IL NUOVO CIMENTO Vol. 26 C, N. 1 Gennaio-Febbraio 2003

Quantitative precipitation forecast of the Soverato flood: The role of orography and surface fluxes

S. Federico(1), C. Bellecci(2) and M. Colacino(3)

(1) *CRATI s.c.r.l. c/o Università della Calabria - 87036 Rende (CS), Italy*
(2) *INFM, Università di Roma "Tor Vergata" Dept. STFE*
Via di Tor Vergata, 00133 Rome, Italy
(3) *CNR-IFA - Via del Fosso del Cavaliere 100, 00133 Rome, Italy*

(ricevuto il 2 Ottobre 2001; revisionato il 3 Settembre 2002; approvato il 6 Novembre 2002)

Summary. — During the night between 9 and 10 September 2000 a strong flood occurred in Soverato, a small town of Ionian coast of Calabria, killing 13 people. This was the top of an intense precipitation event occurred over the region during 8th, 9th, 10th September. In this paper the study of this event is performed, both analysing the synoptical aspects and using a numerical meteorological model either to reproduce the precipitation fields or to highlight some mesoscale features that determined the very intense and abundant rainfall. After a short description of the case study and presentation of measured rainfall fields, simulations are discussed. The study is based on three numerical simulations performed using the CSU-RAMS model (Regional mesoscale Modeling System) developed at Colorado State University and daily used at Crati Scrl to produce weather forecasts over Calabria peninsula. The first run is the control case and assesses the model ability to reproduce the flood cumulated rainfall by comparison with rain gauge data collected by the "Istituto Idrografico e Mareografico-Dipartimento di Catanzaro". Second simulation is made to assess the influence of orographic barriers on the precipitation field, while third simulation evaluates the sensitivity to latent and sensible heat fluxes. Results indicate that the model simulate in satisfactory way the location and amount of rainfall, even if some problems are open and require more investigations.

PACS `92.60.Ek` – Convection, turbulence, and diffusion.
PACS `92.60.Jq` – Water in the atmosphere (humidity, clouds, evaporation, precipitation).

1. – Introduction

In this paper we analyse the performances of the RAMS model in a major destructive flood occurred in Calabria, southern Italy, in the period 8-10 September 2000. During those three days the flood killed thirteen people and damage to properties was extensive. The flood, that cannot be classified as a flash flood, because rainfall lasted for three days,

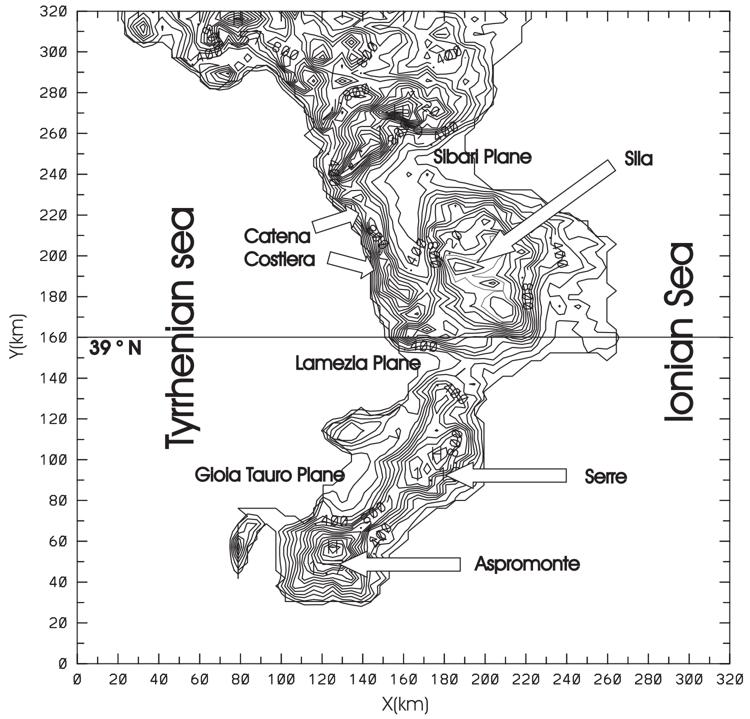

Fig. 1. – Orography of Calabria averaged over 10 km^2. Main orographic features are also reported.

interested the Ionian part of the region producing high precipitation amounts all over the coastal sites. Calabria (fig. 1) is a peninsula characterized by elevated mountains along all its extension and is bounded by the warm central Mediterranean Sea that reaches its temperature maximum in September. These peculiar conditions affect local circulations and the climate of the region [1, 2].

Heavy precipitation amount, as those measured during Soverato flood, requires not only favourable synoptic scale conditions to develop, but also a local favourable environment that can be explored by a mesoscale model [3]. In particular two different aspects are studied in this paper: the orography influence and the role of surface fluxes in determining the precipitation field.

One of the most striking ways in which topography influences the weather is through its strong local control of precipitation. The problem of precipitation over mountains is very complex, especially when the topography is not simple and is located near the sea that act as an energy source, as in the case of Calabria (fig. 1). Several authors performed numerical studies of the 1994 Piedmont flood and showed that the orographycally modified flow was a critical source of extraordinary rainfall [3-6]. A closer look to their conclusion highlights two different regimes of orographic rain that can be important for our case study. In the first regime there is simple orographic uplift occurring under moist neutral conditions. The maximum rain rate is directly related to updrafts. In the second regime there is more complex orographic response in which variations in the orographic-flow response impinging over the mountains determine convergence patterns

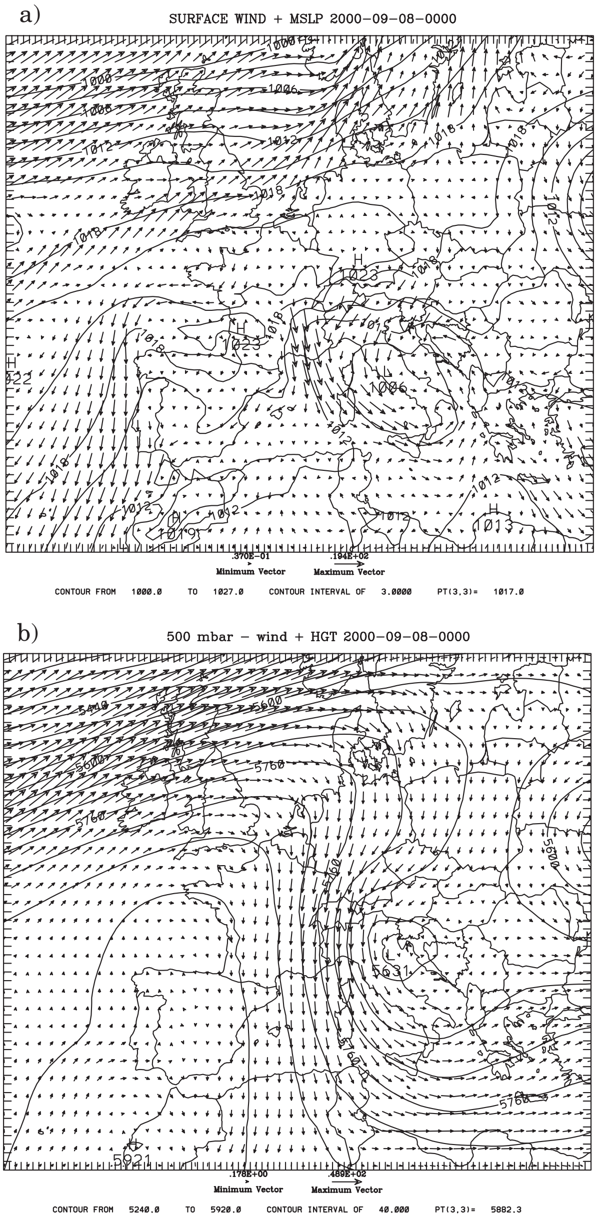

Fig. 2. – a) Sea-level pressure (hPa) and wind field at 0 UTC, 8th September 2000; b) 500 hPa surface geopotential height (m) and wind field, 8th September 2000.

that produce stronger vertical motions and large rain. The orographycally modified flow is determined by environmental static stability, air velocity, Coriolis force and orography.

A second aspect, treated in this paper, is related to the diabatic exchange of latent heat between the sea and the atmosphere. The Mediterranean sea reaches its maximum surface temperature in September and, depending also on atmospheric conditions, large

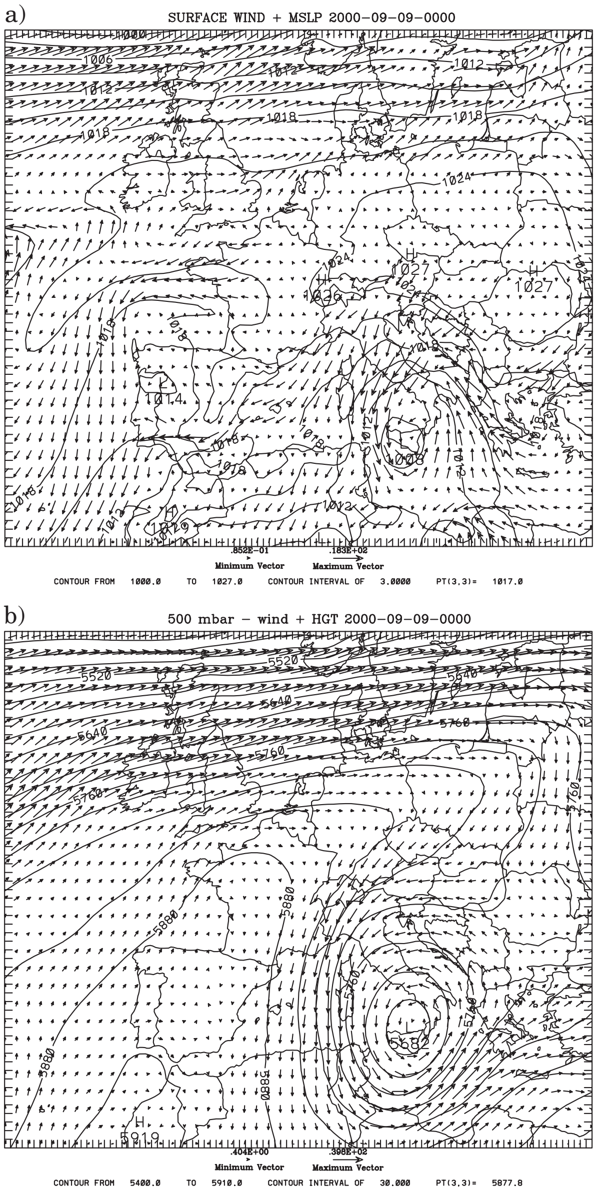

Fig. 3. – a) As in fig. 2a but 24 h later; b) as in fig. 2b but 24 h later.

quantities of water vapour are injected into the atmosphere and, if present, in the storm. The water vapour stored by the storm is converted in rain, if suitable condensation occurs, and the latent heat released during condensation feeds the storm itself.

During Soverato flood, due to the peculiar topography of Calabria peninsula and to the thermal proprieties of the Mediterranean Sea, both these aspects seem to be relevant.

Three model simulations are performed and compared with ground-based data. The first run is the reference simulation and is made to reproduce the flood. Second and third

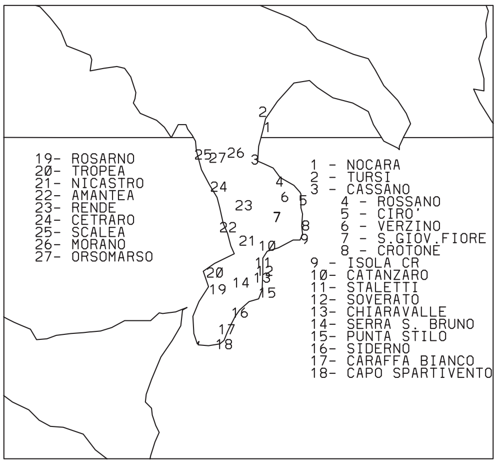

Fig. 4. – Stations locations and names.

simulations assess the role of topography and surfaces diabatic fluxes in determining the precipitation amount over Calabria. Maximum grid resolution for the numerical simulations experiments presented in this paper is 10 km.

2. – Description of the case study

2˙1. *Synoptic description.* – A brief description of the synoptic situation evolution during Soverato flood is presented here, based on ECMWF analyses.

The synoptic situation at initial simulation time (0 UTC, 8th September 2000) is shown in fig. 2. Figure 2a shows sea-level pressure and surface (10 m) wind field, derived from ECMWF data, while fig. 2b represents the 500 hPa height and wind field. Surface map shows a cyclone in central Italy and a ridge extends from Morocco to central-northern Europe. The wind in the central Mediterranean basin is coming from the Northwest. The 500 hPa map shows a well-defined low in north-eastern Italy and a jet flowing from central Europe down to the Mediterranean basin.

During the following day (fig. 3a and b) the cyclone become more defined and moved to South. At 0 UTC, on 9th September 2000, it was located over Sicily and its position favoured advection of warm, unstable, humid marine air from the Ionian sea toward Calabrian Ionian coasts. The surface pressure gradient increased in the central Mediterranean basin determining high wind speeds over the Ionian sea where wind intensity reached values as high as 18 ms^{-1}. Water vapour mixing ratio at surface was greater than 13 gkg^{-1} over the Ionian sea feeding the developing cyclone with large amount of water vapour. The whole system shows little vertical tilting of cyclone axis and determined advection of warm, humid marine air over Calabria at all levels. A ridge extended, well defined, from Morocco to Russia and a jet stream developed in northern Europe.

The synoptic situation one day later, *i.e.* on 10th September 2000–0 UTC, is similar to the ones presented in figs. 3a, b. Surface low slightly moved to East while the upper level low shifted further North and its centre was located West of Calabria, over the Tyrrhenian sea. High surface specific humidity values (> 12 gkg^{-1}) still favoured clouds development and heavy rainfall and the steep orography of the Ionian Calabrian coast

Table I. – *Daily rainfall measured during Soverato flood (mm/24 h).*

STATION	8-10-2000	9-10-2000	10-10-2000	Total event
1) NOCARA	50	80	20	150
2) TURSI	50	70	10	130
3) CASSANO	80	100	25	205
4) ROSSANO	100	175	50	325
5) CIRO’	151	113	7	271
6) VERZINO	90	125	40	255
7) S. GIOVANNI IN FIORE	85	60	20	165
8) CROTONE	50	101	26	177
9) ISOLA DI CAPO RIZZUTO	51	89	16	156
10) CATANZARO	61	76	25	162
11) STALETTI	75	120	150	345
12) SOVERATO	57	70	131	258
13) CHIARAVALLE CENTRALE	133	178	250	561
14) SERRA S. BRUNO	58	150	175	383
15) PUNTA STILO	75	125	251	451
16) SIDERNO	95	125	101	321
17) CARAFFA BIANCO	75	94	76	245
18) CAPO SPARTIVENTO	99	103	50	252
19) ROSARNO	25	50	25	100
20) TROPEA	25	26	24	75
21) NICASTRO	37	41	13	91
22) AMANTEA	19	14	13	46
23) RENDE	30	30	26	86
24) CETRARO	25	16	2	43
25) SCALEA	16	25	2	43
26) MORANO	80	70	30	180
27) ORSOMARSO	37	10	2	49

determined air uplift and storm reinforcement. As a consequence, during the Soverato flood, the synoptic situation remained for two days in a fashion that strongly favoured the advection of humid, unstable, warm marine air toward the peninsula.

During 10th September 2000, the whole system moved toward Balkans.

2˙2. *Precipitation field*. – In this and subsequent sections we will refer to stations location and measured rainfall. For readability we report in fig. 4 the stations locations and in table I we summarize the event as measured by raingauges used in this paper.

In this subsection we report, briefly, the precipitation data measured by a stations subset of the “Istituto Idrografico e Mareografico - Dipartimento di Catanzaro”. These data will be used in sect. **4** to evaluate model performances.

Total precipitation fell during 8th September is reported in fig. 5a. All over the Ionian coast large rain amounts were recorded with two major precipitation spells, respectively, in the northern and southern part of the Ionian coast. The largest amount was recorded at Cirò station (151 mm).

In fig. 5b we show the precipitation recorded on the 9th September. Large precipitation amounts (> 100 mm/day) were measured all over the Ionian coast and the absolute maximum was registered at Chiaravalle Centrale station (178 mm). Also on this day two major precipitation spells were recorded. The first one was located over North-East Sila

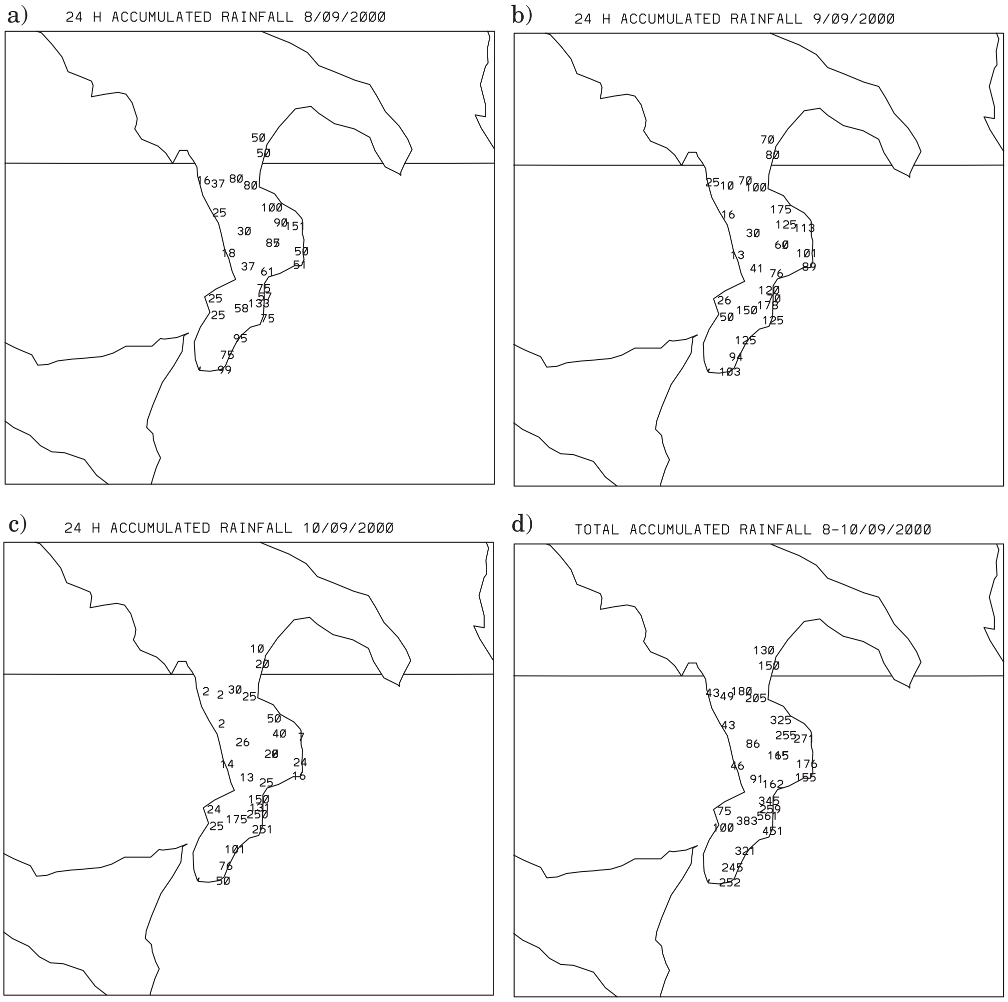

Fig. 5. – a) Measured precipitation during 8th September 2000; b) as in a) but for 9th September 2000; c) as in a) but for 10th September 2000; d) as in a) but for the whole event.

where Rossano station measured 175 mm, while the second spell was registered in the central Ionian coast, between Catanzaro and Siderno.

During 10th September, fig. 5c, the precipitation amount and intensity weakened in the northern Ionian side of Calabria while lasted in the southern part of the peninsula, where the maximum precipitation in one day of the whole event was recorded.

In particular Chiaravalle Centrale and Punta Stilo stations measured, respectively, 150 and 250 mm. About 80% of the precipitation measured along the Ionian coast between Catanzaro and Punta Stilo was registered in the first 6 hours of the 10 September, between 00:00 and 06:00 LST. The maximum intensity, 80 mm/1 h, was realized in Chiaravalle Centrale the 10th September between 04:00 and 05:00 LST. This event (fig. 5d) was extraordinary for Calabria. Chiaravalle Centrale recorded the precipitation maximum since 50 year. Considering the event as a whole two well-defined precipitation spells

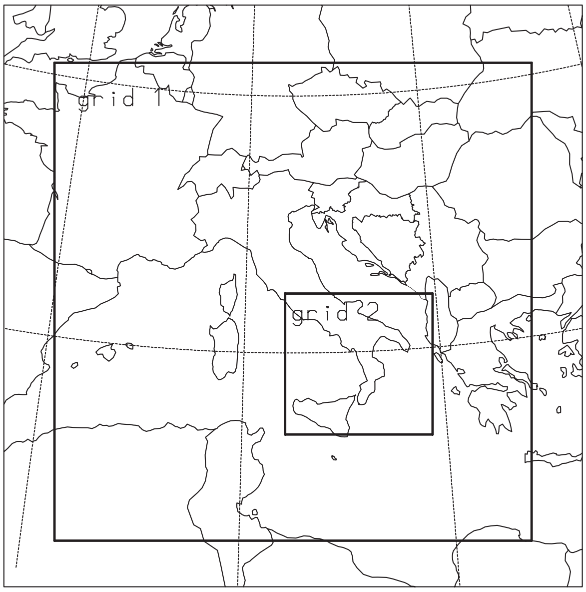

Fig. 6. – Grid configuration. Grid boundaries are denoted by bold line.

are identifiable. The first one is located in the northern Ionian side of Calabria peninsula, where 325 mm was recorded at Rossano station. The second precipitation spell locates in the central Ionian coast, between Catanzaro and Siderno, and in Punta Stilo, Chiaravalle Centrale, Soverato and Siderno stations were registered, respectively, 463, 561, 260 and 321 mm. Chiaravalle Centrale station recorded the maximum precipitation of the whole event (561 mm).

3. – Model set-up

In this paper we use the CSU-RAMS model in its non-hydrostatic compressible form. The following is a brief description of the model set-up including options selected. For details on the RAMS model the reader should refer to Pielke [7]. We utilize two grids. A horizontal grid spacing of 30 km is used for the first grid, that covers the western and central parts of Mediterranean basin; the second grid is nested in the first by a two-way interacting grid procedure with a 10 km grid spacing [8]. Communication from the parent to the nested grid is accomplished immediately following a timestep on the parent grid which updates the prognostic fields. Nested grid timestep is, usually, less than the parent grid time step, so, after the communication, nested grid is updated in a series of smaller time steps until its integration time equals the parent grid simulation time. At this time, the reverse communication is accomplished. Grids configuration, used in this work, is shown in fig. 6.

Twenty five vertical levels, up to 13500 m in the terrain following coordinate system, are used in simulations. Levels are not equally spaced: within the PBL (Planetary Boundary Layer), layers run about 50–200 m tick, while in the middle and upper troposphere they are 1000 m tick. Our study is mainly devoted to study and represent surface rain field, while additional vertical levels are required to better represent the vertical development of the storm.

The parameterization of the surface-atmosphere diabatic processes is described in Walko *et al.* [9]. Non-convective precipitation is calculated from explicit prognostic equations for eight hydrometeors: total water, rain, pristine, cloud particles, ice, snow, hail and aggregates. Convective precipitation is parameterized following Molinari and Corsetti [10] who proposed a simplified form of the Kuo scheme that accounts for updrafts and downdrafts. Sea surface temperature (SST) is a function of the position but, during the simulation, it is held constant in time. The dataset currently used in RAMS contains one degree resolution global monthly climatological values of SST.

Dynamic LBCs (Lateral Boundary Conditions) and initial conditions are provided by the ECMWF analysis available every 6 h and are assumed to vary linearly in time between updates. The horizontal resolution of the ECMWF analysis is half degree.

4. – Results

4˙1. *Control case.* – In this section we often refer to rainfall simulated in correspondence of raingauge stations (fig. 4). In doing this comparison, we simply interpolate to the station location the four nearest model grid points values.

The control case refers to the output of the RAMS model in the configuration illustrated in the previous section. Soverato flood occurred between 8th and 10th September 2000 and, in this subsection, we compare the precipitation amount simulated by the RAMS model with raingauge data for each of the three days.

Figure 7a shows the total accumulated rainfall simulated by the RAMS model for the 8th September 2000. All over the Ionian coast large values are simulated. In particular two main precipitation spells are evident: the first one, located along the North-East side of the mountain Sila, has a maximum value of 200 mm; the second, located more South over the Ionian sea, reaches 142 mm. The comparison between the modelled values and measurements (fig. 5a) highlights few differences. In the extreme South of the peninsula, the model is dry. In particular Capo Spartivento station recorded 99 mm that must be compared with 55 mm simulated by the model. Again the Chiaravalle Centrale station measured 133 mm against 60 mm simulated. This behaviour will be confirmed in the following two days determining a general model dryness in this zone. Moving further North the model performances become better because large rain amounts are measured and simulated along the Ionian coast and on the North-East ridge of the Sila mountain. These large values are representative of the role played by the combined effects of the sea and mountains. Indeed, the humid marine air, coming from the Ionian sea, is forced to ascend along the Sila East ridge producing condensation, large latent heat release and heavy rainfall. In the Sibari plane and Pollino chain the simulated values are larger than measurements. However, some of the simulated precipitation falls during the last hours of the 8th September, while measurements indicate heavy rainfall during the first hours of the 9th September, so the model slightly anticipates the real event. If we exclude the southernmost part of the peninsula, the model is able to reproduce main features of the precipitation field and well reproduce the absolute maximum occurred in the North-East ridge of the Sila mountain. The simulated value in correspondence of the Cirò station, where the maximum precipitation was recorded on 8th September (151 mm), is 130 mm. In addition the strong W-E gradient in the precipitation field is well reproduced.

Forecast verification involves, on a fundamental level, joint distribution of forecasts and observations [11]. That is, any given data set consists of a collection of forecast/observation pairs whose joint behaviour can be characterized in terms of relative

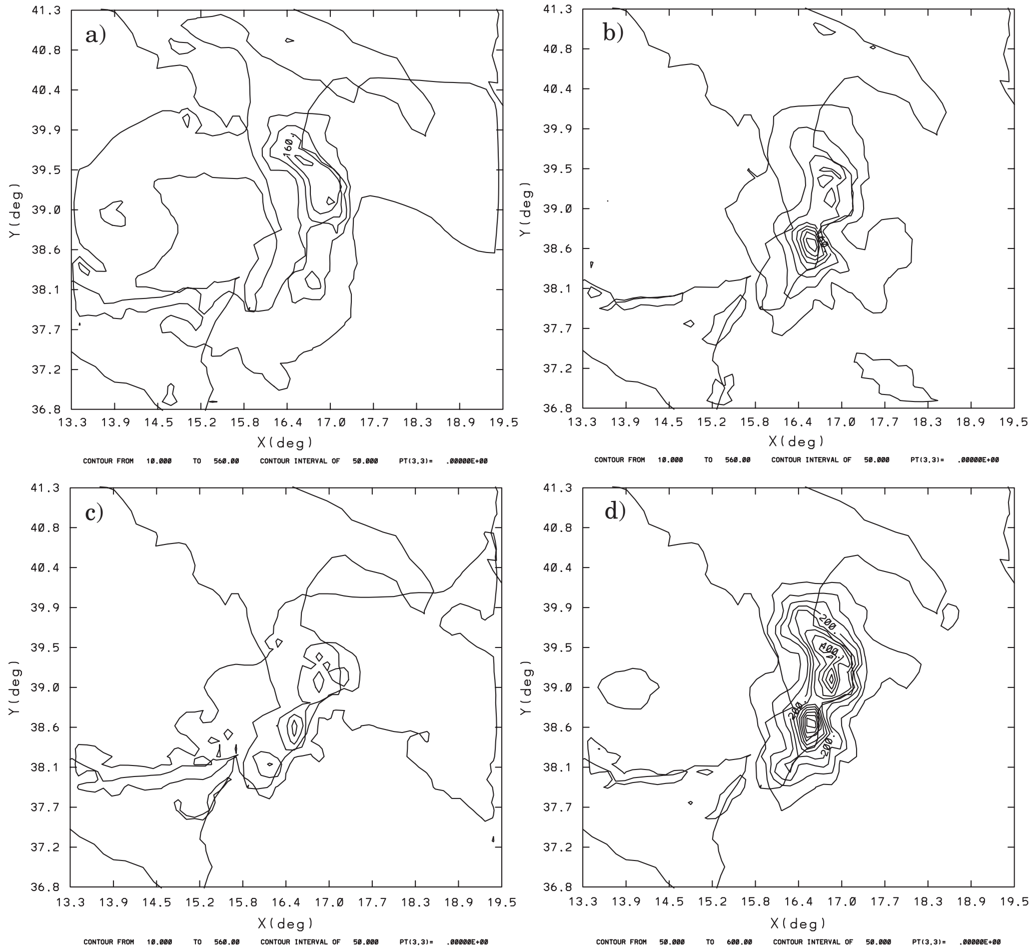

Fig. 7. – a) Total simulated precipitation during 8th September 2000. Contours interval is 50 mm, contour minimum is 10 mm; b) the same as a) but for 9th September 2000; c) the same as a) but for 10th September 2000; d) total simulated precipitation for the whole event. Contours interval is 50 mm, contour minimum is 50 mm.

frequencies of the possible combination of forecast/observation outcomes. A complete review of forecast verification technique can be found in Wilks [12]. In this study we use bias and threat scores to determine model performance because they are rather intuitive and easy to understand. In addition several relevant studies that address the performance of a mesoscale model, using bias and threat can be found in literature for comparison [13-15]. The bias score (B) is defined as the ratio between the forecast stations number above a certain threshold (F) and the observed stations number above the same threshold (O):

$$B = F/O\,.$$

If we introduce CF, *i.e.* the stations number where both model and observations produce precipitation at or above a given threshold, the threat score (TS) is defined as

TABLE II. – *Scores for different threshold for 8, 9, 10 September 2000 and for the whole event. B is the bias score, while TS is the threat score.*

Threshold and score	8 September	9 September	10 September	Total event
B—10 mm	1	1	1.04	1
TS—10 mm	1	1	0.98	1
B—20 mm	1.08	1	1.05	1
TS—20 mm	0.92	1	0.77	1
B—50 mm	0.9	1.05	1.67	1.08
TS—50 mm	0.9	0.93	0.14	0.92
B—100 mm	2.6	1.09	0.33	1.05
TS—100 mm	0.7	0.43	0.25	0.86
B—150 mm	2.0	2.0	0.0	1.06
TS—150 mm	0.0	0.4	0.0	0.84
B—200 mm			0.0	1.16
TS—200 mm			0.0	0.63
B—300 mm				1.0
TS—300 mm				0.5
B—400 mm				0.5
TS—400 mm				0.5
B—500 mm				1.0
TS—500 mm				1.0

the ratio between CF and $(F + O - CF)$:

$$TS = CF/(F + O - CF)\,.$$

Threat score is 1.0 when F and O are exactly the same.

The whole performance of RAMS is summarized in the score table II. Scores are fairly good up to 50 mm threshold due to large amount of precipitation both simulated and measured over the region, then their values show larger modelled values than measured. This is due to timing errors that determine an overestimate of the rainfall in the north area of Calabria.

In fig. 7b we report the total accumulated rainfall for the second day. Also during 9th September heavy rainfall is simulated and measured over all the Ionian coast. In the extreme South of the peninsula the same consideration made for 8th September apply. On this day Capo Spartivento station measured 103 mm where the RAMS modelled 60 mm only. Moving further North the simulated values largely exceed the measured ones. The simulated rainfall at Chiaravalle Centrale, that recorded 175 mm, is 370 mm and the simulated and measured values, in correspondence of Siderno, are, respectively, 200 mm and 125 mm. However, in this day, the modelled precipitation anticipates of 3 h the real event. Indeed, while measured precipitation shows large rainfall rates between 0:00 and 6:00 of the 10th September, the simulated rain spell starts the 9th September at 21:00 and ends at 3:00 the morning after. Over the East ridge of the Sila mountain a second minor precipitation swath is simulated and its maximum value is 236 mm. Large values are reproduced in correspondence of the Rossano stations (140 mm simulated, 175 mm measured) Cirò Marina (100 mm simulated, 113 mm measured). In the Sibari plane and over the Pollino chain the precipitation is slightly underestimated but, as said before, part of the precipitation fallen over this area was simulated the previous day.

Table II summarizes the scores for the 9th September. Also in this case scores show good performance of the model up to 50 mm threshold therefore they suggest an overestimated rainfall compared to measurements. This is due, mainly, to timing errors that produce larger rainfall than measured over Soverato area.

Figure 7c shows the 10th September 2000 total precipitation amount simulated by RAMS. A major precipitation spell is modelled between Catanzaro and Punta Stilo but the simulated values are less than measurements. This compensates the heavy rainfall simulated, in this part of Calabria, on 9th September 2000. Indeed, as said before, the RAMS model anticipates the event of about 3 h. This consideration suggests a good model behaviour considering the event as a whole but, at the same time, highlights model difficulties in reproducing event timing. Moving further South the performances of the model are quite good and the precipitation field gradients are well reproduced in both North-South and West-East directions. The values simulated in the Sibari plane and over the Pollino chain are in good agreement with measurements while in the central part of the Ionian coast the model is rather humid. Table II summarizes scores for this day. Scores suggest an overestimate at 50 mm threshold then a general dryness at larger thresholds. The first point is related to the rainfall overestimate in the East side of the mountain La Sila, while the second aspect is related to timing problems because the main precipitation spell over Soverato area is anticipated simulated about three hours earlier.

Figure 7d shows the simulated rainfall for the whole flood. Two major precipitation spells are identifiable. The first spell is located in the North-East side of the Serre mountains. This location corresponds fairly good with measured maximum. Total precipitation amounts, respectively, recorded and simulated in correspondence of the Chiaravalle Centrale station are 561 mm and 550 mm. The same agreement is obtained for Siderno (measured 321 mm; simulated 308 mm) and Punta Stilo stations (measured 451 mm; simulated 495 mm).

The model is dry in southern Calabria and slightly humid in the Sibari plane and Pollino chain but latter differences are not substantial. Along the Ionian coast between the Sibari plane and Catanzaro the model performs quite well up to the Crotone station where it become rather humid. A source of error, that is under investigation, can be the atmospheric precipitable water defined by ECMWF analysis in the Mediterranea area. The large gradient between the Ionian and Tyrrhenian coasts is well reproduced. Along the Tyrrhenian coast the following results apply (the first value into brackets is the measured precipitation, the second value is the simulated rainfall): Rosarno (100 mm, 86 mm), Tropea (75 mm, 60 mm), Amantea (45 mm, 100 mm), Scalea (43 mm, 40 mm). Table II summarizes scores for the whole event. Scores confirm that the whole event is well simulated by the model.

4·2. *Orography influence.* – This experiment, hereafter also referred to as reduced orography (RO) experiment, is performed by dividing the orographic altitude of the second grid by 5. Thanks to the two-way interacting grid procedure, the first grid orographic altitude is adjusted by the model itself in a consistent fashion [16]. For brevity only the total precipitation amount, shown in fig. 8, is compared to the control experiment but the comments derived for the whole event apply similarly for each day.

At a first inspection of fig. 8 and fig. 7d it is evident that rainfall is greater in the control case compared to the RO experiment confirming the importance of the topography during the flood. In particular the precipitation simulated in correspondence of Chiaravalle and Punta Stilo stations are, respectively, 460 mm and 325 mm to be compared to the 560 mm and 465 mm of the control case. The highest difference between the RO

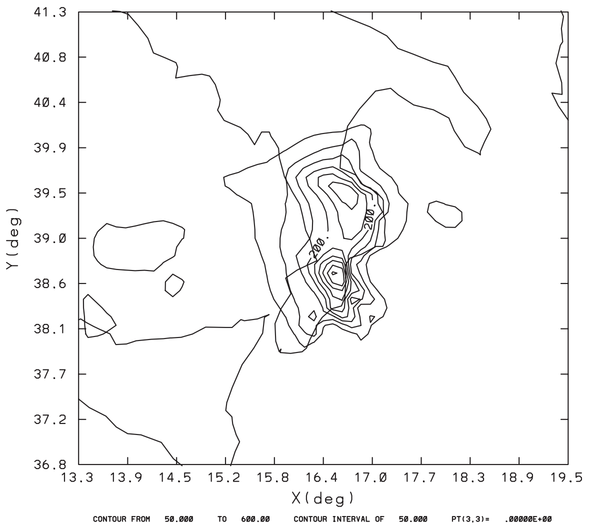

Fig. 8. – Simulated precipitation for the reduced orography (RO) experiment. Contours interval is 50 mm, contour minimum is 50 mm.

and control case is on the East ridge of Sila mountain. This result confirms the major role of orographic uplift in determining this precipitation spell.

A second basic change in the precipitation field between the RO and control case is the field wideness in the West-East direction. The Tyrrhenian coast, that in the control case received little precipitation, is characterized, in this simulation, by larger rainfall. This is obviously related to the orographic obstacles absence to air masses coming from the Ionian sea. Indeed, in the control case, clouds crossing the peninsula from East to West discharge large precipitation amounts along the Ionian coast, reaching the Tyrrhenian side with no or little rain. In the RO experiment cloud systems loss less rain crossing "mountains" and reach the West coast still loading large rain amounts.

It is important to note that, despite to orographic barriers height reduction, the simulated rainfall is high because of favourable large-scale conditions in which the flood developed. Air masses coming from the sea carry on large water vapour amounts and little orographic ascent still determines deep convection and large precipitation.

A second aspect concerns the maximum between Catanzaro and Siderno where thirteen people were killed by the flood. Even if the simulated rainfall is reduced with respect to the control case its position is almost unchanged. This precipitation spell is mainly determined by the little orographic ascent but it is probably enhanced by the convergence of air masses in the flooded area due to the peculiar geographical shape of Calabria in the central Ionian coast. Air masses, coming from South-East are forced to ascend along the Sila and Serre and their trajectories are partially deflected by mountains determining a convergence pattern in the Marcellinara gap that produces much stronger vertical motions. The mechanism of precipitation enhancement due to orographic-flow response along a mountain barrier has been recognized as a key factor for rain enhancement during November 1996 Piedmont flood [3, 5]. While simulated wind field and convergence pattern for the Soverato flood case tend to confirm this hypothesis, additional simulations and higher resolution are required to separate the "flow over" and "flow around" mountains, particularly in the flooded area. This problem is under investigation.

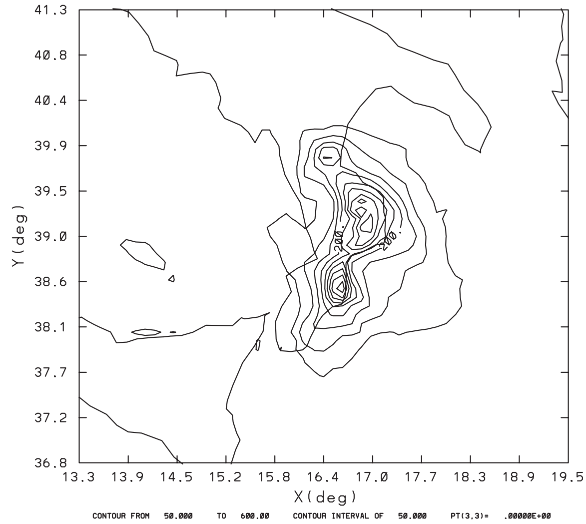

Fig. 9. – Simulated precipitation for the no flux (NF) experiment. Contours interval is 50 mm, contour minimum is 50 mm.

4·3. *Surface fluxes sensitivity test.* – This experiment is performed imposing zero sensible and heat fluxes. Total precipitation for the no flux (NF) case is shown in fig. 9. Also in this case the simulated precipitation is reduced compared to the control case confirming the importance of surface fluxes in feeding the storm. Rainfall simulated in the flooded area, between Catanzaro e Punta Stilo, is as reduced as in the RO case. In the NF simulation the precipitation pattern is quite similar to the control case because of the influence of orographic uplift in determining the precipitation pattern. The maximum in the East ridge of the Sila mountain is well present but values are 100–150 mm less that in control case. The precipitation field gradient in the West-East direction is reproduced with little rainfall in the West peninsula side. This simulation highlights the importance of sea-atmosphere water vapour exchange in feeding the storm that depends, among others, on the sea surface temperature. The Mediterranean SST is maximum in September when the Soverato flood occurred and certainly the sea conditions favoured the injection of water vapour into the cyclone. This aspect is confirmed by a simulation performed as if the Soverato flood had happened in October. In this simulation we used the same initial and dynamic boundary conditions of the control case but the simulation date is one month later, the SST is the October average and the surface flux exchanges are enabled. The precipitation amount in the flooded area is about 100 mm less than in the control case and sizeable rainfall reductions are modelled over all the domain.

However, in our simulation we have not taken into account sea surface temperature anomalies that, as suggested by several authors (see, for example, [17]) and by this simulation, are relevant during extreme events.

5. – Conclusion

In this paper we evaluated the performance of the RAMS model, daily used at Crati Scrl to produce weather forecasts over Calabria since January 2001, in reproducing the Soverato flood. Our attention is focused on the precipitation field, that, as confirmed by this paper, is notoriously a difficult one to predict, especially in mountainous area. The following conclusions can be drawn:

i) the event occurred in the presence of a cyclonic pattern that lasted for three days in a fashion that favoured the advection of humid marine air toward Ionian Calabrian coast.

ii) RAMS works in a satisfactory way, at the resolution used in this paper, considering the event as a whole: the location and amount of precipitation are well simulated. There are, however, problems because rainfall is overestimated in the eastern side of Sila mountain and underestimated in southern Calabria, in addition the event timing is unsatisfactory.

iii) Intense and abundant rainfall occurrence seems to be favoured by the shape of the peninsula and presence of the mountains: these force the humid marine air advected toward the region to ascend, giving rise to adiabatic cooling, condensation of water vapour, release of latent heat and storm reinforcement.

iv) Water vapour exchange between the sea and the storm seems also to be an important factor.

The last two points are still open and require additional investigations that explicitly analyse the orographic uplift-convergence mechanism and take into account sea surface temperature anomalies.

* * *

Raingauge data were kindly furnished by the Istituto Mareografico and Idrografico-Dipartimento di Catanzaro. This work was partially founded by ASI contract number I/C/204/01/0.

REFERENCES

[1] Colacino M., Conte M., Piervitali E., *Elementi di climatologia della Calabria.* IFA-CNR (1997).
[2] Federico S., Dalu G. A., Bellecci C., Casella L., Colacino M., *Nuovo Cimento C*, **24** (2001) 223.
[3] Buzzi A., Tartaglione N., Malguzzi P., *Mon. Weather Rev.*, **126** (1998) 2369.
[4] Romero R., Ramis C., Alonso S., Doswell C. A., Stensrud D. J., *Mon. Weather Rew.*, **126** (1998) 1859.
[5] Rotunno R., Ferretti R., *J. Atmos. Sci.*, **58** (2001) 1732.
[6] Ferretti R., Low-Nam S., Rotunno R., *Tellus A*, **52** (2000) 162.
[7] Pielke R. A., Cotton W. R., Walko R. L., Tremback C. J., Lyons W. A., Grasso L. D., Nicholls M. E., Murran M. D., Wesley D. A., Lee T. H. and Copeland J. H., *Meteorol. Atmos. Phys.*, **49** (1992) 69.
[8] Walko R. L., Tremback C. J., Pielke R. A. and Cotton W. R., *J. Appl. Meteorol.*, **34** (1994) 994.
[9] Walko R. L., Band L. E., Baron J., Kittel T. G., Lammers R., Lee T. J., Ojima D., Pielke R. A. Sr., Taylor C., Tague C., Tremback C. J., Vidale P. L., *J. Appl. Meteorol.*, **39** (2000) 931.
[10] Molinari J. and Corsetti T., *Mon. Weather Rev.*, **113** (1985) 485.
[11] Murphy A. R. and Winkler R. L., *Mon. Weather Rev.*, **115** (1987) 1330.
[12] Wilks D. S., *Statistical Methods in the Atmospheric Sciences* (Academic Press) 1995.

[13] Gaudet B., Cotton W. R., *Weather Forecasting*, **13** (1998) 966.

[14] Anthes R. A., Kuo Y. H., Hsie E. Y., Low-Nam S., Bettge T. W., *Q. J. R. Meteorol. Soc.*, **115** (1989) 763.

[15] Giorgi F. and Bates G. T., *Mon. Weather Rev.*, **117** (1989) 2325.

[16] Walko R. L., Hertenstein R. F. A., Tremback C. J., RAMS The Regional Atmospheric Modeling System – User Guide (version 3b), Available from ASTER Division - Mission Research Corporation P.O. Box 466 Fort Collins, CO 80522 (also available at web site `www.aster.com`) (1995).

[17] Millan M., Estrela M. J., Caselles V., *Atmos. Res.*, **36** (1995) 1.