

## THE 'MONTSERRAT-2000' FLASH-FLOOD EVENT: A COMPARISON WITH THE FLOODS THAT HAVE OCCURRED IN THE NORTHEASTERN IBERIAN PENINSULA SINCE THE 14TH CENTURY

MARÍA DEL CARMEN LLASAT,\* TOMEU RIGO and MARIANO BARRIENDOS

*Group of Analysis of Adverse Meteorological Situations (GAMA), Department of Astronomy and Meteorology, University of Barcelona, Av. Diagonal 647, 08028 Barcelona, Spain*

*Received 17 April 2002*

*Revised 27 November 2002*

*Accepted 27 November 2002*

### ABSTRACT

This paper presents an analysis of the flash floods that occurred in Catalonia (NE Iberian Peninsula) on 10 June 2000, in the context of the historical floods recorded since the 14th century. The study starts with pluviometric and meteorological analyses (essentially synoptic and thermodynamic) of the episode. There follows a comparison of this event with previous floods for which we have instrumental information, information from archives, or both types of information. In some cases this permitted us to make a meteorological comparison of episodes similar to that of June 2000, and the complete series was used to carry out a frequency analysis of floods that have occurred in the basin under study. The conclusions show that although catastrophic flooding in spring is not as typical a phenomenon as autumn flooding, such floods have been recorded at least once each century, and it can be stated that the synoptic meteorological situation, where recorded, showed similar characteristics in all cases. Copyright © 2003 Royal Meteorological Society.

KEY WORDS: Catalonia; Mediterranean Sea; historical data; synoptic and thermodynamic analysis; climatic analysis; floods

### 1. INTRODUCTION

During the early morning of 10 June 2000 there occurred a downpour over Catalonia (NE Spain) that caused serious damage in the Llobregat, Besós, Francolí and Riera de la Bisbal river basins (Figure 1), due both to the rainfall and flooding and landslides and debris flows. The most notable damage consisted of partial destruction of infrastructure at Montserrat Monastery (720 m a.s.l., Figure 1), where some 500 people had to be evacuated, and the destruction of some roads leading up the mountain, the total destruction of many bridges and sections of roadways, and the flooding of built-up and residential zones with the attendant destruction of some dwellings, especially in the tourist municipality of El Vendrell (Figure 1). The episode caused material damage estimated at over €65 000 000. There were five fatalities, which, while tragic in themselves, could have been much worse if the episode had occurred only a few hours later, as the affected zones were prominent for their tourist activity.

The episode was spectacular indeed, and can be classified as a catastrophic flood episode (Llasat and Puigcerver, 1994). The most marked hydrometeorological feature was the considerable intensity of sustained precipitation, with accumulated hourly quantities of over 100 mm and 6 h maximums of over 200 mm. But that was not the first such case recorded this century, neither in terms of rainfall intensity or flows, nor in terms of the counties affected. We need only think back to 25 September 1962, 20–23 September 1971, 6–8

---

\*Correspondence to: María del Carmen Llasat, Group of Analysis of Adverse Meteorological Situations (GAMA), Department of Astronomy and Meteorology, University of Barcelona, Av. Diagonal 647, 08028 Barcelona, Spain; e-mail: carnell@am.ub.es

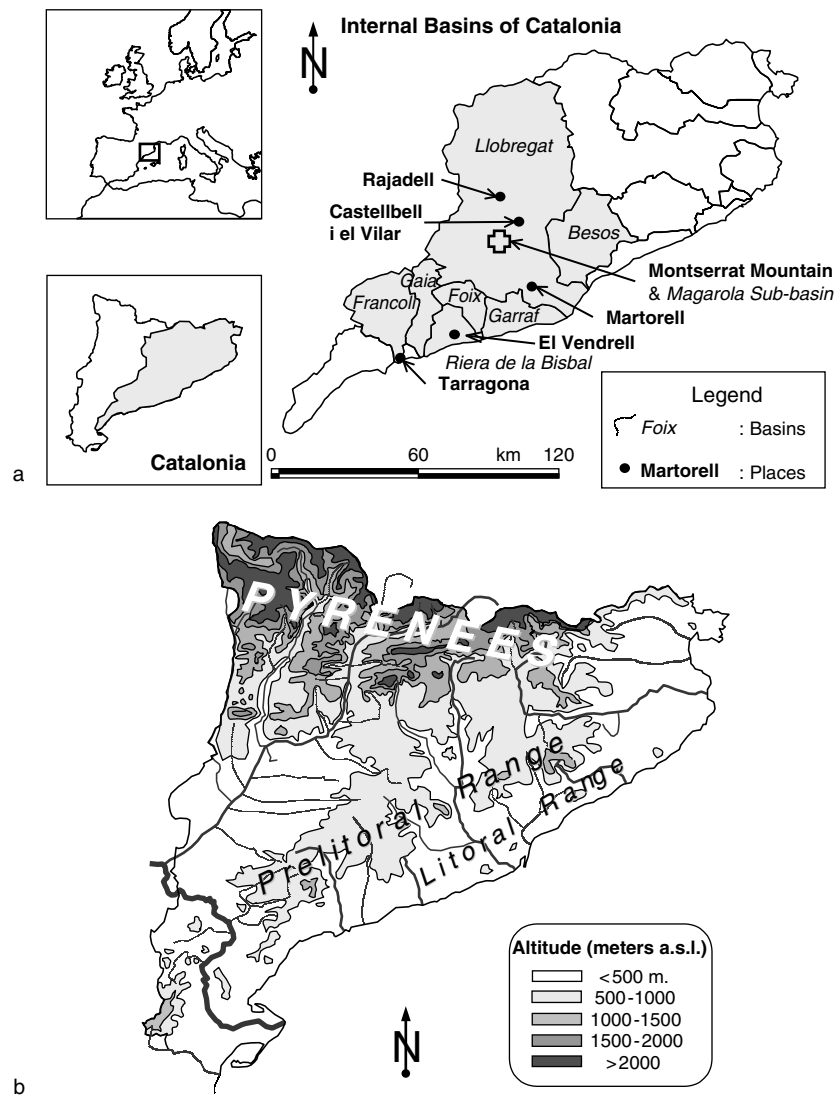


Figure 1. (a) Map showing the location of the Internal Basins of Catalonia (IBC) and the basins and places most affected by the high rainfalls; (b) map of Catalonia showing the main orographical features. In this event the Prelitoral Range was responsible for the heaviest rainfalls

November 1982 and 2–5 October 1987 (Llasat, 1987, 1990, 1991; Ramis *et al.*, 1994). The most unusual feature of this episode, however, lay in the season of the year in which it occurred. In Catalonia, high-intensity (highly convective) episodes usually occur in summer and at the beginning of the autumn (Llasat and Puigcerver, 1997; Llasat, 2001), and are characterized by their brevity and the fact that they give rise to sudden swelling of Pyrenean watercourses and coastal stream beds. Catastrophic floods, with over 200 mm of precipitation in 24 h, occur in autumn, and only exceptionally this century have two or three cases been recorded in winter (e.g. in January 1996; Llasat *et al.*, 2000). Those odd events caused less damage due to the situation being much less convective and longer lasting, which allowed better control of freshets to be implemented.

This study analyses the flooding episode of 10 June 2000 within the context of historical floods and the climatic framework. To this end, the study starts with pluviometric and meteorological analyses (essentially synoptic and thermodynamic) of the episode from a dual objective: to understand the main factors that

gave rise to rainfall exceeding 150 mm in 3 h, and to be able to compare it with previous situations. Such situations have been classified, in the light of the information available, into: (a) episodes after 1950, for which synoptic and thermodynamic information is available; (b) historical floods for which instrumental information is available in relation to surface data (1780–1950); (c) historical floods for which no instrumental information is available (from the 14th century). In cases (a) and (b) a meteorological comparison of episodes similar to that of June 2000 has been made. Those classified under (c) were used to carry out a frequency analysis of the floods.

## 2. PLUVIOMETRIC EVOLUTION

The most intense rainfall affected all the IBC, for which reason this detailed analysis of its pluviometric evolution has been undertaken exclusively for those hydrological basins (Figure 1). To that end the 5 min rainfall data recorded at the automatic stations of the Automatic Hydrological Information System (SAIH) for the IBC have been used. This includes a total of 126 automatic pluviometric stations distributed over an area of 16 000 km<sup>2</sup>. Those pluviometric stations are calibrated once every 3 months. Besides this, an objective analysis scheme of the precipitation cumulated in 72 h is made for each pluviograph. Finally, for those events in which the rainfall rate or the cumulated rainfall is high (usually flood events), precipitation data are compared with other official pluviometric networks

Figure 2 shows the accumulated rainfall distribution in the IBC from 21:00 UTC on 9 June to 21:00 on 10 June. It can be observed that the maximum quantities were recorded in the basin of the River Llobregat, with 224 mm at Rajadell, and in the basin of the Riera de la Bisbal, with 134 mm at Bisbal del Penedés, over 100 mm of which was recorded in less than 2 h. A value of over 100 mm was also recorded in the basins of the Francolí, Gaià and Foix. All the sub-basins of the IBC recorded accumulated rainfall above 50 mm.

Figure 3(a) shows the rainfall distribution at half-hourly intervals from 21:00 UTC on 9 June to 09:00 UTC on 10 June. The rainfall was basically distributed along an SE–NW-orientated axis, whose translation was very slow, remaining stationary for several hours over the same zones. The first rains in the IBC were recorded on 9 June just before 21:30 UTC, mainly affecting the river–stream basins of the Costa Sud. The

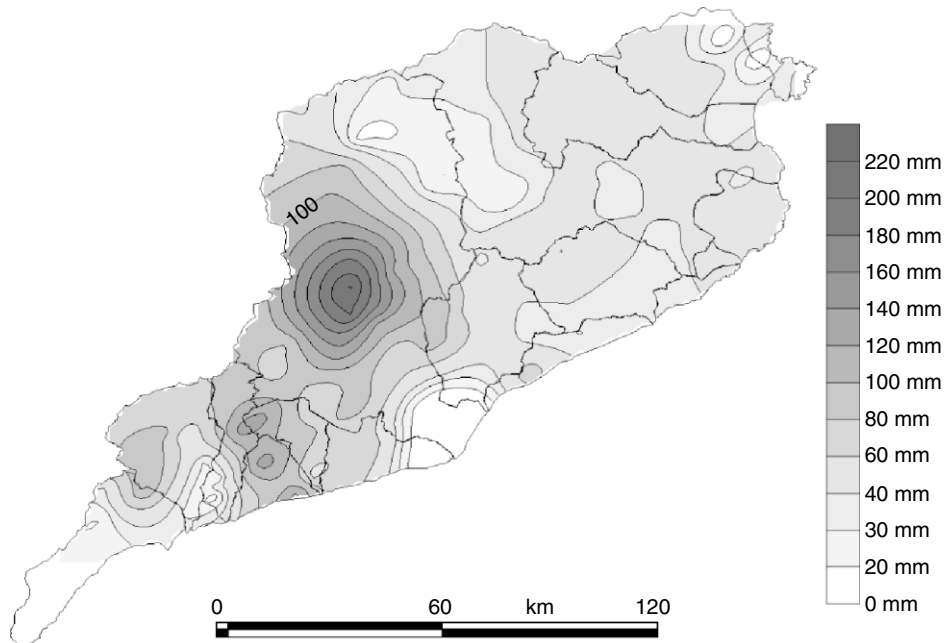


Figure 2. Distribution of accumulated rainfall between 21:00 UTC on 9 June 2000 and 21:00 UTC on 10 June 2000

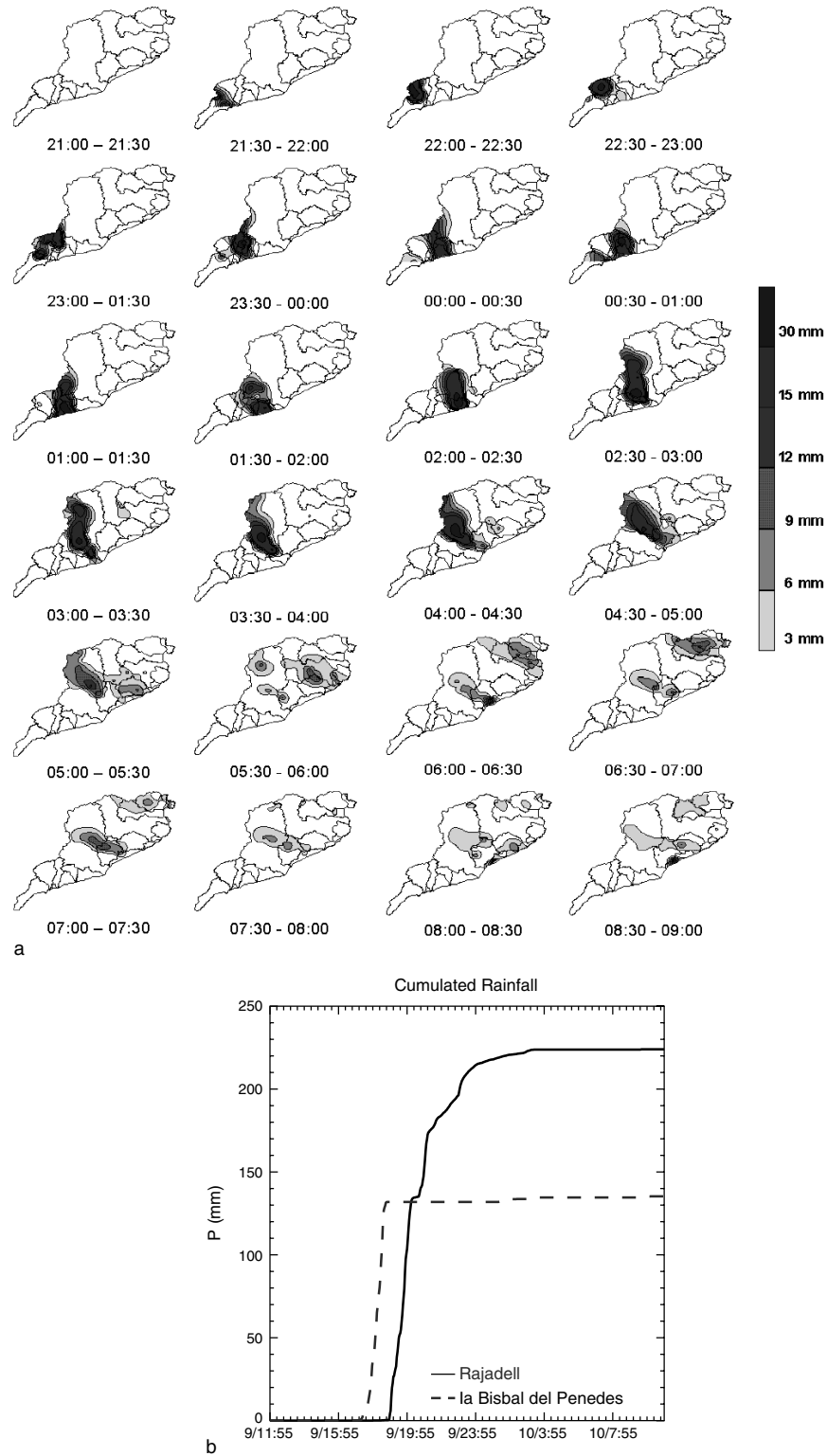


Figure 3. (a) Evolution of the 30 min accumulated rainfall, between 21:00 UTC on 9 June 2000 and 21:00 UTC on 10 June 2000; (b) time series of rainfall cumulated at 5 min intervals, in Rajadell and Bisbal del Penedés, from 21:00 UTC on 9 June to 09:00 UTC on 10 June. See the strong lapse rate produced by the highest rainfall intensities

rainfall band had an NE movement linked to the movement of the surface low located over the Mediterranean Sea, with a translation speed estimated at some 10 km/h. Rainfall evolution in the pluviographs of Rajadell and of La Bisbal corroborates this movement (Figure 3(b)).

Between 01:00 UTC and 03:30 UTC the system hardly moved and gave rise to abundant precipitation over the basins of the south of Catalonia, with 5 min intensities exceeding 120 mm/h. The first rainfall in the River Llobregat basin was recorded around 00:00 UTC and reached maximum values between 02:00 and 05:00 UTC. During the morning of 10 June the rain extended to the basins of NE Catalonia, though large rises did not occur there.

### 3. ANALYSIS OF THE MONTSERRAT EVENT

Given that the purpose of this study is to analyse the floods of 10 June 2000 within the historical-climatic context of the last 500 years, this meteorological analysis will only focus on the main synoptic, thermodynamic and hydrologic aspects of the event.

#### 3.1. Synoptic evolution

The synoptic situation on 9 June 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 itself was under the influence of an anticyclone that affected central and eastern Europe and much of the Mediterranean (Figure 4(a)). At high altitude a cold trough could be detected (Figure 4(a)), the axis of which was situated at 00:00 UTC over Portugal and gave rise at 850 hPa (Figure 4(b)) to cold westerly winds over the western sector of the Iberian Peninsula, and warm southerly winds over the eastern sector. Notable at 850 hPa (Figure 4(b)) was a strong confluence of SE and SW winds over Catalonia. Thus, the region had the basic factors that precede heavy rainfall situations in the east of the Iberian Peninsula (Llasat and Puigcerver, 1994): an anticyclonic situation over Catalonia and the Mediterranean Sea, with an influx of very warm and moist air, which permits the generation of considerable instability that remains latent until some factor, whether orographic or dynamic, triggers the convection.

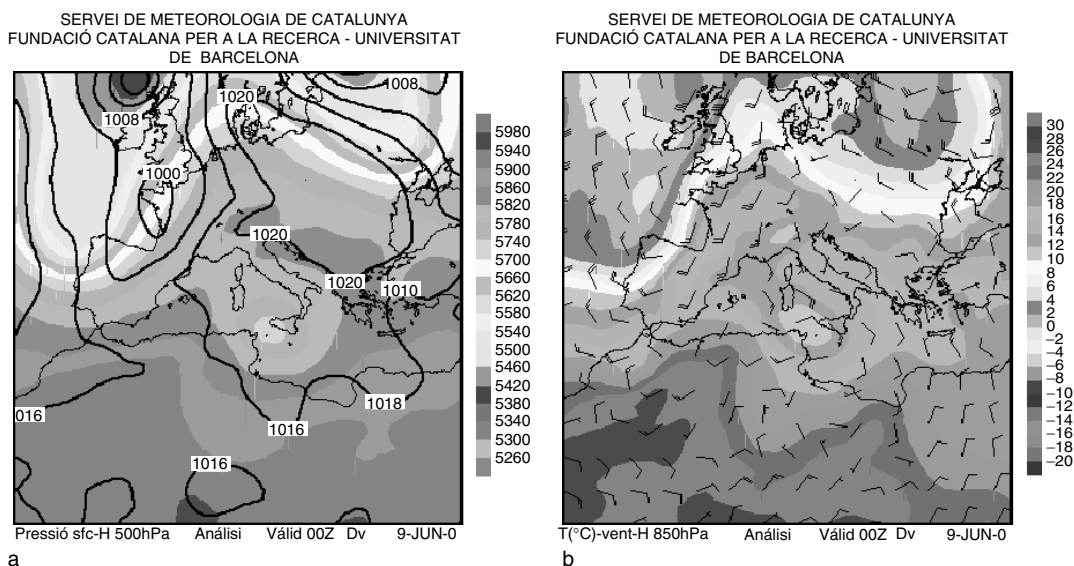


Figure 4. Synoptic situation at 00:00 UTC on 9 June 2000: (a) sea-level pressure (solid lines, hPa) and geopotential at 500 hPa (shaded areas); (b) temperature (°C) and wind (kt) at 850 hPa. Courtesy of the Meteorological Office of Catalonia

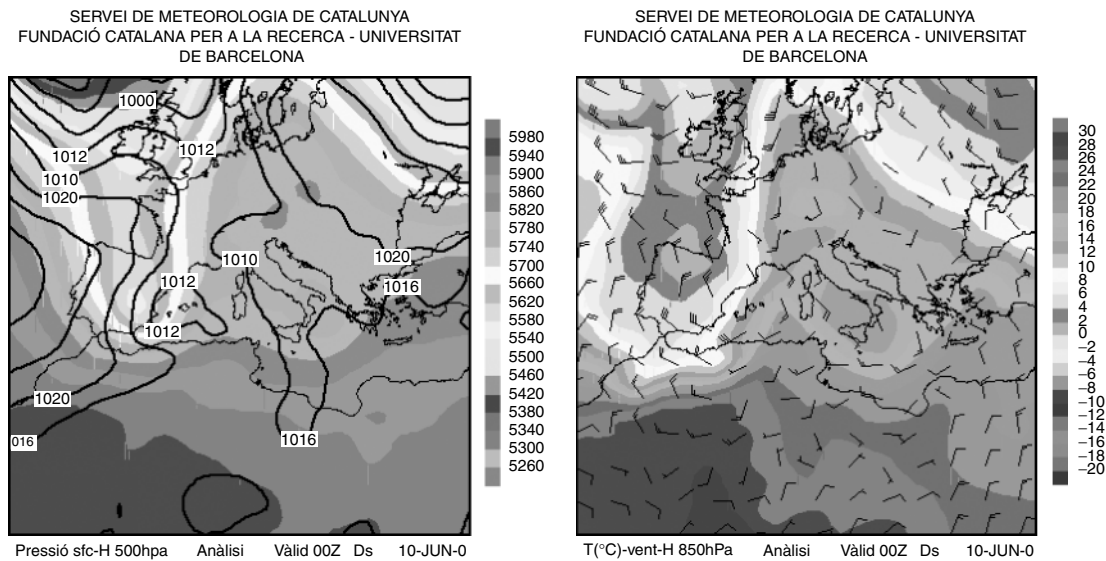


Figure 5. Synoptic situation at 00:00 UTC on 10 June 2000: (a) sea-level pressure (solid lines, hPa) and geopotential at 500 hPa (shaded areas); (b) temperature (°C) and wind (kt) at 850 hPa. Courtesy of the Meteorological Office of Catalonia

On 10 June at 00:00 UTC the cold front was situated around the longitude meridian of  $0^{\circ}$ , to the west of Catalonia. Over the previous few hours a surface depression had been forming, centred on the Balearic Islands, reaching 1008 hPa (Figure 5(a)). Also over the previous few hours, the flow from the west that dominated most of the Peninsula at 850 hPa had been veering, so that by that time it was coming mainly from the north (Figure 5(b)) 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. In this case, everything seems to point to the presence of a cold air pool over the northern coastline of Spain in the strictest sense of the term: minimum of pressure and temperature at 500 hPa that was not detectable at the surface (Llasat and Puigcerver, 1990). It was also capable of playing an active role in the production of rain and snowfall over part of the peninsula, for it went up to 850 hPa. But that was not the only factor responsible for the torrential rains recorded in Catalonia. Indeed, the dominant synoptic situation in this region between 00:00 UTC and 12:00 UTC, the interval over which practically all the rain fell, showed a conjunction of the following factors:

- A mesoscale depression (meso- $\alpha$ ) at the surface, which extended from the Balearic Islands to the IBC and led to the convergence of water vapour at low levels, while 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 an SE–NW axis), as will emerge from the thermodynamic analysis.
- A conjunction of the cold depression in the upper atmosphere and the surface depression, thus deepening the depression.
- A strong wind from the E–SE at low levels (more than 30 kt at 950 hPa) and from the SSW at high levels, over the affected area, that produced a marked shearing, a phenomenon that favours the production of multicellular storms. This wet flow from the Mediterranean impinged perpendicularly to the mountain ranges at 850 hPa.
- A strong orographic component in sustaining the convection, which, combined with the advance of the depression at low levels, was to cause emergence of the spatial evolution features of the heaviest rainfalls. Figure 6 shows a convergence line in surface over the region in which the main rainfalls were produced at 00:00 UTC (winds are measured at 2 m above the soil).

Wind Map (10/06/2000 00:00)



Figure 6. Wind direction at surface at 00:00 UTC on 10 June 2000. Data are provided by the Agrometeorological Network of Catalonia. Wind sensors are placed at 2 m above the soil

### 3.2. Thermodynamic evolution

The thermodynamic analysis was carried out on the basis of information provided by the 24 aerological stations show in Figure 7, with particular prominence accorded to the radiosondes situated between 32–46° latitude north and 10°E–10°W. The Barcelona radiosonde, though currently in an experimental phase, was also taken into consideration; however, given that the episode took place within the warm zone and with a strong southerly component, the Palma radiosonde was felt to be a useful tool for identifying the mass of air at low levels that would later affect Catalonia (Llasat, 1987, 1990). Figure 8 shows the soundings of Palma de Mallorca and Madrid (centre of the Iberian Peninsula) at 00:00 UTC. It is interesting to see the presence of cold air in all the troposphere in Madrid; meanwhile, in Palma de Mallorca there is the strongest temperature gradient in all the troposphere.

Analysis of the lifting index (LI) on 9 June at 12:00 UTC permitted delimitation of a clear line of differentiation between the unstable part (Mediterranean zone) and the stable zone (peninsular zone), situated roughly over an axis running through Murcia, Zaragoza and Bordeaux, which between 00:00 UTC and 12:00 UTC on 10 June shifted strongly towards the east (Figure 9). Analysis of the convective available potential energy (CAPE) shows a significant maximum of over 3000 J/kg, which on 9 June at 1200 UTC was centred on Cagliari and which 12 h later was centred on Palma (Figure 10) with a reading of less than 1700 J/kg. It is important to remember that CAPE values above 1500 J/kg point to a major risk of severe weather or heavy rainfall situations arising in this region (Tudurí and Ramis, 1997). The precipitable water mass followed

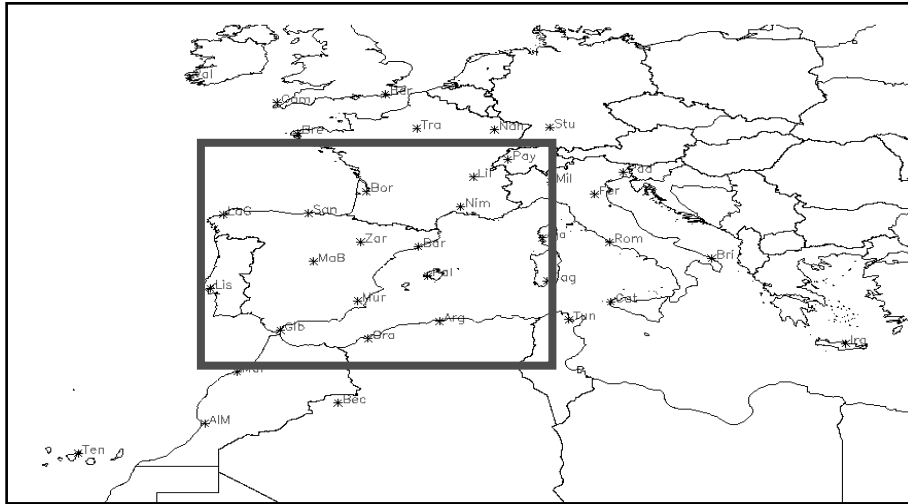


Figure 7. Map showing the position of the aerologic stations used to do the thermodynamic analysis. Bar: Barcelona; Pal: Palma de Mallorca; Mur: Murcia; Zar: Zaragoza; Bor: Bordeaux; Cag: Cagliari; Nim: Nîmes; Mil: Milan; LaC: La Coruña; Lis: Lisboa; Gib: Gibraltar; Arg: Argel; Ora: Orán; San: Santander; Lil: Lyon; Pay: Payenne

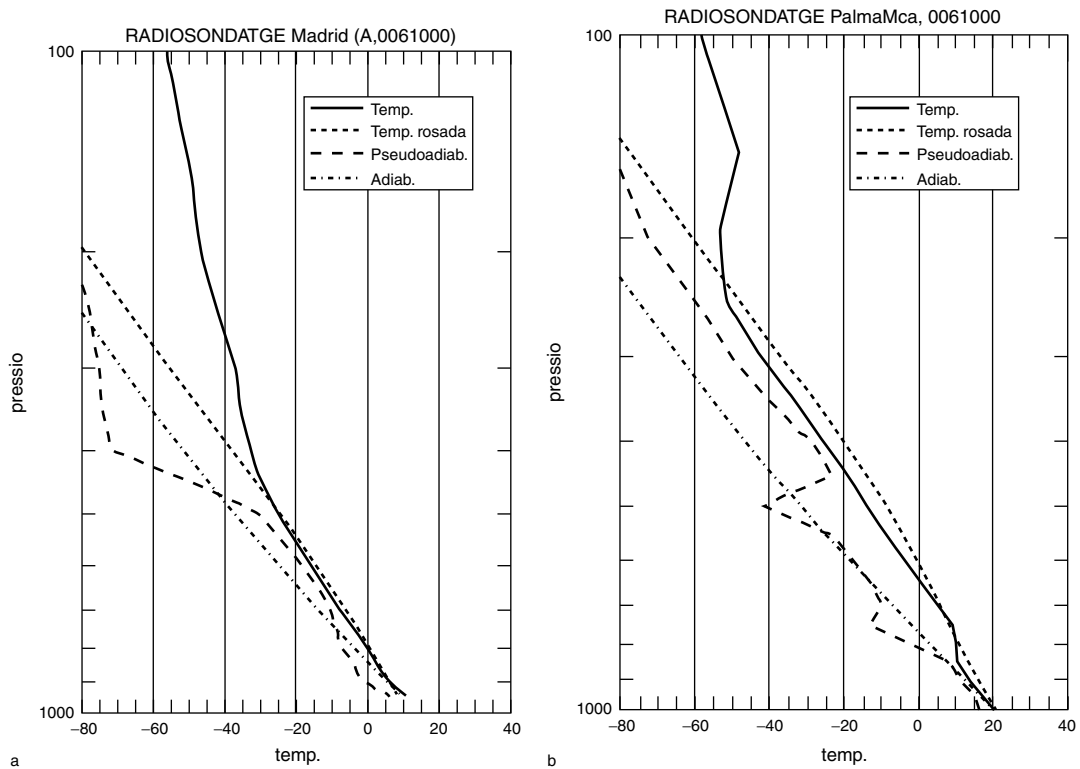


Figure 8. (a) Sounding of Palma de Mallorca at 00:00 UTC; (b) sounding of Madrid at 00:00 UTC. See the presence of cold air in Madrid but the strongest temperature gradient in Palma de Mallorca



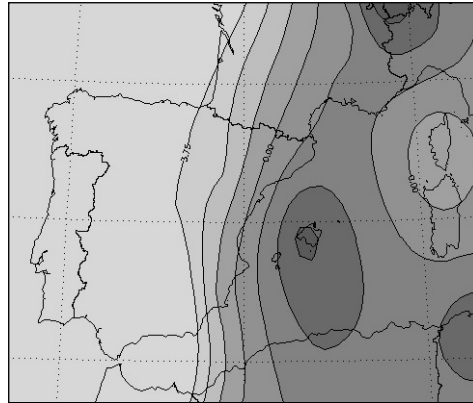


Figure 9. Distribution of the LI at 12:00 UTC on 9 June 2000. Values above the IBC are between  $-1$  and  $-2$ . Contour intervals are of 1.25

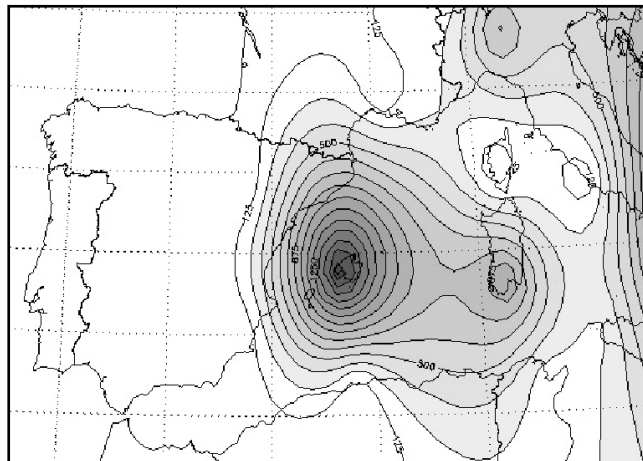


Figure 10. Distribution of the CAPE (J/kg) at 00:00 UTC on 9 June 2000. Values above the IBC are between 1000 and 1500 J/kg. Contour intervals are of 125 J/kg

a similar evolution, with a maximum over Sardinia on 9 June at 12:00 UTC that 12 h later was located over the Majorca island with a value of  $17 \text{ kg/m}^2$  between the surface and 850 hPa (Figure 11). This high concentration of water vapour at low levels was a result of the anticyclonic situation that had been prevailing over the preceding days, accompanied by strong heating and evaporation of sea water. Here, it is worth noting the layer of dry air recorded on 9 June and the early morning of 10 June, between 600 and 850 hPa, a feature of severe weather situations associated with strong winds (Doswell *et al.*, 1996), a phenomenon also recorded in coastal zones of Catalonia and one that corroborated the Barcelona radiosonde.

The compound maps (Ramis *et al.*, 1994, 1995) for 9 June 12:00 UTC and 10 June 00:00 UTC have been made on the basis of distribution of instability, CAPE and precipitable water mass in low levels (Figure 12). It can be seen that the area where the three effects overlap was over the Mediterranean Sea, off Catalonia (due to the strong wind over Barcelona on 10 June 00:00 UTC the globe of the radiosonde burst and no vertical data are available). The flow from the south in low and medium levels advected this area into Catalonia. The convergence line created by the mesoscalar low was enough to trigger this instability. The fact that the rainfall was most intense in the mountainous regions shows the important role of relief in the development of convection, with forced updrafts between 500 and 1500 m (Riosalido, 1998). In this case, the mountain ranges were also important in favouring the stationarity of the convective systems.

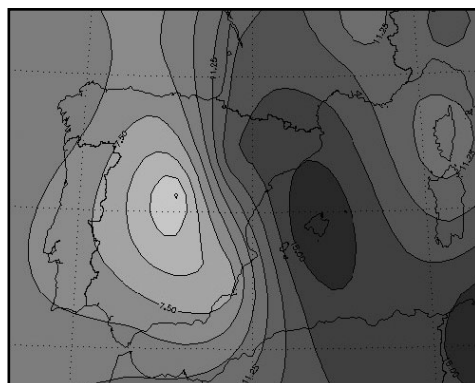


Figure 11. Distribution of the precipitable water mass ( $\text{kg/m}^2$ ) between surface and 850 hPa at 12:00 UTC on 9 June 2000. Contour intervals are of  $1.25 \text{ kg/m}^2$

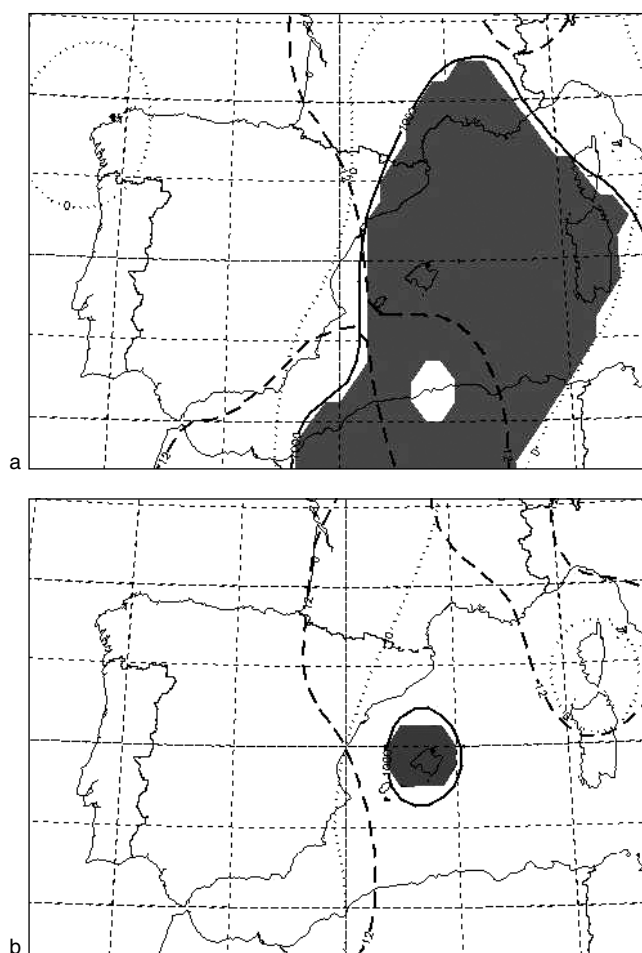


Figure 12. Composite chart at: (a) 12:00 UTC on 9 June 2000; (b) 00:00 UTC on 10 June 2000. Full line CAPE =  $1000 \text{ J/kg}$ . Dotted line LI = 0. Dashed line PWM surface–850 hPa =  $12 \text{ kg/m}^2$ . Dashed zone denotes existence of strong potential instability and high concentration of water vapour in the atmosphere

### 3.3. *Some hydrological aspects*

Old documentary evidence usually makes reference to floods and the damage caused by those events. For this reason, in order to compare this event with the previous ones, it is necessary to introduce some figures relating to some hydrological aspects. In this sense, it should nonetheless be highlighted that the rainfall over the basin of the Francolí between 21:30 UTC on 9 June and 03:00 on 10 June led to an increase of over 2 m in its level as it passed through the city of Tarragona. In the case of the River Llobregat, the highest increase was recorded (the gauging station at Martorell was actually swept away by the freshet) at Castellbell i el Vilar around 00:09 UTC, with over 4.5 m and a peak flow of some 1100 m<sup>3</sup>/s. Another station downriver recorded a peak flow of 1400 m<sup>3</sup>/s. It might be noted that the rises in the levels of the affected rivers were very sudden, with a response in some places that took place in less than 1 h. Fortunately, the various streams that swelled markedly during the episode fed their flows in a staggered way into the River Llobregat, thereby preventing the peak flow recorded at the mouth of the river being even greater (Velasco, 2000). As an example of the intensity of the swelling of the small tributary streams of the Llobregat affected in the episode, in the Magarola stream (basin of 96 km<sup>2</sup>) alone the peak flow reconstructed reached 628 m<sup>3</sup>/s (Francés, 2000), when the usual flow is less than 10 m<sup>3</sup>/s. Some studies published have associated these floods with a return period of nearly 500 years (Velasco, 2000). However, recent studies that take account of the precipitation recorded during the episode at the regional scale indicate return periods close to 200 years (Francés, personal communication).

## 4. THE 10 JUNE 2000 FLOOD EPISODE FROM THE PERSPECTIVE OF PREVIOUS HISTORICAL FLOODS

As noted in Section 3.3, the studies undertaken in order to estimate the flow recorded in the most severely affected basins, together with their return period, have given values ranging between 200 and 500 years. Good climatic referencing of the 'Montserrat' event would require availability of historical information for a sufficiently long period of time for it to be representative. That is why this paper has had to rely on gathering information both on the historical floods recorded in the Llobregat basin and the longer series of instrumental data.

Such information is not homogeneous, therefore it is advisable to distinguish between:

- (a) Episodes recorded after 1950 and for which pluviometric, hydrological, synoptic and thermodynamic information is available.
- (b) Episodes recorded between 1780 and 1950, for which mean monthly surface pressure is available for various places in Europe and daily pressure for Barcelona (situated near the mouth of the River Llobregat), together with technical and handwritten reports. Daily precipitation data for Barcelona is available from 1850.
- (c) Episodes recorded prior to 1780 for which only information from handwritten documents in historical archives is available. This work with proxy data has been done by collecting the continuous records of floods in municipal and private documentary sources, from various places in Catalonia. The information relates to the damage and destruction caused to infrastructure and crops by water courses bursting their banks. This information occasionally contains references to the meteorological episode itself, and even to hydrological aspects. This documentary information permits reconstruction of the flood series for the last 500 years at various localities in Catalonia. The information gathered is of considerable reliability due to it being contained mostly in official documents, and its dating and verification poses no problem, since the information is organized at the daily resolution.

In order to have a minimum homogeneity in all the flood series, three types of high-water situation have been differentiated according to their impact (Barriendos and Pomés, 1993; Llasat *et al.*, 1999). Along general lines, they are as follows.

1. *Simple rises or ordinary floods*: precipitation episodes that cause increases in the flow of the course of rivers or streams, but do not lead to them bursting their banks. They can cause damage and loss of life if work is being engaged near or actually in the river bed at the time of the rise, quite independently of its intensity.
2. *Extraordinary floods*: episodes of precipitation that lead to overflowing of banks, with an intensity or duration that does not cause important damage in the locality. They can give rise to disturbances of the day-to-day life of the population.
3. *Catastrophic floods*: episodes of precipitation that cause overflowing with serious damage or destruction of infrastructure (bridges, mills, walls, roads), buildings and crops.

In the light of this classification, the episode of 10 June 2000 would clearly lie within the type termed catastrophic floods.

#### 4.1. Comparison with the catastrophic flood events recorded in the Llobregat basin between 1950 and 2000

Over the last 50 years, precipitation levels of 250 mm in 24 h have been exceeded in various episodes affecting the River Llobregat basin. On 25 September 1962 that amount was recorded in less than 3 h and led to 441 deaths and 374 missing persons. On 20 September 1971, 308 mm was recorded in less than 24 h and, as consequence of the rainfalls that occurred between the 20 and 23 September, 18 people died. From 6 to 8 November 1982, 341 mm was recorded in 24 h and 510 mm was recorded in less than 3 days, causing 14 deaths in Catalonia, although this episode mainly affected the upper reaches of the River Llobregat. Finally, the floods recorded between 28 September and 5 October 1987 totalled 431 mm over the entire episode near the mouth of the Llobregat river, causing ten deaths in Catalonia and substantial material losses. In the 1962 episode, the material damage was estimated at the time at Ptas. 2650 million (€16 million), a figure that rose to Ptas. 7000 million (€42 million) in the floods of 1971 and Ptas. 45 000 million (€270 million) in those of 1982. This damage amount for the 1982 episode only includes damage in Catalonia. The floods also affected Andorra and France.

Although in the recent episode of 10 June the peak flow of the Llobregat at its mouth has been estimated at 1300 m<sup>3</sup>/s, the floods recorded in this period for the River Llobregat have shown higher peak flows. The Martorell gauging station is usually taken as the point of reference: 1550 m<sup>3</sup>/s in the 1962 episode, 1600 m<sup>3</sup>/s in the 1982 episode and the maximum known value of 3080 m<sup>3</sup>/s in 1971. The floods recorded in the springtime also show peak flow values almost as large as those of the autumn floods (Junta d'Aigües, 1994): on 17 April 1916 Martorell recorded a peak flow of 1300 m<sup>3</sup>/s and on 28 April 1942 the flow reached 1500 m<sup>3</sup>/s. Neither of these two episodes can be classified as catastrophic, however.

Although neither episode occurred in spring, the one most similar from a meteorological point of view and in terms of the area affected was the one in September 1962. In that case, too, the maximums were recorded over the basins of the rivers Llobregat and Besòs (Figure 13), only a few kilometres from those recorded in June 2000. Many of the synoptic features certainly coincided with ones that had arisen before and during the serious flash floods of 10 June 2000. During the flood event of 1962, in addition to the prior situation previously noted and common to these types of episode (Llasat and Puigcerver, 1994), some notable features were: focusing of the instability at very low levels; the advance of a cold front over the peninsula leading to rain and hail in many parts; the advance of the rains in Catalonia from SE to NE; and the fact that the episode occurred at night-time. The precipitable water mass on 25 September at 1200 UTC exceeded 39 mm, a figure equivalent to 131% of the mean figure for the month of September. At that time the LI and the CAPE achieved values of -3 and 1850 J/kg respectively. Figure 14 shows a comparison between the evolution of the various thermodynamic variables for the episodes of 1962 and June 2000.

#### 4.2. Comparison with the catastrophic flood events recorded in the Llobregat basin between 1780 and 1950

Between 1780 and 1950 there are records of 44 flood episodes in the mouth of the River Llobregat, of which six were catastrophic and 38 extraordinary. From all of them, eight events were recorded in spring: one was catastrophic, on 26 May 1853, and the other seven were extraordinary.

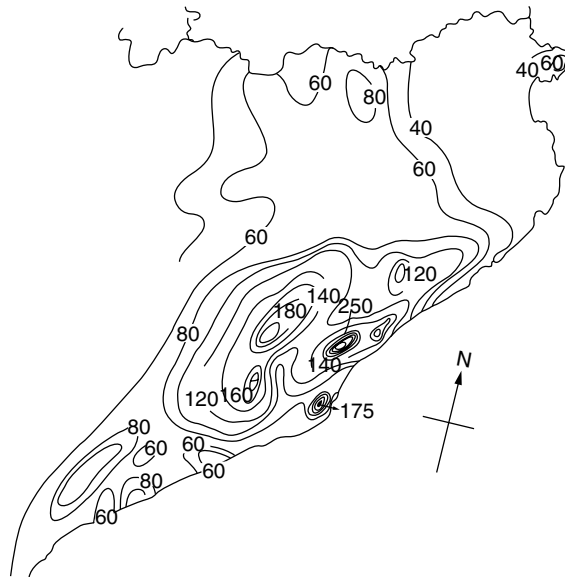


Figure 13. Distribution of accumulated rainfall between 08:00 UTC on 25 September 1962 and 08:00 UTC on 26 September 1962

In addition to the information from the historical archives, instrumental surface-pressure, temperature and rainfall data are available at some stations for this period. However, the fact that for part of the period no data at daily resolution are available (except for certain stations) limits the analysis to a search for coherence between the conceptual models developed for later periods and the available data. This is the case of the analysis of the flood event of June 1794. This event could be considered as extraordinary in the mouth of the Llobregat river, but it was catastrophic in Barcelona and other little basins near to the Llobregat basin (it is not possible to have information about the complete Llobregat basin due to the ongoing war at that time).

The 1794 episode shows certain similarities to the 2000 episode: the precipitation recorded between the evening of 8 June and the morning of 9 June was sufficient to have catastrophic effects on various towns. Throughout the description of the 1794 event it is said that the flooding was so sudden that the population had no time to respond, which allows it to be identified as a flash flood. Analysis of the mean monthly pressure (CRU database, Norwich) shows the presence of a strong anticyclonic area situated over the North Atlantic and extending across to central Europe (Figure 15(a)). Evolution of the daily surface pressure in Barcelona (Figure 15(b)) shows the passage of a deep depression between 8 and 9 June 1794. Besides this, the temperature before the event reaches high values, something that had been observed with other flash-flood events in the western Mediterranean (Llasat *et al.*, 1996). This low probably encouraged a confluence of the warm and moist Mediterranean air mass with the masses of cold air from the N and NE that were advected by the strong anticyclone situated in the North Atlantic. Finally, the reconstruction of the charts using the daily mean surface pressure data of ten European stations (data obtained from the framework of the European projects ADVICE, IMPROVE and SPHERE) corroborates the presence of the low over Catalonia and the presence of a relative high pressure over Europe. These hypotheses fit with the typical situation of floods over Catalonia (Llasat and Puigcerver, 1994) and the 2000 episode itself.

#### 4.3. The climatic context on the basis of analysis of floods recorded in Catalonia from the 15th century

In order to provide an idea of how these episodes are distributed over the course of the year, the complete series of catastrophic floods recorded in the lower part of the River Llobregat (El Prat de Llobregat) has been reconstructed from 1315 down to 1971 (Codina, 1966, 1994). The analysis of this information besides the other information obtained from the framework of the SPHERE project, drives one to the conclusion that 171 flood events have been recorded between the years 1300 and 2000 in the mouth of the River Llobregat: 69 of

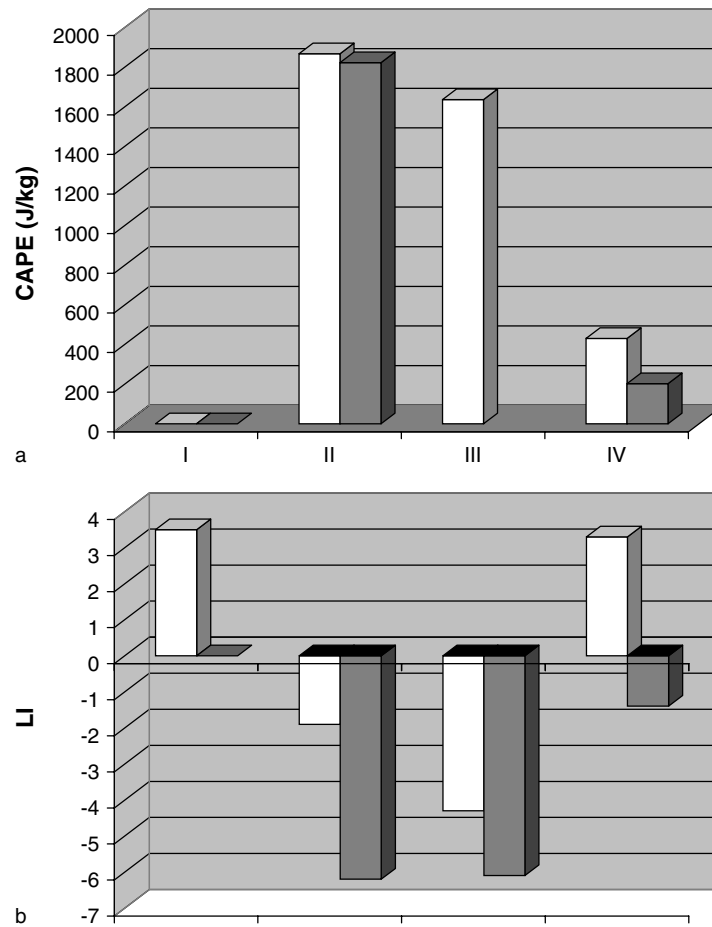


Figure 14. Evolution of (a) the CAPE and (b) the LI for the flood events of September 1962 (white areas) and June 2000 (grey areas). The number III corresponds to the nearest radiosounding hour to the beginning of rainfall (00:00 UTC on 10 June 2000, 00:00 UTC on 25 September 1962)

them were ordinary, 81 were extraordinary and 21 were catastrophic. Although most of them were recorded during the autumn, it is possible to find some cases that occurred in the spring, such as the floods of 2 May 1603, 9 June 1794 and between 24 and 26 May 1853.

Figure 16 shows the climatic evolution of the standardized values of frequencies of such floods. Firstly, flood data have been weighted giving a value of one to extraordinary events and a value of two to catastrophic events. Once this annual index has been calculated, a series of its standardized values has been built for the period 1300–2000. Finally, a smooth filter of a 31 year moving average has been applied. The frequency of the floods in the lower reaches of the River Llobregat, despite the smoothing applied to the standardized values, shows non-regular oscillating behaviour. More specifically, a marked oscillation occurred in the last decades of the 16th century and the first two decades of the 17th century. The second half of the 18th century showed another moderate increase; and, finally, there was a second lengthy and intense oscillation in the middle of the 19th century. These last three oscillations lie within the framework of the climatic episode known as the Little Ice Age, in its most intense and widespread period between the 16th and 19th centuries, the first signs of which can be detected in northern Europe around the beginning of the 14th century.

Despite the fact that the intense precipitation events that cause floods arise out of singular and not necessarily similar atmospheric situations, their concentration over the course of the centuries in intervals of some 40 years duration is a noteworthy climatic aspect. Furthermore, such oscillations constitute a point of connection between climatic variability in the Mediterranean region and in higher latitudes; during the Little Ice Age

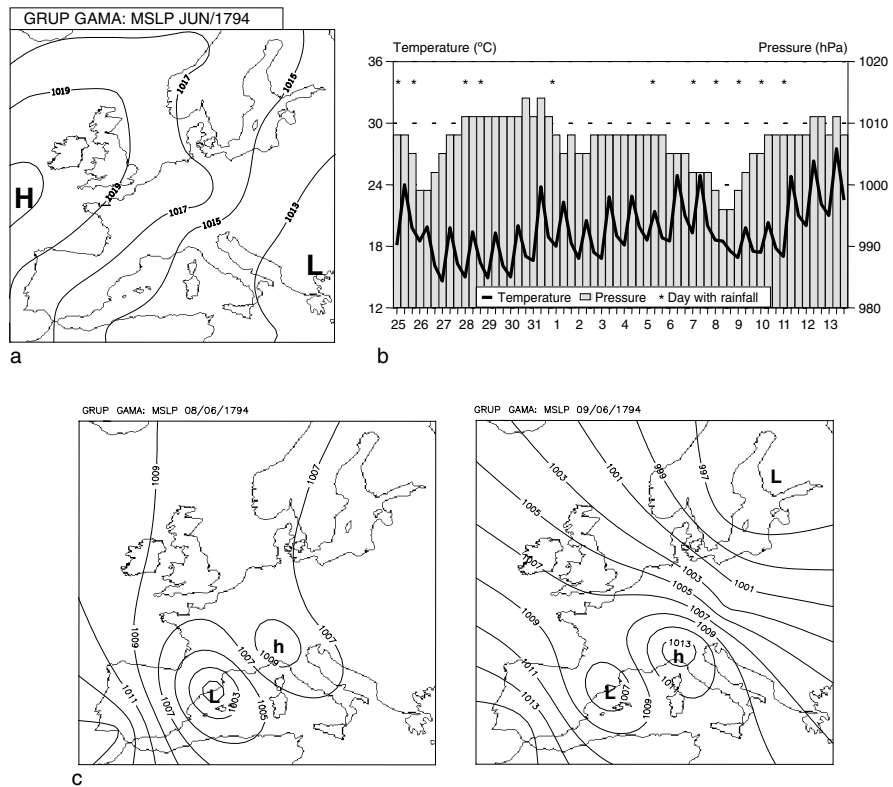


Figure 15. (a) Synoptic monthly configuration for June 1794; (b) evolution of the thrice-daily instrumental records (0600 UTC, 1400 UTC, 2200 UTC) in Barcelona from 25 May to 13 June 1794; (c) analysis of the mean sea-level pressure on 8 and 9 June 1794

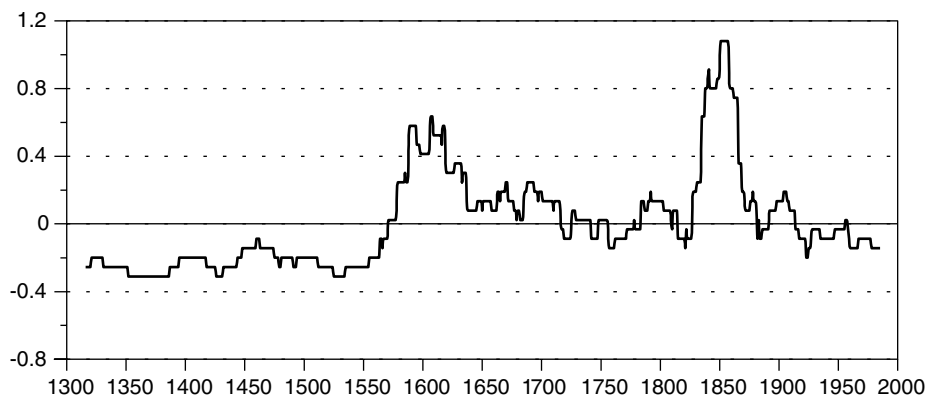


Figure 16. Evolution of the 31-year moving average of the weighted flood index at the mouth of the River Llobregat since the 14th century

the oscillations coincided with the pulses of advance of the Alpine glaciers; in particular, they are nearly synchronous with the studied behaviour of the Grindelwald glacier, thereby showing that these are different effects of the same climatic patterns (Pfister, 1988; Barriendos and Martín-Vide, 1998).

## 5. CONCLUSIONS

During the early hours of 10 June 2000 heavy rainfalls and flash floods were recorded in Catalonia that caused damage calculated at over €66 million and caused five fatalities. The worst affected zones were the basins of the River Llobregat and many of the coastal watercourses. The rain was characterized by its high intensity, in some localities exceeding 100 mm in 1 h, with a maximum accumulated amount of 224 mm in less than 24 h, according to official sources. Still, amounts of that magnitude or greater have, nonetheless, been recorded on more than one occasion over the course of the last century at certain localities in Catalonia, and probably — though we do not have quantitative rainfall data for the episodes in question — also in previous centuries, as may be deduced from the presence of catastrophic flash floods. The fact that the episode occurred in the spring makes it rarer, as this kind of episode normally occurs in Catalonia at the end of the summer and particularly in the autumn. Historical data show that in the 17th, 18th and 19th centuries, too, at least one catastrophic flood episode was recorded in the spring season. Similarly, the increase of flow recorded in this case in the lower reaches of the Llobregat was not the highest of the last century. It might have been highest, however — though there are no records of it due to an absence of gauging stations — in some of the normally dry beds of streams that experienced sudden overflows.

Among the meteorological aspects, we might note the stationary nature of the convective system that led to the accumulation of a large amount of precipitation in a short time. That system, presenting an essentially linear structure (squall line) with the formation of various convective cells within it, was detected for the first time in the SW of Catalonia on 9 June around 23:00 UTC, with a slow translation in an NE direction. In addition to the orography itself, factors that favoured its development were the advection of very warm and moist air at low levels, with the presence of a surface low off the Catalan coast, which induced a flow from the SE and convergence, while a cold air pool was detected in the upper atmosphere (a factor not always recorded in flood episodes in Catalonia). Analysis of the vertical thermodynamic structure of the atmosphere points to the focusing of potential instability around the NE sector of the western Mediterranean.

The three episodes of spring catastrophic flooding known prior to the 20th century and affecting the River Llobregat basin (May 1603, June 1794 and May 1853) took place within the climatic episode known as the Little Ice Age; in particular, the episode of 1794 (similar to that of 2000) took place within the 'Maldà oscillation' (Barriendos and Llasat, in press) and was characterized by exceptionally anomalous climatic behaviour in the Mediterranean basin, with a simultaneous increase of droughts and floods. In the case of the heavy rainfall recorded in June 2000 and analysed in this paper, it is not possible to reach a conclusion about whether or not it forms part of a generalised climatic anomaly or climatic trend or whether it is simply an exceptional *ad hoc* anomaly or episode.

## ACKNOWLEDGEMENTS

Our most sincere thanks to the Catalan Agency of Water of the Department of the Environment of the Government of Catalonia for allowing us access to the SAIH data for the IBC. Our thanks to the Meteorological Office of Catalonia for the meteorological information provided. This work has been carried out thanks to financing under the European project *Systematic, Palaeoflood and Historical Data for the Improvement of Flood Risk Estimation (SPHERE)*, EVG1-CT-1999-00010. Some results from the ADVICE project (ENV4-CT95-0129) and IMPROVE project (ENV4-CT97-0511) have been used. Our thanks to Thomas Molloy for translating the present paper.

## REFERENCES

- Barriendos M, Llasat MC. In press. The study of climatic anomalies by means of zonality and NAO indices. The case of 'Maldà' anomaly in the western Mediterranean basin (AD 1760–1800). *Climatic Change*.
- Barriendos M, Martín-Vide J. 1998. Secular climatic oscillations as indicated by catastrophic floods in the Spanish Mediterranean coastal Area (14th–19th centuries). *Climatic Change* **38**: 473–491.
- Barriendos M, Pomés J. 1993. *L'aigua a Mataró. Inundacions i recursos hídrics (Segles XVIII–XX)*. Caixa d'Estalvis Laietana: Mataró.
- Codina J. 1966. *Delta del Llobregat. La gent del fang. El Prat: 965–1965*. Montblanc: Granollers.
- Codina J. 1994. *Inundacions al Delta del Llobregat*. Col. Episodis de la Història, nos. 147–148. R. Dalmau: Barcelona.



- Doswell III ChA, Brooks HE, Maddox RA. 1996. Flash flood forecasting: an ingredients based methodology. *Weather Forecasting* **11**: 560–581.
- Francés F. 2000. Consecuencia de la lluvia del 10 Jun10 2000 sobre el comportamiento hidrológico de la Riera de Magarola y sus afluentes. In *Proceedings of the "VI Jornades de Meteorologia Eduard Fontseré"*, Barcelona, 25 November; 129–140.
- Junta d'Aigües. 1994. *Recomanacions sobre mètodes d'estimació d'avingudes màximes*. Generalitat de Catalunya : Barcelona.
- Llasat MC. 1987. *Episodios de lluvias copiosas en Cataluña: genesis, evolución y factores coadyuvantes*. Publicacions de la Universitat de Barcelona: Barcelona.
- Llasat MC. 1990. Influencia de la orografía y de la inestabilidad convectiva en la distribución espacial de lluvias extremas en Cataluña. *Acta Geológica Hispánica* **25**(3): 197–208.
- Llasat MC. 1991. *Gota fría*. colec. Boixareu Universitaria, no. 6. Marcombo: Barcelona.
- Llasat MC, Puigcerver M. 1990. Cold air pools over Europe. *Meteorology and Atmospheric Physics* **42**: 171–177.
- Llasat MC. 2001. An objective classification of rainfall events on the basis of their convective features. Application to rainfall intensity in the north-east of Spain. *International Journal of Climatology* **21**: 1385–1400.
- Llasat MC, Puigcerver M. 1994. Meteorological factors associated with floods in the northeastern part of the Iberian peninsula. *Natural Hazards* **9**: 81–93.
- Llasat MC, Puigcerver M. 1997. Total rainfall and convective rainfall in Catalonia, Spain. *International Journal of Climatology* **17**: 1–13.
- Llasat MC, Ramis C, Barrantes J. 1996. The meteorology of high-intensity rainfall events over the west Mediterranean region. *Remote Sensing Reviews* **14**: 51–90.
- Llasat MC, Barriandos M, Rodriguez R, Martín-Vide J. 1999. Evolución de las inundaciones en Cataluña en los últimos quinientos años. *Ingeniería del Agua* **6**(4): 353–362.
- Llasat MC, Rigo T, Montes JM. 2000. Orographic role in the temporal and spatial distribution of precipitation. The case of the internal basins of Catalonia (Spain). In *Proceedings of the EGS Plinius Conference*, Maratea, Italy, October 1999; 41–55.
- Pfister C. 1988. *Klimageschichte der Schweiz. 1525–1860*. Paul Haupt: Bern.
- Ramis C, Llasat MC, Genovés A, Jansà A. 1994. The October-87 floods in Catalonia. Synoptic and mesoscale mechanisms. *Meteorological Applications* **1**: 337–350.
- Ramis C, Llasat MC, Alonso S. 1995. A comparative study between two cases of extreme rainfall events in Catalonia. *Surveys in Geophysics Journal* **16**: 141–161.
- Riosalido R. 1998. *Estudio meteorológico de la situación del 7 de Agosto de 1996 (Biescas)*. Nota Técnica STAP no. 26, Ministerio de Medio Ambiente, Dirección General del INM.
- Tudurí E, Ramis C. 1997. The environments of significant convective events in the western Mediterranean. *American Meteorological Society* **12**: 294–306.
- Velasco E. 2000. Les riudes del 10/06/00 a les conques vessants al Llobregat. In *Proceedings of the "VI Jornades de Meteorologia Eduard Fontseré"*, Barcelona, 25 November; 41–50.