Atmosphärenphysik: Severe Storms and Hail

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in Anlehnung and Rogers and Yau, Kapitel 13 und mit ergänzenden Graphiken aus Houze: Cloud Dynamics

Life cycle of the thunderstorm cell

- Observations show that thunderstorms typically are made up of one or more units of convective circulation, consisting of an updraft area and a region of compensating downward motion.
- Often a cloud is made up of a number of cells in various stages of development, and it is difficult to identify any individual cell. However, it is convenient to consider the thunderstorm cell as the elementary unit of the storm structure.

Life cycle of the thunderstorm cell

- The life cycle of a cell is divided into three stages, depending on the predominant direction and magnitude of the vertical air motion:

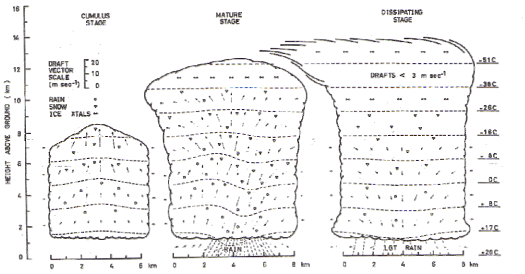


FIG. 13.1 The Byers–Braham model of a thunderstorm cell, indicating air motions and precipitation forms. (From Chisholm, 1973.)

Life cycle of the thunderstorm cell

1. Cumulus stage - characterized by an updraft throughout most of the cell.
2. Mature stage - characterized by the presence of downdrafts and updrafts.
3. Dissipating stage - characterized by weak downdrafts throughout most of the cell.

- As the updraft causes the cloud to grow in the cumulus stage, air flows in through the sides of the top (entrainment) and mixes with the updraft. With continued upward motion a large amount of water condenses and eventually falls as precipitation. This falling water initiates the downdraft because of viscous drag of the water on the air and evaporative cooling of the air. This is the start of the mature stage of development. The air of the downdraft reaches the surface as a cold core in the rain area and spreads over the surface, changing the surface wind pattern.

Life cycle of the thunderstorm cell

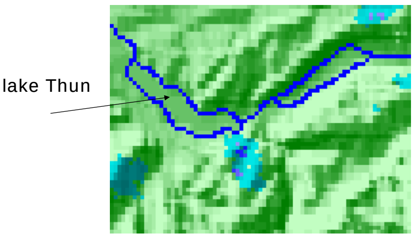
- The downdraft interferes with the updraft at low levels in the cloud, and eventually cuts off the updraft from its source region. The cell then enters its dissipating stage. With the decay of the updraft and consequent elimination of the source of rainfall the downdraft weakens and finally dies out completely, leaving a residue of cloudy air.

- The cumulus stage typically has a duration of 10-15 min. The mature stage lasts 15-30 min; though difficult to specify definitely, the dissipating stage lasts about 30 min.

- Larger thunderstorms often consists of several convective elements in different stages of development. The storm system then has a longer lifetime than the individual elements.

Saxetenbach

Canyon accident, 27 July 1999



Life cycle of the thunderstorm cell

- Because of the change of the environmental wind with height, the updraft and downdraft are horizontally displaced from one another and can interact mutually to sustain a strong, long-lived circulation. First analyzed by Browning and Ludlam (1962), this kind of storm circulation has become known as a "supercell".
- Figure 13.5 is a schematic diagram showing horizontal sections of a supercell echo at three altitudes. The key to this kind of storm is the ambient wind and its variation with height, indicated her by the vectors labeled H,M,L. The updraft enters at low levels and ascends into the region called by Browning the "vault". The updraft is so strong that precipitation is not able to grow to radar detectable size in the vault region. When precipitation does form at higher levels the wind shear prevents it from falling into the updraft at low levels and cutting off the circulation. This circulation is shown in more detail in Figure 13.6.

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Life cycle of the thunderstorm cell

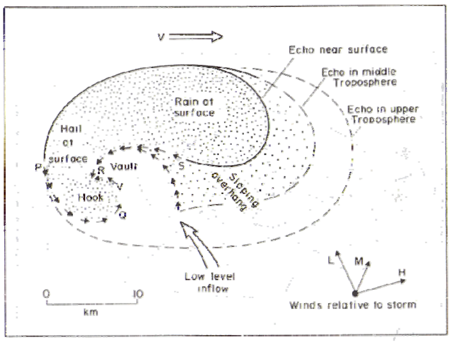

FIG. 13.5. Schematic diagram showing horizontal sections at three levels through the radar echo of a supercell storm. (From Browning, 1964.)

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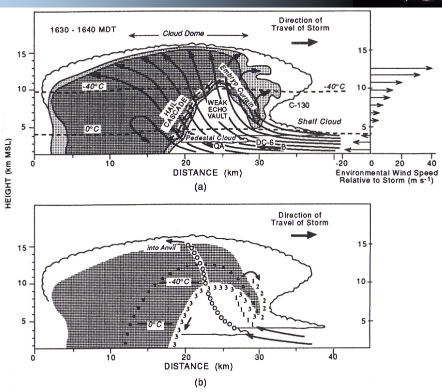
Hailstorm



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Supercell development

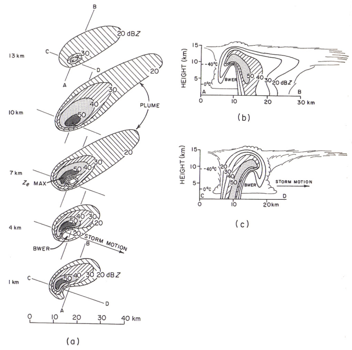

Figure 8.11 Schematic illustrating the variation of radar reflectivity patterns with height in supercell thunderstorms observed in Alberta, Canada. Horizontal sections of reflectivity (dBZ) at various altitudes are shown in (a). Vertical sections are shown in (b) and (c). Cloud boundaries are sketched. BWER refers to the bounded weak echo region. (From Chisholm and Renick, 1972.)

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Supercell with hook echo

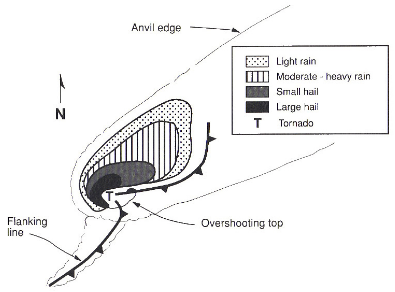

Figure 8.10 Idealized plan view of a supercell thunderstorm as it would appear in a satellite picture and in the low-level precipitation pattern that would be detected by a horizontally scanning radar. Cloud features seen by satellite include the flanking line, the edge of the anvil cloud, and the overshooting cloud top. Positions of the gust front (given by frontal symbols) and tornado are also shown. (Based on U.S. National Severe Storms Laboratory publications.)

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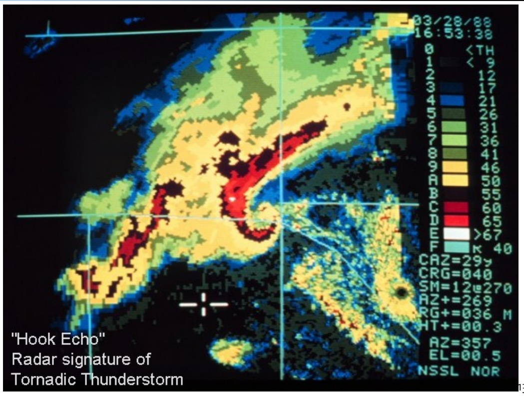
Hook Echo



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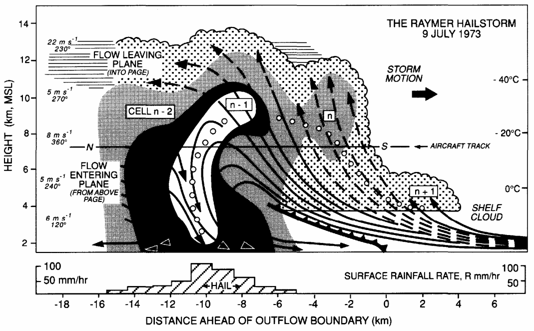
The Raymer Hailstorm 1973



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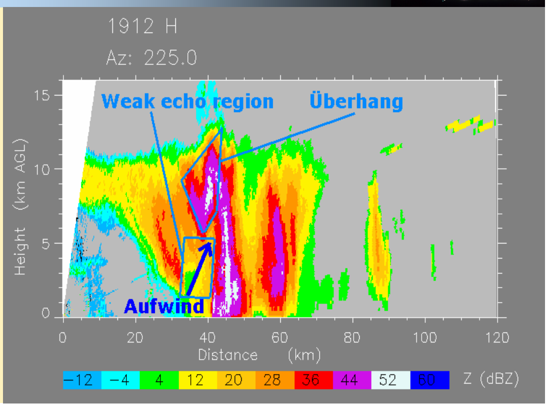
RHI vom Gewitter am 8. Mai 2003



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Life cycle of the thunderstorm cell

- Because of their size and destructiveness, supercell storms have received much attention over the past few years. Yet they occur rather infrequently, owing provably to the special wind pattern required for their existence. A more frequently occurring storm, which can also be large and severe, is the "multicell" storm in Figure 13.7.
- Individual thunderstorm cells develop successively on the RHS of a large storm complex. Though each cell has a limited life cycle, the systematic development of new cells produces a long-lived storm. The distinction between supercell and multicell storms may not always be clear; some storms exhibit a supercell shape yet on close inspection are found to contain small-scale elements of short lifetime.

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Life cycle of the thunderstorm cell

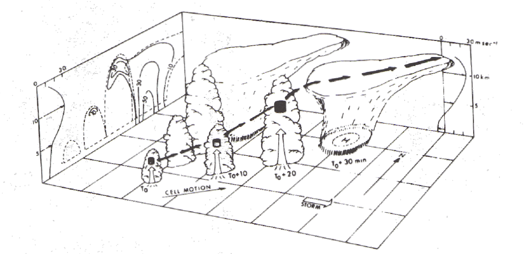


FIG. 13.7. Schematic view of a multicell storm. At the initial time the storm consists of four cells at different stages of development. The development of the youngest (southernmost) cell at successive times is indicated. The heavy dashed arrow is the trajectory of a parcel in the growing cell. A vertical section of the radar echo at the initial time is shown, as well as an indication of the wind profile. (From Chisholm and Renick, 1972.)

Multicell storm

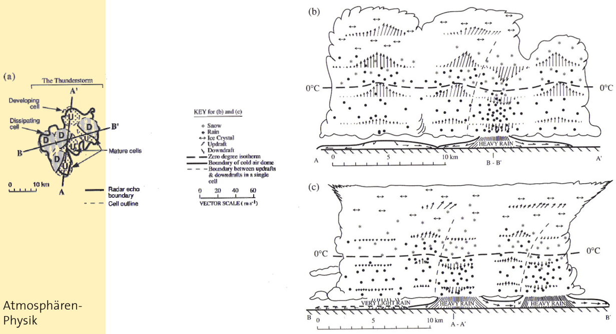
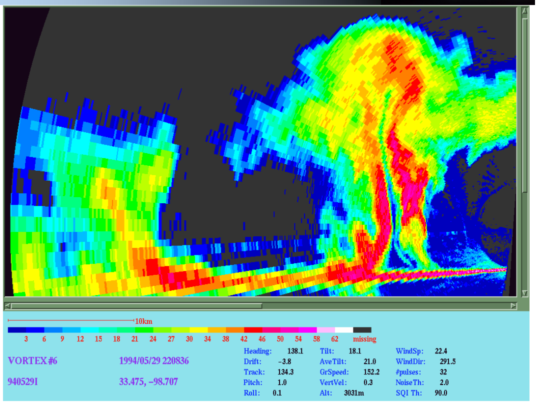


Figure 8.5 Schematic of a multicell thunderstorm in Ohio observed in the Thunderstorm Project. The storm consisted of cells in various stages of development. (a) Plan view. (b) Vertical cross section along A–A′. (c) Vertical cross section along B–B′. (From Byers, 1959. Reproduced with permission from McGraw-Hill, Inc.)

Tornadoes

- One of the most destructive manifestations of a thunderstorm is the tornado. Tornadoes form in supercell thunderstorms that have developed in environments of strong wind-shear and large convective instability. Observations with Doppler radars have shown that a precursor of tornadoes is the development of a mesocyclone – a horizontal circulation about 10 km across with values of vertical vorticity in the order of 0.01/s. Evidently the circulation within small regions of the mesocyclone can become intensified by convergence and the conservation of angular momentum to produce intense vortices with a horizontal extent of a few hundred meters.

Tornadoes



Precipitation production by thunderstorm

- Water that condenses in a thunderstorm updraft is either present in the form of cloud or precipitation or has evaporated. The mass *M* that has condensed up to time *t* may be written:

$$M(t) = C(t) + P(t) + F(t) + E(t)$$

- where *C* is the mass of cloud water at time *t*, *P* is the mass of precipitation aloft, *F* is the mass of precipitation that has reached the ground and *E* is the amount of cloud and falling precipitation that has evaporated. From a series of radar observations of the 3D structure of a thunderstorm it is possible to obtain estimates of two of the terms in this water budget.

Precipitation production by thunderstorm

- using an empirical relation between reflectivity and precipitation content (a Z-R relation) and integrating over the storm volume provides an estimate of *P(t)*. Also applying a Z-R relation to the data in a horizontal plane at a low altitude, and integrating over area, yields an estimate of the instantaneous outflow of precip, *dF/dt*. Integrating this over time gives *F(t)*.

- Define precipitation generating rate:

$$g(t) = \frac{dP}{dt} + \frac{dF}{dt}$$

- the cumulative amount generated up to time *t* is then given by:

$$G(t) = \int_0^t g(s)ds = P(t) + F(t)$$

Precipitation production by thunderstorm

- The ratio $P/(dF/dt)$ has dimensions of time and may be thought of as the characteristic time of the precipitation process. All these quantities can be evaluated from radar data. Several studies of this kind, summarized by Rogers and Sakellariou (1986), led to the following conclusions:

1. Precipitation content of a typical isolated thunderstorm is about 1 Tg during its mature stage of development.
2. The rate of outflow dF/dt is about 10^6 kg/s. If assumed that the area covered is 5 km x 5 km, this corresponds to 15 cm/h.
3. P and dF/dt fluctuate during the storm's history, but are closely correlated with each other.

Precipitation production by thunderstorm

4. The characteristic time of the precipitation process averages about 20 min during the mature stage.
5. The total outflow from a thunderstorm during its lifetime can exceed the amount P that is present in the cloud at any time during its mature stage by a factor of 5 or greater. Equivalently, the lifetime of a thunderstorm can exceed the characteristic time by a factor of 5 or greater.

- Very large thunderstorms or mesoscale storm-complexes can have precip amounts and outflow rates far in excess of these estimates.

Hail growth

- Hailstones are formed when either graupel particles or large frozen raindrops grow by accreting supercooled cloud droplets. Thunderstorms contain both graupel and large drops, and it is not known which serves most frequently as the hail "embryo", although photographic evidence generally points to graupel.
- An important aspect of hail growth is the latent heat of fusion released when the accreted water freezes. Owing to this heating, the temperature of a growing hailstone is several degrees warmer than its cloud environment. In the theory of hail development, the temperature is determined by assuming a balance condition for the hailstone heating rate.

Hail growth

- The heating rate due to accretion of supercooled liquid droplets is given by:

$$\frac{dQ_l}{dt} = \pi R^2 EMu(R)\left[L_f - c(T_s - T)\right]$$

where R is the radius of the stone and $u(R)$ its fall speed, L_f is the latent heat of fusion, c the specific heat of water, M the cloud liquid water content and E the effective collection efficiency, and T_s and T are the temperature of the hailstone and the ambient cloud.

- The heat gained by water vapor deposition is

$$\frac{dQ_v}{dt} = 4\pi RDL_s a\left(\rho_v - \rho_{vR}\right)$$

where ρ_v and ρ_{vR} denote the ambient vapor density and that at the surface of the stone, and a is a ventilation faction depending on hailstone size.

Hail growth

- The rate at which heat is lost to the air by conduction is

$$\frac{dQ_s}{dt} = 4\pi RK\left(T_s - T\right)b$$

where K is the heat conduction coefficient of air and b is ventilation factor.

- Equilibrium exists when

$$\frac{dQ_l}{dt} + \frac{dQ_v}{dt} = \frac{dQ_s}{dt}$$

which may be used to solve for the hailstone equilibrium temperature as a function of size, for given cloud conditions.

Hail growth

- The hailstone growth rate may be determined to a good approximation by adding the separate rates of growth by accretion and by sublimation. Accretion is usually dominant, and becomes more so as the stone grows. If it remains in the supercooled cloud long enough, the stone reaches the size for which the equilibrium temperature is 0°C, because of insufficient heat transfer to the surrounding (typically this might occur for a diameter of about 1 cm).

Hail growth

- When the surface of the hailstone is at a sub-freezing temperature, the collected water droplets freeze quickly and the surface remains essentially dry. When the surface is at 0°C, however, the collected water does not freeze immediately and the surface is wet. Although some water may be shed by the warm stone, much can remain to be incorporated into the stone, forming what is called the "spongy ice".
- It has been deduced that the entrapped liquid can later freeze if the stone enters colder or less dense cloud, where the heat transfer will suffice to chill the stone below 0°C. During its lifetime, a stone my undergo alternate wet and dry growth as it passes trough ac loud of varying temperature and LWC, thus developing the layered structure that is often observed Figure 13.10.

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30

Hail growth

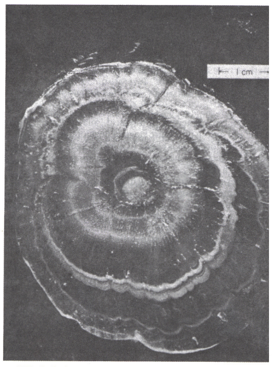
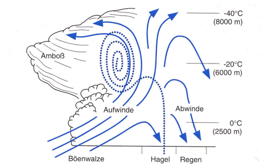


FIG. 13.10. Cross section of a large hailstone, showing the characte layered or "onionskin" structure. (Courtesy B. L. Barge, Alberta Res Council, Edmonton, Can.)



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