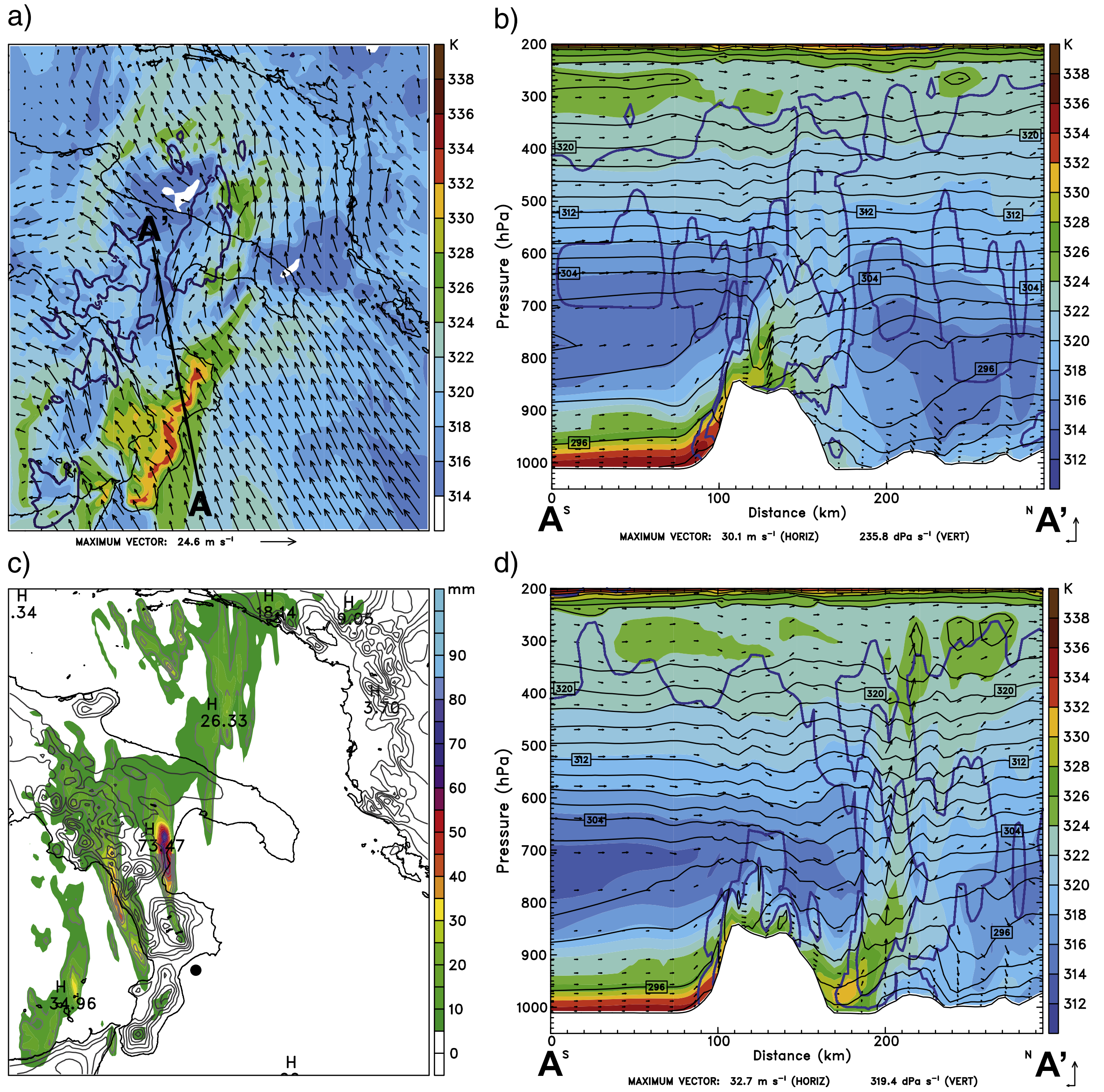

Fig. 8. (a) Wind vectors and θ_e (K, shaded as in legend) at 925 hPa, and hourly precipitation (mm, blue contour) at 17 UTC 12 November 2004; vertical cross section taken along the black line AA' shown in panel (a) of θ_e (K, shaded as in legend), circulation vectors, and total cloud mixing ratio (blue contours at 0.002 and 0.3 g kg^{-1}) at (b) 17 UTC and (d) 20 UTC 12 November 2004; (c) precipitation modeled from 17 UTC to 20 UTC 12 November 2004 and orography (gray contours, every 250 m).

4.3. Secondary cyclone evolution

At 12 UTC 12 November (Fig. 7a and b), just before precipitation begins, the stream of high 925-hPa θ_e and 700-hPa relative humidity elongates from western Libya to the northern Ionian Sea, where θ_e exceeds 330 K. The strong east–west θ_e gradient in the central part of the southern Mediterranean basin suggests that different air masses affect the region. Indeed, as apparent at 925 hPa (Fig. 7b), the low-θ_e, dry air advected by the advancing southeasterly LLJS impinges on a pool of high-θ_e, moist air (nearly saturated, with water vapor mixing ratio up to 13 g kg^{-1}) located to the west of the area affected by the LLJS. A meridionally oriented boundary between these air masses originally existed over the broad Atlas lee, separating the dry African air and more humid air of Atlantic origin that crossed the Atlas Mountains. As shown in HF06 (and present in our simulations, not shown), the border between the air masses is detectable as a low-level PV banner (see Fig. 5b in HF06), which was later advected over the Libyan and Ionian Sea as a consequence of the primary cyclonic circulation centered over northwestern Africa.

Strong shear vorticity associated with this PV banner and the approaching upper level short-wave trough contributed

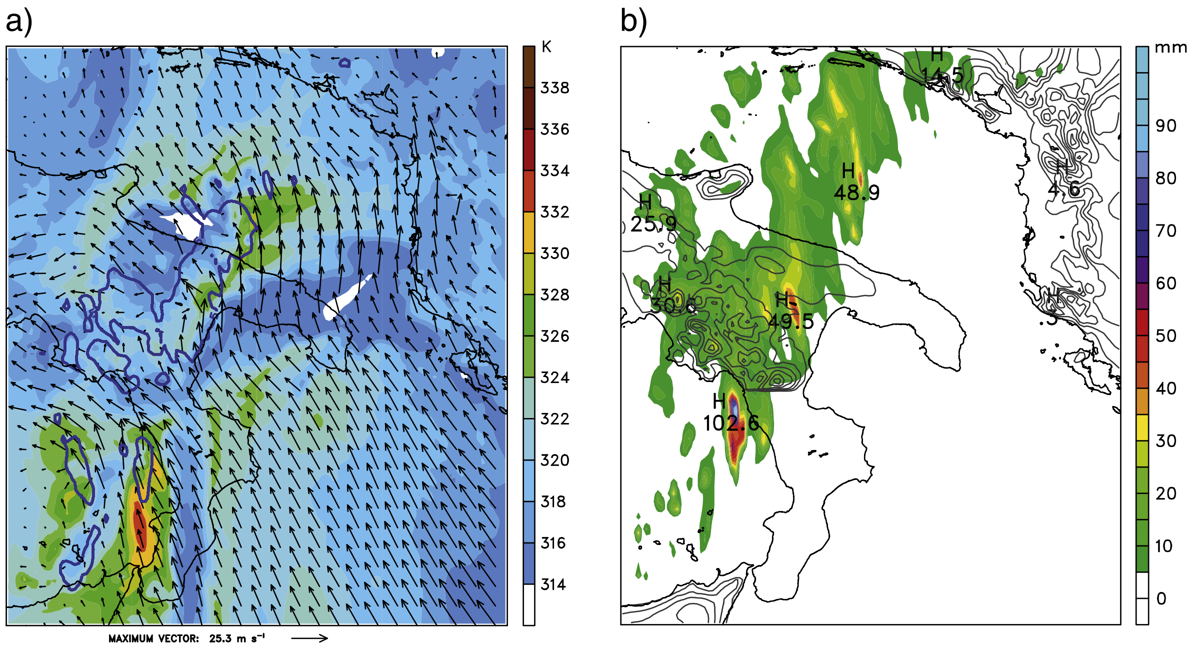

Fig. 9. Inner domain of the WRF run without Calabria orography: (a) 925-hPa θ_e (K, shaded as in legend) and wind vectors, and hourly precipitation (mm, blue contours) at 17 UTC November 2004; (c) precipitation modeled from 17 UTC to 20 UTC 12 November 2004 and orography (gray contours, every 250 m).

to create a weak mesocyclone[2] over the central Mediterranean, which soon moved towards the Tyrrhenian Sea.

In the subsequent hours, a new mesocyclonic system develops in the central Adriatic, as was previously detected in Fig. 5f and is shown in the numerical simulation (Fig. 10b). The simultaneous existence of the two low-level mesocyclones on either side of the Apennines and the unified cyclonic circulation in mid-troposphere and upper troposphere (not shown) suggest that this cyclonic system is a discontinuous mesocyclone. This type of cyclone has been documented for mid-latitude cyclones crossing the Rocky Mountains and Appalachian Mountains (e.g., Chung et al., 1976) and, recently, for cyclones crossing the Apennines and Adriatic Sea and classified as cyclone type C-II (Horvath et al., 2008).

5. Mesoscale aspects controlling convection

Since the initiation of convection occurs over different areas, both over the Ionian Sea and inland, and at different times, it is plausible that distinct mesoscale processes may have provided the lift necessary to release instability. Thus, in the present section, model outputs from the innermost domain are used to investigate the mechanisms triggering and maintaining convection in these regions, focusing our attention on two precipitation maxima observed and modeled over the mainland.

5.1. Orographic lifting

The analysis of numerical outputs starts at 17 UTC 12 November 2004, i.e., when the cells involved in the generation of precipitation over the first maximum area start to appear in the model simulation. Fig. 8a shows the simulated 925-hPa θ_e and wind vectors at this time. The southeasterly LLJS affects most of the Ionian Sea with wind speed up to ~24 m s^{-1} over the southeastern portion of the basin. On the contrary, as shown in the previous section, the θ_e field at this time shows higher values on the western portion of the basin, especially along the Calabria mountain range. This feature, together with the absence of deflection in the wind vectors impinging on the Calabria reliefs, indicates that the LLJS is uplifted over the orography so that the layers with higher θ_e protrude aloft (Fig. 8b). Since the LLJS advects warm and moist air, the air mass close to the orography is destabilized and the orographically induced upward motion may trigger convection. It is possible to evaluate approximately the time required for the orographic lift of the parcel to reach LFC from the vertical displacement $Dh = U(\partial h/\partial x)Dt$ (Chiao and Lin, 2003). In the present case, U (~15 m s^{-1}) is the speed of the impinging LLJS, and $\partial h/\partial x$ (~0.033) is the mountain steepness obtained computing the ratio between the mountain height (~1.5 km) and half-width a (~30 km) in the direction of the impinging wind. The model sounding taken just upstream of the Sila promontory at 16 UTC (not shown) indicates that the LFC for the most unstable parcel, which is close to the ground, is around 1000 m. The time required for the parcel to reach LFC is ~20 min, whereas the time required to reach the mountain top is $a/U \approx 30$ min. Therefore, the parcel lifted at the foothills has yet not reached the mountain top when it passes LFC, and can consequently release convection.

The effects of the interaction between the LLJS and Calabria orography are also evident in the cross section shown in Fig. 8b, referring to 17 UTC 12 November 2004. The unstable LLJS impinging on the upwind side of the Sila promontory is uplifted and, as shown by the total cloud mixing ratio, convection

[2] Mesocyclone is here defined as a cyclonic vortex with at least 1-hPa closed isobar at the surface.

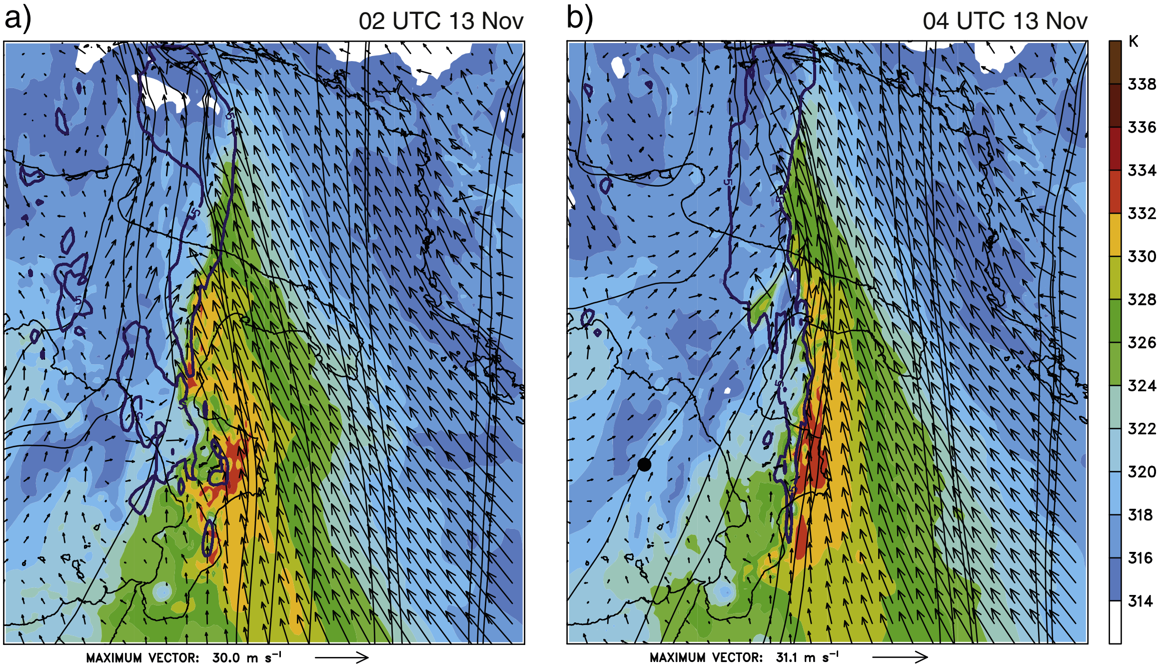

Fig. 10. Wind vectors and θ_e (shaded as in legend) at 925 hPa, hourly precipitation (mm, blue contour), and 700-hPa streamlines at (a) 02 UTC and (b) 04 UTC 13 November 2004. The black dot on panel (b) indicates the area of the modeled soundings shown in Fig. 14.

develops over the top and downslope of Sila. In the subsequent two hours, convection moves from Calabria north–northwestward and intensifies. As depicted in Fig. 8d, at 20 UTC 12 November 2004, a mechanism similar to that described above develops upslope of the hills of southern Basilicata. The resulting precipitation generated from 17 UTC to 20 UTC 12 November 2004 is distributed along a narrow band, which is elongated from Sila to the north–northwest (Fig. 8c) due to the intense advection associated with mid-tropospheric currents.

To better evaluate the role of the Calabria orography in the generation of precipitation, a sensitivity run was performed using a setup identical to the control run except for the suppression of Calabria reliefs from the beginning of the simulation, at 00 UTC 12 November 2004. Fig. 9a evidences that, due to the absence of the orographic obstacle, the LLJS can reach the Tyrrhenian Sea flowing undisturbed over Calabria. Differently from the control run (cf. Fig. 8a), a θ_e peak is not reproduced on the Calabria Ionian side but over the southern Tyrrhenian where the southeasterly LLJS converges with weaker southerly winds.

The comparison of Figs. 9b and 8c confirms that the orography of Calabria, in particular the Sila promontory, is necessary to explain the modeled first maximum rainfall amount as it initiates convection generating most of the rainfall immediately downstream, over the Ionian areas of southern Basilicata. Farther north, over the Basilicata mainland, a lower rainfall amount is still generated due to the uplift of the local orography.

In the last hours of 12 November, intense isolated convective cells, associated with the first precipitation maximum, develop. The cells are repeatedly initiated over the Basilicata and Apulia reliefs directly exposed to the southeasterly LLJS and are subsequently advected downstream (northward) where they dissipate. This process lasts for about three hours and contributes to generating the maximum amount predicted over this zone (cf. Fig. 3c and d). Therefore, while the LLJS supplies moisture and further increases the instability of the atmosphere, the orography of the Italian Ionian regions provides the upward motion necessary to remove CIN (Fig. 4b) and generate deep moist convection during this phase.

5.2. Effects of the secondary cyclone on precipitation

As discussed in Section 3, during the early hours of 13 November 2004, a weak cyclone traverses southern Italy. The influence of the passage of this secondary cyclone on convection and precipitation distribution is described hereafter.

Fig. 10a indicates that at 02 UTC the warm and moist tongue associated with the LLJS moved northward reaching the southern Adriatic. Over central Basilicata and Apulia, the flow converges with a southwesterly flow induced by the cyclone. Along the convergence zone, intense precipitation is generated, suggesting that the upward motion associated with low-level convergence causes convection. No precipitation develops immediately northwest of this convergence zone, whereas weaker residual precipitation affects the Tyrrhenian Calabria and Basilicata coasts. Over these areas, in the subsequent two hours, precipitation ceases to occur apparently moving over the Ionian Sea where it starts to distribute along a line (Fig. 10b). Furthermore, due to the north–northeastward cyclone shift and the SWT approach, southwesterly winds replace the pre-existing mid- and low-tropospheric cyclonic circulation.

Simulated soundings (Fig. 11) are used to investigate the change in the thermodynamic properties of the troposphere in these areas. The vertical profiles of dew point and temperature are computed on southern Tyrrhenian at 22

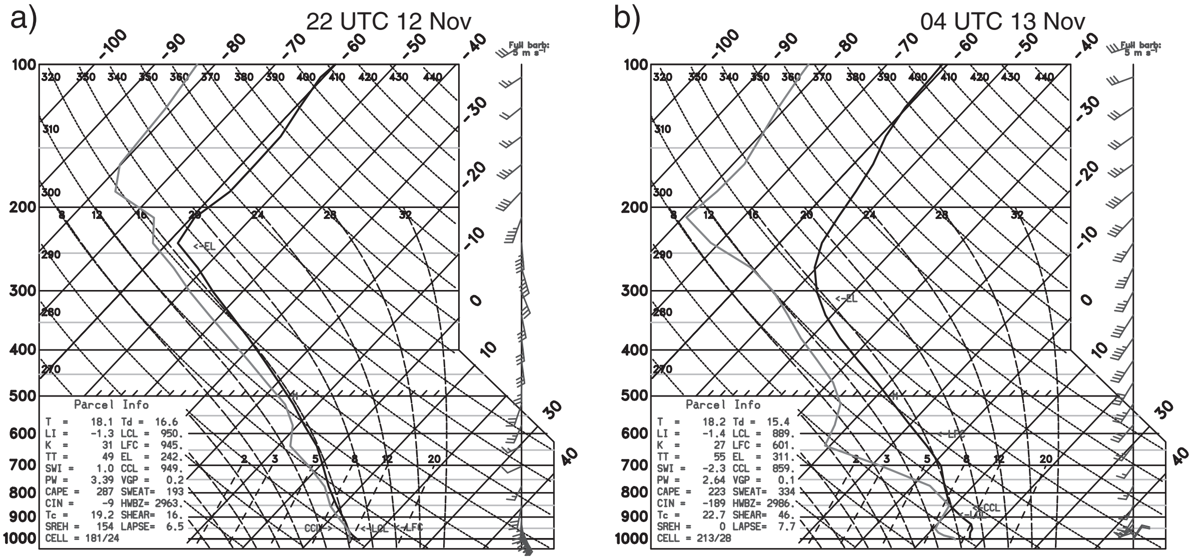

Fig. 11. Sounding modeled on the WRF inner domain at (a) 22 UTC 12 November 2004 and (b) 04 UTC 13 November 2004 on the location indicated by the black dot in Fig. 10b. Temperature (black curve), dew point temperature (gray curve), and wind vectors profiles (one full barb = 5 m s^{-1}) are represented.

UTC 12 November and at 04 UTC 13 November 2004, thus before and after the passage of the low-level cyclone, i.e., before and during the passage of the SWT and associated 320-K PV anomaly. The comparison of the two soundings shows that, during this period, the whole tropospheric column becomes drier, especially in the 600–700 hPa layer. The wind veers along the 250–600 hPa layer because of the cold advection associated with the SWT, leading to an increase in the vertical temperature gradient and possibly enhancing the instability. However, the drier and warmer air in the lowest 100-hPa layer strongly increases the convective inhibition and contributes to raising the LFC as a result of which the instability cannot be released. It can be concluded that the dry air steered by the low-level cyclone and the upper level SWT inhibits the release of convection, bounding it on the Ionian areas still affected by the moist and unstable air masses transported by the LLJS.

5.3. Convective line features

As highlighted in Section 4, a precipitation band extending from Calabria toward the Ionian Sea is modeled starting at around 04 UTC 13 November 2004 (Fig. 10b). In the subsequent three hours, the convective line generating the precipitation band quickly moves eastward and, in accordance with observations, its main axis experiences a light clockwise rotation. In fact, the line orientates along the mid- and high-tropospheric flow which, during this interval, progressively veers to southwest, due to the circulation induced by the passage of the upper level PV anomaly and associated SWT (Fig. 12a). Since the line moves quickly, the locally intense rainfall, up to ~78 mm in one hour at 05 UTC, do not produce the largest accumulation of the second phase.

From around 07–08 UTC, the PV anomaly moves northward (Fig. 12b) so that a uniform and constant upper level southwesterly circulation affects the region for a few hours. In this phase, the motion of the line in the direction perpendicular to its main axis weakens and the rain band becomes quasi-stationary across the Salento. Persisting for about four hours (cf. Fig. 6b), the line generates large precipitation amounts responsible for the second rainfall maximum of the event. The flow remains steady until 11–12 UTC 13 November 2004 (Fig. 12c), when a new change in the upper level flow forces the convective line to finally leave the Salentine Peninsula.

The longevity of the convective line affecting Salento for more than 12 hours implies a continuous generation of convective cells that build and organize into the line (e.g., Schumacher and Johnson, 2008; Schumacher, 2009). Fig. 12 shows that at low levels the wind field is still dominated by the LLJS and convection is repeatedly produced on its western forward flank, which is the most unstable (Fig. 13a) sector of the stream. Specifically, while the LLJS drifts east–northeastward following the synoptic evolution, the southwestern tip of the convective line moves accordingly and regenerates where the wind speed is approximately greater than 16 m s^{-1}.

The mechanism responsible for convection in this phase is explained in Fig. 13a. It shows that, at 09 UTC 13 November 2004, precipitation develops along the area of convergence between the warm LLJS and the weaker southwesterly flow present on the western side of the precipitation band. This result is consistent with the interpretation provided in Italian Air Force National Weather Service analysis maps, where a convergence line is depicted for several hours over the Ionian regions (not shown). The low-level convergence is mainly associated with variation in the wind field, which is particularly intense over Salento because of the presence of stronger winds. The cooler air, transported by the downdrafts to the low levels, provides an additional contribution to the maintenance of convection. The vertical cross section taken along the line-perpendicular direction (Fig. 13b) shows an area of low θ_e and upward-displaced isentropes developing beneath the region of deep convection. This area acts as an

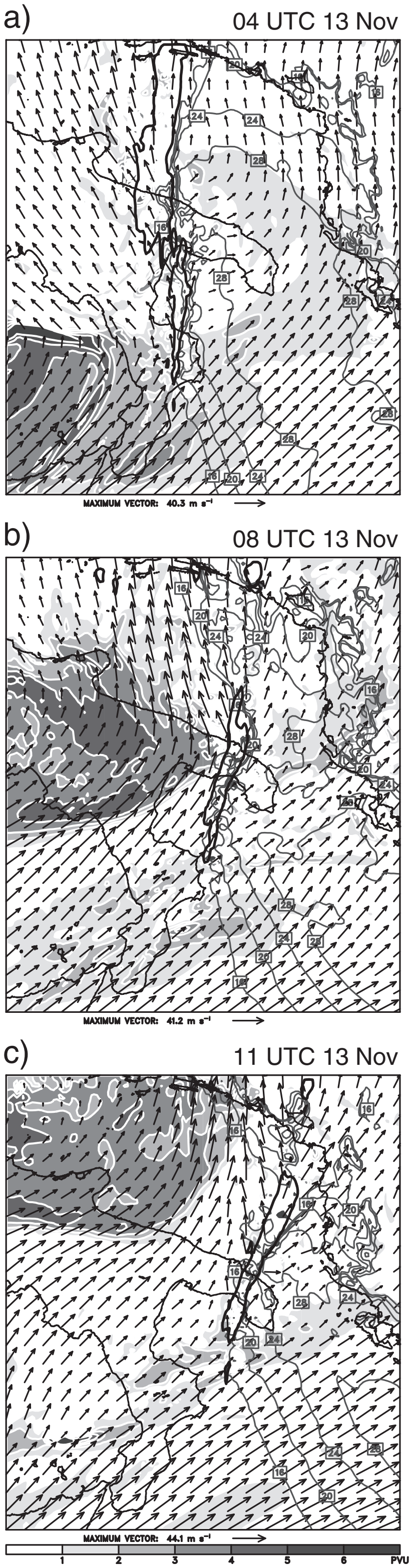

Fig. 12. Potential vorticity at 320-K isentropic level (values > 1 PVU, shaded as in legend), 300-hPa wind vectors, 925-hPa wind speed (gray contours, every 4 m s^{-1} starting at 16 m s^{-1}), and hourly precipitation (black contour at 10 mm) at (a) 04 UTC, (b) 08 UTC, and (c) 11 UTC 13 November 2004.

orographic obstacle to the impinging LLJS, and provides additional uplift.

In conclusion, during the second phase of the event, different features modulate the rainfall intensity and distribution. The slow translation of the synoptic pattern causes the persistence of the LLJS that advects unstable air masses over the Ionian area. Convection is produced at the leading edge of the LLJS and is initially promoted by convergence with the circulation induced by the passage of the secondary low-level cyclone. The approach of the upper level SWT also controls the development of convection favoring ascending motion, by advecting drier and more stable air masses to the west of the line, and inducing changes in circulation that contribute to its shift. After the SWT passage, the mid-level and upper level currents remain south-westerly, and the line quasi-stationary. The resulting wind profile favors the organization of the cells into a line oriented from southwest to northeast. As a result, different cells regenerate along the line and continuously produce precipitation over the same zone, leading to the highest rainfall peaks of the second phase of the event. In this phase, the downdrafts contribute to enhance the low-level convergence, thus favoring the maintenance of convection.

6. Summary and conclusions

This work has investigated a long-lasting heavy precipitation event that occurred on 12 and 13 November 2004 in southeastern Italy. The analysis, based on observations and numerical outputs, focus on the synoptic and mesoscale features leading to convection and on the mechanisms controlling the convective systems responsible for the two observed rainfall maxima.

The synoptic situation at mid- and high-tropospheric levels was dominated by a wide cyclonic circulation centered over the western Mediterranean and confined by a ridge on its eastern side. The stationarity of this configuration, along with the presence of a low-level jet stream (LLJS) and a short-wave trough (SWT), two features frequent in heavy precipitation events observed in the Mediterranean area (e.g., Romero et al., 2000; Nuissier et al., 2008), favored the persistence of precipitation over the same region for more than 24 hours. The rainfall stopped when a deep cyclone developing over northern Africa (Horvath et al., 2006) moved toward the Ionian regions and shifted the LLJS eastward.

Rain gauge data indicated the occurrence of two distinct precipitation phases leading to large amounts of rainfall over different inland areas. Satellite images show that convection persistently affected Ionian coast of Basilicata and adjacent Apulia territory producing the first precipitation maximum. During the last hours of 12 November 2004, a convective line developed over Calabria and the northern Ionian Sea. It subsequently shifted eastward and persisted over Salento, where it produced long-lasting precipitation responsible for the second observed rainfall maximum.

A reference simulation obtained with the WRF model has been compared to the available observations, showing that the precipitation pattern and amounts are realistically simulated, whereas the precipitation timing and the location of the maxima are reproduced less successfully. The simulation was overall satisfactory and was exploited to investigate the main mesoscale features of the event.

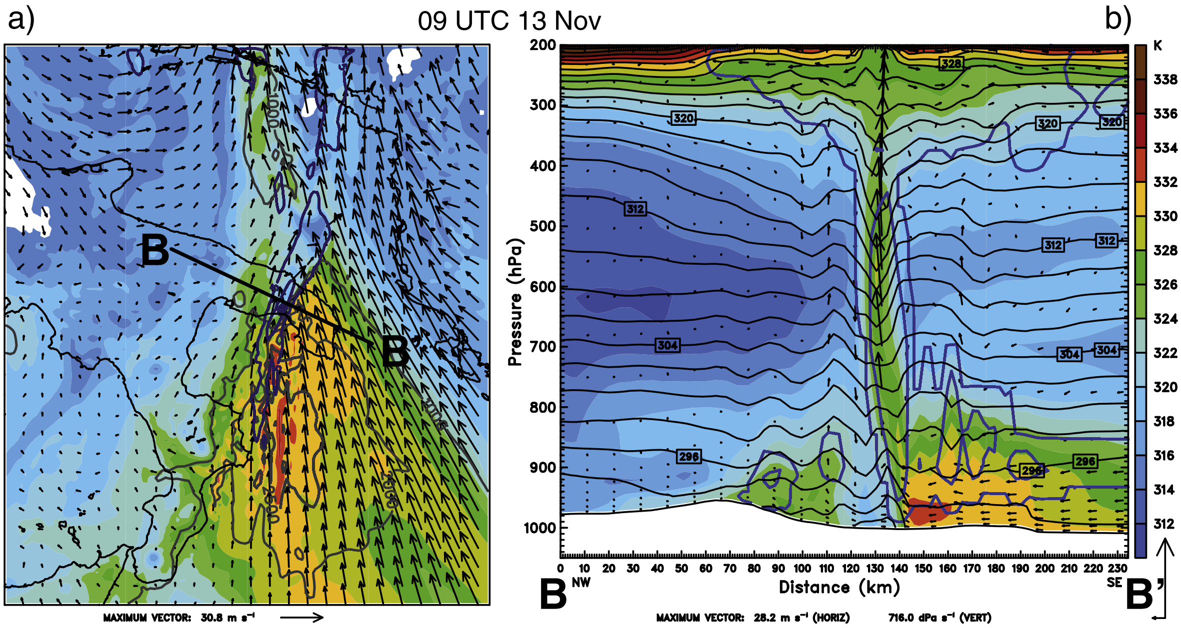

Fig. 13. (a) Wind vectors and θ_e (K, shaded as in legend) at 925 hPa, CAPE (grey contour, every 500 J kg^{-1} starting at 1000 J kg^{-1}), and hourly precipitation (mm, blue contours) at 09 UTC 13 November 2004; vertical cross section taken along line BB′ shown in panel (a) of θ_e (K, shaded as in legend) and total cloud mixing ratio (blue contours at 0.002 and 0.3 g kg^{-1}) at the same hour.

In the first phase of the event, i.e., during the second half of 12 November, the orography resulted in the main lifting mechanism necessary to develop convection. The largest amount was simulated in proximity of the local orographic peaks of Apulia and Basilicata, directly exposed to the impinging LLJS. However, the reliefs of Calabria also contributed to initiate convection at the beginning of the event, as shown in a sensitivity experiment.

The subsequent transition of the precipitating systems towards Salento was observed from the last hours of 12 November, marking the beginning of the second phase of the event. Various features caused the observed shift and the organization of convection into a linear MCS: the numerical outputs showed that a low-level PV banner advected from the lee of the Atlas mountains and an upper level SWT induced the formation of a weak mesocyclone. Moving ahead of the SWT, the mesocyclone crossed southern Italy during the early hours of 13 November. The resulting change in the circulation over Apulia and Basilicata favored the formation of an extended zone of convergence between the cyclonic flow and the southeasterly LLJS. Convection developed along the area of low-level convergence, acquired a linear structure, and moved towards the Gulf of Taranto and Salento, steered by the passage of the upper level SWT. Then, the convective line remained quasi-stationary over Salento, where it intensified, producing the second maximum rainfall amount of the event.

The upper level PV anomaly and associated SWT modulated precipitation during the second phase since they contributed to the formation and movement of the mesocyclone, hence to the formation of the low-level convergence zones, and steered the mid-upper level flow embedding the convective line. Moreover, the delay in precipitation timing, associated with the convective line shift, is consistent with the delay detected in the passage of the upper level PV anomaly over the study area. It seems, therefore, that the correct representation in the initial and boundary conditions of the subsynoptic features embedded in the Atlantic trough is necessary for a successful numerical simulation of the event.

This study identified some features responsible for the heavy rainfall observed in other Mediterranean heavy precipitation events: a wide trough embedding a short-wave trough associated with a subsynoptic upper level PV anomaly, an intense LLJS, and the complex orography of the area affected by precipitation. In particular, by continuously supplying moisture at very low levels and advecting potentially unstable air masses, the LLJS contributed to destabilizing the atmosphere and to maintaining convection throughout the precipitation event, even in the absence of orographic lifting. Therefore, this study shares with Miglietta and Regano (2008) the consideration that a LLJS flowing over the sea and reaching the Italian Ionian regions from the south may represent a hazardous meteorological feature for the exposed areas of southern Italy. It is, therefore, a feature that should be analyzed with attention by forecasters.

Based on the numerical outputs and the identification of an MCS in the SATREP analysis (http://www.knmi.nl/satrep/) at 06 UTC, 12 November, an alert of severe thunderstorms over southeastern Italy was issued by the Italian Air Force National Weather Service in the early morning of 12 November. Courtesy of CNMCA (Centro Nazionale di Meteorologia e Climatologia Aeronautica), we were able to consult the graphical outputs of the different numerical weather prediction models available in 2004 in the Italian national weather service. The ECMWF deterministic forecasts (0.5° horizontal grid spacing) were able to identify correctly several different features leading to the event: the upper level PV advection associated with the upper level low in the Mediterranean, the low-level warm advection and the presence of convergent flow. Nevertheless, the ECMWF forecasts were not able to predict rainfall peaks larger than 50 mm over 12 hours in the runs of 10, 11, and 12 November, 12 UTC. By contrast, the limited area models available at that time at the CNMCA, the hydrostatic HRM (horizontal grid spacing of 28 km) and nonhydrostatic LAMI (horizontal grid spacing of about 7 km) were able to identify the occurrence of heavy rain (a maximum of about 100 mm was predicted in both phases by most of the model runs), although the location of the rainfall maximum was predicted very roughly. Such considerations highlight the need for high-resolution models to properly resolve the orographic features and the surface flux exchanges for an appropriate simulation of the event.

Acknowledgements

The authors are grateful to Prof. D. M. Schultz and two anonymous reviewers for comments and suggestions that helped improve the paper. The authors thank Aeronautica Militare for satellite and lightning strikes images and the graphical outputs from the different numerical weather prediction models available in 2004 in the Italian Air Force National Weather Service and Aeronautica Militare, ARPA Basilicata, and SMA S.p.A. for the rain gauge data. The work of Kristian Horvath was supported by Grant 004-1193086-3036 of the Ministry of Science, Technology and Sports, Republic of Croatia.

References

Buzzi, A., Foschini, L., 2000. Mesoscale meteorological features associated with heavy precipitation in the southern alpine region. Meteorol. Atmos. Phys. 72, 131–146.

Buzzi, A., Richard, E., Romero, R., 2005: Summary report on MEDEX studies and scientific results on Mediterranean cyclones causing high impact weather, Report on scientific results, available at: http://medex.aemet.uib.es/documents/Summary_on_MEDEX_studies_Nov05.pdf.

Chiao, S., Lin, Y.L., 2003. Numerical modeling of an orographically enhanced precipitation event associated with tropical storm Rachel over Taiwan. Wea. Forecasting 18, 325–344.

Chung, Y.S., Hage, K., Reinelt, E., 1976. On lee cyclogenesis and airflow in the Canadian Rocky Mountains and the East Asian mountains. Mon. Wea. Rev. 104, 878–891.

Done, J., Davis, C., Weisman, M., 2004. The next generation of NWP: Explicit forecasts of convection using the Weather Research and Forecast (WRF) Model. Atmos. Sci. Lett. 5, 110–117.

Doswell III, C.A., 1987. The distinction between large-scale and mesoscale contribution to severe convection: A case study example. Wea. Forecasting 2, 3–16.

Doswell III, C.A., Brooks, H.E., Maddox, R.A., 1996. Flash flood forecasting: An ingredients-based methodology. Wea. Forecasting 11, 560–581.

Doswell III, C.A., Ramis, C., Romero, R., Alonso, S., 1998. A diagnostic study of three heavy precipitation episodes in the western Mediterranean region. Wea. Forecasting 13, 102–124.

Ducrocq, V., Nuissier, O., Ricard, D., Lebeaupin, C., Thouvenin, T., 2008. A numerical study of three catastrophic precipitating events over western Mediterranean region (southern France)—Part II: Mesoscale triggering and stationarity factors. Q. J. R. Meteorolog. Soc. 34, 131–145.

Dudhia, J., 1989. Numerical study of convection observed during the Winter Monsoon Experiment using a mesoscale two-dimensional model. J. Atmos. Sci. 46, 3077–3107.

Federico, S., Bellecci, C., Colacino, M., 2003. Quantitative precipitation of the Soverato flood: The role of orography and surface fluxes. Nuov. Cim. C. 26 C, 7–22.

Federico, S., Avolio, E., Pasqualoni, L., Bellecci, C., 2008. Atmospheric patterns for heavy rain events in Calabria. Nat. Hazards Earth Syst. Sci. 8, 1173–1186 doi:10.5194/nhess-8-1173-2008.

Homar, V., Romero, R., Ramis, C., Alonso, S., 2002. Numerical study of the October 2000 torrential precipitation event over eastern Spain: Analysis of the synoptic-scale stationarity. Ann. Geophys. 20, 2047–2066.

Hong, S.Y., Pan, H.L., 1996. Nocturnal boundary layer vertical diffusion in a medium-range forecast model. Mon. Wea. Rev. 124, 2322–2339.

Horvath, K., Fita, L.L., Romero, R., Ivančean-Picek, B., 2006. A numerical study of the first phase of a deep Mediterranean cyclone: Cyclogenesys in the lee of the Atlas Mountains. Meteorol. Z. 15, 133–146.

Horvath, K., Lin, Y.L., Ivančan-Picek, B., 2008. Classification of cyclone tracks over Apennines and the Adriatic sea. Mon. Wea. Rev. 136, 2210–2227.

Horvath, K., Ivančan-Picek, B., 2009. A numerical analysis of a deep Mediterranean lee cyclone: Sensitivity to mesoscale potential vorticity anomalies. Meteorol. Atmos. Phys. 103, 161–171.

Johns, R.H., Doswell III, C.A., 1992. Severe local storms forecasting. Wea. Forecasting 7, 588–612.

Kain, J.S., 2004. The Kain-Fritsch convective parameterization scheme: An update. J. Appl. Meteorol. 43, 170–181.

Kain, J.S., Weiss, S.J., Bright, D.R., Baldwin, M.E., Levit, J.J., Carbin, G.W., Schwartz, C.S., Weisman, M.L., Droegemeier, K.K., Weber, D.B., Thomas, K.W., 2008. Some practical considerations regarding horizontal resolution in the first generation of operational convection-allowing NWP. Wea. Forecasting 23, 931–952.

Lin, Y.L., Chao, S., Wang, T.A., Kaplan, M.L., Weglarz, R.P., 2001. 2001: Some common ingredients for heavy orographic rainfall. Wea. Forecasting 16, 633–660.

Martius, O., Zenklusen, E., Schwierz, C., Davies, H.C., 2006. Episodes of alpine heavy precipitation with an overlying elongated stratospheric intrusion: A climatology. Int. J. Climatol. 26, 1149–1164 doi:10.1002/ joc.1295.

Massacand, A.C., Wernli, H., Davies, H.C., 1998. Heavy precipitation on the Alpine southside: An upper-level precursor. Geophys. Res. Lett. 25, 1435–1438.

Miglietta, M.M., Buzzi, A., 2001. A numerical study of moist stratified flows over isolated topography. Tellus 53A, 481–499.

Miglietta, M.M., Buzzi, A., 2004. A numerical study of moist stratified flow regimes over isolated topography. Q. J. R. Meteorolog. Soc. 130, 1749–1770.

Miglietta, M.M., Regano, A., 2008. An observational and numerical study of a flash-flood event over south-eastern Italy. Nat. Hazards Earth Syst. Sci. 8, 1417–1430.

Mlawer, E.J., Taubman, S.J., Brown, P.D., Iacono, M.J., Clough, S.A., 1997. Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the long wave. J. Geophys. Res. 102 (D14), 16 663–16 682.

Moscatello, A., Miglietta, M.M., Rotunno, R., 2008. Numerical analysis of a Mediterranean 'hurricane' over southeastern Italy. Mon. Weather Rev. 136, 4373–4397.

Nuissier, O., Ducrocq, V., Ricard, D., Lebeaupin, C., Anquetin, S., 2008. A numerical study of three catastrophic precipitating events over Southern France I: Numerical framework and synoptic ingredients. Q. J. R. Meteorol. Soc. 134, 111–130.

Parker, M.D., Johnson, R.H., 2000. Organizational modes of midlatitude mesoscale convective systems. Mon. Wea. Rev. 128, 3413–3436.

Romero, R., Guijarro, J.A., Ramis, C., Alonso, S., 1998. A 30-year (1964–1993) daily rainfall data base for the Spanish Mediterranean regions: First exploratory study. Int. J. Climatol. 18, 541–560.

Romero, R., Doswell III, C.A., Ramis, C., 2000. Mesoscale numerical study of two cases of long-lived quasistationary convective systems over eastern Spain. Mon. Wea. Rev. 128, 3731–3751.

Schumacher, R.S., Johnson, R.H., 2005. Organization and environmental properties of extreme-rain-producing mesoscale convective systems. Mon. Wea. Rev. 133, 961–976.

Schumacher, R.S., Johnson, R.H., 2008. Mesoscale processes contributing to extreme rainfall in a midlatitude warm-season flash flood. Mon. Wea. Rev. 136, 3964–3986.

Schumacher, R.S., 2009. Mechanisms for quasi-stationary behavior in simulated heavy-rain-producing convective systems. J. Atmos. Sci. 66, 1543–1568.

Schwartz, C.S., Kain, J.S., Weiss, S.J., Xue, M., Bright, D.R., Kong, F., Thomas, K.W., Levit, J.J., Coniglio, M.C., 2009. Next-day convection-allowing WRF model guidance: A second look at 2-km versus 4-km grid spacing. Mon. Wea. Rev. 137, 3351–3372.

Schwartz, C.S., Kain, J.S., Weiss, S.J., Xue, M., Bright, D.R., Kong, F., Thomas, K.W., Levit, J.J., Coniglio, M.C., Wandishin, M.S., 2010. Toward improved convection-allowing ensembles: Model physics sensitivities and optimizing probabilistic guidance with small ensemble membership. Wea. Forecasting 25, 263–280.

Skamarock, W.C., Klemp, J.B., Dudhia, J., Gill, D.O., Barker, D.M., Wang, W., Powers, J.G., 2005: A description of the Advanced Research WRF Version 2, NCAR Tech Note NCAR/TN468+STR 88 pp. [Available from UCAR Communications, P. O. Box 3000, Boulder, CO 80307]. Available online http://box.mmm.ucar.edu/wrf/users/docs/arw_v2.pdf.

Thompson, G., Rasmussen, R.M., Manning, K., 2004. Explicit forecasts of winter precipitation using an improved bulk microphysics scheme—Part I: Description and sensitivity analysis. Mon. Wea. Rev. 132, 519–542.

Weisman, M.L., Davies, C., Wang, W., Manning, K.W., Klemp, J.B., 2008. Experiences with 0-36-h explicit convective forecasts with the WRF-ARW model. Wea. Forecasting 23, 407–437.