IL NUOVO CIMENTO Vol. 30 C, N. 2 Marzo-Aprile 2007
DOI 10.1393/ncc/i2006-10020-4

The upper-tropospheric forcing during the 10th-12th December 2003 storm over Calabria

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(ricevuto l'1 Giugno 2006; revisionato il 17 Dicembre 2006; approvato il 31 Dicembre 2006; pubblicato online il 22 Marzo 2007)

Summary. — In this study we revisit an intense and destructive storm that occurred over Calabria, southern Italy, on 10th-12th December 2003. This event was already analyzed by two of the authors at synoptic and planetary scales, however in this work we investigate the mesoscale of the storm by the RAMS (Regional Atmospheric Modeling System) model. Firstly it is shown that large-scale moisture source was mainly from the Mediterranean basin, then RAMS simulations are discussed to focus on the mesoscale of the storm. More precisely we evaluate the roles of Calabrian orography and the surface latent heat fluxes by the factor separation technique. Results show that the role of Calabrian orography, even if important, decreased during the event whilst the role of surface latent heat fluxes was less affected through the entire event. A prominent mid tropospheric trough or cut-off low can be identified through this event prior and during the period of heavy rain. The upper-tropospheric level disturbance, associated with high potential vorticity (PV) values, consequence of a deep tropospheric intrusion of stratospheric air masses, coupled with the surface cyclone and reinforced the whole meteorological system which resulted in the heavy impact rainstorm over Calabria, mainly during 11th and 12th December 2003.

PACS `92.60.Gn` – Winds and their effects.
PACS `92.60.Jq` – Water in the atmosphere.

1. – Introduction

In this section, we firstly introduce some general aspects of the Mediterranean storms, somewhat related to the storm discussed in this work, then we focus on the severe event over Calabria, the southernmost tip of the Italian boot.

The Mediterranean region is often characterized by torrential rainfall and flash floods at different spatial and temporal scales [1] and several cases have been studied, discussed and reported in different countries around the basin.

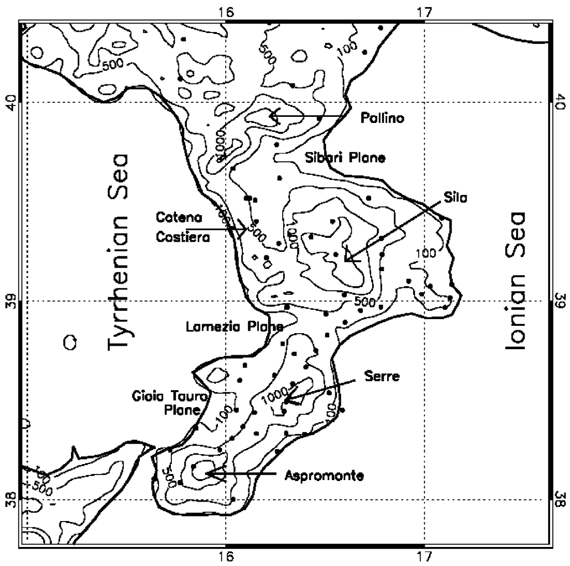

Fig. 1. – Topography of Calabria averaged over $10\,\mathrm{km}^2$. Main features are also reported. Contours: 100 m, 500 m, 1000 m and 1400 m. Dots show raingauges locations.

From the meteorological perspective, there are atmospheric forcings spanning different spatial and temporal scales that determine different types of intense rainfall in the Mediterranean region. The most common type of intense cyclone is the baroclinic lee cyclone of the type described in Buzzi and Tibaldi [2]. Such cyclones can be quite intense over Calabria as its peculiar geographical feature, *i.e.* the presence of a warm sea nearby steep mountainous ranges (see fig. 1 that shows the main topographical features of the region), can determine a persistent precipitation pattern over localized spots [3].

In some cases, intense localized cyclones at sub-synoptic scale were the main cause, as in the case of 4th-6th October 1996 reported by Atlas and Reale [4] or in the case of Crotone supercell-like storm studied by Federico *et al.* [5]. Medicanes (Mediterranean Hurricanes), to whom the 4th-6th October 1996 event belongs, are currently studied by the meteorological community and develop at the sub-synoptic scale.

There are several other instances in which heavy precipitations in the Mediterranean occur without a clear deep cyclone development. During that type of storms, synoptic-scale features resemble other cases in which little rain is observed. Recently, several studies [6-9] suggest that moisture sources outside the Mediterranean basin and large-scale water vapour transport were important for those major floods events.

In the extra tropical atmosphere intense cyclones often develop under upper-tropospheric jet streams that are often characterized by anomalously high values of PV. PV is conserved along the flow on an isentropic surface under adiabatic and frictionless motions [10]. Because of its conservative property, PV is used to trace the areas with specific characteristic of air masses and it is applied in the analysis of atmospheric processes. The frontogenesis, accompanied at the tropopause level by a PV positive filament, influences the timing, amplitude and location of intense surface cyclones and heavy precipitation events, as reported in several studies [11-14]. The mutual interaction between tropospheric upper level forcing and the surface cyclone eventually favours deep convection development which is less anchored to the local topographical features.

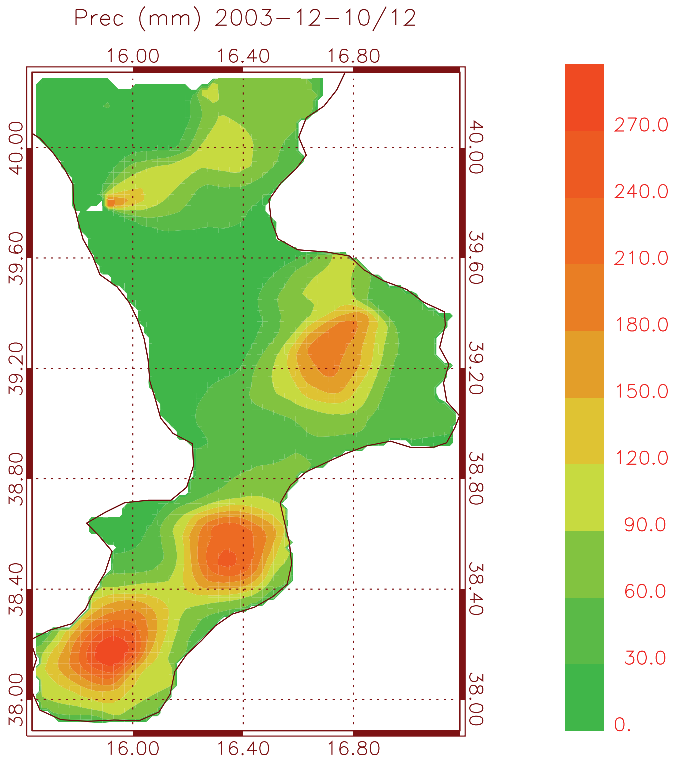

Fig. 2. – Analyzed precipitation accumulated from 00:00 UTC—10th December 2003 to 00:00 UTC—13th December 2003. For the objective analysis we use the Cressman-type method with a search radius of 0.15°. More than 130 raingauges were available for the analysis.

After this short introduction on the Mediterranean storms, we focus on the unusually intense rainfall occurred on 10th-12th December 2003 over Calabria. Figure 1 shows Calabria orography averaged over 10 km^2. The yearly total rainfall amount over the region is about 1000 mm and 83% of this amount is recorded in the cold semester from October to April [15]. Rainfall varies sizeably from the west to the east side and between mountains and lowlands. More precisely, the yearly average precipitation along the west coast is about 800 mm and it decreases to 600 mm along the Ionian side. The yearly total rainfall above 800 m elevation is usually greater than 1000 mm while it is roughly less than 800 mm for valleys and for coastal areas. Despite this rather dry climate, heavy and high impact rainfall is not uncommon over this country [3-5].

Figure 2 reports analyzed precipitation accumulated from 00:00 UTC—10th December 2003 to 00:00 UTC—13th December 2003. Objective analysis is made by a Cressman-type methodology with 0.15° search radius. Raingauges used to analyze precipitation are reported in fig. 1. More than 250 mm were recorded over a vast area in southern Calabria and one station reported about 660 mm in two days (more than half of the yearly climatological value). Accumulated rain is greater over main peaks (mainly over Sila, Serre and Aspromonte) due to the orographic uplift and there is a partial shielding effect of mountain ranges that leaves more precipitation over Ionian coastal areas. Precipitation fell mainly during 11th and 12th December when the storm was more active over southern Calabria. Landfalls were reported in several villages and damages to properties were extensive.

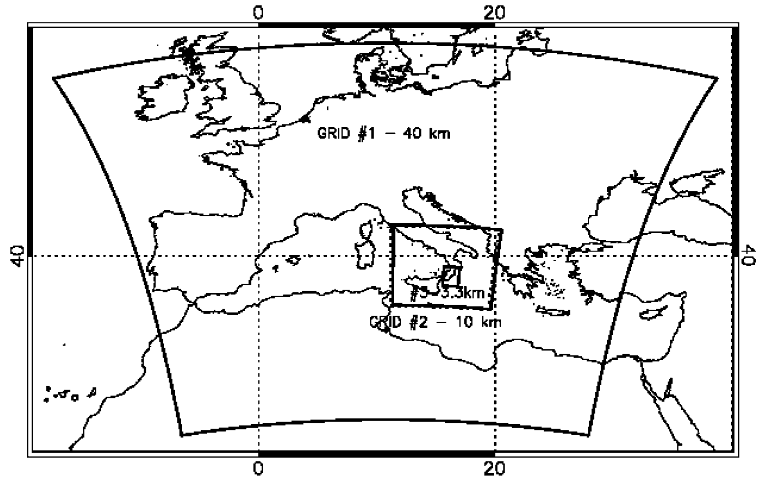

Fig. 3. – RAMS domains.

It is worthwhile to note that orography very often plays a crucial role during severe weather over Calabria. Sometime it is able to trigger convection, as in the case of Crotone flood [5], yet, more often, it is the key mesoscale ingredient that focuses and enhances rainfall in a short geographical spot through several mechanisms (convergence of air masses, flow deflection and channelling, orographic uplift), as in the case of the Soverato flood [3]. Compared to other cases of severe weather in Calabria, this case study shows a sizeable amount of precipitation on the lee of the mountains, particularly across the Aspromonte (fig. 1).

Atlantic meteorological conditions were important for the storm cyclogenesis [16]. More in detail, the tropical storm Odette injected large amounts of water vapour into the atmosphere and this humidity was reorganized by the cooperative action of three main meteorological patterns; the Azores high, a low-pressure system developed off the US east coast and the incipient cyclone that evolved into the 10th-12th December 2003 destructive storm. While the role of Atlantic meteorological patterns is important for the preparatory stages of the storm and for the development of a potential vorticity (PV) streamer, in this paper we show that moisture sources were from the Mediterranean.

The work is organized as follows: in sect. **2** we describe the model set-up and the simulation strategy; in sect. **3** we report and discuss main results. Conclusions are given in sect. **4**.

2. – The model set-up and simulations

The following is a brief description of the model set-up including options selected. For details on the model, the reader should refer to the relevant bibliography [17, 18].

RAMS domains are shown in fig. 3. Horizontal grid spacings are 40 km, 10 km and 3.3 km for the first, second and third grid. Grid nesting uses a two-way interactive procedure and the model is non-hydrostatic in all three domains. The third grid is added to better resolve the Serre and Aspromonte mountains because their shape is more peaked compared to the Sila (see fig. 1) and a greater resolution is needed over southern Calabria to properly take into account the orographic forcing, which is relevant for this case study.

TABLE I. – *Numerical experiments summary.*

Experiment	Physics	Factor separation
f_0	Full physics	$f_0 + f_1 - (f_2 + f_3)$ = combined effect
f_1	No Calabria orography, no surface latent heat flux	
f_2	Calabria orography, no surface latent heat flux	$f_2 - f_1$ = role of Calabrian orography
f_3	No Calabria orography, surface latent heat flux	$f_3 - f_1$ = role of surface latent heat fluxes

Thirty vertical levels, up to 17000 m in the terrain following coordinate system, are used in simulations. Levels are not equally spaced: within the Planetary Boundary Layer (PBL) layers thickness is between 50 and 200 m, whereas in the middle and upper troposphere they are 1000 m thick.

Parameterization of the surface water and energy budgets and fluxes with the atmosphere are described in Walko *et al.* [19].

Non-convective precipitation is computed from explicit prognostic equations for eight water categories: total water, cloud particles, rain, pristine ice, snow, aggregates, graupel, and hail. Convective precipitation is parameterized following Molinari and Corsetti [20] who proposed a simplified form of the Kuo scheme that accounts for updrafts and downdrafts. Convection parameterization is applied to the first and second RAMS domains.

Four simulations are discussed: the first one is the control and is assumed as the reference. To estimate the role of Calabrian orography and Mediterranean surface latent heat fluxes we adopt the methodology proposed by Stein and Alpert [21] to isolate these factors. An important principle in the factor separation is that when more than a factor is considered, it is not sufficient simply to compare a simulation done by removing some physical effect from the control simulation (f_0). Indeed there is a contribution associated with the interaction of two (or more) effects that must be considered. A complete factor separation for n factors requires 2^n simulations. Table I summarizes the numerical experiments discussed in this work.

Initial and dynamic boundary conditions are derived from the ECMWF 12:00 UTC—9th December 2003 operational analysis/forecast cycle for all the numerical experiments. Simulations start the 9th December 2003—12:00 UTC and end the 13th December 2003—00:00 UTC. The first twelve hours are the spin-up time and are discarded.

3. – Results

Figure 4a shows the sea level pressure, the 925 hPa temperature and 925 hPa wind vectors for the 10th December 2003—12:00 UTC. A low-pressure pattern is centred over Algeria and warm and humid air masses are advected on to the Calabria east coast. The cyclogenesis of the storm is illustrated in Federico and Bellecci [16] and is a consequence of the complex interactions between several centres over the Atlantic, including the tropical storm Odette. During the following twelve hours, intense rainfalls were reported in several villages of the Ionian coast. Precipitation is mainly driven by orographic uplift, as shown later.

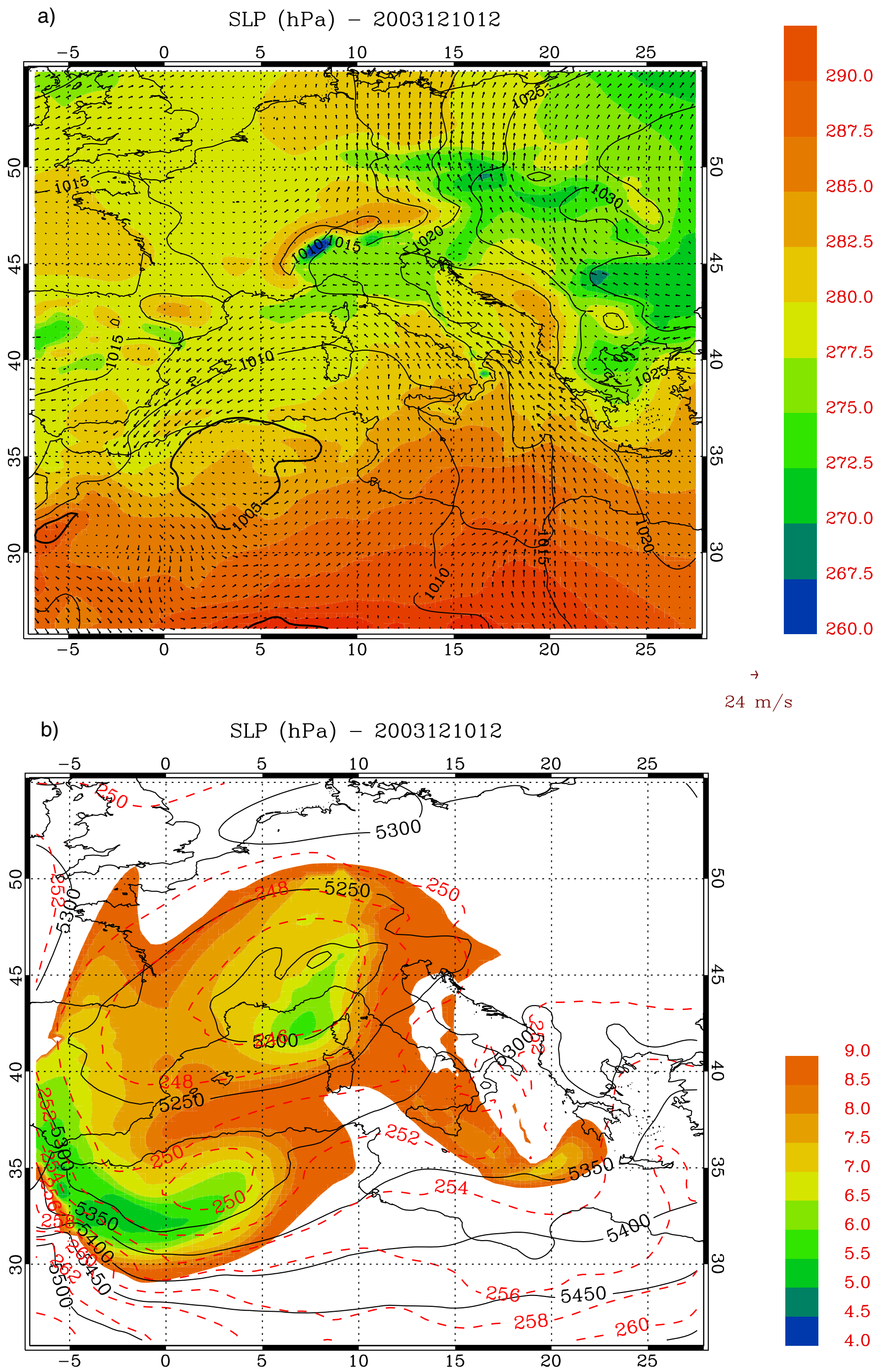

Fig. 4. – a) Sea level pressure (hPa, solid contours), 925 hPa temperature (K, filled contours) and 925 hPa winds. The map is for 12:00 UTC-2003/12/10. b) 500 hPa geopotential height (m, solid contours), 500 hPa temperature (K, dashed contours) and 1.5 PVU surface height (km, filled contours).

Figure 4b shows the 500 hPa geopotential height, the 500 hPa temperature and the height of the 1.5 PVU surface (filled contours, 1 PVU = $10^{-6}\,\mathrm{m^2 s^{-1}\,K\,kg^{-1}}$). PV maps shown in this paper are derived from the RAMS output. The Ertel Potential Vorticity is defined by

$$(1) \qquad PV = (\xi_\vartheta + f)\left(-g\frac{\partial\vartheta}{\partial p}\right); \qquad \xi_\vartheta = \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right)_\vartheta ,$$

where f is the planetary vorticity, ξ_ϑ is the relative vorticity and the subscript ϑ denotes that derivatives are taken on isentropic surfaces. For the extra tropics, PV values above 3 PV units are inferred to represent stratospheric air masses because of the high values of static stability in this portion of the atmosphere. PV values of 1.5–3 PV units represent air that originated near the tropopause. The PV values less than 1.5 PV units represent tropospheric air masses. Positive PV anomalies are often found in areas with downward propagation of stratospheric air masses (see Santurette and Geogiev [22] for a practical review). Following the previous classification, the height of the 1.5 PV units surface represents the height of the dynamical tropopause.

During the following day the storm moved from West to East and the sea level pressure low reached Libyan coasts at about 12:00 UTC of the 11th of December then, due to the synergic interaction between the surface latent heat fluxes from the Mediterranean Sea and the upper-tropospheric level forcing, the storm reinforced and moved northward crossing Sicily and Calabria. This evolution is well illustrated by figs. 5a and 5b that report the same fields of figs. 4a and 4b, respectively, but for 12th December—00:00 UTC. Moreover, from fig. 5b the cut-off associated with the surface low and the elongated tropospheric intrusion of stratospheric air masses located over Africa is evident.

From figs. 4a and 5a, it is worth noting that winds over the Ionian Sea intensify throughout the storm evolution and advect moist and warm air masses toward Calabria Ionian coast. In addition, in fig. 5b the height of the 1.5 PVU surface has lowered compared to fig. 4b and its core is closer to Calabria. Likely, this meteorological situation favoured a mutual interaction between lower- and upper-tropospheric levels and could be favourable to deep convection development where precipitation is less anchored to local topographical features. Deep convection is also aided by Wind Induced Surface Heat Exchange (WISHE) as the surface flow becomes more intense throughout the storm. WISHE, as defined by Yano and Emmanuel [23], is based on the positive interaction between a boundary layer circulation and heated surface. It requires surface heat fluxes to act as the principal mechanism to provide energy source in a warm-developing core with convection used to distribute surface heat aloft.

As discussed previously it is important to give a rough estimation of moisture source scales involved in the storm. To evaluate these scales we did a gross moisture balance over the area 5E-20E, 30N-45N, corresponding to the central Mediterranean. This gross moisture budget was computed from NCEP/NCAR reanalysis dataset [24] which is a widely used and reliable database to perform this kind of analysis. The RAMS output does not span a time period enough to give even the gross estimate of water vapour budget reported in this work, which is of the order of two weeks.

Daily evaporation and precipitation are reported in fig. 6a. The solid curve is the cumulated difference between evaporation and precipitation since the 15th of November. Evaporation is larger than precipitation almost always but for few storms that occurred over the area. Remarkably, four days before the case study reported in this work, another cyclone crossed the central Mediterranean basin and enhanced surface latent heat fluxes

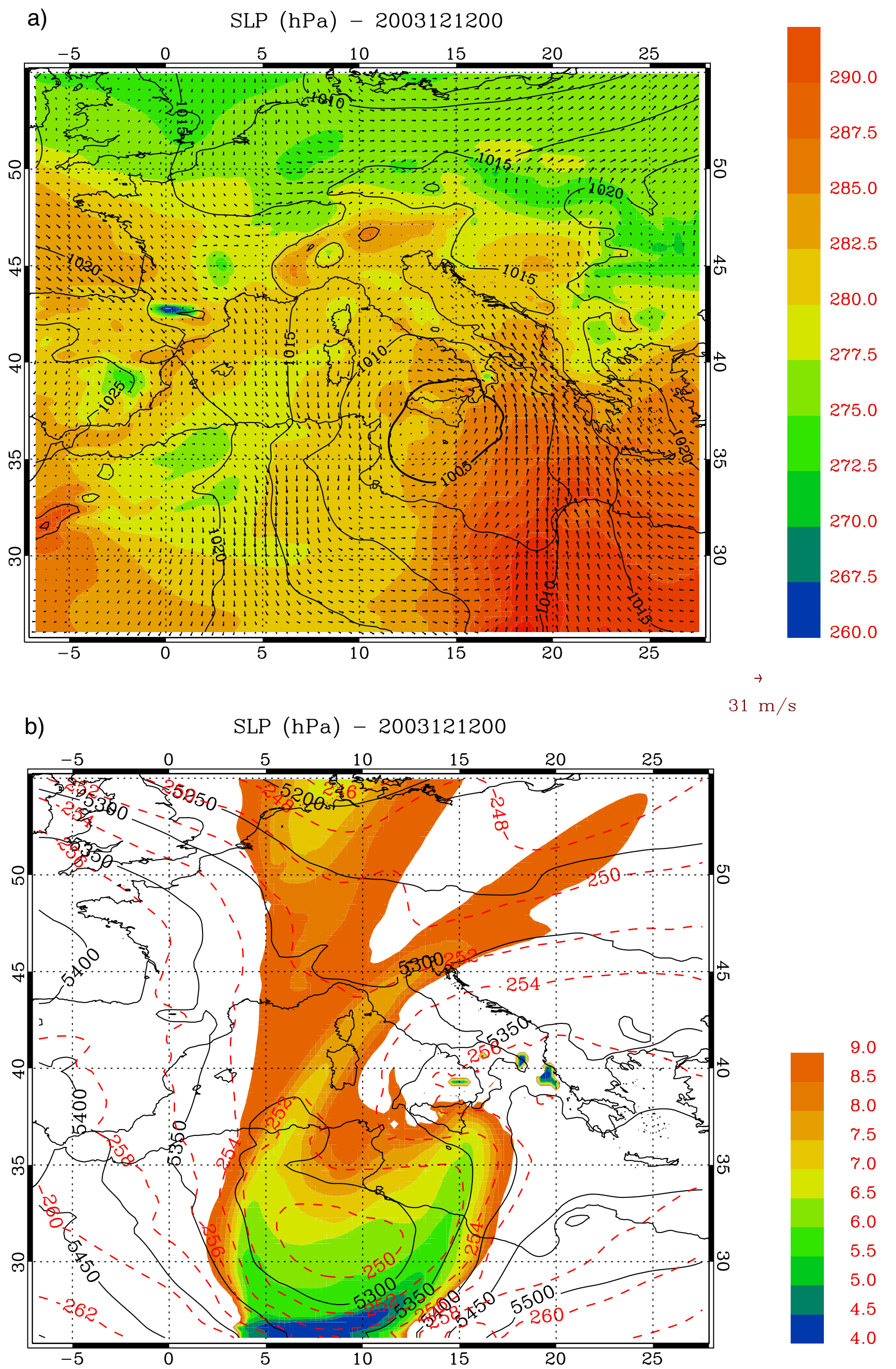

Fig. 5. – a) As in fig. 4a for 00:00 UTC—2003/12/12. b) As in fig. 4b for 00:00 UTC—2003/12/12.

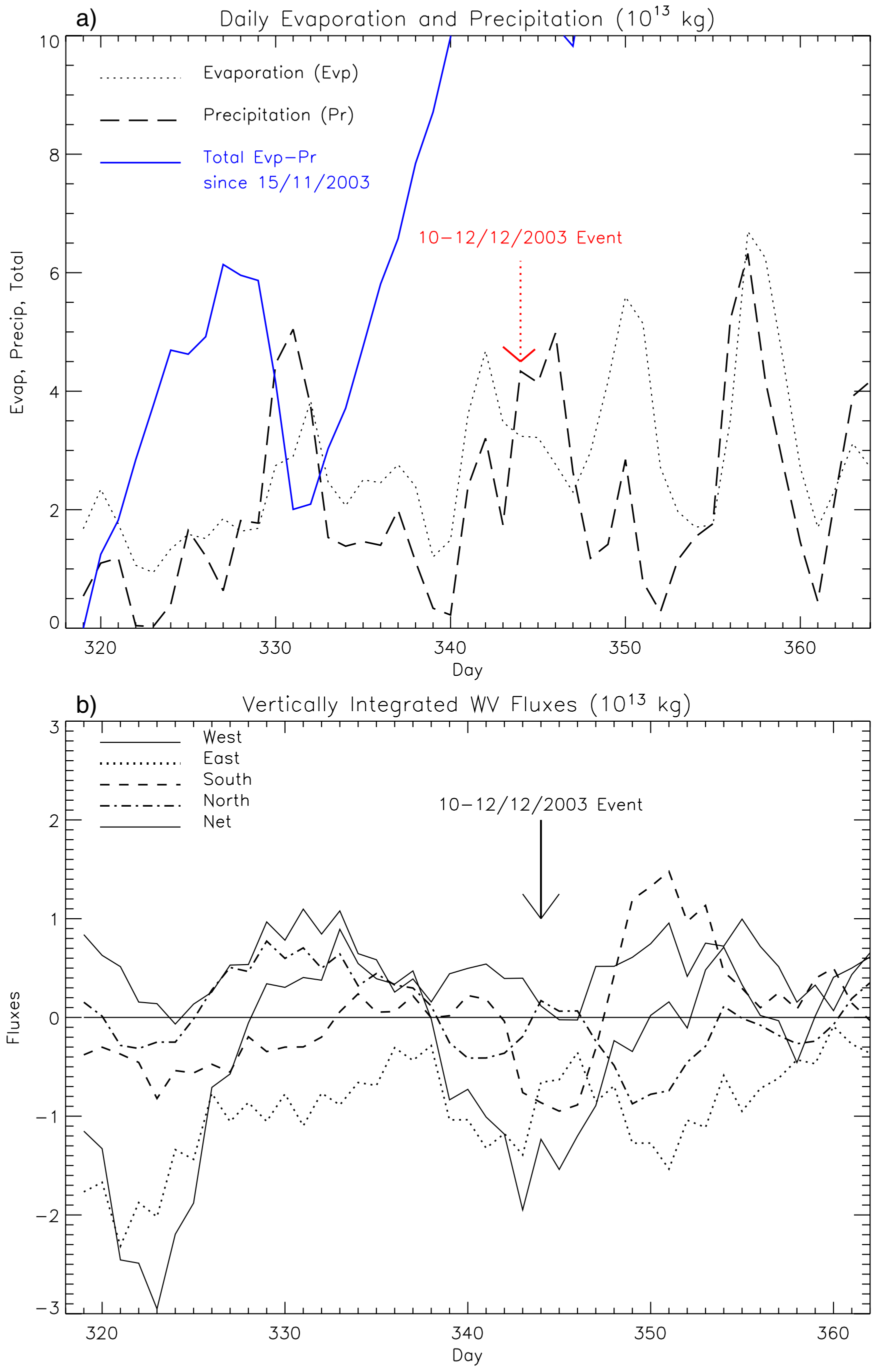

Fig. 6. – a) Daily evaporation (dotted line), daily precipitation (dashed line) and accumulated difference between evaporation and precipitation since 15th November 2003 (solid line). The 10th-12th December case study is indicated by the arrow. b) Fluxes through the boundaries of the area (5E-20E; 30N-45N) and the net flux passing through the volume enclosed by those boundaries up to the 300 hPa level.

by stirring the sea surface with intense winds. The passage of this cyclone is clearly shown in fig. 6a by the relative maxima of precipitation and evaporation few days before the storm discussed in this work. Evaporation is larger than precipitation through the entire meteorological event and this cyclone left a wet environment favourable for deep convection. Figure 6b shows the time-averaged and vertically integrated moisture flux through each boundary of the area (5E-20E; 30N-45N) and the net moisture flux transiting through the volume enclosed by these boundaries up to the 300 hPa level. We first calculate the daily mean of the integral $\frac{\int_{p_0}^{p} V_n q \mathrm{d}p}{g}$ from available analysis (00, 06, 12, 18 UTC), then, in fig. 6b, we report the five-day running mean of this integral. In the former integral V_n is the normal component of the wind vector to each boundary, q is the specific humidity, p_0 is the surface pressure and g is the gravitational acceleration. Fluxes are positive if inward and the net transiting flux is the algebraic sum of the four boundaries fluxes. We do not include vertical fluxes in this calculation because the main purpose is to give an estimation of the external contribution due to the horizontal advection. Fluxes in fig. 6b respond to the synoptic-scale variability; as expected fluxes from the west boundary are positive (inward), those from the east boundary are negative (outward), while the fluxes through the north and south boundaries show a more complex behaviour. The most important point of fig. 6b is, however, that the net flux passing through the area is mainly negative during the two weeks before the event, and there is more moisture exiting the domain than entering.

From fig. 6, it is evident that moisture sources are basically from the Mediterranean basin, even if this is only a crude estimate of the water vapour budget.

Figure 7a shows the precipitation for the RAMS control simulation accumulated over the same time frame of fig. 2. The model is able to represent the main features of the field in terms of total amount and horizontal gradients in the North-South and West-East directions. Intense and abundant precipitation is predicted over the Sila and Pollino mountain ranges but they are underestimated compared to measurements. It is important to note that, as often happens [3, 25, 26], the model overestimates the orographic precipitation. This is clearly evident over Aspromonte (fig. 1) where RAMS over predict rainfall upwind of the mountain peak (*i.e.* East and South of the main peak) and underestimates precipitation leeward. Indeed, as shown by figs. 4 and 5 and as reported in Federico and Bellecci [16], despite the flow is from South/South-East throughout all the event, large precipitation amounts were reported in several stations of the west side of Aspromonte, Serre and Sila and this issue is very important for the crisis management. This suggests that deep convection had an important role during the storm evolution because precipitation, in these conditions, is less anchored to local topographical features.

To better understand the roles of topography and surface latent heat flux we report or discuss the precipitation fields for simulations f_1, f_2, f_3.

Figure 7b shows the total precipitation accumulated over the same time frame of fig. 7a for the no Calabrian orography run (f_3) but with surface latent heat flux activated. Rainfall along the Ionian coast is confined in a short distance near the coastline because of the change in roughness along this line that forces convergence and upward motions. The ambient flow is wet and air masses are able to reach their Level of Free Convection (LFC), which is as low as 950 mbar at 15:00 UTC 10th December, and precipitation occurs. Total precipitation is largely reduced compared to the control case and indicates that orography is a major factor in the precipitation for this case study.

Figure 7c shows the total precipitation accumulated over the same time frame of fig. 7a for the no surface latent heat fluxes run (f_2) but with Calabrian orography. In this case

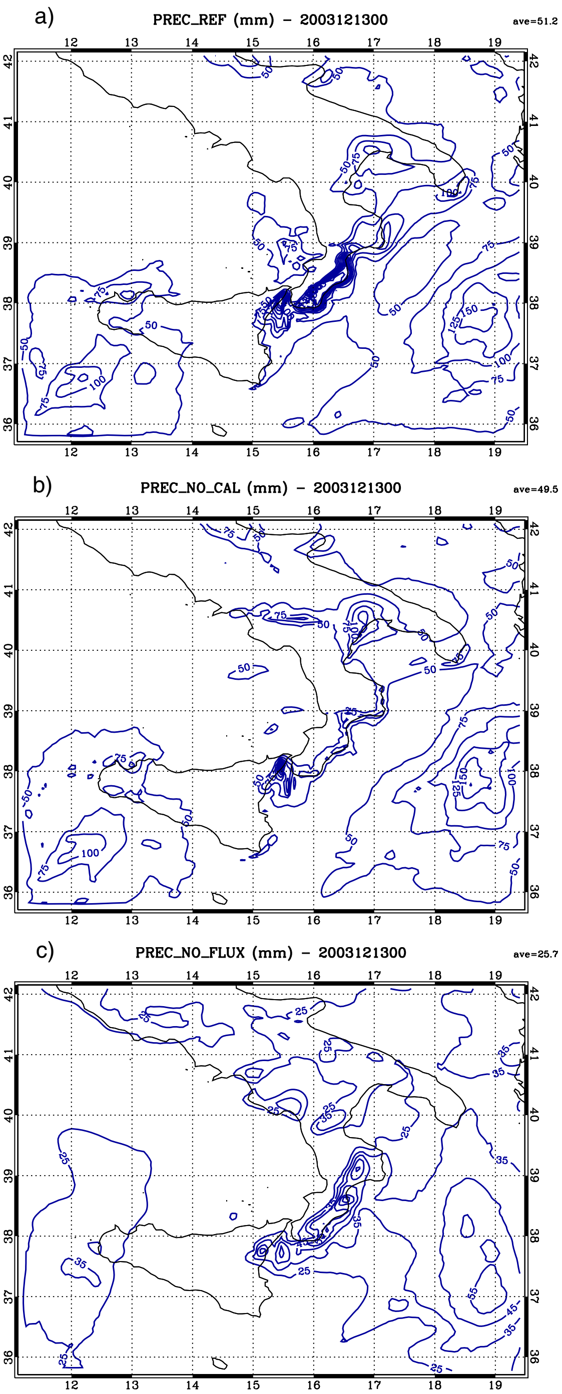

Fig. 7. – a) Total precipitation accumulated for the RAMS control simulation (f_0) over the same time period of fig. 2. Contours from 50 mm to 250 mm every 25 mm. b) As in a) for the f_3 simulation. Contours from 50 mm to 150 mm every 25 mm. c) As in a) for the f_2 simulation. Contours from 25 mm to 75 mm every 10 mm.

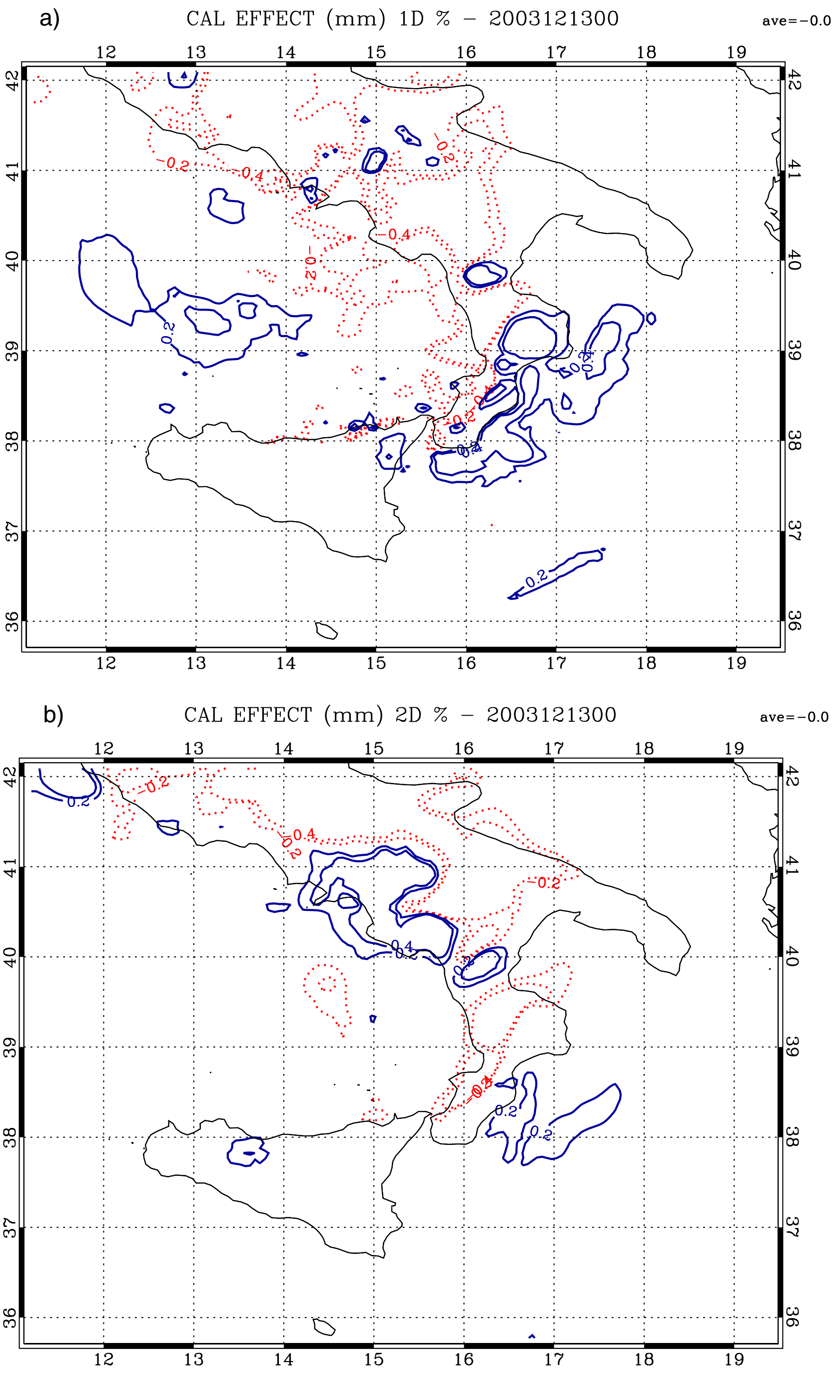

Fig. 8. – a) Contribution of Calabrian orography to precipitation for the first day of simulation (10th December 2003). The field is the normalized difference between f_2 and f_1 experiments in table I. Solid contours are positive values (contours for 0.2 and 0.4), dashed contours (contours for -0.2 and -0.4) are negative values. b) As in a) for the second day of simulation (11th December 2003).

the effect of topography is clear because precipitation maxima are along the main peaks, up windward. Total precipitation is about half of fig. 7b and indicates the key role of surface latent heat fluxes that supply the energy source to the developing storm.

Total accumulated rainfall for the simulation f_1 (not reported) is less than 35 mm everywhere over the domain of fig. 7 and less than 25 mm over Calabria.

Figure 7 indicates that mesoscale processes were a fundamental ingredient of the storm because intense and abundant rainfall was produced by the surface latent heat fluxes, the nearby steep orography and their synergic action, which, as shown below, gives the largest contribution. In order to gain more insight into the storm evolution and the upper-tropospheric forcing, the factor separation technique is applied for the first and second precipitation day over Calabria, *i.e.* for 10th and 11th December 2003.

Figures 8a and 8b show, respectively, the contribution of Calabrian orography (f_2-f_1) for the first and second simulation days. The field reported is the normalized difference between the precipitation field in the experiment in which we consider the physical effect and the precipitation simulated in the experiment in which we remove all physical effects. Normalization is accomplished by the total precipitation amount simulated for the control case for each grid cell and for each day.

The orography of Calabria gives more precipitation on the east side of the country compared to the simulation in which all physical effects are removed. This is a clear consequence of the storm pressure pattern which advects moist and warm air towards the Ionian coast. The shadowing effect of the mountains is evident on the west side of the country where simulated precipitation is greater for the simulation in which all physical effects considered in this work are removed. The previous consideration applies similarly for the second day of integration (fig. 8b).

Figures 9a and 9b show the same fields of figs. 8a and 8b for the surface latent heat flux contribution $(f_3 - f_1)$. For this physical parameter the effects are positive almost everywhere and this is a consequence of the evaporation of the Mediterranean Sea. Indeed, a large amount of water vapour is injected into the overlying atmosphere and reorganized by the storm. This gives more precipitation over the central Mediterranean basin as shown by figs. 9a and 9b.

Figures 10a and 10b show the contribution to precipitation of the interaction between the surface latent heat flux and the orography $(f_0 + f_1 - f_2 - f_3)$ for the first and second day, respectively. The synergic effect of these physical factors is the most important contribution over southern Ionian coast because its pattern accounts for most of the model simulated precipitation. Large water vapour flux from the Ionian Sea is carried toward the south-eastern Calabria, where it interacts with orography.

An important issue revealed by this analysis in the southern Ionian side of Calabria is that the contribution of the physical effects studied (*i.e.* the orography and the surface latent heat flux and the combined effect) decreases through the storm evolution. In particular, we have the following issues:

- there is an evident decrease of the role played by the Calabrian orography;
- the contribution of the surface latent heat flux is less affected, even if it shows a decrease;
- the contribution of the combined effect is larger for the first day when orographic forcing is greater.

The situation is similar when we compare the first and the third day (not reported). Stated in other terms, from figs. 8, 9 and 10, it follows that the storm can be divided

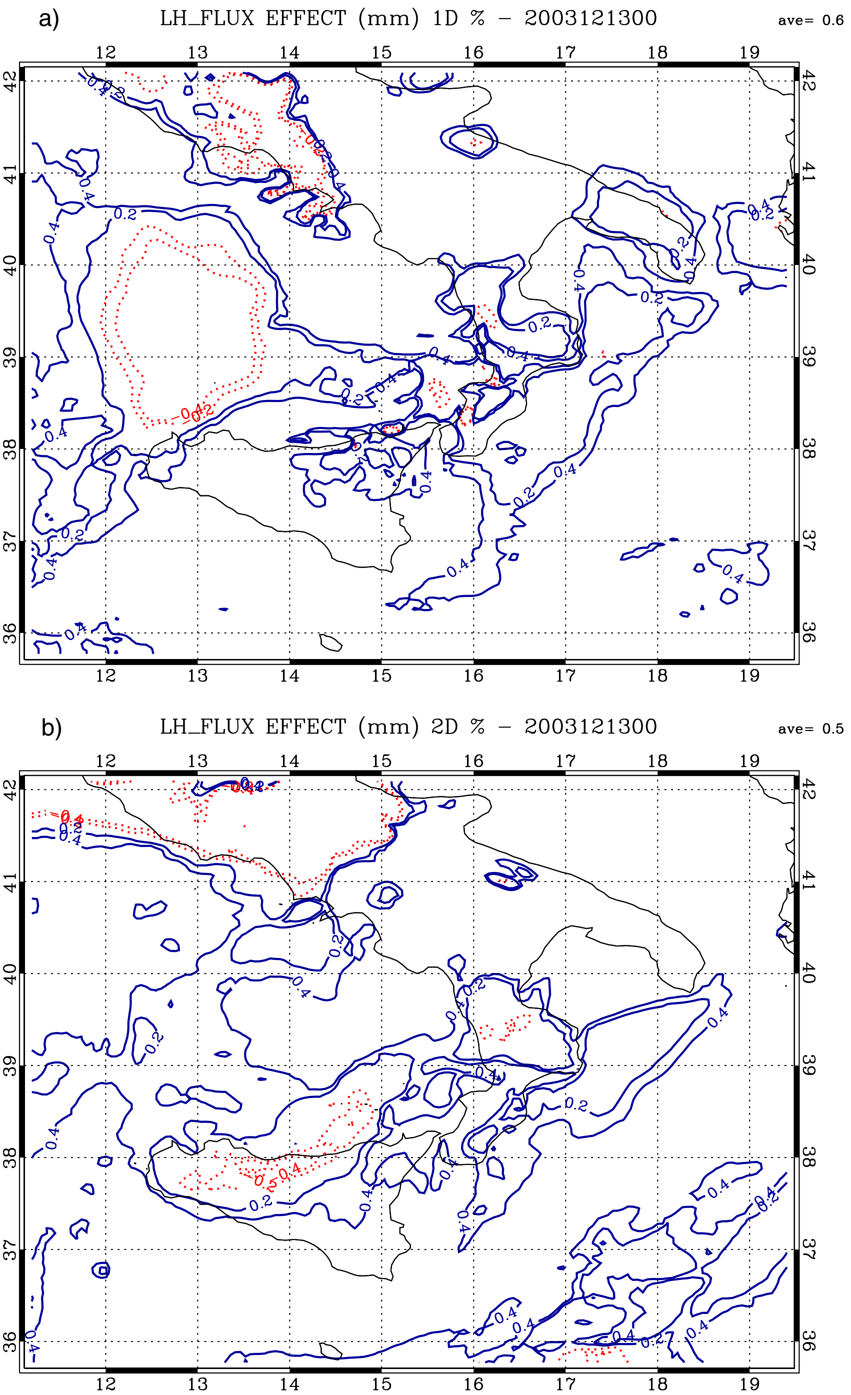

Fig. 9. – a) As in fig. 8a for the surface latent heat fluxes (normalized difference of f_3 and f_1, see table I). b) As in fig. 8b for the surface latent heat fluxes.

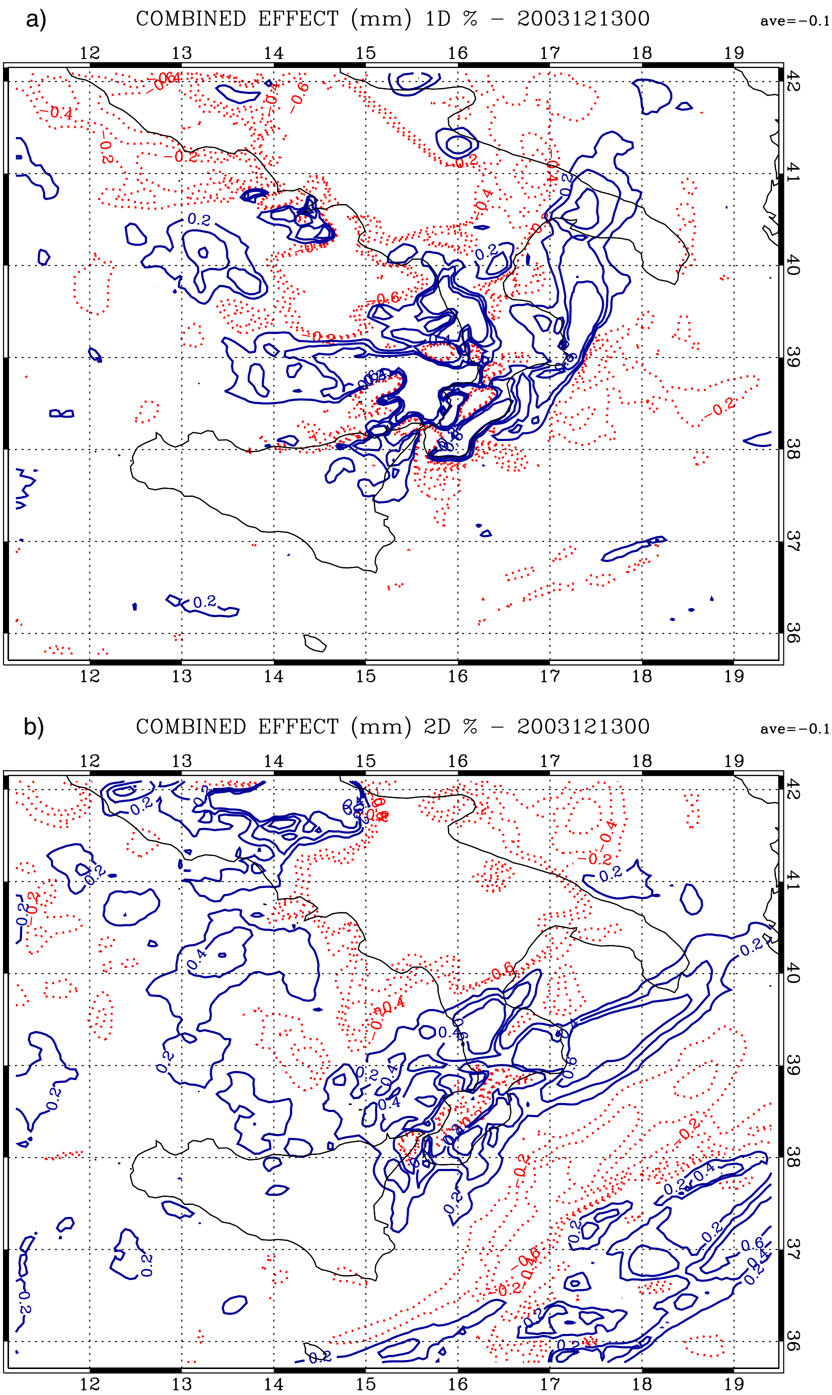

Fig. 10. – a) As in fig. 8a for the combined effect (normalized difference of $f_0 + f_1 - (f_2 + f_3)$, see table I). b) As in fig. 8b for the combined effect.

in two stages. During the first one the orographic forcing was comparatively larger than during the second.

To explain this behaviour we report in fig. 11 the modelled vertical cross-sections, for constant latitude or longitude, of the equivalent potential temperature, vertical velocity and the height of the dynamical tropopause. Figure 11a is for 38.2° latitude and for 10th December 2003—18:00 UTC. Figures 11b and 11c are for 11th December 2003—21:00 UTC and for 38.2° latitude and 14.1° longitude, respectively. These times have been chosen because they are representative of the first and second stage of the storm.

From fig. 11a it is evident that the most intense vertical motions are anchored to local topographical features because they are associated with the orographic ascent in southern Calabria around 16° East. As suggested by fig. 4a too, in the early stages of the storm evolution, the cyclone advected warm and moist air masses on to the Calabrian east coast, and then air masses reached their LFC by orographic forcing. This process determined abundant rainfall and high precipitation rates during the first phase of the storm forced by the orographic features.

As the cyclone approached the central Mediterranean basin, the upper-tropospheric contribution to the vertical motions was greater over Calabria. At this time, as shown in figs. 11b and 11c, the most intense velocity values are not anymore anchored to local topography but are associated with the tropopause folding. This peculiar situation determined still abundant and intense precipitation over Calabria and produced the disastrous event of this case study. Moreover, the most intense precipitation was associated with this kind of forcing.

From the previous results, there are implications for weather forecast over Calabria. First of all one must consider that, at the time of writing, RAMS is one of the two models operational at high horizontal resolution (< 6 km horizontal resolution) for Calabria (see `www.crati.it`). The model output is a very important source for weather forecast issues but its impact is even larger for a data-void country as Calabria. RAMS is able to reproduce the main features of the precipitation field: rainfall is larger in the southern portion of the peninsula and it is greater up windward, if we exclude Aspromonte mountainous range. Nevertheless a deeper inspection of the model rain field output for the Aspromonte area reveals that precipitation is overestimated on the upwind side and underestimated downwind. This is a key issue for local weather forecast because several villages of the Tyrrhenian side, that received large amount of precipitation and damages, would have not been alerted, if the forecaster had considered the RAMS output only.

Atmospheric Limited Area Models (LAMs) and in particular RAMS often overestimates the orographic precipitation, mainly at high horizontal resolution, here assumed to be less than 10 km. It follows that quantitative precipitation forecast of RAMS is often overestimated on the upwind side of mountainous ranges and underestimated leeward compared to measurements. To understand the reason for this behaviour is not an easy task. Likely, this issue is related to the model parameterization schemes. In particular, the parameterization of orography and land use, the convective parameterization and the RAMS microphysical scheme, which also enters in the feedback between the latent heat release and the surface winds, may play an important role. Initial and dynamic boundary conditions can be another source of errors and it is difficult to separate different error components. Now, the upper-tropospheric forcing, and the associated PV anomaly, could be used to correct the forecast at least qualitatively, if the results of this work will be confirmed by additional studies in this direction. Indeed, the strength of the PV anomaly associated with the tropospheric upper level forcing (this parameter is not yet defined), in conjunction with the factor separation technique, could be used to address the role of

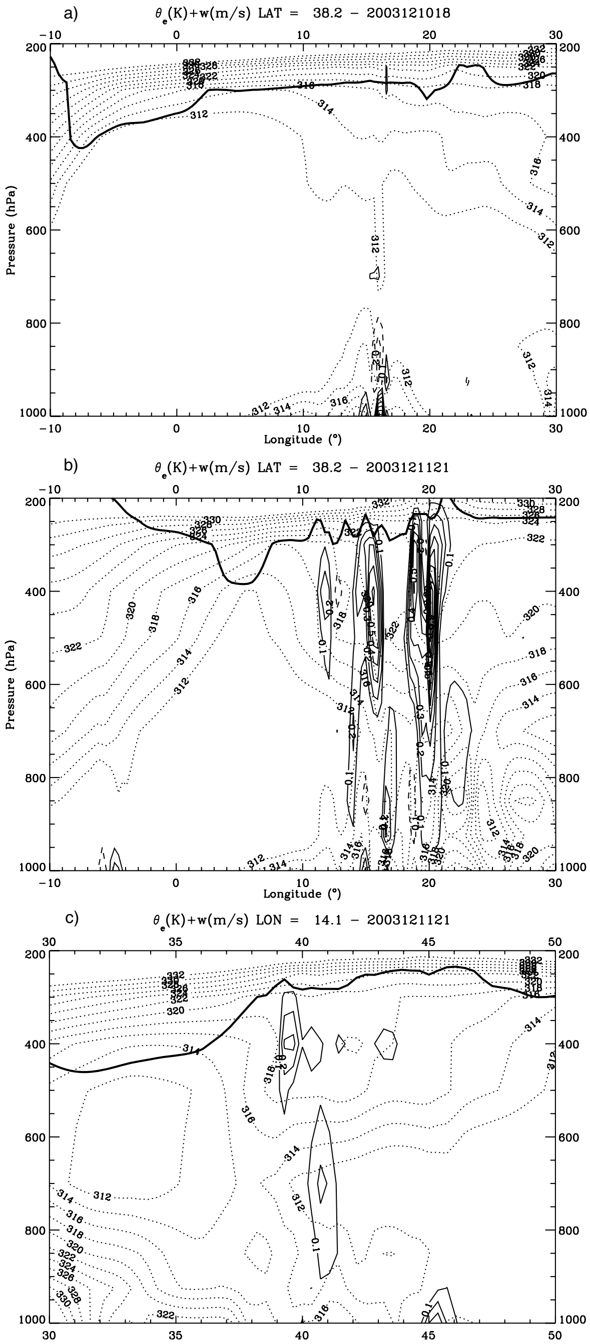

Fig. 11. – a) Equivalent potential temperature (K, dotted contours), vertical velocity (m/s) and the height of the dynamical tropopause (thick solid line) for 18:00 UTC—2003/12/10. For the vertical velocity, solid contours are positive values, dashed contours are negative values and contours increment is 0.1 m/s starting from 0.1 m/s minimum absolute value. b) As in a) for 21:00 UTC—2003/12/11. c) As in a) for 21:00 UTC—2003/12/11 and for a latitude-height cross-section. Longitude is 14.1° E.

the upper troposphere and the kind of vertical motions that develop, *i.e.* if they are more or less linked to local orographic features. This is only a work hypothesis and additional studies are required to clarify this point.

4. – Conclusions

In this study we revisit an intense and high impact storm occurred over Calabria, southern Italy, at the mesoscale, by the Limited Area Model RAMS. To separate the physical factors that were most important for the storm, we adopt the factor separation technique.

Precipitation over Calabria lasted for three days. It is shown that the storm was characterized by two main phases. During the first day orographic forcing played an important role in determining the precipitation pattern and amount. Indeed warm and humid air masses were advected on to the Calabrian east coast where there are several mountainous ranges. The subsequent orographic uplift was enough for air masses to reach their LFC. During the following two days vertical motions were also influenced by the tropopause fold (associated with a positive PV anomaly) with surface air warmed by surface latent heat fluxes over the southern waters of the Mediterranean basin. The combined effect of these factors determined three days of intense precipitation, mainly over south-eastern Calabria, which resulted in a high impact event.

Implications for future developments are briefly discussed.

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This work was partially funded by "Ministero dell'Università e della Ricerca Scientifica" in the framework of the projects "SAI—Messa a punto di un Sistema per l'Allerta precoce di Incendi e per la minimizzazione dei falsi allarmi" and "TAI—Tecniche Agronomiche Innovative per la valorizzazione delle produzioni ed il miglioramento della qualità ambientale". We are grateful to "Aeronautica Militare" and to ECMWF for the MARS access.

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