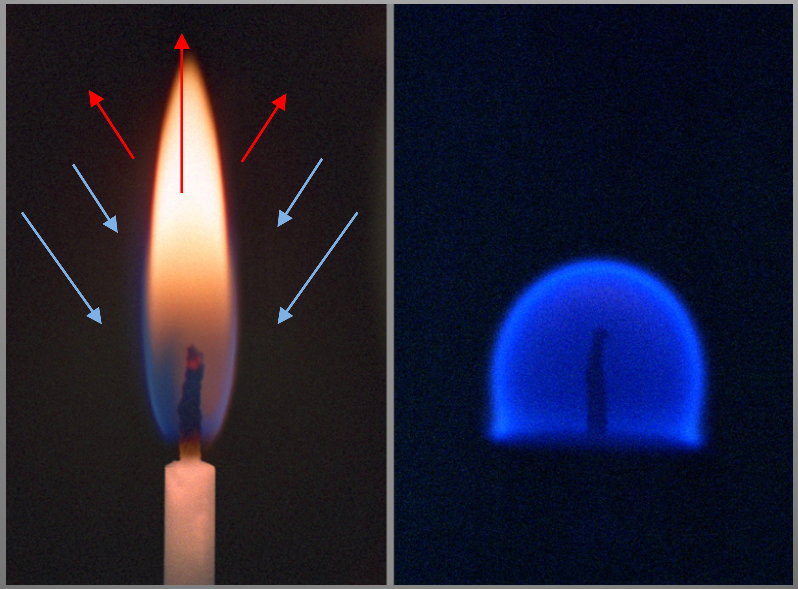
Atmospheric Convection

Review of Fundamentals

Pao K. Wang
Department of Atmospheric and Oceanic Sciences
University of Wisconsin-Madison, Madison, WI 53706, USA
and
Research Center for Environmental Changes
Academia Sinica, Taipei, TAIWAN
September 2, 2019, EUMETSAT Workshop - Thessaloniki, Greece

Natural convection in the atmosphere

- Generally refers to the motion of air due to the buoyancy caused by the density difference in the presence of gravity (yes, you do need gravity)
- The density difference is usually caused by different temperatures.
- Two opposing forces — buoyancy and gravity



Candle flame on the earth surface (left) and in the microgravity environment (right)

Shallow convection vs. deep convection

- Scale height $H = (kT/mg) \approx 8$ km for an isothermal atmosphere of 288 K.
- Convection depth $D \geq H$ — deep convection, otherwise it's shallow convection

$W_{max} \sim 1$ m/s

$W_{max} \geq 10$ m/s

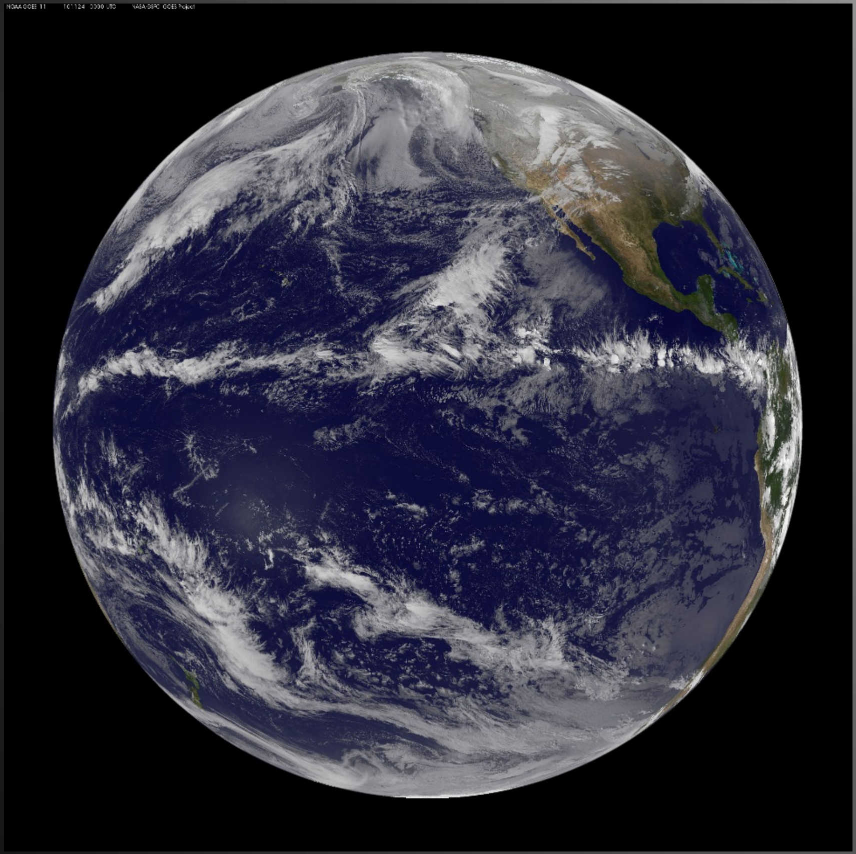
Sometimes shallow can become deep very quickly—visible instability

2010 Praha workshop

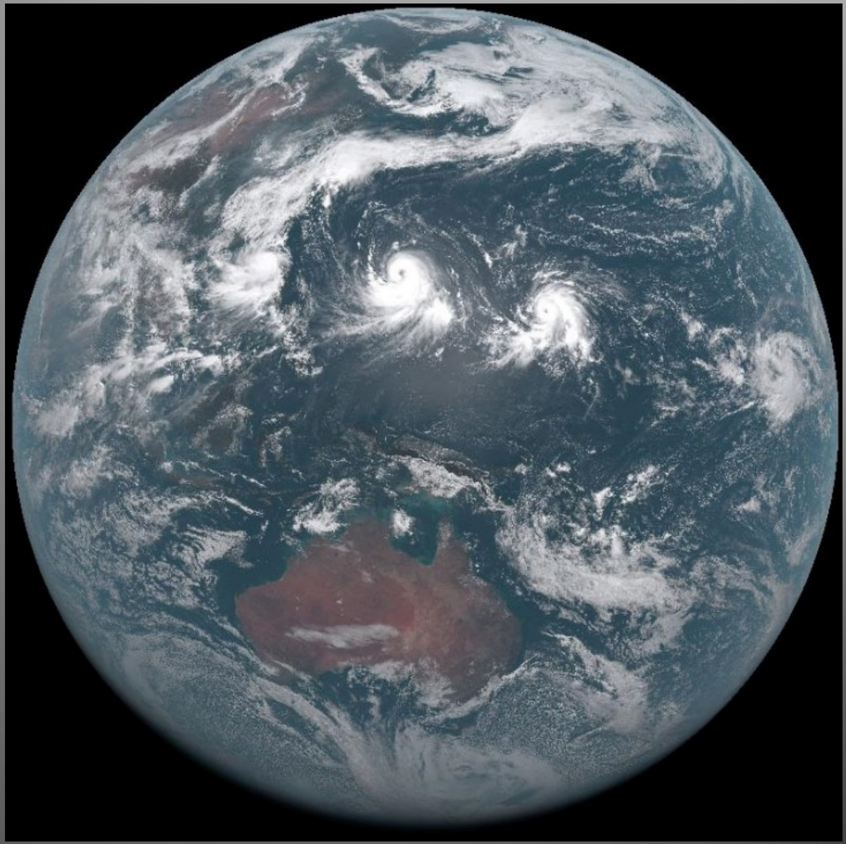
2010 Praha workshop

2010 Praha workshop storm

Where does deep convection occur?



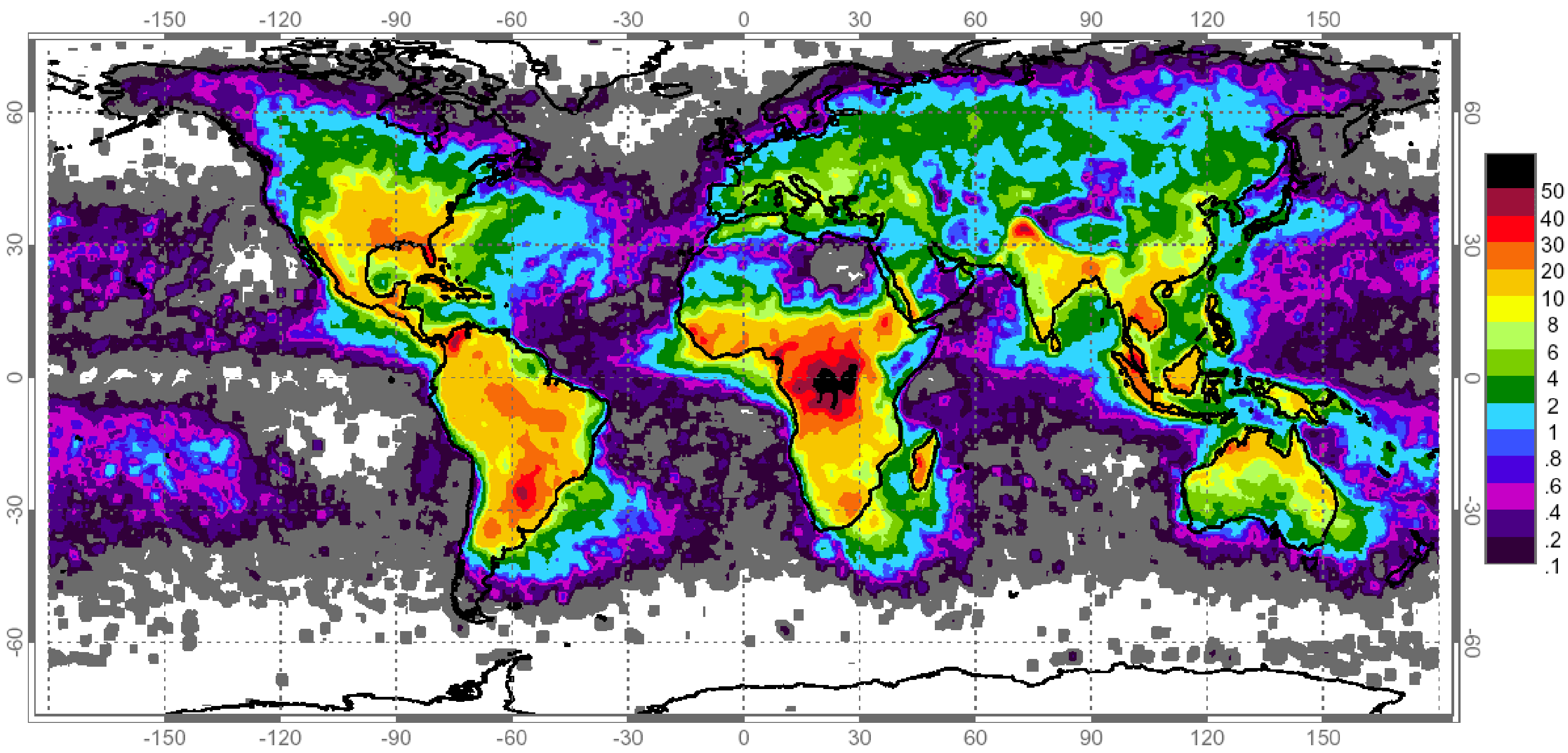
NOAA



Himawari-8/JMA

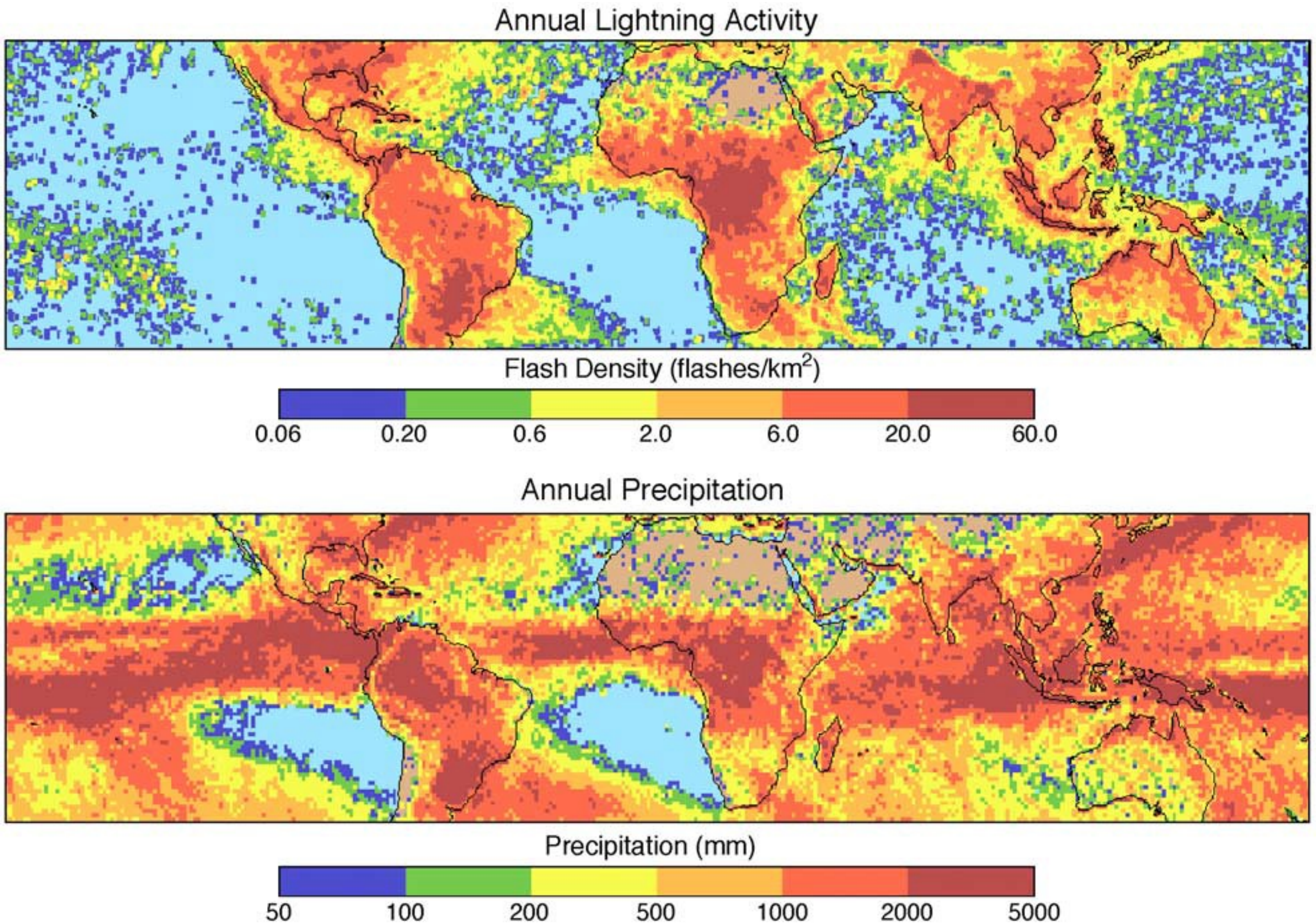
World distribution of thunderstorms as represented by lightning frequency.

Highest in tropics, over land, and in summer



NASA

Lightning and precipitation



Williams (2005)

Tropical maritime cumulus clouds
Cumulus clouds over South China Sea

Instability at the cloud top

How would such a difference seen in satellite images?

bumpy

bumpier

Tropical vs. Midlatitude Clouds-1

- In most of the tropics the atmosphere is approximately in a state of radiative-convective near-equilibrium because deep, moist convection (DMC) stabilizes the environment much more quickly than the large-scale processes can act to destabilize the atmosphere. In other words, the instability is released soon after it is created, and the tropical atmosphere tends to stay rather close to neutral stability conditions with respect to deep convection. (Emanuel, 1994)

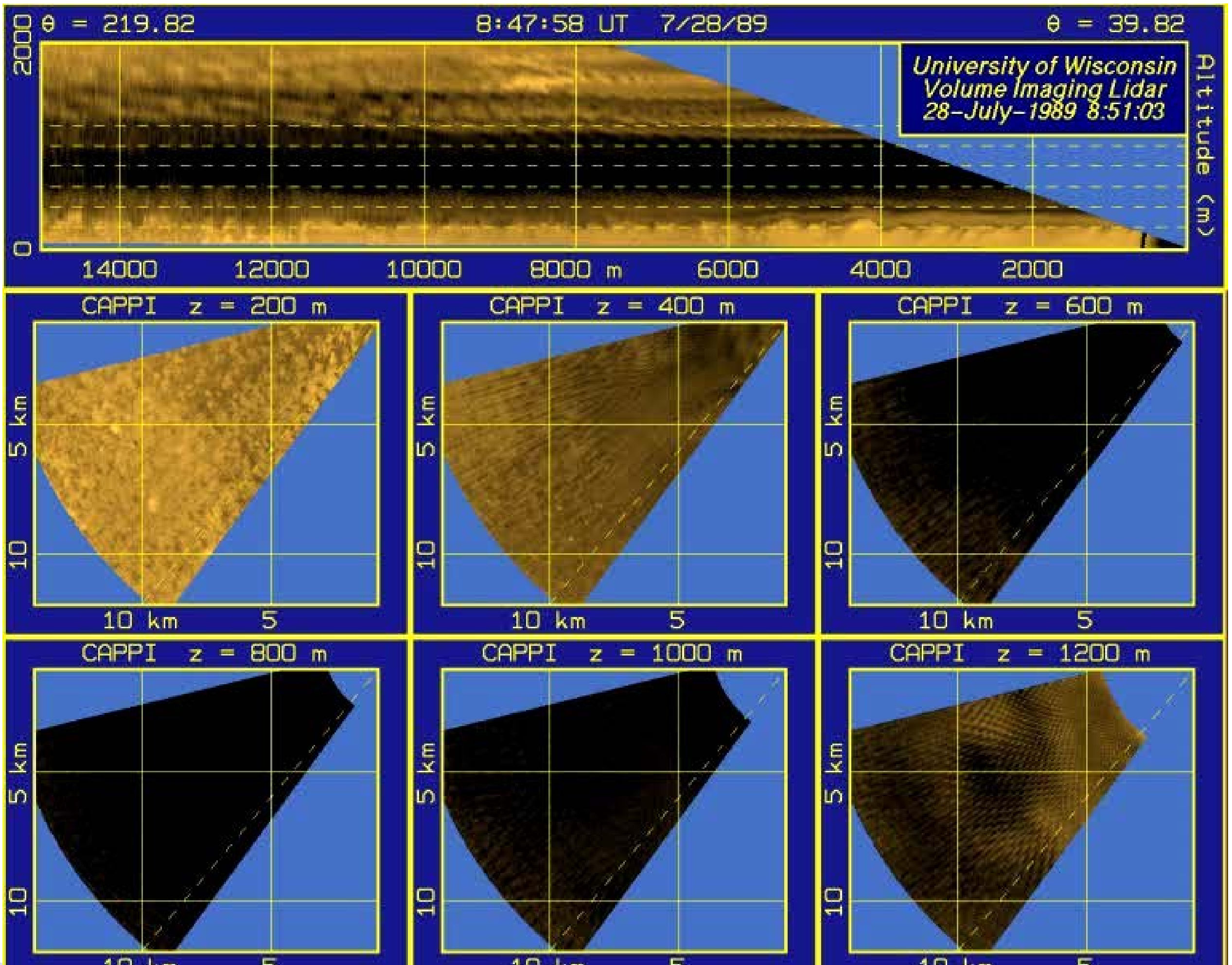
Tropical vs. Midlatitude Clouds-2

- In midlatitude continental convection, the instability is *not* always realized as soon as it is created. Rather, the instability can be "stored" in the environment, owing to convective inhibition (or CIN), and can increase over a period of up to several days, finally to be released explosively in the form of *severe* convection. (Doswell, 2001). **This indicates that there are other dynamical mechanisms operating in midlatitude convective systems.**

Tropical vs. Midlatitude Clouds - 3

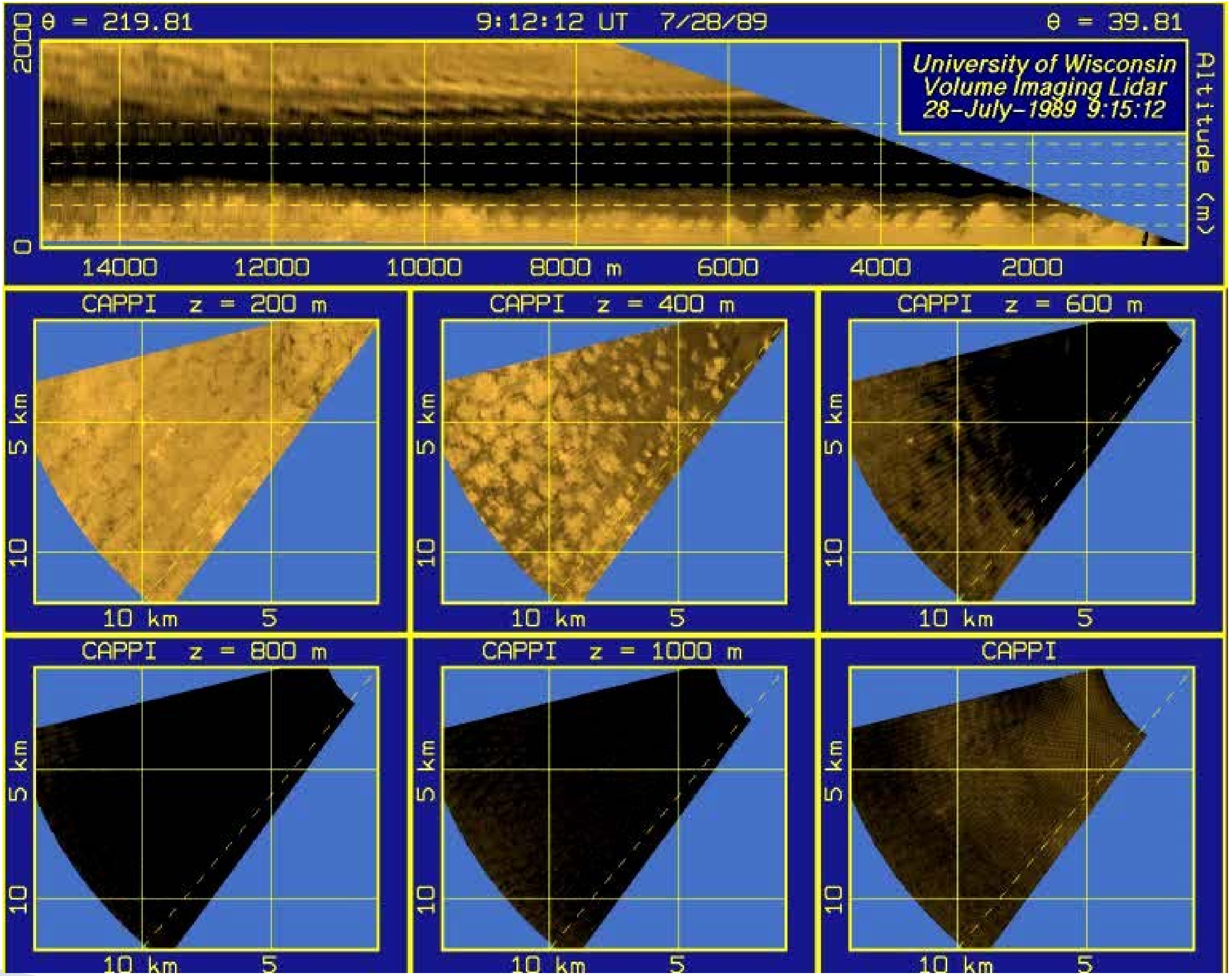
- Even though tropical air masses tend to contain more moisture than midlatitude air, the CAPE of midlatitude deep convective storms are often much greater than those in the tropics and are often more vigorous. In US Midwest, w_{max} in severe storms can often be 50 m/s or greater while in tropical thunderstorms it is usually less than 20 m/s.
- The maximum vertical velocities in hurricanes are ~ 20 m/s peaking at z ~ 2 km whereas their u can be 30-80m/s.

Development of convection in the boundary layer as observed by lidar-1



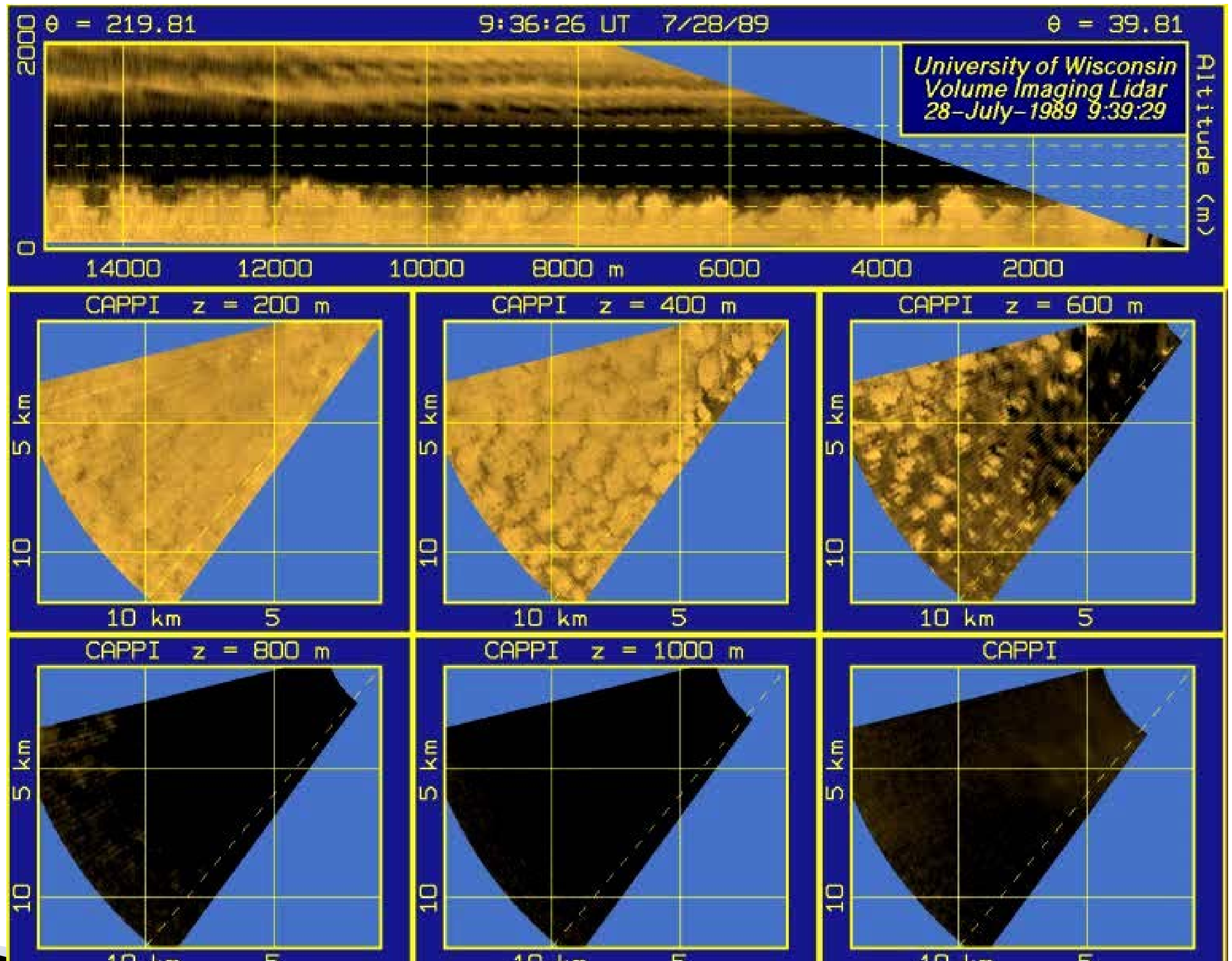
Courtesy of Ed Eloranta

Development of convection in the boundary layer as observed by lidar-2



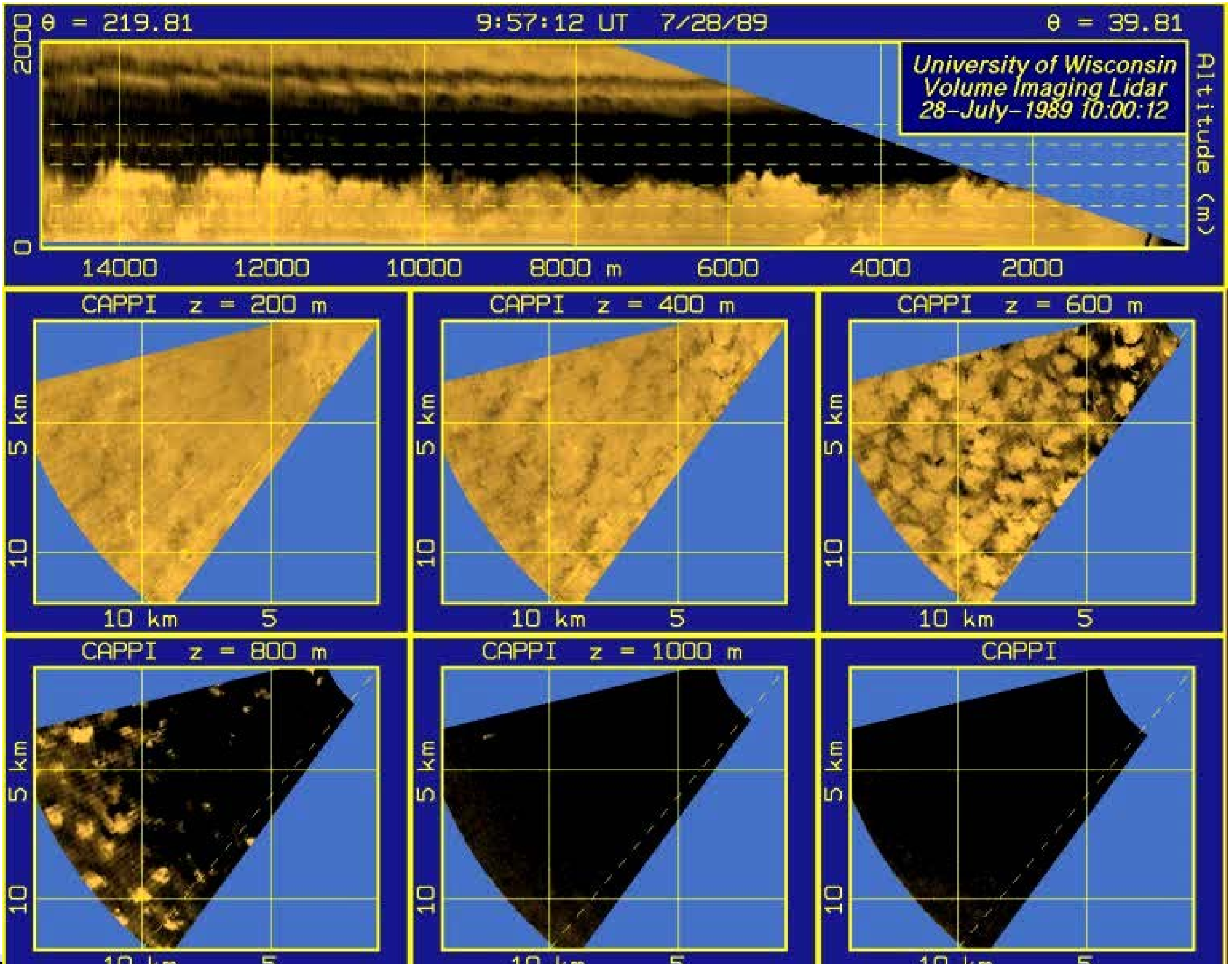
Courtesy of Ed Eloranta

Development of convection in the boundary layer as observed by lidar-3



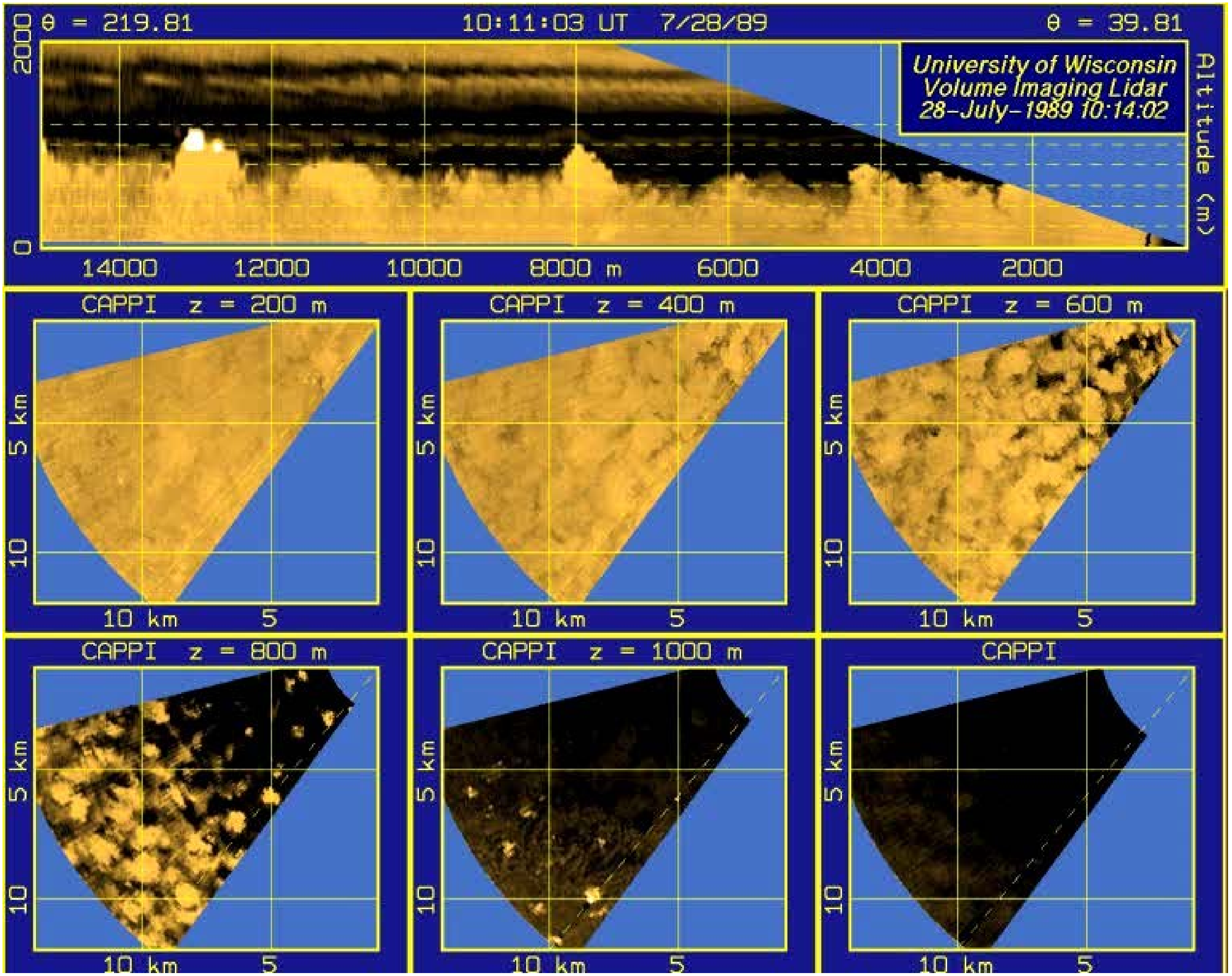
Courtesy of Ed Eloranta

Development of convection in the boundary layer as observed by lidar-4



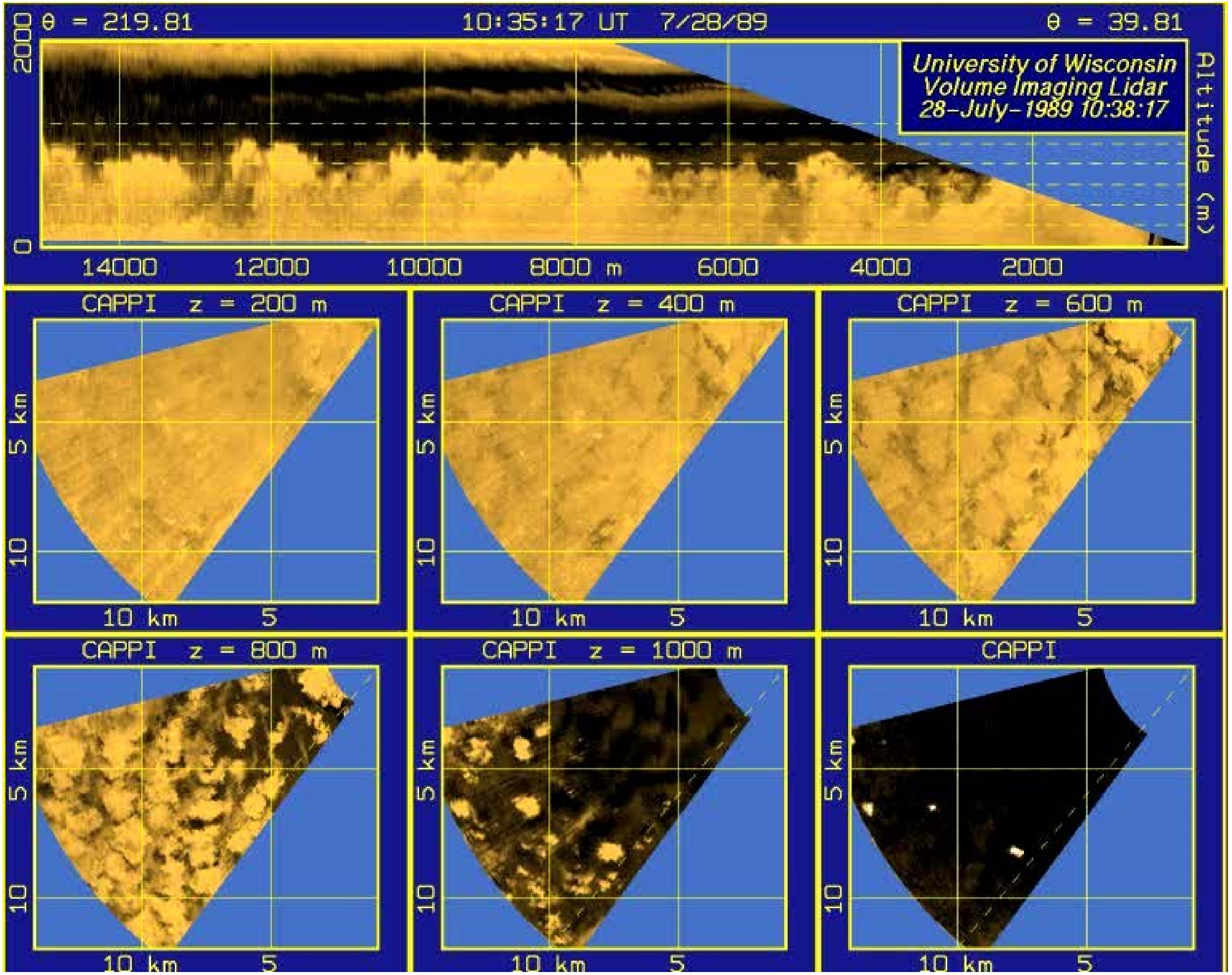
Courtesy of Ed Eloranta

Development of convection in the boundary layer as observed by lidar-5



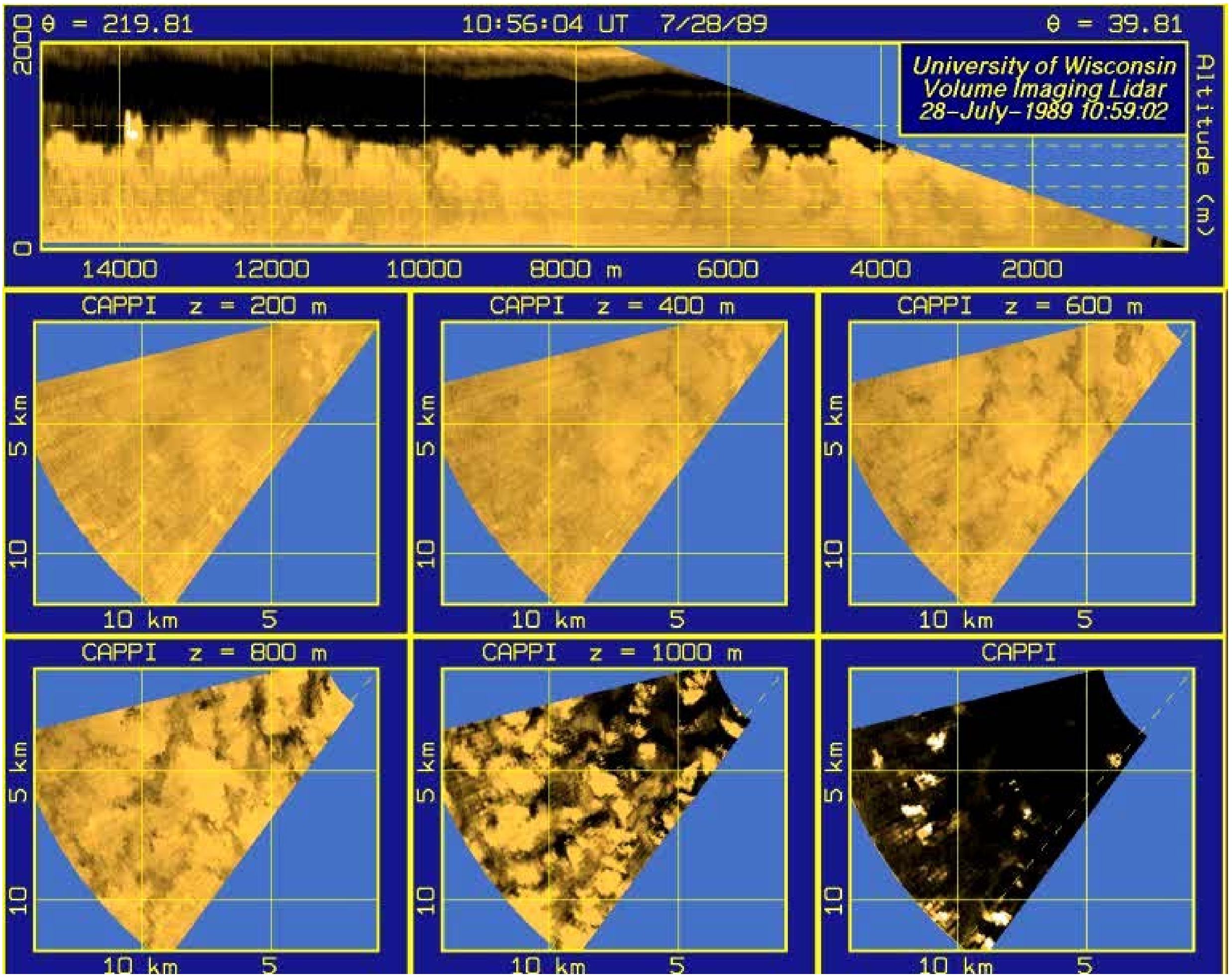
Courtesy of Ed Eloranta

Development of convection in the boundary layer as observed by lidar-6



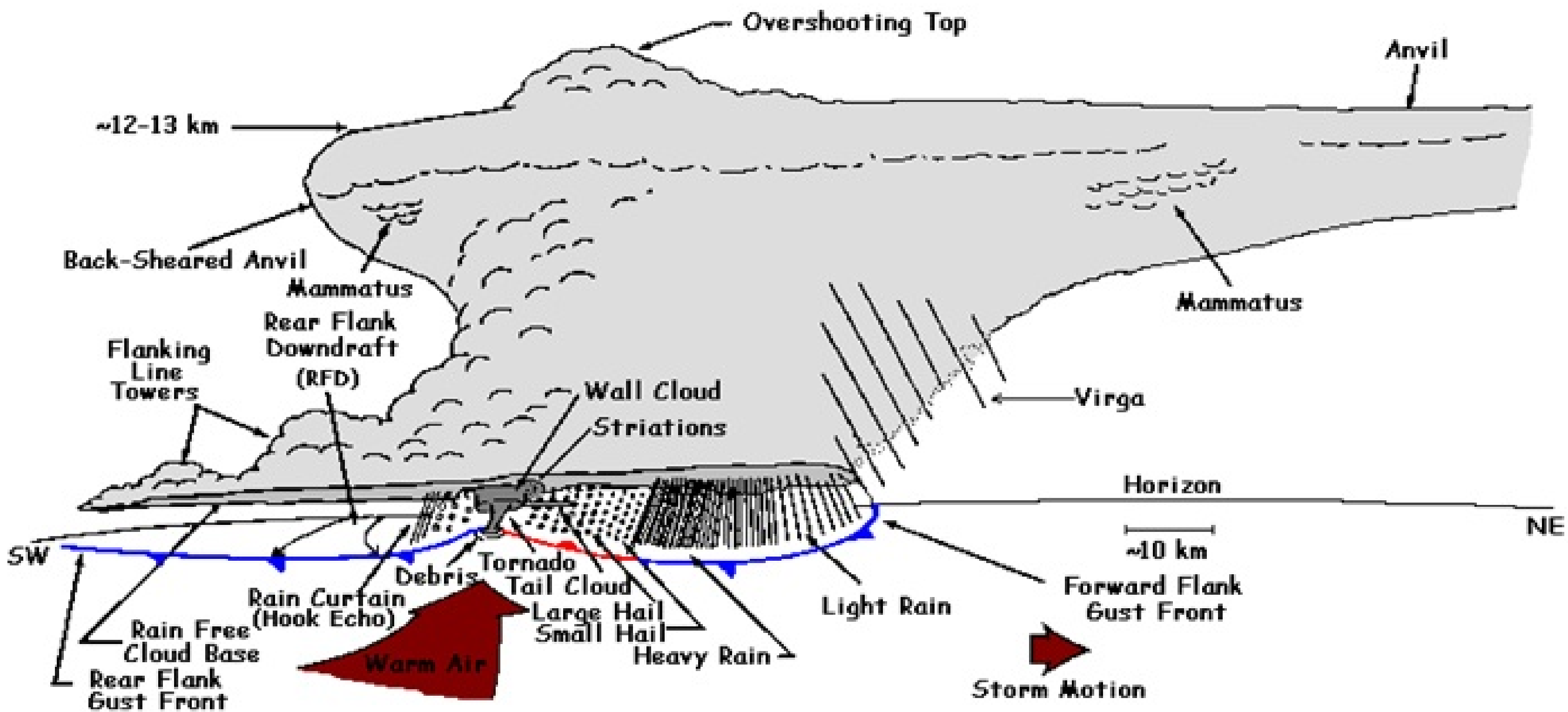
Courtesy of Ed Eloranta

Development of convection in the boundary layer as observed by lidar-7



Courtesy of Ed Eloranta

Thunderstorm appearance



Houze and Hobbs

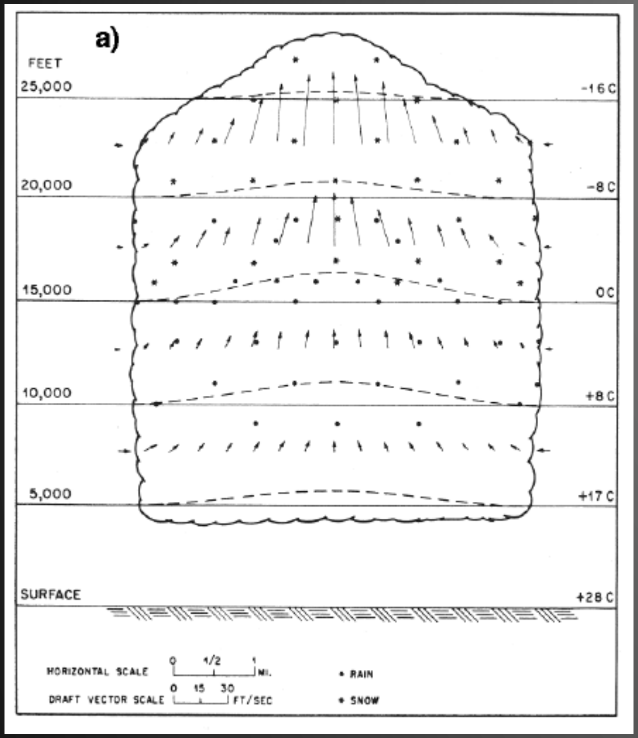
Cb in weak wind shear (over Taiwan Strait)

Advancing overhang with mammatus (storm near Boulder, CO)

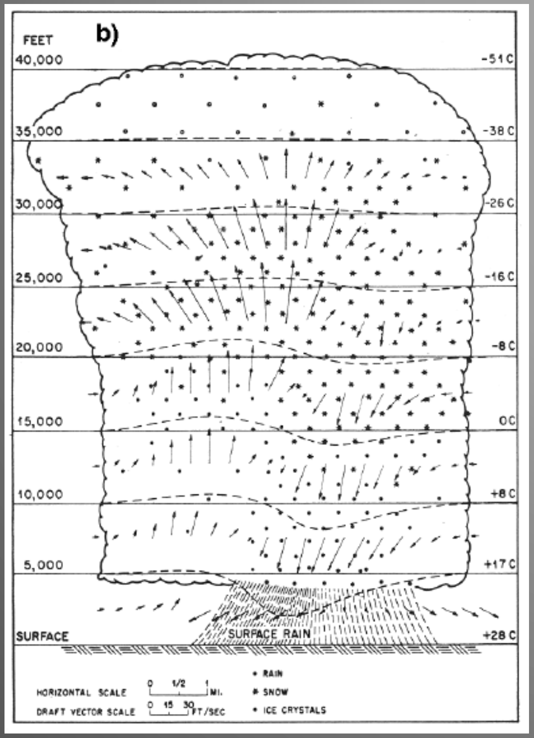
Virga in the overhang
Madison, Wisconsin

Thunderstorm cell concept

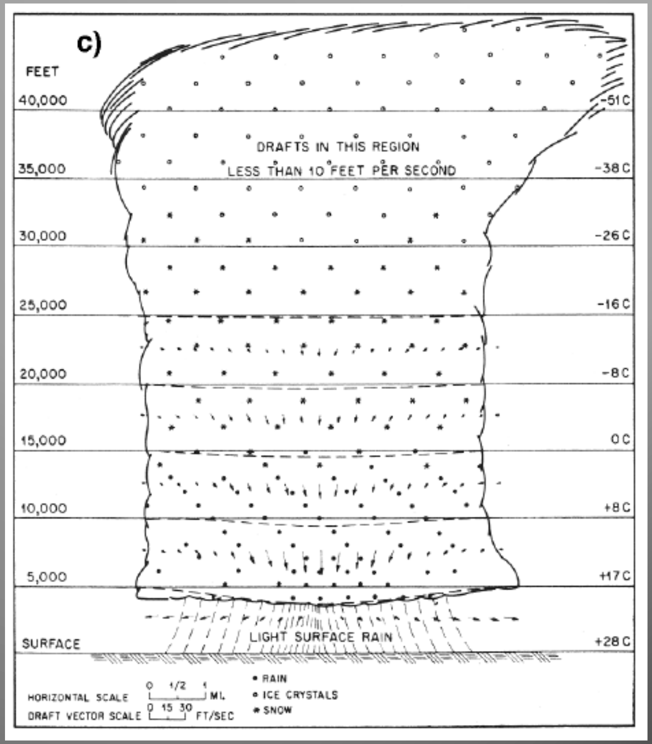
Thunderstorm project (Byers and Braham, 1949)



developing stage



mature stage



dissipating stage

The single cell thunderstorm life cycle

- The *developing stage* of a thunderstorm is marked by a cumulus cloud that is being pushed upward by a rising column of air (updraft). The cumulus cloud soon looks like a tower (called towering cumulus) as the updraft continues to develop. There is little to no rain during this stage but occasional lightning. The developing stage lasts about 10 minutes.

- The thunderstorm enters the *mature stage* when the updraft continues to feed the storm, but precipitation begins to fall out of the storm, and a downdraft begins (a column of air pushing downward). When the downdraft and rain-cooled air spreads out along the ground it forms a gust front, or a line of gusty winds. The mature stage is the most likely time for hail, heavy rain, frequent lightning, strong winds, and tornadoes. The storm occasionally has a black or dark green appearance.

- Eventually, a large amount of precipitation is produced and the updraft is overcome by the downdraft beginning the *dissipating stage*. At the ground, the gust front moves out a long distance from the storm and cuts off the warm moist air that was feeding the thunderstorm. Rainfall decreases in intensity, but lightning remains a danger.

(NSSL/NOAA)

Types of thunderstorms (NSSL)

- Single cell storms
- Multicell storms
  - multicell cluster storms
  - multicell line storms (squall line)
- Supercell storms

THE SINGLE CELL STORM

- Single cell thunderstorms usually last between 20-30 minutes. A true single cell storm is actually quite rare because often the gust front of one cell triggers the growth of another.
- Most single cell storms are not usually severe. However, it is possible for a single cell storm to produce a brief severe weather event. When this happens, it is called a pulse severe storm. Their updrafts and downdrafts are slightly stronger, and typically produce hail that barely reaches severe limits and/or brief microbursts (a strong downdraft of air that hits the ground and spreads out). Brief heavy rainfall and occasionally a weak tornado are possible.
- Though pulse severe storms tend to form in more unstable environments than a non-severe single cell storm, they are usually poorly organized and seem to occur at random times and locations, making them difficult to forecast.

NSSL/NOAA

Multicell Storms

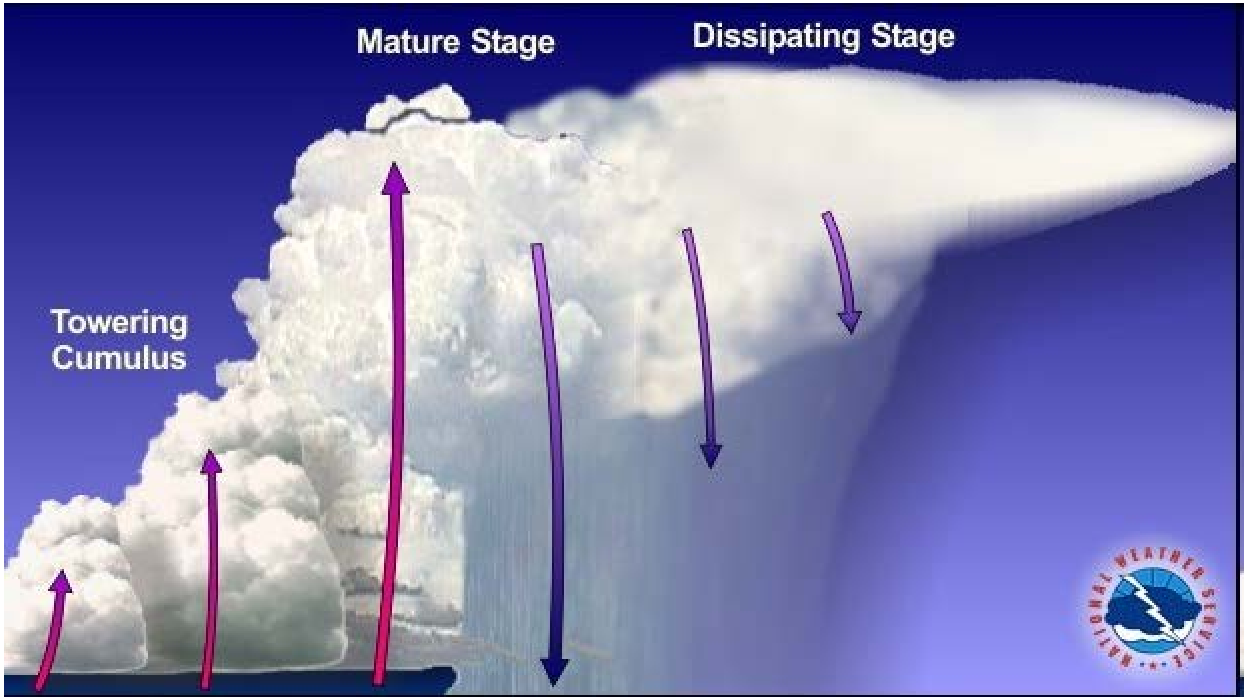
- Multicell cluster storms
- Multicell line storms (Squall line)

THE MULTICELL CLUSTER STORM

- The multicell cluster is the most common type of thunderstorm. The multicell cluster consists of a group of cells, moving along as one unit, with each cell in a different phase of the thunderstorm life cycle.
  - Mature cells are usually found at the center of the cluster
  - dissipating cells at the downwind edge of the cluster.
- Multicell Cluster storms can produce moderate size hail, flash floods and weak tornadoes.
- Each cell in a multicell cluster lasts only about 20 minutes; the multicell cluster itself may persist for several hours. This type of storm is usually more intense than a single cell storm, but is much weaker than a supercell storm.

NSSL/NOAA

Multicell cluster



NOAA

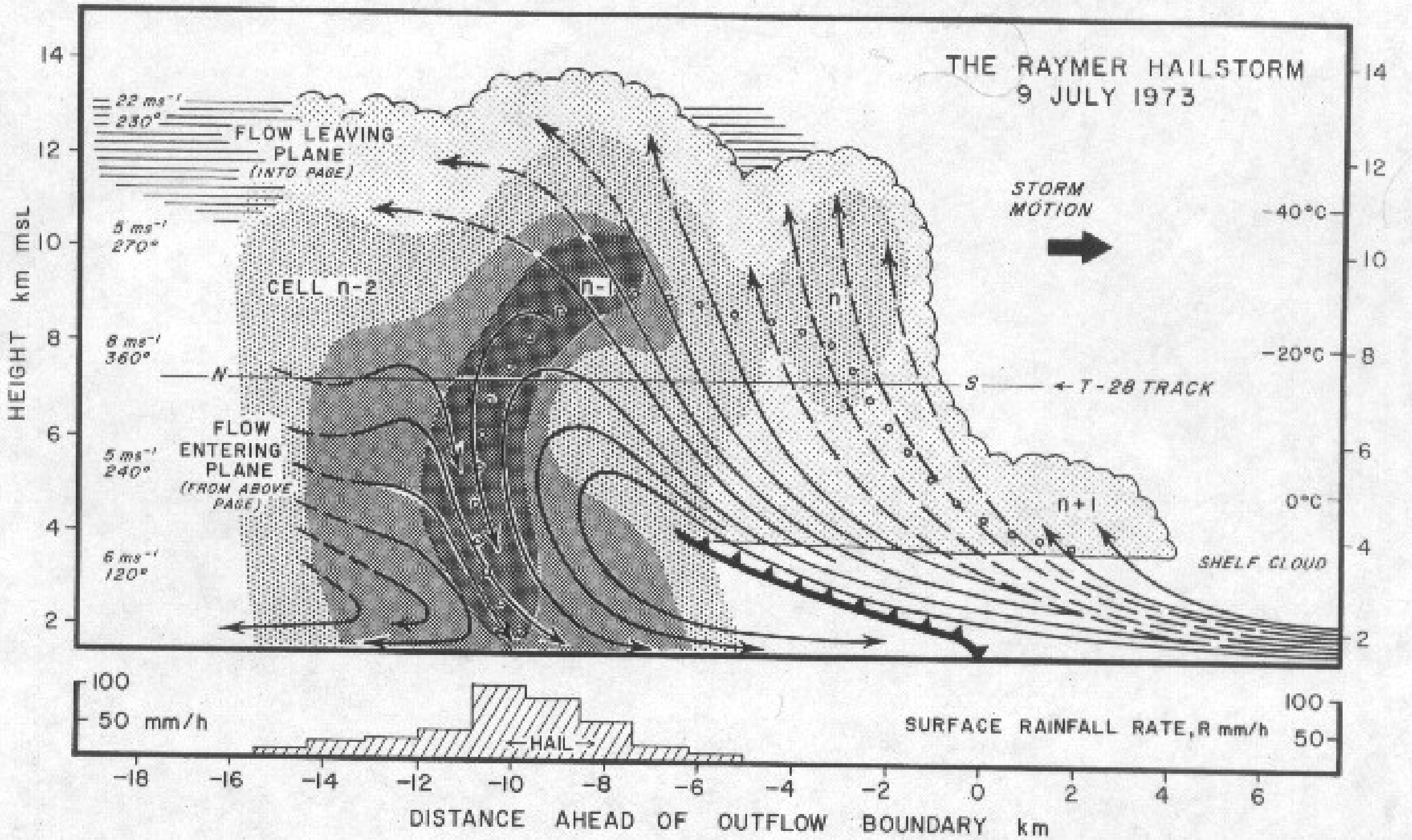


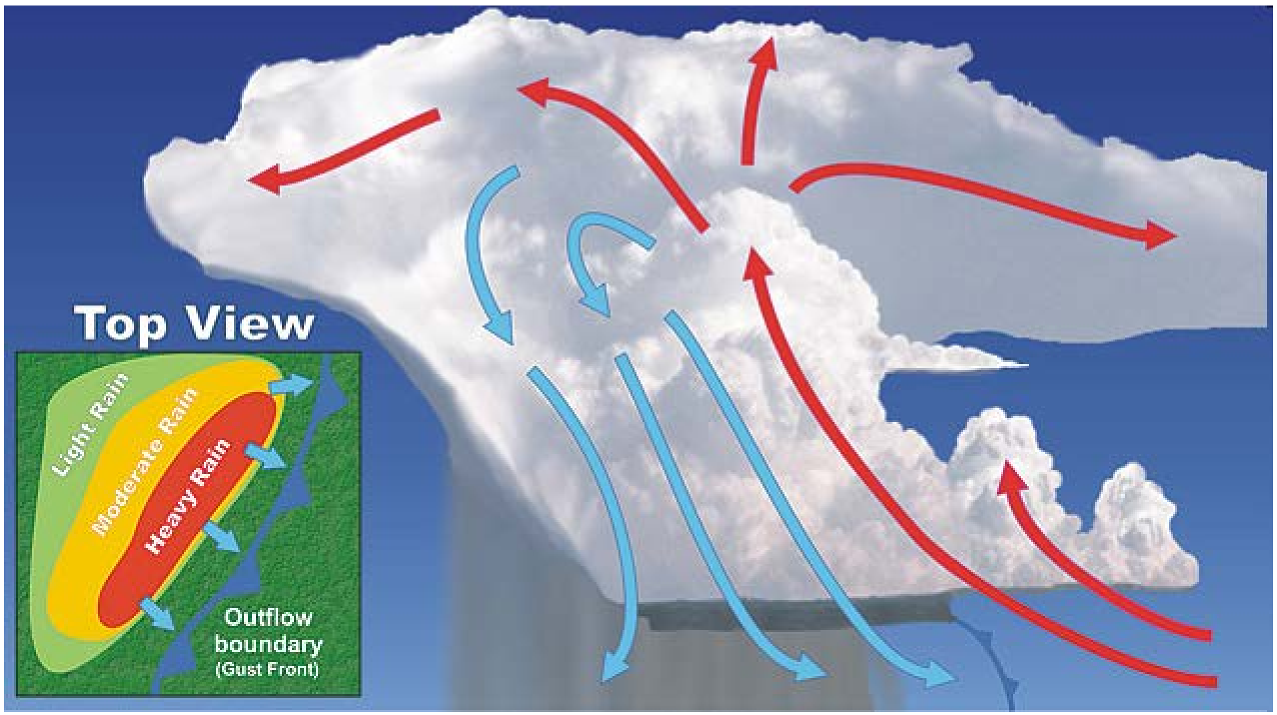
Figure 7.4. Descriptive model of a multicell thunderstorm in northeastern Colorado, showing a vertical section along the direction of travel of the storm. Thick lines: smoothed streamlines of flow relative to moving storm; lightly stippled shading: extent of cloud; darker grades of shading: radar reflectivities of 35, 45, and 50 dBZ; open circles: trajectory of a hailstone during its growth from a small particle. Right: temperature scale: temperature of a parcel lifted from the surface. Left: velocities: environmental winds relative to the storm based on soundings behind the storm. The model can be regarded as an instantaneous view of a typical structure with four different cells ($n + 1$, n, $n - 1$, and $n - 2$) at different stages of evolution, or it can be regarded as showing four stages in the evolution of an individual cell (Browning et al., 1976).

THE MULTICELL LINE STORM (SQUALL LINE)

- The multicell line storm, or squall line, consists of a long line of storms with a continuous well-developed gust front at the leading edge of the line.
  - The line of storms can be solid, or there can be gaps and breaks in the line.
- Squall lines can produce hail up to golf-ball size, heavy rainfall, and weak tornadoes, but they are best known as the producers of strong downdrafts.
- Occasionally, a strong downburst will accelerate a portion of the squall line ahead of the rest of the line. This produces what is called a bow echo. Bow echoes can develop with isolated cells as well as squall lines. Bow echoes are easily detected on radar but are difficult to observe visually.

NSSL/NOAA

Multicell line



NOAA

Bow echo

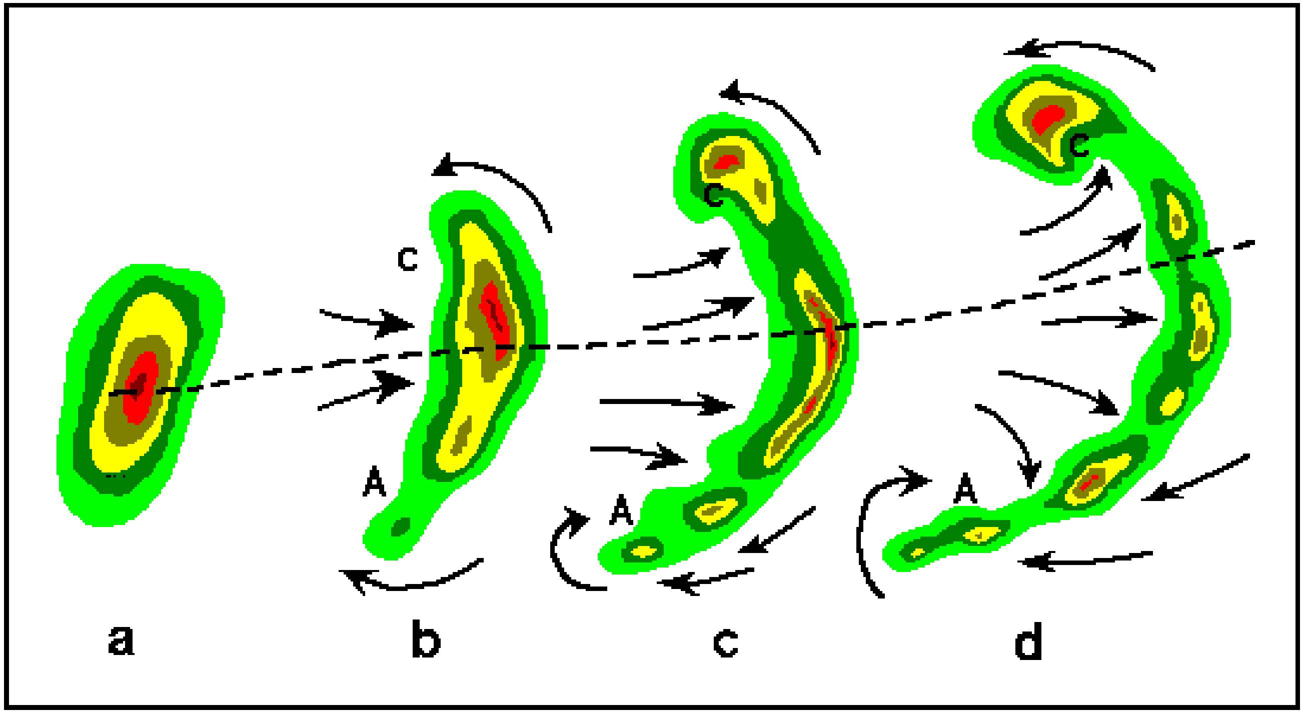
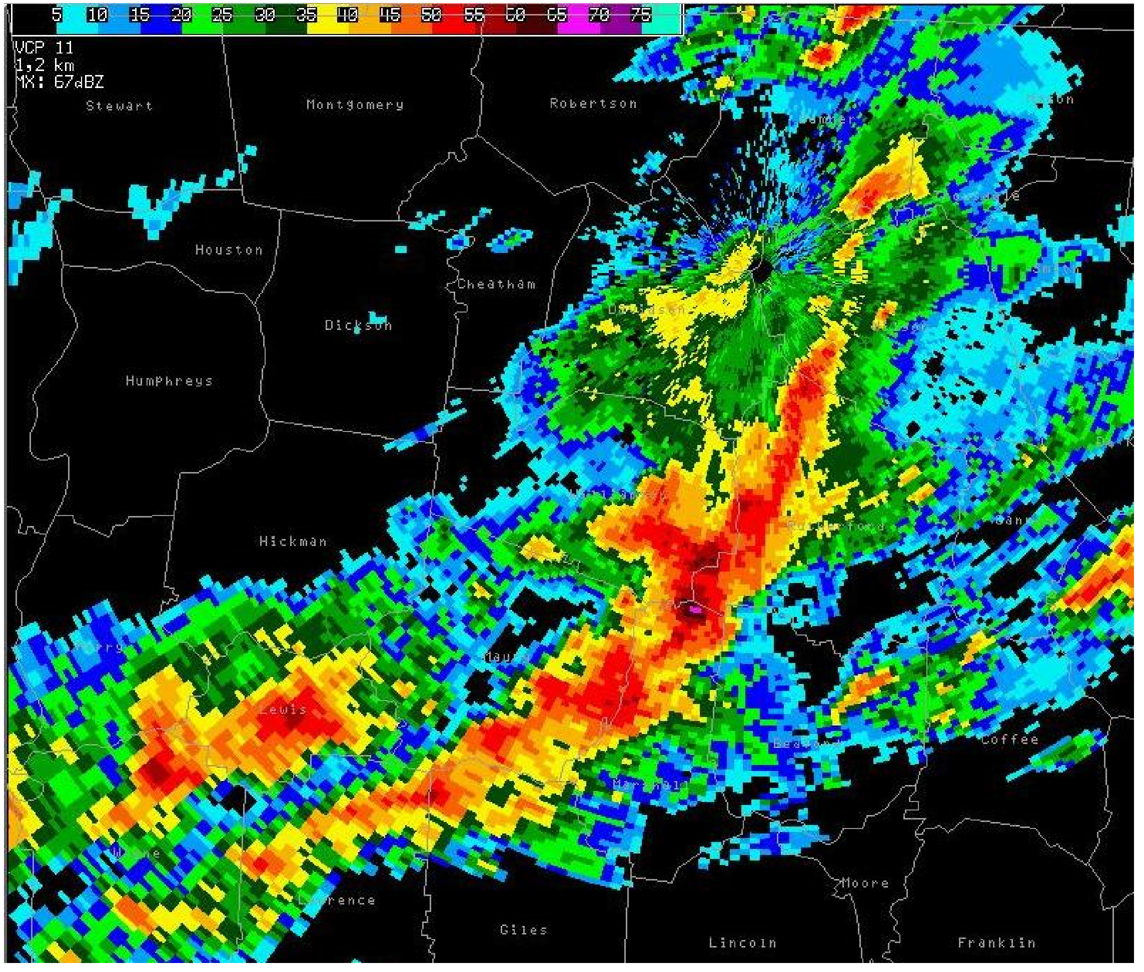


Fig. 1. Bow Echo. Typical evolution of a thunderstorm radar echo (a) into a bow echo (b,c) and into a comma echo (d). Dashed line indicates axis of greatest potential for downbursts. Arrows indicate wind flow relative to the storm. Note regions of cyclonic rotation (C) and anticyclonic rotation (A); both regions, especially C, are capable of supporting tornado development in some cases.

NWS/NOAA

Bow Echo

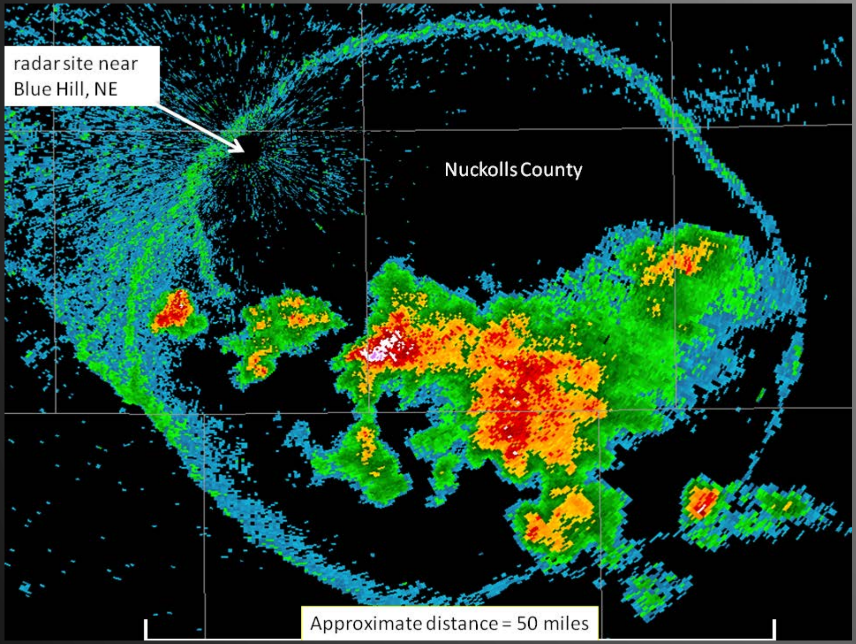


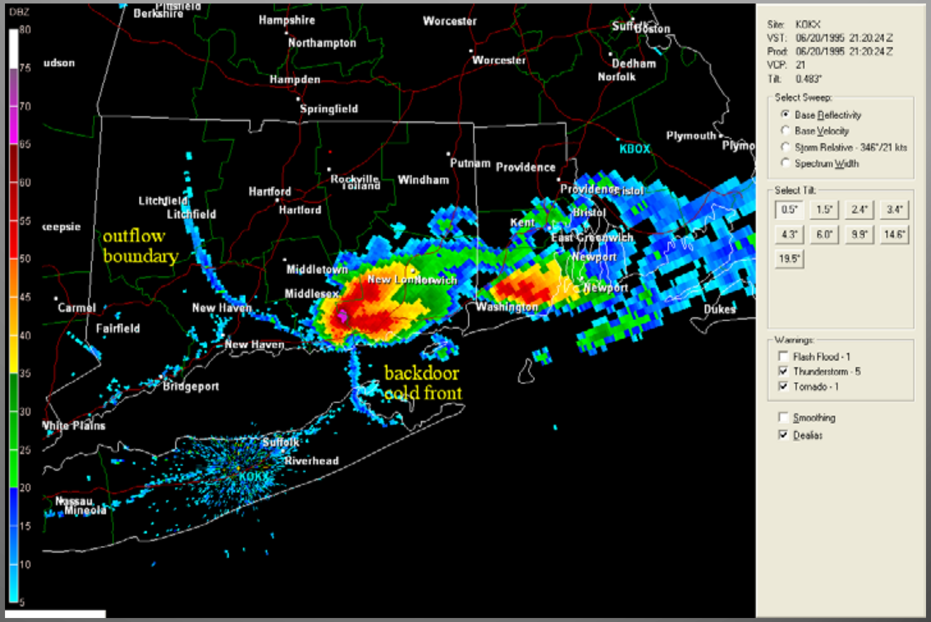
NWS/NOAA

Derechos

- Long-lived strong squall lines are called "derechos" (Spanish for 'straight'). Derechos can travel many hundreds of miles and can produce considerable widespread damage from wind and hail.
- While tornados occasionally form on the leading edge of squall lines they primarily produce "straight-line" wind damage.

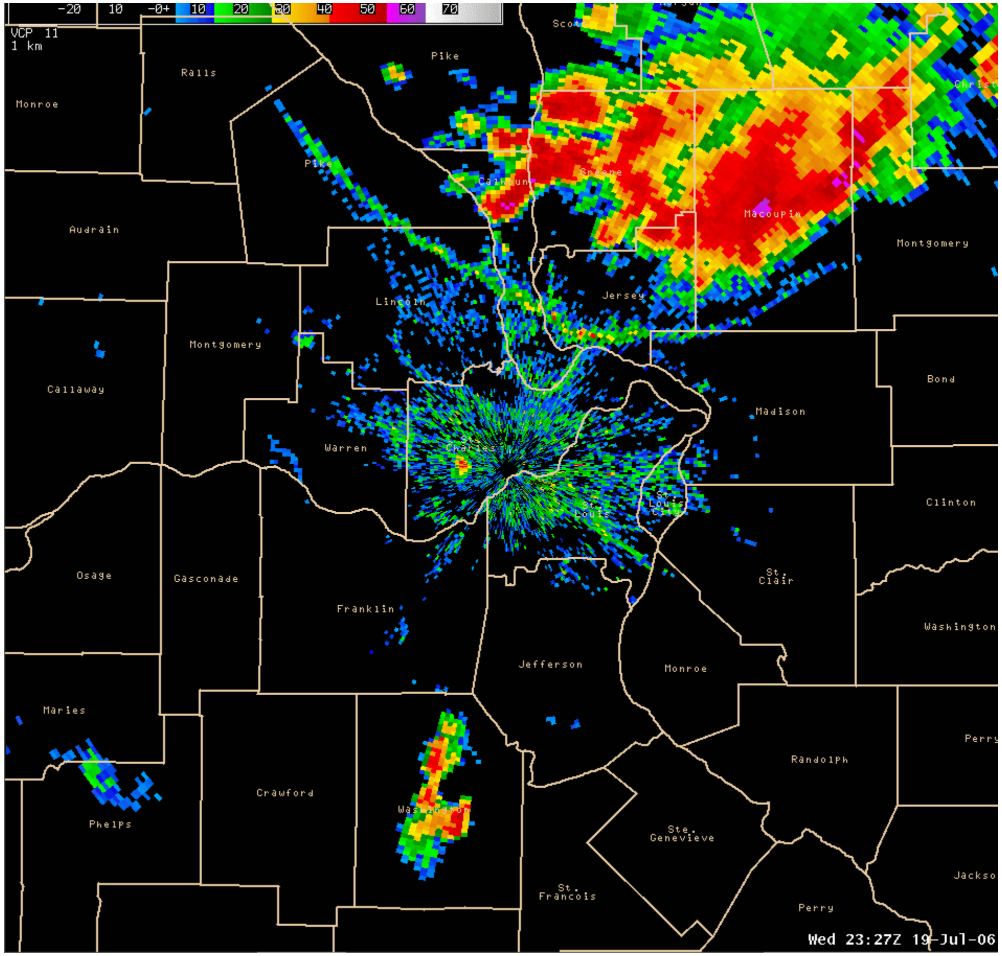
NSSL/NOAA


radar site near Blue Hill, NE
Nuckolls County
Approximate distance = 50 miles


outflow boundary
backdoor cold front
Site: KOKX
VST: 06/20/1995 21:20:24 Z
Prod: 06/20/1995 21:20:24 Z
VCP: 21
Tilt: 0.483°
Select Sweep
Base Reflectivity
Base Velocity
Storm Relative - 346°/21 kts
Spectrum Width
Select Tilt
Warnings
Flash Flood - 1
Thunderstorm - 5
Tornado - 1
Smoothing
Dealias

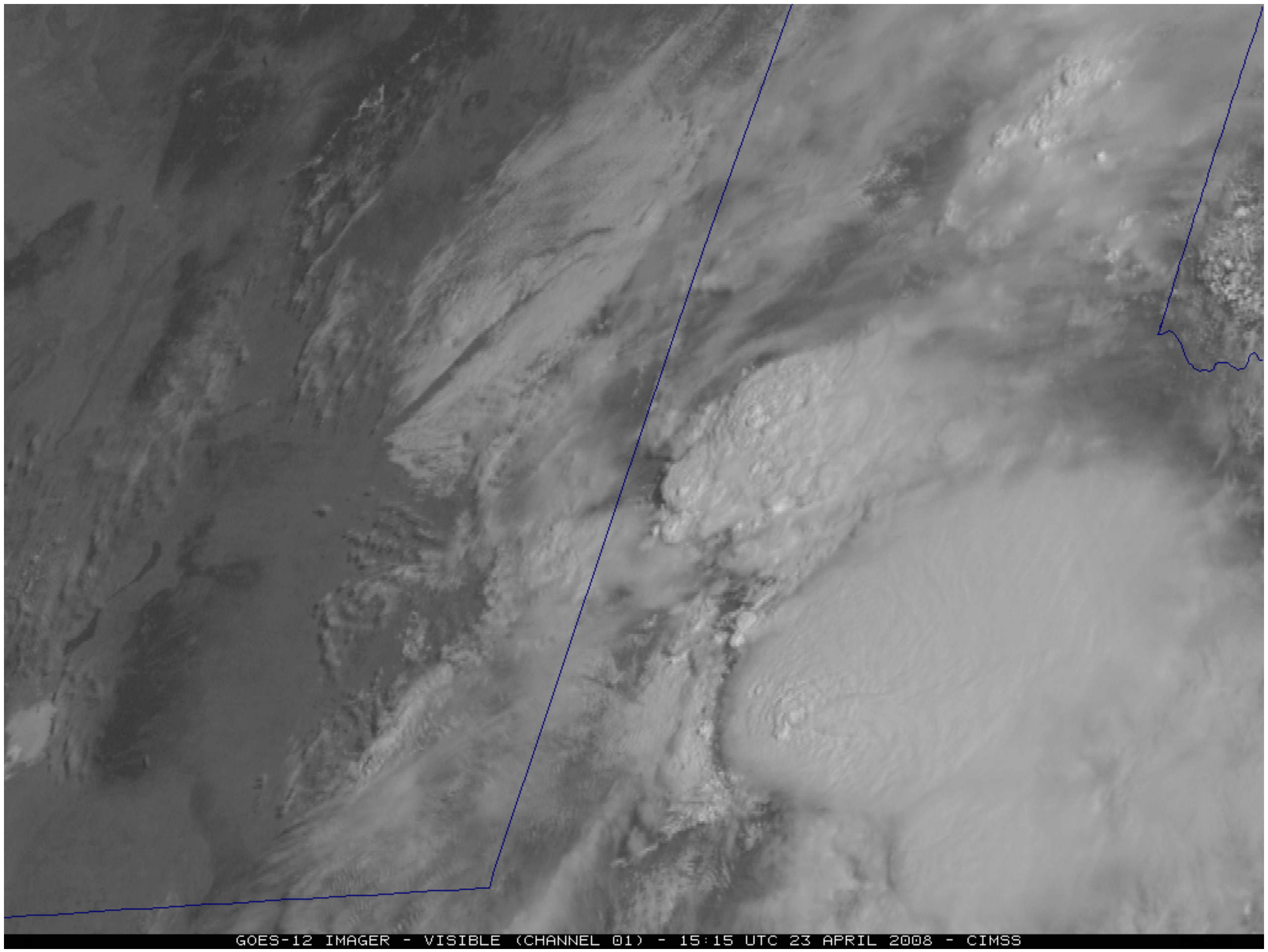
NWS / NOAA

Storm outflow boundary echo



NWS/NOAA

Outflow boundary in satellite storm images



CIMSS/UW-Madison

Outflow boundary from sea breeze induced convections

THE SUPERCELL STORM -1

- The supercell is a highly organized thunderstorm. Supercells are rare, but pose a high threat to life and property.
  - A supercell is similar to the single-cell storm because they both have one main updraft. The difference in the updraft of a supercell is that the updraft is extremely strong, reaching estimated speeds of 150-175 miles per hour.
  - The main characteristic which sets the supercell apart from the other thunderstorm types is the presence of rotation. The rotating updraft of a supercell (called a mesocyclone when visible on radar) helps the supercell to produce extreme severe weather events, such as giant hail (more than 2 inches in diameter, strong downbursts of 80 miles an hour or more, and strong to violent tornadoes.

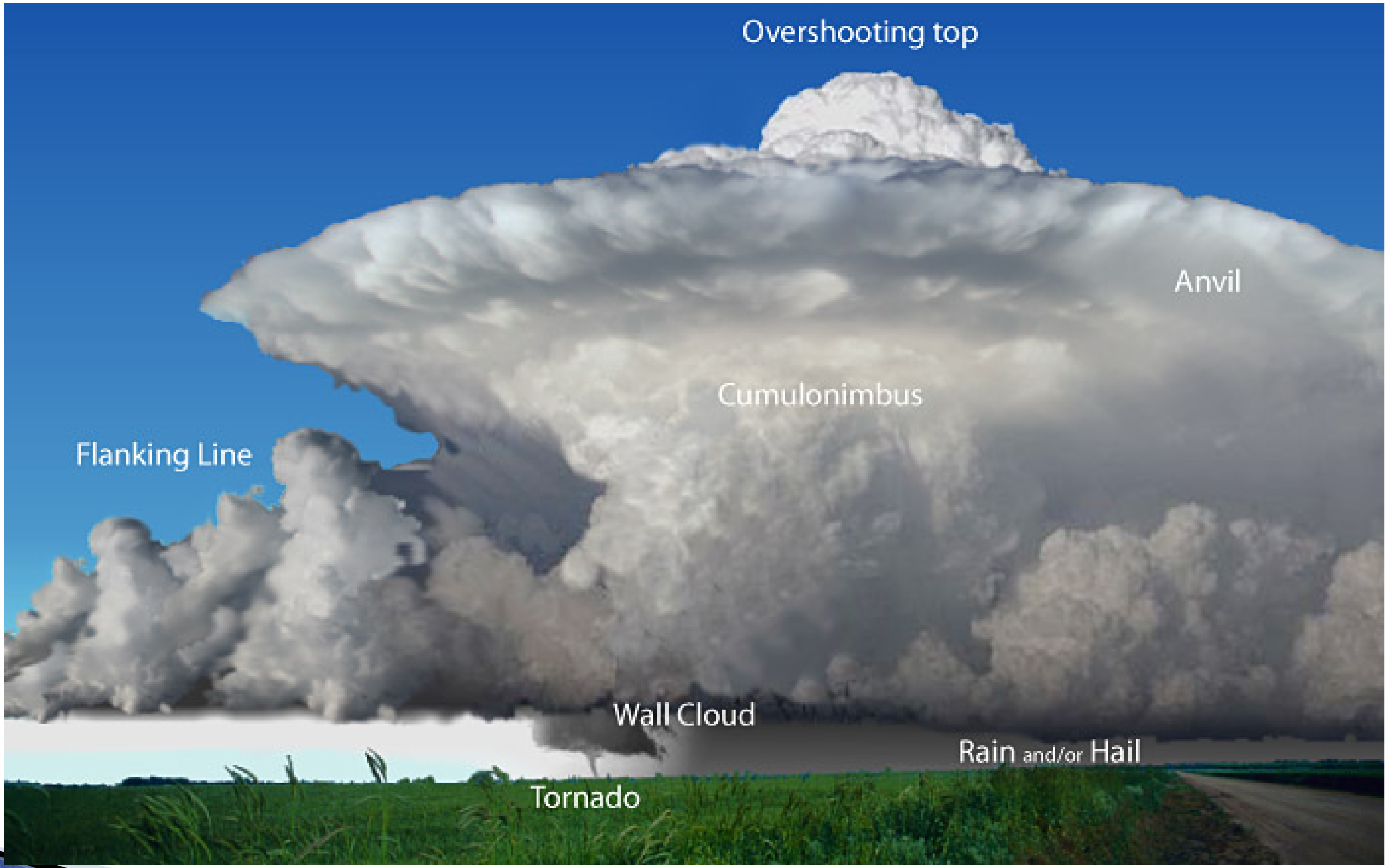
NSSL/NOAA

THE SUPERCELL STORM -2

- The surrounding environment is a big factor in the organization of a supercell.
  - Winds are coming from different directions to cause the rotation.
  - As precipitation is produced in the updraft, the strong upper-level winds blow the precipitation downwind. Hardly any precipitation falls back down through the updraft, so the storm can survive for long periods of time.
- The leading edge of the precipitation from a supercell is usually light rain.
- Heavier rain falls closer to the updraft with torrential rain and/or large hail immediately north and east of the main updraft.
- The area near the main updraft (typically towards the rear of the storm) is the preferred area for severe weather formation.

NSSL/NOAA

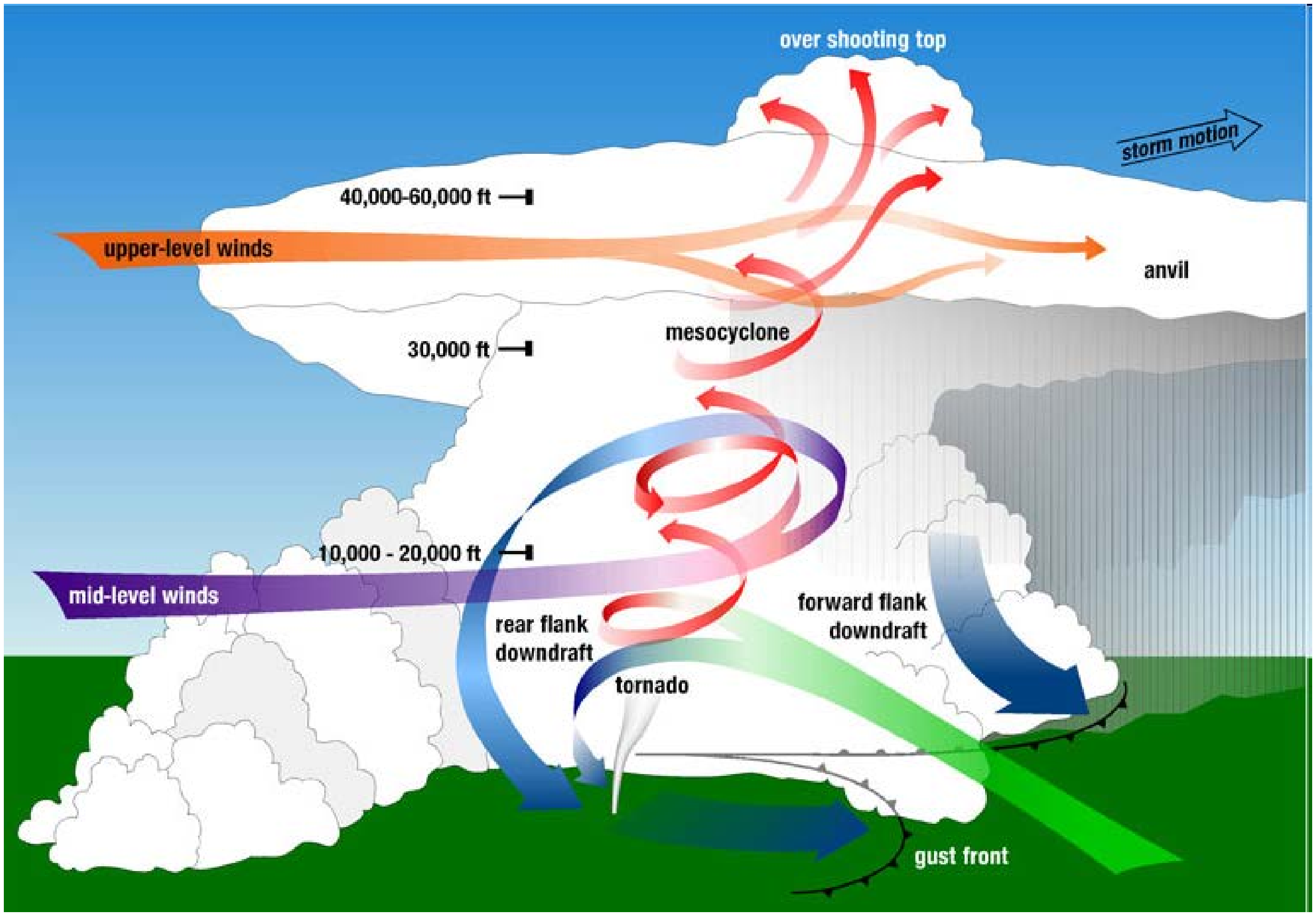
Supercell



NOAA

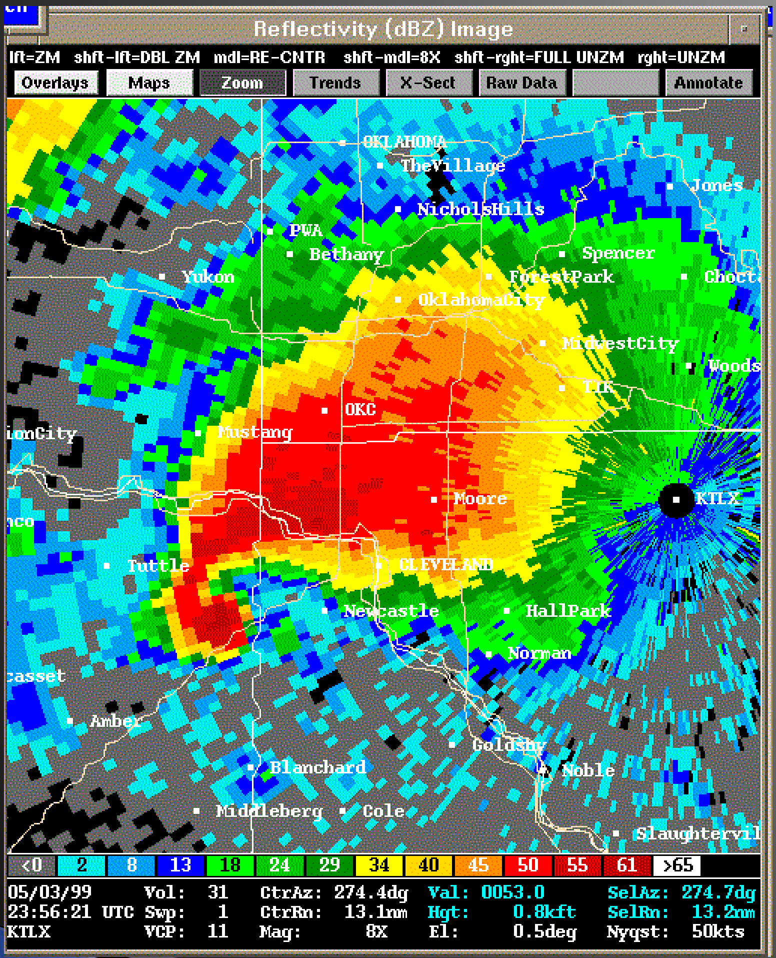
Structure of a supercell storm

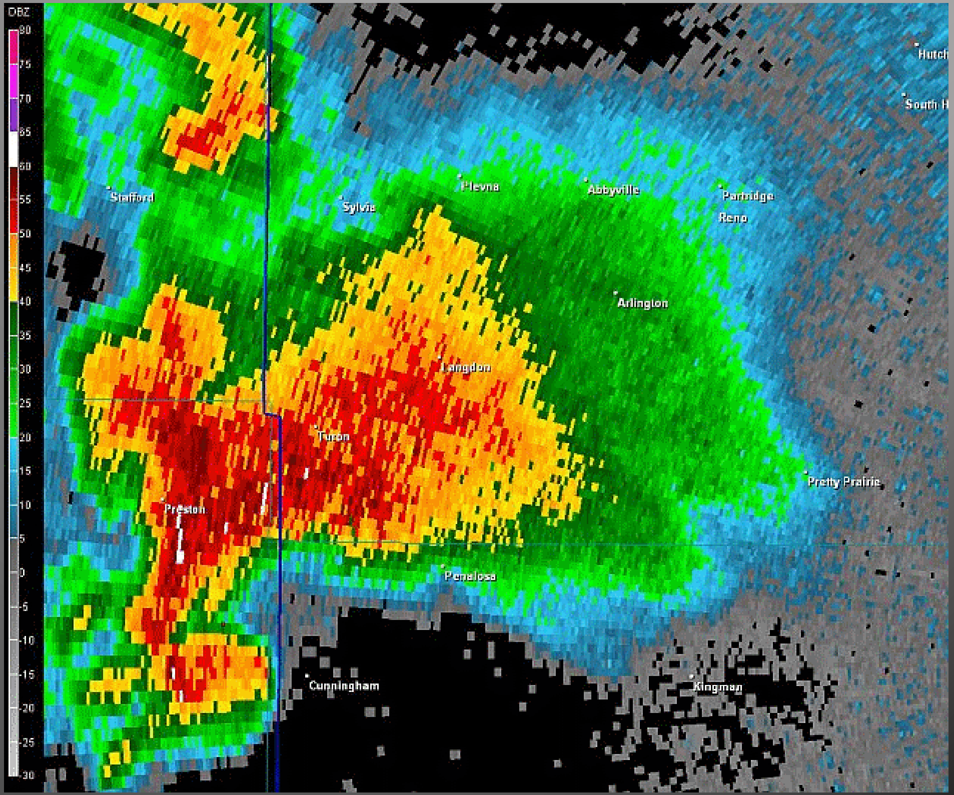
The presence of a mesocyclone



NOAA

Hook echo and BWER (bounded weak echo region) seen in low level radar PPI



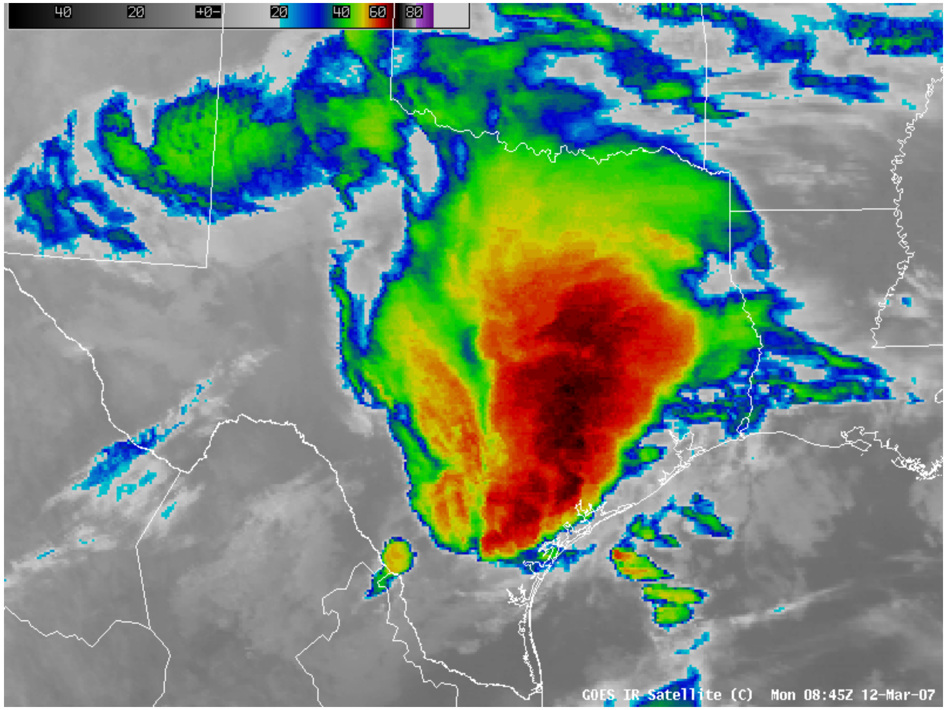


NSSL/NOAA

Mesoscale Convective System (MCS)

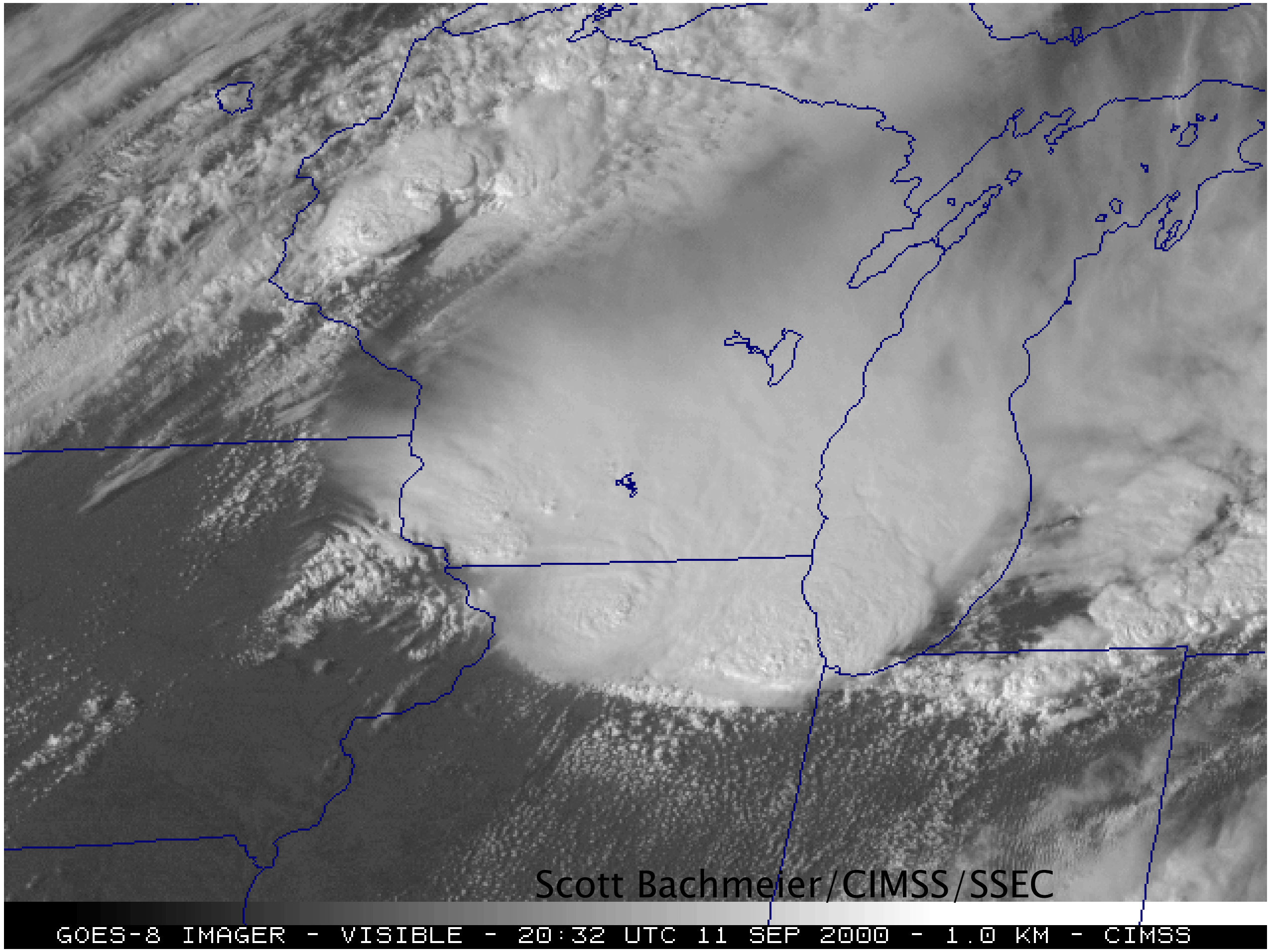
- **mesoscale convective system**—(Abbreviated MCS.) A cloud system that occurs in connection with an ensemble of thunderstorms and produces a contiguous precipitation area on the order of 100 km or more in horizontal scale in at least one direction. An MCS exhibits deep, moist convective overturning contiguous with or embedded within a mesoscale vertical circulation that is at least partially driven by the convective overturning.

(AMS Glossary)

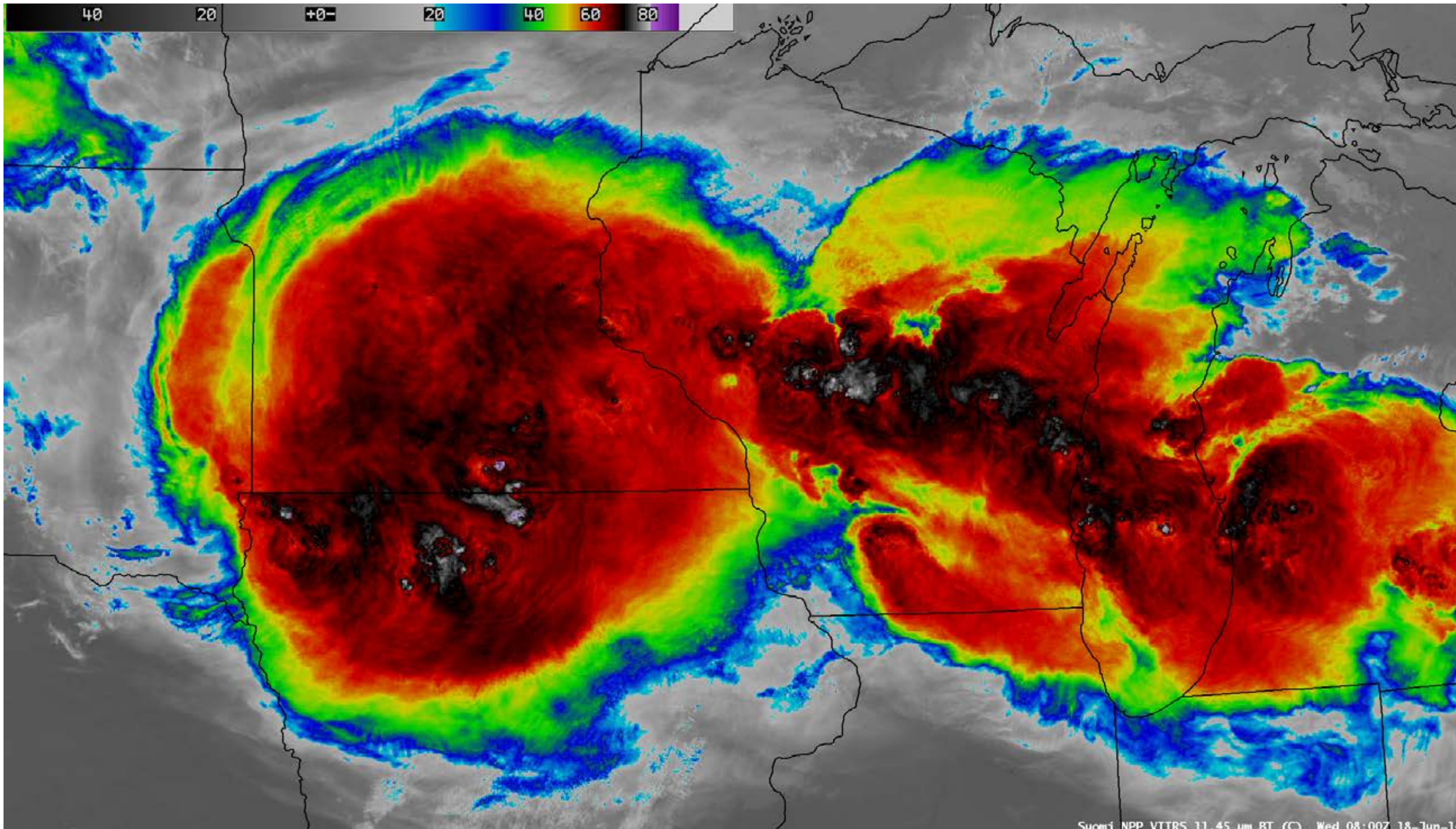


Scott Bachmeier/CIMSS/SSEC

Example of MCS



Mesoscale convective system



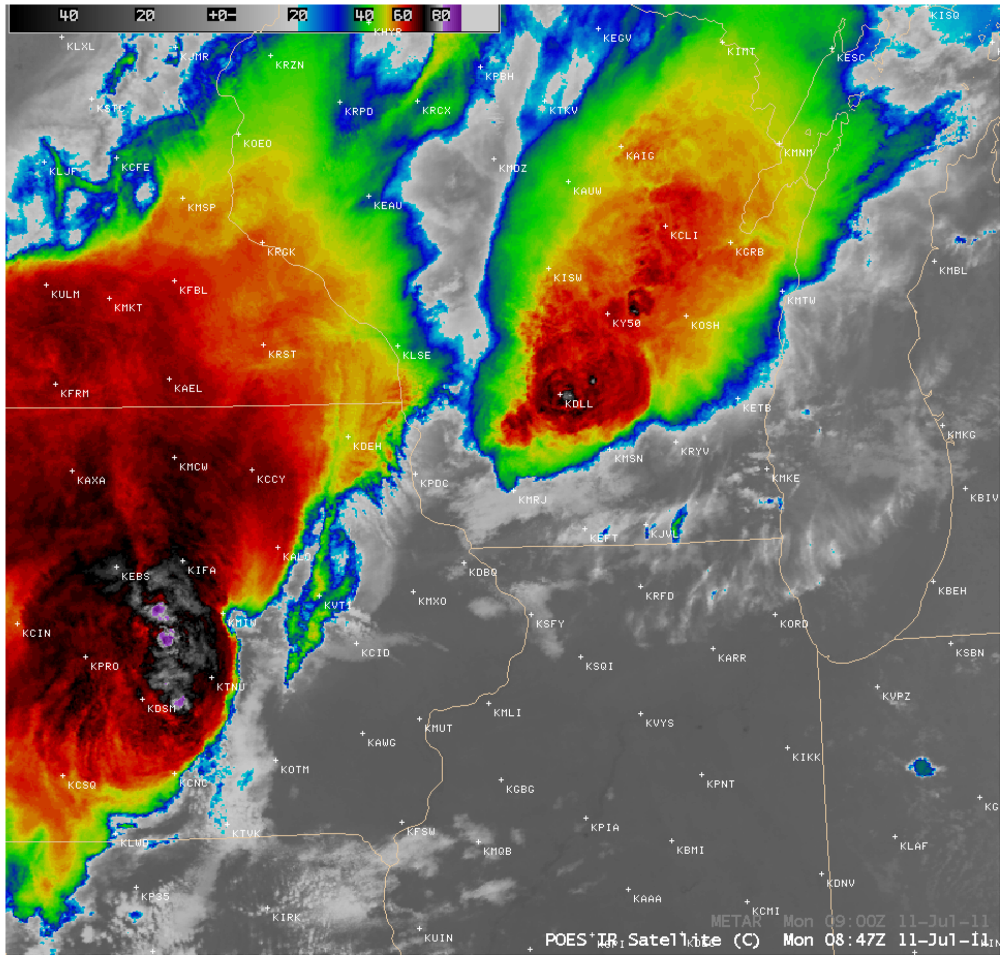
Scott Bachmeier/CIMSS/SSEC

Mesoscale Convective Complex (MCC)

- A subset of mesoscale convective systems (MCS) that exhibit a large, circular (as observed by satellite), long-lived, cold cloud shield. The cold cloud shield must exhibit the following physical characteristics.
  - Size: A – Cloud shield with continuously low infrared (IR) temperature ≤ −32°C must have an area ≥ 105 km^2; and B – Interior cold cloud region with temperature ≤ −52°C must have an area ≥ 0.5 X 105 km2.
  - Initiate: Size definitions A and B are first satisfied
  - Duration: Size definitions A and B must be met for a period ≥ 6 h.
  - Maximum extent: Contiguous cold cloud shield (IR temperature ≤ −33°C) reaches maximum size.
  - Shape: Eccentricity (minor axis/major axis) ≥ 0.7 at time of maximum extent.
  - Terminate: Size definitions A and B no longer satisfied. Alternatively, a dynamical definition of an MCC requires that the system have a Ross **mesoscale convective complex**—(Abbreviated MCC.) by number of order 1 and exhibit a horizontal scale comparable to the Rossby radius of deformation. In midlatitude MCS environments, the Rossby radius of deformation is about 300 km.

(AMS Glossary)

MCC



Scott Bachmeier/CIMSS/SSEC