The Munich Hailstorm of July 12, 1984 – Convective Development and Preliminary Hailstone Analysis

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Abstract:

A preliminary analysis of the Munich hailstorm of July 12, 1984 is presented in this study. Using IR satellite images and radar information the development of the storm is followed from its onset as a mountain induced thunderstorm to its decay as a part of a much larger mesoscale convective complex (MCC). A brief description of the synoptic situation, the hail damages and the hailstone characteristics is given.

Zusammenfassung. Das Münchener Hagelunwetter vom 12. Juli 1984 – Konvektive Entwicklung und vorläufige Hagelanalyse

In dieser Arbeit wird eine vorläufige Analyse des Münchener Hagelunwetters vom 12. Juli 1984 präsentiert. Anhand von IR Satellitenbildern und Radardaten wird die Entwicklung des Sturms von seinem Beginn als eine im Gebirge entstandene Gewitterzelle bis zu seinem Zerfall als Teil eines viel größeren, mesoskaligen Komplexes verfolgt. Die synoptische Situatuation, die durch den Hagel verursachten Schäden sowie Größe und Aufbau der Hagelkörner werden kurz beschrieben.

Résumé: La chute de grêle sur Munich du 12 juillet 1984 – Développement convectif et analyse préliminaire des grêlons.

On présente une analyse préliminaire de la chute de grêle sur Munich du 12 juillet 1984. Grace aux images infrarouges de satellites et aux informations recueillies par radar, l'évolution de l'orage est suivie depuis son début comme orage de montage induit par l'orographie, jusqu' à son déclin comme élément d'un complexe convectif beaucoup plus vaste de mésoéchelle. On donne une brève description de la situation synoptique, des dommages causés par la grêle et des caractéristiques des grêlons.

1 Introductory Remarks

This study presents a preliminary analysis of the convective development producing the Munich hail event of July 12, 1984. It is a documentation of the material available from standard meteorological observation techniques which is completed by some non operational data sets like motor glider observations and hailstone probes. We think, that it is very useful to analyse the available material, especially because it was not possible to predict such a convective event with conventional forecasting tools. Although the present material will undergo further examination like isentropic analysis or extended hailstone statistics by examinating various thin sections, some very interesting conclusions can already be presented.

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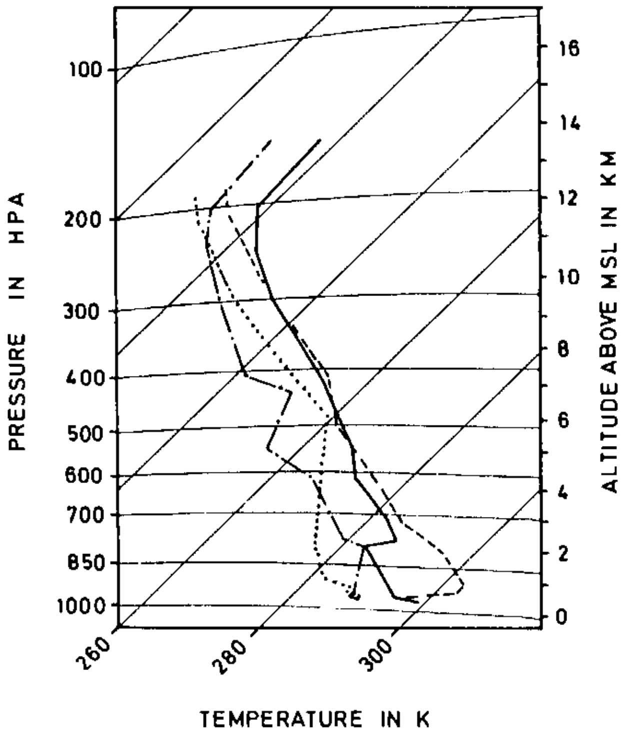
2 Synoptic Situation

During the night hours of July 11 to July 12 a cold front passed southern Germany (see HEIMANN and KURZ, 1985). This cold front replaced an extremely hot continental tropical air mass by a warm maritime air mass without showing significant weather effects in the Munich area during the night. The maximum temperature of the previous day (July 11) reached 37 °C at many stations in southern Germany while it was around 10 degrees lower on July 12. The soundings of Munich from July 12, 00 UTC and 12 UTC also show a substantial cooling in the lower (2 km depth) atmospheric layers (see Figure 1).

In the upper layers (> 4 km) no significant cooling was observed, only the moisture content had decreased. Caused by the cold air advection an inversion layer had formed between 2100 m and 2400 m height (above MSL) with a temperature jump of 4 K. Boundary layer heating during the day was insufficient in producing high enough temperature increase to cause convection to break through the inversion (maximum temperature 27 °C). This is supported by the observation of only small flat clouds in the inversion level during day time before the storm appeared. So we may conclude, that energy had probably accummulated in the boundary layer, without being able to escape into upper atmospheric levels before being incorporated into the approaching storm's circulation. The storm itself had to form under different initial conditions in a different location (see also HEIMANN and KURZ, 1985).

This situation of cooling in the lower layers associated with the formation of an inversion was the reason for the Weather Service to diagnose a stabilizing atmosphere with reduced tendency to develop deep convection. But, on the other hand, the air above the inversion was conditionally unstable, so that a saturated air parcel starting above the inversion, would not loose its positive buoyancy during wet adiabatic ascent before reaching the tropopause. Another way to induce instability would be lifting of the total air column. Indeed, the 12 UTC maps (see HEIMANN and KURZ, 1985) show an area of synoptic scale lifting situated to the NE of the short wave trough over France at this time. Additional orographic effects such as air mass lifting or differential heating could have been important.

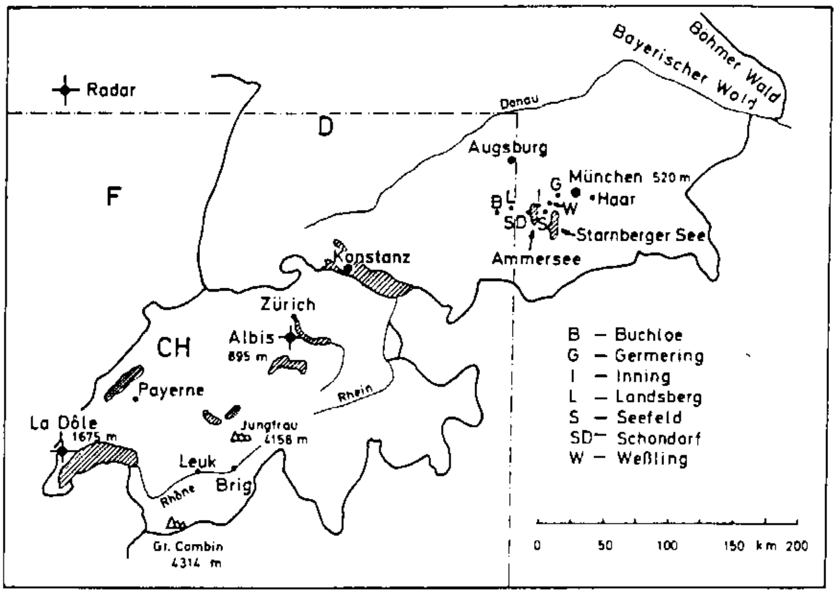


● **Figure 1**

Atmospheric soundings of Munich on July 12, 1984.
------ Temperature 0.00 UTC
—— Temperature 12.00 UTC
...... Dew point 0.00 UTC
–. –.– Dew point 12.00 UTC

3 The Storm Development

The convective development on July 12, 1984 can be analysed from the sequences of satellite and radar images. A series of IR-images is provided every 30 minutes by Meteosat with a resolution of about $6 \times 7\,\text{km}^2$ horizontally in the Munich area. A radar overview is given every 10 minutes by the Swiss radar system. The information from the two radars at La Dôle and Albis is combined to give a 3-dimensional picture of the reflectivity distribution with a horizontal resolution of $2 \times 2\,\text{km}^2$ and a vertical resolution of 1 km. There is no recorded data from radars in southern Germany, so that the area covered by radar ends on a line Augsburg – Landsberg (see dashed-dotted line in Figure 2).



- **Figure 2**
  Schematic map of the observation area. Dashed-dotted line indicates area covered by radar observations.

3.1 Initiation of the First Deep Convective Cells

The first two weak convective radar echos (cells 1 and 2) were detected at 12.35 UTC (14.35 CEST) over the Bernese Alps in the Jungfrau-region. At 12.55 UTC, which is 5 hours before the Munich hailfall, a third system of cells developed in the same region. In the initial stage it consisted of several smaller cells which merge at about 13.25 UTC to form a larger complex (complex 3, see Figures 3a and 4a). At this time cell 1 has already reached Lake Zürich propagating further to the NE, while cell 2 has nearly completely disappeared. A fourth cell is located over the Rhône-valley near Leuk and a fifth over the Grand Combin in the Pennine Alps. These cells are lined up in a SW-NE direction. During this initial stage of convective development the radar reflectivities are quite low corresponding to precipitation intensities smaller than 3 mm/h. The four cells can also be identified in the IR satellite image by the four small areas in Figure 4a indicating temperatures lower than $-20\,^{\circ}\text{C}$.

At 14.05 UTC (Figure 3b) cell 3 and the northern part of cell 4 (cell 4a) have merged and formed a larger cell (cell $3'$, the $'$ indicating cells which have emerged from the original ones) which had rapidly intensified. Precipitation rates of 30–100 mm/h were reached in its core and the 1 mm/h contour reached a height of around 11 km. This system will produce the main hail streak later on. A second larger cell (cell $5'$) has developed out of the southern part of cell 4 (cell 4b) and the northern part of cell 5 (cell 5a) just south of the first cell over the Rhône-valley in the region of Brig. So at this time, four hours before the Munich hailfall, two deep convective cells have formed. They start traveling to the NE with a mean speed (of the reflectivity center) of around 100 km/h (28 m/s). According to the sounding of Payerne at 12 UTC winds of this magnitude and direction are found at about 3.8 km height or 650 hPa.

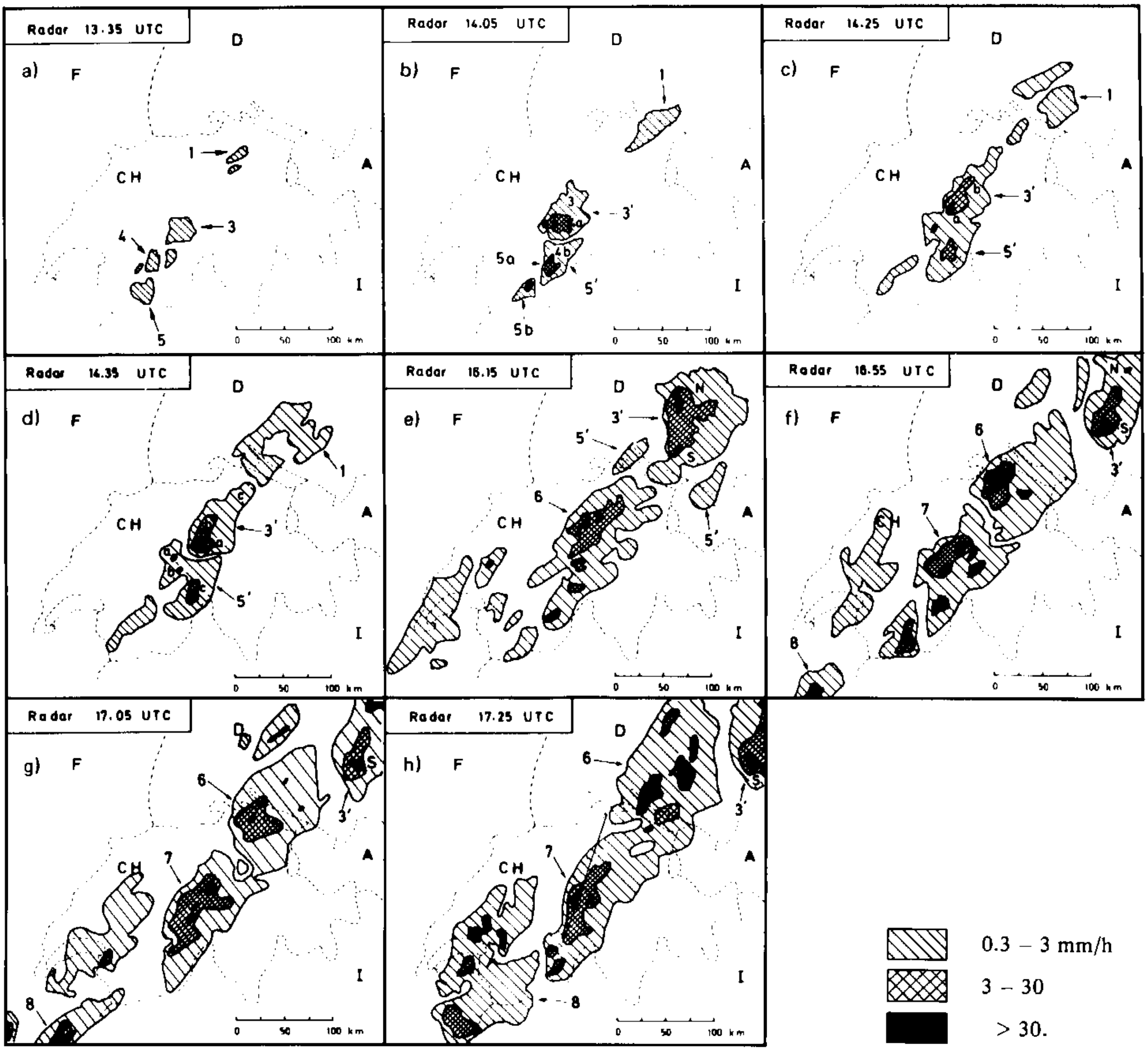
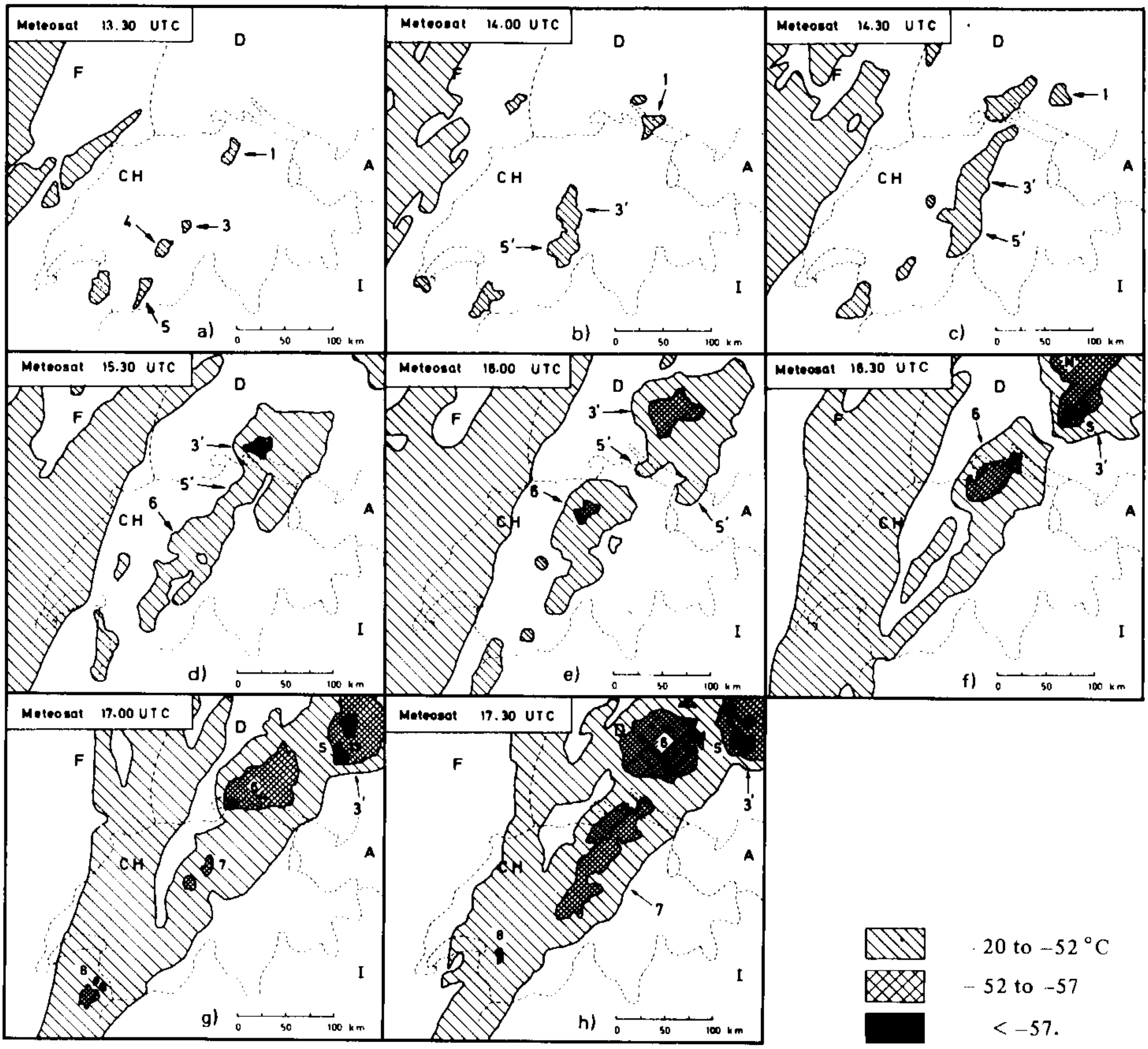


Figure 3 Selected sequence of radar images of July 12, 1984. All radar images are composits taken by the two Swiss radars at La Dôle and Albis. Horizontal cross sections of the distribution of maximum radar reflectivity detected in the vertical direction are shown. The reflectivity or the corresponding rain rate intervalls are:

In the meantime the first cell has reached Lake Constance, showing only very weak activity. This configuration can also be recognized on the IR Meteosat image of 14.00 UTC (see Figure 4b) but no more details on cell structure can be derived from these data. So the first phase in the development of convection which can be seen by radar, namely the formation of the first deep convective cells penetrating to the tropopause, is finished at this time.

3.2 The Thunderstorm Stage

A second phase in the cell development of the later hail system 3′ can be recognized for the next one and a half hours. Storm 3′ travels to the NE developing into a multicell storm. Its track is



● **Figure 4** Selected sequence of IR Meteosat images of July 12, 1984. The temperature scale is:

plotted in Figure 5 where the location of the maximum radar reflectivity is indicated by the black dots. As an example the cell structure as seen by radar is shown in Figure 3c for 14.25 UTC. Cell 3′ now consists of two echo cores 3′a and 3′b. Downwind of the old echo 3′a the new cell 3′b began to develop at around 14.15 UTC. While cell 3′a is in its mature stage just before decaying, cell 3′b is intensifiying taking over the most active part of the storm 10 minutes later at 14.35 UTC when 3′a is shrinking down releasing its precipitation to the ground (to be seen from the vertical cross sections not shown in Figure 3). At this time again a new cell (3′c) is beginning to grow downwind of the old cells. So the radar structure of storm 3′ looks like that of a multicell storm which is integrating newly grown cells from the downwind direction while the old cells are decaying on the upwind side. The new cells travel through the system playing the part of the growing, mature and decaying cell component and thus maintaining the storm system as a whole. The second system 5′ did not grow up into such a stable storm complex. At

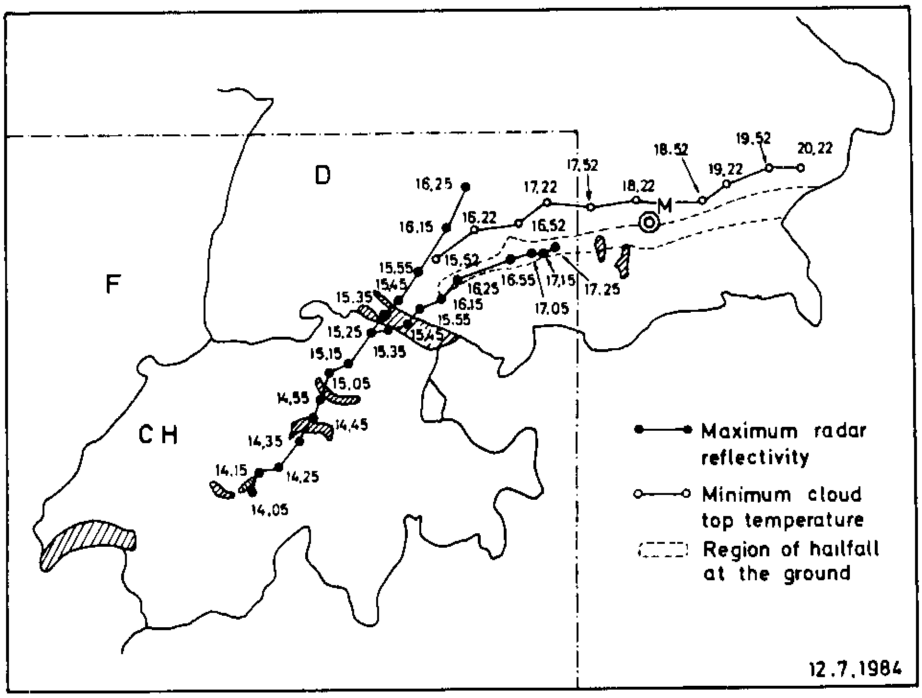


Figure 5
Tracks of the maximum radar reflectivities (Swiss Radar System) and minimum cloud top temperature (Meteosat IR) for the main storm system 3′. The region of the main hail streak at the ground is enclosed by the dashed line. The dashed-dotted line indicates the area covered by radar observations.

14.35 UTC it is composed of three single ordinary cells which are lined up in a direction nearly perpendicular to the middle-tropospheric wind.

A third phase in the development of storm 3′ started at 15.35 UTC when the radar echo began to split into a northern part 3′N which continued traveling into the original NE-direction and a growing southern part 3′S moving to the right of the initial direction of propagation (see Figure 3e at 16.15 UTC and Figure 5). At splitting time the storm was just traveling over Lake Constance. The 16.30 UTC IR satellite image (Figure 4f) shows the storm's cold cloud top region. The two storms can be distinguished very well in the temperature field. The newly grown southern part does already show the coldest temperatures (< − 57 °C). Its center, corresponding to the location of the updraft just below cloud top, is situated to the NE of the maximum radar reflectivity (see Figure 5) of the southern cell 3′S. This indicates the tilt of the updraft into the downwind direction because of the strong upper level winds. The detailed storm structure, as it is provided by radar, cannot be deduced from the Meteosat images. The splitting of the storm and the subsequent right-movement of its southern part is an indication of the change of the storm's internal dynamical mechanism from multicell to supercell characteristics (see e.g. BROWNING, 1977 or WILHELMSON, 1980). In contrast to a multicell storm, a supercell storm consists of a quasi stationary updraft-downdraft pair existing generally for at least 30 minutes, without the incorporation of new cells into this circulation which was the case for the 3′S storm as long as it could be observed by radar. KLEMP and WILHELMSON (1978), for example, found from their numerical experiments on storm splitting that the updraft in the right-moving storm was rotating cyclonically, whereas the updraft in the left-moving storm rotated anticyclonically, but such features cannot be deduced from the present data. They also concluded that one of the storms decayed if the mid-level winds were not parallel to the mean wind shear vector because then the mid-level influx into the two downdrafts supported mainly the upwind storm. Such a decaying of the northern storm can be seen in Figures 3f, 4g and 3g. The remaining right-moving storm had a slower propagation velocity compared to the original multicell system. The radar echo traveled with a velocity of around 80 km/h (22 m/s) into the ENE direction.

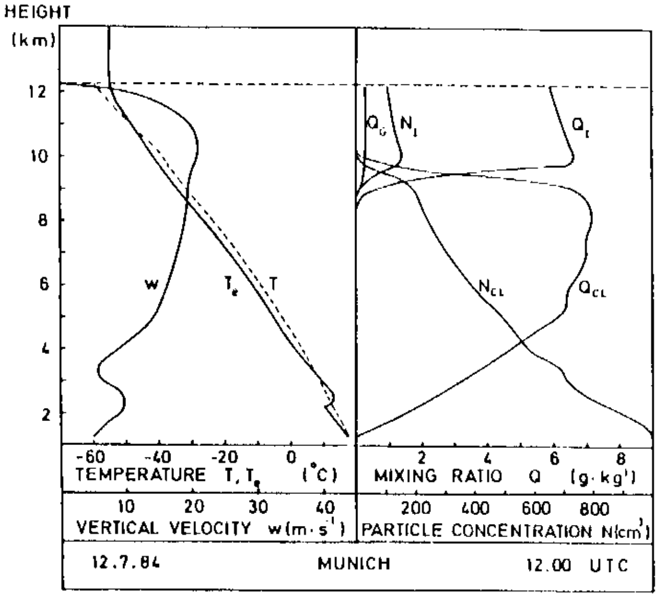
The radar image of 16.15 UTC also shows that the second storm system 5′ has almost completely disappeared (Figure 3e). But a new multicell storm system can be seen now (storm 6, see Figures 3e and

4f). Again, this system had formed in the Jungfrau-region which acted as a point source for triggering new cell formation. The cells then travelled into the NE-direction either intensifying (storm 3′) or decaying again (storm 5′). The next two storms (storm 7 and 8) can be seen on Figures 3g and 3h. While storm 7 was initiated in the same region as the previous storms, storm 8 originated further to the SW.

3.3 The Hailstorm Stage

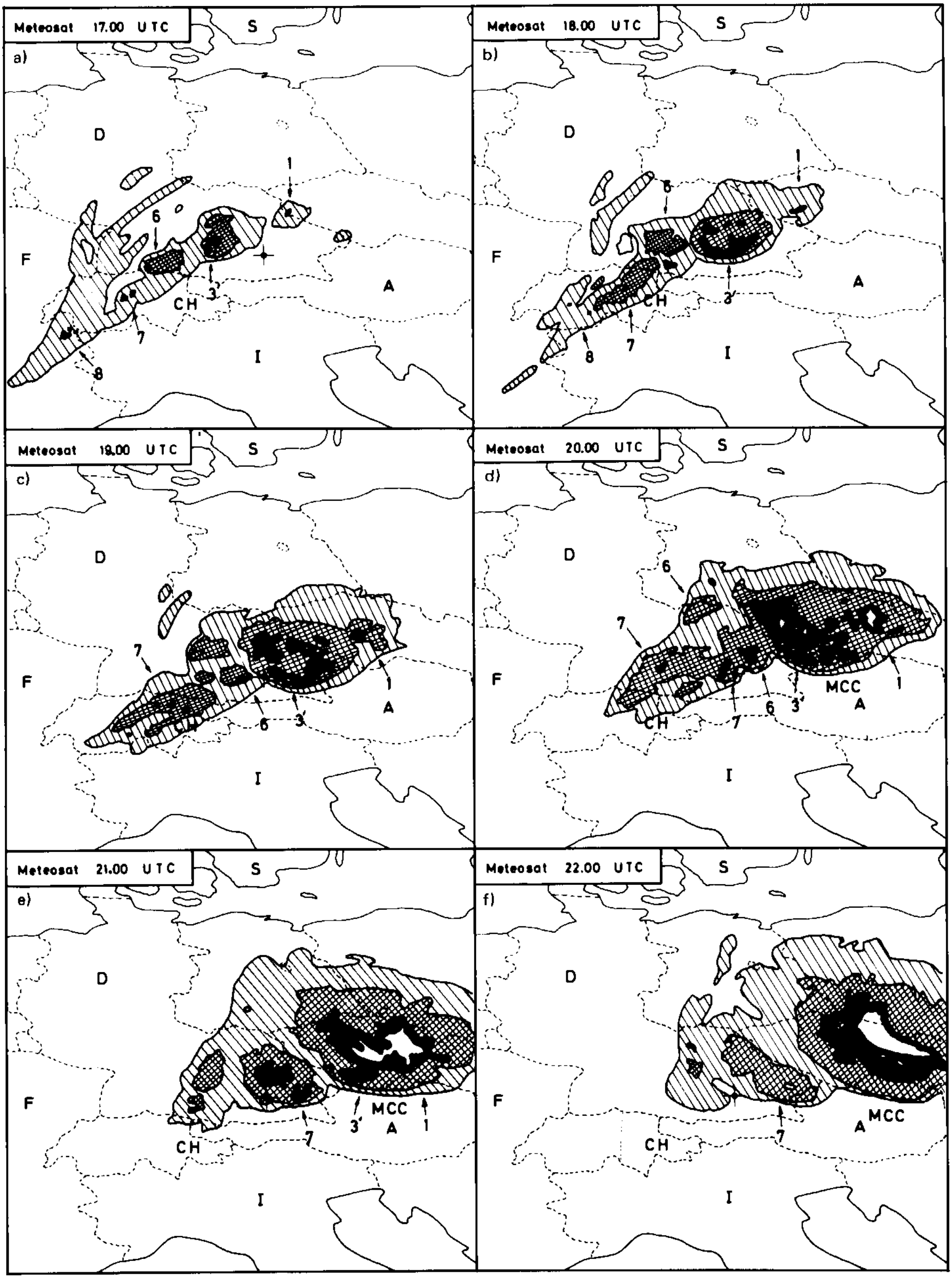
The hailfall itself started at 16.15 UTC as reported from the ground stations, but it cannot be deduced from the radar data which only show total reflectivity caused by all particles in the observed volume. An indication of large hail is probably the appearence of precipitation intensities larger than 100 mm/h at 17.05 UTC at heights above 5 km penetrating down to the ground at 17.25 UTC in the region of Buchloe.

This formation zone of hailstones is also in accordance with the results of a simple, one-dimensional, stationary cloud model as shown in Figure 6 (for a model description see HÖLLER, 1982, 1983). The model uses the vertical soundings of temperature and dewpoint, the cloud base height, a vertical velocity perturbation at cloud base and an initial droplet number concentration as input parameters. It should be mentioned, that the cloud base height and the vertical velocity perturbation had to be chosen such that the air bubble was able to break through the inversion and could produce a deep convective cloud. The main model outputs are profiles of in-cloud temperature, vertical velocity, liquid- (cloud droplets and raindrops) or ice-water (ice crystals and graupels) contents and the corresponding number concentrations of these particles. Entrainment of environmental air is considered for the parcel calculations. As can be seen from Figure 6, two conditions for efficient riming are fulfilled at heights above around 5 km: The cloud temperature is below the freezing level and a rather high liquid water content of more than 6 g/kg is present, being essential for heavy riming. The calculations were done for an assumed continental type of droplet spectrum using an initial cloud droplet concentration of 1000 $\mathrm{cm^{-3}}$ at cloud base. The effect is that collectional growth of water drops is ineffective throughout the main updraft so that the droplets remain small cloud droplets with mean radius not exceeding 16 µm. So the transition to the ice phase occurs at relatively high levels in the cloud, being completed when the −40 °C isotherm is reached at around 10 km height. Therefore this boundary is the upper level for which riming is possible. We may conclude, that under optimum conditions hail growth could have taken place at heights between 5 and 10 km in the main updraft.



- **Figure 6**

Vertical profiles of cloud temperature T, environmental temperature T_e, vertical velocity w, cloud droplet concentration N_{CL}, ice particle concentration N_I and mixing ratios of cloud droplets Q_{CL}, graupels Q_G and frozen droples Q_I as obtained from the one dimensional, stationary cloud model computations after HÖLLER (1982, 1984) using the sounding of Munich 12.7.1984, 12 UTC. Cloud top is indicated by the horizontal dashed line.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3.4 The MCC Stage

The next phase of the upscale development of convection started between 17.30 UTC and 18.00 UTC when new convective cells evolved at the southern and western flanks of storm 3′ (see Figure 7b) organized in a U-shaped pattern. Because radar information is no longer available as the storm has propagated out of the observation domain we have to confine ourselves to the satellite images. So the detailed storm structure can no longer be deduced but the location of the strongest updrafts can still be identified as the coldest cloud tops. Especially the hailstorm can be tracked as it is the coldest cloud top for the next two hours of its lifetime. Its identification is simplified by the ground data on position and time of the hailfall. Its further track, as deduced from the temperature information, is shown in Figure 5. One interpretation of these data is, that the hailstorm continued to travel to the ENE-direction as a quasi steady supercell circulation system maintaining similar favourable growth conditions for the hailstones in a four hours period (16.30–20.30 UTC) and producing a hail streak of about 250 km length having a width between 8 and 18 km. The mean propagation velocity of the corresponding cloud top between 17.30 and 20.30 UTC was around 60 km/h (32 kn). This is about one half of the mean horizontal wind speeds which were determined from cloud top tracking in the Meteosat images. These wind speeds of cloud top level ranged between 50 and 75 km over southern Germany at 18.00 UTC. But the hailstorm was only a part of a fast evolving larger convective system consisting of a number of cells originally growing in a U-shaped configuration.

The situation at 18.00 UTC is shown in Figure 7b. The convective system located over western Czechoslovakia has originated from cell system 1 which has travelled across southern Germany during the last 4 hours. The largest and most intense system is system 3′. The hailstorm is associated with the coldest cloud top at its southern flank and is just approaching the urban area of Munich (see Figure 8 for comparison). In the upwind direction (to the SW) system 3′ is accompanied by storms 6, 7 and 8. The anvil size of system 3′ is now rapidly increasing by the combined action of the different updraft zones. The organization changes from U-shaped to nearly circular when a new updraft line formed over the Bavarian Forest (Bayerischer Wald) with the approach of the storm system at around 19.00 UTC (see Figure 7c). System 1 has intensified further and gets now incorporated into the large anvil of system 3′ so contributing to the formation of a mesoscale convective complex (MCC) according to the definition of MADDOX (1980). This definition is based on IR satellite imagery as reproduced in Table 1.

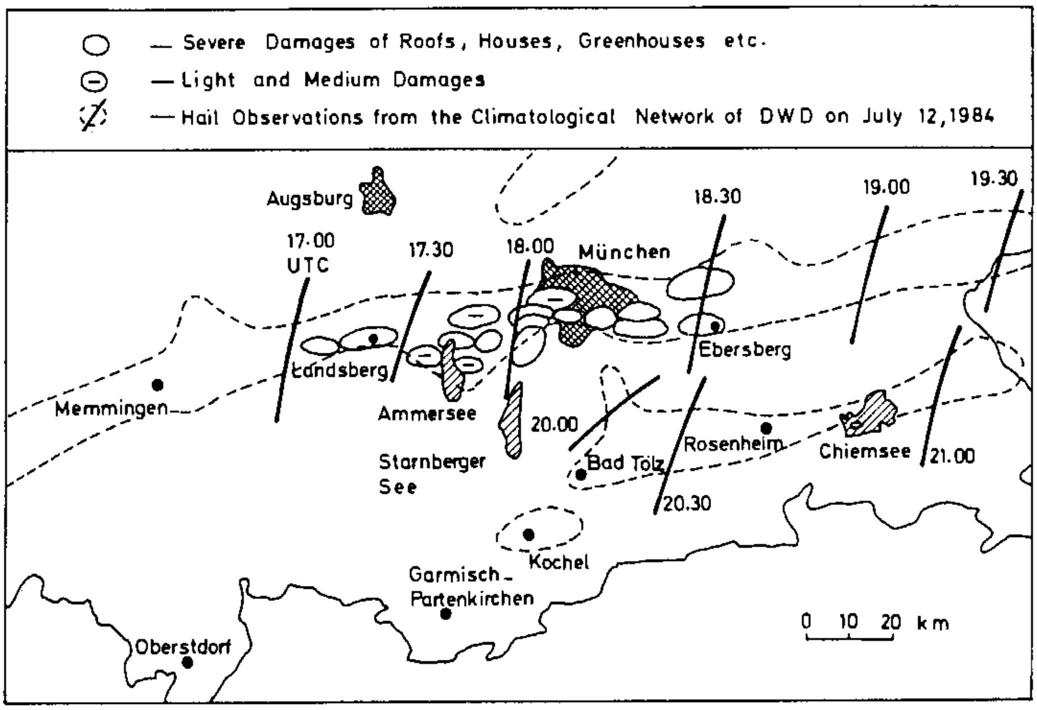
■ **Table 1** Mesoscale Convective Complex (MCC) (based upon analyses of enhanced IR satellite imagery). From MADDOX (1980).

	Physical characteristics
Size:	A – Cloud shield with continuously low IR temperature $\leqslant -32$ °C must have an area $\geqslant$ 100 000 km^2 B – Interior cold cloud region with temperature $\leqslant -52$ °C must have an area $\geqslant$ 50 000 km^2
Initiate:	Size definitions A and B are first satisfied
Duration:	Size definitions A and B must be met for a period $\geqslant$ 6 h
Maximum extent:	Contiguous cold cloud shield (IR temperature $\leqslant$ 32 °C) reaches maximum size
Shape:	Eccentricity (minor axis/major axis) $\geqslant$ 0.7 at time of maximum extent
Terminate:	Size definitions A and B no longer satisfied

● **Figure 7** Sequence of enhanced IR Meteosat images showing Central Europe on July 12, 1984. The temperature scale is

▨ – 20 to – 52 °C ▦ – 52 to –57 °C ■ – 57 to –61 °C □ < – 61 °C.

The location of Munich is indicated by the cross.



● **Figure 8** Airborne observations on July 13, 1984 by 3 DFVLR motor gliders in the region between Landsberg and Ebersberg and hail reports of the climatological network of the German Weather Service (DWD). The beginning of hailfall is indicated by the bold lines (time in UTC).

Because of the limited data available for this study (not principally), it was not possible to examine all of the requirements listed in Table 1 as the time series ended at 24.00 UTC and the MCC traveled out of the data domain. But we can say, that the MCC was initiated, according to the above definition, at 19.30 UTC, i.e. 1.5 h after the hailfall in Munich, when definition B was first satisfied. The extent of the system increased further while the most intense convective cells are orientated now in a line structure (apart from the coldest tops belonging to system 1) parallel to the mountain ranges of the Bavarian Forest and Bohemian Forest (Bayerischer Wald and Böhmerwald) (see Figure 7d). The next two satellite images (Figures 7e and 7f) show that system 1 takes over the most active part of the MCC organizing itself into a line configuration while the previously most active parts of the complex were decaying. The total system (outline of the − 52 °C isotherm) takes on a more and more circular shape.

We can also conclude from the satellite images, that the convective systems 6, 7 and 8 which followed the MCC on it's track did not reach a comparable size and intensity and did not merge with the main complex. Moreover, they began to decay at around 20.00 UTC with the exception of a cell at the southeastern flank of these storm systems, situated west of Munich at 20.00 UTC and producing a second, major hail streak situated south but parallel to the main hail streak (see Figure 8). At around 21.30 UTC these systems began to decay like the other storms following the MCC.

MADDOX (1980) also proposed a conceptual model of the life cycle of an MCC. Many of those features can be recognized in the present case study, so that the following four main steps can be distinguished here:

1. the generation phase (12.30–17.30 UTC): thunderstorms are generated in regions with favourable conditions (conditionally unstable air, influence of orography), some of them intensify to produce hail or other severe weather events, a meso-β scale (20–200 km) region of anomalous warming is produced by latent heat release

2. the development phase (17.30–19.30 UTC): the larger scale environment begins to react to the presence of the warm region, a mid-tropospheric inflow associated with a mean mesoscale ascent develops, indicated by the formation of a long lived, nearly circular cloud shield, new convective zones appear rapidly, the size criteria A and B are reached
3. the mature phase (starting at 19.30 UTC): convective elements continue to form, the main characteristics of the system are now locally heavy rainfall and the large extent of the upward mass circulation associated with the cold cloud top
4. the dissipation phase (not reported in this study): such systems decay often just beyond or eastward the large scale ridge position

MADDOX also stated, that the most significant feature of MCC's would be the upward motion on meso-α scales (200–2000 km) and interpreted this as a tendency of the atmosphere to produce mean, mesoscale ascent in respond to convective forcing, as indicated by the long-lived, nearly circular cloud shield.

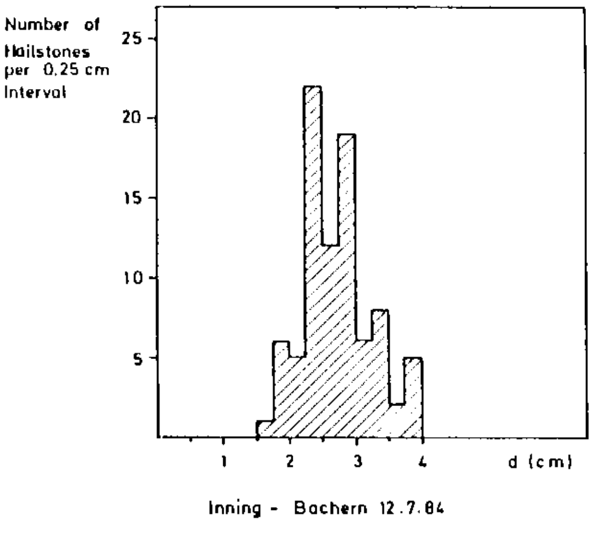
4 Hail Damages and Hailstone Characteristics

It exists a wealth of pictorial documentation of various kinds showing especially the Munich area during, just after and also the following days of the hailfall. A very informative compilation is given by MÜNCHENER RÜCKVERSICHERUNGS GESELLSCHAFT (1984).

By photo flights of the three motor gliders of DFVLR during the next morning the track of the hail swath was followed to the west, the south and the east of Munich, recognizing damaged areas by wrecked greenhouses, preferably destroyed west sides of houses and roofs, damage on windows, crops, trees, and bushes and branch covered roads. Figure 8 gives an overview of the observed damage area completed by the reports of the climatological stations of the German Weather Service (DWD). The later hailfall, about 20 km south of the first one, caused no severe damages.

Hailstone samples have been taken at various locations along the hail streak (between Landsberg and Munich) by attentive private persons and members of the DFVLR-staff. A data base of around 100 hailstones was selected for further evaluations consisting of determinations of size and crystal- and layer structure made from photographs of thin sections in transmitted, reflected and polarized light. These investigations are kindly carried out by A. WALDVOGEL (ETH-Zürich). Because final results are not yet available up to date, we only can present some preliminary information.

A size distribution of hailstones which fell in Inning/Ammersee (35 km WSW of Munich) is shown in Figure 9. It is not representative for the number concentration of hailstones during their fall bacause it has been deduced from the hailstones collected from the ground, thus only showing the distribution of



● **Figure 9**
Size distribution of hailstones collected from the hail swath associated with storm 3′ at Inning. Hailstones were collected from the ground so that the distribution does not represent a volume concentration. Nearly all stones were spherical in shape. d is the maximum dimension.

hailstones with size. The majority of the stones had maximum dimensions between 2.25. and 3 cm while the smallest ones were 1.5 cm and the largest ones 4 cm in size. Most hailstones were spherical in shape showing a well recognizable lobe structure. A minority of the stones were wheel-like, oblate spheroids whose internal structure was well distinguishable from the outside. Larger hailstone sizes with maximum dimensions up to 6 cm were reported from the central and eastern parts of Munich, in one case a hailstone of 9 cm size was collected. Typically, three major growth layers were found: an opaque core (with diameter between 2 and 11 mm, approximately) covered with a layer of clear ice which was surrounded again by an opaque outer layer. The hail coverage at the ground had a depth of up to 10 cm.

5 Conclusions

We may state two main conclusions from the present study:

1. The initiation of the first storms took place in mountaineous regions. Subsequently, the storms traveled out of the mountains into flat terrain. So for predictional or modeling purposes orographic effects should be taken into account carefully.
2. Convection developed further into a meso-α scale convective complex, the hailstorm being only a minor but intense constituent of the total system. Not very much is known about the physics of such systems, so that these MCC's seem to be a promising objective for further research because they are accompanied by damaging weather events like hailstorms, tornados or heavy rainfalls.

Acknowledgement

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