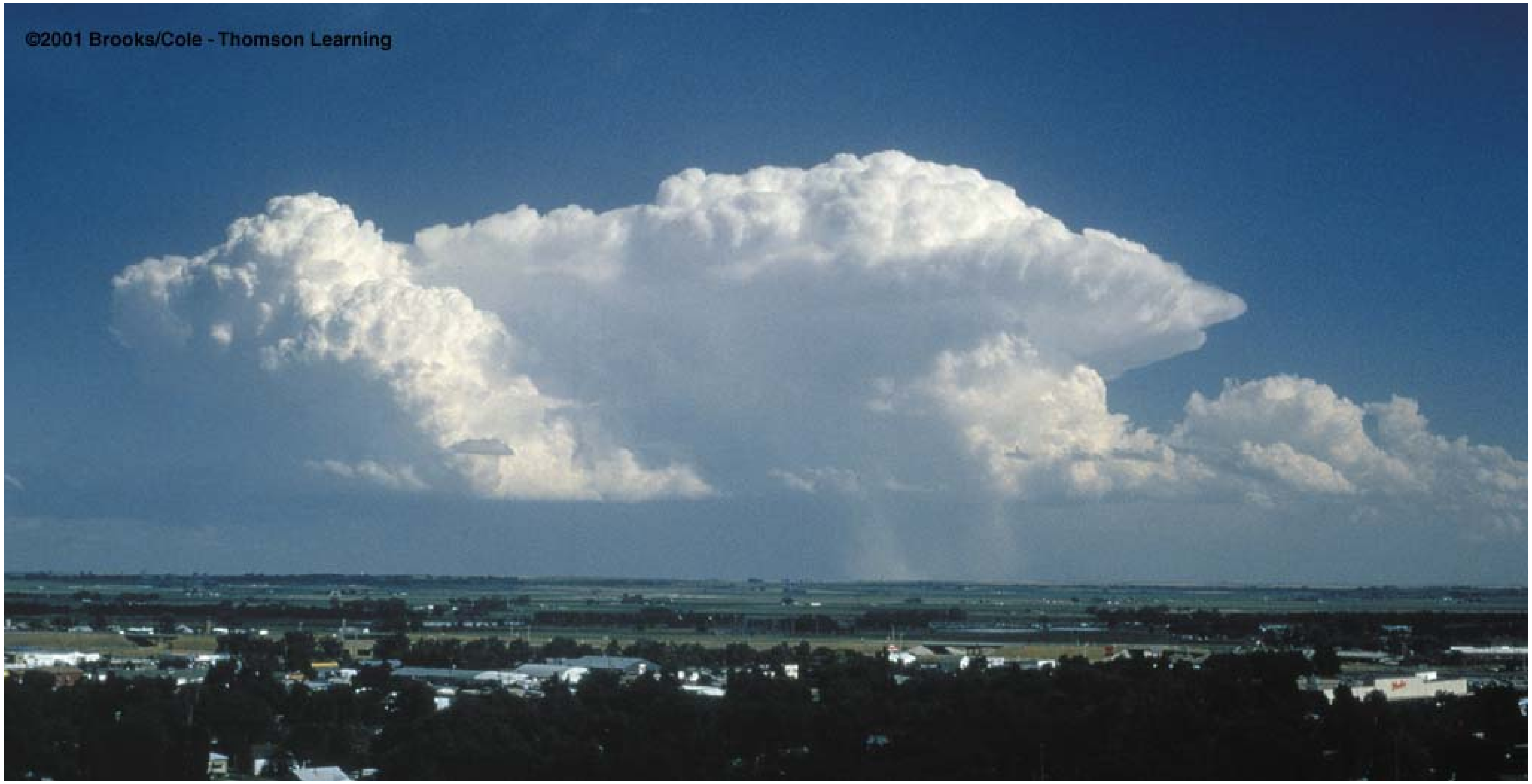
8) Conceptual Models of Cumulonimbi



Outline

8.1) Introduction

8.2) Ordinary Cumulonimbus Clouds

8.3) Severe Thunderstorms

8.4) Tornadic Thunderstorm

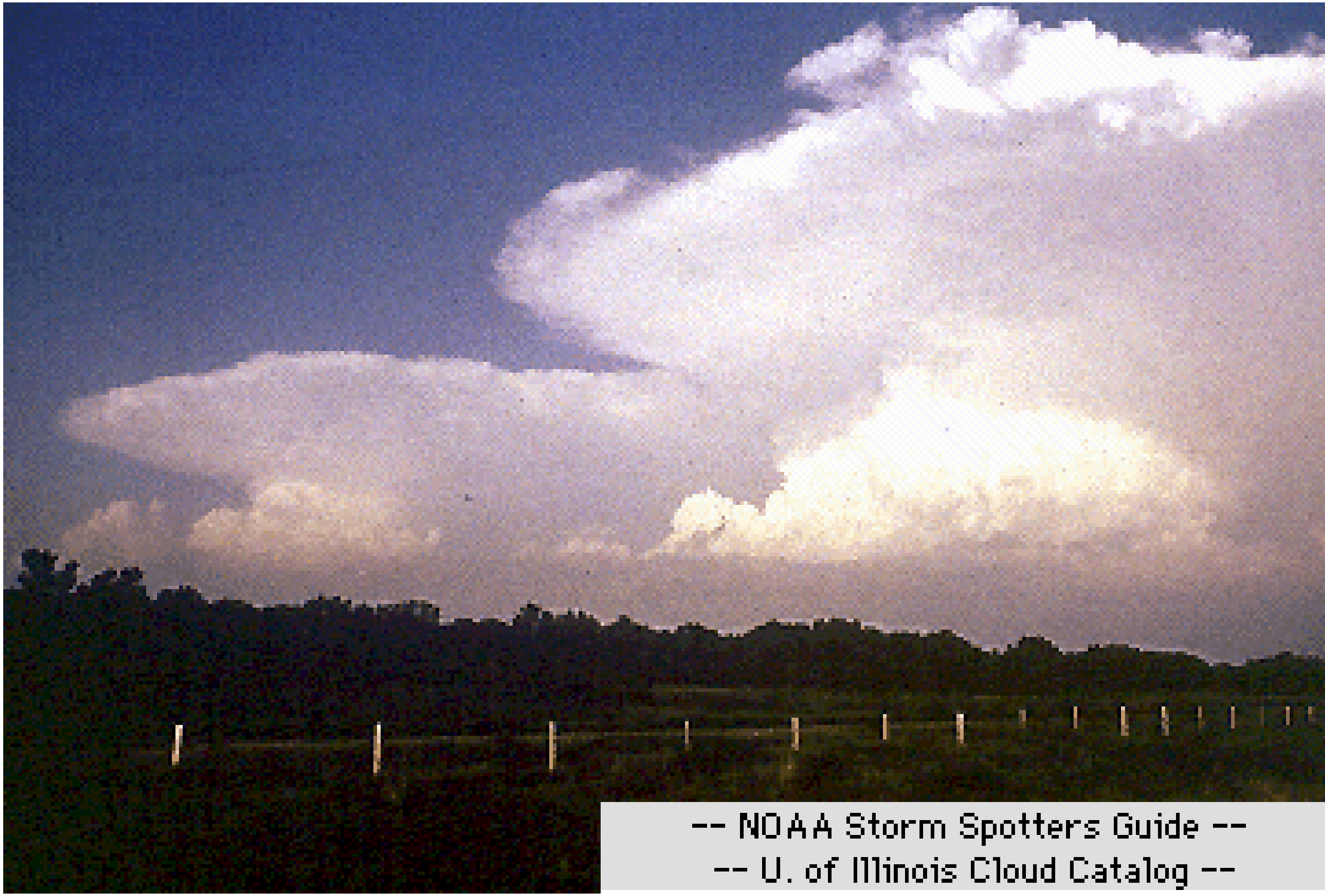
8.5) Hailstorms

8.6) Heavy Rain Producing Thunderstorms

8.1 Introduction

8.1.1 Some Definitions

- **Cumulonimbus**—(Abbreviated Cb.) A principal cloud type (cloud genus), exceptionally dense and vertically developed, occurring either as isolated clouds or as a line or wall of clouds with separated upper portions (from the AMS Glossary)
- **Cumulonimbus** - The parent cloud of a thunderstorm. The cumulonimbus cloud towers above ordinary cumulus clouds, with stronger or severe storms often having a more sharply outlined "hard" appearance with relatively rapid rising motions visible. The cloud's upper portion includes the anvil. Accompanying precipitation is often heavy and the usual occurrences of lightning and thunder with these clouds leads to the popular names of thunderhead or thundercloud (NWS Storm Spotter’s Glossary)


-- NOAA Storm Spotters Guide --
-- U. of Illinois Cloud Catalog --

8.1.2 Weather Associated with Thunderstorms

- Heavy rains, hail, lightning, straight-line winds, downbursts and tornadoes may be associated with thunderstorms
- Flash-flooding
  - Number one cause of weather-related deaths in the USA
  - June 9 1972: 38 cm (15”) of rain fell in Rapid City, ND within 5 hours –> 238 fatalities and $168 million in property damage
  - July 28, 1997: 25 cm (10”) of rain fell in Fort Collins, CO within 6 hours –> 5 fatalities and $200 million in property damage
  - Caused by rainfall intensity and duration

- Hail
  - Over $1 billion in damaged drops annually and countless dollars in property damage
- Lightning
  - ~ 7 700 000 cloud to ground lightning strikes per year (15 per minute)
  - 90 deaths and 272 injuries annually
  - Majority of casualties in eastern states, as well as CO and TX
- Straight-line Winds
  - Significant property damage due to its frequency
- Downbursts
  - Area of strong winds produced by a downdraft
  - Serious threat to planes in the air and structures on the ground
- Tornadoes
  - Damage ranges from broken tree branches to houses being lifted off their foundations

8.1.3 Thunderstorm Classification

•Typical thunderstorm is made up of a single cumulonimbus cloud (cell) – this cloud is formed by a strong, vertical updraft and is the building block of all other types of storms

• Cell: normally identified on radar as a relatively intense volume of precipitation

Damage Potential	**Storm Structure**
Ordinary	Single cell
Severe	Multi-cell -> clusters -> lines
	Supercell

• Ordinary storms are typically single cell storms, while severe storms are typically multi-cellular or supercellular

8.1.4 Thunderstorm Distribution

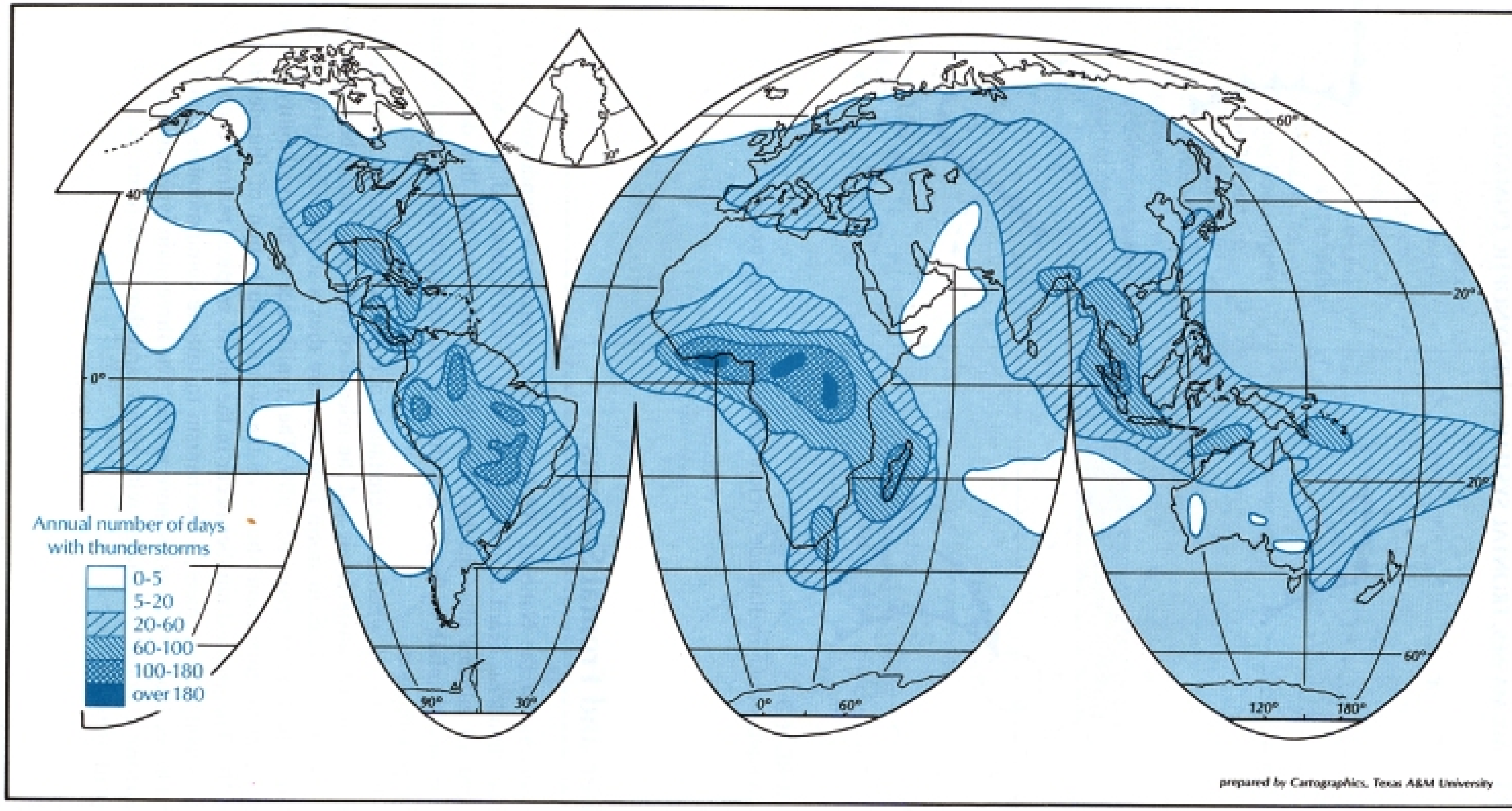
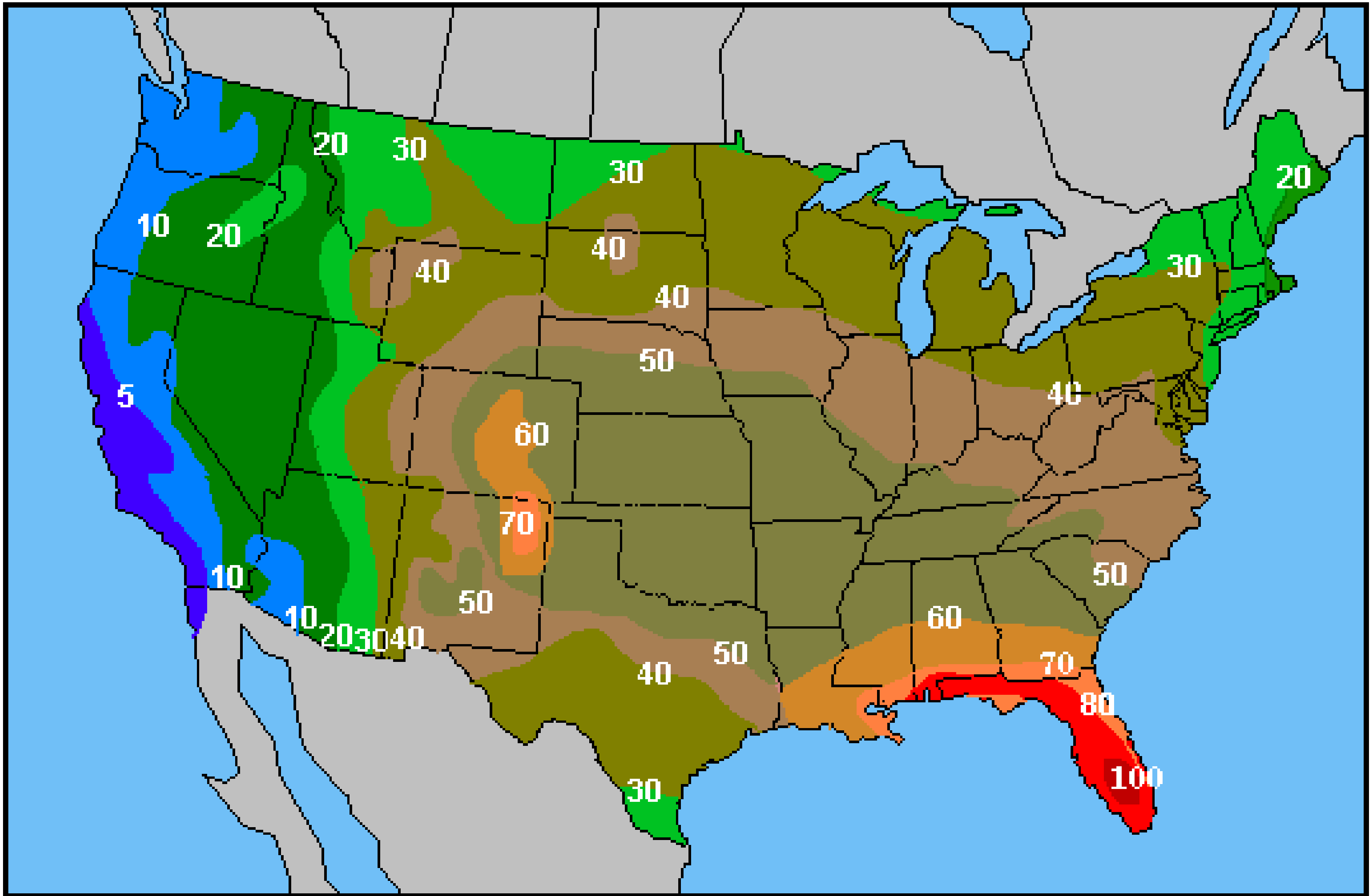


FIGURE 10.10
World distribution of thunderstorms.
Source: After S. D. Gedzelman, *The Science and Wonders of the Atmosphere*. (New York: John Wiley & Sons, 1980), 333.



U.S. map: Average number of days per year with thunderstorms

From website of UV Stout Physics Program, Phys 255 Meteorology

8.1.5 Environments Favorable for Thunderstorm Development

- Ordinary (or “air-mass”) thunderstorms
  - typically form within warm, moist, unstable air masses
  - don’t often occur along frontal zones
  - usually relatively short-lived
- Severe thunderstorms
  - normally associated with air-mass boundaries such as fronts and “dry-lines”
  - typically relatively long-lived

8.2 Ordinary Cumulonimbus Clouds

- Ordinary cumulonimbus cloud or thunderstorm has a well-defined lifecycle
- Lifecycle lasts around 45 minutes to an hour
- Lifecycle has three stages:

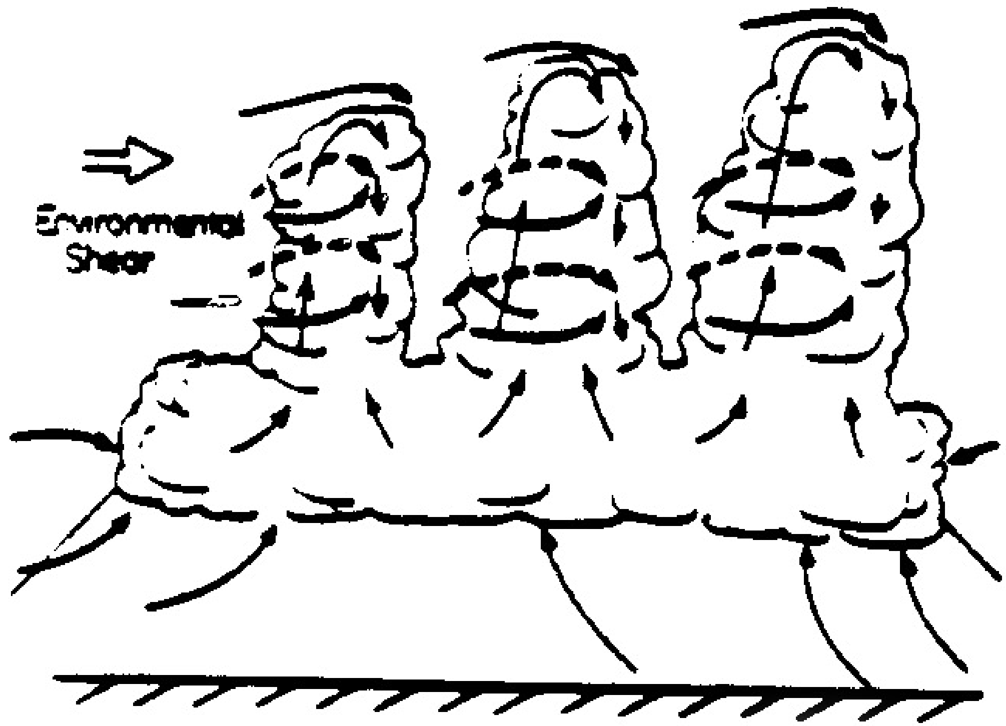
1. Growth (or Cumulus) stage
2. Mature stage
3. Dissipation stage

8.2.1 Growth (or Cumulus) Stage

- Thunderstorms generally develop in a region of low-level convergence of warm, moist air
- Warm, moist air rises in a buoyant plume or in a series of convective updrafts
- Water vapor condenses and a convective cloud grows
- Release of latent heat further enhances convection
- Towering cumulus often merge to form a larger cloud system, or a vigorous cumulus cloud expands into a larger cloud

Stage characteristics:

1. Updrafts dominate
2. Precipitation just beginning at upper levels
3. Development of towering cumulus clouds



(a)

Growth

Schematic model of the lifecycle of an ordinary thunderstorm (from Cotton and Anthes, 1989). (a) The cumulus stage is characterized by one or more towers fed by low-level convergence of moist air. Air motions are primarily upward with some lateral and cloud top entrainment.

Cumulus Stage

Photo: Barbara Neil and ECOMM/SKYWARN.

Cumulus stage (Steve Davis, **WSFO Milwaukee/Sullivan)**

8.2.2 Mature Stage

- This stage begins with rain settling in the sub-cloud layer
- Condensate loading and entrainment of dry air into the storm generates downdrafts in the cloud interior
- Downdrafts rapidly transport precipitation particles to the sub-cloud layer
- When reaching the surface, the downdraft air spreads out horizontally
- At the interface between the cool, dense downdraft air and the warm, moist air, a gust front forms (surface winds rapidly change in speed and direction at the gust front)
- More warm moist air is lifted into the cloud system along the gust front
- The precipitation particles in the sub-cloud layer partially evaporate, further cooling the sub-cloud air and strengthening the low-level outflow and gust front

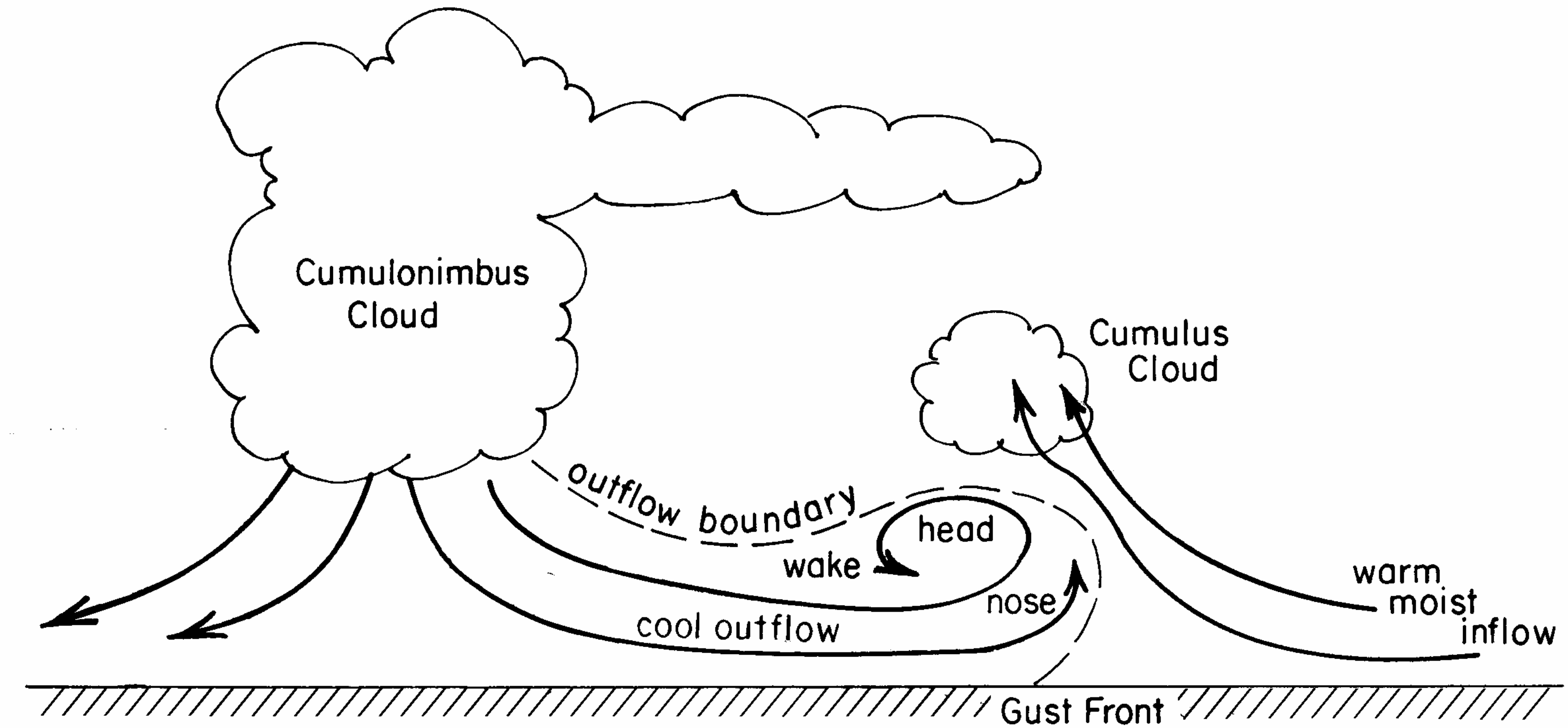
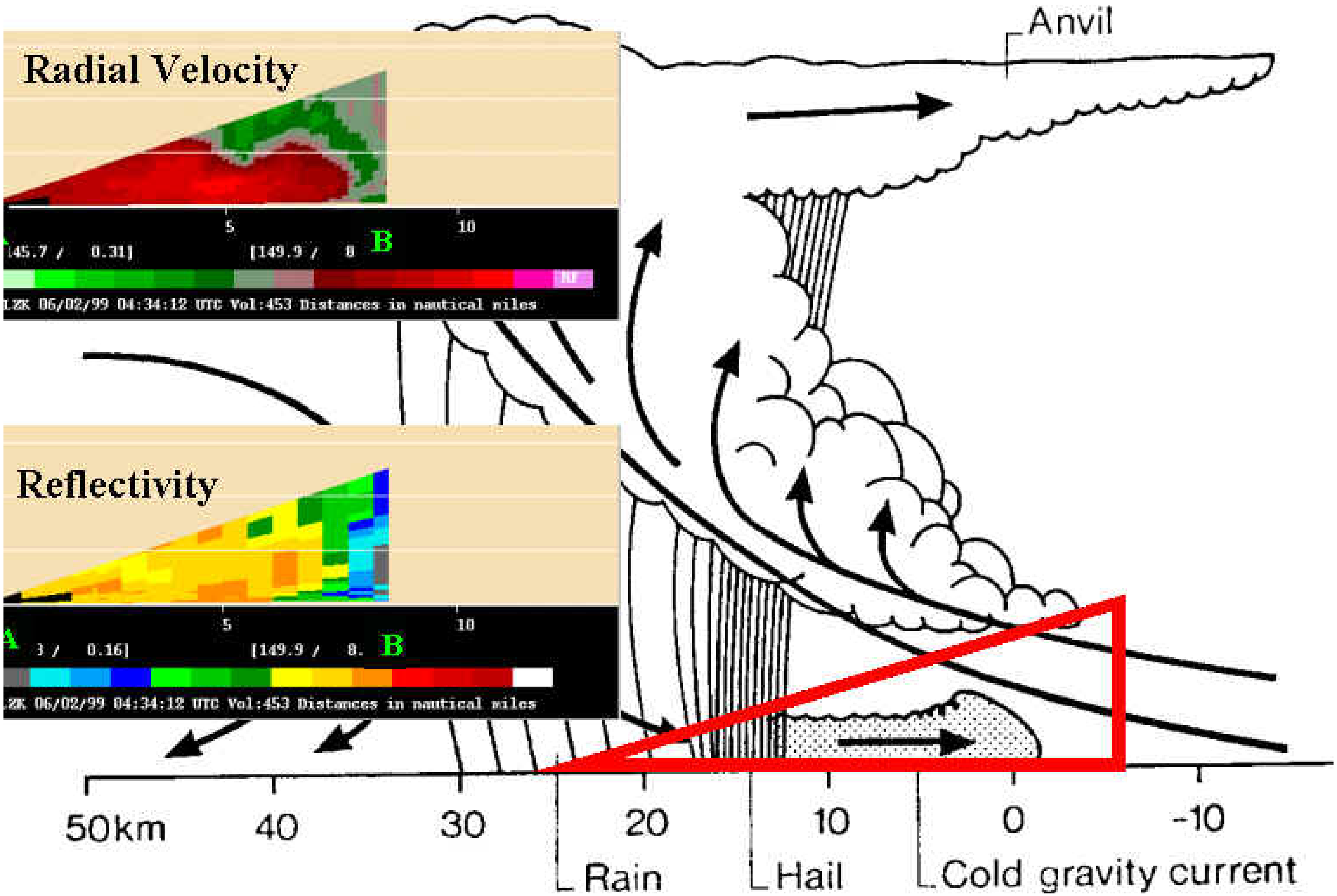


Illustration of a gust front and other associated features formed at the leading edge of the downdraft outflow from a thunderstorm



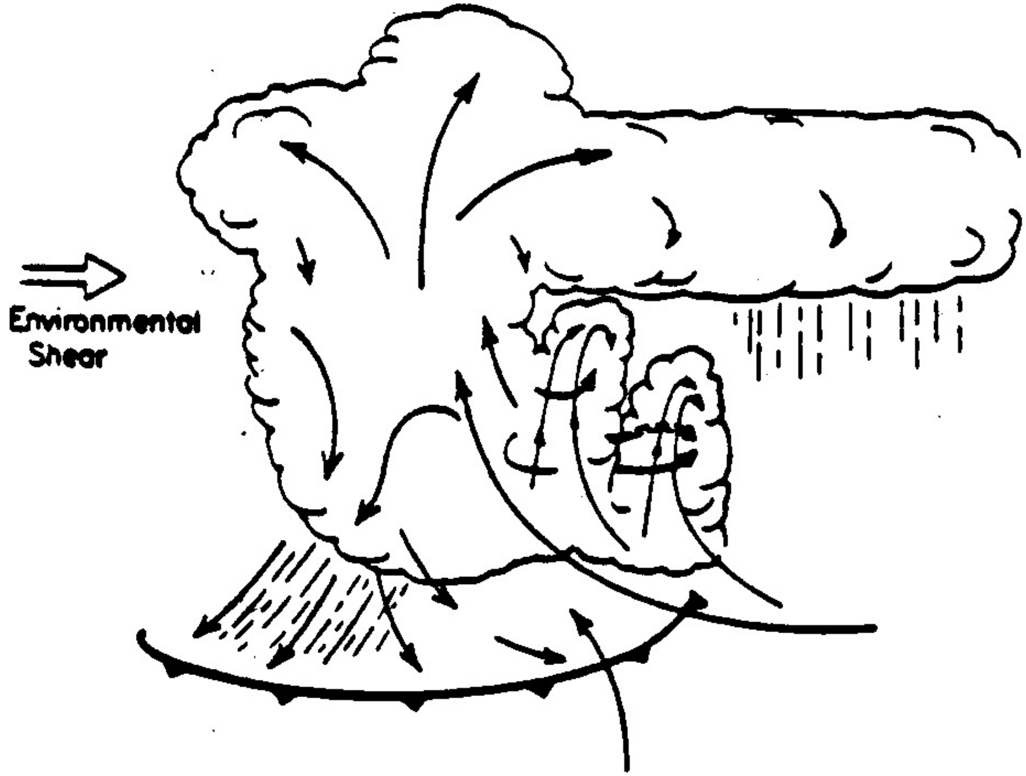
Anvil
Radial Velocity
5
10
[45.7 / 0.31]
[149.9 / 8
B
LZK 06/02/99 04:34:12 UTC Vol:453 Distances in nautical miles
Reflectivity
5
10
A
3 / 0.16]
[149.9 / 8.
B
LZK 06/02/99 04:34:12 UTC Vol:453 Distances in nautical miles
50km
40
30
20
10
0
-10
Rain
Hail
Cold gravity current

- Thus, continued uplift of warm, moist air into the cloud system is sustained during the mature stage – this provides further energy for maintaining strong updrafts
- When reaching the tropopause the updrafts spread horizontally - > spew out ice crystals and other cloud debris horizontally to form an anvil cloud
- In many cases, the updrafts are strong enough to penetrate into the lower stratosphere creating a cloud dome called an overshooting top
- Lowering of the pressure at middle-levels in the storm as a result of warming by latent heat release and diverging air flow results in an upward-directed pressure gradient force which helps to draw the warm, moist air lifted at the gust front up to the height of the LFC
- Thus the storm becomes an efficient “machine” during its mature stage in which warming aloft and cooling at low-levels sustains the vigorous, convective cycle

- Propagation speed of the gust front increases as the depth of the outflow air increases and the temperature of the outflow decreases
- Optimum storm system is one in which the speed of movement of the gust front is closely matched by the speed of movement of the storm as a whole

Stage Characteristics:

1. Updrafts and downdrafts are both active
2. Maximum precipitation intensity from storm
3. Heavy rainfall and gusty winds



(b)

Mature

(b) The mature stage is characterized by both updrafts and downdrafts and rainfall. Evaporative cooling at low-levels forms a cold pool and gust front that advances, lifting warm, moist unstable air. An anvil at upper-levels begins to form.

Mature Stage (Steve Davis, WSFO Milwaukee/Sullivan)

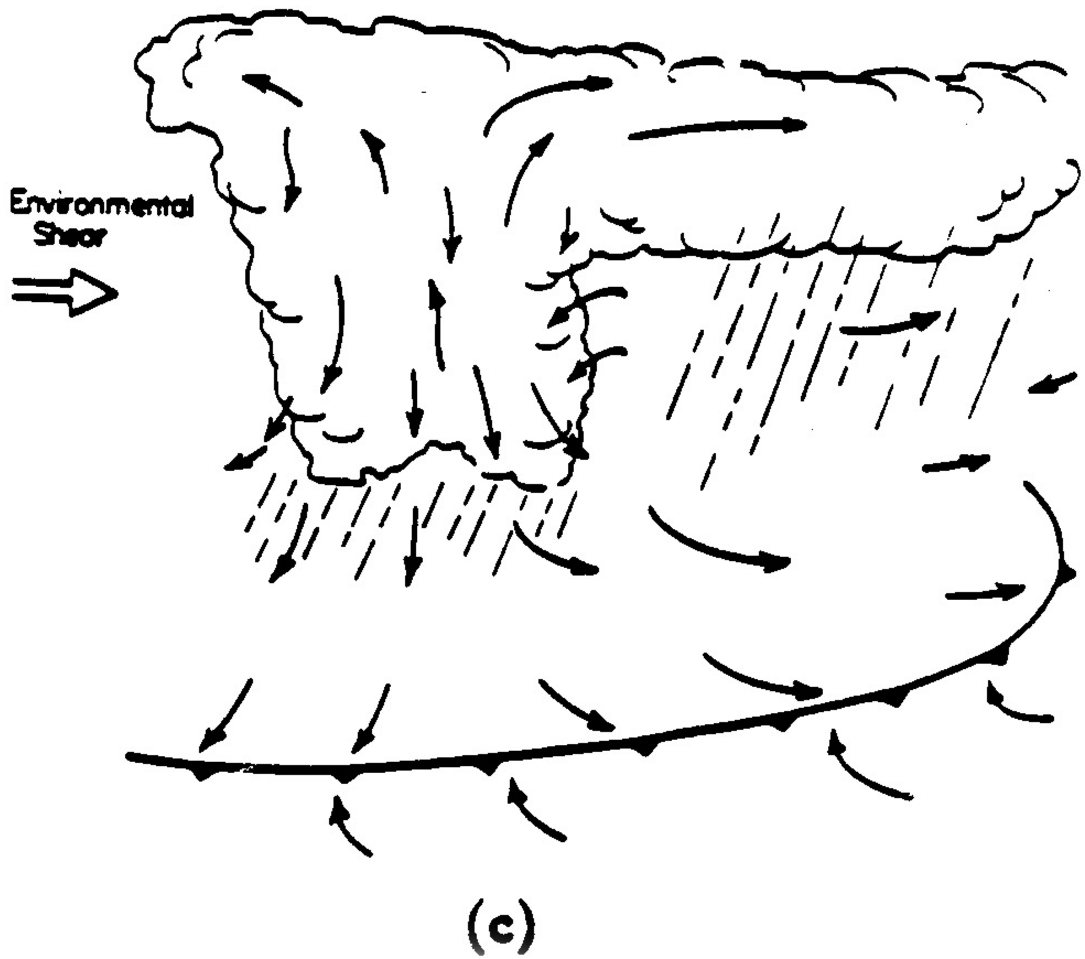
Single Cell Storm in mature stage Photo: NSSL

8.2.3 Dissipation Stage

- The beginning of the dissipation stage is marked by the gust front advancing too far ahead of the storm system – deprives storm of energy
- Air lifted at the gust front does not enter the updraft air of the storm, but may only form fair weather cumulus clouds along the gust front
- Updrafts weaken and downdrafts become predominant
- Rainfall intensity subsides, often turning into a period of light, steady rainfall

Stage Characteristics:

1. Downdrafts dominate
2. Reduced convective precipitation
3. Stratiform rainfall

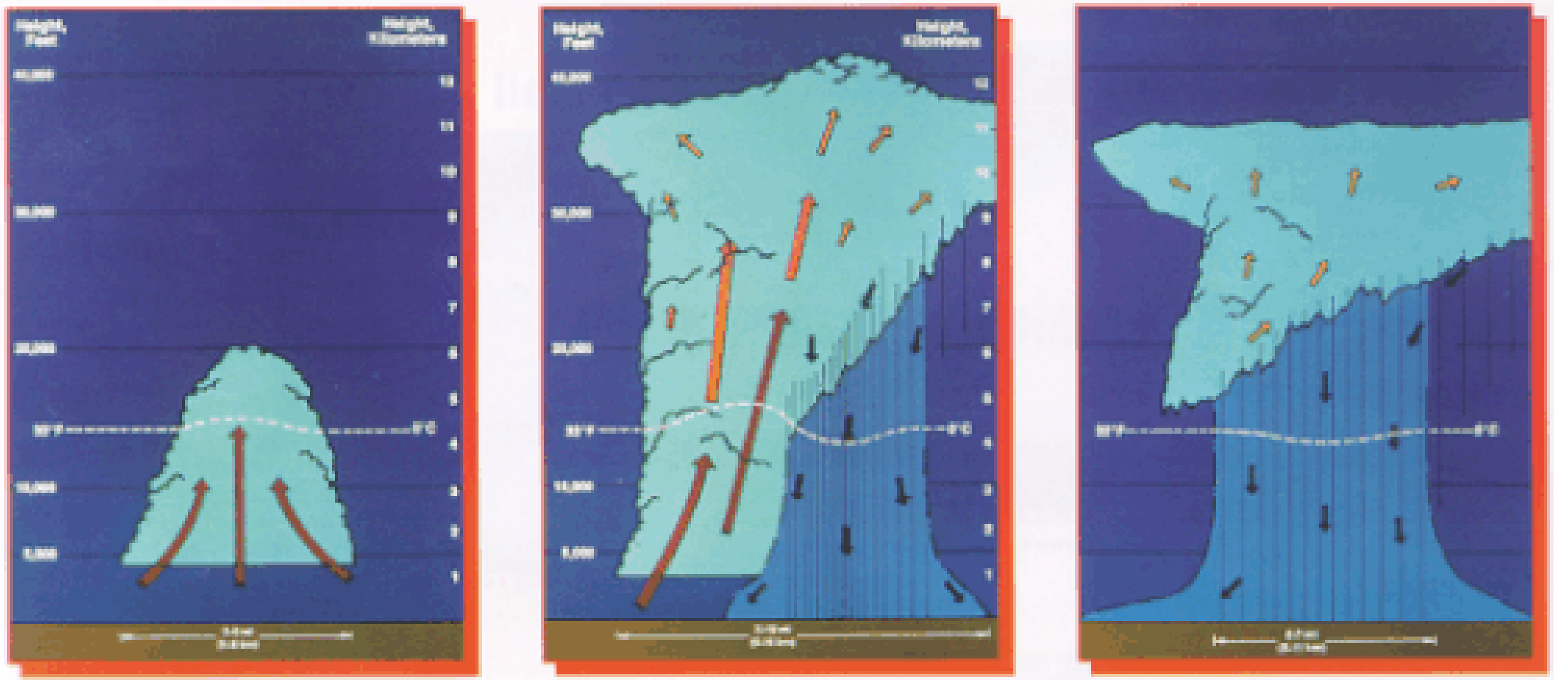


Decay

(c) The dissipating stage is characterized by downdrafts and diminishing convective rainfall. Stratiform rainfall from the anvil cloud is common. The gust front advances ahead of the storm preventing air from being lifted at the gust front into the convective storm

Dissipating Stage (Steve Davis, WSFO Milwaukee/Sullivan)

Life Cycle of a Thunderstorm



NOAA

Developing Stage

- ✔ Towering cumulus cloud indicates rising air.
- ✔ Usually little if any rain during this stage.
- ✔ Lasts about 10 minutes.
- ✔ Occasional lightning during this stage.

Mature Stage

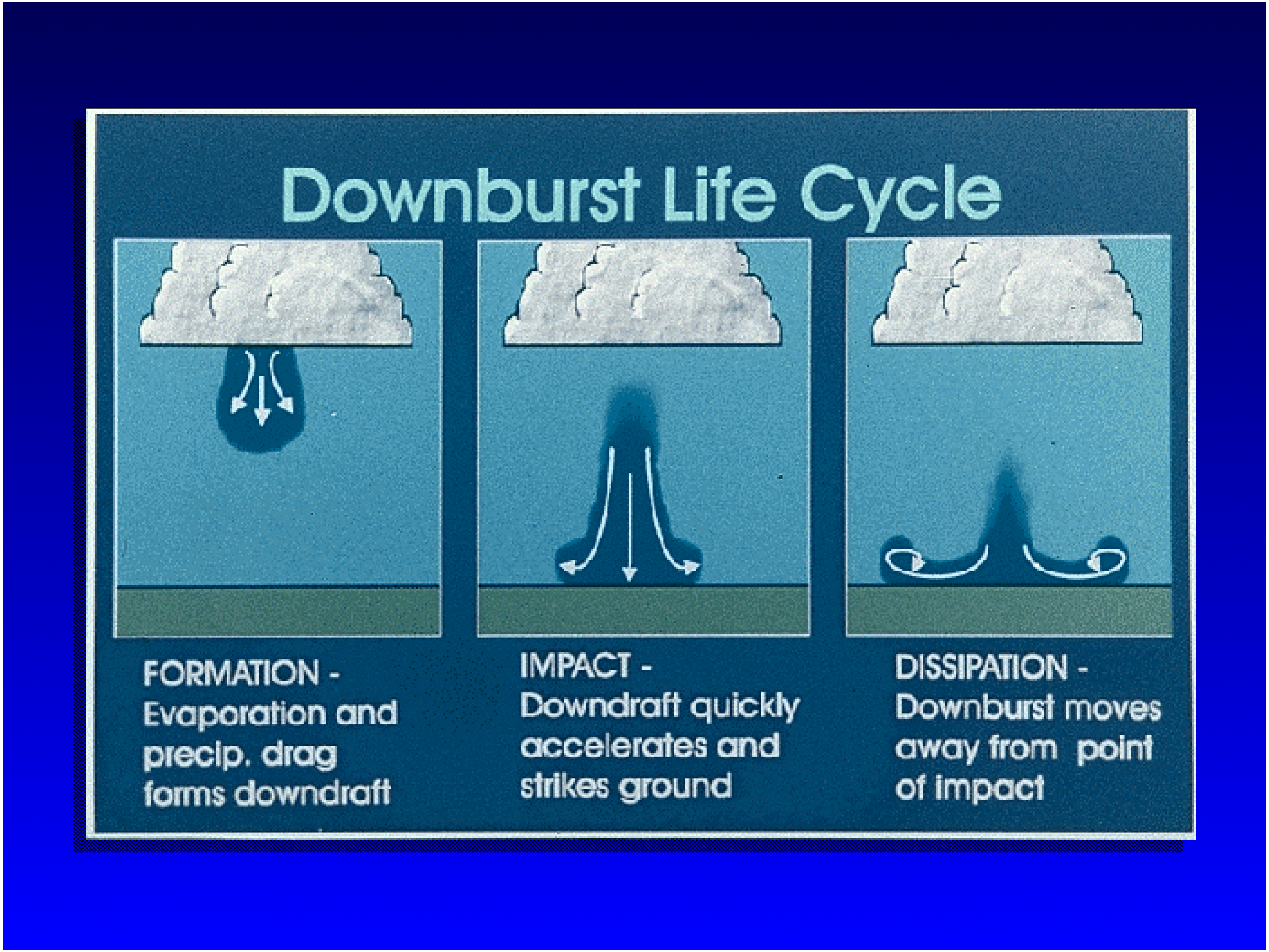
- ✔ Most likely time for hail, heavy rain, frequent lightning, strong winds, and tornadoes.
- ✔ Storm occasionally has a black or dark green appearance.
- ✔ Lasts an average of 10 to 20 minutes but may last much longer in some storms.

Dissipating Stage

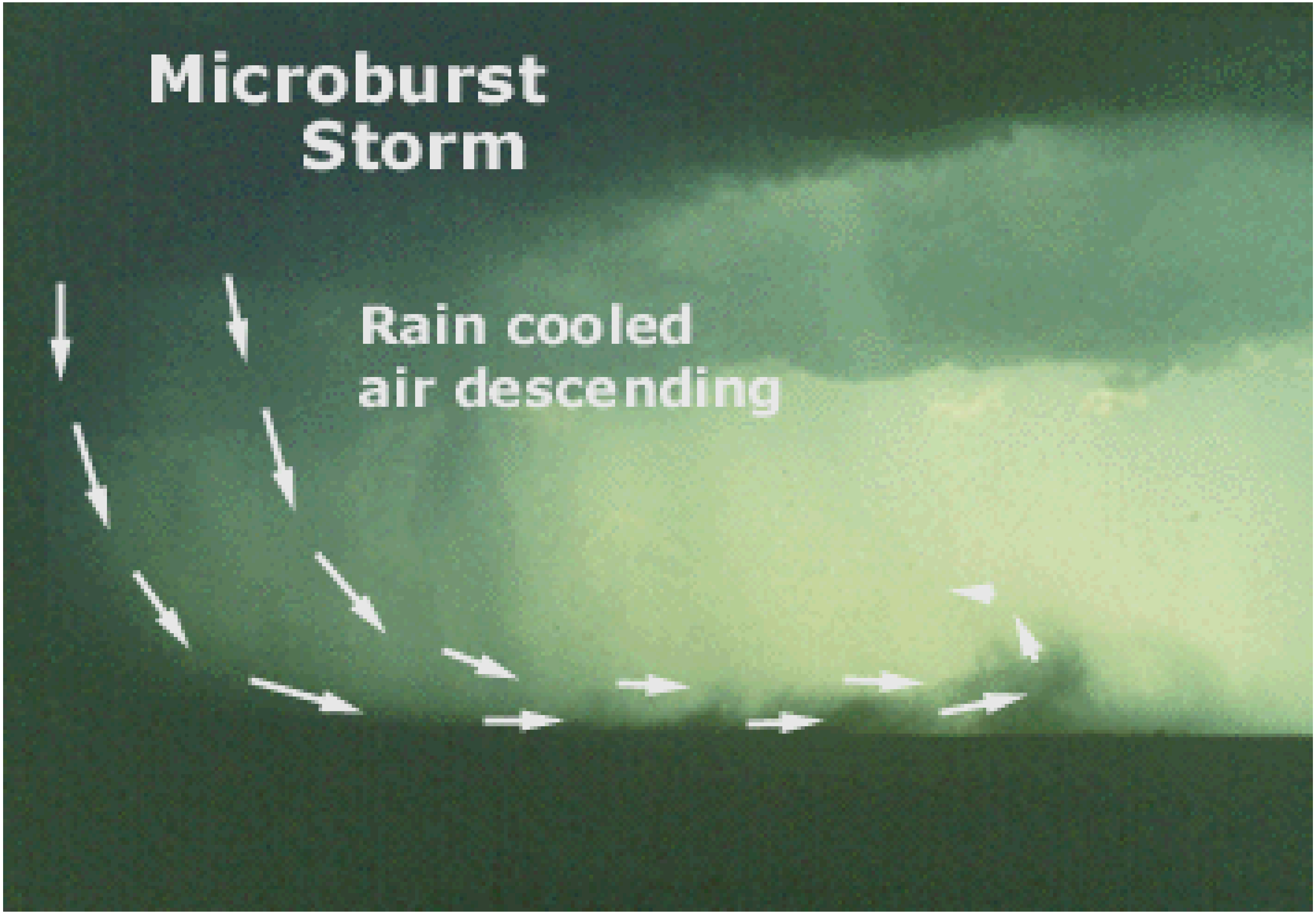
- ✔ Rainfall decreases in intensity.
- ✔ Some thunderstorms produce a burst of strong winds during this stage.
- ✔ Lightning remains a danger during this stage.

8.2.4 Ordinary Thunderstorm Characteristics

1. Intense rainfall
2. Strong, gusty winds at the surface
3. Lightning and thunder
4. Downbursts
   - If the sub-cloud layer is deep and very dry, downdrafts can be so strong that they pose a hazard to airplanes, especially planes trying to land at slow airspeeds
   - Such strong, low-level downdrafts are called downbursts
   - Downbursts forming in deep, dry sub-cloud layers are referred to as dry downbursts
   - Occasionally downbursts form from cumulonimbus clouds that have relatively shallow, moist sub-cloud layers – called wet downbursts and usually are accompanied by short bursts of intense rainfall
   - Downbursts in which the winds extend over an area of 4km or less are referred to as microbursts



(Steve Davis, WSFO Milwaukee/Sullivan)


Microburst
Storm
Rain cooled
air descending

Microburst

NOAA photo library


A wet microburst on 1 July 1978 west of Wichita, Kansas at intervals of several minutes or less (this and following slides) (photographs ©1978, Michael Smith, and WeatherData, Incorporated)
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A high-based thunderstorm near Stapleton International Airport producing heavy rain and associated outflow at the surface (Photograph ©1984, National Center for Atmospheric Research/National Science Foundation; taken by W. Schreiber)

A gust front vortex of tornadic strength (gustnado) and blowing dust spawned by a high-based storm along the landing approach to Denver's Stapleton International Airport, 1984. The light from an aircraft attempting to land is visible through the gustnado. (Photograph ©1984, National Center for Atmospheric Research/National Science Foundation; taken by W. Schreiber)

8.3 Severe Thunderstorms

- Severe thunderstorms are the most violent storms on earth
  - tornadoes with wind speeds in excess of 100 m / s (200 mph)
  - damaging straight-line winds
  - grapefruit-sized hailstones
  - over 25 cm (10 in rainfall) in 6 to 12 hours
- The NWS classifies a thunderstorm as severe if one or more of the following criteria are met:
  - wind gusts reach 58 mph or faster
  - hail is ¾ " in diameter or bigger
  - the thunderstorm produces a tornado or tornadoes.

8.3.1 Multicell Storms

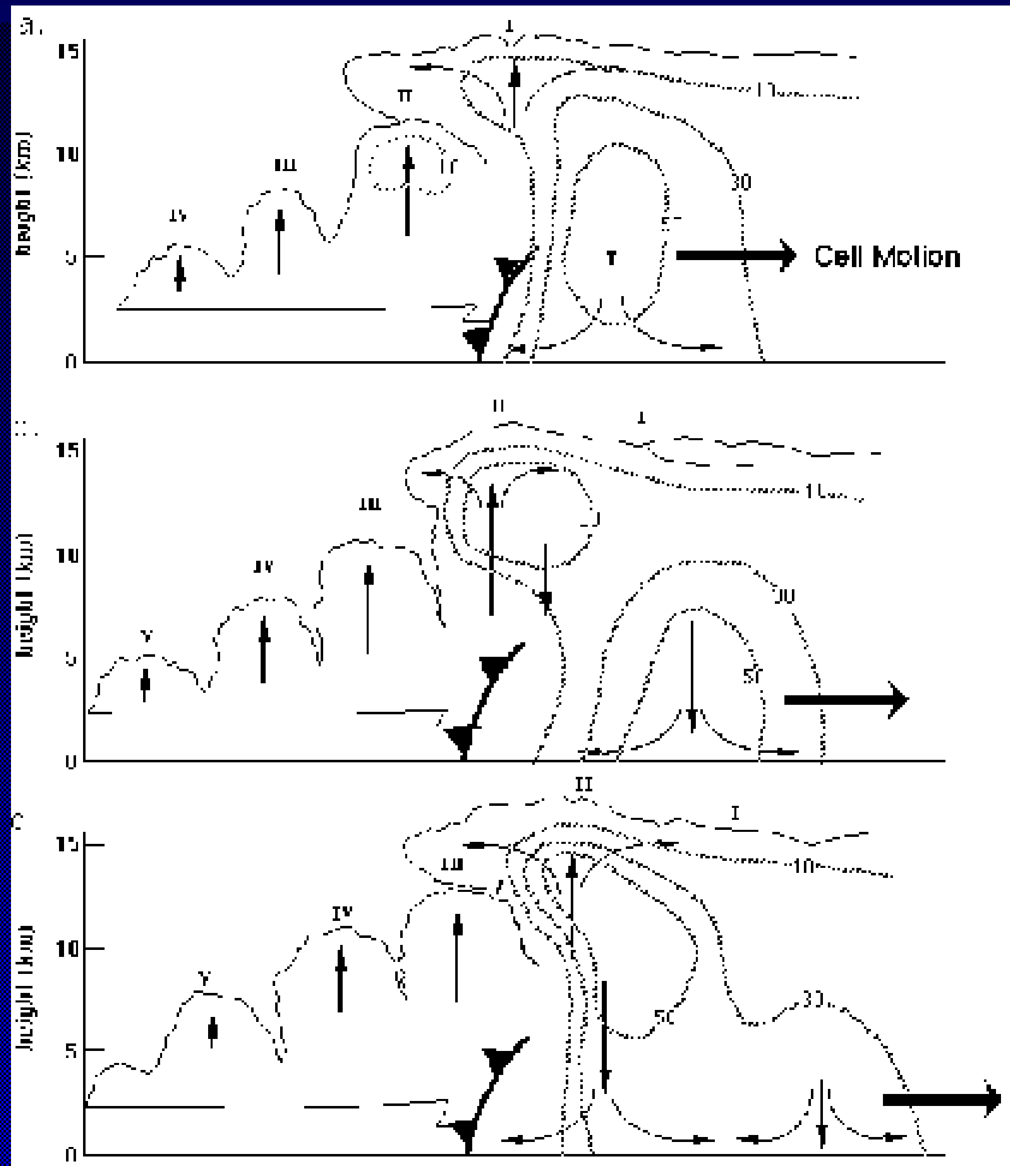
- Lifetimes on the order of several hours
- Composed of a number of cells that move together as a group, each having a lifecycle of about 45 to 60 minutes
- Exist as lines or clusters
- Can produce tornadoes, moderate-sized hailstones (golfball-sized), severe straight-line wind damage, and flash floods
- Updrafts can range from 25-35 m/s
- Typically form in regions where the atmosphere is unstable and the vertical wind shear is moderate
- Develop from the parent-daughter effect – ordinary storm creates neighboring storms due to downdraft and gust front effects
- Each cell will be in a different phase of its life and each cell will have a turn to be the dominant cell
- New cells tend to form on the western to southwestern edge of the cluster, mature cells in the center, and dissipating cells on the northeastern or eastern edge

A multicell sequence schematic.

Early stage

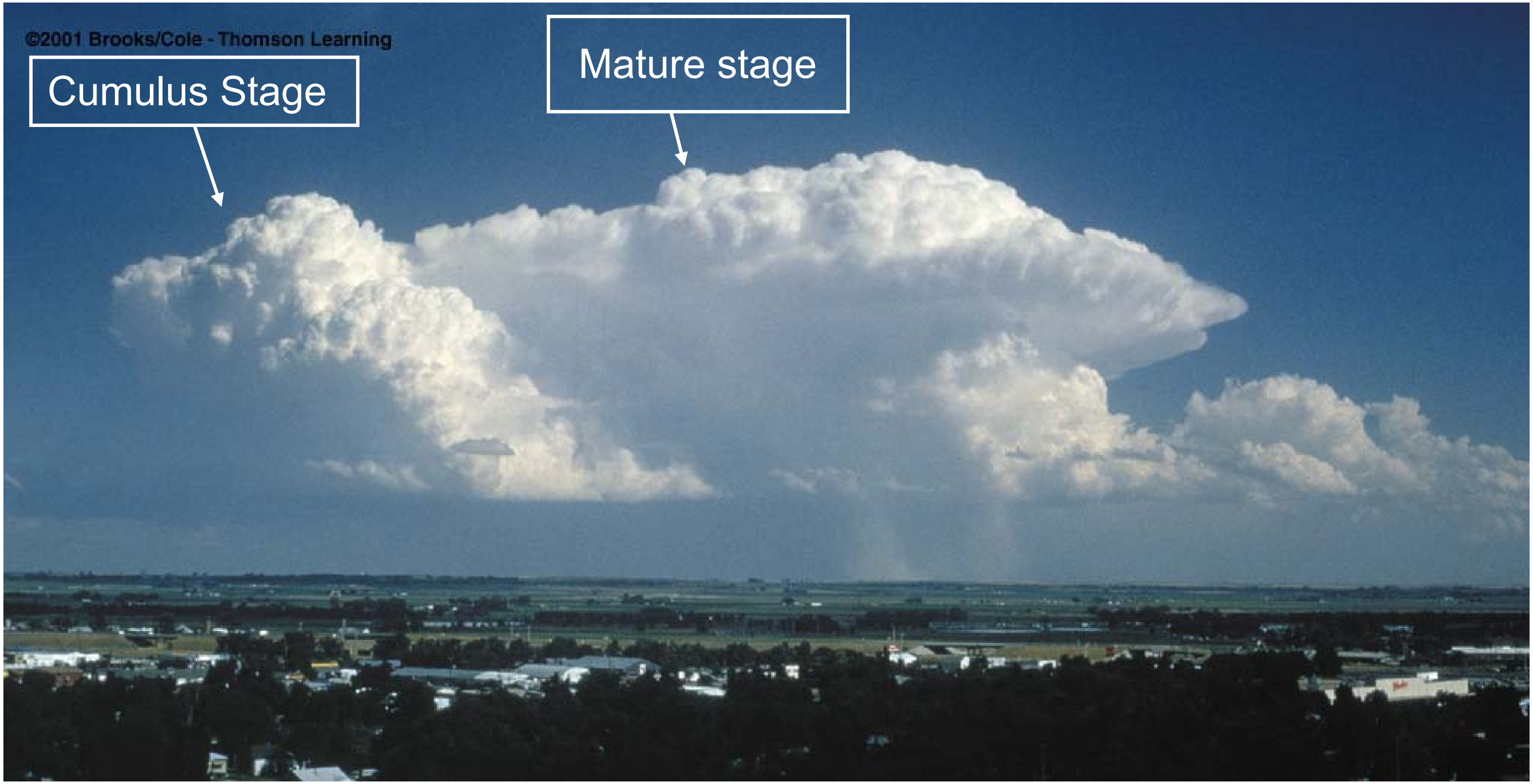
Next evolution

Later stage



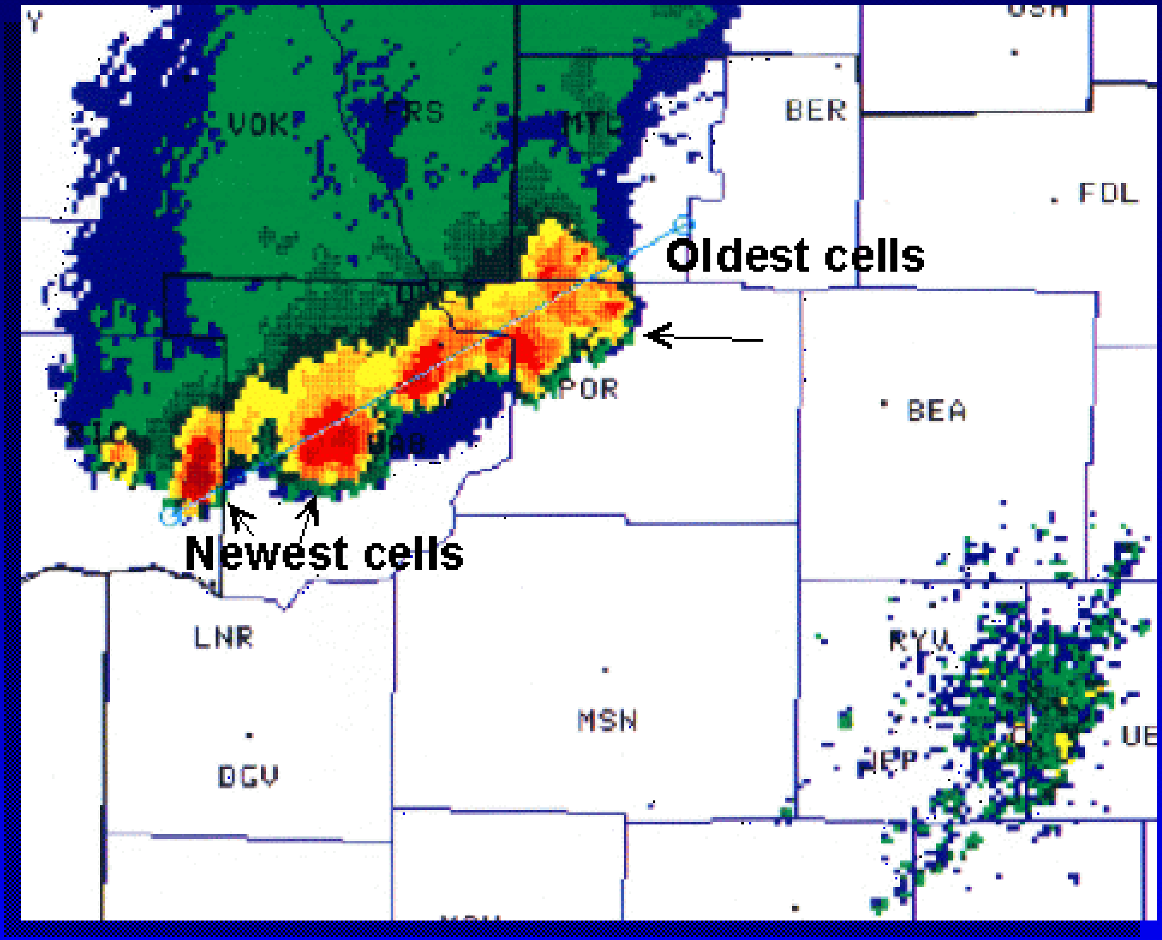
Steve Davis, WSFO Milwaukee/Sullivan

Multi-cell Storm



Brooks/Cole – Thomson Learning

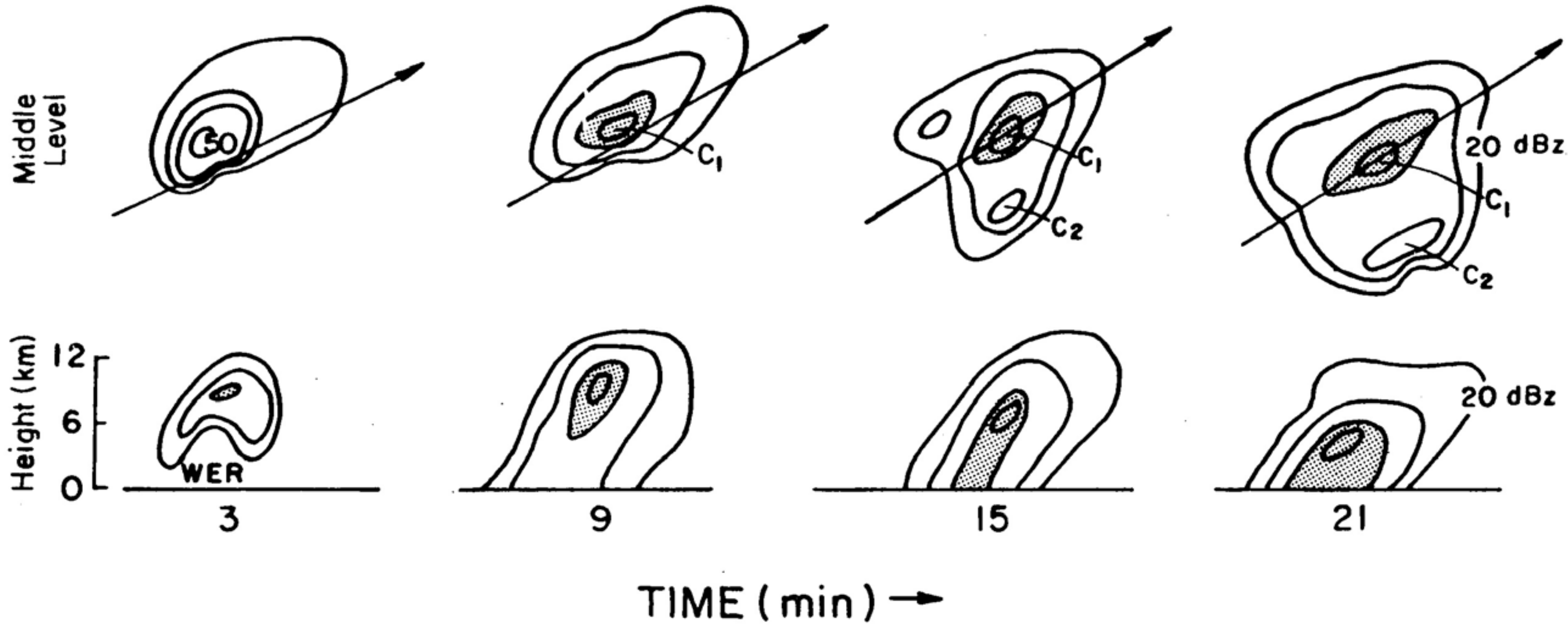
Multicell Line



July 11, 1994   5:55 PM

Steve Davis, WSFO Milwaukee/Sullivan

- The next slide shows a schematic of the development of a multicell as shown by radar
- 3 minutes: the vertical cross section through a vigorous cell, C1, shows a weak echo region (WER) at low levels, where there is an absence of precipitation particles large enough to be seen on radar. Updrafts in this region are so strong that there is not enough time for precipitation to form. The region of intense precipitation at middle levels is due to a cell that existed previous to C1.
- 9 minutes: Cell C1 exhibits a well-defined precipitation maximum at middle levels, while the weak echo region has disappeared.
- 15 minutes: precipitation from C1 has reached the surface and a new cell, C2, is evident on the right forward flank of the storm (relative to storm motion).
- 21 minutes: the precipitation maximum associated with C1 has lowered and C2 has grown in horizontal extent. Cell C2 will soon become the dominant cell of the storm, only to be replaced by another cell shortly.



Conceptual model of horizontal and vertical radar sections for a multicell storm at various stages during its evolution, showing reflectivity contours at 10 dBZ intervals. Horizontal section is at middle (levels ~6 km) and the vertical section is along the arrow depicting cell motion. (Adapted from Chisholm, A.J., and J.H. Renick, 1972)

8.3.2 Supercell Storms

Introduction

- More than 90% of supercells are associated with severe weather (tornadoes, large hail, flash flooding, strong straight-line winds)
- About half of all supercells produce tornadoes, and the majority of strong or violent tornadoes are generated by supercells
- Relatively rare storm type, however, their contribution to thunderstorm-related damage and loss of life is proportionately high

Definition

A supercell is a convective storm that contains a deep, persistent mesosyclone (e.g. Johns and Doswell, 1992; Moller et al., 1994)

- Deep: >~1/3 of the storm
- Persistent: ~10 to 20 minutes
- Mesocyclone: vertical vorticity > 0.01 s^{-1}

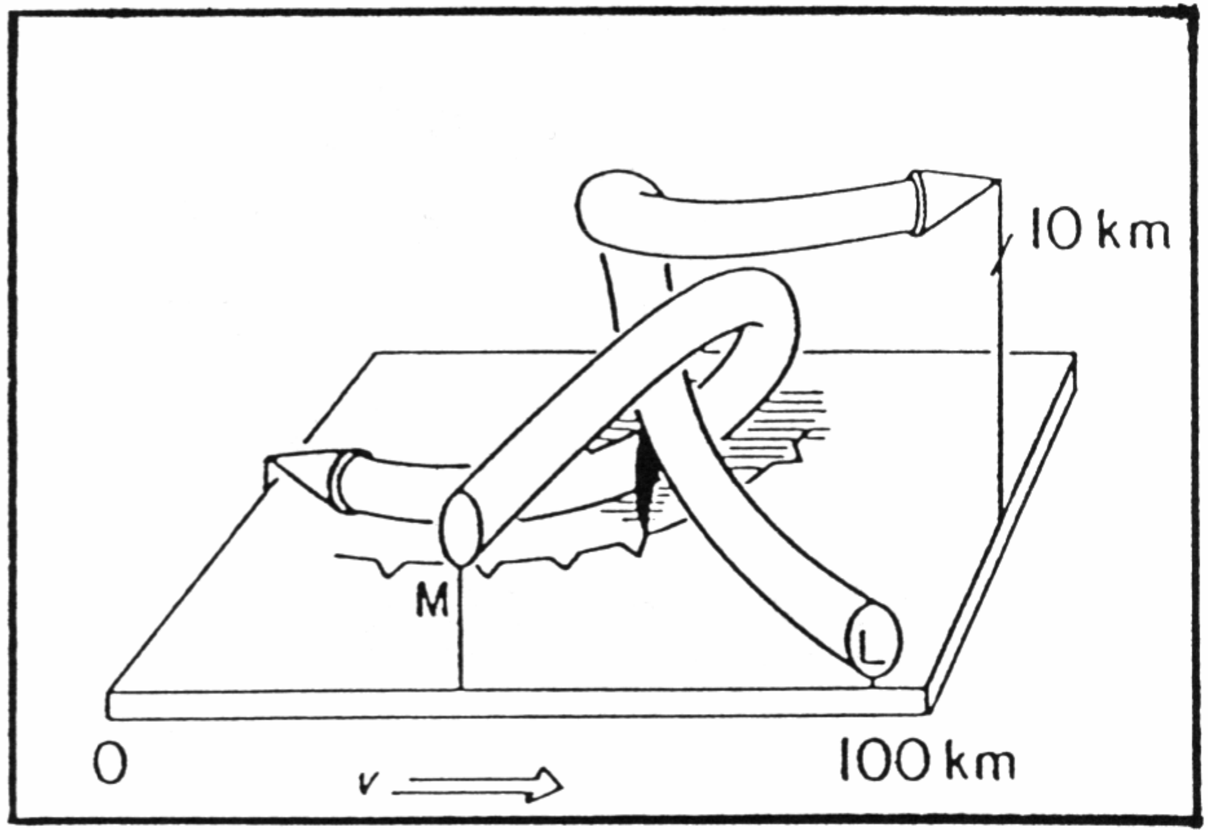
Characteristics

- Rotating storms
- Last 2-6 hours
- Single cell structure
- Updrafts may exceed 40 m/s – capable of suspending hailstones as large as grapefruit
- Also called severe-right moving storms because they typically move to the right of the mean flow in the northern hemisphere – left-moving supercells also occur, but are not as frequent
- Rotational characteristics and strong updrafts result in storm systems that produce the largest and most persistent tornadoes as well as the largest hailstones

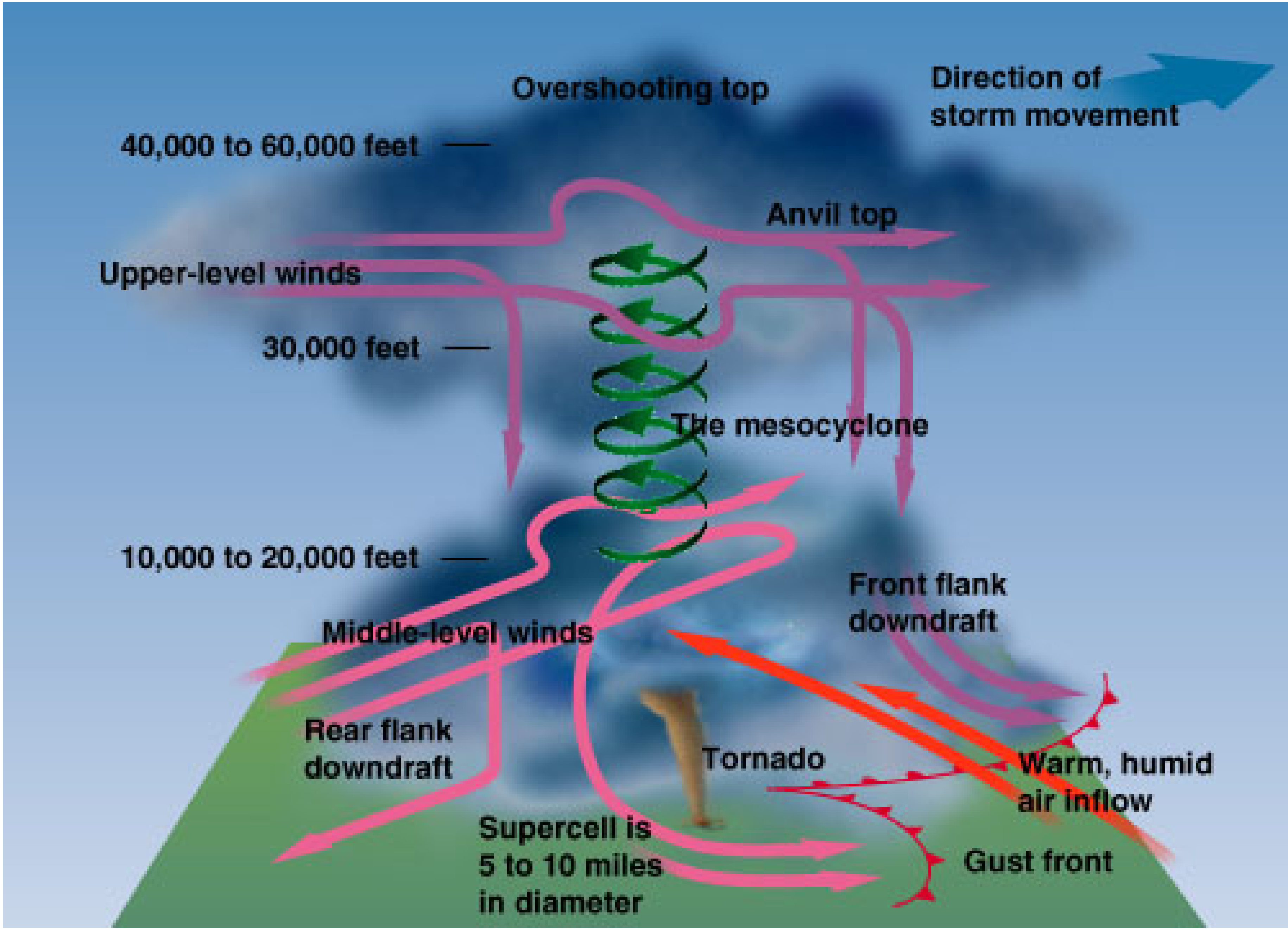
Supercell Storm Structure

- Browning (1964) suggested that supercells achieve longevity through an airflow pattern that allows the updraft to unload its precipitation without disrupting the storm's inflow of warm, moist air
- Low-level air that is moist and buoyant approaches the storm from the forward right flank where it rises in the rotating updraft
- This inflow air is then carried upwards through the storm and diverges in the anvil cloud where it is turning counter-clockwise
- The coldest air entering the storm is generally located at middle levels on the right rear flank – this cold, dry air flows ahead of the updraft through the region of precipitation where it is evaporatively cooled
- A strong, evaporatively-induced downdraft develops and descends on the left rear flank of the updraft

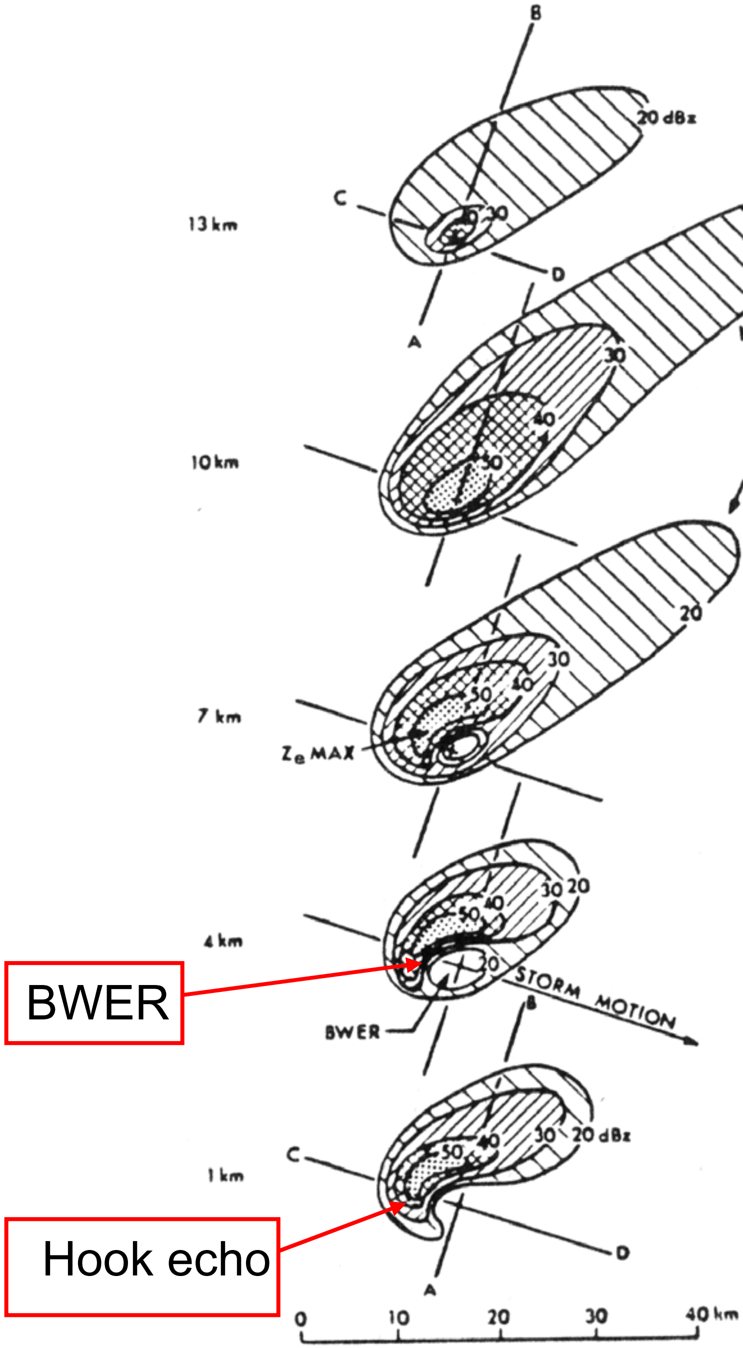
- Precipitation produced in the storm is transport out of the updraft and into the downdraft by the mid-level inflow (enhanced by the rotational nature of the updraft) –> precipitation doesn’t interfere with inflow air
- Evaporative cooling continues to strengthen downdrafts which diverge in all directions when reaching the surface
- Resulting gust front along the forward right flank enhances the influx of low-level warm, moist air into the storm
- The cycle continues and the storm strengthens
- The separation of the updraft and downdrafts due to the rotational nature of the storm, the removal of precipitation from the updraft, and the enhanced convergence and moisture influx along the gust front all result in a self-perpetuating, long-lived storm – may last several hours

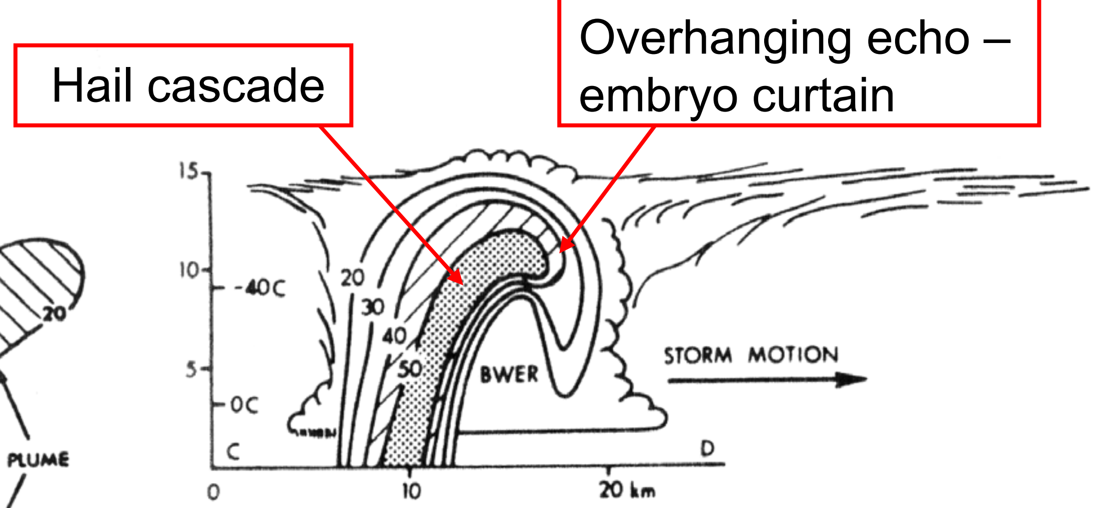


A three-dimensional model of the airflow within a right-moving supercell storm. The updraft and downdraft circulations are shown relative to the storm. Convergence and divergence is neglected. L and M refer to the predominant origins of the updraft and downdraft, respectively. Also shown is the approximate area of precipitation at the surface, and the positions of the surface gust front and tornado (should one occur). The vertical scale has been exaggerated five times (after Browning, 1964).



Source: UCAR Web Page





C/S along line CD in figures to the left

Radar Signatures of Supercells

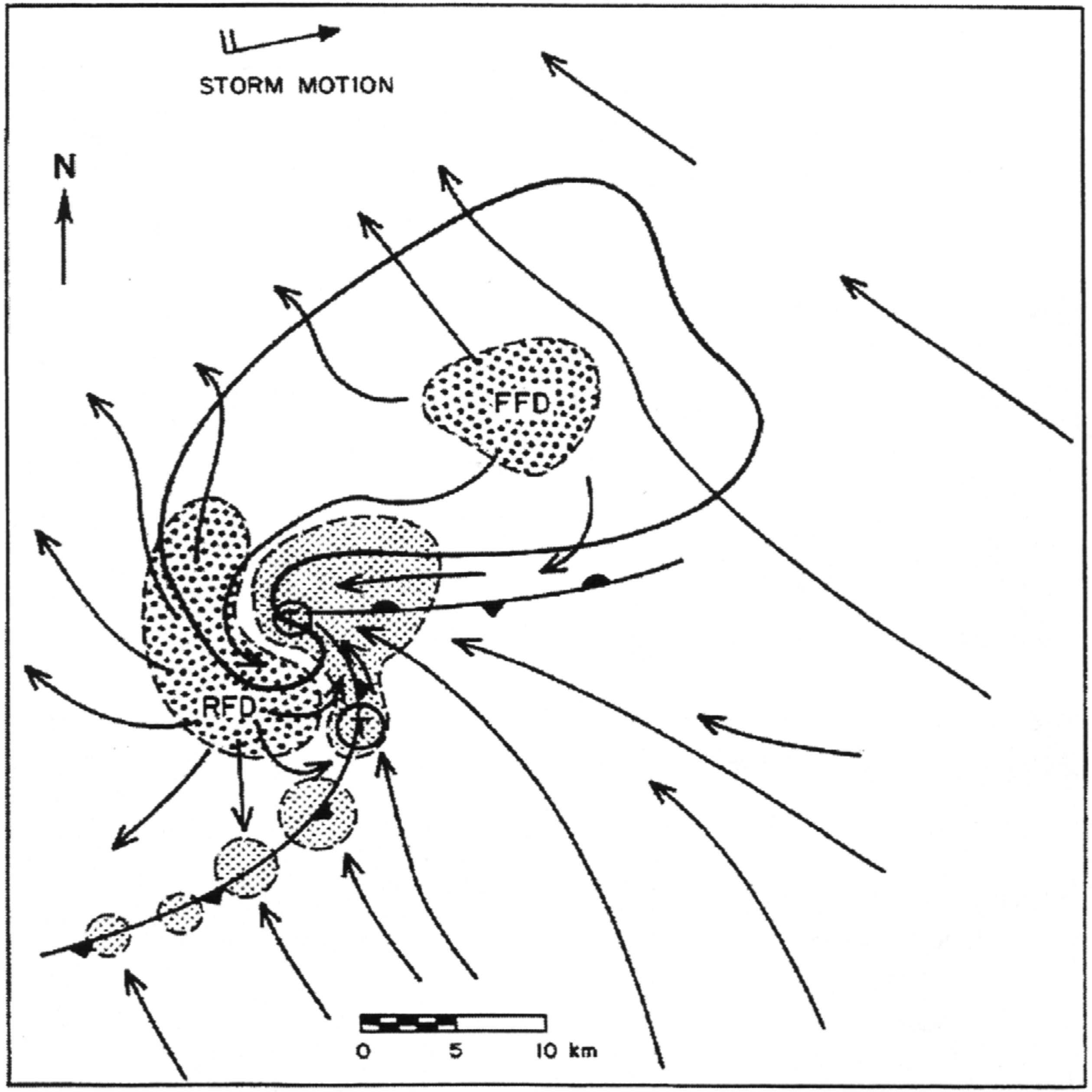
- Overhanging echo ahead of storm – referred to as the embryo curtain
- Bounded weak echo region (BWER) – region of low reflectivity
- Hook echo
- These features are usually, although not always present

Figure from Chisholm and Renick, 1972

- A distinct feature of the supercell is the region that is free of radar echo – this is called the bounded weak echo region (BWER) or an echo free vault
- The BWER is the result of strong updrafts in that region which do not provide enough time for precipitation to form in the rapidly rising air
- Multicell storms also show WERs, but they are not as strong or persistent as those in supercells, nor are they typically bounded
- Cyclonic rotation of the updrafts may also contribute to the BWER by causing any precipitation that does form in the updraft to the pushed outward by the rotating updraft

- Lemon and Doswell (1979) examined transition of supercell from mature to collapsing phase in detail – their ideas are still generally consistent with Browning
- Main structural features: an intense updraft and two downdrafts:
  – Forward flank downdraft (FFD): located downwind of the mid-level flow in the region of strong precipitation
  – Rear flank updraft (RFD): lies upwind of the updraft (relative to the 7-10 km flow)
  – The main updraft generally lies above the intersection of the forward flank and rear flank gust fronts
- New convective towers usually develop along the rear flank outflow boundary and are known as the flanking line
- Most of the precipitation falls to the north and west of the updraft

- As the updrafts weaken, the RFD strengthens and interacts with the FFD outflow, thereby forming an occlusion
- The mesocyclone then descends as the RFD increases, and the RFD wraps cyclonically around the low-level mesocyclone
- As the occluding gust front progresses, the low-level inflow of warm, moist air is cut off and the storm collapses
- Tornadoes are normally located at the tip of the occlusion, but can also occur along the trailing gust front



The low-level airflow structure and precipitation distribution of a supercell thunderstorm based on surface observations and radar analysis (from Lemon and Doswell, 1979; adapted by Davies-Jones, 1986). FFD is the forward flank downdraft, RFD is the rear flank downdraft and T indicates the position most conducive for tornado formation.

Photo showing both the parent cumulonimbus cloud and the tornado   Photo: NWS

Hard, cumuliform anvil overhang, a vertical Cb edge, and flanking line are all visible in this southeastward view of a supercell storm.

Mammatus can be seen on the underside of the north Texas supercell.

Golf ball size hail, downbursts, flash flooding, and rotating wall clouds occurred without any known tornadoes

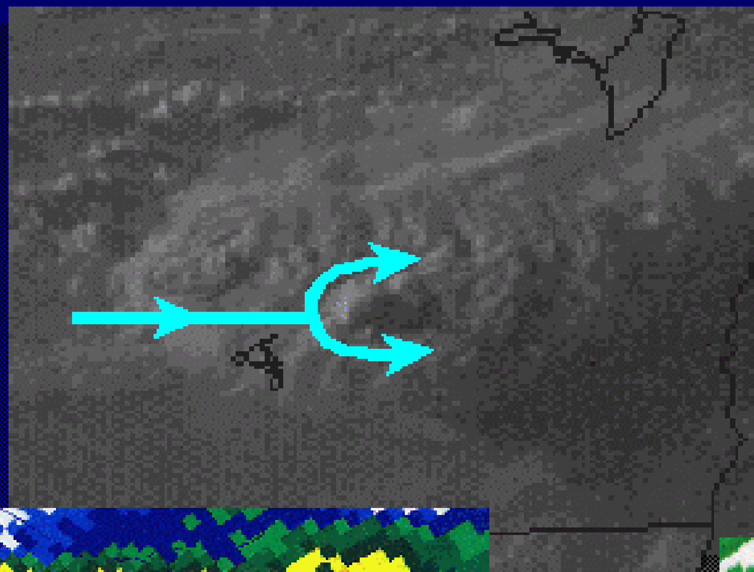
Photo: Alan Moller

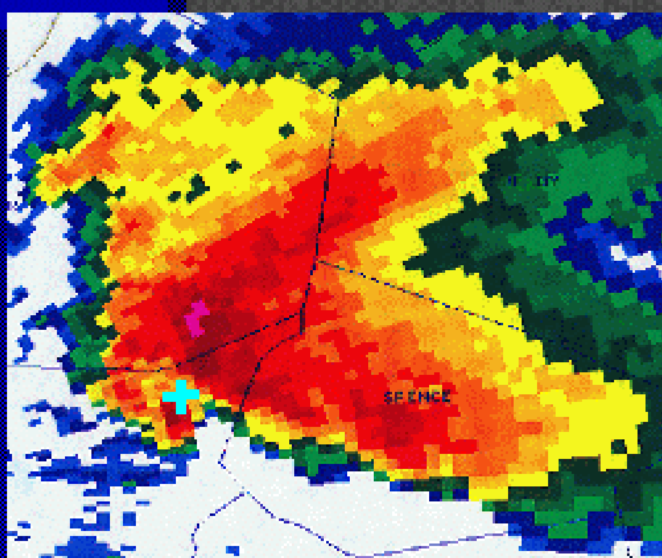
Supercell with domed top Photo: Howard Bluestein

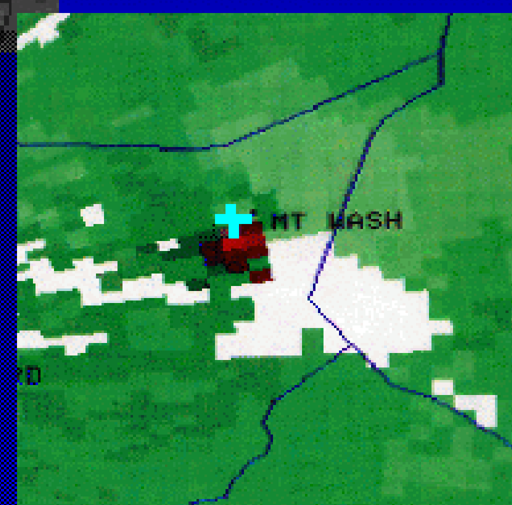
Supercell - The V Notch

A good indicator of intensity/dynamics

Theory explains this as the mid/upper level winds encounter storm core and are diverted around it's mass.



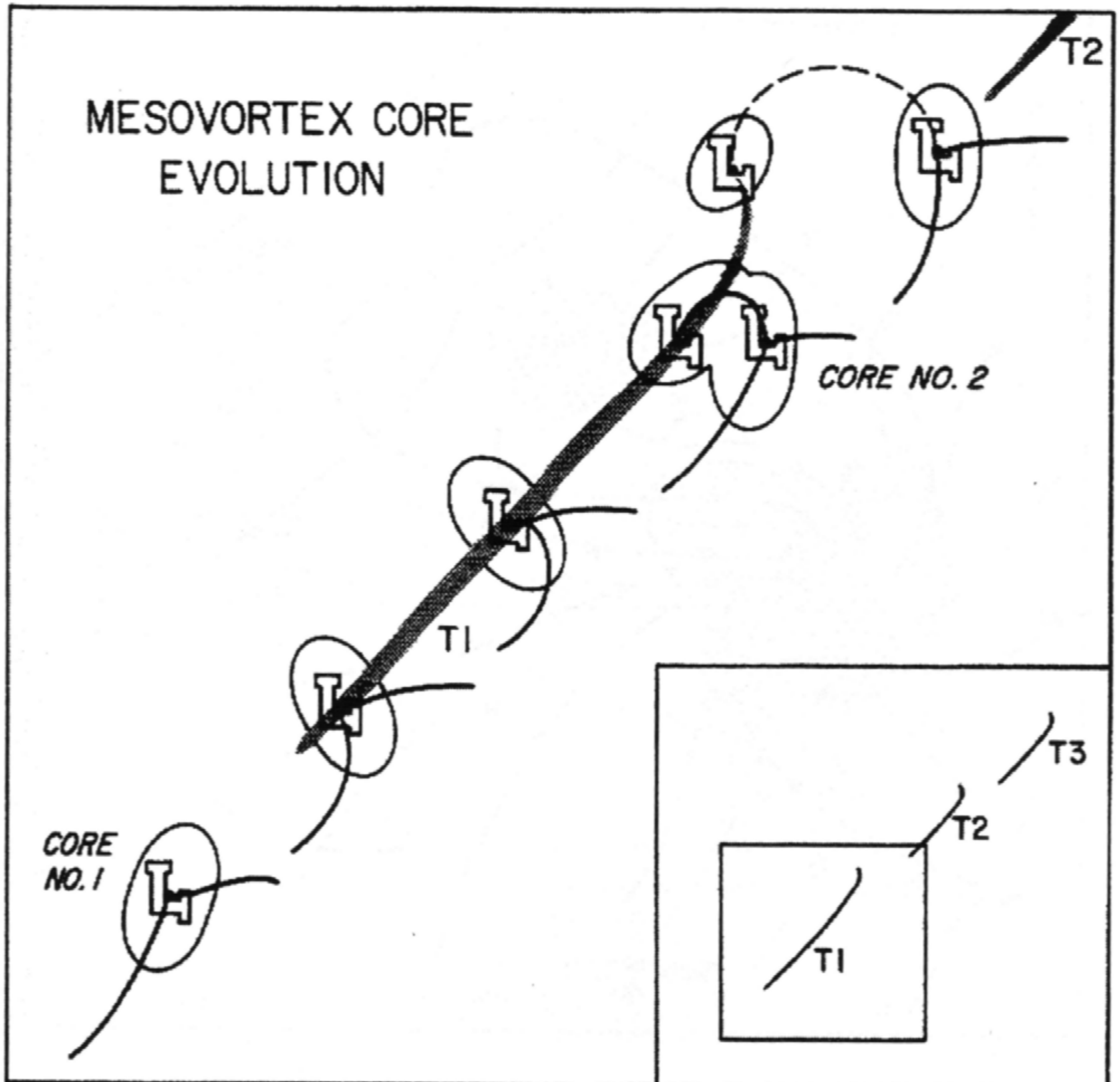




Steve Davis, WSFO Milwaukee/Sullivan

Cyclic Mesocyclogenesis

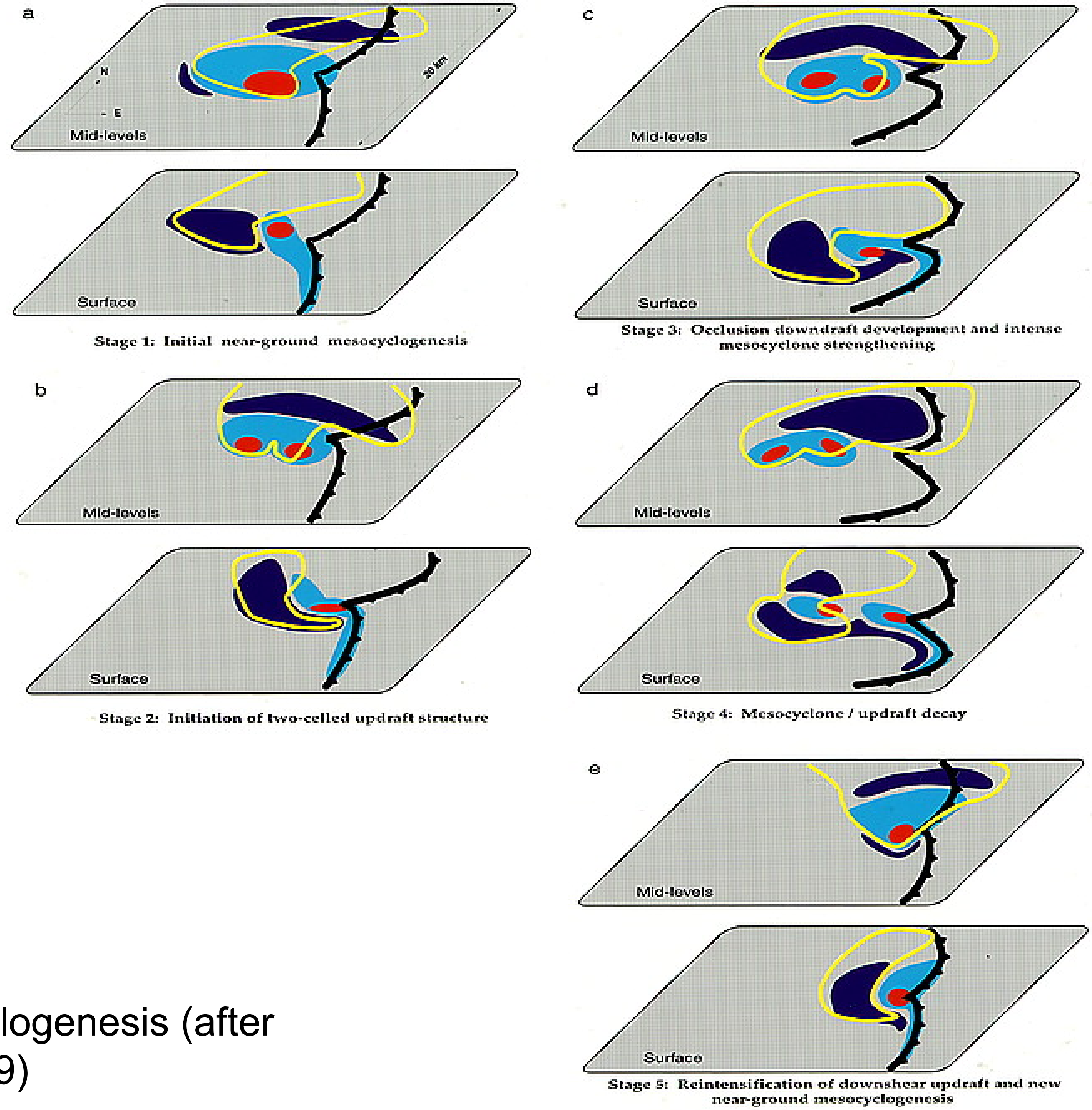
- Process whereby a supercell can produce a periodic succession of mesocyclones, both at mid- and low-levels
- Burgess et al developed a conceptual model of cyclic mesocyclogenesis:
  - the gust front is accelerated around the right flank of the mesocyclone by the strong low-level rotation
  - occlusion occurs which separates the original mesocyclone from its warm inflow and the first core dissipates
  - Strong convergence occurs at the point of the occlusion and a new mesocyclone core develops
  - Second mesocyclone core develops more rapidly as the environment is rich in vorticity and becomes the storm's new mesocyclone
  - The cycle then repeats itself
  - Some supercells undergo this process many times during its lifecycle -> produce "tornado families"



Conceptual model of mesocyclone core evolution as hypothesized by Burgess et al. (1982). Tornado tracks are represented by the dark, shaded lines, and the low-level wind discontinuities (gust fronts) are given by the thin lines (after Burgess et al., 1982).

Based on modeling results Adlerman et al (1999) suggested a more detailed 5 stage cyclic mesocyclogenesis process:

- Stage 1: RFD intensifies, wraps cyclonically around the updrafts and forces the updraft to bow outward; low-level mesocyclone intensifies due to stretching and tilting of vorticity
- Stage 2: RFD forces the gust front to propagate even further eastward -> produces an updraft on the east (downshear) side of the storm; dual updraft structure seen at upper levels
- Stage 3: Low-level mesocyclone / updraft center occludes and the vertical vorticity near the surface rapidly increases.
- Stage 4: Following the development of the occlusion updraft, the old updraft and mesocyclone separate from the gust front and a new updraft and mesocyclone develop further downshear
- Stage 5: Old updraft has completely dissipated after being cut off from its source of buoyant air by the gust front; downshear updraft continues to strengthen and move eastward (this supercell is very similar to original supercell). Cycle is then repeated



5 stages of mesocyclogenesis (after Adlerman et al., 1999)

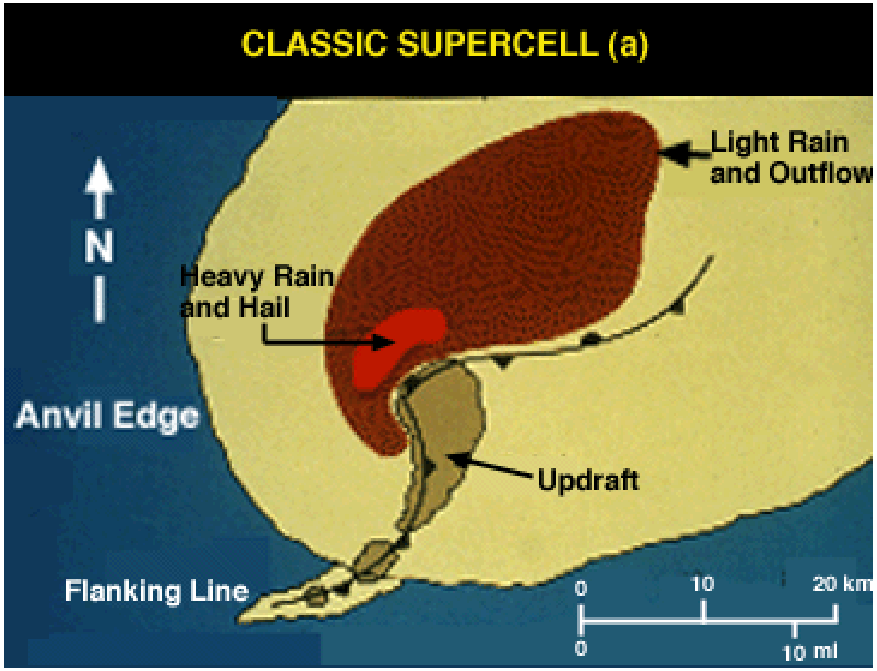
Supercell Spectrum

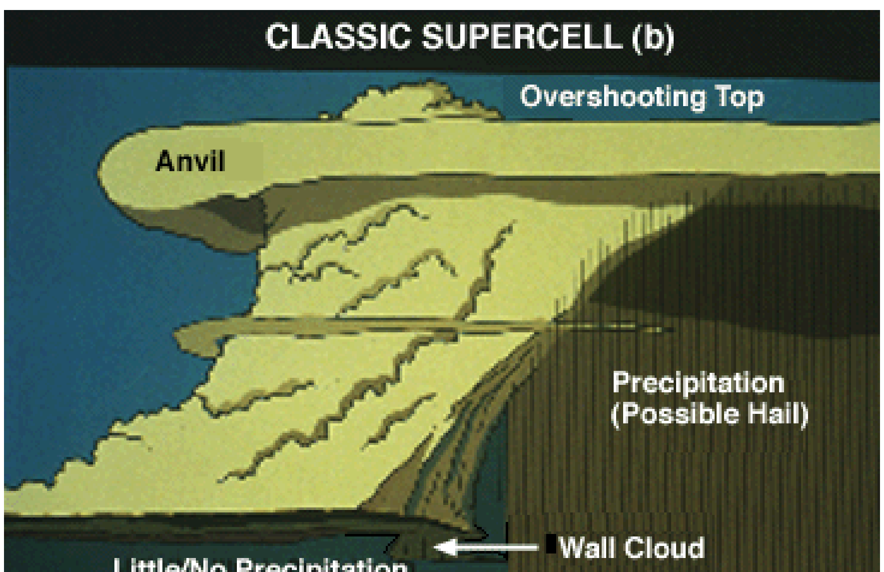
- A spectrum of supercells exists – based on where the precipitation is situated with respect to the updraft and on the amount of precipitation they produce
- Although it is better to think of a ‘storm spectrum’ rather than well defined boundaries between storm types, supercells can be broken into 3 general types:
  1. Low-precipitation (LP) supercells
     - produce little if any precipitation
  2. Classic (CL) supercells
     - produce moderate amounts of precipitation
  3. High-precipitatation (HP) supercells
     - produce copious amounts of precipitation
- All of these supercells have a deep, persistent mesocyclone, despite their varying precipitation characteristics
- Actual supercell storms may transition from being an LP storm to a CL storm and then to an HP storm

Classic Supercells

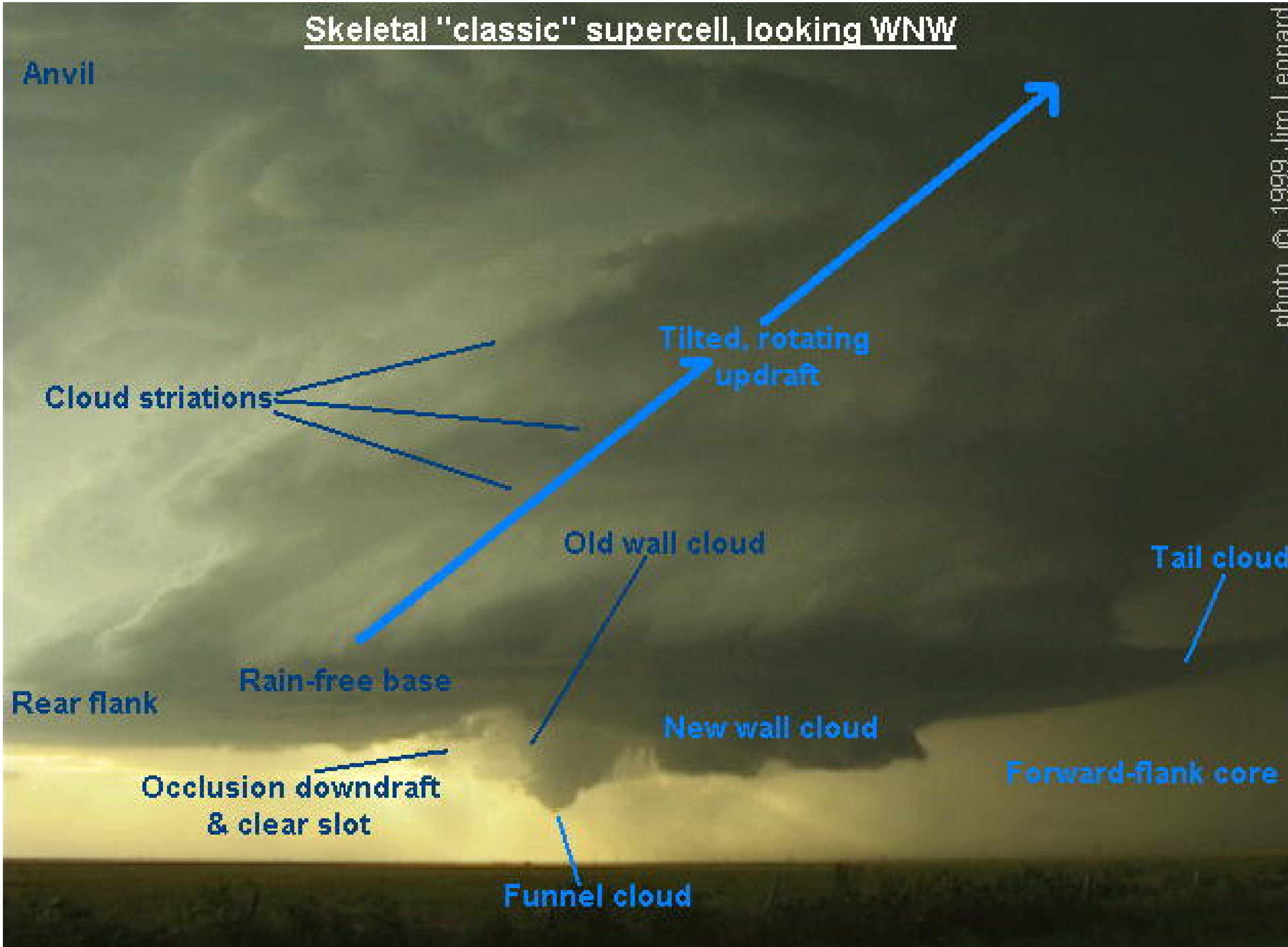
- The models of Browning and Lemon and Doswell were based on CL supercells
- Precipitation:
  - moderate amounts
- Environment:
  - moderate to high moisture
  - low to intermediate LFC values
  - strong low- and mid-level shear
  - most common in the southern Great Plains
  - develop away from competing storms
- Severe Weather:
  - most prolific producers of severe weather like large hail and tornadoes
  - not often associated with flash flooding
  - account for the majority of F4 and F5 tornado occurrences.

- Appearance:
  - Easily detectable both visually and via radar.
  - Updraft is highly visible and usually free of precipitation, although some precipitation may wrap around to the left and rear of the updraft (along storm motion).
  - Cloud base is normally precipitation-free, although scattered hail and raindrops may occur
  - A region of heavier precipitation is clearly evident downshear of the updraft
  - Flanking convective lines are often visible
  - Some precipitation usually occurs within the mesocyclone, however, it is not heavy.
  - Hook echo frequently occur - radar reflectivities within the hook are generally less than those in the precipitation core.
- Special Characteristics:
  - often exhibit well-known radar signatures e.g. WER/BWERs, storm-top above the low-level hook echo, v notch, etc.





Classic supercell features shown by a plan view (top left) of the precipitation (red), surface outflow boundaries (frontal symbols), updraft maxima (brown) and cloud boundaries (yellow) (after Doswell and Burgess, 1993), a schematic(bottom left) indicating the visual characteristics seen by an observer on the ground (after Doswell and Burgess, 1993), and (c) a photograph of a classic supercell that occurred near Alma, Nebraska on 30 May 1991 (after Rasmussen and Straka, 1998).



Source: Jim Leonard; Hutchinson County, Tx, June 29, 1999

CL Supercell

Photo: Brooks/Cole-Thomson Learning

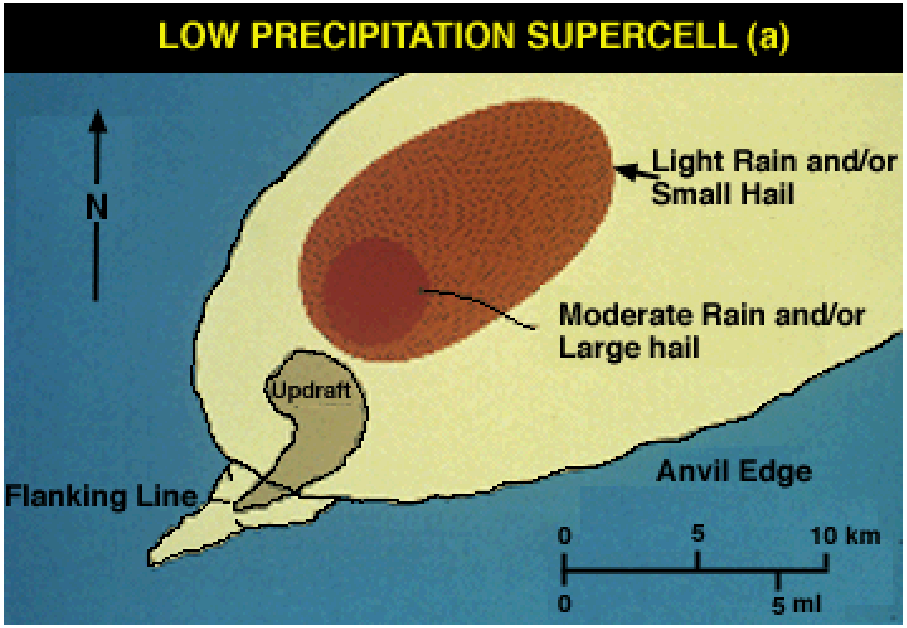
Low-Precipitation (LP) Supercell

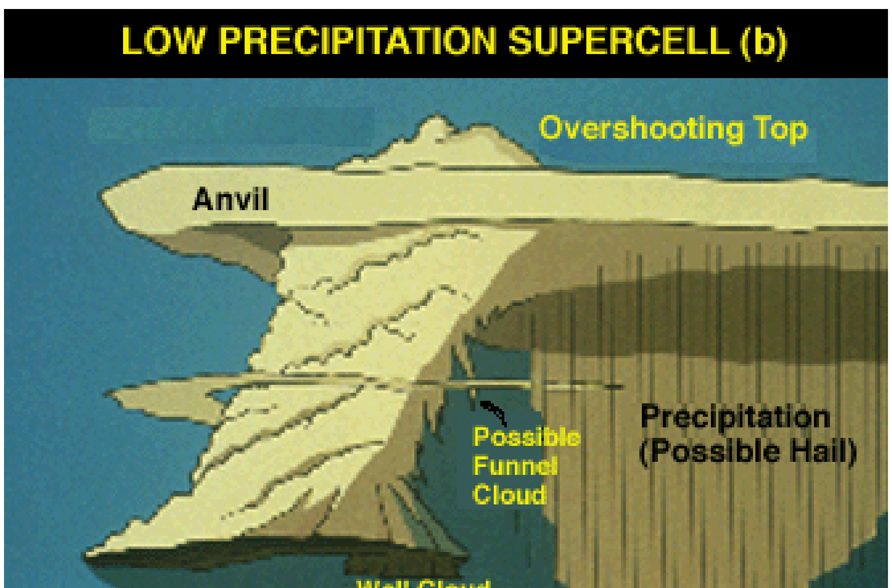
- LP supercells produce relatively little precipitation and do not exhibit all the classic supercell radar characteristics, but still show signs of rotation
- Precipitation:
  - characterized by a relative absence of rain in and near a deep rotating updraft and by light to moderate rain and/or large hail falling from the anvil
  - most of the precipitation appears to consist of large hail and/or a few large raindrops
  - considered to be low precipitation efficiency storms.
- Environment:
  - low to moderate moisture
  - relatively high LFC values
  - slightly weaker low- and mid-level shears compared with CL supercells
  - occur predominantly near the surface dryline
  - found mainly in the High Plains east of the Rocky Mountains and in the western regions of the Great Plains
  - tend to develop as isolated cells.

- Severe Weather:
  - large hail
  - weak tornadoes occasionally.
- Appearance:
  - highly visible
  - dry environment in which they develop prevents much of the intervening cloudiness
  - relatively little rain in, and near, the deep rotating updraft, and the cloud base is precipitation free
  - light to moderate rain, and/or large hail fall from the anvil
  - flanking lines are not often observed.
  - lack of precipitation in and around the updraft and mesocyclone makes the rotation associated with these storms difficult to detect on radar

- reflectivities associated with LP supercells are often low, even though they may produce large hail
- low-level hook echoes do not normally exist
- precipitation core is displaced away from the updraft.

- Special Characteristics:
  - strong evaporatively-cooled downdrafts are absent
  - the physical mechanisms favoring LP supercell development are still not well understood
  - Hail production is favored over rain production -> the reasons for this are not known





Low-precipitation supercell features shown by a plan view (top left) of the precipitation (red), updraft maxima (brown) and cloud boundaries (yellow) (after Doswell and Burgess, 1993), a schematic (bottom left) indicating the visual characteristics seen by an observer on the ground (after Doswell and Burgess, 1993), and (c) a photograph of a low-precipitation supercell that occurred in the Texas panhandle on 28 May 1994 (after Rasmussen and Straka, 1998).

LP supercell with tornado

Photo: Allan Moller

Seibert, CO LP supercell   Photos: Brian McNoldy

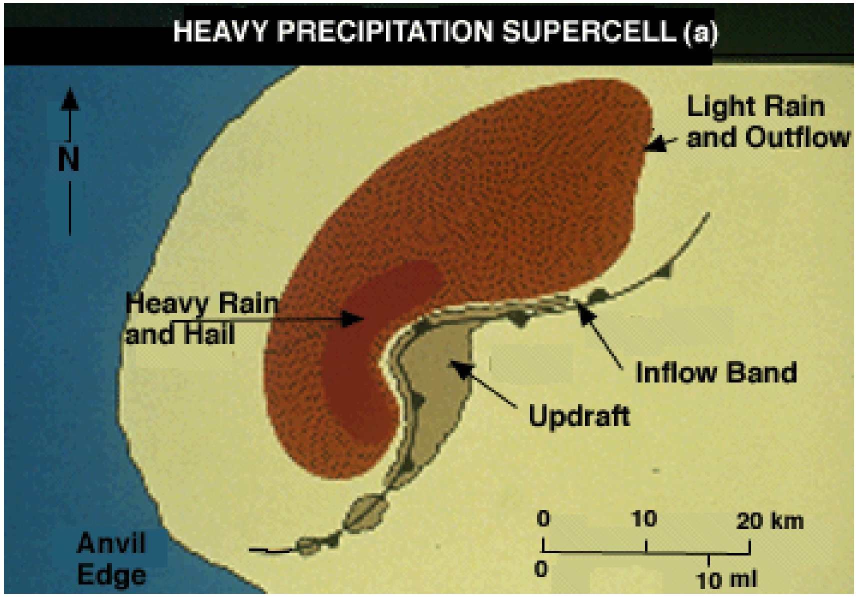
Seibert, CO LP supercell
Photos: Brian McNoldy

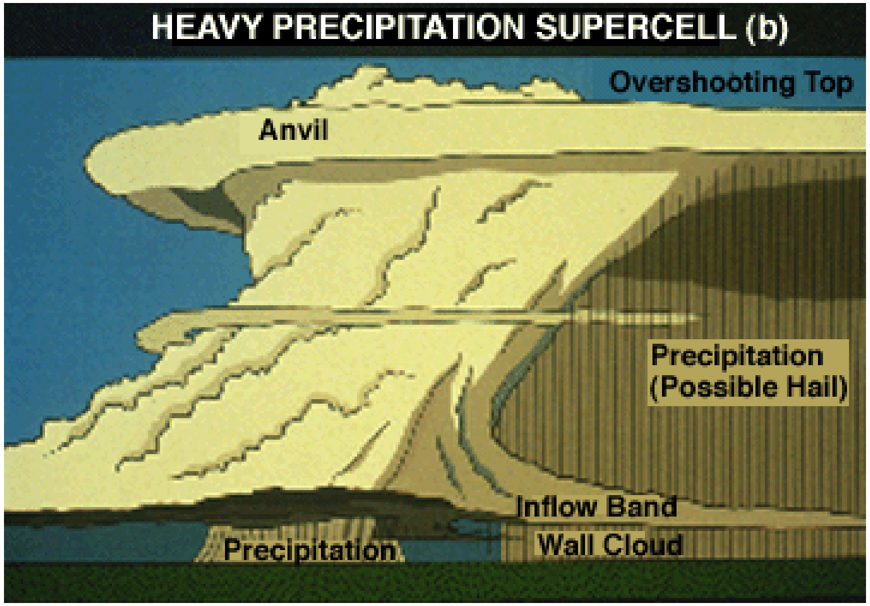
Seibert, CO LP supercell
Photos: Brian McNoldy

High-Precipitation (HP) Supercells

- Precipitation:
  - substantial precipitation within the mesocyclone.
- Environment:
  - humid, cloud-filled environments
  - often travel along pre-existing thermal boundaries where baroclinically-generated vorticity may enhance the mesocyclone
  - develop in all regions of the United States, but most frequently in eastern US and western High Plains
  - often develop near other storms.
- Severe Weather:
  - downbursts and flash flooding
  - tornadoes, however, they are not normally as strong, violent or frequent as those with CL supercells
  - large hail and strong winds

- Appearance:
  - humid, cloud-filled environment and the precipitation in the updraft make it difficult to visually identify the mesocyclone and tornadoes
  - should they be visible, then heavy precipitation under the updraft and the forward anvil are evident
  - the heavy precipitation within the updraft makes HP supercells easy to detect using radar
  - a distinguishing radar characteristic of these storms is that their mesocyclones are prominent
  - if a hook echo is present, which they often are not, reflectivities within the hook echo are comparable to or larger than those in the precipitation core
- Special Characteristics:
  - Moller et al. (1994) warn that the HP supercell category is used as a "catchall" category for any storm that has a deep, persistent mesocyclone embedded in precipitation
  - results in a large range of HP supercell storm structures and radar signatures, enhancing the difficulties in identifying of these storms.

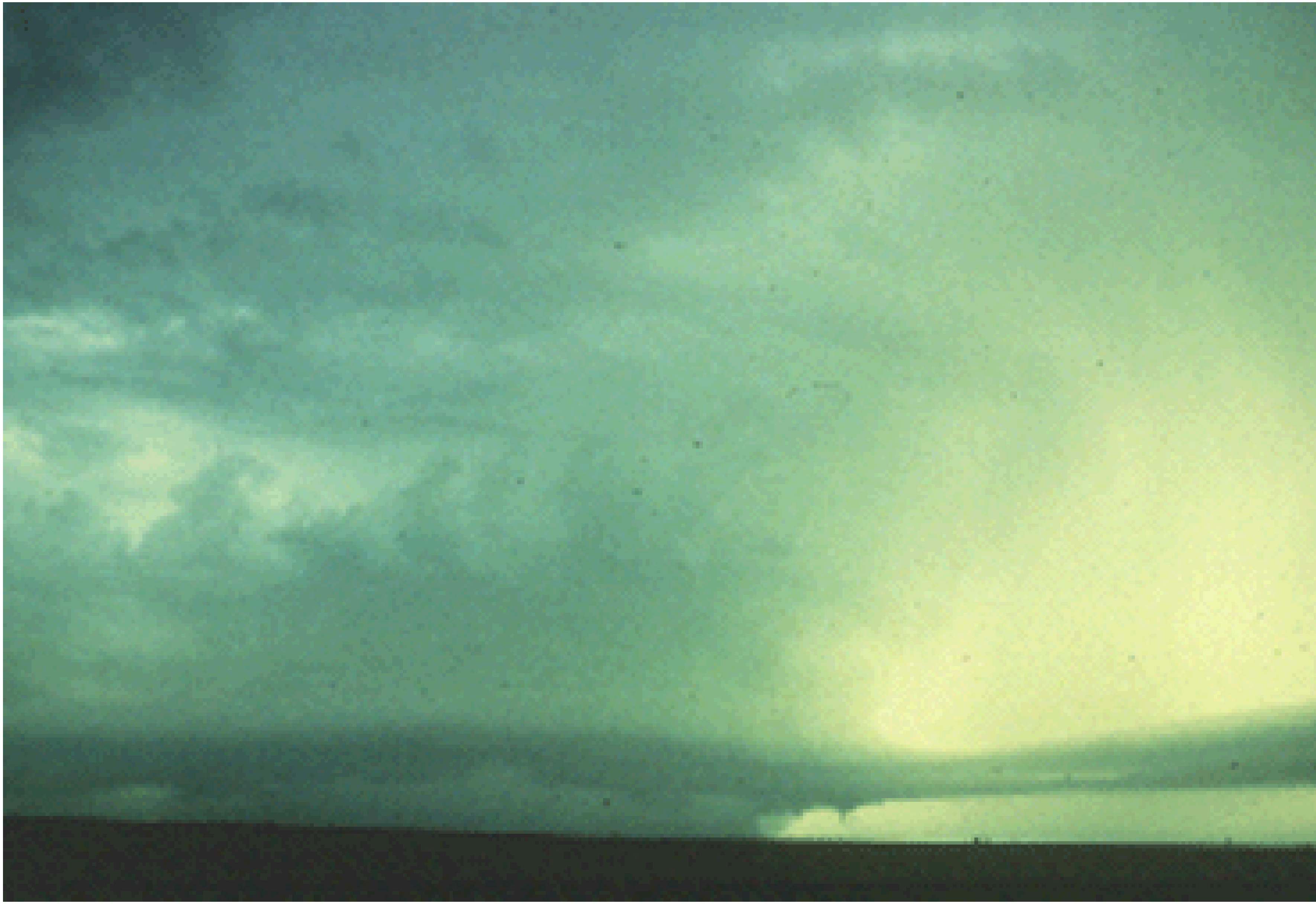




High-precipitation supercell features shown by a plan view (top left) of the precipitation (red), surface outflow boundaries (frontal symbols), updraft maxima (brown) and cloud boundaries (yellow) (after Doswell and Burgess, 1993), a schematic (bottom left) indicating the visual characteristics seen by an observer on the ground (after Doswell and Burgess, 1993), and (c) a photograph of a high-precipitation supercell that occurred in southwest Oklahoma on 19 April 1992 (after Rasmussen and Straka, 1998).

Colorado HP supercell

Photo: Paul Neiman

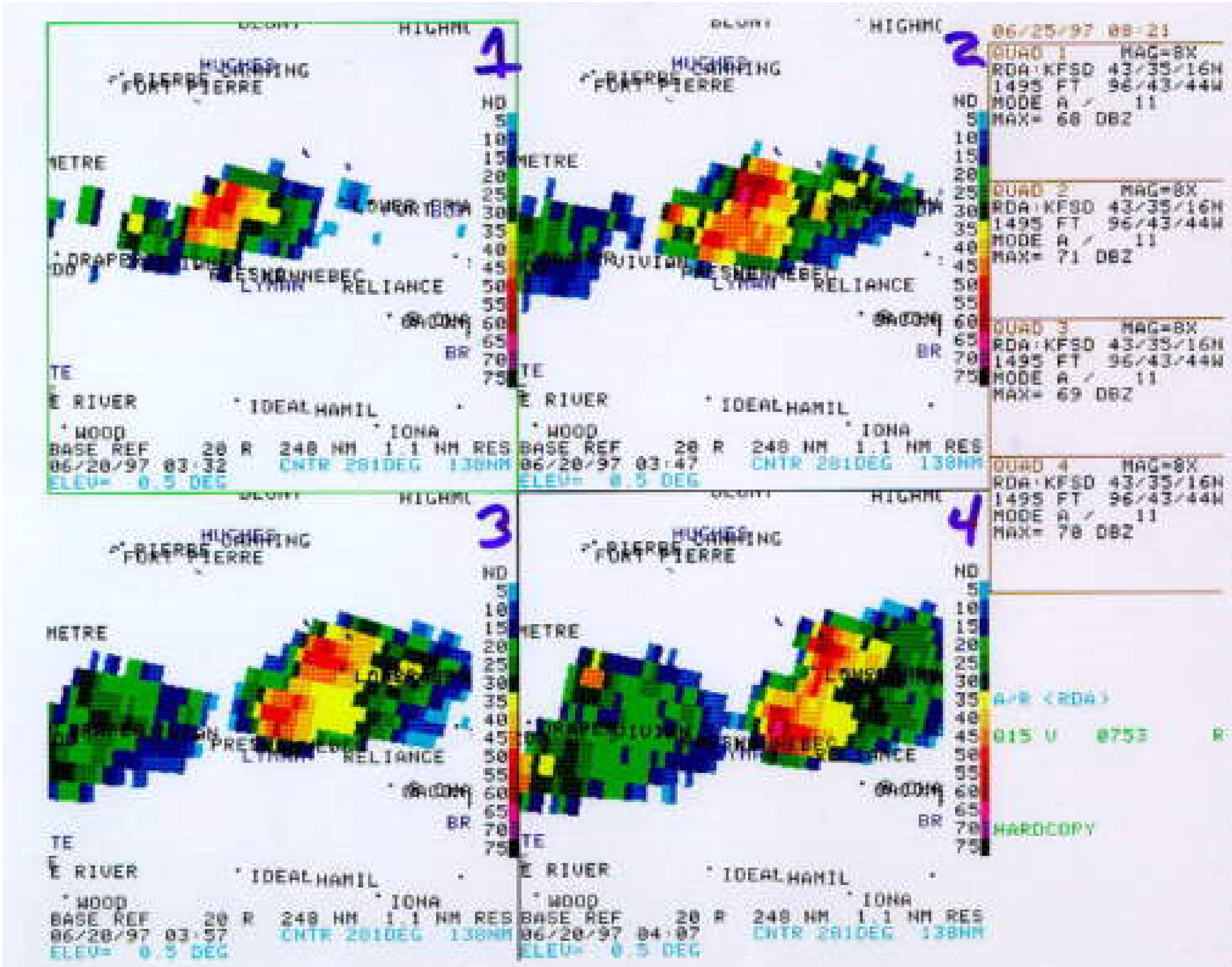


HP Supercell Photo: Doswell

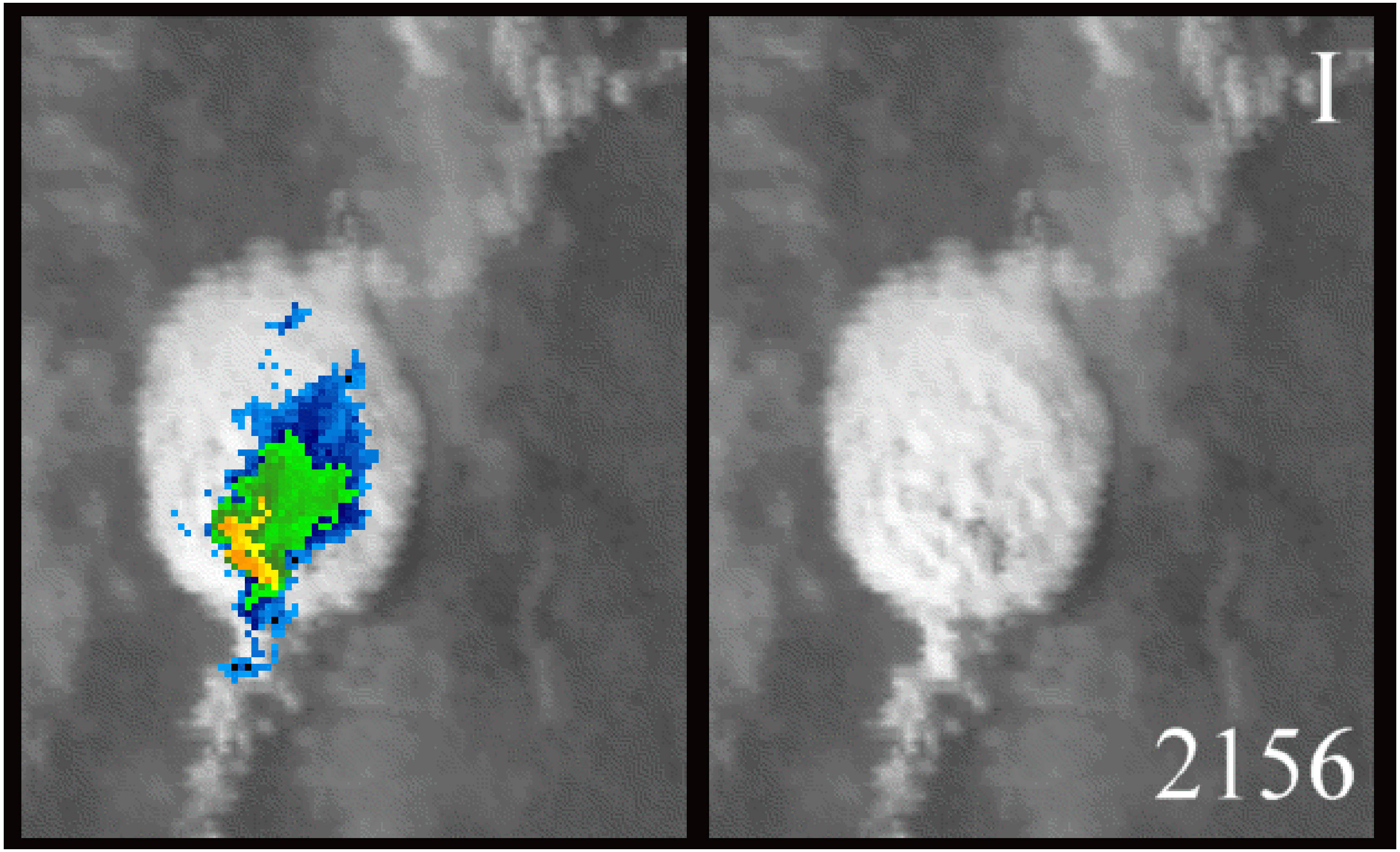
HP Supercell Photo: NWS

8.3.3 Storm Splitting

- Storm splitting was first observed using radar reflectivity
- Two storm cells develop following the splitting process
- The right-moving (RM) storm moves to the right and the left-moving (LM) storm moves to the left of the mean wind
- RM (LM) have cyclonically (anticyclonically) rotating updrafts
- Storm splitting begins with the splitting of the updraft core, and the subsequent storm propagation and rotation are linked



Radar imagery of storm splitting that occurred over Ethan, SD on June 19-20, 1997 (source: NWSFO Sioux Falls, SD)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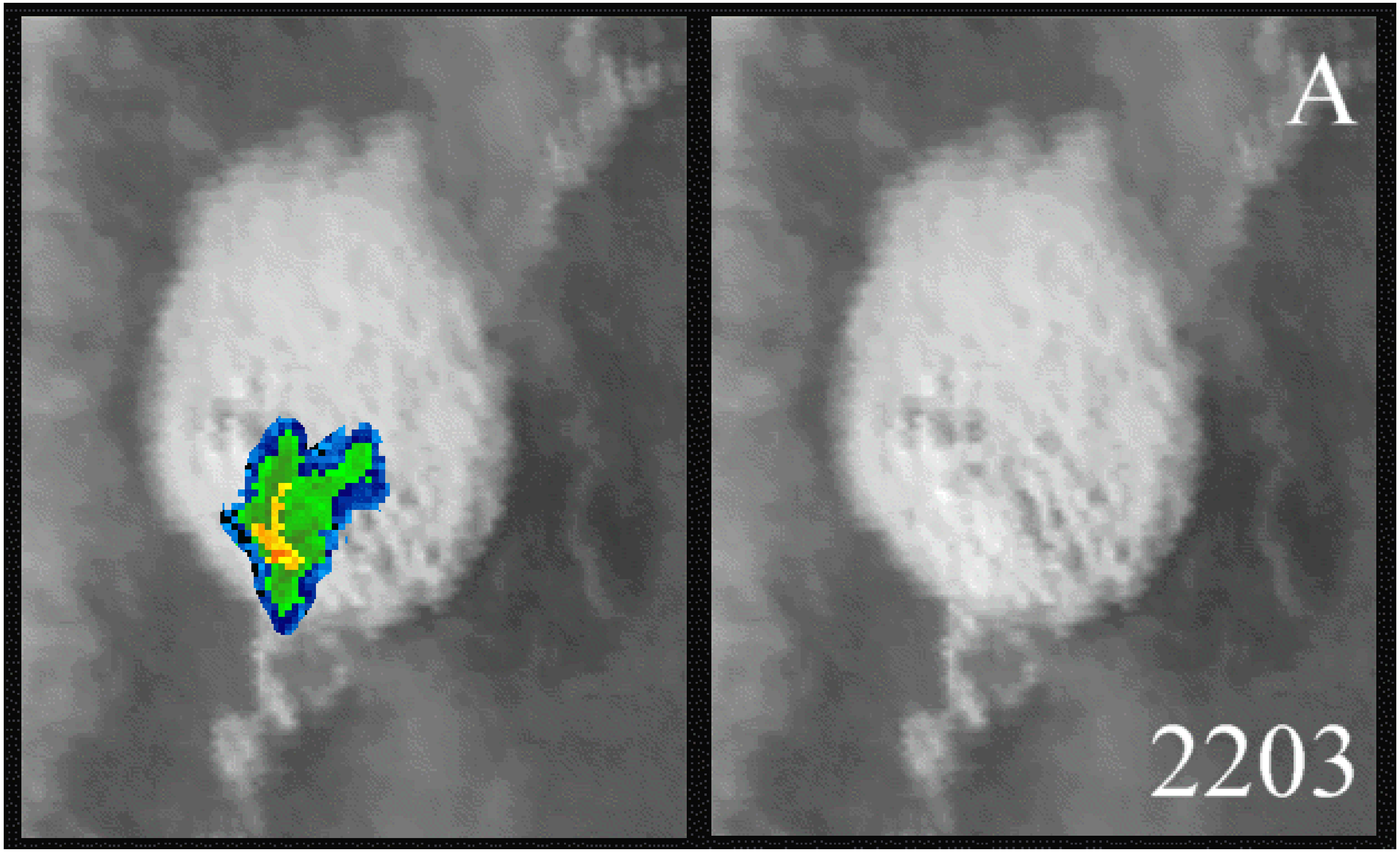
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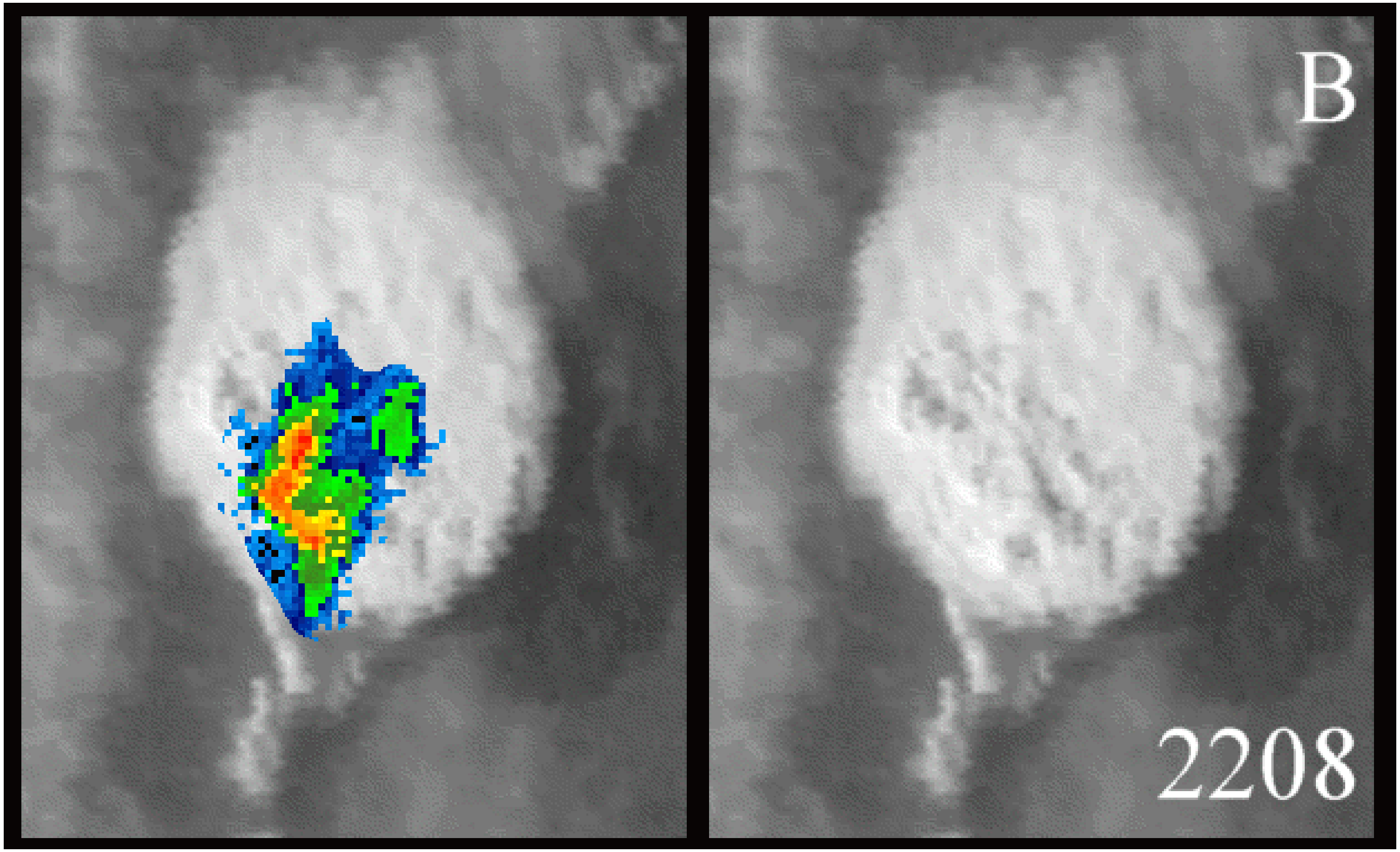
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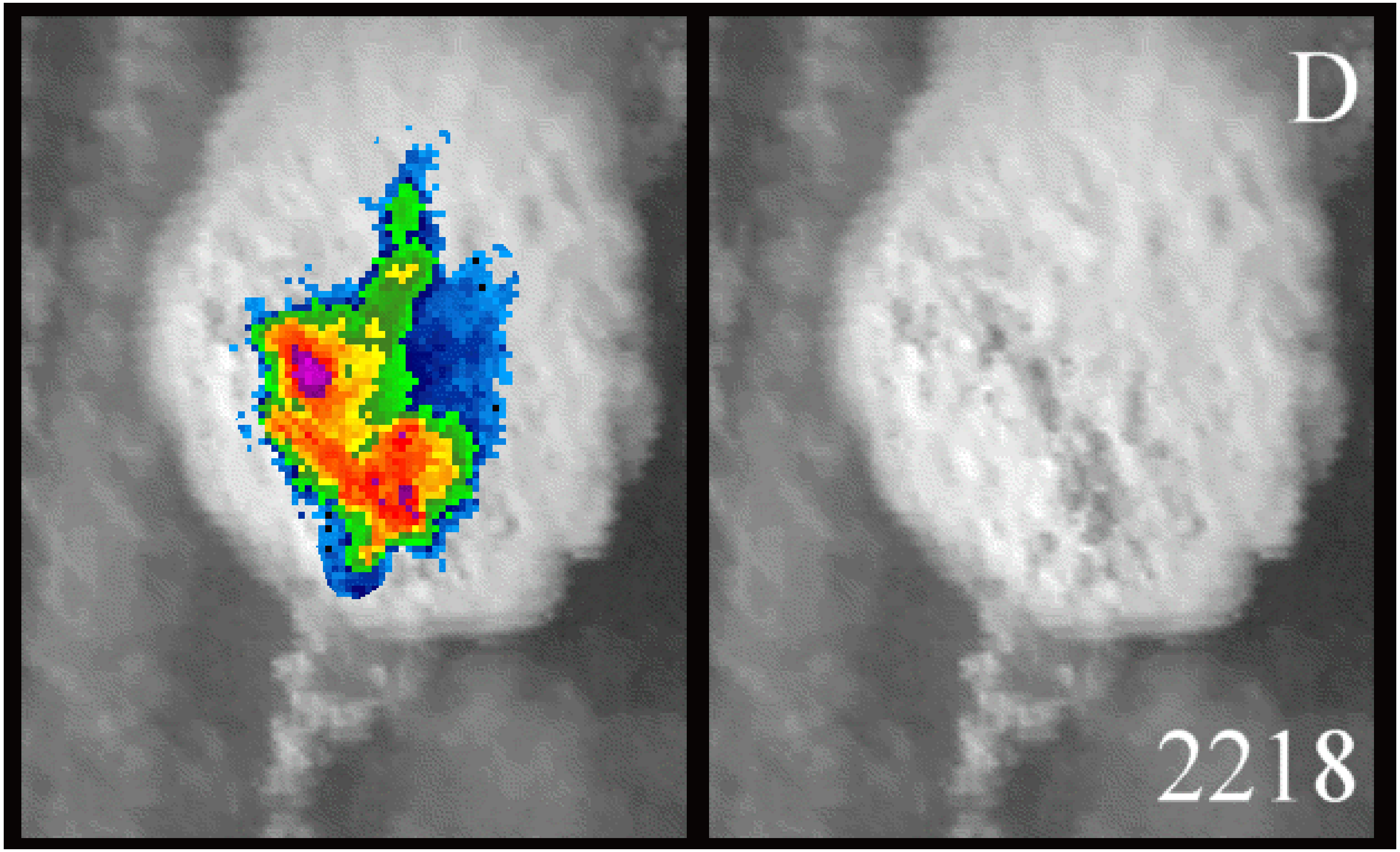
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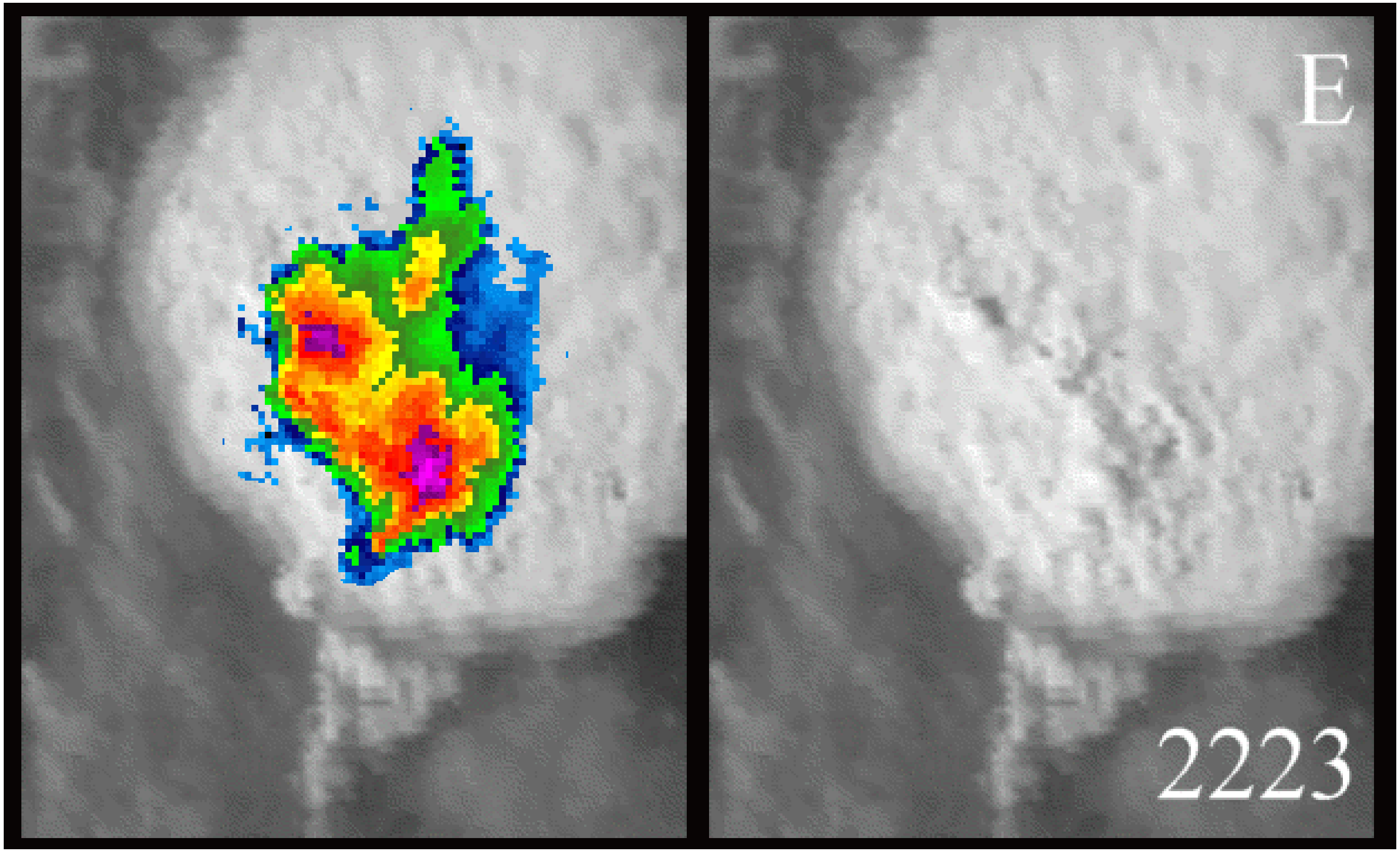
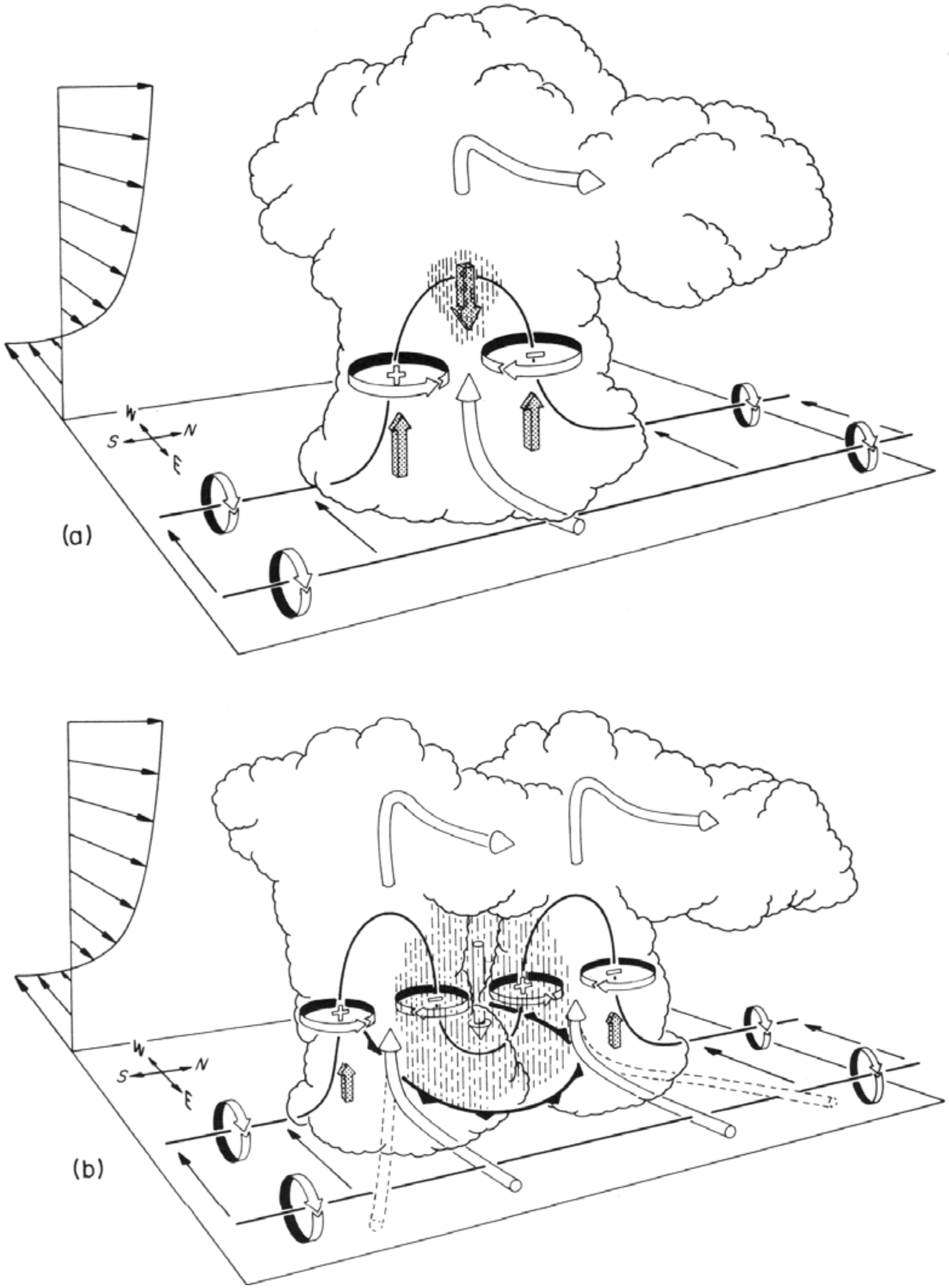


Radar and visible satellite imagery of severe storm splitting over Nebraska

(17 May, 1996) Source: CIRA Integrated Sensor Training

- 2 questions:
  1. How does storm splitting actually occur?
  2. What causes the RM storm to rotate cyclonically, while the LM rotates anticyclonically?
- Three-dimensional modeling studies with unidirectional, westerly hodographs have helped to answer these questions
- Initial Stage
  - Horizontal vortex tube is associated with the vertical wind shear
  - Following the development of a convective updraft, the horizontal vortex tube is tilted into the vertical by the horizontal gradients in vertical velocity
  - A cyclonically (anticyclonically) rotating vortex develops on the right (left) of the updraft (with respect to the shear vector) at both the mid- and low-levels
  - Vertical vorticity will be greatest just below the region of maximum vertical velocity in the updraft -> stretching amplifies but does not significantly change the distribution of the mid-level vertical vorticity



Schematic showing how a horizontal vortex tube generated by westerly environmental shear is tilted as it interacts with a convective cell. Cylindrical arrows show the direction of the storm-relative airflow, and heavy sold lines represent vortex lines with the sense of rotation indicated by circular arrows. Shaded arrows represent the forcing influences that promote new updraft and downdraft growth. Vertical dashed lines denote regions of precipitation. The cold outflow beneath the storm is represented by conventional frontal symbols. (a) Initial stage: horizontal vortex tube is swept into the vertical by the developing updraft. (b) Splitting stage: a downdraft forms between the splitting updraft cells and this tilts the vortex tubes in this region downward, producing two vortex pairs (adapted by Klemp (1987), from Rotunno, 1981).

- Splitting Stage
  - Begins with the weakening of vertical velocity in the updraft center
  - As the downdraft develops, the vortex tubes are tilted downward and two vortex pairs develop, one on either side of the shear vector
  - The central portion of the updraft is replaced by a downdraft
  - The initial storm splits producing two storms each containing a vortex couplet
  - The storm with the cyclonically (anticyclonically) rotating updraft moves to the right (left) of the mean wind
- How then does splitting actually occur? Several different theories which include the effects of water loading, vertical pressure gradient forces and vertical shear:

1. Water loading
   - Klemp and Wilhelmson, 1978 (referred to as KW78); Wilhelmson and Klemp, 1978
   - used numerical model
   - strong water loading developed in the center of the updraft following the development of rain
   - precipitation-induced downdraft caused an initial split of the updraft at lower levels and also generated a gust front beneath the storm
   - enhanced convergence between gust front and the ambient air increased the influx of warm, moist air into storm
   - increased low-level updrafts located on flanks of initial cell
   - low-level updrafts continued to move apart as gust front split and propagated outward

- upper level updrafts then split as they followed the low-level updrafts
- downdrafts then also split

2. Vertical perturbed pressure gradient force
   - Schlesinger (1980), Clark (1979)
   - used numerical model and observations
   - rainwater loading and vertical perturbed PGf are of comparable magnitude
   - downward directed PGF in middle of initial cell acts in same direction as drag to enhance downdraft
   - upward directed PGF on both storm flanks enhances updraft development in these locations
   - dynamical processes may therefore initially control splitting, while water loading may later enhance this process – observations indicate that two updrafts are often evident before the radar echo splits

3. Vertical Shear

- KW78
- used numerical model
- if there was no vertical shear then the initial cell did not split
- negative buoyancy associated with precipitation loading soon resulted in the cell dissipation
- directionally varying shear was not necessary for storm splitting
- the low-level shear needed to be sufficiently strong to inhibit the gust front from propagating away from the storm too quickly
- if the low-level shear was too strong, splitting did not occur as the updraft and downdrafts were both weak due to mixing

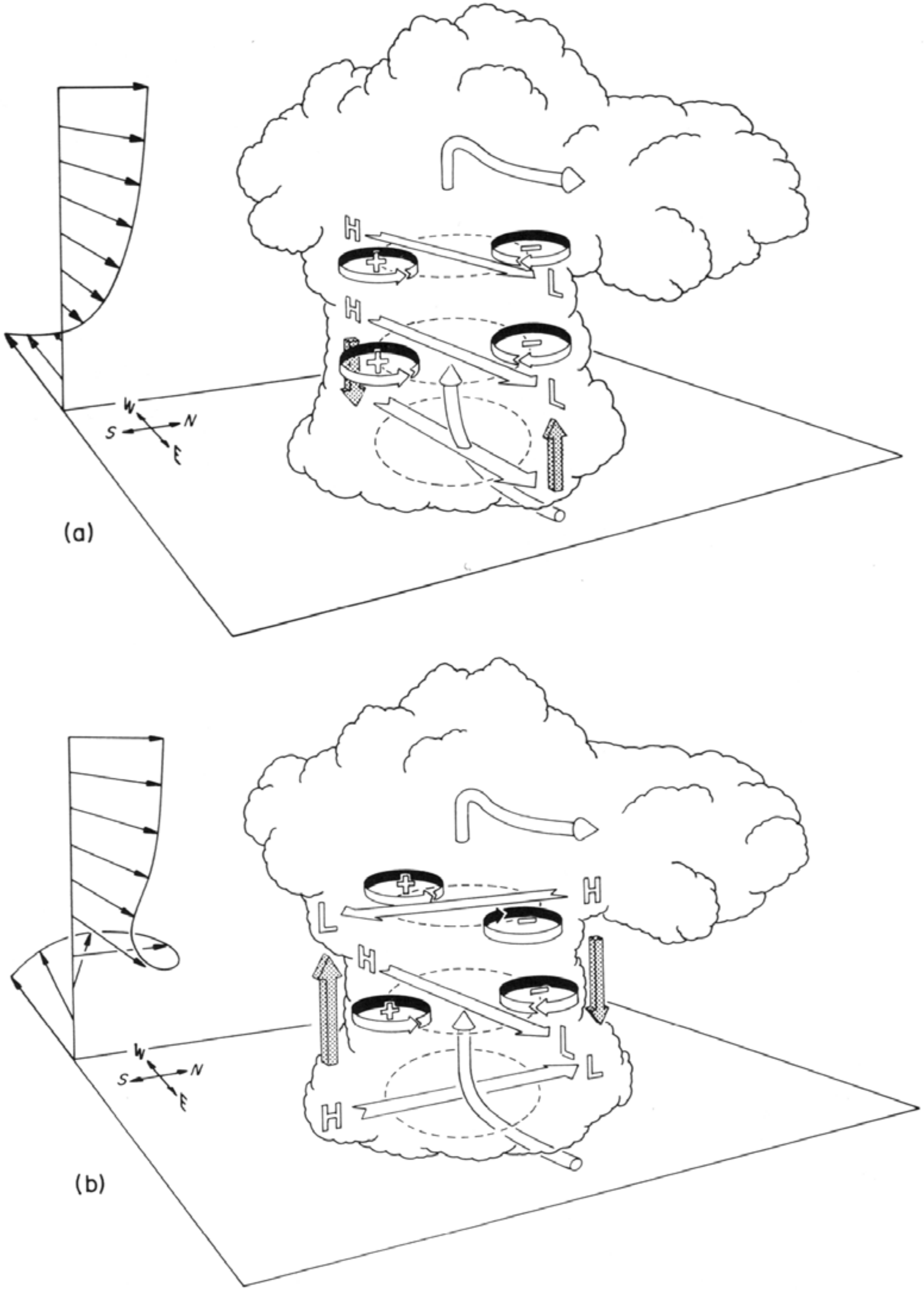
8.3.4 Storm Motion

- Storms move to the left and right of the mean wind following the splitting of the initial cell
- RM storms are observed more frequently (in the Northern Hemisphere)
- RM (LM) storms maintain their intensity by propagating slower and to the right (faster and to the left) of the mean wind -> ensures maximum inflow of air into the storm at low- and mid-levels
- Using a numerical model KW78 found that:

  Clockwise turning (veering) of the hodograph with height favors RM storms, whereas counterclockwise turning (backing) of the hodograph favors LM storms.
- This bias is most pronounced for hodograph curvature in the lowest levels

- KW78 suggested the following:
  - When the hodograph turns clockwise with height, the mid-level inflow into the downdraft of the RM increased, thereby enhancing the downdraft, the low-level outflow and the development of the gust front.
  - This in turn strengthens convergence along the gust front and storm longevity.
  - Clockwise turning of the hodograph with height reduces the mid-level inflow of air into the LM, which produces the opposite effects to those of the RM. The LM is therefore weak and short-lived.
  - The situation is reversed when the hodograph backs with height, and the LM is then the long-lived storm.
  - When the hodograph is unidirectional (and with no CF), the RM and LM are mirror images of each other

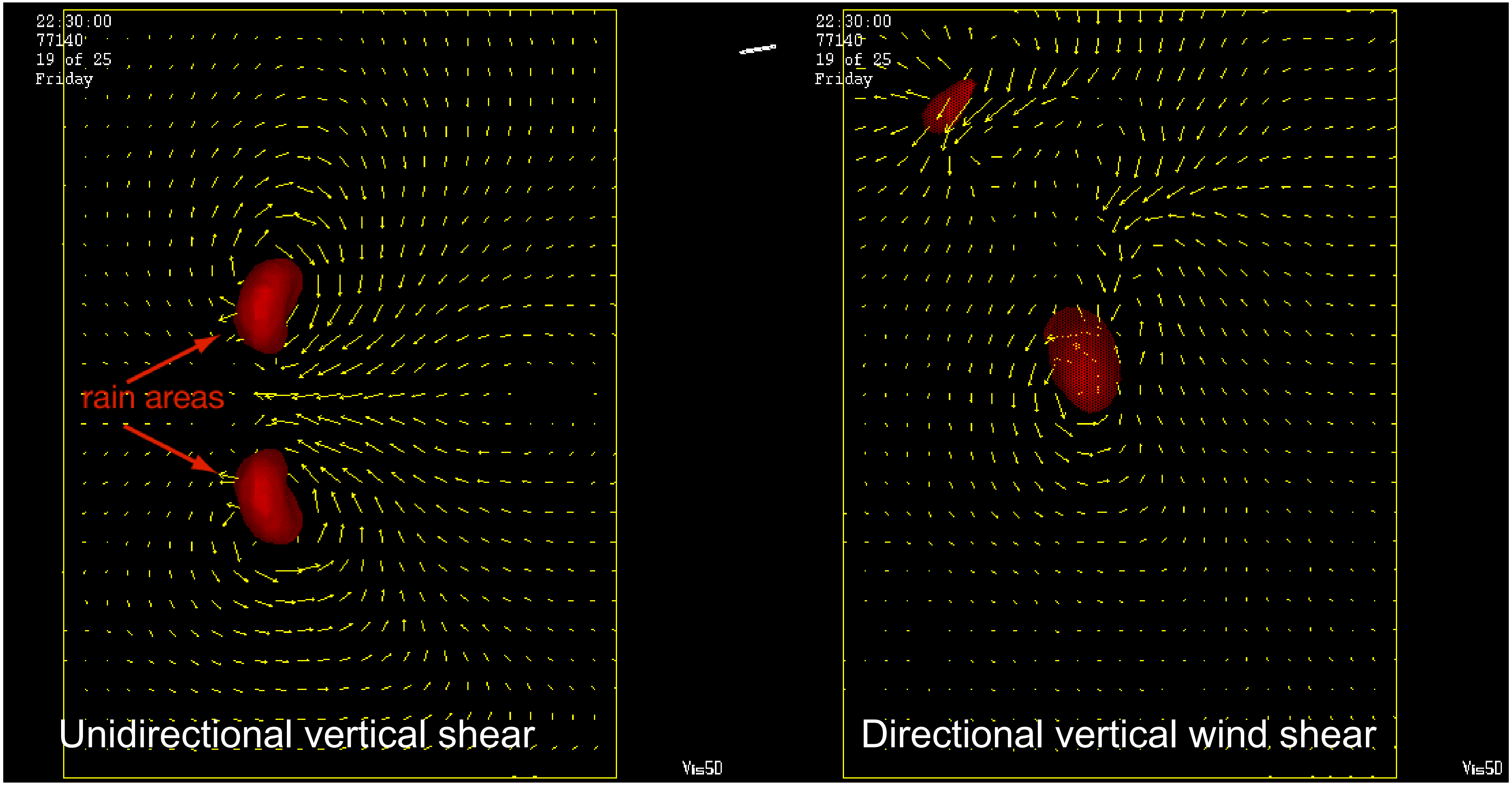
- Rotunno and Klemp (1982) made use of a numerical model and linear theory to suggest the following:
  - An updraft growing in wind shear develops pressure perturbations such that positive pressure perturbations are produced on the upshear flank of the updraft and negative pressure perturbations on the downshear flank
  - If the shear vector does not change direction with height, areas of relative high (low) pressure will be stacked above areas of relative high (low) pressure, and the storm will develop symmetrically (see next slide)
  - If the shear vector changes direction with height, then vertical pressure gradients will develop that favor storm development on one side of the original cell and suppress development on the other side.



Schematic showing the distribution of pressure and vertical vorticity perturbations that develop as an updraft interacts with an environmental shear vector that (a) is unidirectional with height and (b) veers with height. The high (H) to (L) horizontal pressure gradients parallel to the shear vectors (flat arrows) are labeled along with the preferred location of cyclonic (+) and anticyclonic (-) vorticity. The shaded arrows depict the orientation of the resulting vertical pressure gradients (adapted by Klemp (1987) from Rotunno and Klemp (1982)).

- Typically when the hodograph veers (backs) with height, the right (left) flank of the original cell experiences a favorable upward directed pressure gradient while the left (right) flank experiences an unfavorable downward-directed pressure gradient. The result is a dominant RM (LM) counter-clockwise (clockwise) rotating supercell
- From the perturbation vorticity equation it can be shown that cyclonic (+) and anticyclonic (-) vorticity centers will develop on the right and left side of the shear vector, respectively
- When the hodograph veers (backs) with height, the positive (negative) vertical vorticity and the updraft are positively correlated

- RK also showed that p' ~ -ζ^2 Therefore wherever there was rotation, the pressure was lowered. Low pressure was therefore induced on both flanks of the initial cell, and this enhanced storm splitting
- Is has also been suggested that under veering conditions that the left flank may be predominantly forced by convergence along the gust front, whereas the right flank is primarily controlled by the vertical PGF which aids splitting and differences between the LM and RM storms (Weisman and Klemp, 1984)
- Under veering hodograph conditions, the LM may decay more rapidly than the RM based on the greater ingestion of cold pool air (Grasso, 2000; van den Heever, 2001)
- Storm splitting and the development of RM and LM storms can therefore develop with both unidirectional and directionally varying hodographs, however, the dominance of the RM or LM storm is directly related to the veering or backing motion of the shear vector



Rotating supercell storms are favored by environments having considerable vertical wind shear, and can form as a result of the splitting of preexisting convection. The simulation at left had only vertical wind speed shear. The original convective cell split into two new storms of equal strength but having opposite senses of rotation and very different trajectories. With directional shear (right), one of the split storms is definitely favored. The reddish area is a rainwater isosurface and vectors indicate midtropospheric wind perturbations. *Source: R. Fovell, UCLA; made with the ARPS model*

8.3.5 Supercell Storm Environments

- Supercells occur throughout the world and have been documented in numerous regions including Argentina,Australia, Belgium, Canada, England, France, Japan, Russia, South Africa, Switzerland and the USA
- Within the USA supercells are most common in the central regions but they also occur to the east of the Appalachians, and even to the west of the Continental Divide
- Two predominant environmental factors that determine what type of convective storm will develop are buoyancy (represented by CAPE) and vertical wind shear (particularly in the lower 3 to 4 km)
- Severe storms occur when CAPE is large and when the vertical wind shear ($\partial\vec{V}/\partial z$) is moderate to strong

- Typical values for supercells:
  - CAPE > 2000 J kg^{-1} (although supercells do form in environments with CAPE < 1500 J kg^{-1})
  - Vertical wind shear > 20-25 $m.s^{-1}$ over the lowest 4-6 km
- The strength of the mid-level and upper-level shear may also be important in supercell development and the types of supercells that develop
- To determine the type of severe storm that is likely to develop we can use the bulk Richardson number (BRN) which is the ratio of CAPE to the square of the mean vertical shear integrated over height (S^2):

$$\boxed{\mathrm{BRN} = \frac{\mathrm{CAPE}}{S^2}} \quad \text{where} \quad S^2 = \frac{1}{2}\left(\overline{u}_{6000} - \overline{u}_{500}\right)^2$$

where $\overline{u}_{6000}$ and $\overline{u}_{500}$ are the pressure-weighted mean vector wind speeds in the lowest 6 km and 500 m respectively

- Supercells: BRN between 15 and 40

  Multicells: BRN > 40
- For a self-sustaining supercell:
  - if the low-level environment is too stable for the amount of CAPE available (buoyancy effect) or if the gust front moves away from the developing storm too quickly (shear effect) then successive storm development can not occur
  - if there is sufficient CAPE but the vertical wind shear is too weak, the downdraft is not displaced away from the updraft and a self-sustaining structure will not develop
  - if the vertical wind shear is too strong, the developing storm will be sheared apart.
  - the BRN therefore indicates the balance needed between the buoyancy and shear effects if supercells are to develop

- Two other measures of the atmosphere's ability to produce a mesocyclone are helicity and storm-relative helicity (SRH)
- Helicity is defined in general as:

$$\boxed{H = \vec{V} \cdot \vec{\omega}}$$

where H is the helicity, $\vec{V}$ is the three-dimensional wind vector and $\vec{\omega}$ is the vorticity vector

The vertical component of storm-relative helicity (SRH) is given by:

$$\boxed{\mathrm{SRH} = \int_0^d \zeta \cdot \vec{V}\, dz = -\int_0^d \vec{k} \cdot \left[\left(\vec{V} - \vec{c} \right) \times \frac{\partial \vec{V}}{\partial z} \right] dz}$$

where d is the depth of an assumed inflow-layer (normally 3 km), $\vec{k}$ is the unit vector in the vertical direction, $\vec{c}$ is the storm velocity vector, $\vec{V}$ is the environmental ground-relative horizontal velocity vector

- SRH is therefore the product of the storm-relative velocity and the streamwise vorticity

- SRH is also a predictor of the correlation between vertical velocity and the vertical vorticity, and hence of mesocyclones
- SRH can be found from a hodograph and is given as minus twice the area enclosed within the hodograph between the vector connecting the storm motion with the ground level wind, and the vector connection the storm motion with the 3km wind
- Critical value above which supercells are possible is between when SRH ≥ 100-150 m^2s^{-2} and when SRH ≥ 250 m^2s^{-2}
- SRH values for weak, strong and violent tornadoes are 150-299, 300-449 and > 540 $m^2\ s^{-2}$ respectively
- Rasmussen and Blanchard (1998) found that SRH was better at distinguishing between supercells and other storms than other hodograph-based parameters such as mean wind shear

- Problems exist with using both the SRH and BRN as forecasting tools:
  - SRH: depends on accurate wind and storm motion measurements; it is assumed that storm motion is known a priori
  - BRN: although it makes use of the low-level shear, it does not account for any directional changes in the shear vector with height
- Rasmussen and Blanchard (1998) found that parameters that combine the impacts of buoyancy and shear on supercells appear to have more value in the prediction of supercell environments than those parameters that only include one of these effects, eg energy-helicity index:

$$EHI=(CAPE \times SRH)/1.6 \times 10^5$$

- Weisman and Rotunno (2000) concluded from their simulations that the helicity explanation of supercell rotation, while generally correct as a diagnostic tool, is of limited use as a forecast tool, because it predicts rotation as a function of a given storm motion, whereas in reality the storm motion is a function of the rotation (as we will see in the next section)

8.4 Tornadic Thunderstorms

8.4.1 Introduction

- Definition: A violently rotating column of air, in contact with the ground, either pendant from a cumuliform cloud or underneath a cumuliform cloud, and often (but not always) visible as a funnel cloud (Glossary of Meteorology)
- Tornadogenesis is still not well understood !!
- It is likely that tornadoes can form from several different processes
- Tornadoes are most frequently associated with the mesocyclone in <u>supercell</u> storms
- However there are many reports of tornadoes forming below towering cumulus clouds that form along the flanking line of a multicellular thunderstorm system, and smaller, short-lived tornadoes are even observed to form beneath relatively isolated towering cumulus clouds.

- Tornadoes produced by <u>nonsupercell</u> storms are typically associated with low-level boundaries produced by the convective storm, or low-level boundaries *not* produced by the convection but which interact with the convection
- Majority of tornadoes rotate counterclockwise but some rotate clockwise too
- Tornado’s circulation is evident at the ground either as a funnel-shaped cloud or as a swirling cloud of dust and debris
- Tropical cyclones or hurricanes can also be a source of tornadoes:
  - As many as 25% of the hurricanes in the US spawn tornadoes, and these hurricanes produce 10 tornadoes on average
  - Hurricane Beulah in 1967 produced 141 torndoes

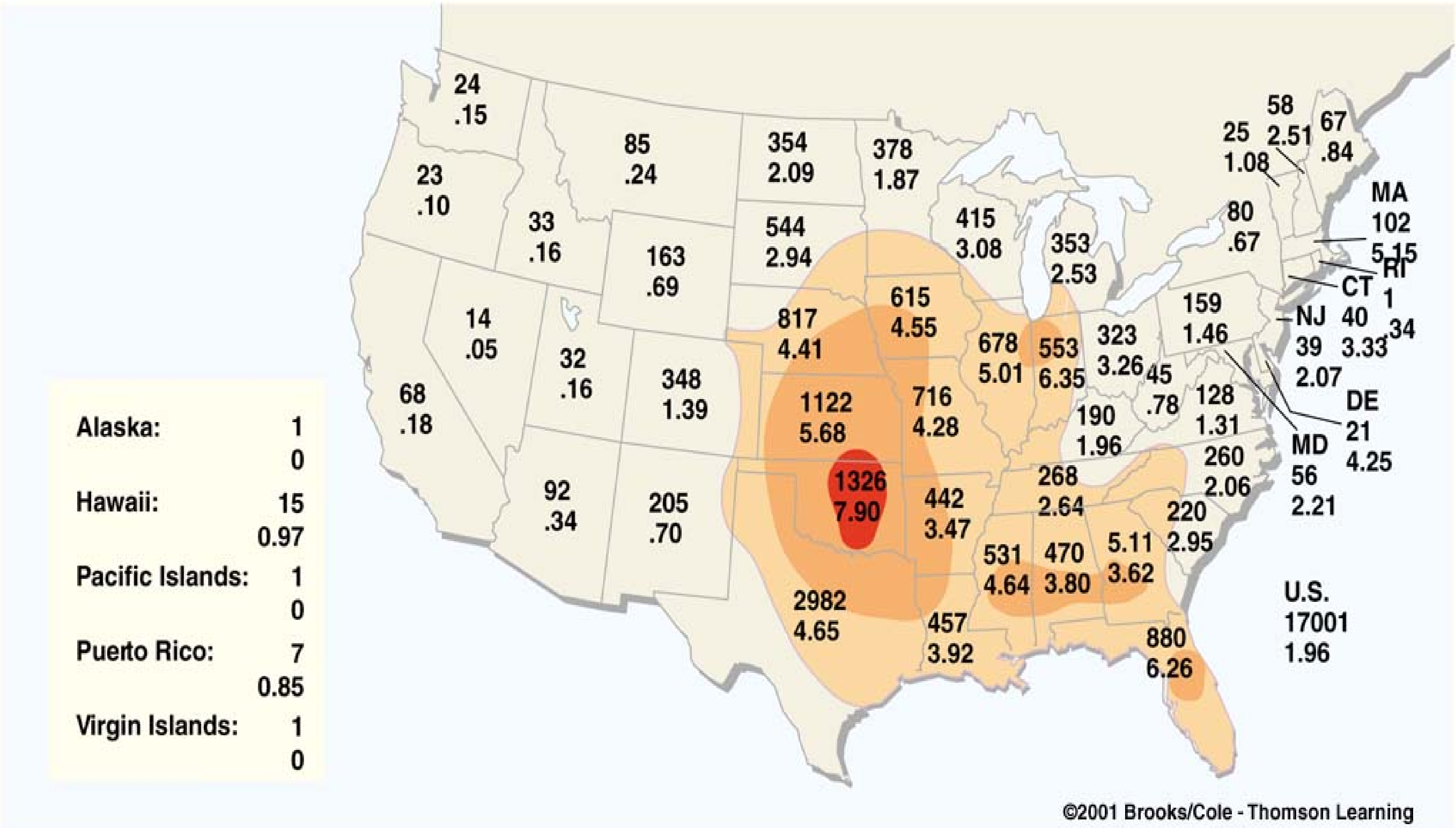
Tornado Outbreak

- Definition: a series of tornadoes that forms within a particular region, often associated with widespread damage and destruction; a region may include several states
- April 3, 1974: 16 hour period, 148 tornadoes cut through parts of 13 states, 307 people killed, >3700 people injured, damage > $600 million
- The greatest occurrences of tornadoes is in the US; average: >1,000/yr; 1,424 during 1998
- Tornado alley: Tornado belt, Central Plains, stretches from central Texas to Nebraska

Tornadoes and their Impacts

- Lifting railroad coach with 117 passengers and dumping it 25 m away
- Schoolhouse was demolished and 85 students inside were carried over 100 m without one of them being killed
- Pressure in the center of a tornado may be more than 100 mb lower than the surrounding and there is a momentary drop in outside pressure when tornado is above a structure

Tornado Occurrences



Tornado incidence by State; upper:number by each state (25 yrs); lower: average annual number/100,000 square miles; darker: greater frequency   Source: Brooks/Cole Thomson Learning

- Supercell tornadoes:
  - link between mesocyclones and tornadoes in supercells -> conservation of angular momentum may explain supercell tornadoes
  - development of tornadoes in the region of the wall cloud suggests that nearby downdrafts play an important role in getting tornadic/mesocyclonic vorticity to low levels in the storm
  - processes leading to tornado development may be different from those controlling the large-scale vorticity

The first tornado captured by the NSSL doppler radar and NSSL chase personnel – Union City, OK, May 24, 1973. The tornado has reached the mature stage of formation. Photo: NOAA photo library

- Nonsupercell Tornadoes (source: Doswell)
  1. Landspouts:
     - occur due to the intensification of pre-existing, shallow vertical vortices near the surface by vortex stretching when a developing convective updraft moves over them
     - the vortices often occur along convergence boundaries
     - also may occur when boundaries collide

An example of a non-supercell tornado event near Sublette, Kansas on 15 May 1991. Note that this is a relatively high cloudbase, estimated at about 5,000 ft. Photograph by C. Doswell.

2. Gustnadoes

- Very small scale, shallow vortices may develop near the surface along outflow boundaries and/or cold fronts, with or without deep convection overhead
- Sometimes, for reasons that essentially are not known, those circulations become quite intense; at least as intense as weak tornadoes.
- It is thought that they are different from landspouts as they remain shallow
- Don’t depend on developing updraft above them

An example of a circulation along a gust front (sometimes called "gustnadoes") near Welch, Texas on 23 May 1982. In contrast to the landspout figure this cloud base is quite low, around 500 ft or less. Photograph by C. Doswell

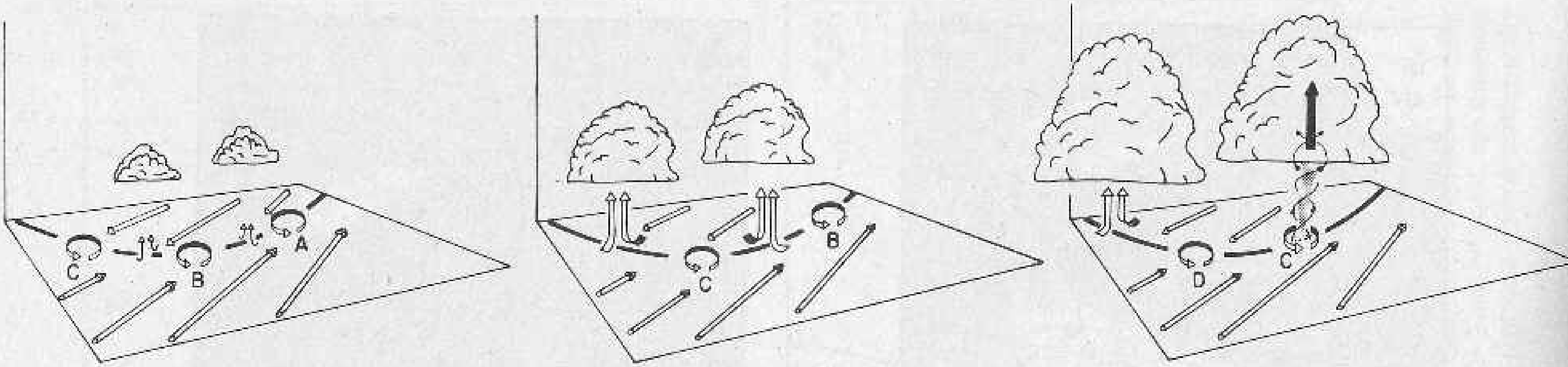
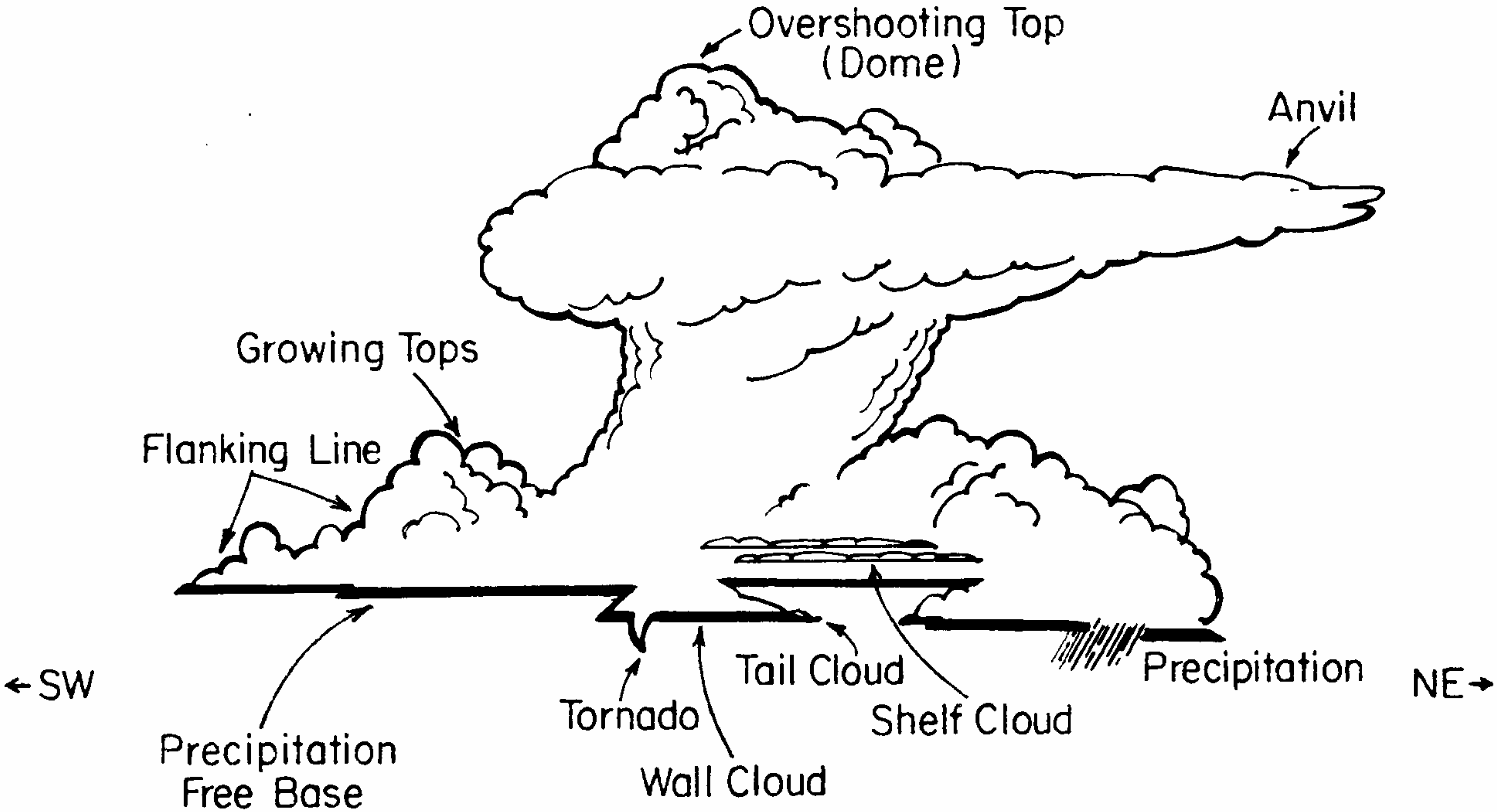


FIG. 20. Schematic model of the life cycle of the non-supercell tornado. The black line is the radar detectable convergence boundary. Low-level vortices are labeled with letters.

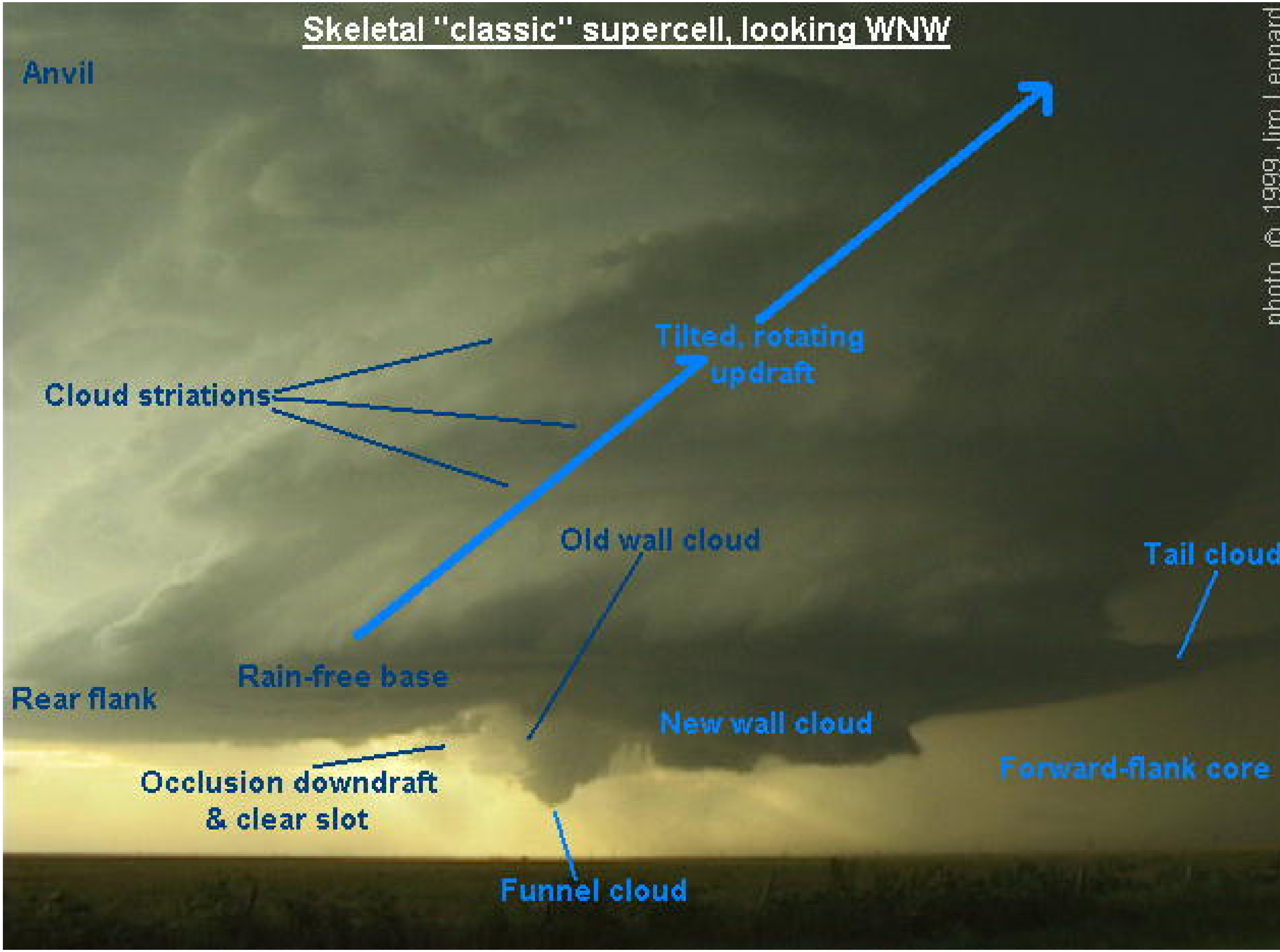
Life cycle of non-supercell tornadoes (Wakimoto and Wilson, MWR, 1989).

8.4.2 Tornadic Storm Features

- A schematic of a typical Great Plains tornadic thunderstorm is shown on the next slide. Features include:
  - relatively flat cloud base
  - wall cloud: mark area of strongest updraft in the storm; as storm intensifies updraft pulls in air from its surroundings, including low-level air from the rain area -> this air is very moist and condensation soon occurs forming the wall cloud; preferred location of tornado formation
  - precipitation: typically out of the northern and rear storm flanks
  - flanking line
  - solid core of rotating cloud through much of the troposphere
  - anvil cloud
  - overshooting tops due to the vertical momentum of strong updrafts – updraft air can be transported 5 to 6 km into the stratosphere
  - funnel cloud – spinning column of air thrusts mass outwards, and lowers the pressure so that air cools adiabatically below its dewpoint producing the visible funnel cloud.



An idealized tornadic thunderstorm as viewed from the southeast. The vertical scale is exaggerated by about a factor of two. Courtesy of Joseph Golden, NWS-NOAA. (From Klemp, J.B.,1987: Dynamics of tornadic thunderstorms. *Ann. Rev. Fluid Mech*., **19**, 369-402. Reproduced, with permission, from the Annual Review of Fluid Mechanics, Volume 19, Copyright 1987 by Annual Reviews Inc)



Source: Jim Leonard; Hutchinson County, Tx, June 29, 1999

Left: Wall cloud and towering cumulus with rain-free base. A wall cloud, a lowering of the cloud base underneath main storm updraft, forms in this thunderstorm. Tornadoes can form out of the wall clouds. Photo: NOAA Photo library

Wall cloud with tail cloud – June 16, 1980 Photo: NOAA Photo Library

Wall cloud with lightning Photo: Brad Smull, NOAA Photo library

Wall cloud and funnel off Long Beach, MD, April 28,2002

Photo by Ted L. Dutcher, NWSFO

8.4.3 'Typical' Tornado Lifecycle

- Large tornadoes typically undergo a 3-stage lifecycle:
  1. Funnel Stage
  2. Mature Stage
  3. Rope Stage

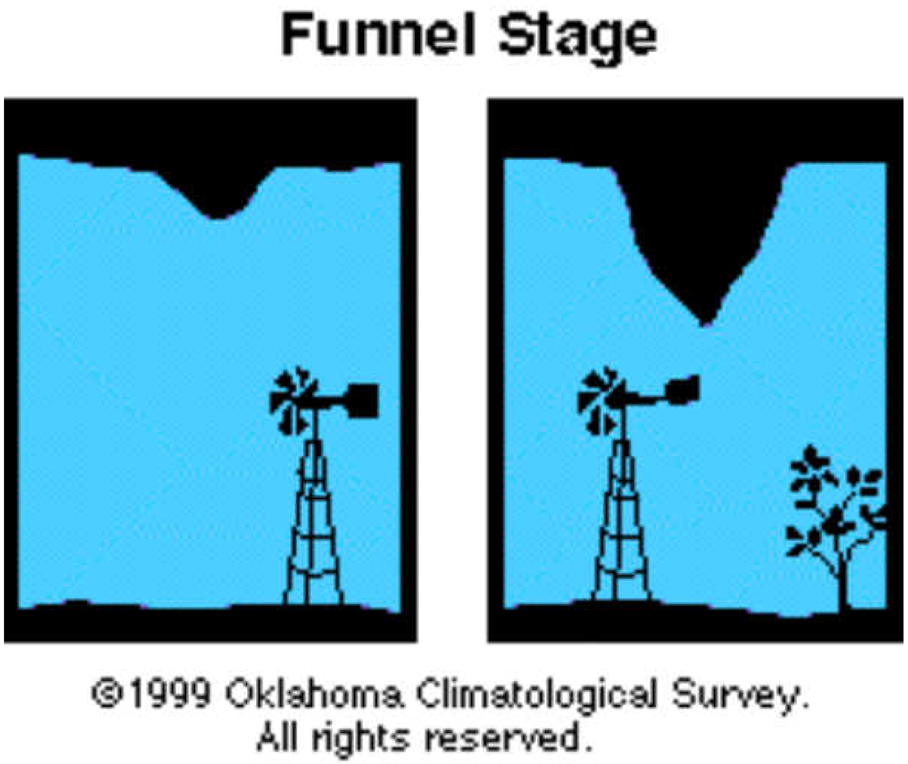


Photo: R. Houze (Univ of Washington)

Mature Stage

Rope Stage

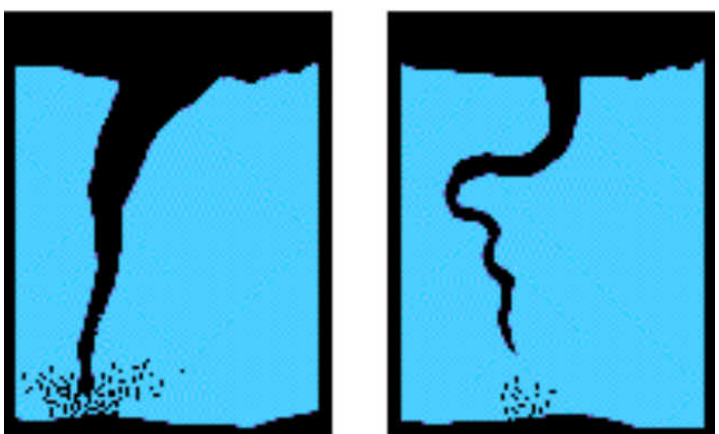
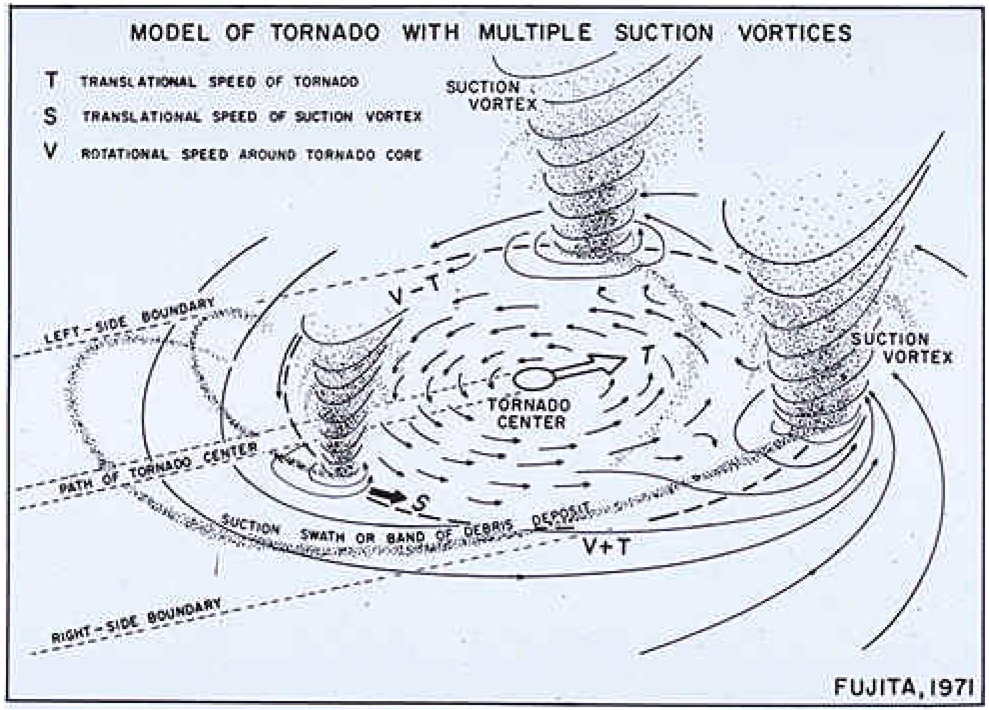


Photo: R Houze (Univ of Washington)

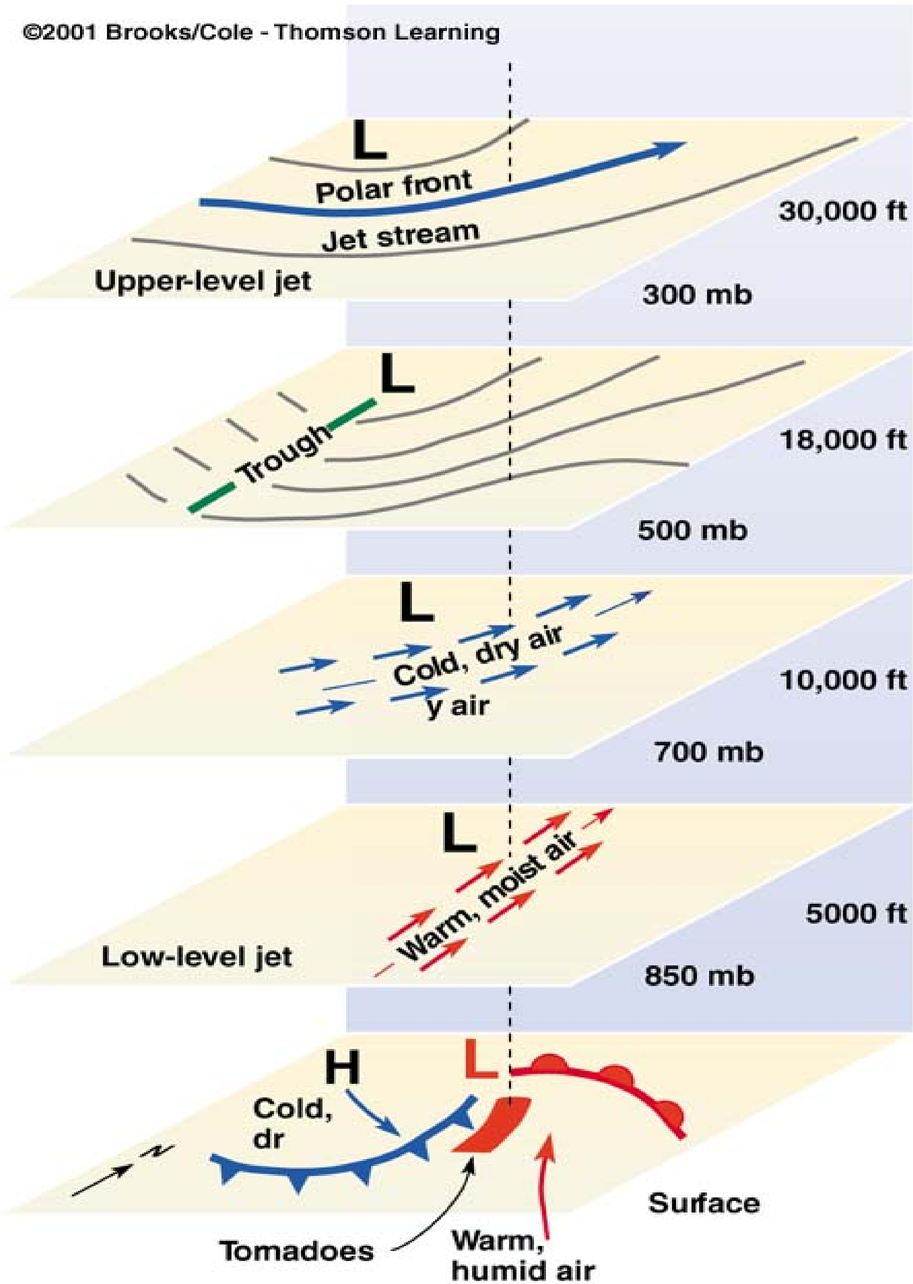
8.4.4 Multi-Vortex Tornadoes



Schematic (top) of tornado with multiple suction vortices (Fujita, 1971); photos of tornado with multiple suction vortices (top right) and the damage caused by a storm with multiple suction vortices (bottom right) (photos: Kelvin Droegemeier website, Univ of Oklahoma)

8.4.5 Tornadic Storm Environments

- Tornadic thunderstorms develop preferentially in regions with the following characteristics:
  - significant supply of warm, moist air at low levels, which is the source of energy for the storm
  - strong wind shear
- Ideal location is in the warm sector of springtime, extratropical cyclones (see next slide):
  - ahead of the surface cold front is a low-level jet which in the spring time over the Great Plains can transport warm, moist air from the Gulf of Mexico to the Oklahoma-Kansas region
  - an upper jet stream overlays the low-level jet
  - this is the region where the vertical wind shear is the greatest and the low-level supply of warm, moist air is also large

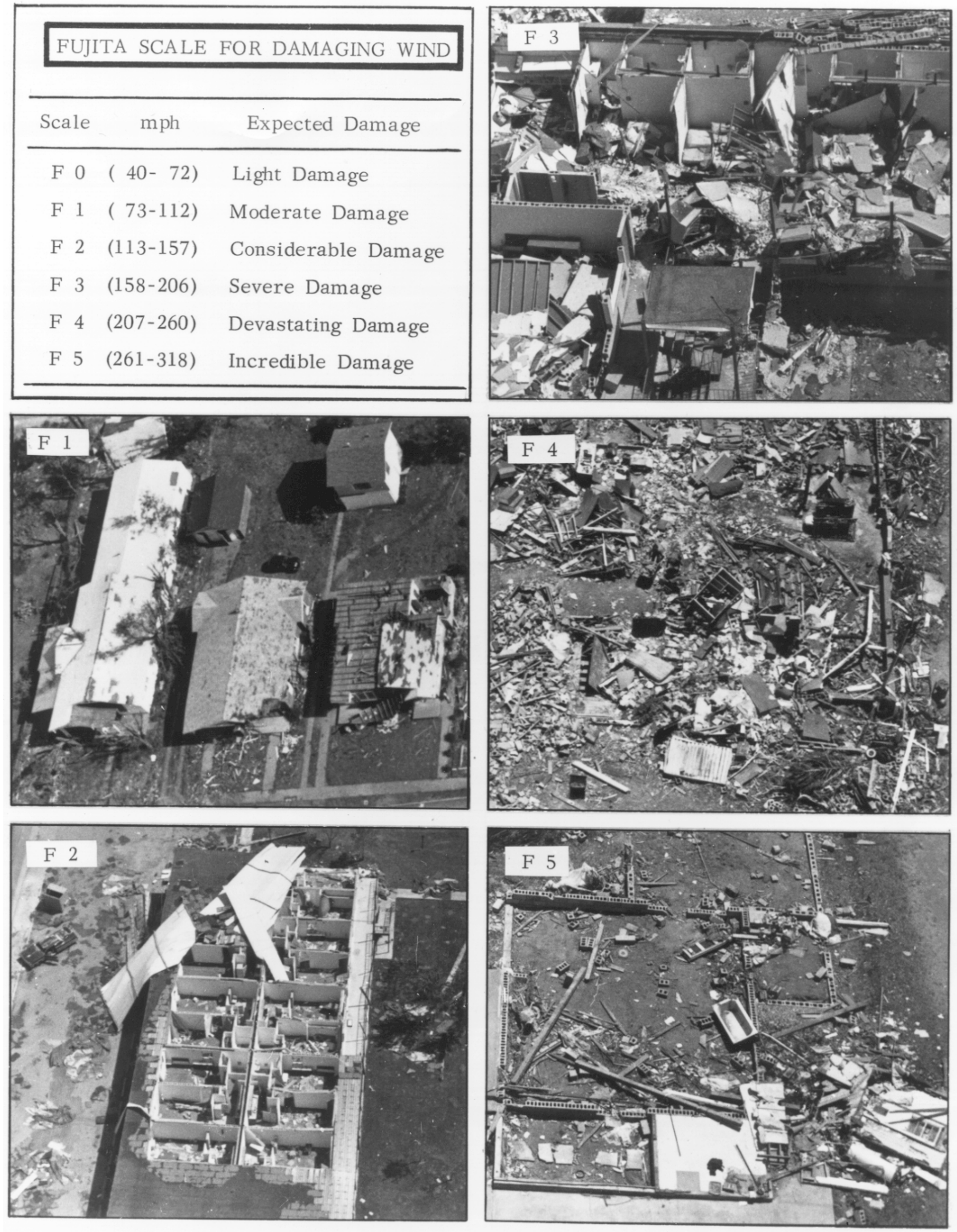


Schematic showing ideal conditions for development of severe thunderstorms

Source: Brooks/Cole-Thomson Learning

8.4.6 F-Scale

- Fujita devised a damage scale called an F-scale in which the wind speeds associated with tornadoes can be assessed



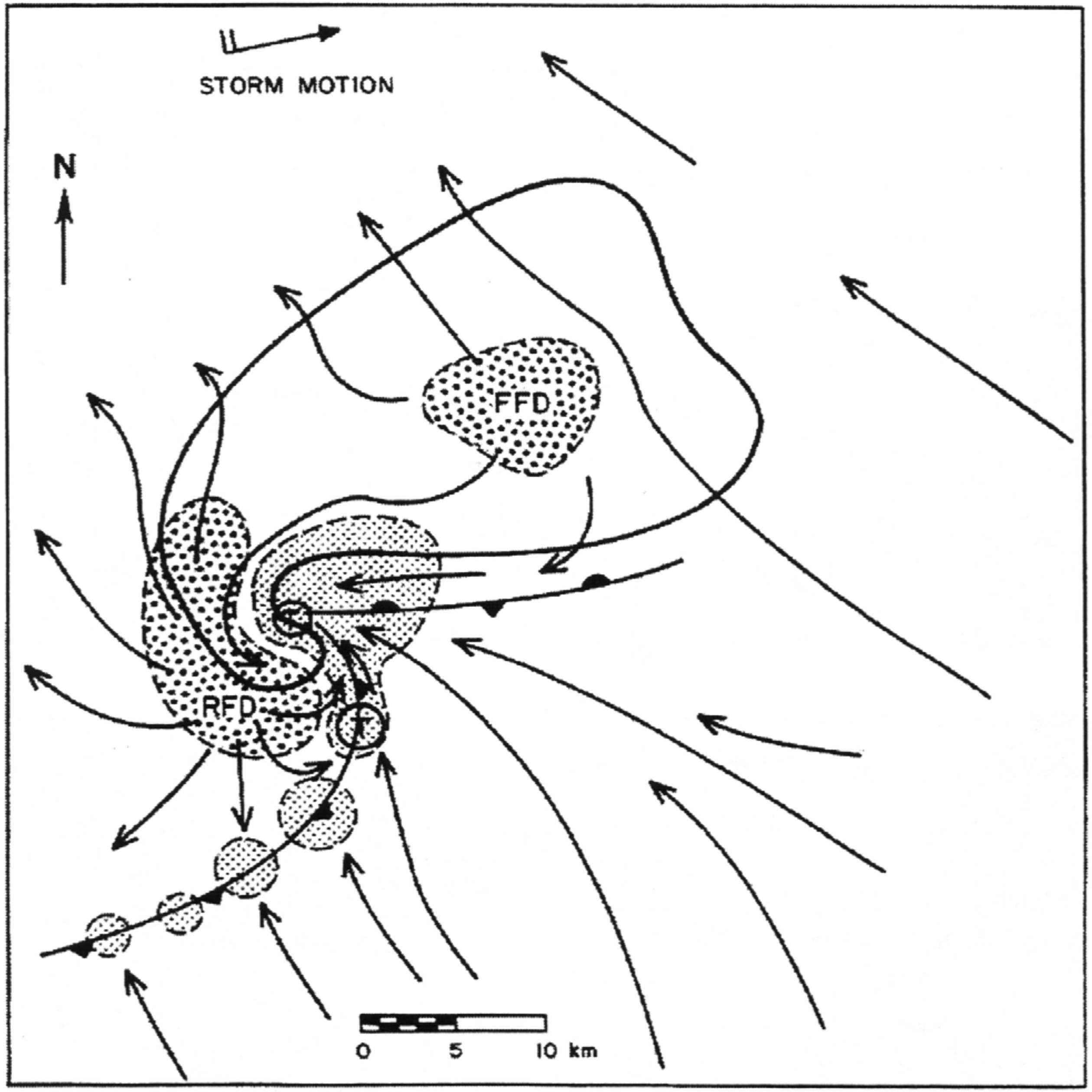
FUJITA SCALE FOR DAMAGING WIND

Scale	mph	Expected Damage
F 0	(40- 72)	Light Damage
F 1	(73-112)	Moderate Damage
F 2	(113-157)	Considerable Damage
F 3	(158-206)	Severe Damage
F 4	(207-260)	Devastating Damage
F 5	(261-318)	Incredible Damage

Examples of damage produced by tornadoes and corresponding Fujita damage scale. (From Fujita, T.T., 1973: Tornadoes around the world. *Weatherwise*, **26**, 56-83.)

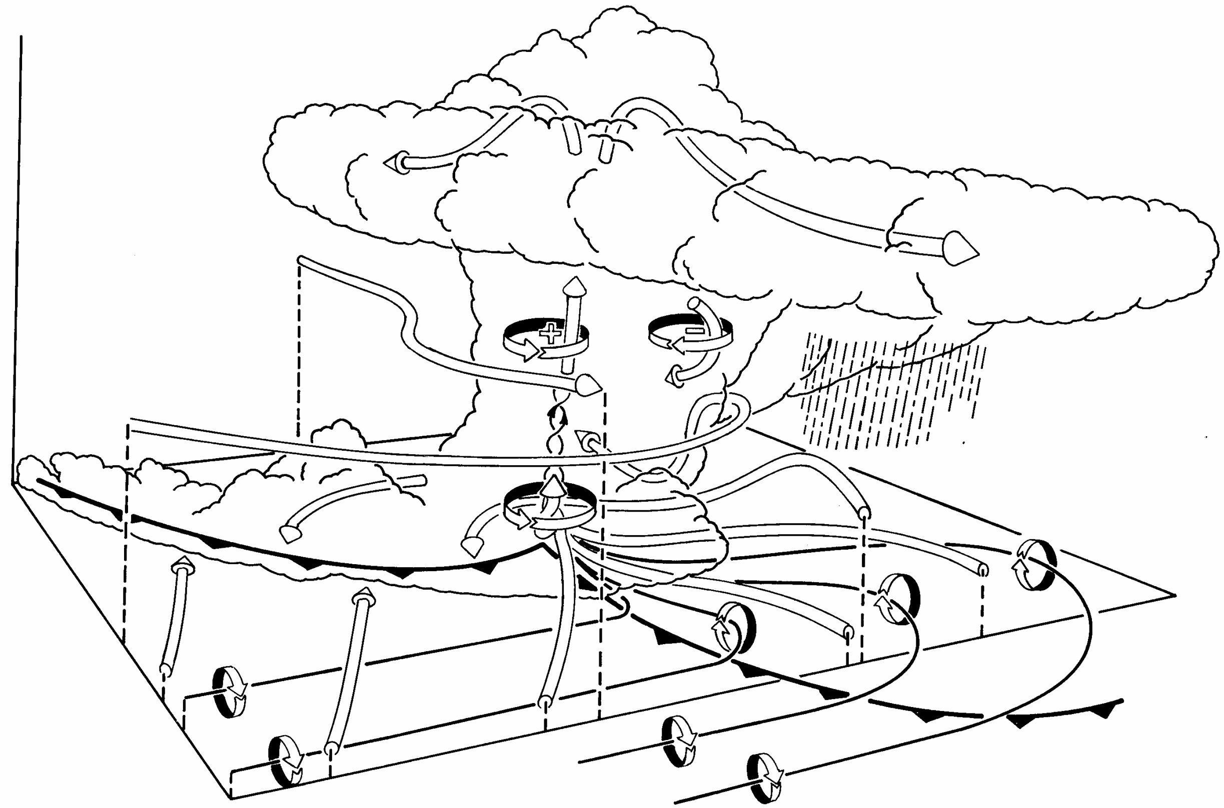
8.4.7 Rotation in Supercells

- Rotation within supercells has been recognized since the 1950s and 1960s
- The development of Doppler radar in the 1970s confirmed the existence of rotation in supercells, and showed the cyclonic-anticyclonic couplet at mid-levels and the predominantly cyclonic (anticyclonic) structure at low levels in RM (LM) storms
- Lemon and Doswell (1979):
  - observational study documented the importance of the RFD in the transition of the storm into a tornadic supercell
  - tornado formation is favored where the RFD progresses around point T in the next slide
  - showed that the tilting term appeared to predominate
  - solenoidal effects might be important at the interface between the RFD and the downdraft

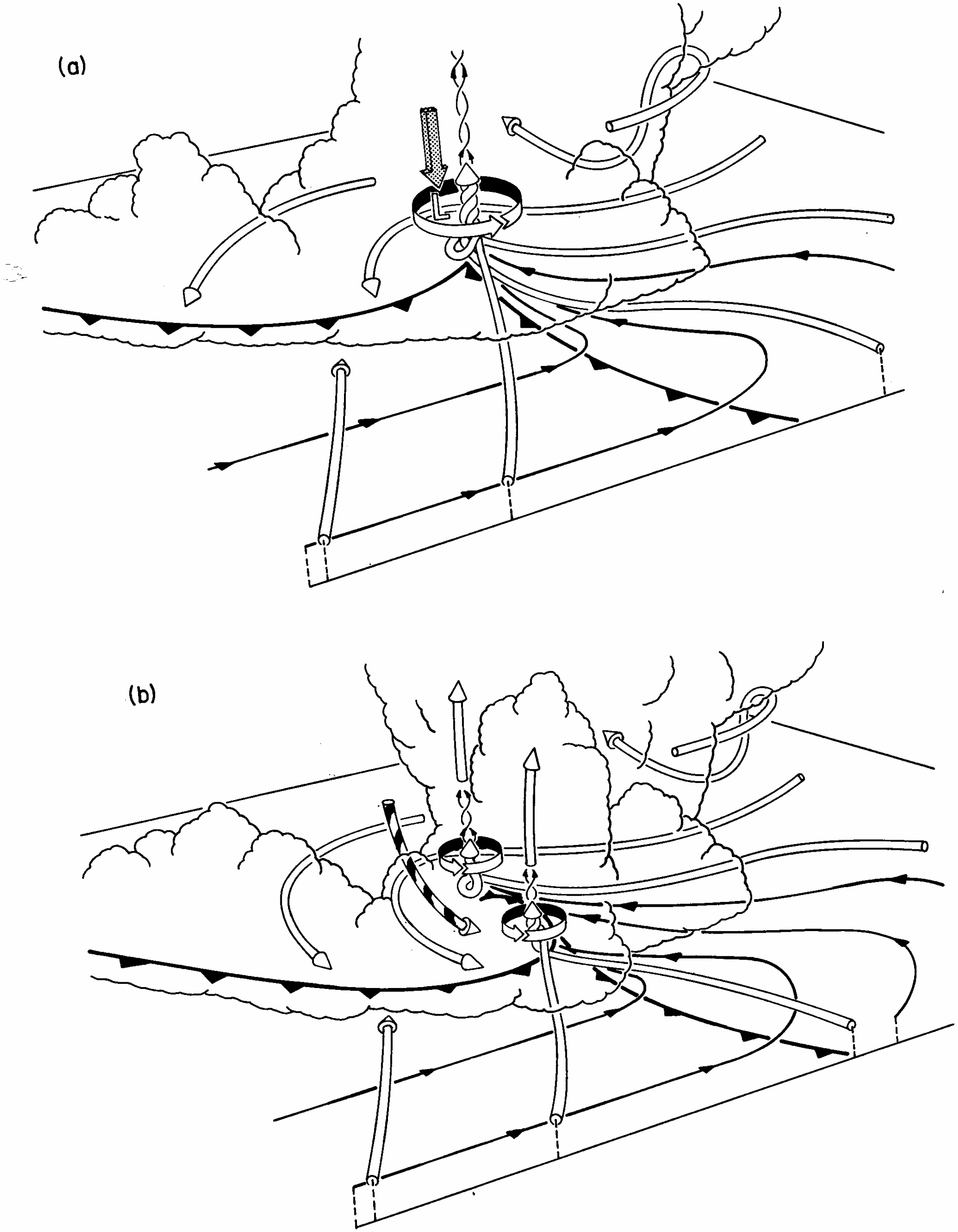


The low-level airflow structure and precipitation distribution of a supercell thunderstorm based on surface observations and radar analysis (from Lemon and Doswell, 1979; adapted by Davies-Jones, 1986). FFD is the forward flank downdraft, RFD is the rear flank downdraft and T indicates the position most conducive for tornado formation.

- Numerical modeling in the late 1970s and early 80s showed rotating updrafts and downdrafts, that horizontal vortex tubes could be tilted into the vertical when interacting with a convective updraft, and that the mid-level cyclonic-anticyclonic vortex pair is aligned in the direction of the environmental vorticity vector
- A depiction of the flow structure of a rotating thunderstorm derived from computer simulations is shown in the next slide. The ascending air is shown to be rotating in a counter-clockwise direction.
- As the low-level rotation intensifies, the RFD forms in response to lowering of the pressure caused by the rotating updraft. The so-called cyclostrophic reduction of pressure is due to the displacement of mass outward from the center of the rotating updraft. The reduced pressure at low-levels, in turn creates a downward-directed pressure gradient force which drives air downward in the RFD (see following slide)
- Studies suggest that mid-level mesocyclones develop by different processes than low-level (below 1km AGL) mesocyclones



Three-dimensional schematic view of a numerically simulated supercell thunderstorm at a stage when the low-level rotation is intensifying. The storm is evolving in westerly environmental wind shear and is viewed from the southeast. The cylindrical arrows depict the flow in and around the storm. The thick lines show the low-level vortex lines, with the sense of rotation indicated by the circular-ribbon arrows. The heavy barbed line marks the boundary of the cold air beneath the storm. (From Klemp, J.B., 1987: Dynamics of tornadic thunderstorms. *Ann. Rev. Fluid Mech.*, **19**, 369-402)

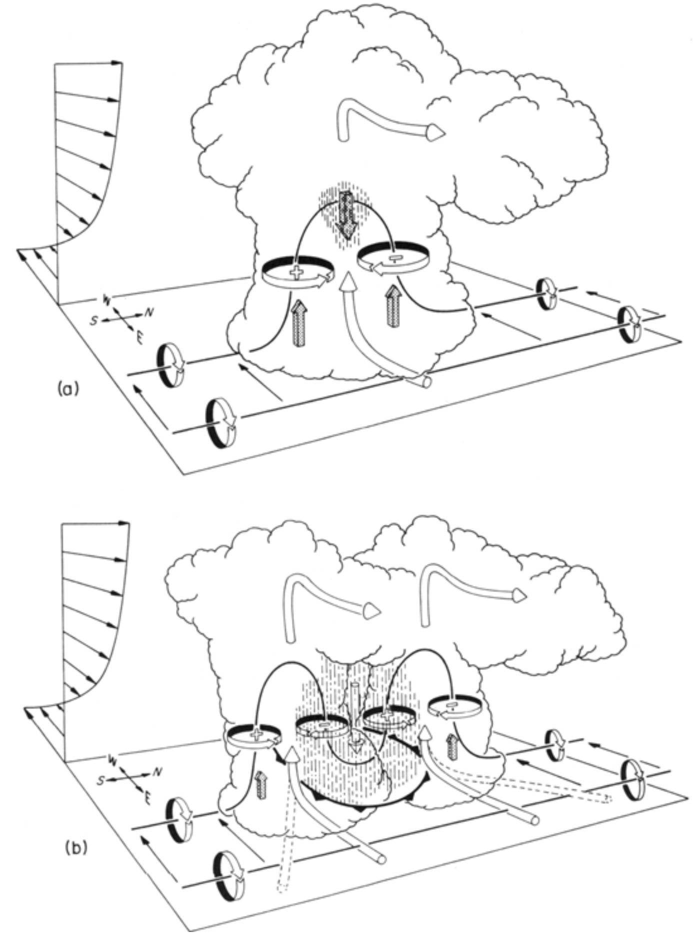


Expanded three-dimensional perspective, viewed from the southeast, of the low-level flow (a) at an earlier time and (b) about 10 min later after the rear-flank downdraft has intensified. The cylindrical arrows depict the flow in and around the storm. The vector direction of vortex lines are indicated by arrows along the lines. The sense of rotation is indicated by the circular ribbon arrows. The heavy, barbed line works the boundary of the cold air beneath the storm. The shaded arrow in (a) represents the rotationally induced vertical pressure gradient, and the striped arrow in (b) denotes the rear-flank downdraft. (From Klemp, J.B., 1987: Dynamics of tornadic thunderstorms. *Ann. Rev. Fluid Mech.*, **19**, 369-402)

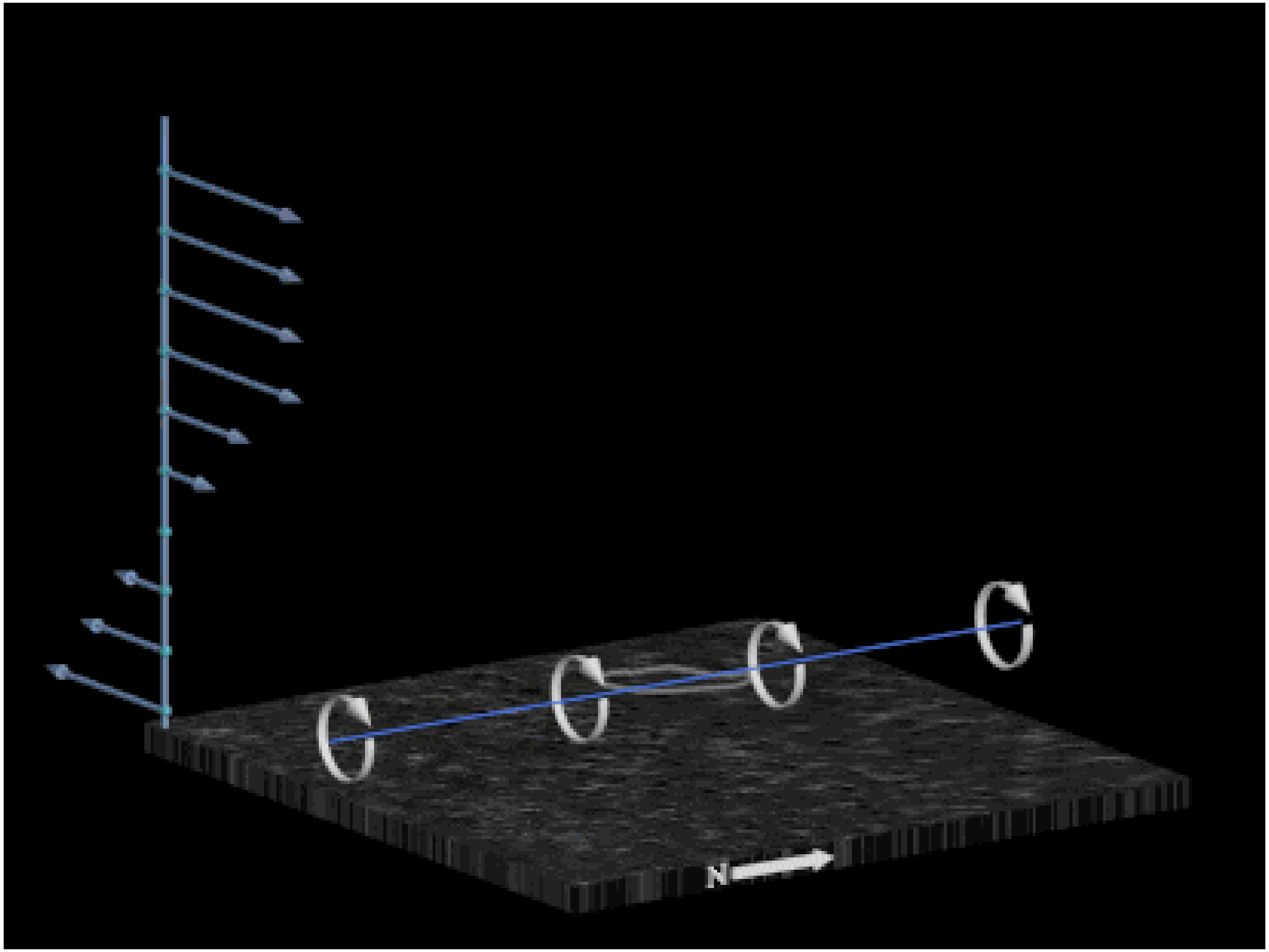
- An unanswered question: how does the low-level rotation intensify to tornadic magnitudes?
- Scientists disagree on the answer to this question

Mid-level Rotation

- The mechanism is generally agreed on
- We discussed the details earlier in updraft splitting
- Mid-level rotation is initially horizontal vorticity and is strengthened later by stretching and further tilting



(a) Initial stage: horizontal vortex tube is swept into the vertical by the developing updraft. (b) Splitting stage: a downdraft forms between the splitting updraft cells and this tilts the vortex tubes in this region downward, producing two vortex pairs (adapted by Klemp (1987), from Rotunno, 1981).



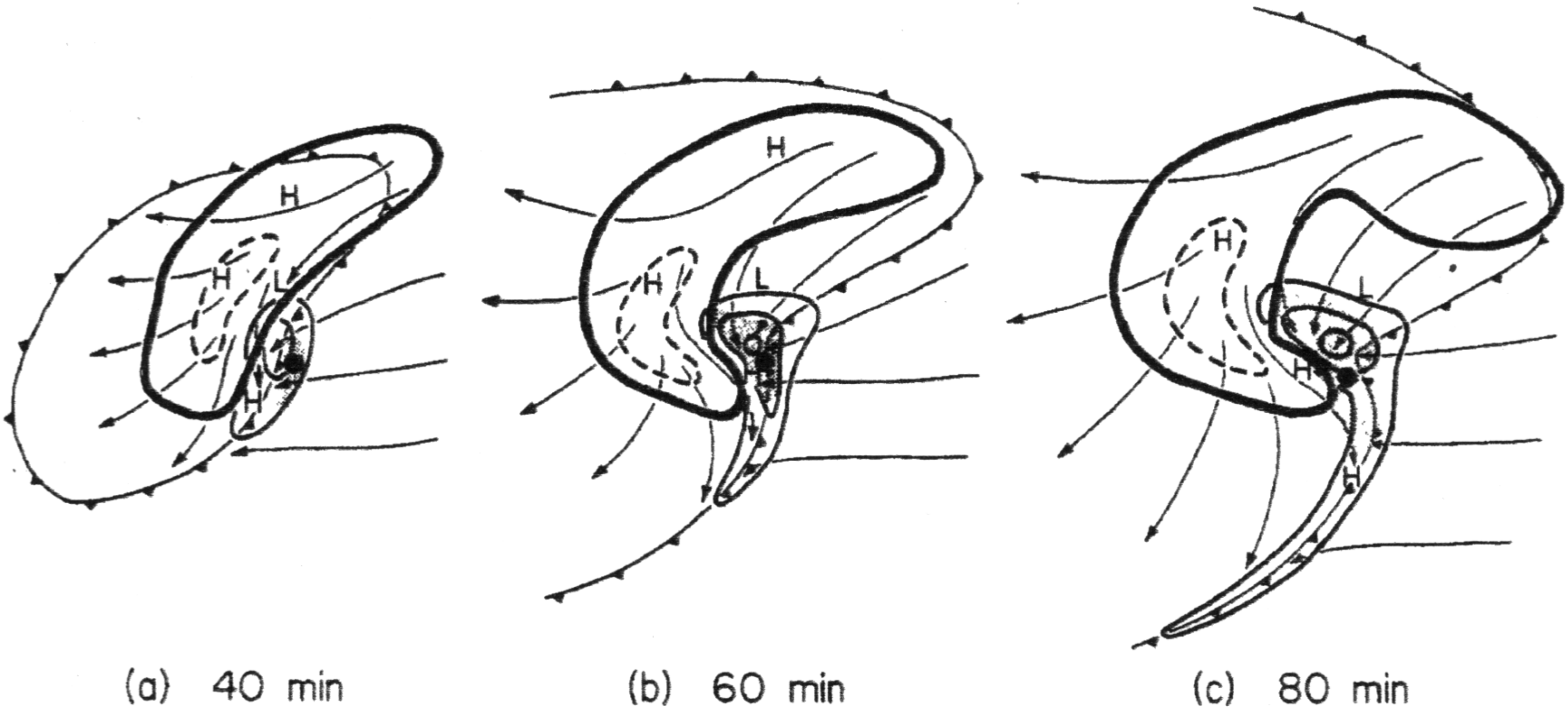
Animation demonstrating storm splitting

Source: Kelvin Droegemeier webpage
Univ of Oklahoma

Low-level Rotation

- Observations show that at mid-levels a vorticity couplet is observed in both LM and RM storms, but at low levels positive (negative) vorticity completely dominates the negative (positive) vorticity in the RM (LM)
- Mid-level vorticity and low-level vorticity appear to develop independently of one another
- Two different mechanisms for the generation of low-level vorticity have been suggested. Baroclinic generation of vorticity is considered important in both theories, but in the first theory tilting and then stretching of horizontal vorticity by the updraft is considered important (Klemp and Rotunno (KR83); Rotunno and Klemp, 1985 (RK85); whereas in the second theory, tilting of vorticity by both the updraft and downdraft are found to be necessary (Davies-Jones, 1992a,b (DJ92); Davies-Jones and Brooks, 1993 (DJB93)

- First theory: KW83 and RK85
- Low-level vertical vorticity is initially generated through tilting
- It is enhanced by strong low-level convergence along the gust front, which develops as the downdraft develops (see next slide)
- The vorticity maximum then moves from the front to the back of the convergence line and increases rapidly due to the following processes:
  - as the cold outflow air progresses underneath the storm, the inflow air from the northeast flows almost parallel to the forward-flank outflow boundary, and horizontal vorticity develops through baroclinic forcing.
  - this horizontal vorticity is then tilted into the vertical as it encounters the updraft.
  - as the horizontal vorticity vectors and the storm-relative inflow point in the same direction, positive vertical vorticity is produced in the updraft.
- This may be seen by examining the vertical component of the inviscid, Boussinesq vorticity equation given by:



Flow field from the storm scale (1km grid resolution) model simulation performed by Klemp and Rotunno (1983) at z=250m at (a) 40 min, (b) 60 min and (c) 80 min. Vertical velocity is contoured at 1m.s-1 intervals with the zero line omitted. Arrows represent storm-relative streamlines at the surface. The thick solid line shows the 0.5 g.kg-1 rainwater contour. A potential temperature perturbation of –1°C is indicated using frontal symbols. The location of maximum vertical vorticity is marked by a black circle with the region of ζ>0.002 s-1 being shaded. The locations of surface high and low pressure are shown using H and L respectively (after Klemp and Rotunno, 1983).

$$\frac{\partial \zeta}{\partial t} = -\vec{V} \cdot \nabla \zeta + \vec{\omega}_h \cdot \nabla_h w + \zeta \frac{\partial w}{\partial z}$$

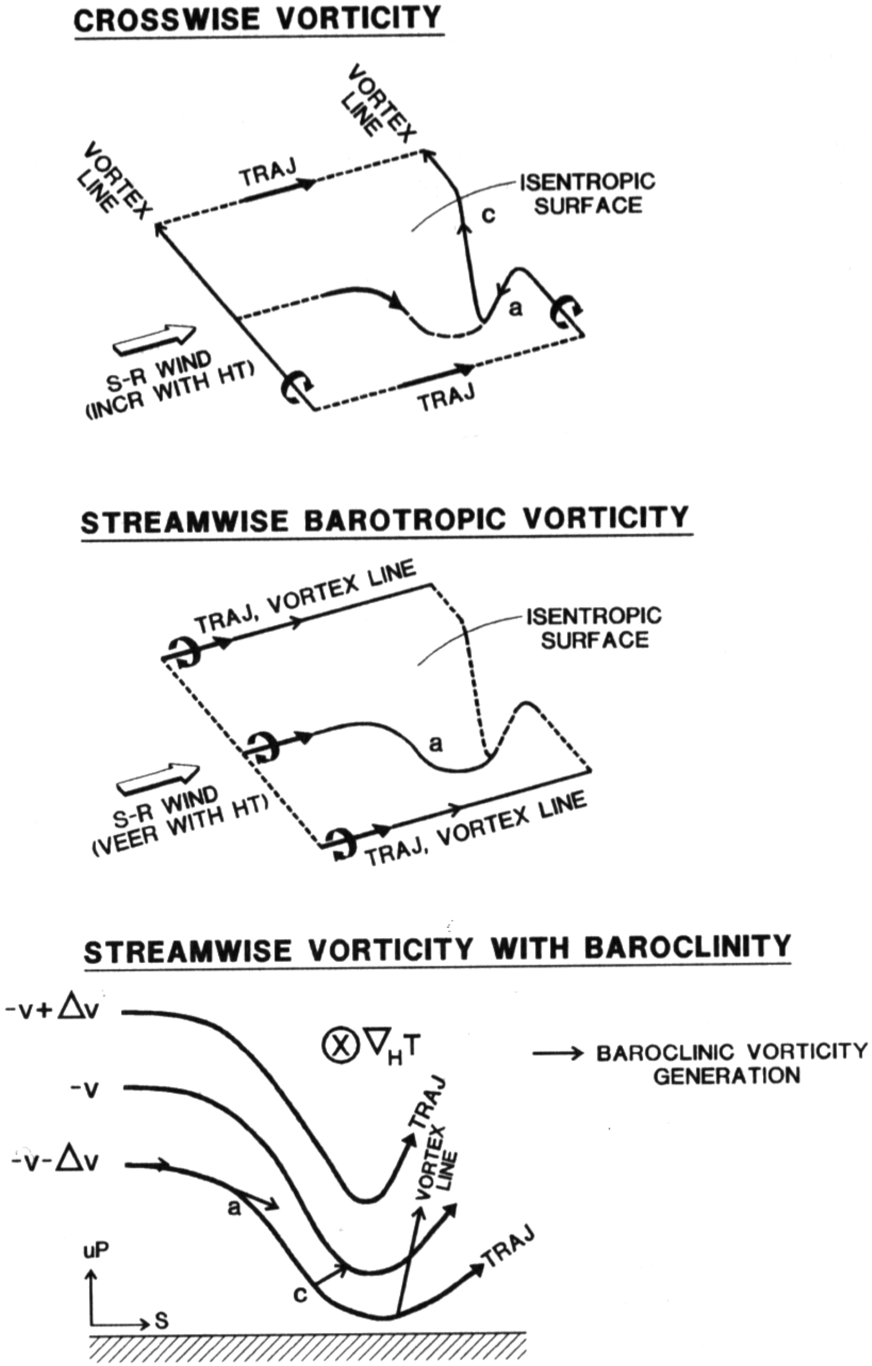
The tilting term is the dot product of the horizontal component of vorticity with the horizontal gradient of vertical velocity. If these two vectors point in the same direction, the tilting term is positive, and the vertical vorticity is enhanced. Maximum positive contributions from tilting therefore occur on the left (north) side of the updraft, while negative values occur on the right (south), which is completely the opposite of what tilting the environmental vorticity would give.

- Finally, convergence effects then enhance the low-level vertical vorticity.
- Low-level rotation is therefore acquired from upward tilting of the baroclinically generated horizontal vorticity that develops along the gust front northeast (upstream) of the low-level updraft.

- RK hypothesized that the primary importance of the mid-level rotation is to transport potentially dry, cool air to regions where it can be evaporatively cooled, descend, produce cold air outflow, and generate the thermodynamic gradients in regions suitable for the baroclinic generation of low-level horizontal vorticity

- Second Theory: DJ82, DJB93
- Evaporative and baroclinic processes are also considered to be important in the generation of low-level vertical vorticity - simulations with and without precipitation showed that the maximum vertical vorticity at 100m AGL was 6 or more times greater with full microphysics.
- However, DJB93 claimed that although baroclinic effects along the gust front would greatly enhance horizontal vorticity, tilting of horizontal vorticity into the vertical by the updraft would still not produce the magnitude of vertical vorticity observed in the lowest 1km AGL

- DJB93 hypothesized that downdrafts play an important role in low-level mesocyclogenesis and observed from their simulations that there was positive vorticity at the lowest levels in the downdraft.
- They showed that tilting of crosswise and streamwise horizontal vorticity by the downdraft could not cause the vorticity reversal of the descending parcels, but that the baroclinic generation of streamwise vorticity could (see next slide)
- This process operates as follows
  - consider a cool mass of air descending on the north side of the mesocyclone and spreading out toward the south so that it is nearly parallel to the isotherms of the gust front
  - warm air exists to the east of this cool air due to the presence of the updraft
  - horizontal vorticity is generated baroclinically as a result of the temperature gradient between the updraft and downdraft, the vector of which points to the south



Schematic diagram showing how cyclonic vorticity may be generated in a downdraft through the tilting of barotropic and baroclinic horizontal vorticity. For crosswise barotropic vorticity (top diagram), tilting by the downdraft produces cyclonic (anticyclonic) vorticity on the left (right) of the downdraft in the direction of the storm-relative wind vector. For streamwise barotropic vorticity (middle diagram), tilting by the downdraft produces a purely anticyclonic downdraft and a cyclonic updraft. In the streamwise case in which there is flow to the right of the horizontal buoyancy gradient and a southerly shear component (bottom diagram), both tilting and baroclinic generation of vorticity causes a change in sign of the vorticity of the parcels in the downdraft from anticyclonic to cyclonic while the parcel is still descending (after Davies-Jones and Brooks, 1993).

– as the downdraft descends, the vortex lines turn downward due to barotropic effects, however, they are inclined less than the trajectories due to the contributions from the baroclinic forcing, which are in a southward, *horizontal* direction
– as the air approaches the ground, the barotropic effects turn the vortex lines, which now have a baroclinic, horizontal contribution, upward
– positive vertical vorticity is therefore generated in the lowest levels of the downdraft
– this air, which already has a positive component of vertical vorticity, is then entrained into the updraft on the southwest side of the storm below ~100m AGL, from where the vertical vorticity is significantly enhanced by stretching and tilting to a lesser degree
– Baroclinic generation of streamwise vorticity therefore explains the vorticity reversal in the downdraft, and the strength of the convergence term near the ground. If the horizontal vorticity were simply tilted into the updraft there would be no vertical vorticity adjacent to the surface to stretch, as the updraft speeds at the surface are near zero and tilting is thus weak

- This mechanism is also suggested in the simulations by Grasso and Cotton (1995)
- DJB93's mechanism differs from that of RK85 in that the air tilted into the updraft already has a component of positive vertical vorticity, and convergence in the lower levels can immediately amplify this vertical vorticity. In RK's mechanism, the vertical vorticity first needs to be generated through tilting before it may be stretched which, according to DJB93, cannot produce strong rotation very near the ground.

Oldest known photograph of a tornado: Howard, SD, August 28, 1884
Photo: NOAA library

- April 3, 1974
- 6 F5 tornadoes occurred on this day
- Photos from Sayler Park, OH
- Photos by Melissa Humphrey
- Picture of the F5 tornado that hit Sayler Park (top left), and the damage that it did to the photographer's aunt's and grandparents houses (bottom left and right)

Project Vortex. The Dimmitt (Texas) Tornado - June 2, 1995. Photo: Noaa Photo Library

Left photos: Project Vortex-99. Occluded mesocyclone tornado. This tornado was forming while the new circulation was beginning to form the tornadoes which preceeded the F5 Oklahoma City tornado. May 3, 1999. Photo: NOAA Photo Library

Top right: Tornado about to strike house. Photo: Wayne Stokes, NSSL collection

8.5 Hailstorms

8.5.1 Introduction

- Hailstones can range in size from pea-size to grapefruit-size
- Grapefruit-size -> kill people and livestock, millions of dollars of property damage
- Pea-size -> extensive crop damage especially when combined with strong winds
- Hailstones come in a variety of shapes: spherical, conical, lobed
- Hail causes ~ one billion dollars in damage to property and crops annually
- The costliest United States hailstorm: Denver, Colorado, July 11, 1990. Total damage was 625 million dollars (U.S.).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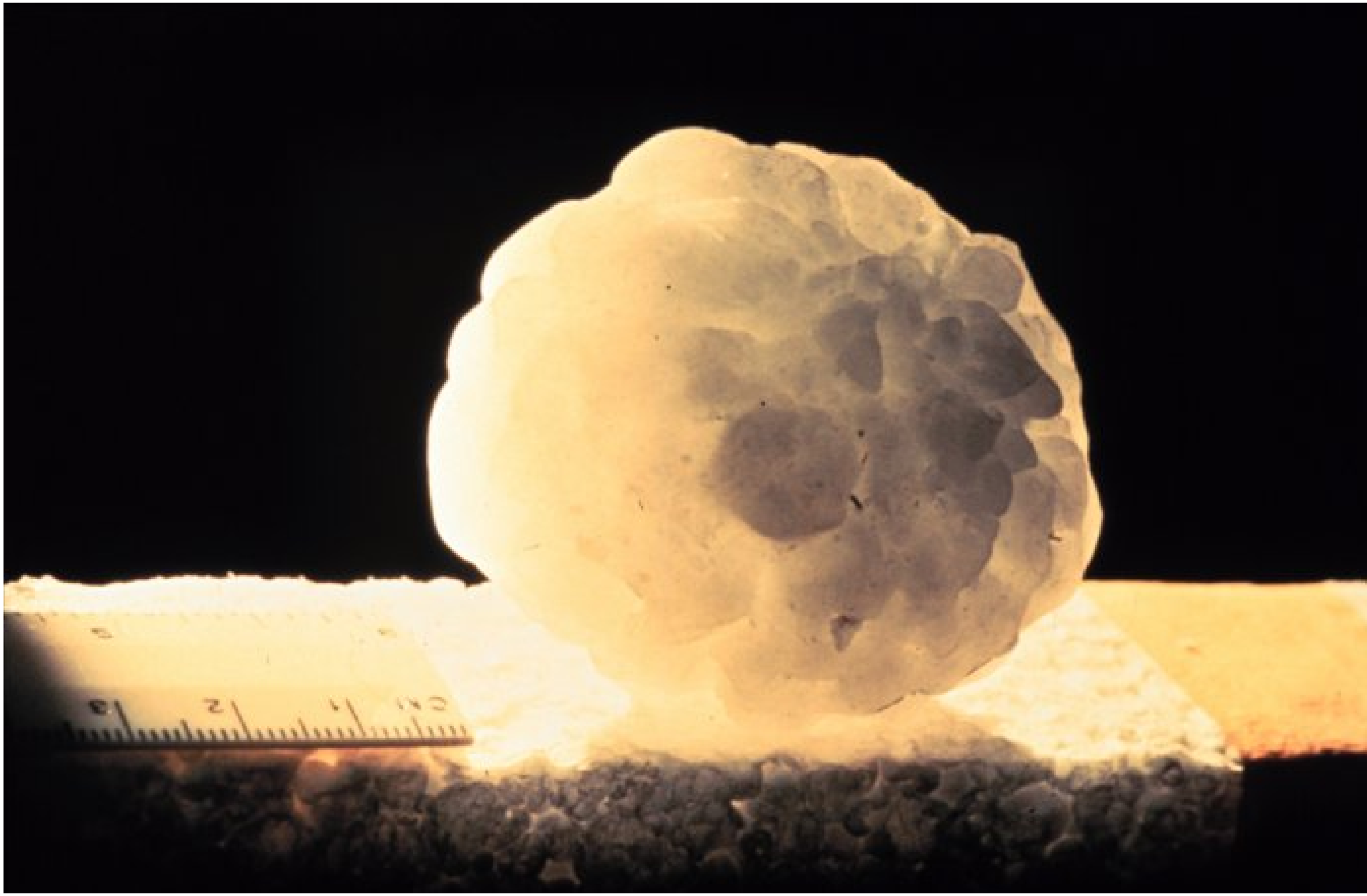
2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19

Examples of several large hailstones

Photo: Nancy Knight



Aggregate hailstone. Large hailstone with smaller stones visible. Diameter is approximately 6 inches - the size of a grapefruit Photo: NOAA Photo Library

- Largest hailstone ever recovered in US history fell in Aurora, Nebraska on June 22, 2003: a record 7-inch diameter and a circumference of 18.75 inches
- The old record for the largest hailstone had a diameter of 5.7 inches, a circumference of 17.5 inches and was found in Coffeyville, Kansas, on September 3, 1970.
- According to Lawrimore of the NOAA National Climate Extremes Committee the Aurora hailstone didn’t break the record for the heaviest hailstone – it was difficult for them to get an accurate weight of the stone as some of it hit the gutter of a house and 40 percent of the stone was lost. It also seems that some of the stone’s mass might have melted before it was preserved in freezing conditions
- The Aurora hailstone is preserved at NCAR

Photos of the Aurora, Nebraska hailstone Photos: NOAA

The Aurora hailstone together with other hailstones that fell that day (top) and the damage that one of these stones left in the ground (right)

Photos: Quilla Ulmer/Jim Reed Photography

8.5.2 Environmental Conditions for Hailstorms

1. Significant positive buoyancy: strong updrafts capable of suspending hailstones falling through the air at speeds of 15 to 25 m/s
2. Strong windshear: storms producing the largest hailstones normally develop in an environment with strong windshear -> favors the development of supercells
3. The height of the melting level is also important in determining the size of hailstones that will reach the surface:
   – It has been estimated that as much as 42% of the hailstones falling through the melting level melt before reaching the ground over Alberta, Canada, while it may be as high as 74% over Colorado and 90% over Arizona -> consistent with the observations indicating that the frequency of hail is greater at higher latitudes

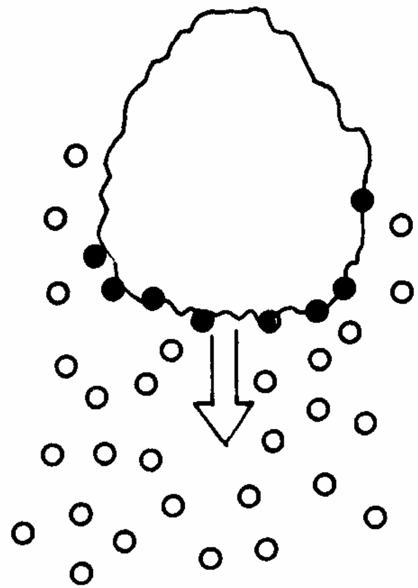
8.5.3 Hailstone Growth

- Hailstone growth is a function of the airflow in thunderstorms and the growth of precipitation particles
- Hailstones grow primarily by the collection of supercooled cloud droplets and raindrops
- At temperatures below 0°C many cloud droplets and raindrops do not freeze and can remain unfrozen to temperatures as cold as -40°C
- Some of the ice particles do freeze, perhaps by collecting an aerosol particle that can serve as a freezing nucleus
- If the frozen particle is small, it will first grow by vapor deposition, forming snowflakes such as dendrites, hexagonal plates, needles or columns
- After some time (5-10 mins) the ice crystals become large enough to settle relative to small cloud droplets which immediately freeze when they impact the surface of the ice particle

- If enough cloud droplets are present or the liquid water content of the cloud is high, the ice particle can collect enough cloud droplets so that the original shape of the vapor-grown crystal becomes obscured and the ice particle becomes a graupel particle of several millimeters in diameter
- As first, the density of the graupel is low as the collected frozen droplets are loosely compacted on the surface of the graupel particle
- As the ice particle becomes larger, it falls faster, sweeps out a larger cross-sectional area, and its growth by collection of supercooled droplets increases proportionately
- As the growth rate increases, the collected droplets may not freeze instantaneously on impact, and therefore flow over the surface of the hailstone, filling in the gaps between collected droplets
- The density of the ice particle, therefore, increases close to that of pure ice as the dense hailstone falls still faster, growing by collecting supercooled droplets as long as the cloud liquid water content is large

- The ultimate size of the hailstone is determined by:
  1. the amount of supercooled liquid water in the cloud
  2. the time that the growing hailstone can remain the high-liquid water region
- The time that a hailstone can remain in the high-liquid-water-content region is in turn dependent on the updraft speed and the fall speed of the ice particle -> if the updraft is strong (35-40 m/s) and the particle fall speed through the air is only of the order of 1-2 m/s then the ice particle will be rapidly transported into the anvil of the cloud before it can make full advantage of the high liquid water content region
- The ideal circumstance for hailstone growth is that the ice particle reaches a large enough size as it enters the high liquid water content region of the storm so that the ice particle fall speed nearly matches the updraft speed -> hailstone will only slowly ascend or descend while it collects cloud droplets at a very high rate

- Eventually the hailstone fall speed will exceed the updraft speed or it will move into a region of weak updraft or downdraft
- The size of the hailstone reaching the surface will be greatest if it settles into a strong downdraft, as the time spent below the 0°C level will be lessened and the hailstone will not melt very much
- Optimum Conditions for Hail Growth:
  - Storms with strong updrafts ($w > 15$-20 m/s) and large LWCs
  - Initial growth stages: terminal fallspeed of hail ~ updraft speeds in large LWC region
  - Hailstones fall into strong downdrafts to minimize melting / evaporation
  - Moist hail growth occurs between -10 to -25 °C

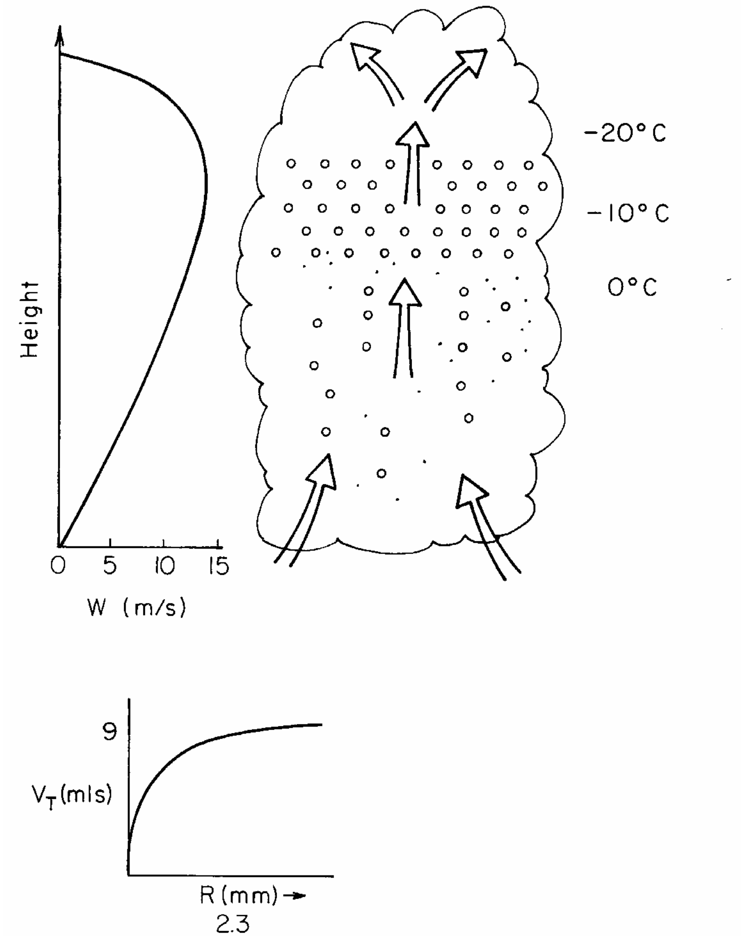


Schematic of a hailstone growing by collecting supercooled droplets

8.5.4 Models of Hailstone Growth

The Soviet Hail Model

- Based on the ordinary thunderstorm model
- If the storm develops particularly vigorous updrafts and high LWCs during the growth stage, raindrops may form by collision and coalescence with smaller cloud droplets
- As the growing raindrops are swept aloft, they continue to grow and eventually ascend into supercooled regions



The Soviet hail growth model. Left panel shows a favorable updraft profile. Right panel shows the formation of an accumulation zone. Bottom panel illustrates variation in terminal velocity of raindrops with size

- If the updraft exhibits a vertical profile as shown on the previous slide, with a maximum updraft speed in the layer between -10 and -20°C, many raindrops may become supercooled just above the updraft maximum
- The region just above the updraft maximum serves as a trap for large raindrops, and rainwater accumulates in this region. Supercooled LWCs greater than 17 g/m^3 have been reported in such regions - normal values of supercooled LWC rarely exceed 2-4 g/m^3
- If a few supercooled raindrops then freeze in the zone of accumulated liquid water content, they will experience a liquid-water-rich environment and hailstone growth can proceed quite rapidly
- Observations of thunderstorms near Huntsville, Alabama, USA, revealed regions of very high radar reflectivity where ice particles were not detected. Light hailfall was observed at the surface. These observations are consistent with the Soviet hail model.

- The Soviets designed a hail suppression scheme around this concept ->artillery shells were loaded with an artificial ice nucleant and targeted into the regions of high radar reflectivity. The exploding, artificial-ice-nuclei-laden shells were hypothesized to freeze the supercooled drops before they grow to hailstone size. They theorized that by producing numerous, smaller frozen raindrops, supercooled liquid water would be depleted and only small hailstones would form; many of which would melt before reaching the ground.
- The Soviet results lead to intensive hailstorm research in the 1970s in the USA – carried out on the High Plains where:
  1. cloud bases are high => temperature of air entering cloud base is relatively low and hence low in moisture content
  2. cloud droplet concentrations are large => small cloud droplets

- The combination of large cloud droplet concentrations, cold base temperatures, and little distance (time) between cloud base and the freezing level, means there is little opportunity for raindrops to form before freezing temperatures are encountered in High Plains thunderstorms => the Soviet hail model is not applicable to vast regions of the High Plains of the United States and Canada
- Nonetheless, the High Plains are plagued by some of the most frequent and damaging hailstorms anywhere in the world => the presence of an accumulation zone of supercooled raindrops is not a necessary and sufficient condition for hail formation.

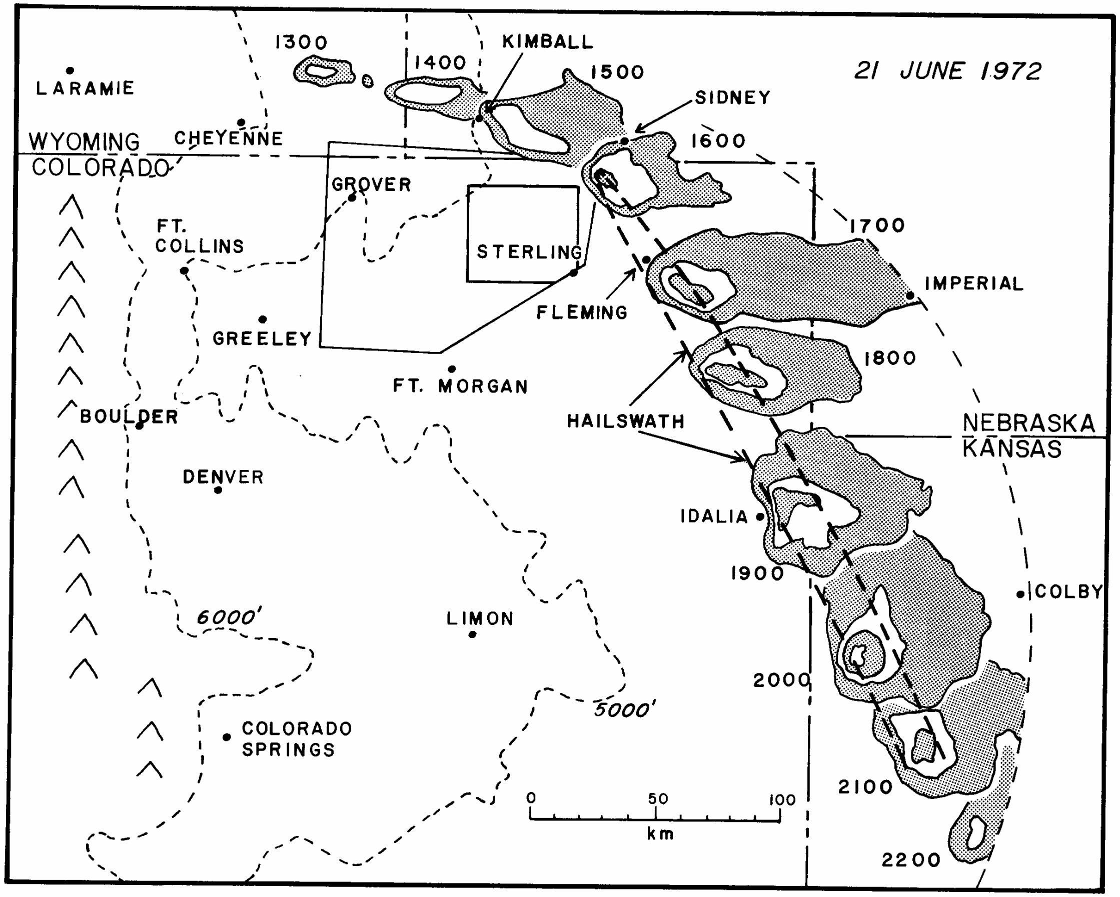
Conceptual Model of Hail Formation in Multicell Storms

- Over the High Plains of the United States and Canada, hailstones are most frequently produced by multicell thunderstorms
- Large hailstones grow during the mature stage of the cells when updrafts may exceed 30 m/s. In such strong updrafts, the time-scale for the growth of hailstones from small ice crystals to lightly rimed ice crystals, to graupel particles or aggregates of snowflakes, to hailstone embryos, is only 5 or 6 minutes. This time is too short as it takes some 10-15 minutes for an ice particle to grow large enough to begin collecting supercooled cloud droplets or aggregating with crystals to form an embryonic hailstone.
- The mature stage of each thunderstorm cell provides the proper updraft speeds and LWCs for mature hailstones to grow, but they must be sizeable precipitation particles at the time they enter the strong updrafts in order to take advantage of this environment.

- Here is where the growth stage of each cell is very important to hailstone growth - the weaker, transient, updrafts provide sufficient time for the growth of graupel particles and aggregates of snow crystals, which can then serve as hailstone embryos as the cell enters its mature stage -> growth stage pre-conditions the ice particles and allows them to take full advantage of the high water contents of the mature stage of the storm.
- Upon entering the mature stage, the millimeter-sized ice particles settle through the air at 8-10 m/s and therefore rise slowly as the updrafts increase in speed from 10-15 m/s at low levels to 25-35 m/s at higher levels -> allows time to collect supercooled droplets
- Fortunately, not all multicellular thunderstorms develop hailstone embryos of the appropriate sizes during the growth stage nor do the embryos enter the updrafts of the mature cell at the right location for optimum hailstone growth.

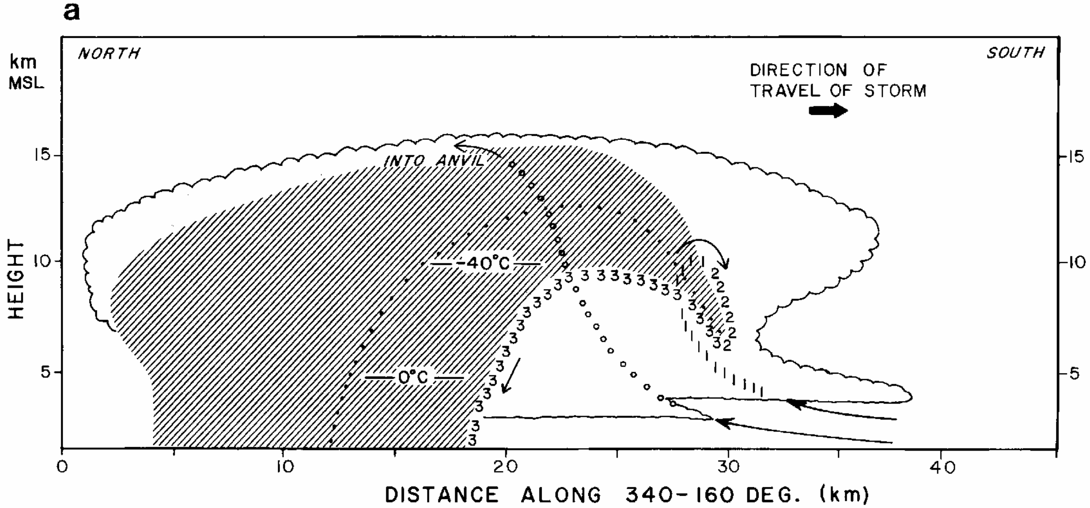
Conceptual Model of Hailstone Growth in Supercell Storms

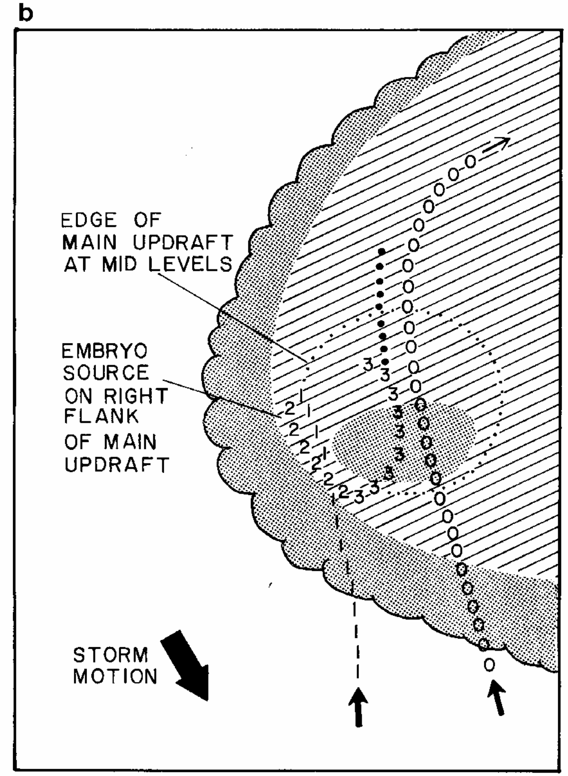
- Supercell updraft speeds are so strong that they are characterized by having a bounded weak echo region in which precipitation particles of a radar-detectable size do not form. Nevertheless the supercell thunderstorm produces the largest hailstones, sometimes over very long swaths.
- The Fleming hailstorm that occurred on the 21st of June 1972 (next slide) first reached supercell proportions in northeast Colorado and produced a nearly continuous swath of damaging hail 300 km long over eastern Colorado and western Kansas.
- How can a storm system consisting of a single, steady updraft with speeds in excess of 30 m/s develop hailstones before the ice particles are thrust into the anvil of the storm?



Hourly positions of the Fleming hailstorm as determined by the NWS Limon radar (CHILL radar data used 1300-1500 MDT). The approximate limits of the hailswath are indicated by the bold, dashed line. Continuity of the swath is not well established but total extent is. Special rawinsonde sites were located near the towns of Grover, Ft. Morgan, Sterling and Kimball. Contour intervals are roughly 12 dBZ above 20 dBz. (From Browning, K.A., and G.B. Foote, 1976: Airflow and hail growth in supercell storms and some implications for hail suppression. Quart. J. Roy. Meteor. Soc., **102**, 499-533. Copyright by the Royal Meteorological Society).

- Browning and Foote visualized hail growth in a supercell thunderstorm as a three-stage process (see next slide)
- Stage 1:
  - hail embryos form in a relatively narrow region on the edge of the updraft, where speeds are on the order of 10 m/s -> allows time for the growth of millimeter-sized hail embryos.
  - particles forming on the western edge of the main updraft have a good chance of sweeping around the main updraft and entering the region called the *embryo curtain* on the right-forward flank of the storm. These particles will follow the trajectory labeled 1.
  - particles that enter the main updraft directly follow the trajectory labeled 0 and do not have sufficient time to grow to hailstone size. They are thrown out into the storm anvil.
- Stage 2:
  - the embryos formed on the western edge of the main updraft are carried along the southern flank of the storm
  - some of the larger embryos settle into the region of weak up-drafts that characterizes the embryo curtain.





(a) and (b) Schematic model of hailstone trajectories within a supercell storm based upon the airflow model inferred by Browning and Foote (1976). (a) Shows hail trajectories in a vertical section along the direction of travel in the storm. (b) Shows these same trajectories in plan view. Trajectories 1, 2 and 3 represent the three stages in the growth of large hailstones. The transition from stage 2 to 3 corresponds to the re-entry of a hailstone embryo into the main updraft prior to a final up-and-down trajectory during which the hailstone may grow large, especially if it grows close to the boundary of the vault. Other, slightly less favored, hailstones will grow a little farther away from the edge of the vault and will follow trajectories resembling the dotted trajectory. Cloud particles growing "from scratch" within the updraft core are carried rapidly up and out into the anvil along trajectory 0 before the can attain precipitation size. (From Browning, K.A., and G.B. Foote, 1976: Airflow and hail growth in supercell storms and some implications for hail suppression.*Quart. J. Roy. Meteor. Soc.*, **102**, 499-533.)

- particles following the trajectory labeled 2 experience further growth as they descend in the embryo-curtain region. Some of the particles settle out of the lower tip of the embryo curtain and re-enter the base of the main updraft, commencing stage 3.

- Stage 3:
  - the mature and final stage of hail growth, in which the hailstones experience very high liquid water contents and growth by collecting numerous cloud droplets during their ascent in the main updraft
  - the growth of hailstones from embryos is viewed as a single up-and-down cycle.
  - embryos that enter the main updraft at lowest levels, where the updraft is weakest, are likely to have their fall speed nearly balanced by the updraft speed. As a result of their slow rise rate, they will have plenty of time to collect the abundant liquid water. Eventually their fall velocities will become large enough to overcome the large updraft speeds and/or they will move into the downdraft region and descend to the surface on the northern flank of the storm.

- Some researchers argue that hail embryos are not formed on the flanks of a single, main updraft, where updraft speeds may be weaker, but, instead the embryos form in towering cumulus clouds that are flanking the main updraft of the storm. They argue that the towering cumulus clouds are obscured by the precipitation debris falling out of the main updraft. Embryos thus can form in the transient, weaker towering convective elements and `feed' the main updraft with millimeter-sized embryos.
- In some thunderstorms, such transient, flanking cumulus towers are visually separated from the dominant parent cell. Such thunderstorms are a hybrid between the single supercell storm and the ordinary multicell storm and are called *organized multicell thunderstorms* or *weakly evolving thunderstorms.* Such thunderstorms are characterized by a single, dominant cell, which maintains a steady flow structure similar to a supercell thunderstorm, including a BWER and a rotating updraft. They also contain distinct flanking towering cumulus clouds that can serve as the

manufacturing plant for hailstone embryos that can settle into the main updraft of the steady cell. The so-called ‘feeder’ cells have to be relatively close to the parent cell in order to be effective suppliers of hailstone embryos.

- Whether or not a supercell actually contains such embedded feeder clouds or is just a single cell is not known at the present time

8.6 Heavy Rain Producing Storms

8.6.1 Introduction

- In many parts of the world rainfall from cumulonimbus clouds is the dominant contributor to the rainfall necessary for crop growing and to the supply of water for people, livestock, and wildlife.
- Cumulonimbi can also produce heavy rainfall and flash floods -> can kill people, livestock and wildlife, and cause millions of dollars in property damage and losses.
- The amount of rainfall produced by a thunderstorm depends on the organization and structure of weather systems over a broad range of scales, extending from the global circulation down to the mesoscale and the scale of individual thunderstorms.
- Often, flash floods occur during periods when the large-scale flow pattern appears innocuous -> forecasters are likely to predict fair weather or ordinary thundershowers.

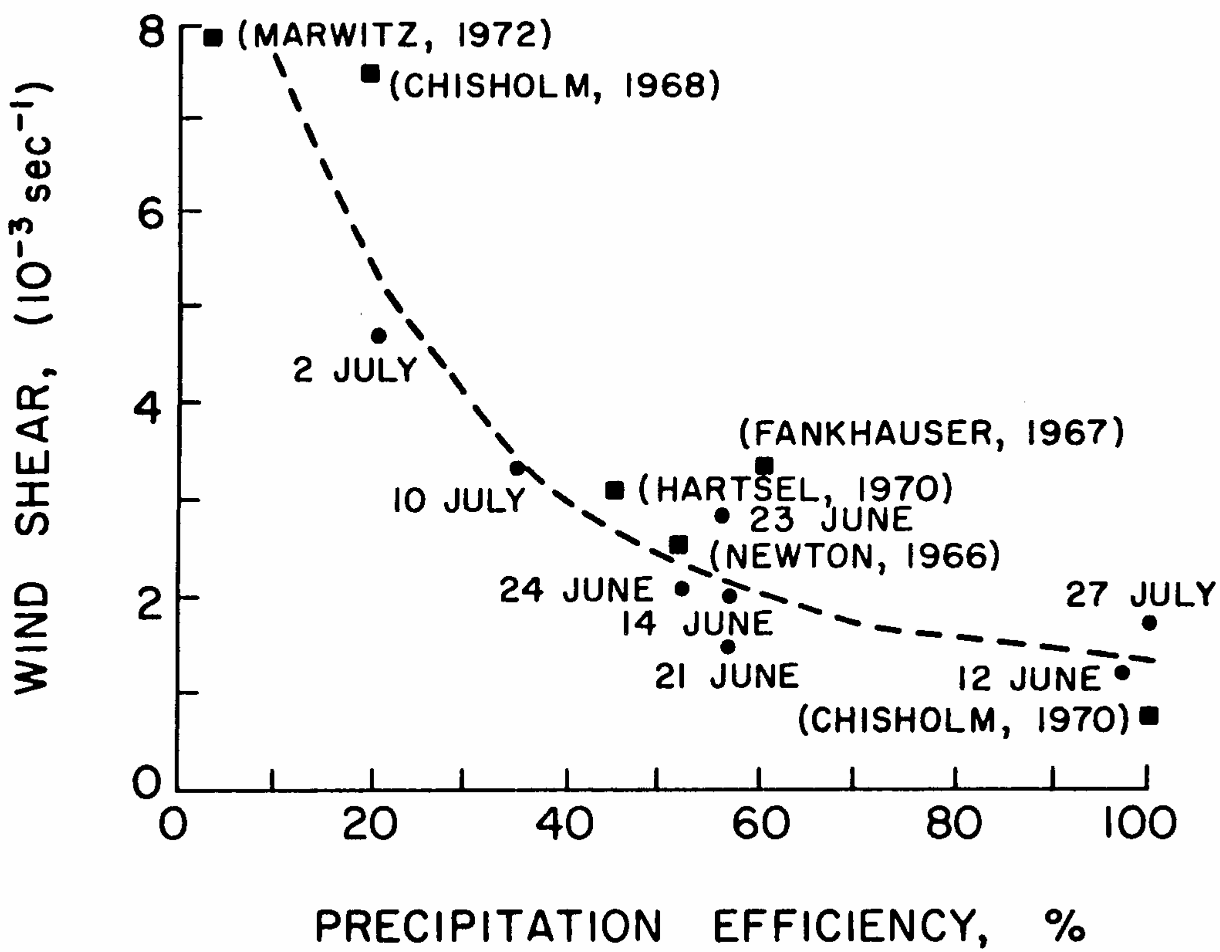
8.6.2 Environmental Conditions for Heavy Rain

- Factors influencing the amount of rainfall produced by thunderstorms include:
  - moisture content of the air
  - wind shear
  - wind strength
  - co-location of synoptic and mesoscale features
- Moisture content: rainfall depends strongly on the moisture content of the airmass near the surface as well as the moisture content of the air through the depth of the troposphere.
- Co-location: the co-location of stationary, large-scale fronts or slowly-moving, upper-level troughs and mesoscale circulations such as sea-breeze fronts, mountain/valley slope flows, air rising over small, heated hills, or urban heat islands can be contributing factors to locally heavy rainfall.

- Wind Strength:
  - winds at low levels are generally strong (called a low-level jet) which fuels thunderstorms with moisture. The intersection of such a moisture-laden, low-level jet with mountains or hills creates a situation in which uplifting of the moisture-laden jet can focus thunderstorms over specific locations, and the rainfall from those storms can be channeled down valleys, causing flash floods.
  - weak winds aloft result in reduced storm motion and localized heavy rainfall, whereas fast winds aloft cause rain to spread over a larger area
- Wind Shear: the presence of weak winds aloft and weak to moderate vertical shear of the horizontal winds is often a characteristic of the environment of heavy rainfall events.

8.6.3 Precipitation Efficiency

- Precipitation efficiency: the ratio of the measured precipitation rate at the ground to the water vapor flux through the base of the cloud system.
- The efficiency of precipitation production in thunderstorms varies with the strength of wind shear. The figure on the next slide shows the variation of precipitation efficiency with vertical shear of the horizontal wind for High Plains thunderstorms over the United States
- The figure suggests that cumulonimbi residing in high wind shears have low precipitation efficiencies, whereas clouds existing in a low wind shear environment exhibit high precipitation efficiencies



Scatter diagram of wind shear versus precipitation efficiency for 14 thunderstorms which occurred on the High Plains of North America. (From Marwitz, J.D., 1972: Precipitation efficiency of thunderstorms on the high plains. *J. de Rech Atmos*., **6**, 367-370.)

- To understand this result, let us examine the budget of water associated with a typical thunderstorm (see next slide):
  - the primary source of water for a cloud is the flow of water vapor into its base.
  - as the air ascends and cools, the vapor is converted into liquid droplets and some is further converted into liquid or frozen precipitation elements
  - a portion of the water rapidly falls out as surface rainfall, and some is ejected into the anvil portion of the cloud, where it eventually evaporates or slowly settles out as steady rainfall
  - some of the water is evaporated at the sides of the cloud as dry, environmental air is entrained into the cloud
  - as the cloud decays, some of the remaining, small, cloud droplets and raindrops evaporate.
  - another portion evaporates in the dry, subcloud layer in low-level downdrafts

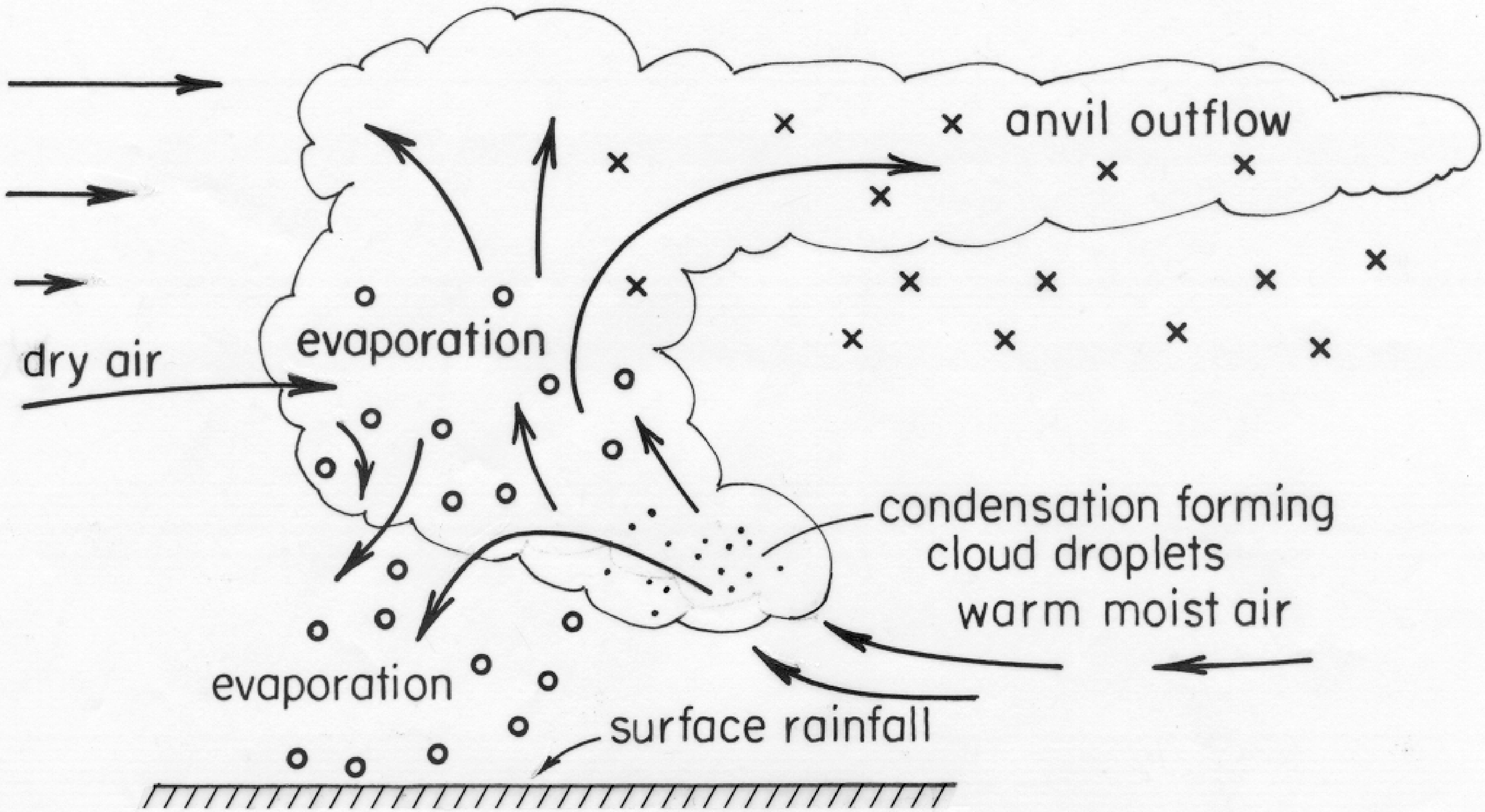
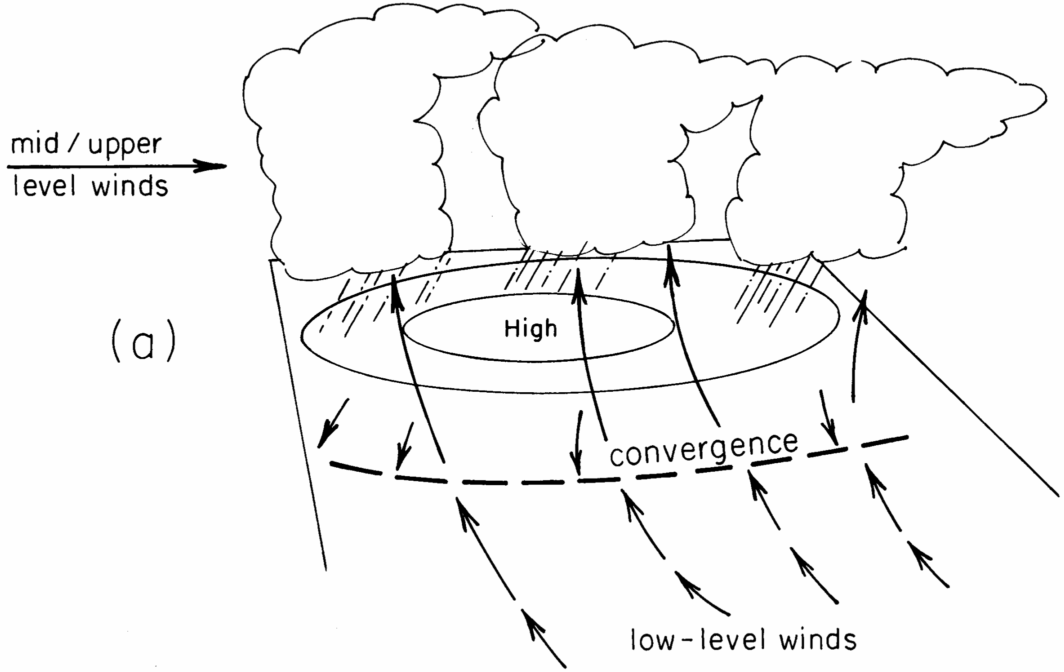


Illustration of the sources and sinks of water entering a thunderstorm.

- In a strong wind shear environment:
  - the entrainment of dry, environmental air into the storm increases
  - the downdrafts become better organized, in part due to the evaporation of entrained dry air
  - as the rainfall descends in the downdrafts, the air compresses and warms, causing greater amounts of evaporation of rainfall
  - greater amounts of water are thrust out into the anvil of the storm
  - the storm system becomes a less efficient rain producer when the vertical shear of the horizontal wind is large.
- Increased wind shear is not always detrimental to precipitation amount:
  - wind shear may increase the storm-relative flow of warm, moist air into the storm system by causing the storm to move faster relative to the low-level flow
  - this may sustain the cloud lifetime, such that, even with reduced precipitation efficiencies, greater amounts of precipitation may be produced by the moving storm than in low-shear environments

- The next slide shows a multicellular thunderstorm system which develops in a wind profile where the low-level winds are perpendicular to the upper level winds (a), and in which the winds are parallel at all levels (b):
  - the strong winds aloft cause the rainfall to settle out of the storm in an elongated pattern parallel to the upper-level flow
  - as the rain settles into the sub-saturated, sub-cloud layer, evaporation of the raindrops cools the low-level air and builds a high-pressure region, which is also elongated in a direction parallel to the upper-level flow.
  - Perpendicular flow (a): the intersection of the low-level flow and the elongated, high-pressure region causes lifting of the moist, low-level air all along the line of convergence between the inflow air and thunderstorm-downdraft air -> new cell development occurs repeatedly along the line of convergence between the inflow air and the downdraft outflow at a nearly constant geographical location, yielding intense, persistent rainfall
  - Parallel flow (b): only the leading edge of the thunderstorm outflow is exposed to the moist-low-level air. As a result, new cell development is localized to the upwind edge of the line, and the total volume of rainfall produced in the multicellular storm is much less that in (a)

Veering winds



Unidirectional winds

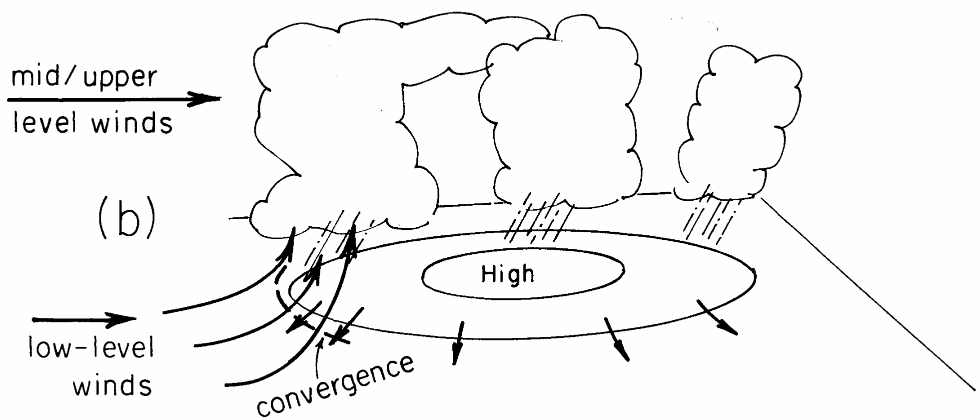


Illustration of a multicellular storm growing in an environment. (a) The low-level winds are perpendicular to the middle- and upper-level winds, and (b) the low-level winds parallel to middle- and upper-level winds. [Adpated from Miller, M.J., 1978: The Hampstead storm: A numerical simulation of a quasi-stationary cumulonimbus system. *Q. J. R. Meteorol. Soc.*, **104**, 413-427].

8.6.4 Optimum Conditions for Flash Floods

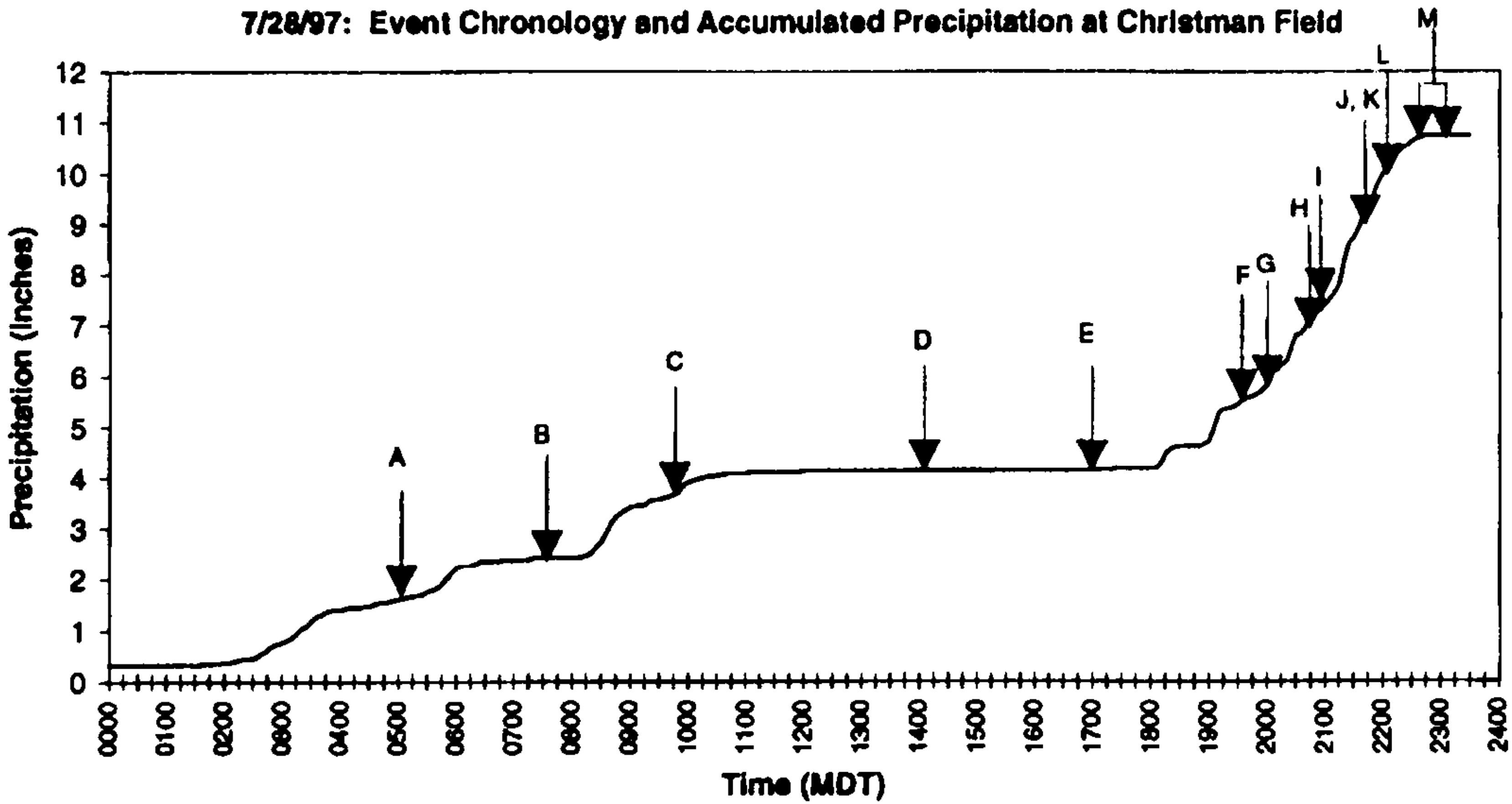
- High values of low-level moisture over U.S:
  - vapor mixing ratios between 10 and 14 g/kg
- Strong LLJ
- Weak winds aloft and weak to moderate wind shear
- High precipitation efficiencies
- Veering wind profile favors flash floods

8.6.5 Case Study: Fort Collins Flash Flood

Statistics

- 28 July 1997
- 5 fatalities
- > $200 million damage
- 1 of largest rainfall events ever documented over a developed urban area in Colorado
- At CSU: 5.3 in (13.46 cm) of rain fell in under 6 hours
- 4 km southwest of CSU: 10.2 in was recorded in 6 hours
- The Fort Collins 100 year 6-hr and 24-hr rainfall amounts are 3.5 and 4.8 in respectively (NOAA Atlas-2)
- Prior to 1997 there were 7 documented storms that produced at least 10 in. of rain within 24 hours – most publicized was the Big Thompson storm (31 July 1976) -> 139 fatalities and 7 missing
- Reference: Petersen et al., 1999: Mesoscale and Radar Observations of the Fort Collins Flash Flood of 28 July 1997. BAMS, 80, 2, 191-216.

Event Chronology

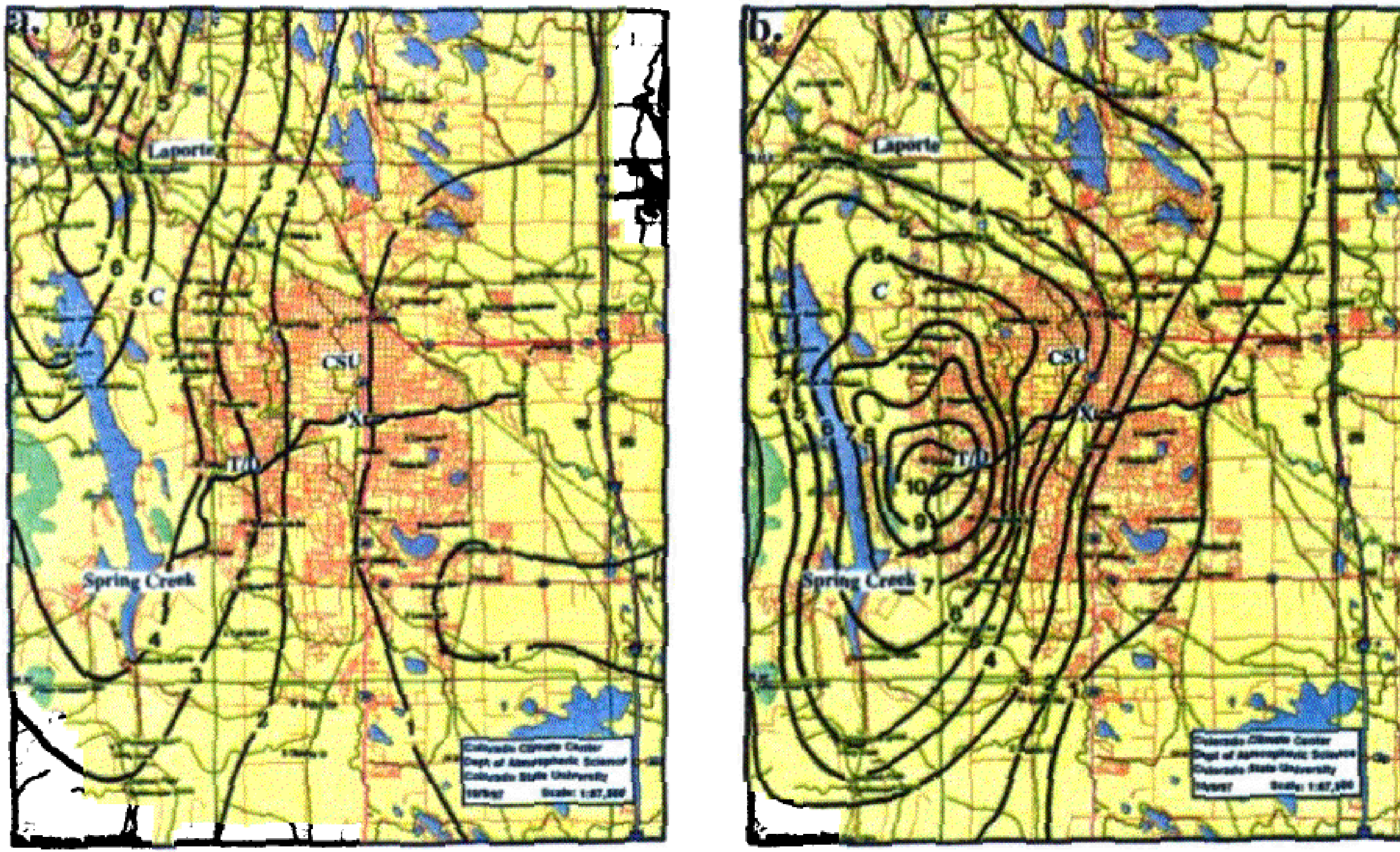


Chronology of events for 28 July 1997 vs accumulated precipitation (inches) at Christman Field. Time (MDT) is indicated on the abscissa. Events labeled A-M are discussed in detail in the article by Petersen et al., 1999.

- On the evening of 27 July, the foothills to the west and northwest of FC had already received up to 2.42 in of rain
- Followed by another episode of heavy rain on the morning of 28 July on the west side of FC – flooding was occurring in Laporte and to the northwest of Laporte where 7-9 in of rain had fallen
- Rainfall ended around 12:00 MDT but heavy rainfall redeveloped over foothills to the west and northwest of FC by 1700 MDT
- Between 1700 and 2000 MDT 2 convective storms moved over FC produced brief heavy rains (0.5-0.75 in in 30 mins)
- Rainfall began to increase after 2000 MDT and between 2100 and 2200 MDT the rainfall became very heavy (4-5 in per hour), particularly over western region of FC
- By 2134 MDT homes in SW FC began to flood
- Between 2230 and 2300 MDT the Sprint Creek detention pond started to overflow
- 2300 MDT freight train derailed in same area by flooding

Rainfall Measurements

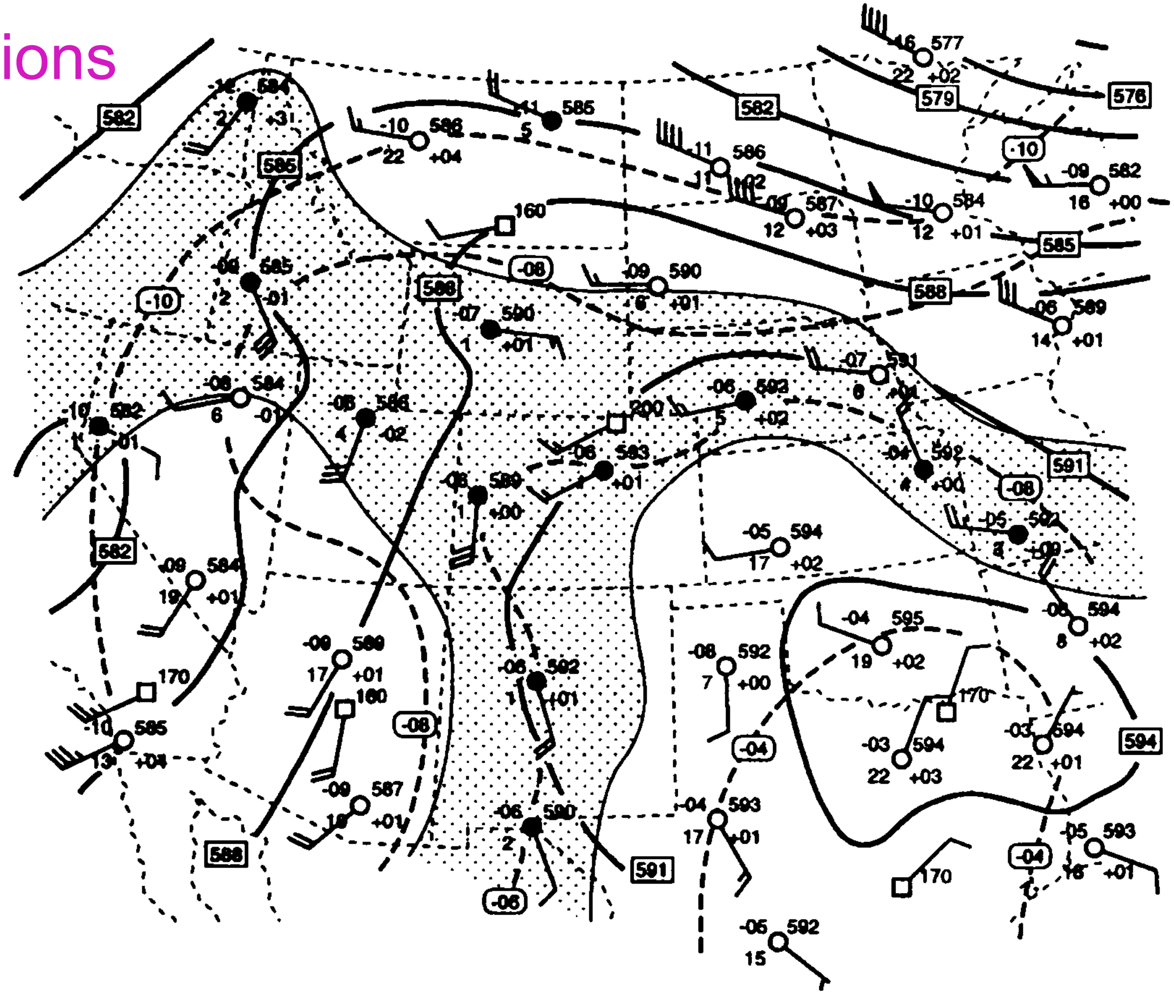
- Recorded rainfall measurements for two time periods are shown in the next slide
- Late afternoon 27 July through midday 28 July: most of FC recorded between 0.6 and 2.0 in; but as much as 4 in. of rain fell over far western part of FC and more than 9 in. fell to the northwest of FC
- Evening of 28 July: Southwestern FC received more than 10 in. over 5.5 hours, and most portions of western FC received more than 6 in.
- Strong gradient to the southeast of point of maximum precipitation -> rainfall totals decreased from 10 in. to less than 2 in. in a distance of only 4 km



Isohyetal maps of rainfall for FCL, contoured in inches: (a) 1600 MDT 27 July 1997-1300 MDT 28 July 1997; and (b) 1730-2300 MDT on 28 July 1997. The location of Spring Creek is highlighted by a bold line that extends from western FCL at the marker Spring Creek through the “X” in central FCL. The intersection of Taft Hill and Drake Roads is indicated by “T/D” and the approximate location of the flooded mobile home park is shown by an “X” (after Petersen et al., 1999, adapted from Doesken and McKee, 1998)

Midtroposphere Conditions

- Negatively tilted ridge
- Weak shortwave trough
- Light to moderate southerly and southwesterly winds advected a deep layer of moisture into Colorado – dewpoint depressions at 500 hPa were 1°C at all sounding sites in NM, CO and WY
- Main synoptic features aloft similar to those of Big Thompson flood



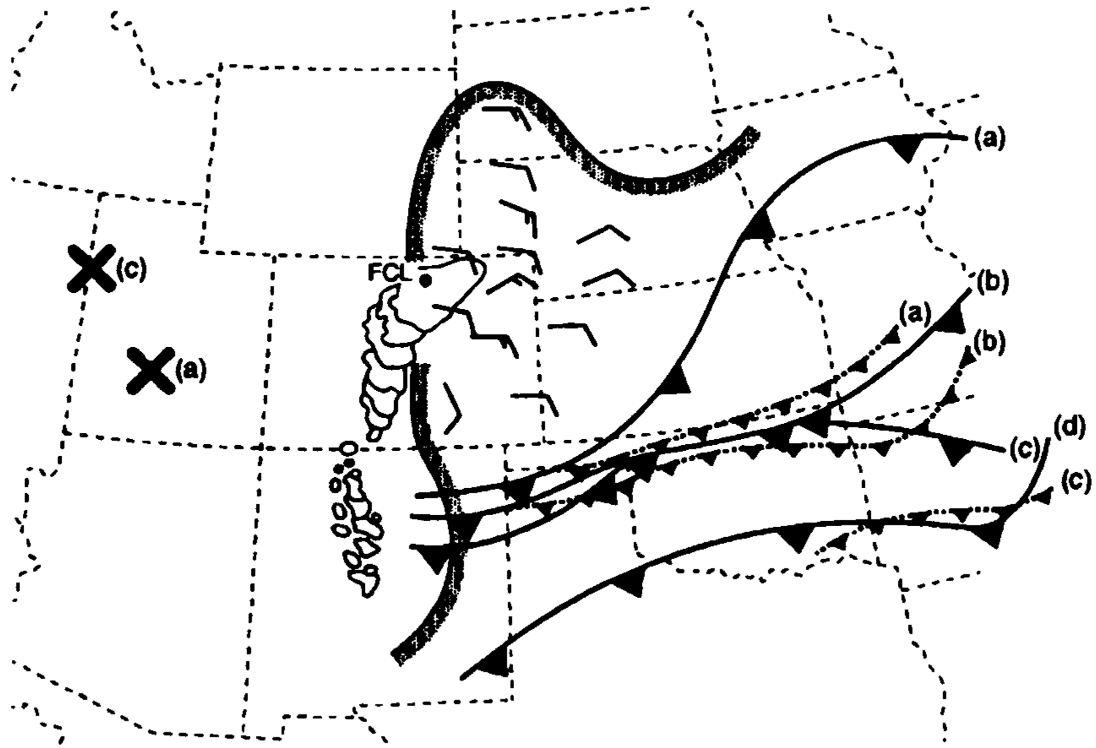
500-hPa analysis for 1800 MDT 28 July 1997. Isolines of geopotential height (solid) are contoured at an interval of 30m. Isotherms (dashed) are contoured at an interval of 2°C. Shaded regions indicate dewpoint depressions ≤ 6°C (after Petersen et al., 1999)

Surface Conditions

• Cool and exceptionally moist Canadian air mass lodged against the eastern face of the Rockies in CO and WY

• Dewpoints were 16-18°C (61-64°F) along the foothills and 18-20°C a few hundred kms to the east

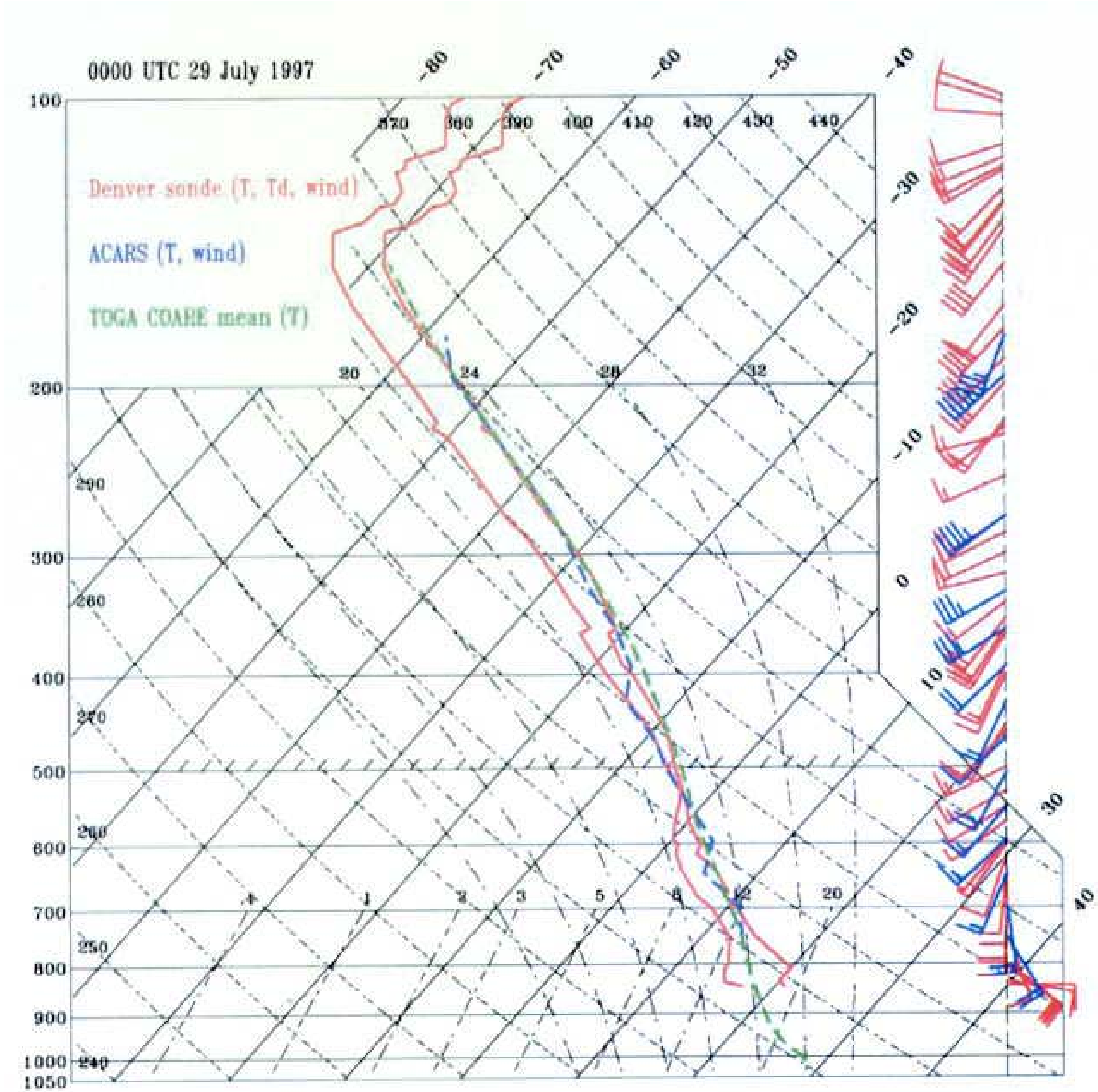
• Northeasterly to southeasterly winds over high plains from anticyclonic flow associated with the Canadian air mass



Schematic of synoptic and mesoscale features for 28 July 1997. Two large X's represent the locations of a 500-hPa vorticity maximum. Closed solid contours indicate pertinent regions of cloud top colder than -20°C for 1-h intervals between 0600 and 1800 MDT. The wide shaded line shows the northwestern edge of surface dewpoints > 15.5°C (60°F). Wind barbs are for the surface; short barbs are 2.5 m/s, long barbs are 5 m/s. Synoptic fronts are indicated by solid lines; mesoscale boundaries by broken lines with pairs of dots. Times are (a) 0600, (b) 1200, (c) 1800, and (d) 2400 MDT (after Petersen et al., 1999)

Soundings

- DNR sounding shows very moist conditions throughout the troposphere
- No lower-tropospheric inversion or cap above the BL
- Midtropospheric winds were weak to moderate and southwesterly
- Winds from the surface to 750 hPa were east to southeasterly
- CAPE: 868 J/kg -> relatively small
- Low LCL (764 hPa) and low LFC (690 hPa) due to small dewpoint depressions

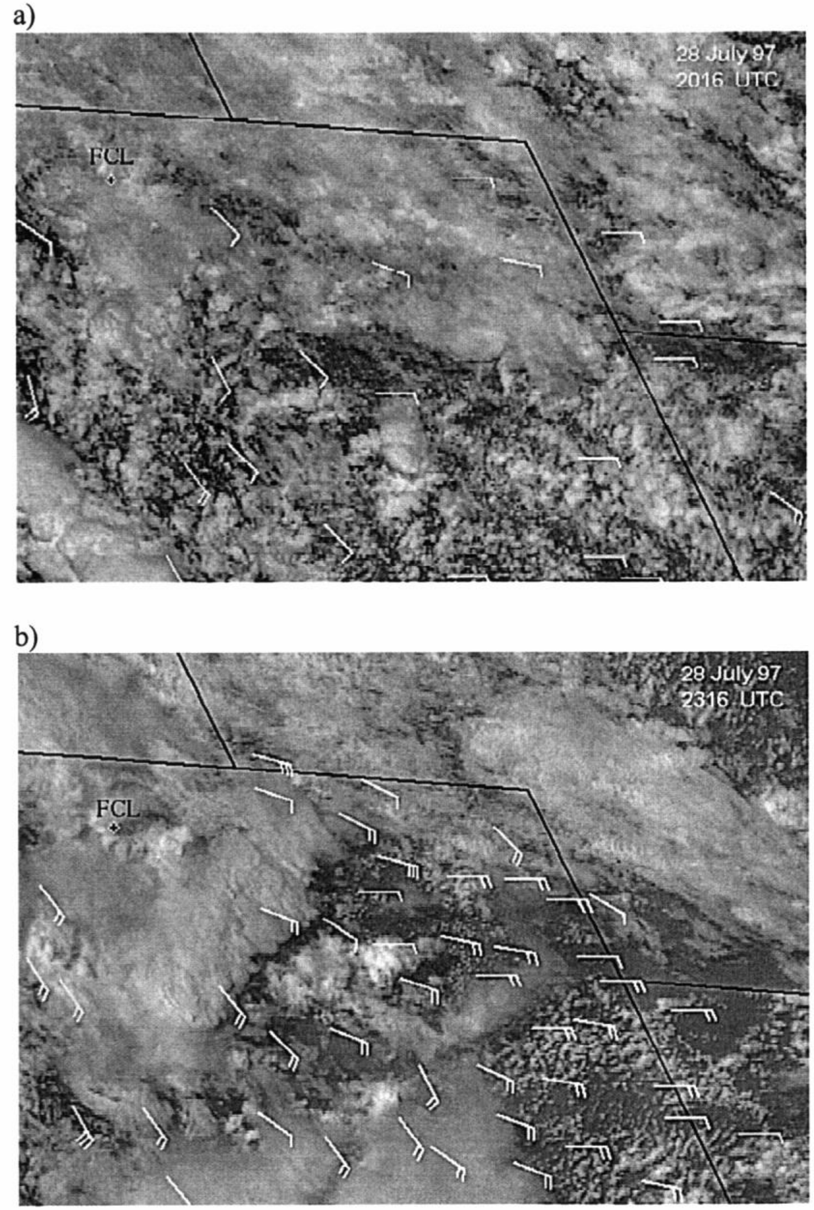


Skew-T plot for Denver, CO at 1800 MDT and for TOGA COARE. Wind barbs are plotted in knots.

Convection

- Only apparent trigger for the initial convection was the foothills unlike the Big Thompson storm where a front combined with orographic lift provided the primary convective trigger. The lower LFC in the FC case would have permitted generation of heavy rainfall as the flow reached its first pronounced orographic lift on the west side of FC.

- At 1416 MDT the cloud-drift winds indicate the presence of a 5 m/s low-level southeasterly wind. However, at 1715 MDT the cloud-drift winds suggest that the winds backed slightly, becoming more east-southeasterly and increasing in speed by 5 m/s. The increase in upslope flow over the plains of northeastern CO was nearly coincident with an increase in convection along the northern and central sections of the Front Range



Cloud drift winds derived from GOES-9, 28 July 1997: (a) 1416 MDT and (b) 1715 MDT. Wind barbs are plotted in knots.

- So numerous precursors in the storm environment shaped the character and motion of the convection:
  - warm, moist south-southwesterly flow above the BL
  - low-level east-southeasterly wind
  - relatively low CAPE and LFC
  - high humidity through the depth of the sounding
- The moist monsoonal flow likely promoted high precipitation efficiencies due to:
  - minimal entrainment of dry air with its associated evaporation in developing convection
  - high BL humidities coupled with low cloud bases likely prevented substantial evaporation of precipitation below cloud base

Summary of Meteorological Aspects

- Negatively tilted 500-hPa ridge over the area and some forcing from a weak shortwave trough that moved northward in the western side of the ridge
- Post-frontal moist easterly upslope flow at low levels
- A veering, but weak to moderate, moist south-southwesterly flow aloft
- Slow system movement
- Deep, moist warm layer conducive to precipitation production via warm-rain / collision-coalescence processes
- Compared to Big Thompson flood the thermodynamic instability was moderate and the LFC was lower -> led to storm development where the easterly flow encountered its first abrupt lift on the western side of FC, as opposed to the Big Thompson flood, where parcels needed lifting to higher elevations in order to reach LFC