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The Berlin Hailstorms of 19 August 2000

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Introduction:

In the evening of August 19, 2000, severe hail storms hit Berlin. Nickel to quarter-sized hail was widely observed, in some places the hail stones reached even hen-egg to tennisball size, weighing more than 30 grams. Traffic broke down in many parts of Berlin; the fire department declared a state of emergency just after the severe weather had set in. In the areas affected, a lot of the foliage was ripped down from the trees and significant damage was inflicted to cars and roofs as well as to glass structures. In Zehlendorf (southwest Berlin), several residents had to be treated for head injuries. Strong straight-line winds caused further damage.

During that time, Europe was influenced by a weather pattern which favored the development of severe thunderstorms.

In this report we wish to describe the weather situation that lead to the formation of supercells (part 1); a brief overview of supercell structure and of the basic factors that favor supercell development is given in part 2. Part 3 summarizes observations made from the "Institute for Meteorology of the Free University of Berlin".

1. Description of the Weather Situation

1.1 Synoptic-scale Setting (see appendix for charts)

In front of a pronounced long-wave trough over the eastern Atlantic Ocean, Central Europe was dominated by a marked southwesterly current. The frontal zone associated with this trough, where winds in excess of 65 knots were measured, reached from the Biskay across the Benelux countries and northern Germany to the Baltic states. While north of this frontal boundary cool air masses were dominant, the Alpine regions, southeastern Germany and Poland lay in the area of moist subtropical air (xS). Surface analyses show a frontal boundary which extends from central Spain across southern France and the German "Mittelgebirge" to northern Poland. Along this front several wave cyclones developed, which moved rapidly to the northeast. In the Mediterranean regions, hot air originating from the Sahara Desert (cT) was dominant. This air also reached the Balkans, setting new local temperature records.

Generally, there was not much change of this situation in the period from August 16 to August 20, since the eastern Atlantic long-wave trough hardly advanced eastward. So the above mentioned strong temperature gradient - its crowding zone lay over Germany - could be maintained. Correspondingly, the wind increased strongly with height and above 500 mb a strong jet stream was evident. This vertical change of wind speed and direction is a general phenomenon in the atmosphere when a horizontal temperature gradient is present, and it is called "thermal wind". The subtropical air (xS) south of the frontal boundary was characterized by moderate to high convective available potential energy. If this energy is released by upward motions within the troposphere, in conjunction with vertical wind shear, complex and organized convective structures (MCSs, supercells) will be likely to develop.

1.2 Development on August 19

A short-wave trough, which was located West of Ireland on Aug 19 at 00 UTC moved along the eastern edge of the long wave to the northeast and its axis had reached the western Baltic Sea on August 20 at 00 UTC. To the east of this trough the surface low-pressure system "Oktavia" tracked from the Biskay (August 18, 00 UTC) to the eastern North Sea (August 20, 00 UTC) and was further deepening to below 1000 mb. On the morning of August 19, maritime subtropical air (mS) entered northern Germany in the low-pressure system's warm sector.

From the North Sea, the cold front associated with "Oktavia" advanced eastward and crossed northwestern Germany until midday. Simultaneously, the short wave moved quickly to the northeast and apparently induced further lift along the cold front. Owing to the wave cyclones over France along this frontal boundary, it did not move much further to the south; towards the east, however, it was accelerated and crossed the area of Berlin in the evening hours. Obviously, this fast eastward propagation was at least partly due to the thunderstorms which occured along this front. So the cold front showes a distinct "bulge" to the east in the 18 UTC-surface analysis, which is probably caused by thunderstorm outflow.

Before however, the subtropical air (xS) reached Berlin, as it had been integrated into the warm sector of "Oktavia" by southerly winds. According to rawin -sonde data from Lindenberg (about 40 miles southeast of Berlin), a well defined inversion was located at 775 mb in the morning hours. Until 12 UTC this inversion had descended to 910 mb, and at 18 UTC the warm air had made its way to the surface. Apparently independent of this, the tropopause height increased from 250 mb to 200 mb. Obviously, air of tropical origin had advanced at high altitudes up to northeastern Germany. Several stable layers and veering mid- to upper-level winds, as well as the fact that rawing-sonde data from Meiningen (located upstream) revealed a tropopause height at 200 mb already at 12 UTC, suggest warm advection at high levels.

2. Supercells: Theory and Development

A supercell is an intense thunderstorm cell which has a single, rotating, quasi-steady updraft and which significantly deviates in its motion from the mean tropospheric winds (usually to the right).

2.1. Wind Shear and Vorticity

Synoptic-scale weather patterns may favor currents, which exhibit great changes in wind speed and direction with increasing height. Such a current is characterized by the presence of shear vorticity. To better understand this, envision a weak southerly flow at low levels and a strong southerly flow at upper levels. An imaginary stick, that has been put upright into this wind field, starts to rotate about an east-west axis. Parallel to this axis, the vorticity vector points due west.

The vorticity vector's magnitude is proportional to the stick's rotation speed (i.e. to the magnitude of the vertical shear). In addition, the stick moves with the mean current to the north and thus normal to the vorticity vector ("crosswise vorticity").

Further, we consider a flow pattern in which only wind direction changes with height, e.g. a southeasterly wind near the surface and a southwesterly wind aloft (directional shear). Our imaginary stick now moves with the mean wind due north. It is also rotating, with its upper tip moving to the east and its bottom moving to the west. Now the vorticity vector is directed to the north, i.e. parallel to the stick's direction of motion. Thus, the vorticity vector and the "stick-motion vector" are parallel; this quality is called "streamwise vorticity". *Davies-Jones et al.* [1990] compare this to a perfectly spiralling football.

If the wind field is known, we can determine the vorticity vector. $\partial \mathbf{v}_h/\partial z$ desribes the change of the horizontal wind $\mathbf{v}_h$ as a function of the height. $\partial \mathbf{v}_h/\partial z$ is called shear vector. As in the above examples, the vorticity vector is expected to be directed normal to the shear vector as well as normal to the vertical z-axis. This is determined as the cross product of the shear vector and the unit vector **k**.

$$\boldsymbol{\omega}_h = \mathbf{k} \times \frac{\partial \mathbf{v}_h}{\partial z}$$ with

$\boldsymbol{\omega}_h(z)$: horizontal shear vorticity vector

$\mathbf{k}$: z unit vector

$\frac{\partial \mathbf{v}_h}{\partial z}$: shear vector

2.2 Rotation of Convective Cells

With the air entering a thunderstorm, the shear vorticity is transported into the updraft. It is necessary that the horizontal shear vorticity vector has a large component parallel to the inflow vector. Then the air has streamwise vorticity, which is necessary to have the vorticity located within the updraft. This is not the case when the vorticity vector is normal to the inflow vector [e.g. *Davies-Jones, 1984*]. Since the cell itself is also moving, we need to consider the air flowing into the cell from a storm-relative frame. Thus we introduce the storm-relative winds as the vector difference of the environmental wind vector vh and the storm-motion vector **c**.

$$v_r = \mathbf{v}_h - \mathbf{c}$$ with

$v_r(z)$: storm-relative wind vector

$\mathbf{v}_h(z)$: horizontal environmental wind vector

$\mathbf{c}$: storm-motion vector

According to this, the storm-relative wind vectors should be parallel to the environmental vorticity vectors within the inflow layer. This means that we are interested only in the component of the vorticity vector that is parallel to the storm-relative wind vector.

To obtain this component, we project the vorticity vector onto the storm-relative wind vector by means of the scalar product. The result is the streamwise vorticity.

$\omega_s = \omega_h \cdot v_r$ with $\omega_s(z)$: streamwise vorticity

Altogether we can express streamwise vorticity as follows:

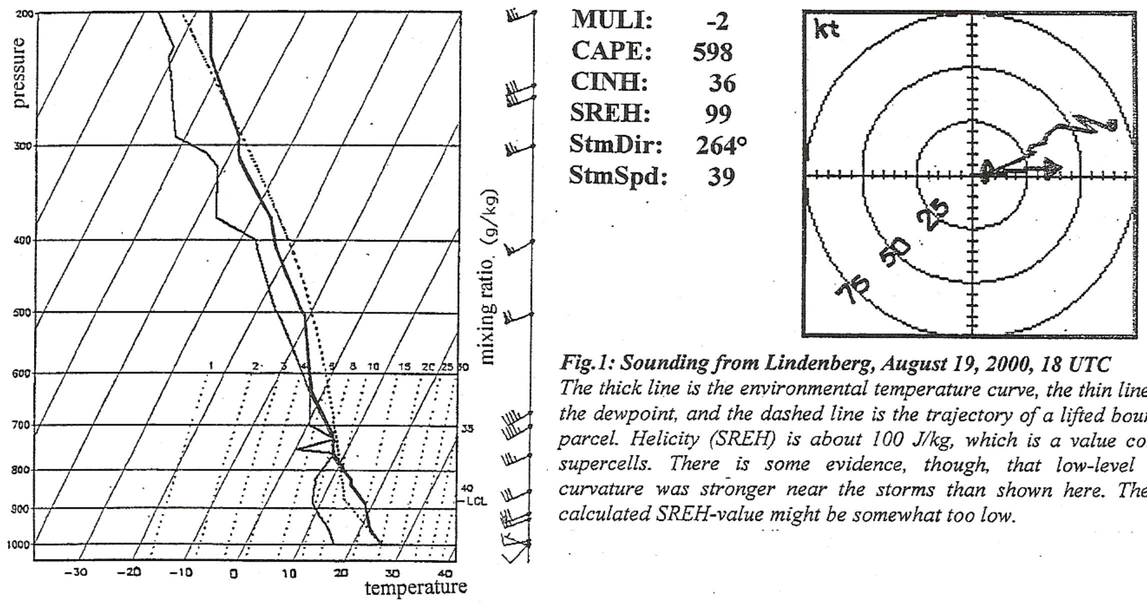
$$\omega_s = \mathbf{k} \times \frac{\partial \mathbf{v}_h}{\partial z} \cdot v_r = - \mathbf{k} \cdot v_r \times \frac{\partial \mathbf{v}_h}{\partial z}.$$

To obtain the whole value of streamwise vorticity that can be brought into the updraft, we integrate with respect to z and obtain the "helicity" (commonly abbreviated SREH for "storm-relative environmental helicity"):

$$\mathrm{SREH} = -\int_{z_0}^{z} \mathbf{k} \cdot (\mathbf{v}_h - \vec{c}) \times \frac{\partial \mathbf{v}_h}{\partial z}\, dz.$$

In this shape, the useful interpretation of this intergal becomes clear: It is the negative of twice the area swept out by the storm-relative wind vector between the surface and z on a hodograph (Fig 1). Usually, this integral is taken over the lowest 3 km.

Within the updraft of the storm, the streamwise vorticity is tilted to the vertical and converted to rotation. By streching within the updraft this rotation is amplified ("ice-skater" effect), so that predominantly the mid-level parts of the thunderstorm cell begin to rotate. This rotating updraft is called "mesocyclone".



MULI:	**-2**
CAPE:	**598**
CINH:	**36**
SREH:	**99**
StmDir:	**264°**
StmSpd:	**39**

Fig.1: Sounding from Lindenberg, August 19, 2000, 18 UTC
The thick line is the environmental temperature curve, the thin line represents the dewpoint, and the dashed line is the trajectory of a lifted boundary-layer parcel. Helicity (SREH) is about 100 J/kg, which is a value conductive to supercells. There is some evidence, though, that low-level hodograph curvature was stronger near the storms than shown here. Therefore, the calculated SREH-value might be somewhat too low.

2.3 Low-level Rotation

In addition to inducing mid-level rotation of the convective cell, the vertical wind shear also causes the updraft to tilt. In this case, precipitation does not fall back into the updraft but produces a separated downdraft region. In contrast to short-lived single-cell storms, a long-lasting circulation is enabled. Usually, the shear vector veers with height (from southerly to westerly directions), then the cell rotates cyclonically and the main downdraft region is located northeast of the updraft.

Owing to the cell's rotation, parts of the precipitation-laden downdraft are carried southward around the mesocyclone. These parcels possess "baroclinic" vorticity, with their left sides moving upward and their right sides moving downward, looking downstream (warm rising air to their left, cool descending air to their right). The parts of the downdraft carried around the mesocyclone make up the "rear-flank downdraft" (RFD, see Fig. 2). The vorticity within the RFD can be converted to vertical cyclonic rotation [*Davies-Jones and Brooks,* 1993]; these spinning parcels are re-ingested into the updraft, where the vorticity is streched in association with convergence below the updraft. Since this air is cool and relatively moist, a rotating cloud feature forms below the cloud base, the so-called "wall cloud". These conditions are favorable for the development of tornadoes.

A schematic model of a supercell is shown in Fig 2.

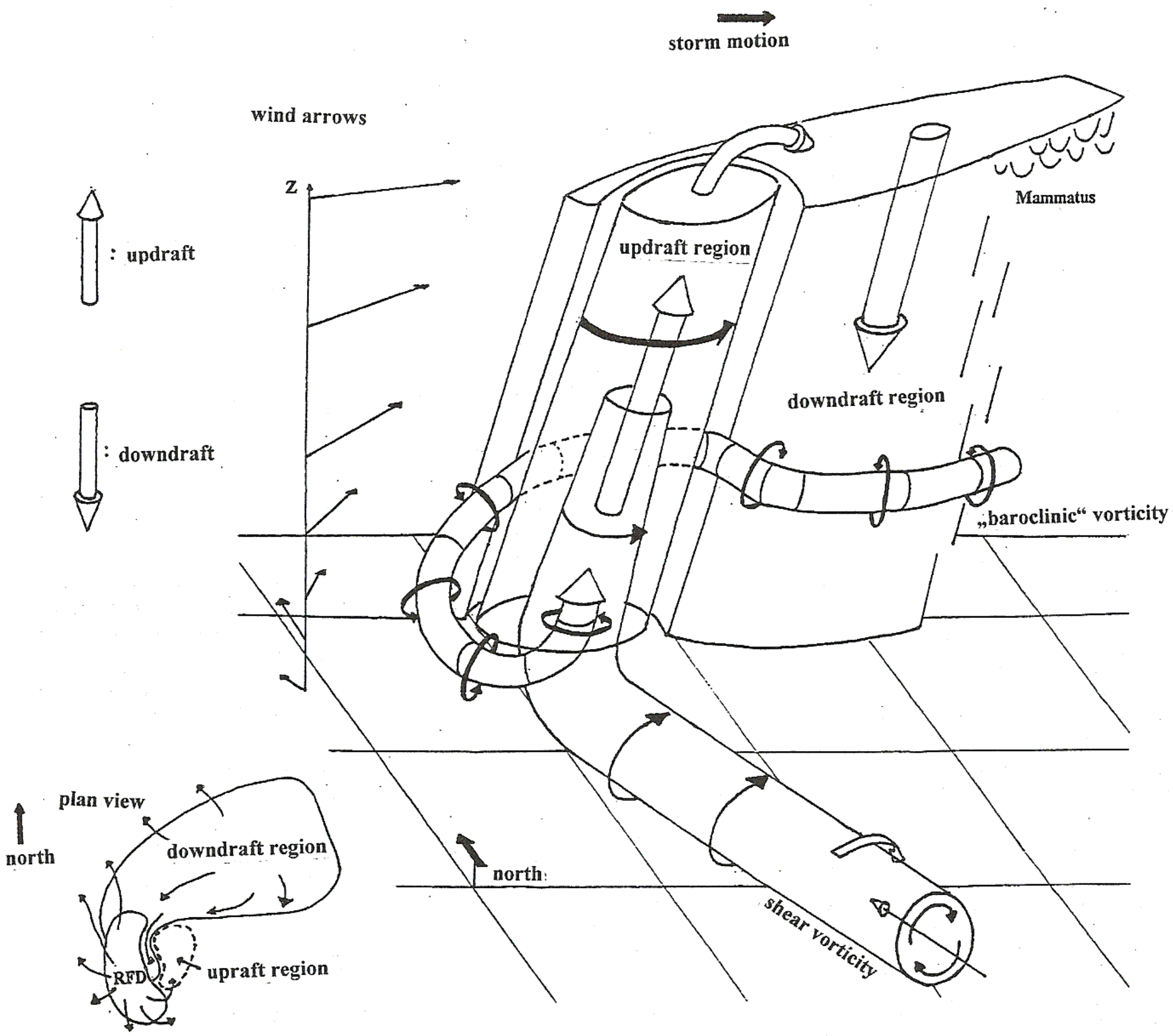


Fig. 2: Sketch of a supercell storm
The environmental shear vorticity is shown schematically as a "tube", that is drawn into the updraft from southerly directions. The "baroclinic" vorticity is represented by another „vortex tube“, originating at the edge of the downdraft region.

2.4. Supercell Thunderstorm Motion

Supercells usually have a significantly deviant motion relative to the mean tropospheric wind vector. A Supercell is exposed to strongly veering storm-relative winds with height, which cause pressure perturbations on the flanks of the cell. Usually, storm-relative winds veer from easterly to southwesterly directions with height. On the southern flank, upward perturbation pressure gradient forces arise due to a pressure drop at mid-levels on the southern side of the thunderstorm cell [*Rotunno and Klemp*, 1982; *Rotunno and Klemp,* 1985; *Davies-Jones*, 1985; *Rotunno,* 1993]. Thus, parcels in the southern parts of the cell experience an upward acceleration, which supports a continuous propagation of the updraft center to the south and additionally an amplification of the mesocyclone. New development on the southern flank is also favored as storm inflow enters from southerly directions.
Thus the cells on August 19 did not follow the mean southwesterly current (roughly represented by the current at 500 mb), but rather moved, owing to the southerly components, directly to the east.

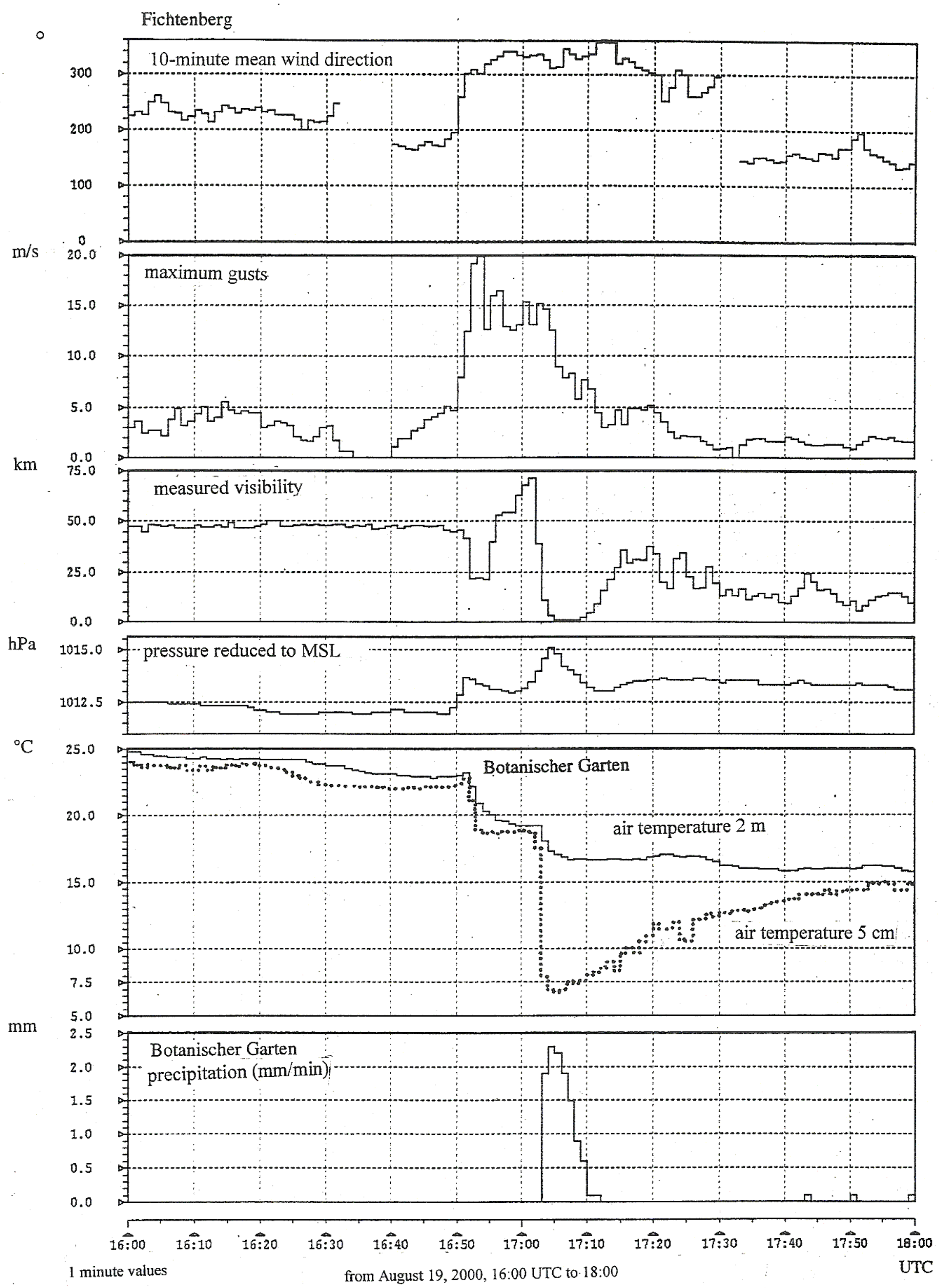
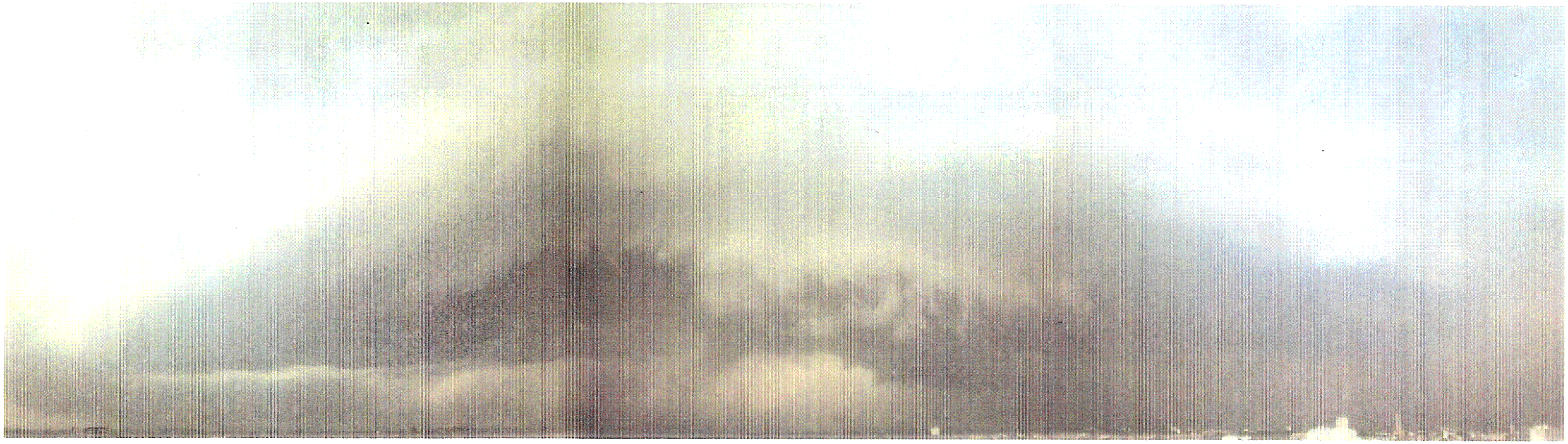


Fig. 6: Some measurements taken at the institute (Fichtenberg/Botanischer Garten):
Note the sudden increase of the visibility at about 17 UTC, which might be associated with RFD air (see 2.3), that has descended from high levels and is thus fairly dry and clear.
With the approach of the northern cell, the wind shifts to 165°, after having been calm for a short time. After the passage of the outflow boundary, the wind blows from northwesterly directions with gusts up to 20 m/s (45 mph).



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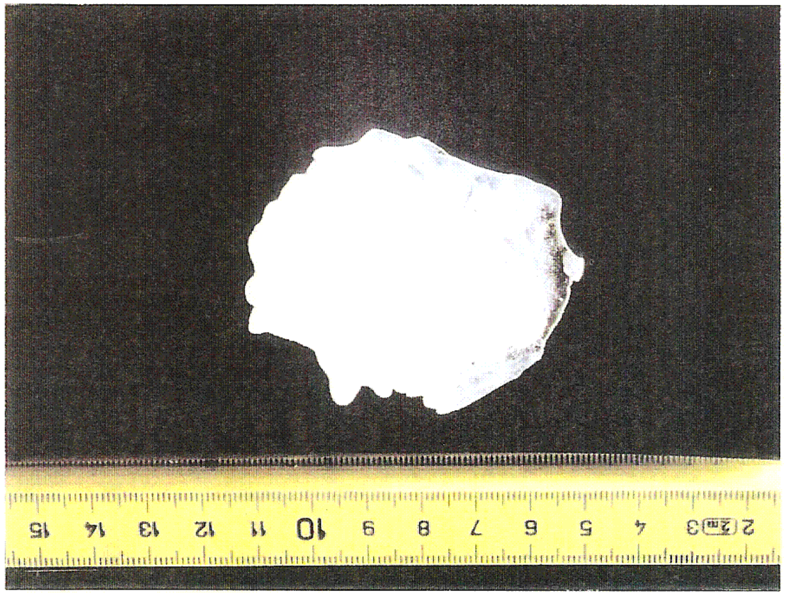

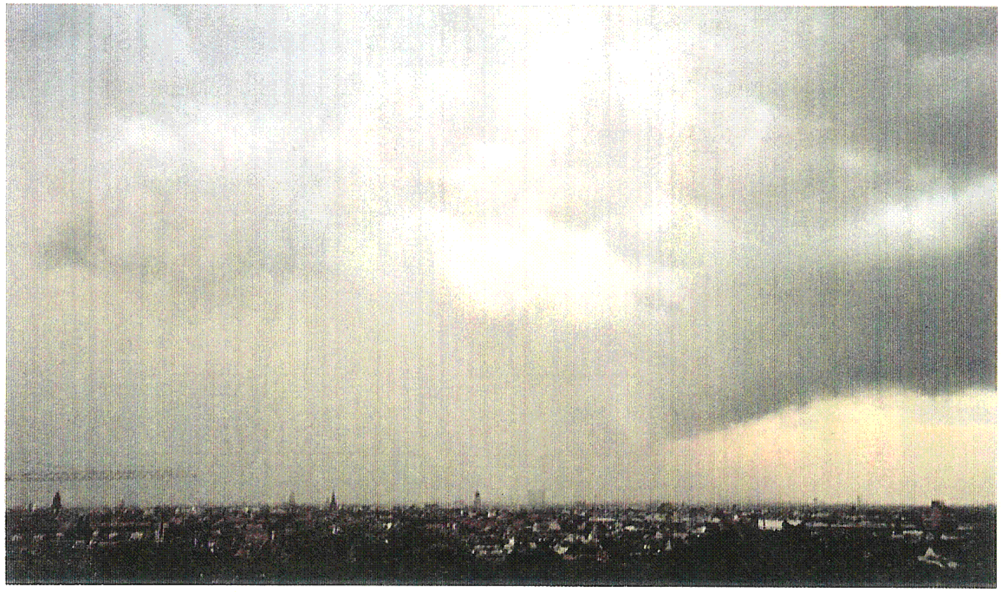

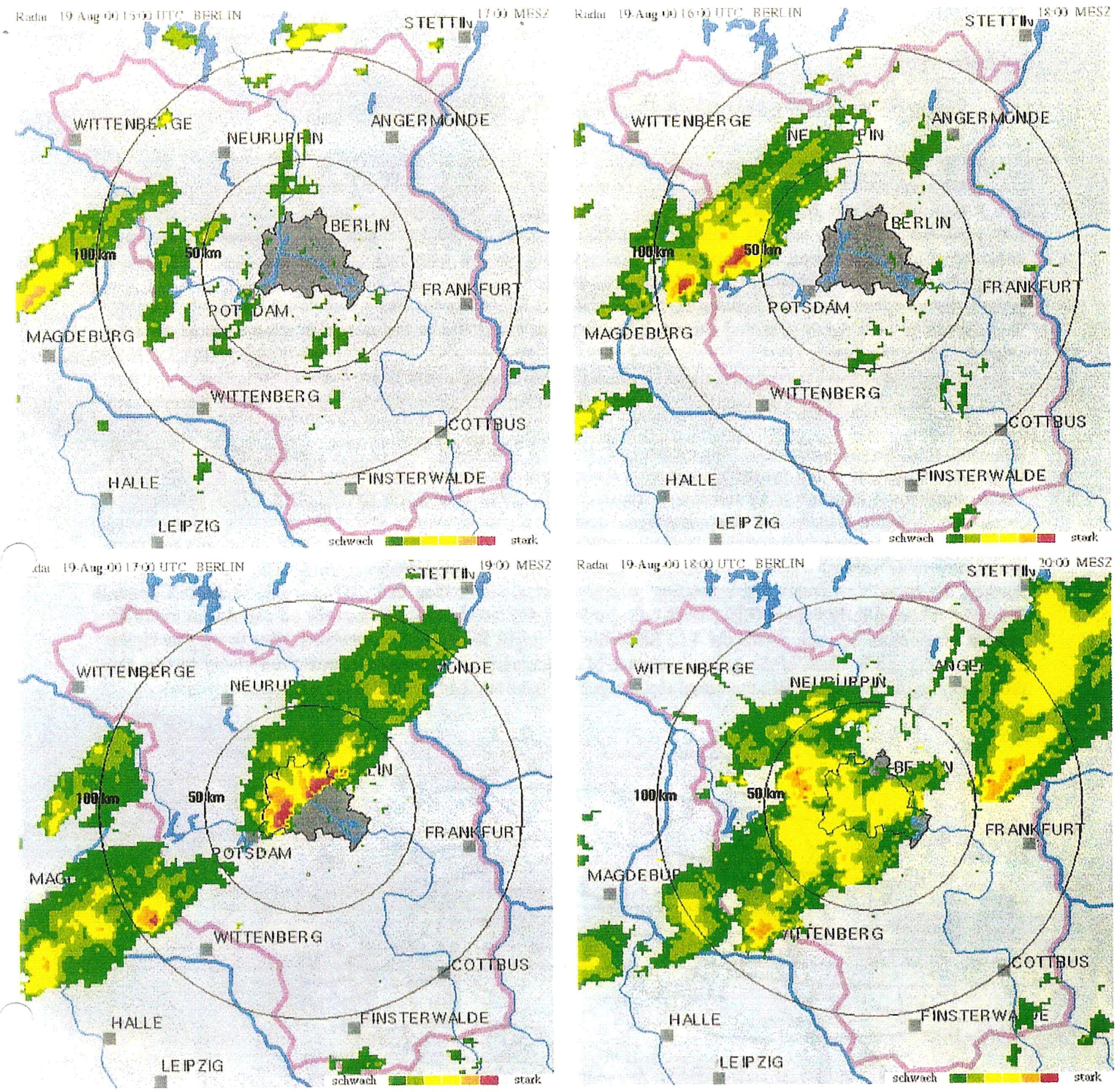

Fig 5. Radar data (this page)

left top: 1500 UTC: North of Magdeburg strong echoes, which are associated with the supercellular storms, emerge; right top: 1600 UTC: The cells reach Brandenburg (the area enclosed by the red line) and amplify considerably. Note the deviant motion to the east despite the general southwesterly current; Left bottom: 1700 UTC: The two supercells are located exactly over the western parts of Berlin. At this time, the cells have the highest reflectivity and produce large hail; right bottom: 1800 UTC: The supercells weaken and further (non-severe) thunderstorms cross Berlin.

Figure 4 (previous page):

Panorama of the northern supercell to the west

This image is a composite of three pictures made at 1650 UTC. Some prominent supercell features are visible: The striated updraft, which exhibits a spiral structure (barely seen on this image); further below, the ragged cloud features mark the position of the gust front. In the center, the wall cloud, which is just about to dissipate, can be seen, while to its right the main downdraft region is located. To the left, precipitation suggests the presence of the RFD .

Hail stone found in Berlin-Hönow-

by Marta Schwarz: The hail stone has a diameter of 6,3 cm (2.48 inches) and weighes 31 grams. The opaque center is surrounded by clear ice (not very well visible on the photograph). Like the hail stones found in other parts of Berlin, this one has a rather irregular shape.

Hail core over "Berlin-Mitte"

This picture was taken at 1655 UTC fom the institute in Berlin-Steglitz.

3. Observations

3.1 Analysis of the Sounding from Lindenberg of August 19, 2000 18:00 UTC (Fig.1)

The updraft region of the northern supercell exhibited laminar features at its base (so-called "striations"). The 18 UTC rawin -sonde data from Lindenberg, which represent the air mass in which the storms developed quite well, show a significant stable layer between 950 mb and 780 mb for boundary-layer parcels. Above this layer the parcels become positively buoyant. This level is called the level of free convection (LFC). Either the capping stable layer must be eroded by synoptic- or mesoscale lift, or the boundary-layer parcels must be punched through the stable layer to their LFCs by some source of lift.
In the latter case, laminar cloud features develop below the LFC, where the rising parcels are negatively buoyant. This appears to be a result of strong laminar inflow into the cloud. These features often show a spiral structure when the cell is rotating.
The necessary low-level convergence might be caused by lift along the gust front. Vertical perturbation pressure forces (see also 2.4) might also contribute to upward acceleration. [*Rotunno and Klemp*, 1982; *Rotunno and Klemp,* 1985].
It is worth mention that CAPE was rather weak with only 598 J/kg in the vicinity of the storms (see sounding, Fig 1). In general, CAPE is the "positive" area on a thermodynamic diagram. It is likely, however, that the CAPE values represented here are a bit too low to represent the actual near-storm environment. This is suggested because surface temperatures and dewpoints were somewhat higher elsewhere in this air mass than in Lindenberg at the time of the ascent. Nevertheless, this shows that even in a low-CAPE environment, supercells can form given a favorable vertical wind-shear profile [see also *Kerr and Darkow*, 1996].
Further, the sounding reveals that ascending parcels became cooler than their environment at about 270 mb. However, this equilibrium level (EL) cannot be regarded as the cloud-top level since the parcels do not lose their upward momentum at once above the EL. Since the EL might have been somewhat higher (owing to higher CAPE values) and because of the gradual increase of the temperature difference between the rising parcels and the surounding air above the EL, the actual cloud tops may have reached up to 200 mb (tropopause height).

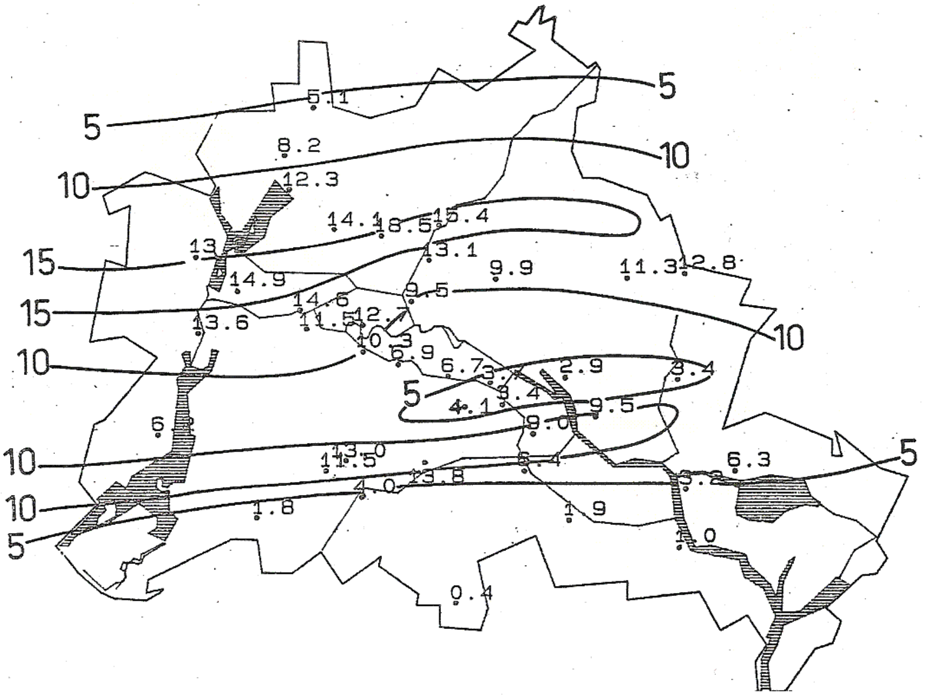

Fig. 3: The distribution of precipitation in Berlin (in mm)
The two cells that crossed Berlin from west to east left two elongated zones of precipitation. Within the track of the northern cell almost 20 mm (0,78 inches) of rain were recorded despite the fast storm movement. The path of the other cell, which hit primarily the southern parts of Berlin, is somewhat more distinct in the south because the precipitation fields of both cells overlap to the north.

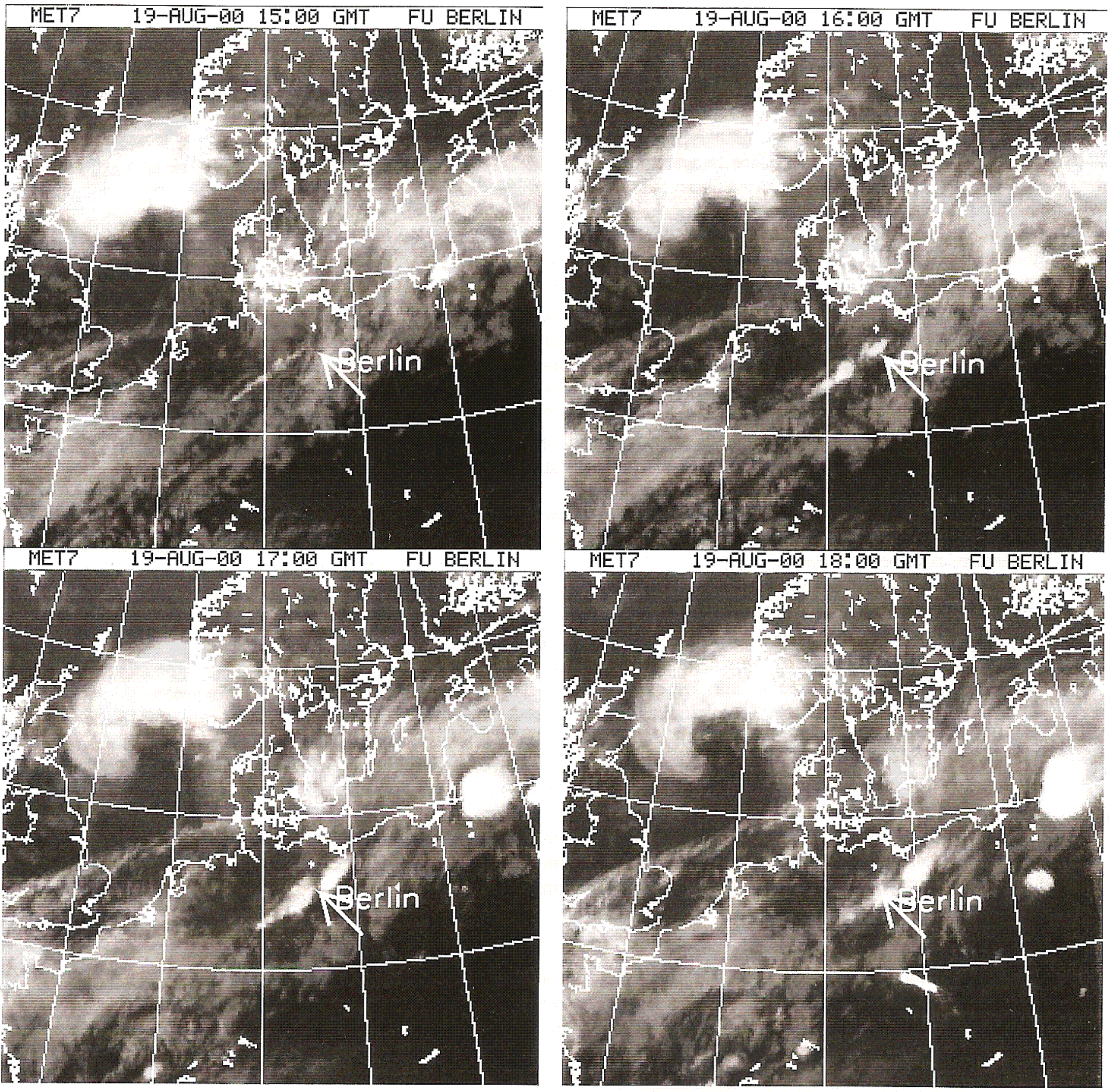

Fig. 7: METEOSAT IR-imagery
left top: 1500 UTC: The low pressure system "Oktavia" is located over the North sea. Its cold front trails southwestward across Denmark and northern Germany to France. A line of deep convection forms over central Germany along the cold front; right top: 1600 UTC: The bright spots denote low cloud-top temperatures; left bottom: 1700 UTC: The storms are located directly over Berlin; the cloud tops probably reach up to 12 km (40, 000 ft); right bottom: 1800 UTC: The cells begin to dissipate; note the rapid cell growth over east Poland and the MCS over the Baltics.

3.2 Observations from the Institute (Berlin-Steglitz)

The course taken by the weather that afternoon was observed attentively from the meteorological Institute of the Free University of Berlin.

In association with the inversion described above, mid-level clouds (Altocumulus, Altostratus) had been dominant for most of the day and thus strong surface heating and convective mixing within the boundary layer had not been possible. Correspondingly, the convective temperatures derived from the Lindenberg soundings, were much higher than the surface temperatures. Nonetheless, small Cumulus clouds developed, since locally much higher surface dewpoints were measured than in Lindenberg.

At about 13 UTC, first convective activity occurred near Cologne. In this area, the conditionally unstable air had advanced above the boundary layer, and elevated storms were initiated along the cold front. By 15 UTC, a line of thunderstorms had developed, which reached from the "Rothaar Mountains" to the "Brandenburgische Altmark" (Fig. 7). Shortly after this, an amateur station reported 12 mm (0.47 inches) of precipitation within 6 minutes and hail up to quarter size. At this time, first strong echoes north of Magdeburg appeared on the radar sceen (Fig. 5). These storms had apparently been initiated above the boundary layer as well.

Around 15 UTC, two particularly intense cells evolved about 60 miles west of Berlin and impressive convective towers could be observed at the western horizon, in spite of their great distance to the institute. These cells moved directly to the east towards the metropolitan area. The north one of these cells reached Berlin first. Shortly after 16 UTC an impressive image was provided: The huge Cumulonimbus cast a dark shadow upon the mid-level clouds, and the tilted updraft, which displayed striations, became visible. Although the storms were about 20 miles away, thunder roars could be heard.

From 1630 UTC, the striations were well pronounced and a cyclonically rotating wall cloud began to form. At this time, severe hail was reported from northern parts of Berlin (Spandau). At 1645 UTC, a funnel shaped cloud appendage developed below the wall cloud. It did not develop any further, however, and vanished after a short time. While the main precipitation of this cell was located over the central parts of Berlin, the institute was crossed by a marked gust front. The wind shifted from southeasterly to northwesterly directions; gusts up to 20 m/s (45 mph) were measured and the pressure rose by almost 2 mb.

At 1700 UTC the hail core of the southern supercell hit Berlin-Zehlendorf (southwest Berlin). Three minutes later, severe hail of quarter to walnut size commenced at the institute and lasted for seven minutes. Within 9 minutes 11,5 mm (0.45 inches) of precipitation were measured. The downdraft caused a further pressure increase of 2 mb. The 2m-temperature dropped to 17°C (62.6°F). The 5 cm-temperature (2 inches above ground), which decreased already with the passage of the gust front by 4 Kelvin, fell further by 12 Kelvin to 6,7°C (44°F), resulting in thick ground fog. To the west patches of fog came up, which rose between the trees. The development of the weather at the institute is shown in the diagrams (Fig. 6).

The storms struck almost every part of Berlin, locally hen-egg to tennisball-sized hail was reported, for instance in Wannsee, Wedding, Mahlsdorf and Hohenschönhausen. According to radar data, the cells began to weaken just east of the metropolitan area and dissipated about 60 miles east of Berlin.

Acknowledgements

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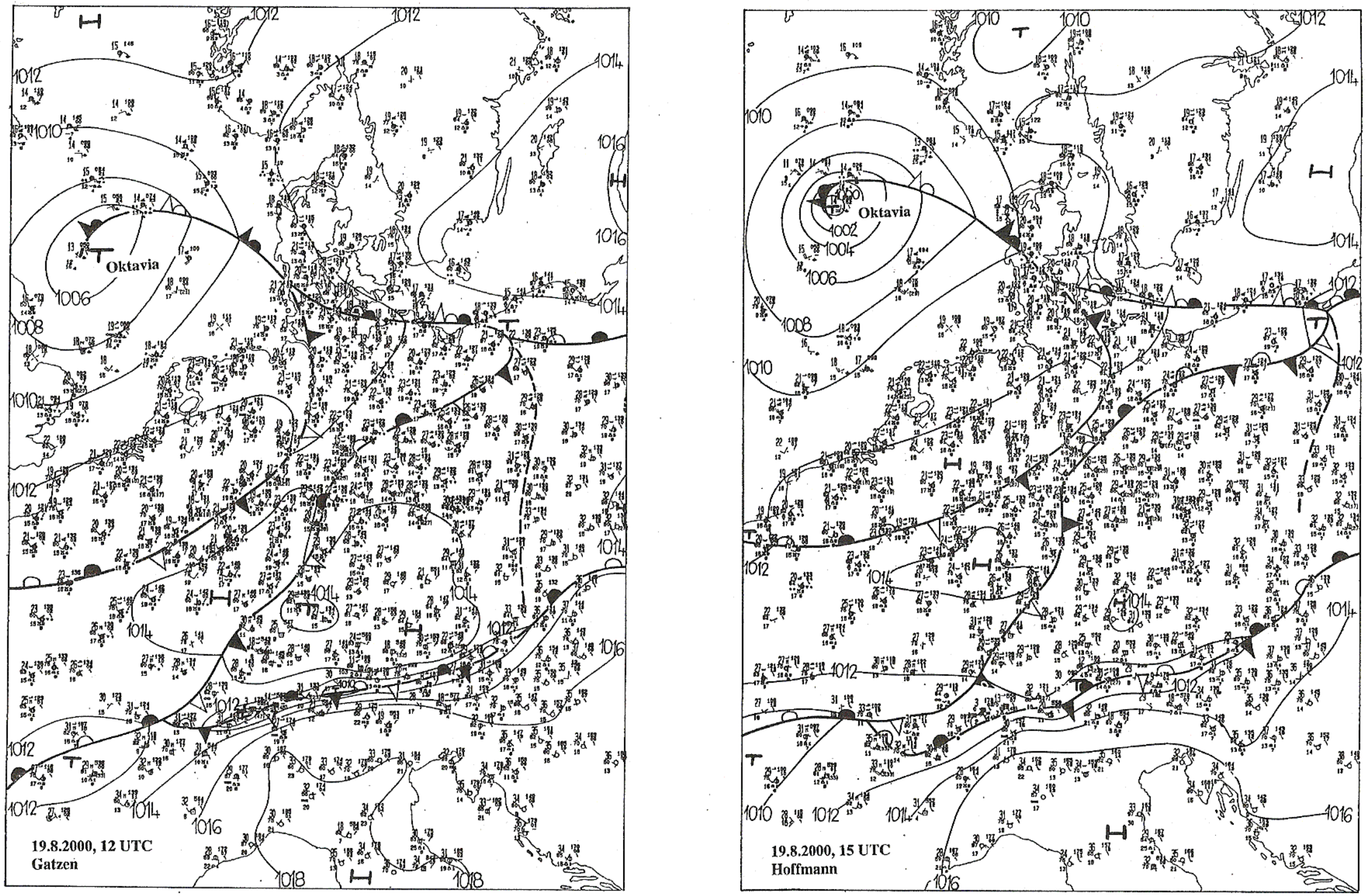
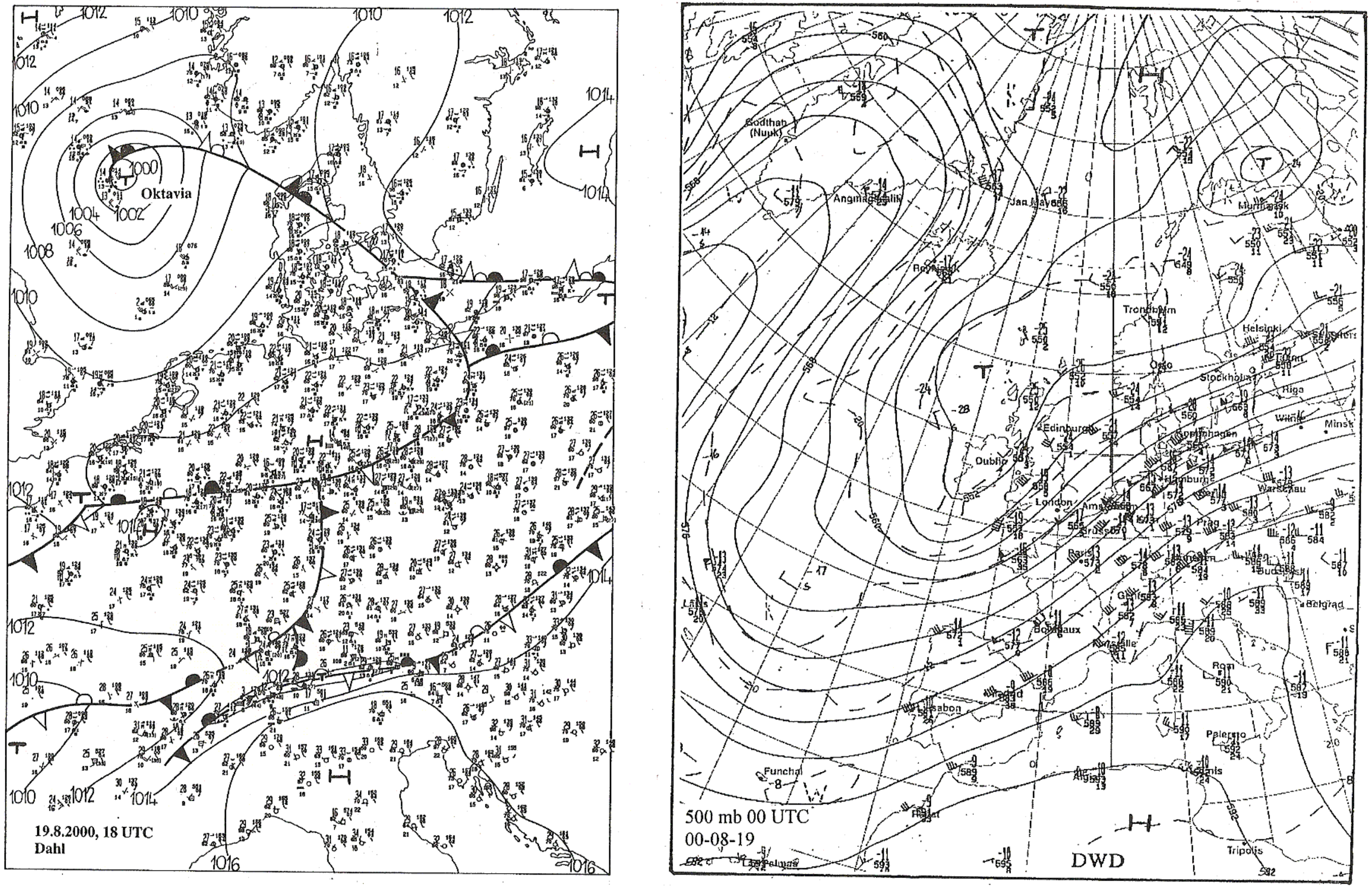


Synoptic charts I.
Left: Surface analysis, 12 UTC: The situation at the surface is characterized by two frontal boundaries: The cold front associated with „Oktavia", and another boundary lying nearly diagonally over Germany; south of this boundary, the conditionally unstable xS-air mass is dominant, which advances slowly northward. In the Alpine regions, a third (quasi-stationary) front separates dry, hot air in the Mediterranean regions from the xS-air mass. At 15 UTC (right chart) the xS air has reached Berlin.



Synoptic charts II.
left: Surface analysis, 18 UTC: The cold front has crossed Berlin; the rapid eastward movement of the surface front may well be a result of thunderstorm outflow; right: 500 mb geopotential height and isotherms: At the eastern side of the long-wave trough, a strong jet stream is present. A short wave, that is developing over France crossed northwestern Europe in the afternoon of August 19 and might have contributed to convective initiation along the cold front.

Notes:

Airmass nomenclature used in the text (according to *Geb,* 1971):

„xS“ is subtropical air, that has both, continental and maritime characteristics. xS-air typically originates from the Mediterranean Sea.

„mS“-air (maritime subtropical) is cooler but more moist than the xS; usually, mS air is generated over the southern Atlantic. Its THETA-e values are generally lower than those of the xS.

„cT“-air is continental tropical air that originates from the Sahara Desert. Although it often plays an important role in severe convective weather events in Germany, it seldom penetrates to the surface. Note that on August 19, 2000, the cT-air was not present over northeastern Germany.

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