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M. Milelli, M. C. Llasat, Vincent Ducrocq. The cases of June 2000, November 2002 and September 2002 as examples of Mediterranean floods. *Natural Hazards and Earth System Sciences*, 2006, 6 (2), pp.271-284. hal-00330909

HAL Id: hal-00330909

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Submitted on 18 Jun 2008

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The cases of June 2000, November 2002 and September 2002 as examples of Mediterranean floods

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Received: 24 October 2005 – Revised: 30 January 2006 – Accepted: 20 February 2006 – Published: 2 May 2006

Part of Special Issue “HYDROPTIMET”

Abstract. Four flood events that affected three different countries are here described in terms of meteorological genesis and in terms of consequences on the population and on the territory. Each event is a good representative of a class of phenomena that produce important effects on the urban and extra-urban tissue and that must be taken into account in an optic of civil protection and risk evaluation. This is the subject of the HYDROPTIMET project, part of the Interreg IIIB program, which is collocated in the framework of the prevention of natural hazards and, in particular, those related to severe meteo-hydrological events. This paper aims at being a general introduction of the four events which are the subject of more detailed studies, already published or under submission.

1 Introduction

Floods are the most common kind of natural hazard in the Western Mediterranean region, where, during recent years, all the countries had to face with some intense floods and their consequences. Two main categories of floods may be distinguished in this area, according to the catchments characteristics. On the one hand, when a flood happens within a large river basin, affecting large portions of the plain, huge economic damages are expected to buildings and infrastructures, but frequently there is enough time to limit the loss of human lives. Examples of works on this subjects are Arreola et al. (2002), Boni et al. (1996), Llasat et al. (1999), M.I.S. de l’Eau (1993) and Ramis et al. (1994). On the other hand, when a flood is triggered by an intense rainfall over small catchments (flash floods), the main cost is in terms of human lives, because its rapidity does not permit the actuation of alert procedures (see for instance Chastan et al., 1993;

Comby, 1993; Doswell et al., 1996; Sénési et al., 1996, and Riosalido et al., 1997). In any case, any procedure modifying the exposure of lives and properties to floods, such as flood forecasting and warning, do not avoid the occurrence and the effects of floods, but is aimed at limiting their social and economic cost.

In this context, the EU project HYDROPTIMET funded within the Interreg IIIB Medocc program, has been developed (<http://hydroptimet.medocc.org>). Its goal is the improvement of the knowledge of these severe events phenomena, the optimisation of the meteorological and hydrological aspects for the prevention of natural hazards, the experimentation of new tools (such as numerical models) to be used operationally for the Quantitative Precipitation Forecast (QPF), for the Quantitative Discharge Forecast (QDF) and the improvement of the collaboration between the partners (exchange of data, methodologies, information). For this purpose, four events have been chosen to be analysed. They fall into the categorization that we propose before and, in particular, they are listed in Table 1.

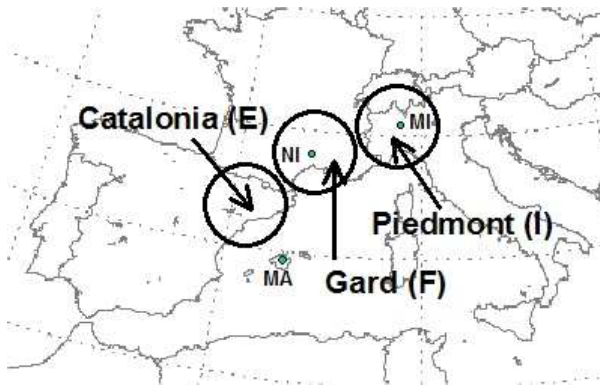
The regions affected by the events are shown in Fig. 1. They all belong to the North-Western part of the Mediterranean basin and a complex orography characterizes them: high mountains, narrow valleys, plains and the coastline are sometimes very close. The particular topography (with the presence of Alps, Apennines, Pyrenees and Massif Central), can heavily interact with the atmospheric flow, in particular with the approaching upper-level troughs, which could trigger range of mesoscale phenomena such as lows moving into the Western Mediterranean Sea and affecting the countries which are along their trajectory. Moreover quasi-stationary mesoscale convective systems may develop in the warm sector of a frontal disturbance, and may be kept in place by the orography inducing large amounts of precipitation in less than 24 h.

Consequently, the aim of this paper is to show an example of each kind of Western Mediterranean floods evidencing

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Table 1. The HYDROPTIMET test cases.

Name	Date	Characteristics
Piedmont 1 (Italy)	14–16 Nov 2002	extended flood
Piedmont 2 (Italy)	23–26 Nov 2002	extended flood
Gard (France)	8–9 Sep 2002	flash flood
Montserrat (Spain)	9–10 June 2000	flash flood

**Fig. 1.** Domain of the Western Mediterranean region with the three areas hit by the events described in the work. The green dots represent the radiosounding stations used: Milan (MI), Nîmes (NI), Palma de Mallorca (MA).

their main synoptic features, trying to find common ingredients and so posing the background for different and more detailed analysis performed by other authors from other points of view. In particular we would like to stress the relationship between large-scale meridional flow, mesoscale structures and local orographic effects in the onset of strong rain events, taking inspiration from other works, such as Plaut et al. (2001) who classified the large-scale flow patterns leading to heavy precipitations over the Alpine chain or Rotunno and Ferretti (2001) who gave particular emphasis on topographic enhancement of precipitation. Table 2 shows a list of works related to the discussed events.

The paper is organized as follows: in Sect. 2 we describe the two Piedmont cases; then we present the Gard and the Montserrat events in Sects. 3 and 4, respectively; eventually the main conclusions are drawn in Sect. 5 with a comparison among the main features of the four events.

Table 2. Works based on the described events.

Piedmont Cases	Elementi et al. (2005), Rabuffetti and Milelli (2005), Taramasso et al. (2005)
Gard Case	Delrieu et al. (2005), Ducrocq et al. (2003), Huet et al. (2003)
Montserrat Case	Mariani et al. (2005), Zampieri et al. (2005), Llasat et al. (2003), Rigo and Llasat (2005)
Overall Comparison	Lacava et al. (2005), Romero et al. (2005), Anquetin et al. (2005)
Inherent thematic	Delitala (2005)

2 Analysis of the Piedmont events

The description of the events, with the meteorological genesis and the consequences from an hydrological point of view, are taken from an internal report (A.R.P.A. Piemonte, 2002) by Arpa Piemonte, which is available on line at the address <http://www.arpa.piemonte.it> (in Italian).

2.1 Synoptic conditions: first case (14–16 November 2002)

This event occurred between 14 and 16 November 2002 in Piedmont (Fig. 2), and was originated by the development and the expansion of an upper-level low, which gradually moved from the Atlantic Ocean towards Italy. For a better comprehension of the phenomenology of the event, it is appropriate to analyse the pre-existent synoptic conditions, starting from 12 November. That morning was characterized by the presence of a weak ridge over the Central Mediterranean Sea and a trough stretching from North-Western Europe to the Atlantic coastline of the Iberian Peninsula.

During that day, the axis of the trough gradually moved Eastward, causing therefore the upper levels winds to become South-Westerly over all Northern Italy. At the same time the sea level pressure decreased over Piedmont. This situation remained almost unchanged during 13 November except for the onset of precipitation over the Western Alps. In the following days, 14 and 15 November, the synoptic situation was characterized by a further extension of the Atlantic trough towards Northern Africa (Fig. 3), with a latitudinal extension of the polar jet stream, reaching Morocco. This provided a strong southerly flow over the Western Alps.

The sea level pressure was characterized by the motion of a minimum from Ireland to the Iberian Peninsula (Fig. 4), and by the formation of a secondary minimum starting from the afternoon of 15 November: this minimum formed over the

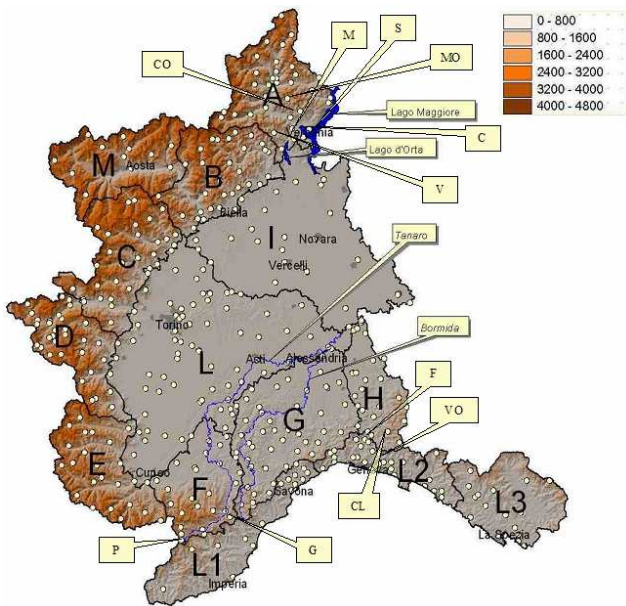


Fig. 2. Location of the rain gauges of the Piedmont, Val d’Aosta and Liguria high resolution networks with the respective warning areas (basins) which are characterized on the base of hydrologic and geologic criteria (homogenous hydrogeological answer to intense meteorological events) and with meteorological, climatological and orographic criteria. The names of the rivers, lakes and stations affected by the events are also indicated (see Table 3 for details). See Fig. 1 for the localization of the area.

Table 3. Names and labels of the lakes, rivers and localities affected by the events and named in this work.

M	Mergozzo
CO	Cursolo Orasso
C	Cossogno
V	Valstrona
MO	Montcrestese
S	Stresa
P	Piaggia
G	Garessio
CL	Carrega Ligure
VO	Vobbia
F	Fraconalto

Balearic Islands and gradually moved towards the Ligurian Gulf.

This synoptic configuration determined a strengthening of the moist flow over Piedmont and the intensification of the precipitation: from the morning of 14 November, it gradually extended to the whole region and the greatest values were recorded over the Southern mountains, where there was orographic updraft due to the interaction of the winds with

Table 4. Names and labels of the warning areas used in the work. The labels are indicated in Fig. 2.

A	Toce
B	Sesia
C	Orco
D	Dora Riparia
E	Varaita
F	Alto Tanaro
G	Belbo - Orta
H	Scrivia
I	Pianura Settentrionale
L	Pianur Meridionale
M	Valle d’Aosta
L1	Ligure di Ponente
L2	Genova
L3	Magra

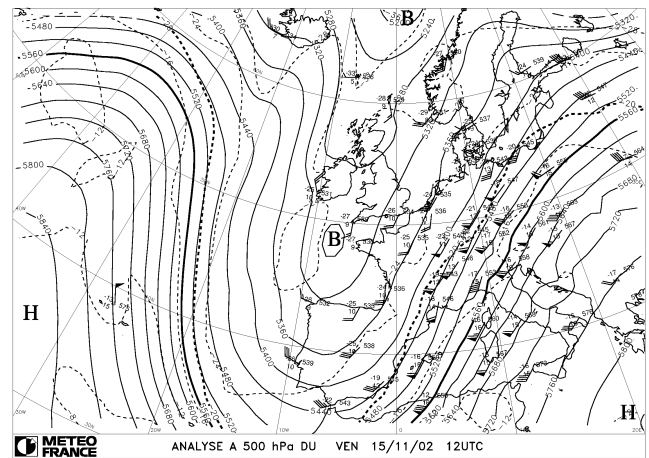


Fig. 3. 15 November 2002 12:00 UTC, analysis at 500 hPa: geopotential (in m) and temperature (in °C) are drawn, respectively, as solid and dashed lines (H for high centre and B for low centre of geopotential).

the Alps and the Apennines. Then the situation remained almost unchanged till the evening of 16 November (Fig. 5), when the sea level pressure minimum shifted towards North-Eastern Europe (Fig. 6) moving along the French and Swiss sides of the Alps. During the event, the temperature aloft did not change substantially; only in the night between 16 and 17 November, the passage of a cold front (Fig. 6) from West caused a fall of about 3°C in the temperature at 700 hPa over the whole Region (A.R.P.A. Piemonte, 2002).

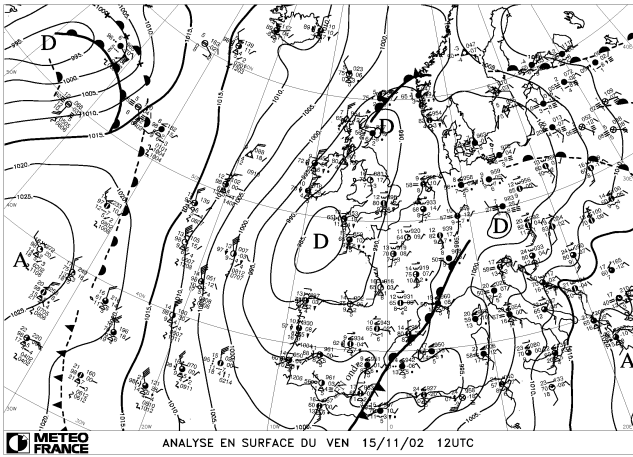


Fig. 4. 15 November 2002 12:00 UTC, surface analysis: slp (in hPa) is shown by solid lines (A for high centre and D for low centre of slp).

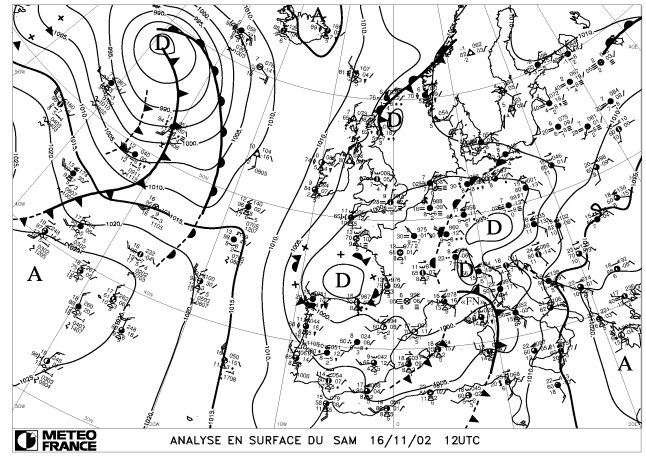


Fig. 6. 16 November 2002 12:00 UTC, surface analysis: slp (in hPa) is shown by solid lines (A for high centre and D for low centre of slp).

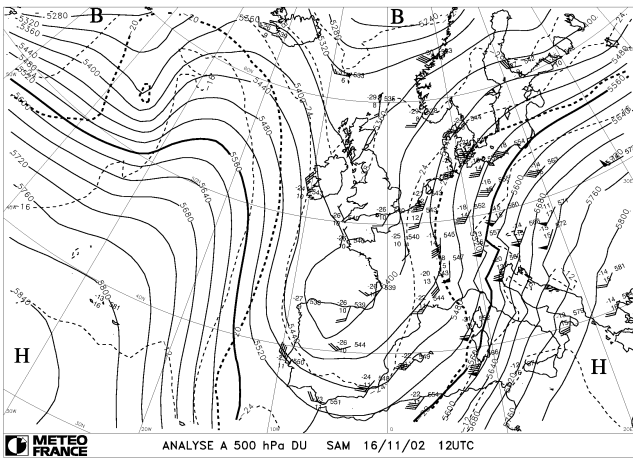


Fig. 5. 16 November 2002 12:00 UTC, analysis at 500 hPa: geopotential (in m) and temperature (in °C) are drawn, respectively, as solid and dashed lines (H for high centre and B for low centre of geopotential).

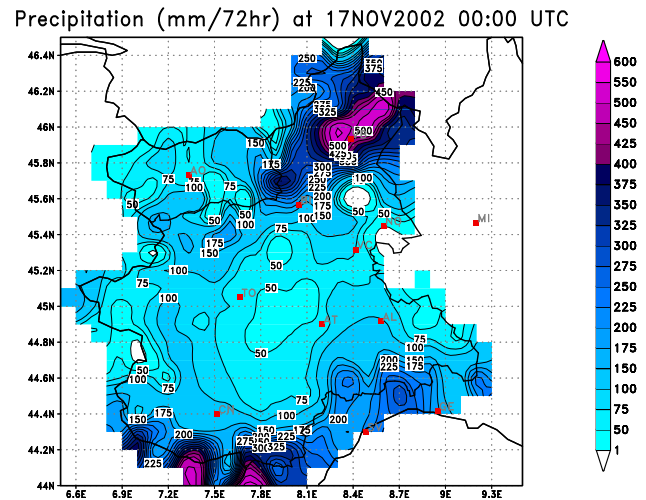


Fig. 7. Total observed precipitation in Piedmont from 14 to 16 November 2002. See Fig. 1 for the localization of the area.

2.2 Analysis of the impacts: first case

In the days 14–16 November, the precipitation affected particularly the Toce area in the North and Alto-Tanaro in the South of Piedmont (Fig. 7). It has to be pointed out that the extension of the heavy precipitation areas over the French border plotted in Fig. 7, are the effect of the Cressman interpolation method (Cressman, 1959) adopted in this case; no data are actually available over the French territory. The maxima of precipitation accumulated in 72 h have been recorded in the Toce lowland with 490 mm in Mergozzo, 554 mm in Cursolo Orasso, 540 mm in Cossogno, and 560 mm in Valstrona (see Fig. 2 for their location and Table 3 and Table 4 for the labels and names correspondence).

In various rain gauges of the area (around 1500 km²) the total values recorded exceeded 400 mm. In the Southern part (Alto Tanaro), the highest values of rain in 72 h were observed in Piaggia with 480 mm and in Gressio with 390 mm, but important precipitations have been recorded also in the river basin of Scrivia with peaks of 250 mm in Carrega Ligure. The areal values were around 325 mm over the Toce basin, and 210 mm over Alto Tanaro in 72 h. Such critical values have been compared with the return time curves, which indicate that the 20 years time was exceeded (A.R.P.A. Piemonte, 2002). In the Southern zones the peaks of precipitation have been recorded during 14 and 15 November while in the North-Western part the highest values of precipitation have been observed during 16 November. Only the Toce area

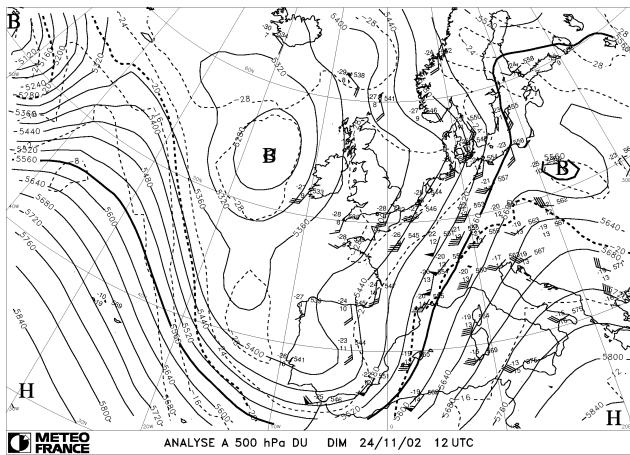


Fig. 8. 24 November 2002 12:00 UTC, analysis at 500 hPa: geopotential (in m) and temperature (in °C) are drawn, respectively, as solid and dashed lines (H for high centre and B for low centre of geopotential).

in the North of the region has been affected for the whole event (14–16 November).

The response of the hydrological network was particularly complex. In the Northern part of the region, the first increase in the rivers flux has been registered during 14 November, with few approaches to the warning levels, without overcoming. From the evening of 15 to the morning of 16 November though, the intensification of the precipitation brought to the overcoming of the warning levels in all the main rivers and, in particular, in the Maggiore Lake which overcame the warning threshold of 5 m, reaching the level of 6.62 m. In the Southern part of the region, the situation was similar: in fact, the main rivers (Tanaro and Bormida, 8000 and 2600 km² catchments size respectively) had a first critical phase during 14 November, but the most important effects have been recorded the days after with overcoming of the attention thresholds.

All these areas were affected by some phenomena of hydrogeological instability with movements of land and localized floods. In particular, in the Northern provinces there were damages in the municipalities by the increase of the level of the Maggiore lake and in smaller degree by the one of the Orta lake. Also some retaining walls were destroyed. No casualties were registered during the entire event.

2.3 Synoptic conditions: second case (24–26 November 2002)

During the beginning of the third ten days of November, the synoptic situation was characterized by an upper-level trough with an associated surface cyclone standing off the Irish coastline, and by a ridge with the axis centred between Southern Italy and Greece. From 23 November, the trough began to expand Southward reaching the North-

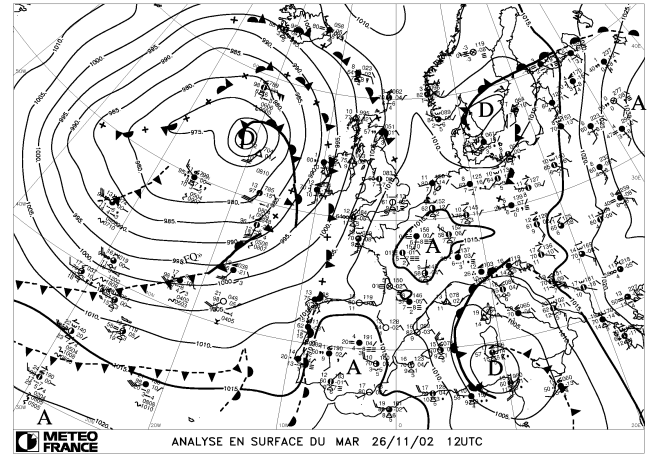


Fig. 9. 26 November 2002 12:00 UTC, surface analysis: slp (in hPa) is shown by solid lines (A for high centre and D for low centre of slp).

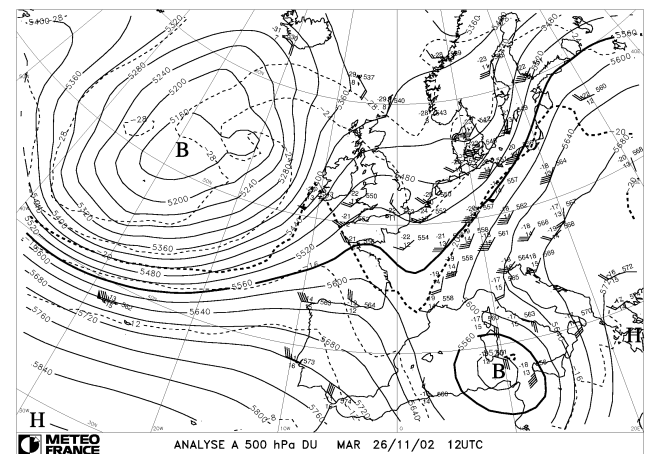


Fig. 10. 26 November 2002 12:00 UTC, analysis at 500 hPa: geopotential (in m) and temperature (in °C) are drawn, respectively, as solid and dashed lines (H for high centre and B for low centre of geopotential).

African coastline and directing a moist South-Westerly flow over Northern Italy (A.R.P.A. Piemonte, 2002).

During 24 November, the widening of the trough towards East caused a backing of the flow over Northern Italy from South (Fig. 8), with a general increase of humidity at all levels. This situation lasted also for the whole day after, when there was a further deepening of the trough over Northern Africa and a rotation of its axis towards East. During 26 November a deep low associated to a sea level pressure minimum, isolated over the Sardinia Channel and stayed stationary for about 24 h, causing a very wet South-Easterly flow from the Tyrrhenian Sea towards Piedmont (see Fig. 9 and Fig. 10).

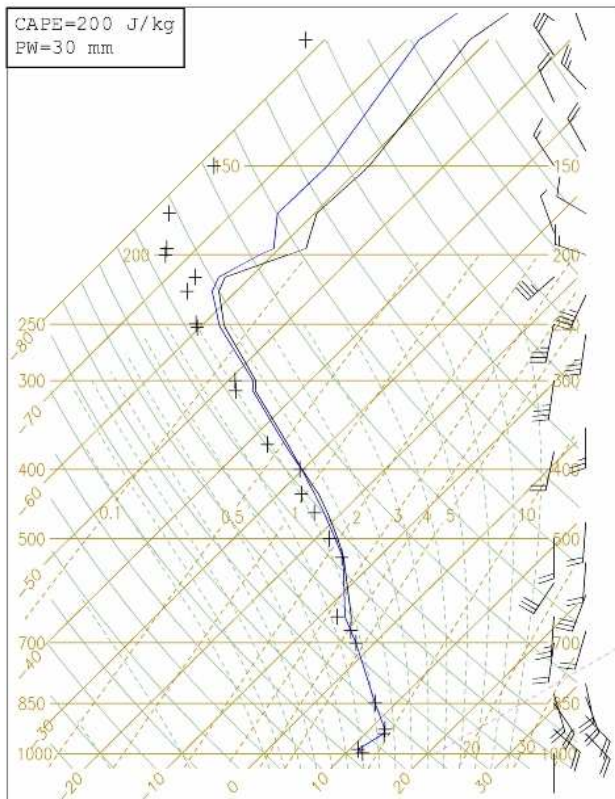


Fig. 11. 26 November 2002 17:00 UTC, Milan radiosounding: in the upper-left corner of the panel, CAPE stands for Convective Available Potential Energy (Jkg^{-1}) and PW for Precipitable Water (mm). The CAPE computation is based on the most unstable parcel. See Fig. 1 for the location of the station. On the right, the wind direction and intensity is displayed.

Finally, during 27 November, the Eastward movement of the low towards Southern Italy, favoured the weakening of the precipitation over Piedmont with an increase of the sea level pressure which passed from 1010 hPa the 26 at 12:00 UTC to 1014 hPa the 27 November at 00:00 UTC and then to 1019 hPa during the following night.

The precipitation related to this event was heavy and continuous because of the long persistence of the wet Southerly winds: this flow caused typically orographic rain over the Northern part of the region, from the night of 23 to the morning of 27, and over the Apennines from the night of 23 to the evening of 26 November. The heaviest precipitation was recorded during the 24 h between 06:00 UTC of 26 and 06:00 UTC of 27 November with moderate values all over the region and very heavy rain on the Toce and Scrivia basins (see Sect. 2.4). In particular, on the Scrivia basin, the highest values were recorded during the first 6 h of 26 November.

Owing to the long duration of the Southerly flow, the height of the freezing level was constantly increasing from 23 November, when the mean value over North-Western Italy was around 1900 m, to 26 November, with a mean value

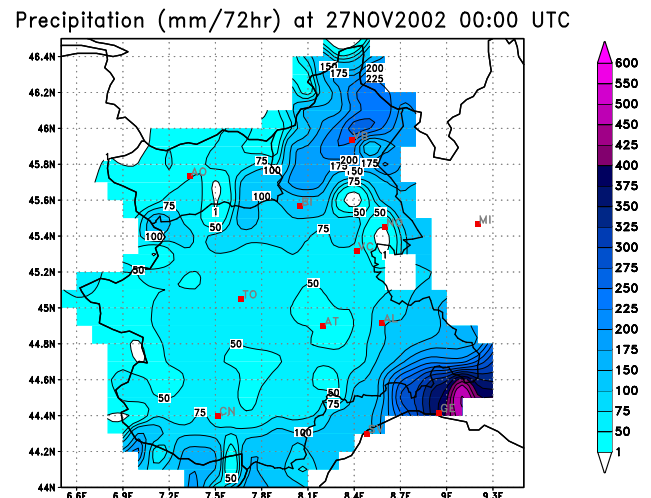


Fig. 12. Total observed precipitation in Piedmont from 24 to 26 November 2002. See Fig. 1 for the localization of the area.

around 2600 m (Fig. 11) and a further increase up to 2900 m the day after. This effect contributed to increase the amount of water discharged into the rivers during the event.

2.4 Analysis of the impacts: second case

The precipitation (Fig. 12) extended in particular over the Southern part of the region from 24 to 26 November (Scrivia area) with maxima of 442 mm in Vobbia, 360 mm in Carrega Ligure and 340 mm in Fraconalto, recorded in 72 h; in smaller measure also the Northern part (Toce area) was affected with 260 mm in Montecrestese, 283 mm in Mergozzo and 235 mm in Stresa in 72 h (see Fig. 2 for their location and Table 3 and Table 4 for the labels and names correspondence). Considering the average rain over warning areas, the highest values have been recorded in the Scrivia basin (≈ 250 mm in 72 h) and in the Toce area (≈ 150 mm in 72 h). Such values have been compared with the return time curves, which indicate that the 20 years time was exceeded in the Scrivia area but not in the Toce one. Considering the kind of precipitation, it was persistent and diffuse with the exception of Vobbia (in correspondence with the Apennines watershed) where the rain gauge registered 76 mm in 3 h and 143 mm in 6 h, indicating the presence of a localized system of convective cells which have been originated over the Western Mediterranean Sea and was moving Northwards, following the synoptic flux and affecting mainly the Ligurian side of the Apennines.

In the first phase of the event, from 24 to 25 November, the rain gave rise to ordinary floods of some small water courses in the South and in the North, and to a limited increase of the Maggiore Lake. During the second phase of the event, from the second part of 25 to the morning of 26, the intensification of the phenomena produced localized floods along the

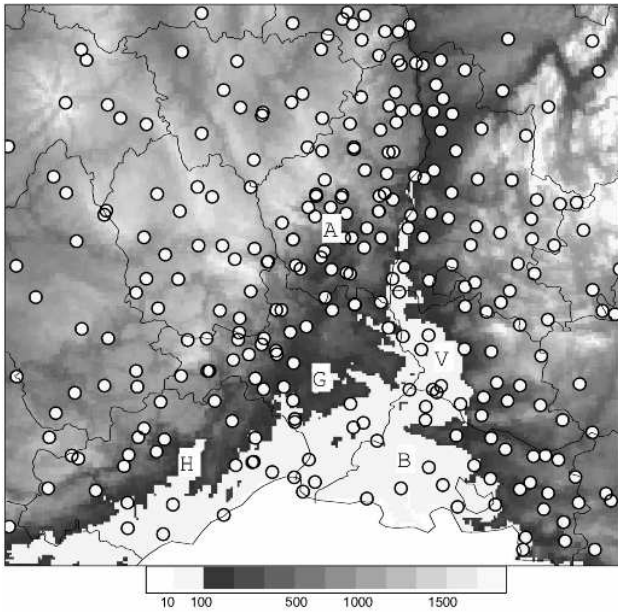


Fig. 13. Location of the rain gauges of the regional high-resolution networks (Météo-France, DDE Ardèche, Gard,...) superimposed to relief of South-Eastern France. Departments are displayed in solid black line: A for the Ardèche Department, G for Gard, V for Vaucluse, H for Hérault, B for Bouches-du-Rhône. See Fig. 1 for the localization of the area.

Tanaro and Bormida rivers. It is important to emphasize the situation of the soil which was already saturated because of the particularly rainy period from the beginning of the month and, therefore, it amplified the response of the basins. In any case, the effects were not relevant also because only rural areas were hit: there were problems in the smallest rivers because of the obstruction effect near bridges; there were serious damages to a pillar of a bridge of a highway next to the border with Liguria; the sliding of the slope also affected some vineyards of the area; no casualties were registered during the entire event.

3 Analysis of the Gard event

3.1 Synoptic conditions

During 8 and 9 September 2002, a heavy precipitation system affected the Gard region, Southern France (Fig. 13), causing enormous damages and loss of human lives.

The system was generated by an upper-level cold low centred over Ireland, extended meridionally to the Iberian Peninsula, which created a South-Westerly flow over South-Eastern France (Fig. 14) (Delrieu et al., 2005).

At surface and ahead of the trough a front undulated over Western France (Fig. 15).

Convection formed well ahead of the surface cold front, in the warm sector, where low-level South-Easterly flows pre-

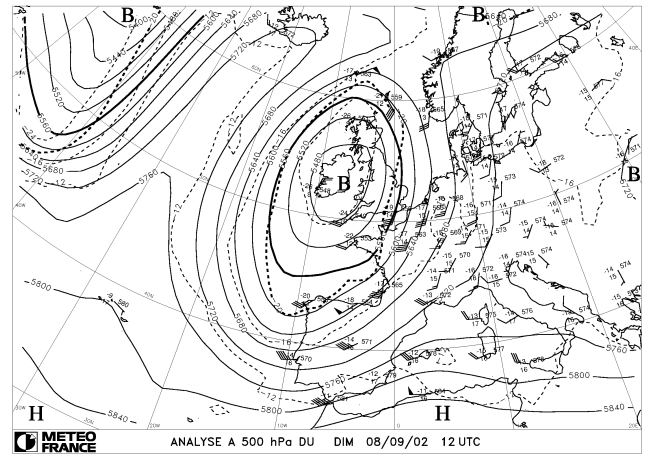


Fig. 14. 8 September 2002 12:00 UTC, analysis at 500 hPa: geopotential (in m) and temperature (in °C) are drawn, respectively, as solid and dashed lines (H for high centre and B for low centre of geopotential).

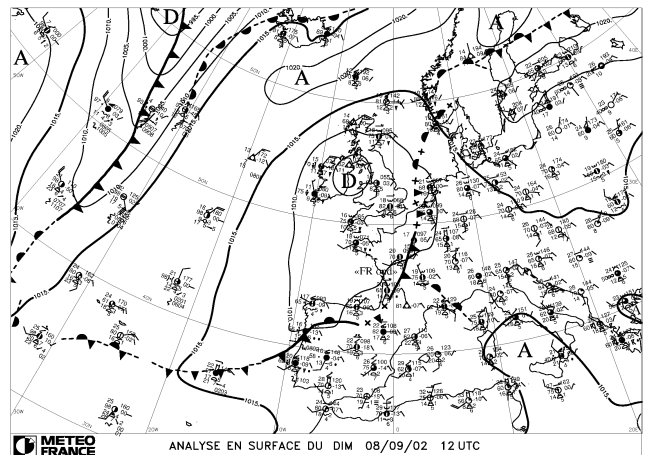


Fig. 15. 8 September 2002 12:00 UTC, surface analysis: slp (in hPa) is shown by solid lines (A for high centre and D for low centre of slp).

vailed. Prior to the development of the convection, the atmosphere was conditionally unstable in this region as evidenced by a significant CAPE value on the midnight Nîmes sounding of 8 September (about 850 Jkg^{-1} at 00:00 UTC as shown in Fig. 16).

Precipitable water computed by the radiosoundings shows that the humidity content of the atmosphere was already high (33 mm) and in particular this value was on the upper 10% of the distribution of precipitable water for this radiosounding between 1994 and 2003, the average value being 22 mm. After the onset of the convection, the 12:00 UTC radiosounding was almost saturated and the CAPE value still indicated a potential for convective development (Fig. 17). Although these values are punctual, and it is known that CAPE can

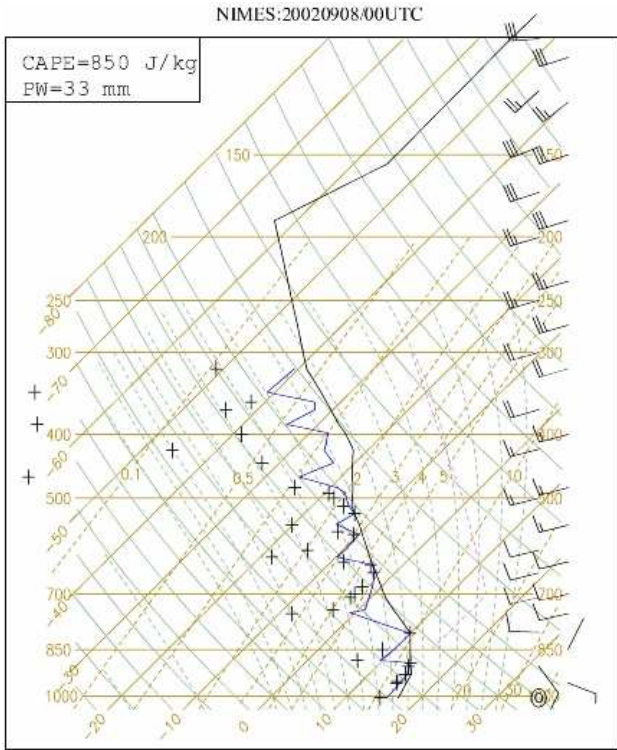


Fig. 16. 8 September 2002 00:00 UTC, Nîmes radiosounding: in the upper-left corner of the panel, CAPE stands for Convective Available Potential Energy (Jkg^{-1}) and PW for Precipitable Water (mm). The CAPE computation is based on the most unstable parcel. See Fig. 1 for the location of the station. On the right, the wind direction and intensity is displayed.

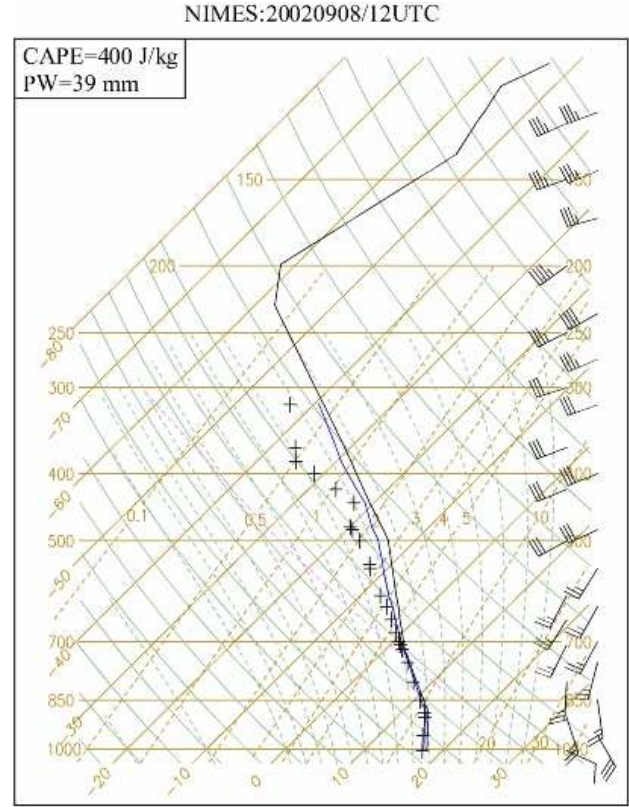


Fig. 17. 8 September 2002 12:00 UTC, Nîmes radiosounding: in the upper-left corner of the panel, CAPE stands for Convective Available Potential Energy (Jkg^{-1}) and PW for Precipitable Water (mm). The CAPE computation is based on the most unstable parcel. See Fig. 1 for the location of the station. On the right, the wind direction and intensity is displayed.

have a strong spatial variability, they can be considered as an indication of the local atmosphere instability. During the afternoon and night of 8 to 9, the surface cold front slowly progressed Eastward and the low-level flow over the Gulf of Lion accelerated. During the same time, the main upper-level deep trough swung into a North-West/South-East orientation leading to an upper South/South-Westerly flow over South-Eastern France (Fig. 18).

As the surface front passed over the Gard region, it contributed to the heavy precipitation, but also swept the convective activity with it (Fig. 19).

Convective cells started to develop over the Western Mediterranean sea around 04:00 UTC, 8 September 2002. They progressed Northward to reach the French coasts where they constituted a quasi-stationary Mesoscale Convective System (MCS) around noon. The quasi-stationary back building MCS assumed the typical V-shape in the infrared imagery due to the interaction of the convection with the Southerly flow (Fig. 20).

New convective cells were continuously generated at the tip of the V, whereas older cells were transported toward the V branches. It produced high rain intensities and strong

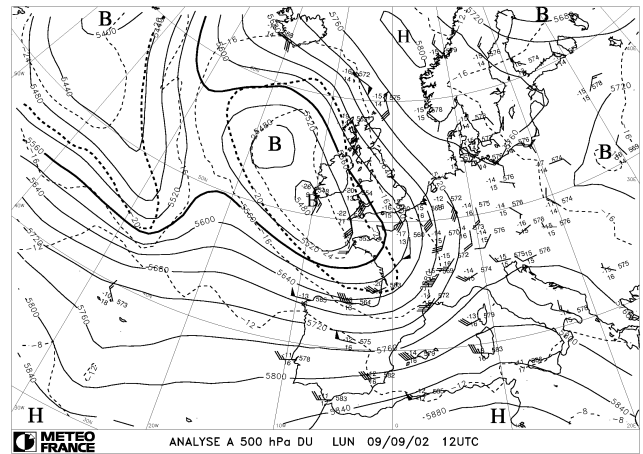


Fig. 18. 9 September 2002 12:00 UTC, analysis at 500 hPa: geopotential (in m) and temperature (in $^{\circ}\text{C}$) are drawn, respectively, as solid and dashed lines (H for high centre and B for low centre of geopotential).

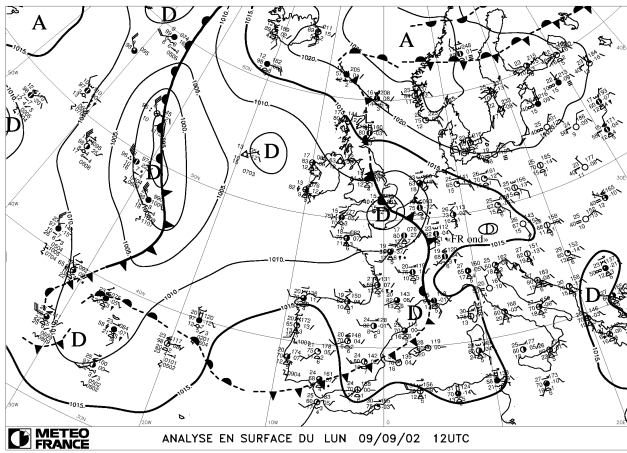


Fig. 19. 9 September 2002 12:00 UTC, surface analysis: slp (in hPa) is shown by solid lines (A for high centre and D for low centre of slp).

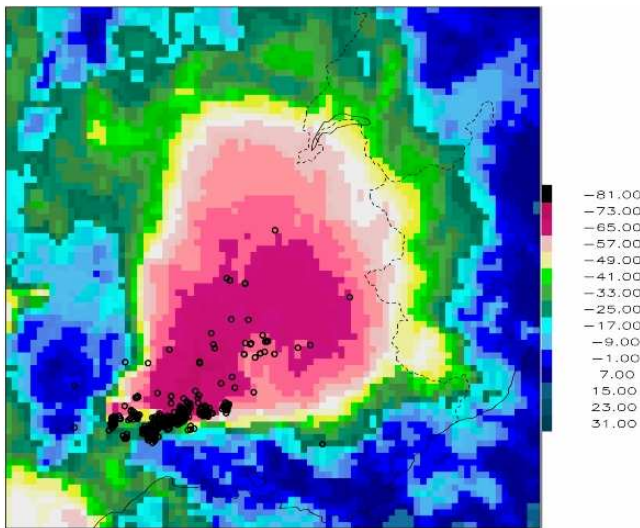


Fig. 20. 8 September 2002 21:00 UTC, Infrared METEOSAT brightness temperature (in °C) together with 10 min Cloud to Ground lightning (circles). See Fig. 1 for the localization of the area.

electrical activity, affecting mainly the Departments of Gard, Herault and Vaucluse. The relief played a fundamental role in the maintenance of the convective activity, since they determined the stationarity of the system (Ducrocq et al., 2003).

3.2 Analysis of the impacts

Both the size of the precipitation area and its intensity are exceptional. Precipitation peaks of 680 mm in 24 h have been recorded in several places (Fig. 21).

Accumulated rainfall greater than 200 mm have been recorded on a area of about 5400 km². Three phases in the

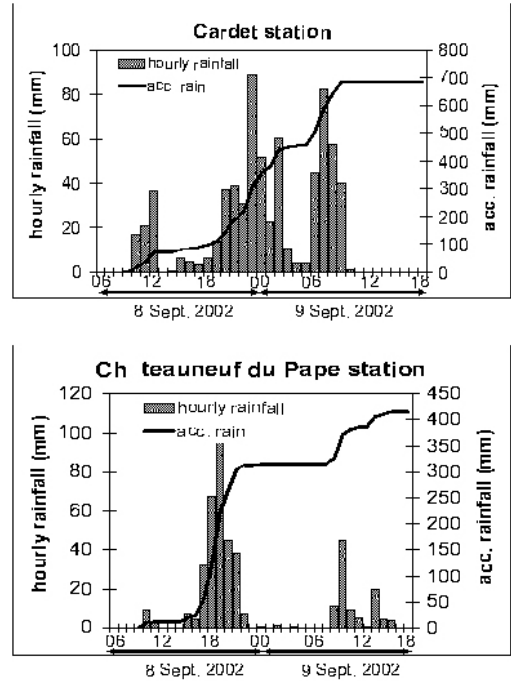


Fig. 21. Hourly rainfall (histogram, scale given at left of the panel) and accumulated rainfall (solid curve, scale given at right of the panel) from 06:00 UTC, 8 September 2002 to 18:00 UTC, 9 September 2002 for two rain gauge stations (see Fig. 22 for location of Cardet (CA) and Châteauneuf du Pape (CH)).

precipitation event have been identified (Delrieu et al., 2005) (Fig. 22):

- during the first phase, prior to 22:00 UTC 8 September 2002, the precipitation induced by the MCS was mainly over the plain region of the Gard and Vaucluse departments;
- then, between 22:00 UTC, 8 September 2002 to 04:00 UTC, 9 September 2002, the MCS shifted toward the upper regions at the limit of the mountain ridge (near Cardet), where it merged with the surface front that has progressed Eastward in the same time;
- after 04:00 UTC, 9 September 2002, the front with the embedded convection moved Eastward and swept again the Gard plain region.

Figure 21 shows the temporal evolution of the hourly rainfall for two rain gauges from the Météo-France rain gauge network; one (Cardet station, see Fig. 22 for the location) is located inside the maximum of daily surface rainfall area in the Gard Department. The second one (Châteauneuf du Pape station), is situated in the plain areas, at the limit of the Gard and Vaucluse department. The Cardet station, is one of the station that has recorded more than 680 mm in 24 h in the Gard department. For that station, high rain

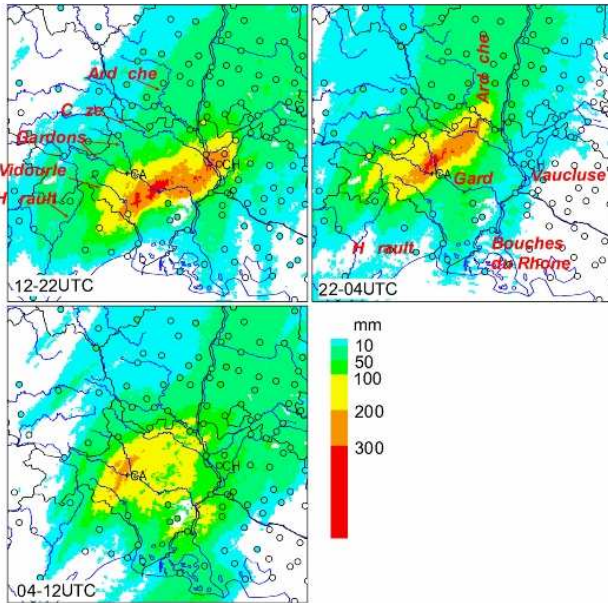


Fig. 22. Accumulated rain gauge rainfall (colored circle) superimposed to radar rainfall from the Météo-France rain gauge and radar networks for the three phases of the event: from 12:00 to 22:00 UTC, 8 September 2002; from 22:00 UTC, 8 September 2002 to 04:00 UTC, 9 September 2002; from 04:00 UTC to 12:00 UTC, 9 September 2002. For the upper left panel, the names of the rivers (blue lines) of the Massif Central region are indicated. For the upper right panel, the names of the Department (black lines) are given. The location of the Cardet (CA) and Châteauneuf du Pape (CH) stations are also indicated. See Fig. 1 for the localization of the area.

rates have been recorded, with 90 mm in one hour between 22:00 and 23:00 UTC, 8 September. For the Châteauneuf du Pape station, the accumulated rainfall reached more than 400 mm in 24 h with a time evolution of the hourly precipitation that clearly identified the three phases of the event: before 22:00 UTC, the quasi-stationary MCS induced large rain rates over the region, then precipitation almost vanished between 22:00 UTC and 07:00 UTC the day after. Afterward, the front with the embedded convection passed over the region and contributed to increase again the accumulated precipitation.

The flood that took place in this event is namely a flash-flood. The strong precipitation caused the swelling of some river like the Cèze, Vidourle, Gardons and Gard. The peak specific discharges (the quantity of water obtained from a basin per time's and surface's unit) were around $5\text{--}10\text{ m}^3\text{ s}^{-1}\text{ km}^{-2}$ for these rivers, reaching locally values as high as $20\text{ m}^3\text{ s}^{-1}\text{ km}^{-2}$. The cities where the floods had more impact were Anduze, Alès, Nîmes, Aramon, Bessèges and Sommières. The floods destroyed numerous cars, houses, factories and commerce and 24 casualties were recorded. The water and electricity networks had to interrupt their services and the total amount of damages ascended to 1.2 billion euros (Huet et al., 2003).

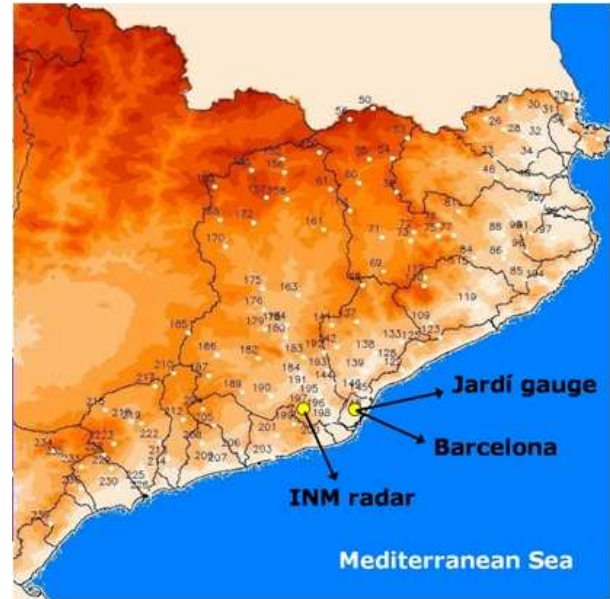


Fig. 23. Location of the rain gauges of the high resolution network of Catalonia. See Fig. 1 for the localization of the area.

4 Analysis of the Montserrat event

4.1 Synoptic conditions

The synoptic situation on 9 June 2000 shows the entry from the Western part of the Iberian Peninsula of a cold front associated with a low situated to the North of the British Isles, while Catalonia (Fig. 23) was under the influence of an anticyclone that affected Central and Eastern Europe and much of the Western Mediterranean Sea (Fig. 24 and Fig. 25). The upper-level cold trough, the axis of which was situated at 00:00 UTC over Portugal, gave rise to cold Westerly winds over the Western sector of the Iberian Peninsula, and to warm Southerly winds over the Eastern sector.

On 10 June at 00:00 UTC the cold front was situated around the Greenwich meridian, to the West of Catalonia. At that time a sea level pressure minimum formed, centred over the Balearic Islands, reaching 1008 hPa (Figs. 26 and 27). The Westerly flow that dominated most of the Peninsula had been veering, so that by the time it was coming mainly from the North and had advected very cold air that extended right to the upper troposphere and was responsible for the snow that fell that day over the North and centre of Spain (López and Arán, 2005).

But that was not the only factor responsible for the torrential rains recorded in Catalonia. Indeed, the dominant synoptic situation in this region on 10 June between 00:00 UTC and 12:00 UTC, the interval over which practically all the rain fell, showed a conjunction of the following factors (Llasat et al., 2003):

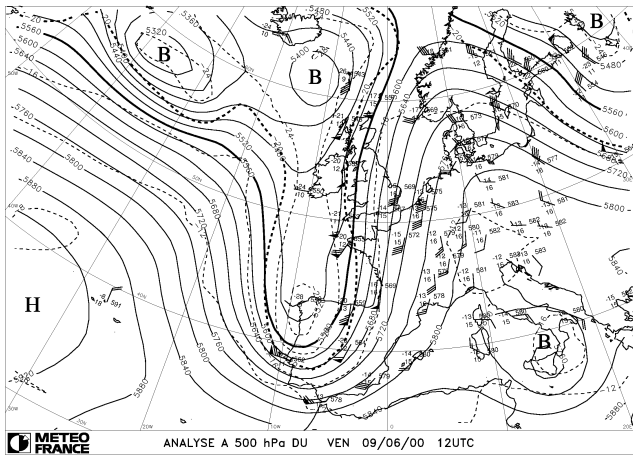


Fig. 24. 9 June 2000 12:00 UTC, analysis at 500 hPa: geopotential (in m) and temperature (in °C) are drawn, respectively, as solid and dashed lines (H for high center and B for low centre of geopotential).

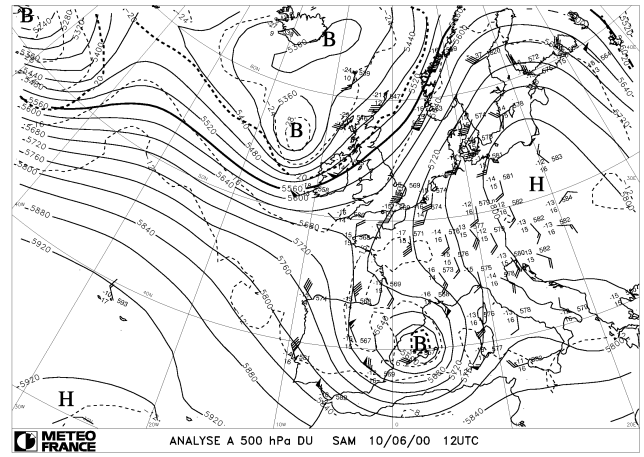


Fig. 26. 10 June 2000 12:00 UTC, analysis at 500 hPa: geopotential (in m) and temperature (in °C) are drawn, respectively, as solid and dashed lines (H for high centre and B for low centre of geopotential).

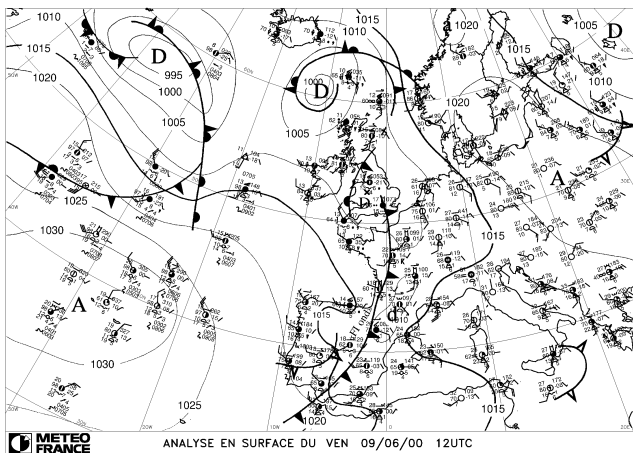


Fig. 25. 9 June 2000 12:00 UTC, surface analysis: slp (in hPa) is shown by solid lines (A for high centre and D for low centre of slp).

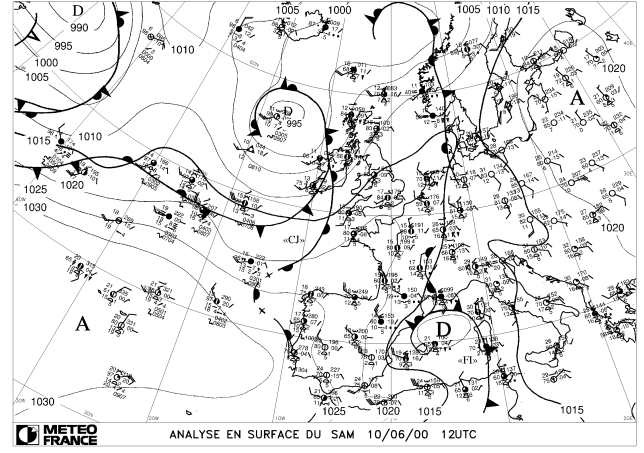


Fig. 27. 10 June 2000 12:00 UTC, surface analysis: slp (in hPa) is shown by solid lines (A for high centre and D for low centre of slp).

- A mesoscale depression (meso- α) at surface which extended from the Balearic Islands to Catalonia and led to the convergence of water vapour at low levels, playing a direct part in triggering the potential instability accumulated previously (the location of the convective system on the radar imagery pointed to the existence of a line of convergence that was advancing over Catalonia along a South-West/North-East axis);
- A strong wind from the East/South-East at lower levels (more than 30 kt at 950 hPa) and from the South/South-West at upper levels over the affected area, that favoured the production of multicellular storms. This moist flow from the Western Mediterranean impinged perpendicularly to the mountain ranges;

- A strong orographic component in focusing and sustaining the convection, which combined with the advance of the depression at low levels.

Analysis of the CAPE shows a significant maximum exceeding 1600 Jkg^{-1} in Palma de Mallorca on 10 June at 00:00 UTC (Fig. 28). At the same time the precipitable water mass had a maximum of 17 mm between the surface and 850 hPa.

This high concentration of water vapour at low levels was a result of the anticyclonic situation that had been prevailing over previous days. The convergence line created by the mesoscale low was enough to trigger the instability. The fact that the rainfall was most intense in the mountainous regions shows the important role of topography in the development of convection, with forced updrafts between 500 and 1500 m.

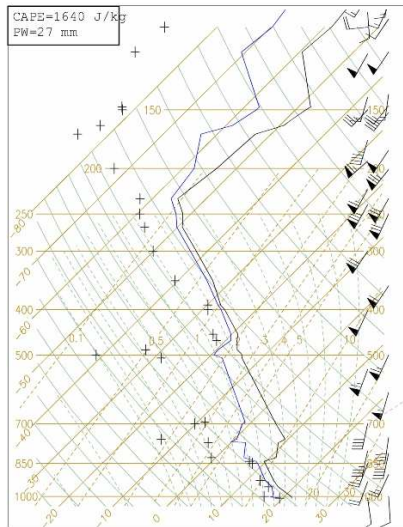


Fig. 28. 10 June 2000 00:00 UTC, Palma de Mallorca radiosounding: in the upper-left corner of the panel, CAPE stands for Convective Available Potential Energy (Jkg^{-1}) and PW for Precipitable Water (mm). The CAPE computation is based on the most unstable parcel. See Fig. 1 for the location of the station. On the right, the wind direction and intensity is displayed.

In this case, the mountains were also important in favouring the stationarity of the convective systems.

4.2 Analysis of the impacts

The maximum rainfall was recorded over the Llobregat basin, close to the Montserrat Mountain, with 224 mm in Rajadell and 202 mm in Sant Salvador de Guardiola (Fig. 29).

More than 80% of this precipitation was recorded in less than 6 h. As a consequence of this heavy and sudden rainfall, some flash floods were produced in different Llobregat tributaries and wadis that are normally dry. The Llobregat river experienced a swelling of more than 4.5 m in Castellbell i el Vilar, with a maximum flow of $1100 \text{ m}^3 \text{ s}^{-1}$ at 09:00 UTC on 10 July. A similar problem arose over the Riera de la Bisbal and Francolí basins, where some wadis that cross the Vendrell village were overflowed producing great damages, due to the heavy rainfalls along all their way, with a maximum of 134 mm in La Bisbal in less than 3 h. In total, more than 50 mm were recorded on 10 July in an area of about $16\,000 \text{ km}^2$. Those rainfalls were produced by two MCS's that moved slowly from the South-West to the North-East, remaining stationary over different places for two hours or more (Rigo and Llasat, 2005). Successively the system, composed by different convective cells, remained over the Tarragona basins and over the mountains of the centre of Catalonia (mainly over the Montserrat Mountain area).

The estimated damages were $\approx 65\,000\,000$ euros and 5 people died. There was a partial destruction of infrastructures of the enclosure of the Monastery of Montserrat, the



Fig. 29. Location of the most affected places of Catalonia. See Fig. 1 for the localization of the area.

destruction of some routes of access to the mountain, the total destruction of a bridge of one of Catalonia's highways. Moreover, serious damages were produced in very populated coastal and tourist areas with total or partial destructions in commercial zones, cuts in the electrical network, telephone provisions, potable water and partial loss of transport routes.

5 Conclusions

We analysed four cases of severe precipitation over three different Western Mediterranean regions with the aim of finding a link among them and a relationship between the large scale forcing and the local orographic effect. In details, we described the events from the meteorological (synoptic) and from the hydrological (local effects) point of view, trying to identify the similarities and the discrepancies.

These events could also be compared with two of the most important floods happened in the past in Piedmont and which were subject of a number of studies (see for instance Buzzi et al., 1998, and Gabella and Mantovani, 2001): the November 1994 and October 2000 floods.

In fact, the disastrous flood that occurred in Southern Piedmont at the beginning of November 1994, associated with heavy rainfall episodes over a relatively small area during 3 to 6 November 1994, was generated by a quasi-stationary cyclonic area over Western Europe (A.R.P.A. Piemonte, 1997). The most intense rainfall (for which values over 200 mm were reported) occurred in two regions located in the upper reach of the Tanaro and Bormida river basins and over the North-West sector of the Alps. The intense rainfall over these

two mountain areas was enhanced by the confluence of the surface South-Easterly flow and of the upper-level Southerly current. This confluence was strongest over the two zones in which the maxima of rainfall and vertical wind velocity were observed.

Also between 13 and 16 October 2000, another tremendous flood affected Piedmont with extreme and persistent precipitation, in particular over the North-Western area of the region: values exceeding 600 mm in four days have been reported over the Alps, causing huge damages and loss of lives (A.R.P.A. Piemonte, 2000). During those days, the Western Europe was interested by a quasi-stationary deep trough over Great Britain associated to a minimum of sea level pressure, which caused a constant strong Southerly flow all over the Alps. In a second time, the trough cut-off over the Alps generating an upper-level low associated to a sea level pressure minimum in the North Tyrrhenian Sea which continued to bring moist flow over Piedmont both at lower and at higher levels of the atmosphere.

In summary, some common ingredients to the cases can be drawn:

- Presence of a deep trough extended from the British Islands to the Iberian Peninsula generating a South to South-Westerly moist flow in the mid to upper troposphere over the regions;
- Slow moving patterns at synoptic scale, which allow the stationarity of the precipitating systems;
- At low-levels, strong wet meridional winds impinging the relief of the regions, favouring triggering of deep convection or enhancement of the precipitation over the upwind flanks of the mountain ranges.

All these ingredients favoured either slow-moving frontal systems or/and quasi-stationary convective systems with large amounts of precipitation accumulated, for the former, in several days and leading to extended floods (Piedmont cases), or for the second type of events, accumulated in less than one day and inducing flash-floods (Gard and Montserrat cases).

The orographic forcing induced by the South to Easterly low-level winds that face the mountains of the Western Mediterranean countries constitutes an omnipresent stationary low-level forcing (Llasat et al., 2000), but it is not the only one; upwind low-level convergence associated with cyclogenesis over the Western Mediterranean Sea (Montserrat case) or blocked cold pool generated by the convection itself (Gard case) can trigger and maintain deep convection over the same area during several hours.

Acknowledgements. The authors wish to acknowledge all the HYDROPTIMET partners for the strong collaboration demonstrated during the project. Moreover we would like to thank the Agencia Catalana de l'Aigua (Generalitat de Catalunya) for the rainfall data of the Spanish case.

Edited by: R. Romero

Reviewed by: V. Homar and another referee

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