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Two cases of severe weather in Catalonia (Spain): an observational study

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Surface observations, satellite and radar imagery and cloud-to-ground lightning data are used in an observational study of two cases that produced severe weather in Catalonia (Spain). The first one occurred on 24 August 1993; a squall line crossed Catalonia from west to east producing heavy rain with rates of up to 100 mm h^{-1} and hail of 7 cm diameter. The observational information provided is a good tool for monitoring the event and issuing a reasonable nowcast. The second case, which occurred on 31 August 1994, was associated with the development of a tornado (F1 in the Fujita scale) as well as hail of up to 5 cm diameter. In this case the convection was almost stationary and no clear signatures of severe weather can be identified from available satellite and radar imagery.

1. Introduction

Catalonia, in the north-eastern part of Spain (Figure 1), is known for its sunny and pleasant weather. However, Catalonia is affected, especially during the autumn, by hazardous weather events. The best known are heavy rain episodes, which are also frequent in autumn in some other coastal regions of Spain: Valencia, Murcia, Andalucia and the Balearic Islands (Figure 1). In fact, most of the observational sites in eastern Spain, including Catalonia, have recorded precipitation amounts exceeding 200 mm in 24 hours (Font, 1983), although much greater rainfalls have been recorded in some places. For example, precipitation exceeded 800 mm in Gandia (Valencia region) on 3 November 1987. Heavy precipitation sometimes produces flash floods with high economic damage and occasionally loss of human life. Llasat (1987) provides an extensive study of heavy rain events in Catalonia and Ramis *et al.* (1994) present a detailed study of synoptic and mesoscale mechanisms acting in the October 1987 event.

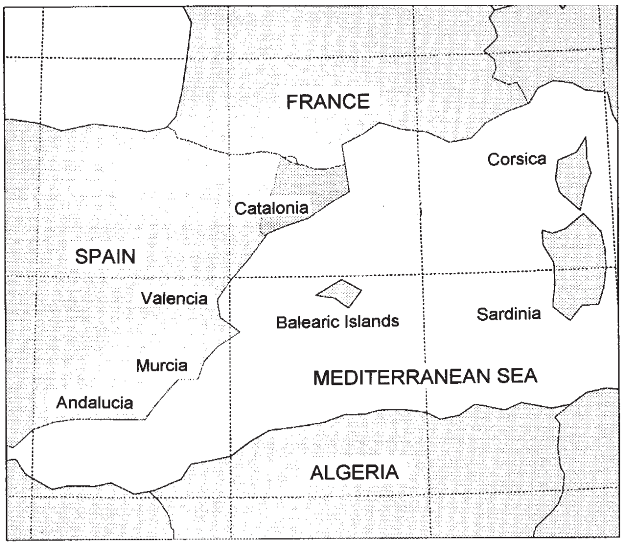

Figure 1. *The western Mediterranean. The shaded zone represents Catalonia. Some regions referred to in the text are indicated.*

Many authors (e.g. Maddox, 1980) argue that the term 'severe weather' should be reserved for hazardous events in which large hail or strong winds, associated with downbursts or tornadoes, are present. Here, however, it will be assumed that heavy rain can be considered to be severe weather.

During recent years there have been reports in the Spanish newspapers of severe weather events in the Mediterranean area, and it seems that their occurrence is much more frequent than that indicated by the meteorological archives. Curiously, there are only a few studies in the meteorological literature about severe weather events over Spain. Those include studies dealing with the vertical structure of the atmosphere over Palma de Mallorca when a tornado developed in Menorca (Balearic Islands) (Gayá & Soliño, 1993), the meteorological situation when a tornado developed in the Guadalajara region (central Spain) (Martín *et al.*, 1995) and the atmospheric thermodynamic environment associated with a large hail event in Mallorca

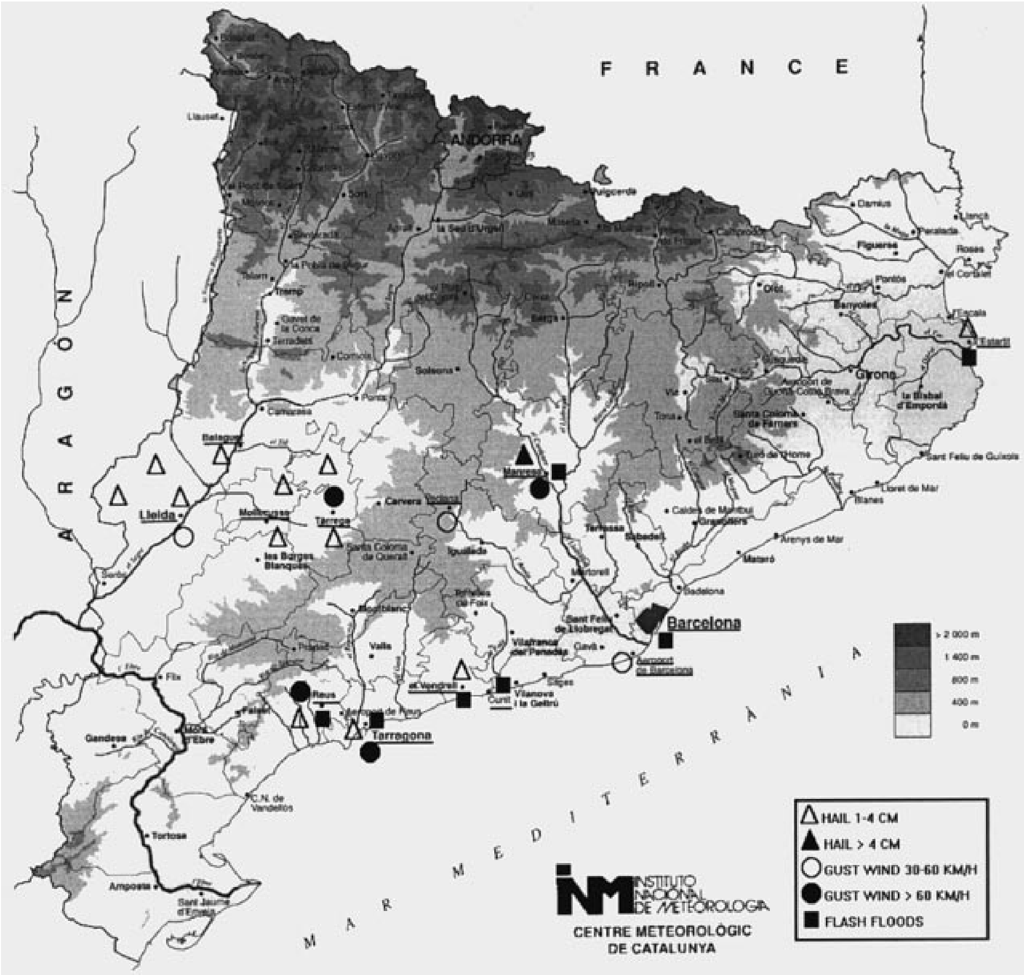

Figure 2. *The Catalonia region. Symbols represent meteorological observations on 24 August 1993. The major geographical features are included. Sites referred to in the text are underlined.*

(Balearic Islands) (Miró-Granada, 1969). Some information on recent severe weather and heavy rain events which occurred in Spain can be found in Riosalido (1994). In addition, since 1992 the Meteorological Center of Palma de Mallorca produces every six months a catalogue (named Boletín PEMMOC) of cyclones and hazardous meteorological phenomena in the western Mediterranean.

This paper presents an observational study (using meteorological surface observations, Meteosat and radar imagery and cloud-to-ground lightning data) of two cases of severe weather in Catalonia. The first one occurred on 24 August 1993. Large hail (up to 7 cm in diameter) was observed in the central part of Catalonia. The second one took place on 31 August 1994 and the most significant aspect was the development of a tornado in the south of Catalonia. The aim of the paper is to provide more background knowledge on the observational aspects of severe weather events in southern Europe and show that the examination of case studies should help forecasters identify severe weather events and therefore issue timely warnings. A companion paper will deal with the study of the meteorological scenarios of both events.

2. The 24 August 1993 case

2.1. The event

During the early afternoon heavy rain occurred on the southernmost coastal area of Catalonia. In one hour (1230 to 1330 UTC) 37 mm fell in el Vendrell (see Figure 2 for the location of this site plus others to which reference is made), although higher amounts were registered in smaller towns around el Vendrell. Thunderstorms produced many lightning strikes which affected the electric supply in all of Catalonia and Andorra during a two-hour period.

Later, in the evening, at about 1850 UTC, rainfall and hail with diameters of 2–3 cm were observed in the Lleida area. At about 2030 UTC heavy rain and hail with diameter of 6–7 cm fell close to Manresa. The area around Manresa became flooded as a result of 117 mm of rainfall in one hour. At about the same time heavy rain and hail with diameter of 2–3 cm were observed in Reus Airport and Tarragona. Precipitation rates of 50 mm in 30 minutes at Reus Airport and 25 mm in 20 minutes at Tarragona produced flooding. At 2200 UTC the thunderstorms arrived at Barcelona where lighter

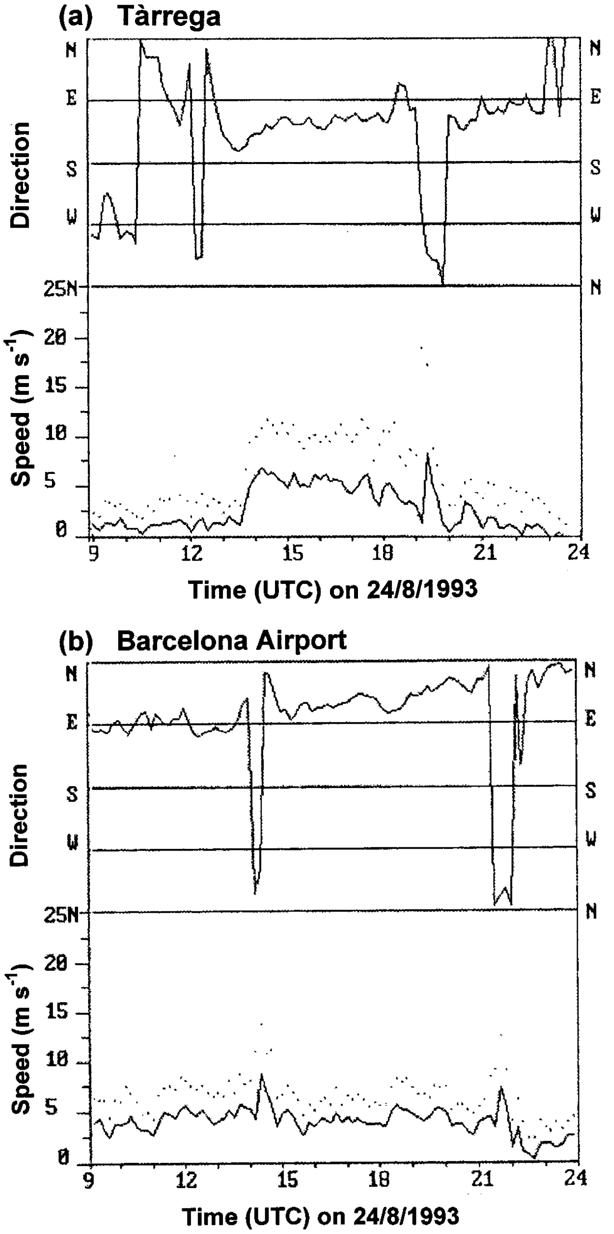

Figure 3. *Wind registers at* (a) *Tàrrega and* (b) *Barcelona Airport on 24 August 1993. Dots represent maximum gusts at 10 minute intervals.*

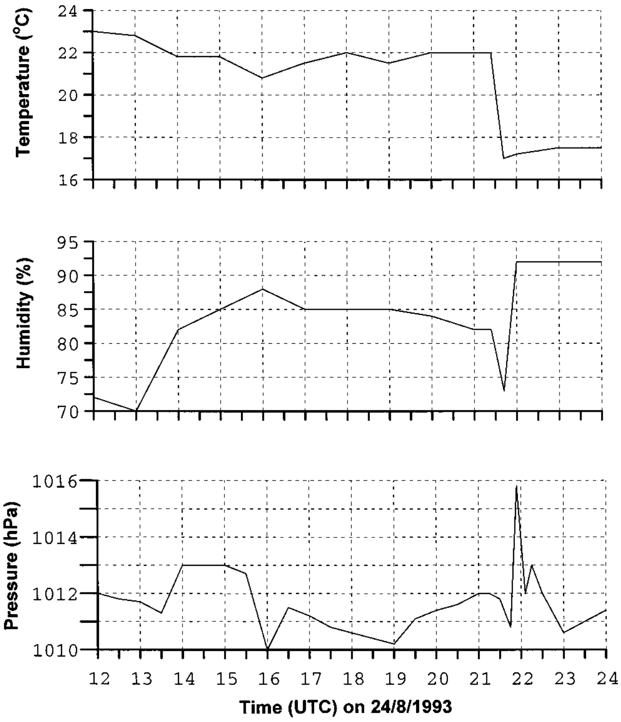

Figure 4. *Temperature, relative humidity and pressure record in l'Estartit on 24 August 1993.*

precipitation occurred, although there was a small amount of flooding in the downtown area. The lightning strikes produced another power cut in that city and neighbouring towns. At about the same time, hail with diameters of 2–4 cm fell in l'Estartit (located in the northern coast) and precipitation reached 20 mm in 20 minutes.

Although there were no reports of loss of human life, many fruit trees and farms were affected by the hail and floods. Several highways and railways also became partially destroyed.

Looking at the timing of the meteorological phenomena, it seems that the severe weather took place as a moving convective system crossed the region from the west to east with a speed of 40–50 km h^{-1}.

2.2. Meteorological surface observations

Some automatic weather stations and standard observatories provided information about wind, pressure, temperature and humidity during the event. Figure 3 shows the wind records at Tàrrega and Barcelona Airport. During the afternoon before the severe weather outbreak, the wind inland (Tàrrega) was mainly from the south-east with speed of 6–7 m s^{-1} and gusts of 12–13 m s^{-1}. Associated with the passage of the convective system at about 1900 UTC the wind veered quickly to the north-west and increased in speed with gusts reaching 18 m s^{-1}. At the coast (Barcelona Airport) the wind was from the east during the day, but with the arrival of the convective system at about 2130 UTC the wind change has a similar form to that recorded inland. The change in direction and speed observed at 1430 UTC was related to a thunderstorm which moved along the coast during the early afternoon, as we will show later, and produced heavy rain over coastal areas. In both locations the structure of the record is very similar; the veer of the wind was simultaneous with the increase of the speed. Subsequently an interval of calm preceded a restoration of the direction and speed existing before the event. The maximum wind gusts were observed in Manresa and Reus Airport with peak speeds of 20 m s^{-1}.

During the increase of the wind, the temperature decreased with a mean value of about 5 °C and up to 7 °C in Tàrrega. Humidity decreased by about 10% simultaneously with the decrease of temperature.

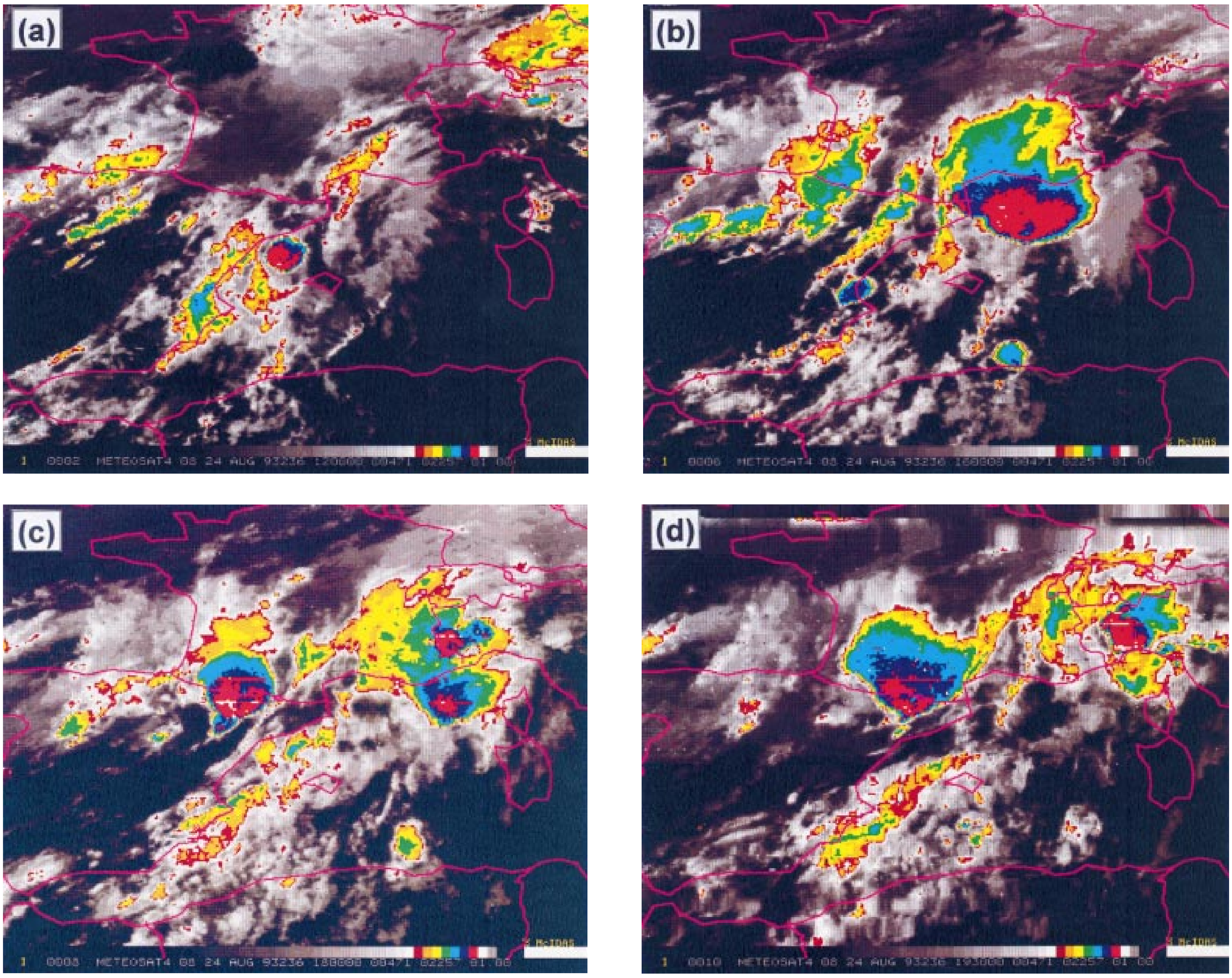

Figure 5. *Meteosat infrared images on 24 August 1993 at (a) 1200 UTC, (b) 1600 UTC, (c) 1800 UTC and (d) 1930 UTC. Colours represent temperature (°C) intervals: brown –32 to –35; orange –36 to –39; yellow –40 to –43; green –44 to –47; blue –48 to –51; deep blue –52 to –55; red –56 to –59; white –60 to –63.*

Pressure variations were also notable. A small decrease of pressure occurred just before the arrival of the thunderstorms, but when they arrived pressure increased very quickly and then decreased rapidly to the previous values. The observed variations of pressure attained 6.5 hPa in Veciana, 2.5 hPa in Barcelona and 5 hPa in l'Estartit. Figure 4 shows temperature, relative humidity and pressure records from l'Estartit. In the harbour of this coastal town, sea level oscillations of about 50 cm amplitude and periods of 10 minutes were observed simultaneously with the passage of the thunderstorms. This type of surges has been observed previously in the Catalan coast and in the Balearic Islands associated with short-period pressure oscillations (Ramis & Jansà, 1983).

2.3. Remote sensing observations

(a) Meteosat imagery

At 1200 UTC (Figure 5(*a*)) a cloud band extended from Gibraltar to south France over eastern Spain. Embedded in this band was a deep convective cell over the Mediterranean Sea, close to the southern coast of Catalonia. This thunderstorm was responsible, during its displacement towards the north-east, for the heavy rain observed in the coastal area of Catalonia during the early afternoon. That convective cell originated between the Balearic Islands and Valencia. Later, new convection developed in the same area. Over the north of Spain a cloud band associated with a weak cold front. Ahead of the cold front, a line of structured convection can be identified.

At 1600 UTC (Figure 5(*b*)) the Mediterranean convective cell has became more extensive and was located over south France. New shallow convective cells appeared to the west of Catalonia with a linear structure. The linear band located 150–200 km ahead of the frontal system had increased in size. Furthermore, this convective system continued increasing its size rapidly, displaced towards the east and acquired a triangular shape. Meanwhile, the linear cloud band over the west of Catalonia remained almost stationary. Figure 5(*c*) shows the Meteosat image at 1800 UTC. It shows the triangular shape of the thunderstorm with the overshooting tops on the southern flank, as well as new cells developing south

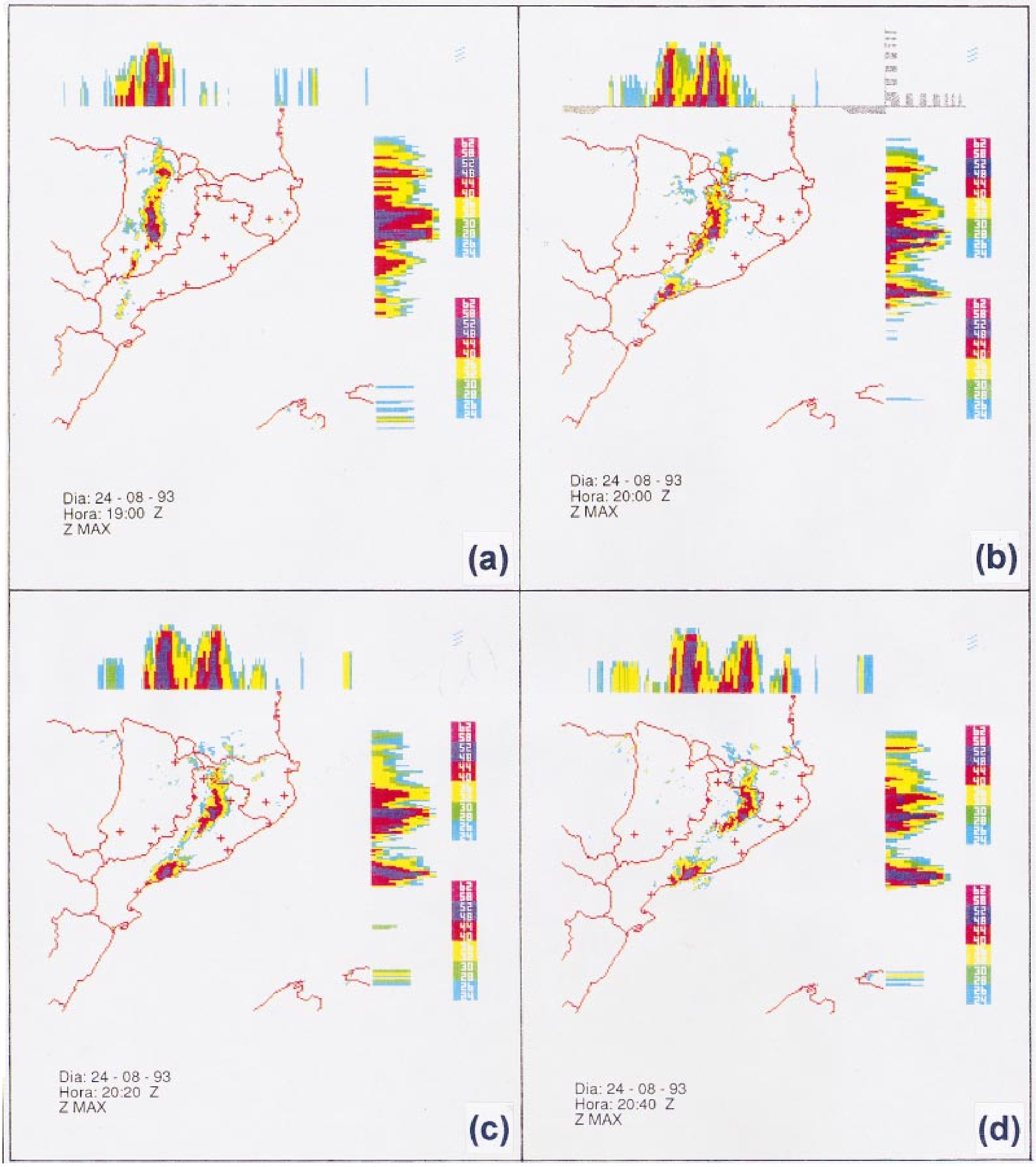

Figure 6. *Zmax radar (λ=10 cm) reflectivity (dBz) on 24 August 1993 at (a) 1900 UTC, (b) 2000 UTC, (c) 2020 UTC and (d) 2040 UTC.*

of the major storm. At this time the thunderstorms are completely separated from the cold front. The shallow convection to the west of Catalonia is dissipating. At 1930 UTC (Figure 5(*d*)) thunderstorms are in western Catalonia; they show the maximum development and a V-shaped structure with a warm spot behind the colder area (McCann, 1981) is apparent. The convective system continued its displacement towards the east but progressively lost its V-shaped pattern. At 2330 UTC it was located over the sea, east of Catalonia.

(b) Radar imagery

The echotop images (not shown) show that at 1750 UTC a convective line with a north–south orientation entered Catalonia. The highest tops, up to 13 km, were concentrated in the northern half of this line. At 1850 UTC the convective line was located 50 km to the east of its previous position, matching with the observation of hail in the Lleida area. At 1950 UTC the echotops of the northern part were lower while in the southern part they were higher. Approximately 30 minutes later,

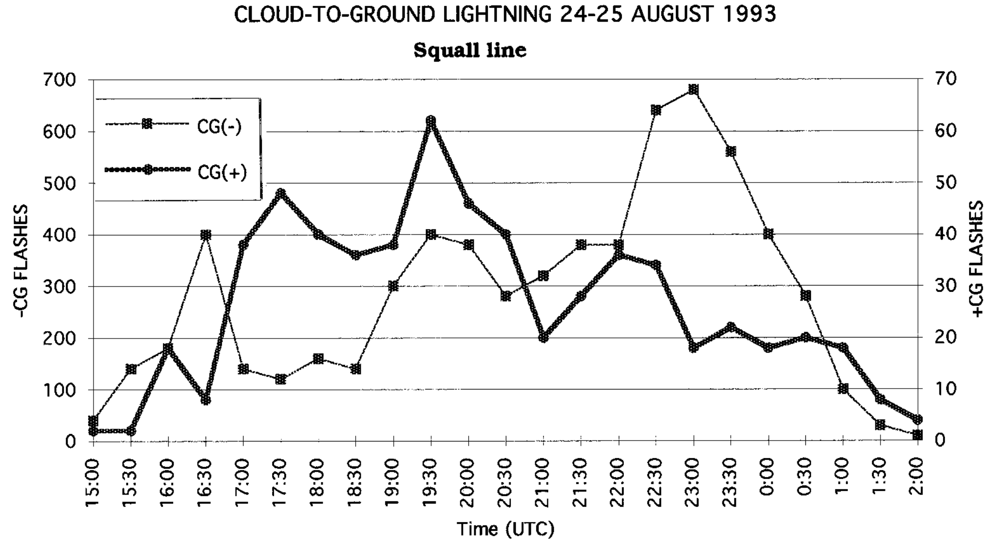

Figure 7. *Temporal distribution of CG(–) and CG(+) strokes on 24 August 1993 over Catalonia.*

large hail was observed in the areas around Manresa, Reus Airport and Tarragona.

Later, at 2050 UTC, the convective line broke. After that time the displacement of the northern part was towards the east and at 2150 UTC it reached the coast. The southern part, as an independent system, moved towards the north-east following the coast.

The volumetric scan of the radar can be used to study the horizontal and vertical distribution of Zmax (maximum reflectivity). This product is obtained by projecting in the horizontal plane and vertical cross-sections, the maximum value of reflectivity (*Z*) obtained in each column of the cartesian volume. Figure 6 shows the Zmax distribution during the period of maximum intensity of the thunderstorms. The linear structure is clearly visible. An interesting aspect is the arc shape of the echoes, known as bow echo configuration, in the central part of the line as well as the wave form called Line-Echo Wave Pattern (LEWP). These signatures have been previously identified as an indicator of severe weather (e.g. Johns & Doswell, 1992; Johns, 1993). Reflectivity attained 52 dBz in broad areas with some points reaching 58 dBz. Vertical cross-sections show more clearly the multi-cellular structure. It is also clear that cells of the northern part of Catalonia decreased in size during their displacement towards the east, although large and concentrated reflectivity of 52 dBz is identified at 2040 UTC. On the other hand, the southernmost cell increased its size and reflectivity between 2000 UTC and 2040 UTC. No clear supercell signatures are evident as a Weak Echo Region (WER) (Lemon, 1980), but at 2040 UTC some WER in the east–west direction can be identified in the southernmost cell.

In conclusion, radar imagery shows that very deep convection with a linear and multi-cellular structure crossed Catalonia from west to east. Some evidence of supercell development can be inferred. Radar images show the organization of convection in multi-cellular linear structure much more clearly than Meteosat images.

(c) Cloud-to-ground lightning data

The Spanish lightning detection and localisation system (named REDDEL) consist of fourteen antennae covering the whole country uniformly. The system discriminates cloud-to-ground positive and negative flashes (CG(+) and CG(–)) from other signals, but it does not provide information on intra-clouds flashes (ST, 1992).

The information provided by REDDEL shows that during 24 August a total of 17 401 strokes were detected in Catalonia. These data indicate that convection was very frequent in the region throughout the whole day. During the period in which severe weather affected Catalonia, the first strokes, related to the convective system, appeared around 1700 UTC, with the latest at 0230 UTC on 25 August.

The temporal distribution of the number of strokes over Catalonia (Figure 7) shows that CG(–) has three maxima. The maximum at 1930 UTC coincides with the time the Meteosat image shows strong development of the thunderstorm. The absolute maximum appears at 2300 UTC, but at this time the storm was over the sea. The rapid increase of CG(–) in a storm has been identified as an indicator of the reactivation of the convective currents in the storm (Branick & Doswell, 1992). There is a dominance of CG(+) during the passage of the thunderstorm over Catalonia. Also significant is the maximum at 1930 UTC. The dominance of CG(+) over CG(–), and particularly a maximum in CG(+), has been identified previously as precursor of severe weather (Branick & Doswell, 1992)

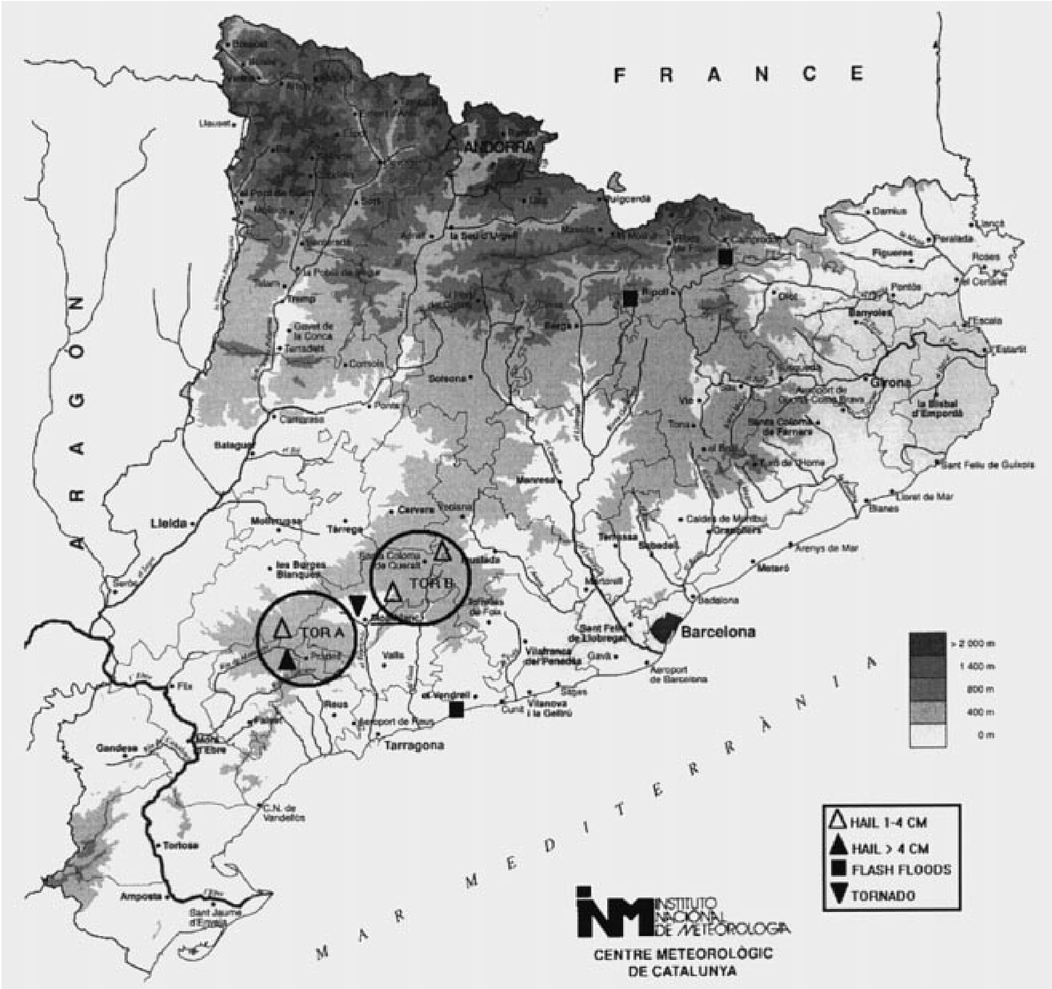

Figure 8. *The Catalonia region with indication of the tornado location and hail observations on 31 August 1994.*

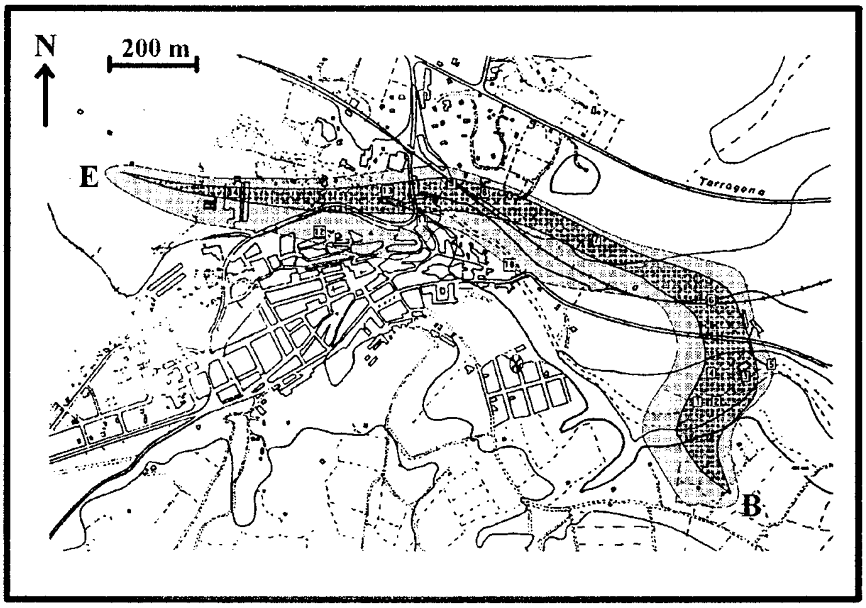

Figure 9. *Path of the tornado. B = beginning of the touchdown, E = end of the touchdown. The dark shadow represents where tornado attained F1, the light shadow where tornado attained F0 (courtesy of M. Gayá).*

2.4. Summary

The observational study of this case shows that the convective line that crossed Catalonia in the late evening on 24 August 1993 can be considered to be a *squall line* with an embedded bow echo and LEWP case. The surface observations of wind, temperature, humidity and pressure during the passage of the line

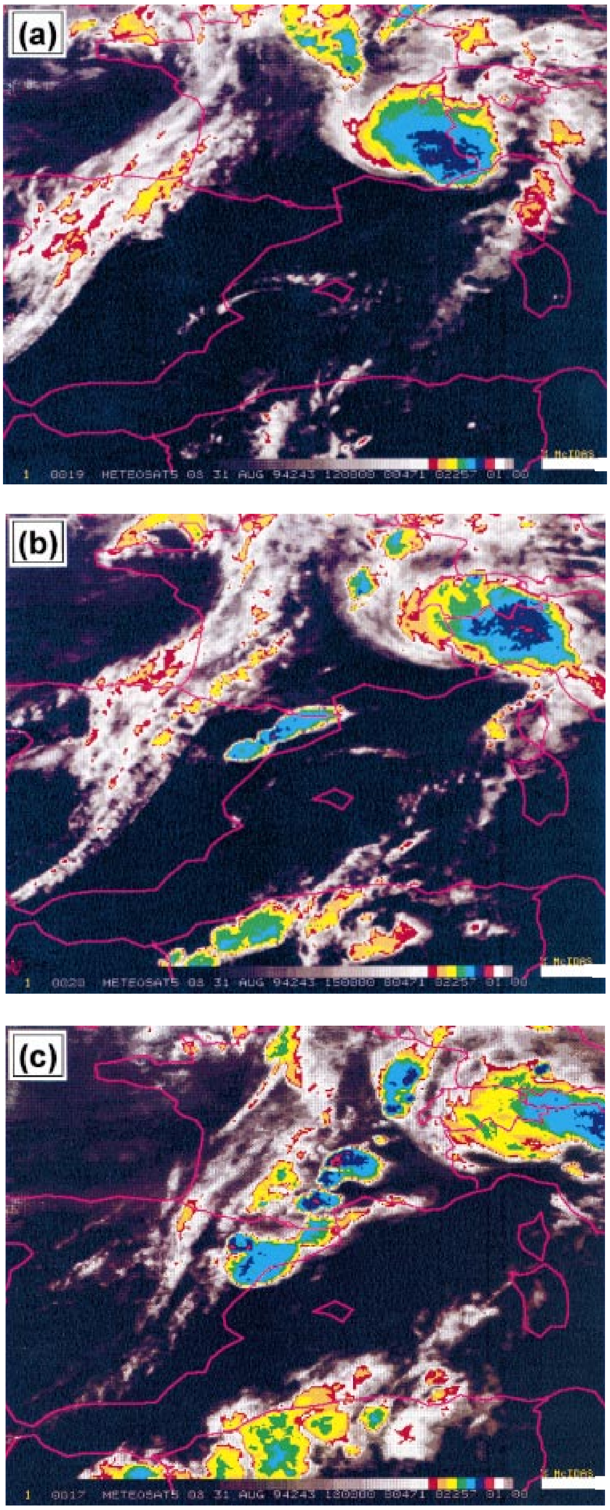

Figure 10. *Meteosat infrared images on 31 August 1994 at* (a) *1200 UTC,* (b) *1500 UTC and* (c) *1800 UTC. Colours represent temperatures, as in Figure 5.*

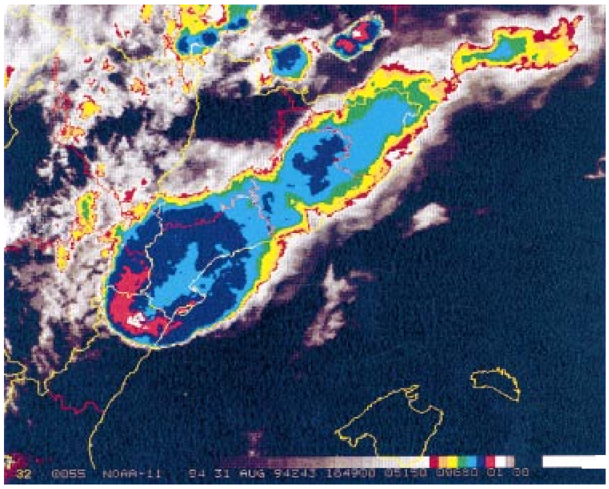

Figure 11. *V-shape on NOAA infrared image on 31 August 1994 at 1649 UTC. Colours represent temperatures, as in Figure 5.*

and the development of convection in the warm sector, 150–200 km ahead of the cold front, matches the description of a *squall line* (e. g. Barry & Chorley, 1992; Browning, 1986; Maddox, 1980; Wallace & Hobbs, 1977). The observed weather (particularly large hail) indicates the existence of deep convection.

The Meteosat and radar imagery also show that the convection in the *squall line* was deep (high echo tops, high reflectivity), with a multi-cellular organisation, matching again previous descriptions of squall line organisation (e.g. Maddox, 1980). Radar shows that the convective line moved from west to east at a speed of 40–50 km h^{-1}. The REDDEL also shows a dominance of CG(+) over the CG(–) during the passage of the thunderstorm over Catalonia with a maximum of CG(+) just prior to the observation of very large hail.

This study also shows that a real-time monitoring of the event through Meteosat, radar, REDDEL and automatic weather stations providing information at short time intervals (for example 10 minutes) can be decisive. It might allow forecasters to issue accurate warnings in order to mitigate the damaging effects of such hazardous phenomena. Of course, forecasters have to know the dynamics of the meteorological situation in which this kind of phenomenon develops. Then an accurate diagnosis of the meteorological situation has to be made in order to identify the forcing mechanisms. This diagnosis should provide information to forecasters on which the issuing of warnings can be based.

3. The 31 August 1994 event

3.1. The event

During the early afternoon convection developed over Catalonia along the coastal mountain range. During the afternoon large hail (up to 6 cm in diameter) fell in several sites (see Figure 8) as well as heavy rain in scattered locations.

About 1445 UTC a tornado developed close to l'Espluga town (near Montblanc, see Figure 8 for location). The tornado lasted about 30 minutes and the path-length on the ground was about 2 km (Figure 9). The tornado destroyed electric towers, affected the railways and damaged houses and farm buildings. Some big trees were also uprooted. Fortunately, no loss of human life occurred. Wind speed was estimated to be between 45 and 50 m s^{-1} (F1 in the Fujita scale; Fujita, 1989) but probably attained the F2 level during some periods (Gayá, personal communication).

3.2. Remote sensing observations

(a) Satellite imagery

The Meteosat image on 1200 UTC (Figure 10(*a*)) shows a large convective system over the south of France which developed there during the morning. Over Spain, an undulating front associated with a low located over the north-west of France, with a secondary centre over Spain, moved rapidly towards the east. Over Catalonia no clouds appear in this image.

Convection then developed very quickly over Catalonia in a line parallel to the coast over the mountain range. At 1430 UTC three cells can be identified, two over south Catalonia and the third to the south-west of Catalonia. At 1500 UTC (Figure 10(*b*)) the two cells located over Catalonia merged close to the point where the tornado developed. Cloud tops at that moment attained values as low as –60 °C in an explosive development following the merging. Convection continued over Catalonia during the evening and at 1800 UTC (Figure 10(*c*)) big convective cells remained over the area and finally merged with the front.

Although the area of the tops with temperature less than –60 °C is small, the explosive development of convection after merging of two cells has been observed to be a favourable condition for the formation of landspouts (Bluestein, 1985); these are weak tornadoes which form in the vicinity of a rapidly developing cumulunimbus.

A corresponding NOAA image at 1649 UTC illustrates the spatial structure of temperature at the top of the thunderstorms (Figure 11). The clearest structure is associated with the southernmost cell, which seems not to have participated in the tornado formation. The V-shaped signature (McCann, 1981) is very clear, with a warm spot behind the overshooting tops. This structure matches, in size and form, previous observations (Heymsfield & Blackmer, 1988). The V-shape has been observed in many supercells and identified as a precursor of severe weather (McCann, 1981; Heymsfield & Blackmer, 1988). Curiously, this clear signature appeared two hours after the development of the tornado but produced heavy rain and floods in the southern coastal region of Catalonia.

(b) Radar imagery

At 1420 UTC the echotops image (Figure 12(*a*)) shows three important cells. Two of them, with tops at 11 km and Plan Position Indicator (PPI) displaying 50 dBz at some points (not shown), are over Catalonia. The other is to the south-west, just at the limit of the region. At 1450 UTC, radar echotops (Figure 12(*b*)) show that the two cells over Catalonia interacted and increased the area where tops reached 11 km. The third cell increased its size as well as the area where tops attained 11 km. Later at 1520 UTC (Figure 12(*c*)), the cells over central Catalonia decreased in size and at 1550 UTC (Figure 12(*d*)) convection is definitively weaker. Meanwhile the cell to the south-west of Catalonia increased its size and started a slow displacement towards the east. During that interval, no hook shapes (indicative of a supercell with a mesocyclone according to, for example, Weisman & Klemp, 1986 and Lemon, 1980) can be identified on PPI images. However, tornadoes from non-supercell thunderstorms have been observed (Wakimoto & Wilson, 1989). Unfortunately, no *Z*max, cross-sections and Doppler information are available for this case.

(c) Cloud-toground lightning data

At the time of the tornado formation, the CG strokes were concentrated in two areas indicated as TOR A and TOR B in Figure 8. There was a dominance of CG(–) against CG(+). Figure 13 shows the total number of strokes in TOR A and TOR B at the time of the tornado formation. The most important feature is the rapid increase of the number of strokes just prior to that time. This increase can be considered as an indicator of a rapid development of the convective clouds. Curiously the tornado developed between the two active cells (see Figure 8). A similar fact has been observed previously (Wakimoto & Wilson, 1989).

3.3. Summary

Although Meteosat and radar imagery showed a fast and intense convective development over the coastal zone of Catalonia, in particular over the mountain range, no clear signatures of the severity of the convection can be identified. At the time of the tornado development only the merging of two convective cells is significant, but no supercell signatures can be identified in the available information. When a V-shape appeared on a NOAA image, indicating the possibility of severe weather, the tornado had disappeared half an hour earlier. The overshooting tops were located south of the location where the tornado developed. The convective cells remained practically stationary for several hours. No weather stations are located close to the area where the tornado developed, and therefore the meteorological surface information is not very useful for monitoring the convective system. This is evidence for the difficulty in monitoring and nowcasting severe weather events, particularly when convective systems are small and slow moving.

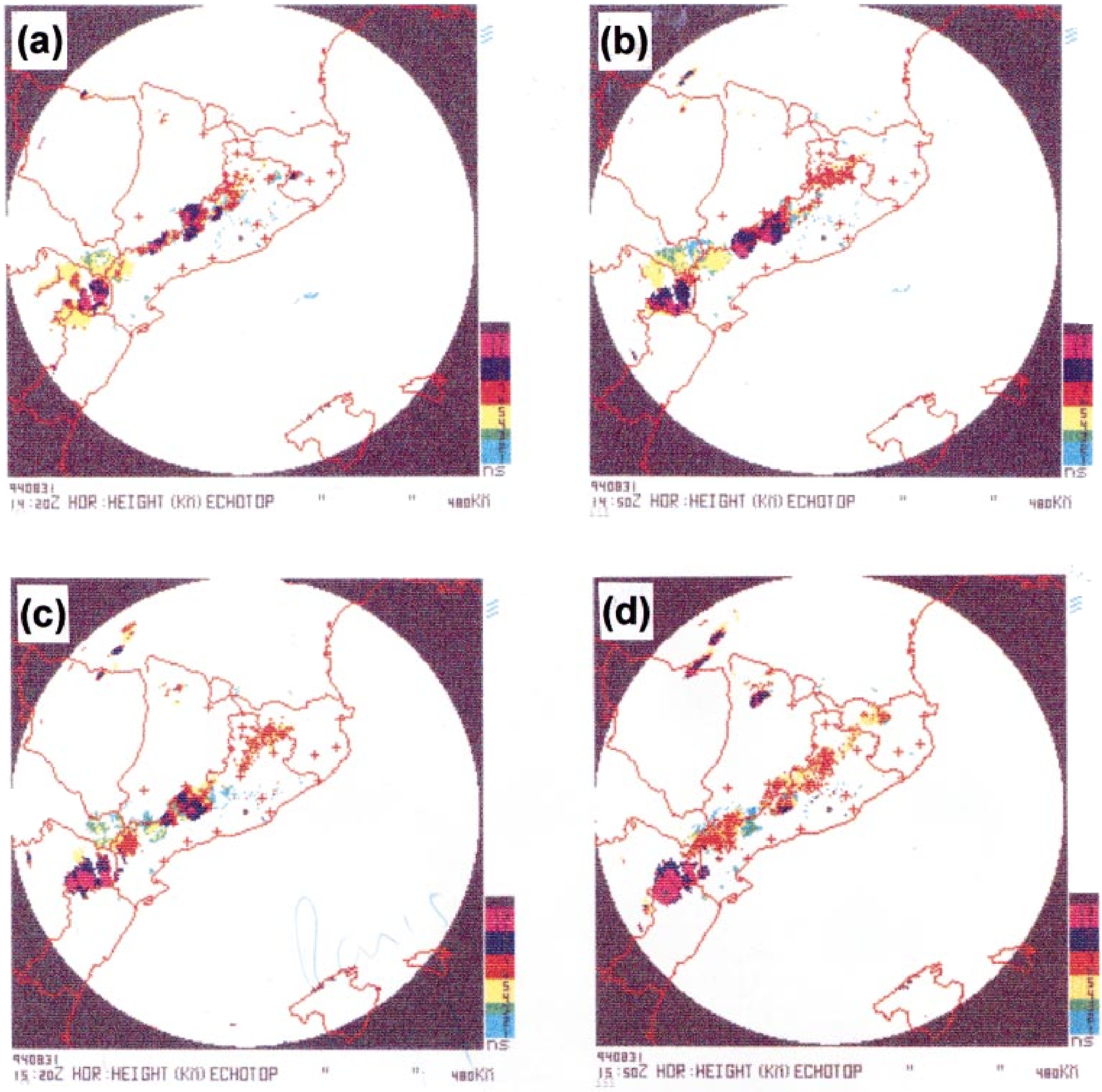

Figure 12. *Echotop radar (λ=10 cm) on 31 August 1994 at (a) 1420 UTC, (b) 1450 UTC, (c) 1520 UTC and (d) 1550 UTC.*

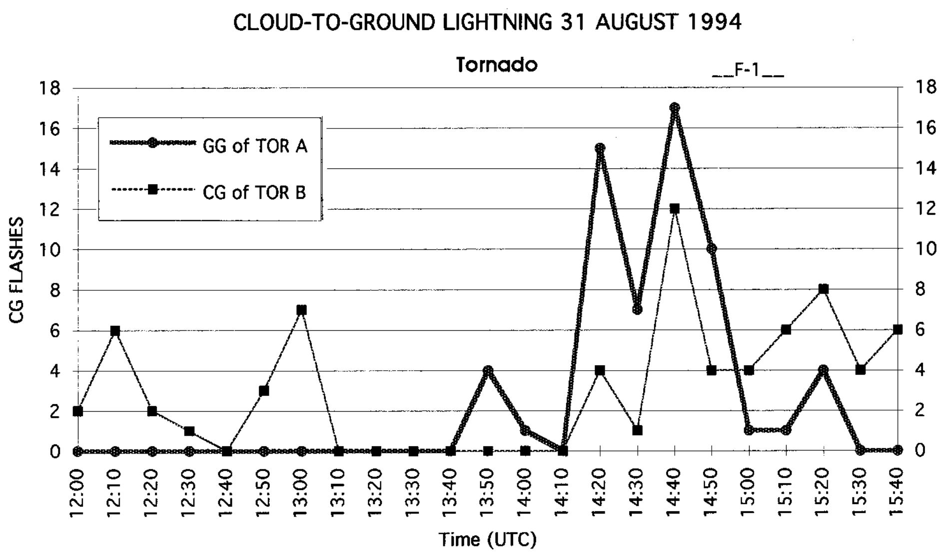

Figure 13. *Temporal distribution of strokes in areas TOR A and TOR B. In TOR A, CG(–) = 60 and CG(+) = 0. In TOR B, CG(–) = 67 and CG(+) = 3.*

The observational study of this second case also shows the importance of an accurate diagnosis to identify mechanisms able to support severe convection.

4. Comments and conclusions

An observational study of two cases of severe weather in Catalonia has been presented. The first one can be identified as a *squall line*. The radar information shows clearly bow echo and LEWP configurations. The information provided by automatic weather stations and the remote sensing systems gives a quite good guidance for monitoring the event, identifying the phenomena and providing reasonable nowcasts.

The second case represents a challenge for forecasters. Although Meteosat, flashes and radar provided good information on the fast development and growth of the convective cells, no evidence of the severity can be easily identified. The merging of two cells was the only signature. When significant satellite patterns (V-shape) appeared, they corresponded to a cell that seemed not to have participated in the tornado formation, although this cell produced heavy rain later. The very slow movement of the convective cells increases the difficulty of monitoring the event.

This study also shows the necessity of attaining a good diagnosis of the meteorological situation, both at synoptic scale and mesoscale, in order to identify mechanisms that are able to develop and sustain severe convection. In addition, it also shows how difficult it can be to produce an accurate nowcast. Numerical predictions only can provide the first indication to the forecasters but the real warning has to be attained through accurate diagnosis.

Acknowledgements

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References

Barry, R. G. & Chorley, R. J. (1992). *Atmosphere, Weather and Climate*. Routledge, 392 pp.

Bluestein, H. B. (1985). The formation of a 'landspouts' in a 'broken line' squall line in Oklahoma. In *Proceedings of 14th Conf. On Severe Local Storms, Indianapolis*. Am. Meteorol. Soc., 267–270.

Branick, L. & Doswell III, C. A. (1992). An observation of the relationship between supercell structure and lightning ground-strike polarity. *Wea. Forecasting*, **7:** 143–149.

Browning, K. A. (1986). Conceptual models of precipitation systems. *Wea. Forecasting,* **1:** 23–41.

Font, I. (1983). *Climatologia de España y Portugal*. Instituto Nacional de Meteorología, Apartado 285, 28071 Madrid, 296 pp.

Fujita, T. T. (1989). Tornadoes and downbursts in the context of generalized planetary scales. *J. Atmos. Sci.*, **38:** 1511–1534.

Gayá, M. & Soliño, A. (1993). Tornadoes and downbursts in Menorca (in Catalan). *Rev. de Menorca*, **I:** 5–18.

Heymsfield, G. M. & Blackmer Jr., R. H. (1988). Satellite-observed characteristics of midwest severe thunderstorms anvils. *Mon. Wea. Rev.*, **114:** 2200–2223.

Johns, R. H. (1993). Meteorological conditions associated with bow echo development in convective storms. *Wea. Forecasting*, **8:** 294–299.

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

Lemon, L. R. (1980). *Severe thunderstorms radar identification thecniques and warning criteria*. NOAA Thechnical Memorandum NWS NSSFC-3. 60 pp.

Llasat, M. C. (1987). *Inundaciones en Cataluña. génesis evolución y fenómenos coadyuvantes*. PhD Thesis, University of Barcelona Press. 250 pp.

Maddox, R. A. (1980). Mesoscale convective complexes. *Bull. Am. Meteorol. Soc.*, **61:** 1374–1387.

Martín, F., de Esteban, L. & Riosalido, R. (1995). *El tornado de Siguenza*. Nota Técnica nº 25. Instituto Nacional de Meteorología, Apartado 285, 28071 Madrid. 42 pp.

McCann, D. W. (1981). *The Enhanced-V, a satellite observable severe storm signature*. NOAA Thecnical Memorandum NWS NSSFC-4. 31 pp.

Miró-Granada, J. (1969). Una granizada excepcional en Mallorca. *Rev. de la Soc Hist. Natural de Baleares*, **XV:** 20–56.

Ramis C. & Jansà, A. (1983). Condiciones meteorológicas simultáneas a la aparición de oscilaciones del nivel del mar de amplitud extraordinaria en el Mediterráneo Occidental. *Rev. de Geofísica,* **39:** 35–42.

Ramis, C., Llasat, M. C., Genovés, A. & Jansà, A. (1994). The October-1987 floods in Catalonia: synoptic and mesoscale mechanism. *Meteorol. Appl.*, **1:** 337–350.

Riosalido, R. (1994). *SCM Campaña previmet 93*. Nota técnica Nº16. Instituto Nacional de Meteorología, Apartado 285, 28071 Madrid.

ST (1992). Red de detección de rayos del INM. *La Meteorol. Mundo Iberoamer*. nº10, 23–27.

Wallace, J. M. & Hobbs, P. V. (1977). *Atmospheric science. An introductory survey*. Academic Press, 467 pp.

Wakimoto, R. M. & Wilson, J. M. (1989). Non-supercell tornadoes. *Mon. Wea. Rev.*, **117:** 1113–1140.

Weisman, M. L. & Klemp, J. B. (1986). Characteristics of isolated convective storms. In *Mesoscale meteorology and forecasting*, P. S. Ray, ed., Am. Meteorol. Soc., 331–358.