Doppler radar observations of the 7 September 2005 tornadic thunderstorm near Barcelona, Spain

Joan Bech¹, Tomeu Rigo¹, Nicolau Pineda¹, Ramon Pascual¹, José Manuel López², Joan Arús², Miquel Gayà³

¹ Servei Meteorològic de Catalunya, Barcelona (Spain).
² Instituto Nacional de Meteorología, CMT Catalunya, Barcelona (Spain).
³ Instituto Nacional de Meteorología, CMT Balears, Palma de Mallorca (Spain).

1 Introduction

During the afternoon of 7 September 2005, at least five tornadoes occurred in the SW Barcelona metropolitan area and no less than 10 funnel clouds could be seen. The next morning, another tornado (17 km NE of Barcelona city) and other waterspouts were observed. Though earlier reports pointed less tornadoes (INM, 2005) others indicated a higher number (Massagué, 2005). In any case this was the larger outbreak ever recorded in Catalonia (NE Spain), one of the most tornado-prone regions in Spain (Gayà, 2005). In spite of the extensive damage, fortunately there were no fatalities.

Most of all these phenomena started over the sea and moved inland from the south-eastern sector. Because a great part of the tornado tracks was over urban or periurban areas, the surveying task was started the day after the tornadoes occurred. Evident effects were observed in the towns of Castelldefels (Fig. 1a), Gavà and El Prat de Llobregat where the Barcelona international airport is located (Fig. 1b). Moreover, some visual observations indicated the presence of rotational cloud structures (Fig. 1c).

Most tornadoes started as waterspouts and their track finished close to the shoreline probably due to the higher friction found inland. One tornado had associated a strong down-flow as indicated by divergent debris found over land when surveying. The stronger and larger tornado crossed the runways of the Barcelona airport. The tornado started as waterspout and it was assessed onshore as F1 (Fujita, 1981). The vortex increased its force when it was over the platforms and some hangars were destroyed or seriously damaged. Two aircrafts were moved or partially lifted when the passengers were boarding. The tornado track reached a length of 7.4 km. In spite of these flashy pictures, the survey analysis pointed out that was a F2 tornado. The rest of tornadoes were estimated as F0-F1.

Fig. 1. a) The first Castelldefels tornado (ca. 1700 UTC) damaging the railway power lines. b) View from the Barcelona airport runways (1751 UTC). c) Cloud structures with rotational aspect (1720 UTC).
2 Synoptic and mesoscale setting

The 12 UTC synoptic analysis from ECMWF 0.5º model indicates that 5 hours before the outbreak, a deep cold low (–18 ºC at 500 hPa) was centered over the northeastern Iberian Peninsula. A northerly jet streak (300 hPa wind speeds greater than 80 kt) was located over the western half of the Iberian Peninsula (Fig. 2). During the next 12 hours, the low moved southeastward and the jet streak pointed with a SE-NW orientation. The left part of the jet exit region probably produced, over central Catalonia, upper-level divergence that induced an area of upward vertical motion.

The synoptic low-level pattern (12 UTC) showed a thermal boundary SW-NE oriented over the Western Mediterranean, with the warmer and moister airmass to its SE side, establishing a weak warm advection below 850 hPa over Catalonia.

Fig. 2. 7 September 2005 12 UTC ECMWF analysis at 300 hPa (left) and 925 hPa (right) showing geopotential height (thick line), temperature (dashed line) and synoptic observations.

According to Barcelona radiosonde data, the potential for convective activity diminished notably between 00 UTC and 12 UTC. The main indices showed then moderate values: K= 30 ºC, TT= 45 ºC and LI= -1 ºC. However they increased in the next 12 hours. Surface-based CAPE (with virtual temperature correction) evolved from 554 J/kg (12 UTC 7th) to 669 J/kg (00 UTC 8th). On the other hand, high-level winds (250 hPa) increased with time from 12 UTC 7th (35 kt SW) to 00 UTC 8th (50 kt SE) and the easterly low-level wind also intensified and a stronger southeast low level jet (40 kt) appeared at 850 hPa (Fig. 3). The appearance of the two jets probably increased, between 12 UTC and 17 UTC (first tornadoes observed), the vertical wind shear value and the helicity, already very high at 12 UTC (217 m2/s2).

3 Observation of storm features

In this section Meteosat Second Generation (MSG) and radar imagery and lightning observations from SMC database have been used to describe the smaller scales features. Characteristics of the SMC C-band Doppler radar network and the lightning detection system can be found, respectively, in Bech et al. (2004) and Montanyà et al. (2006).

3.1 Remote sensing observations

Convective cells associated to observed waterspouts and tornadoes developed and moved along the convergence line. A cumulus congestus line was observable in MSG-1 high resolution visible channel at 1600 UTC (Fig. 4a). At 1640 UTC some small convective cells appeared along the NW-SE oriented line. This spatial distribution of convective cells, developing over the sea (Fig. 4b), and moving NW along the line, persisted until 1940 UTC. The convective line reached a maximum length of 200 km but the highest radar reflectivity values were located in a shorter part (60 km long) located at the western edge of the line. Vertical cross sections along the line showed small intense convective cells over the sea (40-50 dBZ at 4 km) but with low echotops (12 dBZ below 6 km). This vertical reflectivity profile shape is frequently observed in Catalonia maritime areas (Pascual, 2001).

Fig. 3. SMC Barcelona radiosonde observations.

The mesoscale analysis based on outputs from INM HIRLAM 0.05º model showed, between 12 and 18 UTC, a low pressure center below 850 hPa located in front of the Southern Catalonia coast. This configuration established a low-level E/NE flow and a S/SE flow aloft. In Northern Catalonia coast low-level flow intensified with time. Model outputs again indicated a warm advection as also was suggested by the radar S-shaped zero-isodope radial wind.

The wind field analysis indicated, below 850 hPa, an E-W oriented convergence line between 12 and 18 UTC, showing a slow northward displacement. North of the convergence line, the flow was E/NE while at the south side ranged from SE to SW. As a consequence, there was horizontal directional shear across the convergence line but no evident mesoscale temperature gradient was present.

Fig. 4. MSG VIS 1600 UTC image (left). Radar reflectivity factor (dBZ) 1 km CAPPI 1738 UTC composite of the SMC radar network (right); the rectangle indicates the convergence area.
From 1610 to 2020 UTC, in the rectangle area marked in Fig. 4b, 504 intra-cloud (IC) and 101 cloud-to-ground (CG) flashes were observed. In the tornadic period (1700 to 1800 UTC), there were 92 IC and 17 CG flashes. From the 101 CG flashes, only 4 had positive polarity, and no positive CG flashes were registered from 1700 TU to 1800 TU. The overall average IC/CG ratio was 5.0 which corresponds— in terms of severity—to a normal thunderstorm for this region; the 2005 average IC/CG ratio in Catalonia was 5.1 (Pineda, 2006). Surface observations, 12 UTC Barcelona radiosonde data and Doppler wind field show that an easterly low-level jet (LLJ) was present just north of the convergence line. Maximum velocity (≈ 110 km/h) was located between 950 m and 1500 m and surface wind gusts reached 100 km/h (17 UTC) in some coastal range peaks (500 m ASL). LLJ was observed between 1604 UTC radar volume scan and 1708 UTC. Fig. 5 shows the intensification of the wind maximum as observed by the Vallirana (PBE) radar. It is important to notice that maximum vertical velocity shear was located over or just north horizontal directional shear line.

Although at 1700 UTC the larger dimension of the convective structure was not great enough to be considered a mesoscale convective system (MCS), shape, internal dynamics and propagation suggest classifying it as a back building squall line (Bluestein and Jain, 1985). Furthermore, its very slow movement (≈ 50 km/3 h), perhaps associated to the Llobregat river valley orientation (NW-SE), implied that some new convective cells (and new vortices) passed over the same area in the so called convective train effect (Doswell et al., 1996). The squall line was well defined between 1650 UTC and 1840 UTC and during this time period some structures resembling mini bow echoes seem to develop along it. At 1700 UTC, waterspouts were observed in front of Llobregat delta river, associated to new convective cells over the convergence line. Between 1710 UTC and 1810 UTC the convective line passed over the Barcelona airport, and surface automated observations showed a wind shift direction (NE changing to SE) and a velocity decrease.

3.2 Other radar smaller scale features
As mentioned above, the radar observed convective structures associated to the waterspouts and tornadoes were relatively low topped and of modest horizontal extension. Classical super-cell tornadic storms, characterized by deep convection and the presence of a persistent and intense mid-level mesocyclone (ME)—typically 4 to 10 km wide and visible as a characteristic couplet in radar radial wind PPIs—(Doswell and Burgess, 1993) are remarkably different. Non-supercell tornadoes (Wakimoto and Wilson, 1989, hereafter WW) lack a ME and they typically develop misocyclonic rotation along converge lines at low levels. On the other hand, in a different variety of smaller, low-topped supercells known as mini-supercells (McCaul, 1991; Kennedy et al., 1993; Suzuki et al., 2000), the ME present diameters smaller than 4 km—in fact a misocyclone (MI), in terms of Fujita (1981). From the radar point of view, a number of reasons—including range effects or beam blockage due to complex topography—may difficult ME and, particularly, MI identification (Chapman et al., 1998; Conejo and Elizaga, 2004). However, in this case the convective structure was relatively near to the PBE radar (located at 620 m ASL); the Barcelona airport is at 20.5 km. Moreover, though there are important blockages to the N (Bech et al., 2003), coverage is good to the S. A velocity couplet was identified in 4 different PPIS of the 1700 UTC PBE volume scan (Fig 6). The couplet was embedded in a high vertical shear environment and was located very near the radar (8 km). It extended from 1.5 to 3.0 km and was approximately 2.5 km wide. If associated to a rotating structure, it would be a misoanticyclone (MIA). It was observed in the limit of a precipitating structure coming from the SE, the same direction where the tornado shown in Fig. 1.a was heading when dissipating. Another remarkable feature, related to the vertical wind shear, is the overhang structure shown in the relatively low-topped cell shown in Fig.6 (right).

![Fig. 5. 4.0º PPI radial velocity field (m/s) observed by the PBE radar at 1608 UTC (left) and 1644 UTC (right). The square length is 32 km.](image)

![Fig. 6. Left: PBE radar 6º PPI (17:03 UTC) velocity couplet in the radial wind field (bottom) and the corresponding cross section (top) between the segment AB. Rings are at 5 km intervals and maximum height is 5 km. Right: PBE radar 16º PPI (18:11 UTC) reflectivity factor (bottom) and the corresponding cross section (top) between the segment CD. Rings are at 10 km intervals and maximum height is 10 km. Colour scales as in Fig. 4 and 5.](image)

Fig. 7 shows the same cell later (1834 UTC). The reflectivity structure exhibits a small core with a sharp gradient which resembles the classical “hook echo” shape associated to ME. The corresponding radial velocity field indicates intense azimuthal shear and might suggest traces of (cyclonic) rotation, though is not as clear as in Fig. 6. This cell was coming from the airport and could be associated to the thunderstorm that spawned the F2 tornado.
4 Summary and discussion

An observational description and preliminary diagnostic of the tornadic event of 7 September 2005 in Barcelona is presented. A possible origin of the general mesoscale setting is the interaction of the synoptic flow with the Balearic Islands, as suggested by mesoscale lee side vortices present in the wind analysis. In fact, in other strong convective events with a similar synoptic situation, convergence zones with the same characteristics have been identified over the same area (Rigo and Llasat, 2005). In this case, the convergence line was forecasted by the models a few kilometers northward than suggested by satellite and radar imagery.

Fig. 7. PBE radar 8º PPI (18:34 UTC) reflectivity factor (left) and radial wind (right). Rings are at 10 km intervals. Colour scales as in Fig. 4 and 5.

Homar et al. (2001) identified, near to the Balearic Islands, a northward-moving mesoscale convergence line where waterspouts and tornadoes appeared. Again, no thermal boundary was diagnosed. Some authors as WW or Brady and Szoke (1989, hereafter BS) have shown that convergence lines with horizontal wind shear across it are favorable zones to the development of mesoscale circulations at lower levels. If these circulations collocate with the strong updrafts supporting cumulus and cumulonimbus clouds, vorticity can propagate upward and the circulation becomes a tornado or a waterspout. The presence of a LLJ could contribute to generate cyclonic shear at south side of convergence line and development of Helmholtz instabilities would be possible.

Photographic analysis of waterspouts and tornadoes showed two main characteristics: 1) Funnel clouds connected to cumulus/cumulonimbus bases observed in almost all the cases and 2) Vortices probably developed at the southern edge of the cumulus/cumulonimbus line. Southward of this line cloud development was impeded. Although the first feature disagrees with observations and tornadogenetic processes proposed by WW and BZ the second one suggests again that vortices developed over the shear/convergence line as WW and BZ proposed to explain non mesocyclonic (supercell) tornadoes. Moreover, radar observations showed a number of features that might suggest the mini-supercell character of some of the convective structures observed. A possible misocyclone could be associated either to downdrafts (Kessinger et al., 1988; Bluestein et al., 1997) or to a dissipating structure of a previous tornado (Brown and Knupp 1980; Monteverdi et al., 2001)

As in previous studies (Martin et al. 1997; Ramis et al. 1997; Homar et al. 2003) it should be remarked, from the operational point of view, that remote sensing observations used here –with the appropriate conceptual models– provide good guidance to help forecasters in the surveillance process but are of limited use to detect the precise occurrence and location of this type of events.

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