1. INTRODUCTION

Many authors have studied relationships between different lightning observations, radar reflectivity, cloud dynamics and precipitation. The present work intends to get a better understanding of the life cycle of summer thunderstorms studying such relationships.

The events examined occurred in Catalonia (NE of the Iberian Peninsula) in summer of 2004 using lightning observations and meteorological radar products of the Catalan Meteorological Service (Meteocat). The region of interest covers an approximate area of 32000 km². The lightning network is based in the Vaisala SAFIR 3000 system and is made up of three different detectors. On the other hand, radar observations were obtained from the weather radar network made up by three C-band Doppler radars.

Ten summer thunderstorm events were selected for the analysis. The study was focused in individual convective structures which were followed during their evolution. To perform the analysis, the data set was grouped in time intervals of six minutes, according to the weather radar data acquisition rate. For each interval, lightning information was integrated with radar products (reflectivity, echo tops) in order to study the rise, evolution and decay of the convective structures.

The tracking of the structures has been done using the following procedure: first of all, selection of areas where radar features were to be verified. Secondly, characterisation of the structures was done considering mean and maximum radar product values and also lightning information.

Complementary, quantitative precipitation forecasts (QPF) provided by a mesoscale Numerical Weather Prediction (NWP) system have also been considered. In particular, the impact of assimilating radar and satellite information upon the 6-h QPF is discussed and illustrated with an example.

The final aim of the study is to evaluate the relationship between different sources of remote sensing observations of convective structures available in real-time in order to enhance the performance of operational weather surveillance tasks.

2. DATA

In this section a description of the different type of data used is given, including details of the radar and lightning observations network (Fig. 1) and the NWP Mesoscale Atmospheric Simulation System (MASS). The data used in the present paper correspond to some events happened in summer of 2004 in Catalonia (Table 1). This season presents usually the higher electrical activity (Terradelles, 1999).

2.1 Radar products

Weather radar observations were collected with the Vallirana radar, which is located at 25 km W of Barcelona city. It is a Kavouras TDR-3070 C band Doppler radar, with 1.3 degrees beamwidth and a transmitter based in a Travelling Wave Tube providing 8 kW of peak power. The receiver and processor of the radar were updated in 2003 with a digital RVP-8 unit manufactured by Sigmet, Inc. The Vallirana radar was the first system of the Doppler radar.
network of the Catalan Meteorological Service (Bech et al., 2004). The radar products considered in this study were TOPS (maximum height of an echo with a given reflectivity threshold), radar reflectivity factor of the 1000 m altitude CAPPI, and radar cumulative precipitation estimated after applying several corrections (see Bech et al., 2005 for further details). Figure 1 shows the area covered by the Vallirana radar.

2.2 Lightning observations

Lightning information was collected by the METEOCAT lightning detection network (MLDN). The network is composed by three Vaisala SAFIR sensors, covering the region of Catalonia, in the NE of Spain, of approximately 32000 square kilometers. The SAFIR spatial accuracy for the whole region studied is around 3 kilometers (Fig. 1). The MLDN spatial accuracy for the inland region covered by the radar is between 1 and 2 km.

2.3 NWP model data

Numerical simulations were produced with the Mesoscale Atmospheric Simulation System (MASS), a hydrostatic atmospheric model based on a set of primitive equations. The original version of MASS used in this research was developed by Kaplan et al. (1982) and later evolved into the Goddard Mesoscale Atmospheric Simulation System (Manobianco et al., 1996). The version of MASS used in this research was developed by MESO, Inc., and includes a prognostic grid-scale moisture scheme, an enhanced surface energy budget, a modified Kuo cumulus parameterization scheme that includes convective scale downdrafts (Kuo et al., 1993), and a comprehensive long- and shortwave radiation scheme (Zack et al., 1991; MESO, Inc., 1995; Manobianco et al., 1996).

In this work three simulations of the MASS model were used: the first one over a large domain with 30 km horizontal grid spacing and 25 vertical sigma levels. Operationally, the SMC uses the US AVN model as the first-guess data source and forecast lateral boundary conditions. The second one is a nesting simulation with 12-km horizontal from the first, centered over Catalonia and the last one is a nested domain with 4-km horizontal grid spacing with 25 vertical sigma levels to evaluate the impact of the higher-resolution grid in simulating the observed mesoscale structure.

3. METHODOLOGY

3.1 Radar and Lightning

Lightning data was grouped in six-minute intervals, the frequency of the radar data sampling. Total lightning data was divided into intra-cloud (IC) and cloud-to-ground (CG) flashes. The lightning network configuration considers an IC sample duration of 100 µs with an associated radius of 7 km. For the CG flashes, the multiplicity delay is 0.5 seconds, while the multiplicity radius is also 7 km.

The comparison of lightning and radar data has been done as follows. Firstly, a temporal evolution of the event has allowed studying the life cycle of the convection, comparing maximum values of rain rate, and maximum and mean radar Echotop, with IC and CG rates every 6 minutes. The aim of this part is a follow-on of former studies over the same area (Pineda et al., 2004). On the other hand, a preliminary spatial analysis has been performed, considering fields with characteristics showed in Table 2. The main goal of this study was to compare the areas more affected by the electrical activity with those where existed high values of precipitation or Echotop (greater vertical developments of convection).

The EHIMI system (an integrated hydrometeorological tool) has been used in order to generate rain rate fields from radar observations. This tool applies different correction algorithms (ground echoes mask and beam blockage corrections) in order to improve the quality of the resulting chart. In spite of the fact that these corrections improve the quality of the imagery, some factors (e.g. anomalous propagation, hail,...) can produce an overestimation of the rain rate values. To calculate rainfall rate R from radar reflectivity
factor $Z$, the Z-R relation used is $Z = 200 R^{1.6}$ (Marshall and Palmer, 1948). Complementary, in the METEOCAT some research works are currently performed in order to improve the nowcasting of convective cells using radar information. It is expected to combine the results of these studies with lightning data for obtaining an improved short-range forecasting of individual thunderstorms (Rigo et al., 2004; Rigo and Llasat, 2004).

3.2 Satellite and radar assimilation

The Meteosat infrared (IR) satellite imagery is used to determine the amount of cloud cover in each grid box of the model. The scheme incorporated in MASS is based in the work of Hamill et al. (1992). A cloud is detected if

$$
\Delta T_{\text{obs}} = T_{\text{clr}} - T_{\text{obs}} \geq T_{\text{thresh}},
$$

where $T_{\text{clr}}$ estimates the brightness temperature that the satellite would measure under clear skies, $T_{\text{obs}}$ is the IR brightness temperature the satellite observes, and $T_{\text{thresh}}$ is an uncertainty in the estimate of $T_{\text{clr}}$ because $T_{\text{obs}}$ is likely to be large when clouds are present in a relatively dry, unstable atmosphere (MESO, Inc. 1995). With use of the IR data, the height of the topmost cloud layer is calculated by matching cloud-top brightness temperatures with atmospheric temperatures from the rawinsonde analysis. The cloud base is estimated in one of two ways. If surface data are available and the cloud coverage is 80%, MASS assumes the cloud base coincides with the highest broken or overcast cloud base at the nearest surface station. If surface data are unavailable or cloud coverage is <80%, MASS assumes the cloud base to be 500 m below cloud top (MESO, Inc. 1995). The satellite imagery also dries cloud-free areas. This is a critical procedure that significantly affected the results of moisture enhancement. The maximum relative humidity is set to 75% above cloud tops. At any point where the satellite-determined cloud fraction is <100% but >5%, the relative humidity at any given level cannot exceed the value calculated from

$$
RHI = (3.0 + C^{0.33}) / 4.0
$$

where $C$ is the areal coverage of cloudiness and relative humidity equals 1 at saturation (MESO, Inc. 1995). At any point having a satellite-determined cloud fraction of <5%, the relative humidity at any given level cannot exceed the mean plus one standard deviation of the relative humidity from the clear skies category in the statistical database (MESO, Inc. 1995). The final part of the satellite data enhancement is a scheme after Adler and Negri (1988) to locate convective towers. This scheme in MASS finds all of the IR temperature minima and then calculates a slope parameter for each temperature minima. Each convective tower is assumed to represent a 64 km$^2$ saturated region.

After all convective towers are found, a new adjustment of moisture is applied at each grid cells.

Gridded analyses of areal coverage (AC) of precipitation and radar video integrator processor (VIP) levels (National Oceanic and Atmospheric Administration, 1982) provide estimates of rainfall rates for MASS. The VIP levels are assigned a value at the nearest Manually Digitised Radar data (MDR) grid point, having a 1-km horizontal grid spacing. To estimate cloud tops when infrared satellite imagery data are unavailable, MASS will use the VIP data and the relationship where

$$
\sigma_{\text{top}} = 0.7 \cdot 0.11(VIP)^{0.91}
$$

and $\sigma_{\text{top}}$ is the top of the model domain or 100 hPa (MESO, Inc. 1995).

We use the AC provided by de radar data for moistening the atmosphere with an idealised profile. For AC of less than 0.45 the RH is estimated by an empirical AC-RH relationship:

$$
RH = RH + (1 - RH) \left( \frac{1.0}{0.45 \cdot AC} \right)^p
$$

where $p=0.5$ in the top 20% and bottom 15% of the cloud and 2.0 elsewhere.
4. RESULTS AND CONCLUSIONS

4.1 Comparison of radar and lightning observations

The study of the life cycle (Fig. 2) of the thunderstorms has shown some patterns associated to the development of the convection. In the first stages, when the Echotops do not reach the isotherm of -20ºC, there is no lightning activity. Once the Echotop is above the -20ºC, the first IC appears, and a period of continuous IC activity begins. As the thunderstorm grows, the Echotop reaches the -40ºC isotherm, and after that, a rapid increase in the IC rate is produced. These increases, termed lightning “jumps” (Williams et al., 1999) occur typically before severe weather features are observed at the ground level.

A standard sequence comprising the following stages has been found in all the analysed episodes:

1. Echotops reach the -20ºC isotherm (and stays above from that moment)
2. Continuous intracloud activity begins (the range is between 6 and 48 minutes).
3. Echotops reach the -40ºC isotherm level (and stay above) 50 minutes after the -20ºC crossing (range between 6 and 84 min)
4. IC “jump”: the rapid increase of the IC rate comes more or less 1 hour after the Echotops reached the -40ºC isotherm.

According to Krehbiel (1986) a thunderstorm does not become strongly electrified until its radar echo extends above a certain altitude threshold and is growing vertically. This threshold altitude is approximately 8 km, corresponding in summer months to an air temperature of -20ºC. In the present study, a mean altitude for the -20ºC isotherm of almost 7 km (within a range from 6700 to 7500m) has been found using the rawindsonde of Barcelona. For all the studied episodes, it has been observed that with a maximum Echotop under this altitude, there is no IC activity. As the convection develops, and the Echotops exceed the -20ºC isotherm, the IC activity begins. However, the IC jump only occurs when the Echotops reached the -40ºC level, which indicates that the positive (upper) charge has well-developed (-30 to -60 ºC). This is illustrated in figure 3 which shows a cross-section of the radar reflectivity observation at 13:30 UTC time of 17th August 2004 and the isotherms observed in the rawindsonde of 12:00 UTC.

According to Williams et al. (1999), the lightning jump varies in magnitude from 20 to 100 flashes per minute (fpm) /minute. In the presented case, values found were even greater, reaching almost 200 flashes per minute/minute. Table 3 summarizes the different stages of the formation of the thunderstorms described before.

Table 3 also includes the IC/CG ratio, which is an indicator of severity. Reference values for this ratio are 1 for weak intensities, 10 for moderate and 100 for severe storms. However, these thresholds ratios correspond to tropical storms, meanwhile for mid-latitudes severe weather associated to thunderstorms has been observed with a ratio of 10.

Comparing the IC/CG ratio to the IC jump, which is also a thunderstorm severity index, it can be seen (fig 4) that there is a correspondence between both indexes, a higher IC jump (fpm/min) usually correspond to a higher IC/CG ratio. Williams et al. (1999) defined an IC “jump” threshold of 10 fpm/min for thunderstorms with severe weather. However, in the present study such threshold has been always exceeded. Then, it seems that a more elevated threshold will be suitable in the analysed area. According to the hail registry (ground observations) associated to these events, if a threshold of 100 fpm/min is defined in the IC jump indicator, and it is combined with a IC/CG above 5, it results a good indicator of thunderstorms with hail.

The tracking of the life cycle of individual thunderstorms is not possible considering the presented methodology, especially for those events with isolated and non-organised convection, with an elevated number of thunderstorms simultaneous at different stages.
This is the most common feature in practically all the analysed events in the present study, unlike the previous year (Pineda et al., 2004) where many well-organised convective structures were identified. The spatial analysis shows a brief comparison between daily maps of cumulated precipitation, the maximum and mean Echotop, and the distribution of IC and CG, considering the chart introduced in the previous section. Even it is possible than more than one thunderstorm affected one point of the grid, the comparison is quite representative of each event. This fact affected especially the Echotop maximum, because this chart presents an instantaneous moment. The purpose of this analysis was to identify the maximum areas for all magnitudes, as well as their spatial coincidence.

The main results are associated with the identification of thresholds for the radar magnitudes associated with an elevated electrical activity:

- For the ICs, the 24-hour cumulated rainfall exceeded 10 mm, the mean Echotop was over 4 km, and the maximum Echotop was higher than 9 km

- In the case of the CGs, the thresholds were: 20 mm (precipitation, figure 5), 6 km (mean Echotop), and 10 km (maximum Echotop)

4.2 NWP assimilation

The cumulative rain between 18 and 24 UTC for the 6th September of 2004 have been simulated, and it has been compared with the radar and satellite images, in order to verify the different model runs.

The satellite image (fig. 6) of the 7th September at 00 UTC allows to estimate the overcast and clear zones. In a first guess it is possible to identify cloudy zones with cool zones and clear zones with warm zones. The cold zones most important that can be observed were over the Mediterranean coast, associating these areas with the higher probability of convective rainfall identification. In the other hand, clouds with warm temperatures at top were observed inside Catalonia, expecting that the rain was less important than in the coast. The radar image (Fig. 7) represents the 6-hourly cumulative precipitation, between 18 and 24 UTC. The image practically covers the area of Catalonia and shows where the rain took place. The radar confirms the first estimation of the rain based in the satellite image: the most important affected area was the coastal zone, meanwhile in the interior of Catalonia the rain was weak or inexistent.

Four simulations have been done using the IAU technique with different assimilations:

1. Without radar, without satellite.
2. Without radar, with satellite.
3. With radar, without satellite.
4. With satellite, with radar.

The different precipitation forecasts (figures 8 a-d), show that when the satellite has been considered the impact over the forecasts is strong and rainfall is overestimated where low temperature cloud tops are found (Fig. 6). When only the radar is added the impact over the rain field forecasted is lower, producing the smoothing of the rainfall field, and making the forecast closer to reality. Using both data, radar and satellite, the combination of the two effects is appreciated: the satellite enhanced the precipitation in the cloudy areas with lower temperatures, while the radar smoothed the field adapting the forecasting to observations.

References


**Table1.** Summer thunderstorm events. Lightning information for the studied time periods.

<table>
<thead>
<tr>
<th>Event</th>
<th>Start</th>
<th>End</th>
<th>IC</th>
<th>CG</th>
<th>IC/CG</th>
</tr>
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<tbody>
<tr>
<td>E1</td>
<td>28/29-jul</td>
<td>12:00</td>
<td>23:48</td>
<td>17268</td>
<td>3014</td>
</tr>
<tr>
<td>E2</td>
<td>01-aug</td>
<td>06:00</td>
<td>23:48</td>
<td>6107</td>
<td>1496</td>
</tr>
<tr>
<td>E3</td>
<td>03/05-aug</td>
<td>19:00</td>
<td>07:00</td>
<td>127129</td>
<td>20166</td>
</tr>
<tr>
<td>E4</td>
<td>09-aug</td>
<td>10:00</td>
<td>23:18</td>
<td>20796</td>
<td>4651</td>
</tr>
<tr>
<td>E5</td>
<td>17-aug</td>
<td>07:00</td>
<td>22:00</td>
<td>44010</td>
<td>4564</td>
</tr>
<tr>
<td>E6</td>
<td>03-sep</td>
<td>00:00</td>
<td>15:00</td>
<td>40281</td>
<td>3094</td>
</tr>
<tr>
<td>E7</td>
<td>06/07-sep</td>
<td>12:00</td>
<td>05:54</td>
<td>70867</td>
<td>7885</td>
</tr>
<tr>
<td>E8</td>
<td>29-aug</td>
<td>00:00</td>
<td>23:54</td>
<td>37819</td>
<td>4847</td>
</tr>
<tr>
<td>E9</td>
<td>14-15/sep</td>
<td>00:00</td>
<td>12:00</td>
<td>161223</td>
<td>19107</td>
</tr>
<tr>
<td>E10</td>
<td>12-oct</td>
<td>03:00</td>
<td>23:54</td>
<td>12251</td>
<td>2771</td>
</tr>
</tbody>
</table>
Table 2. Features of the spatial comparison files of radar and lightning data.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gridsize</td>
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</tr>
<tr>
<td>X0</td>
<td>0.0088336° E</td>
</tr>
<tr>
<td>Y0</td>
<td>40.439396° N</td>
</tr>
<tr>
<td>Number of columns</td>
<td>32</td>
</tr>
<tr>
<td>Number of rows</td>
<td>24</td>
</tr>
</tbody>
</table>
Table 3. Time and isotherm heights of the different thunderstorm formation stages identified in the ten studied episodes. The IC jump value is in intracloud flashes/min. TT column is the total time elapsed between the -20ºC isotherm threshold and the IC jump. IC/CG is a severity ratio. The last column is about hail ground observations.

<table>
<thead>
<tr>
<th>Above Altitude IC Cont.</th>
<th>Above Altitude IC Jump</th>
<th>TT</th>
<th>IC/CG</th>
<th>Hail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Below -20ºC</td>
<td>-20ºC activity</td>
<td>-40ºC time</td>
<td>value</td>
<td></td>
</tr>
<tr>
<td>E1 23:30 7224</td>
<td>23:36 9986</td>
<td>00:06 119</td>
<td>00:36 5.4</td>
<td>Y</td>
</tr>
<tr>
<td>E2 12:24 7308</td>
<td>12:30 9739</td>
<td>15:18 178</td>
<td>01:54 3.5</td>
<td>N</td>
</tr>
<tr>
<td>E3.1 20:42 7153</td>
<td>22:36 9830</td>
<td>23:12 141</td>
<td>02:30 4.6</td>
<td>N</td>
</tr>
<tr>
<td>E3.2 07:54 7153</td>
<td>09:00 9830</td>
<td>11:30 128</td>
<td>03:30 7.7</td>
<td>Y</td>
</tr>
<tr>
<td>E3.3 22:12 6740</td>
<td>23:36 9221</td>
<td>00:18 113</td>
<td>02:06 7.1</td>
<td>Y</td>
</tr>
<tr>
<td>E4 12:24 7546</td>
<td>13:06 10176</td>
<td>14:30 112</td>
<td>02:06 4.3</td>
<td>N</td>
</tr>
<tr>
<td>E5 09:54 7006</td>
<td>10:42 9627</td>
<td>12:18 107</td>
<td>02:24 8.5</td>
<td>Y</td>
</tr>
<tr>
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<td>03:42 192</td>
<td>01:36 17.5</td>
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<td>E7 18:06 7008</td>
<td>18:30 9653</td>
<td>20:42 51</td>
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<tr>
<td>E8 06:54 7008</td>
<td>07:00 9653</td>
<td>09:24 169</td>
<td>02:30 11.4</td>
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</tr>
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<td>E9.1 23:54 6797</td>
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<td>01:12 132</td>
<td>01:16 8.0</td>
<td>N</td>
</tr>
<tr>
<td>E9.2 21:24 6797</td>
<td>21:00 9603</td>
<td>22:00 174</td>
<td>01:00 17.8</td>
<td>Y</td>
</tr>
<tr>
<td>E10 12:12 6025</td>
<td>12:24 8657</td>
<td>13:18 47</td>
<td>01:06 4.5</td>
<td>Y</td>
</tr>
<tr>
<td>E11 17:48 7051</td>
<td>18:00 9644</td>
<td>19:54 69</td>
<td>02:06 3.2</td>
<td>N</td>
</tr>
</tbody>
</table>
Figure 1. Coverage of the METEOCAT Weather Radar Network and the Lightning Detection Network. Lighter coloured area corresponds to the radar coverage. Blue diamonds correspond to the three radar locations, and red squares to the SAFIR lightning sensors. The three magenta vectors correspond to 1, 2 and 5 km location accuracy of the lightning detection network.
Figure 2. Thunderstorm lifecycle of the episode of 6/7 September 2004. In blue, the echotops max (km), in cyan, rainfall (mm), in red, intraclouds (in 6 minutes), in orange, cloud-to-ground flashes (in 6 min), and in green, isotherms -20°C(7008 m) and -40°C(9653 m) according to the Barcelona rawindsonde (Sept. 7th 00 UTC).

Figure 3. Cross section of radar reflectivity from the thunderstorm of 17th August 2004 one hour after the IC jump. Four isotherms are overlayed to the crosssection (from the rawindsonde of 17th August 12:00), and also the cloud charge distribution is overlayed.
Figure 4. Comparison of the IC/CG ratio to the IC jump (in red: hail observed at ground).

Figure 5. 24-hour cumulated precipitation (in mm) for 7th September 2004 obtained from the meteorological radar. Cloud-to-Ground flashes are indicated in yellow.
Figure 6. A portion of Meteosat-7 infrared satellite imagery (temperature) with 4-km resolution (used to enhanced MASS nest run for 00UTC 7th September 2004).

Figure 7. 6-hour cumulated precipitation (in mm) for the period 18 UTC to 24 UTC of 6th September 2004 obtained from the meteorological radar.
Figure 8. Mass Nested grid (12km) 6 h cumulative precipitation forecast (mm) from the control run (no moisture enhancement) for (a) 18-00 UTC 06 September 2004, (b) from the enhanced run (with satellite), (c) from the enhanced MDR (with radar) and (d) from the enhanced run (MDR, satellite, and surface data) for the same period.