Heavy Convective Rainfall Forecasting:

A Comprehensive Look at Parameters, Processes, Patterns, and Rules of Thumb

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The heaviest convective rainfall usually occurs in regions of high moisture, maximum ambient or elevated instability, best mesoscale lift, and slow system movement.

Brilliant, eh!!??

Well, obviously it's not that easy. A detailed assessment of many parameters and processes is necessary, as discussed within.

Discussion Topics

- Forecast skills needed; pattern recognition; scale analysis
- Parameters useful in assessing heavy rain potential
- Processes associated with heavy rain production
  - Low-level jet
  - Upper-level jet dynamics
  - Frontogenesis
  - Boundaries
- Elevated convection
- Thunderstorm movement and propagation
- Characteristics of backward, forward, and regenerative convection
- Precipitation efficiency
- Mesoscale convective vortices
- Flash flood event: Aug 22, 2003
- Synoptic/mesoscale patterns and climatology associated with heavy convective rainfall across the central U.S.
  - Maddox patterns
  - Patterns during Midwest floods of 1993
  - Climatology of elevated convection over central U.S.
  - Patterns across Ohio Valley and northern Plains
- Models and QPF
- Rules of thumb/summary

Basic Forecast Skills Needed

- Must possess good pattern recognition skills
- Must possess knowledge of local heavy precipitation climatology
- Must determine where, when, and how much rainfall will occur
- Must understand atmospheric processes and interactions, which determine the size, scale, and intensity of an area of precipitation
- Must understand and assess numerical models, especially model biases and why they occur
- Must possess good mesoscale/storm-scale analysis skills, both before and during an event, and effect on precipitation distribution and amounts
- Must understand system movement/propagation, which affects rainfall amounts in any one location
- These skills are gained through experience and research

Pattern Recognition

- Pattern recognition is very important. A good assessment and forecast of quantitative precipitation starts with recognizing those patterns and parameters that historically have produced heavy rainfall over particular areas.
- Forecasters must not only recognize patterns conducive to heavy rainfall, but they must especially understand atmospheric processes that may lead to heavy rainfall, given the recognized pattern.
- Caution: Important processes can occur on the synoptic-scale, mesoscale, and storm-scale that can alter precipitation amounts and distributions from those expected within a recognized pattern.
- Patterns can vary by season, geographic region, and scale.
- Synoptic/mesoscale patterns associated with heavy rainfall across the central U.S. are shown later in this presentation

How Much Precipitation Will Fall?

Precipitation amount in any given location is dependent on:

- Available moisture (both relative and absolute):
  - Look for high values of RH, PW, and low-level dewpoints
- Degree and breadth of low-to-middle level moisture transport:
  - Horizontal and vertical extent of moisture field and transport; replenishment
- Rainfall rate/intensity:
  - Is precipitation convective or stratiform?
- Areal coverage of precipitation:
  - Is rain widespread (strong isentropic lift) or localized (scattered convection)?
- Motion and speed of precipitation area:
  - What is movement and speed of precipitation due to mean cloud-layer wind?
- Precipitation propagation:
  - Due to new cell development, is propagation forward, backward, or regenerative (cell training)?
- Precipitation efficiency:
  - How efficient is convection in converting ingested water vapor into rainfall that reaches the ground?

Will Flash Flooding Occur?

Flash flood potential is dependent on:

- Rainfall amount at a given location:
  - Dependent on the factors stated on previous slide
- Topography:
  - Flash flooding is more likely in hilly/mountainous terrain than in flat areas
- Urbanization:
  - Flash flooding often is more likely in urbanized versus rural areas
- Land Use:
  - Flash flooding is more likely in deforested versus forested areas
- Soil Type:
  - Water normally will run off faster given a hard clay soil versus a sandy soil
- Antecedent conditions:
  - Flash flooding is more likely from future rain if the soil is nearly saturated and/or streams are running high from recent rain; however, intense rainfall on initially very dry, hard soil can cause runoff until soil wetness increases

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Assessing Heavy Rain Potential: Scale Analysis

First, assess the synoptic scale (the big picture):

- Use observed and model data. There is a clear association between large scale forcing mechanisms (e.g., shortwave troughs, jet streaks, etc.) and convection. While these mechanisms may not initiate convective heavy rainfall, they do help to
  - Steepen lapse rates
  - Promote moisture transport
  - Affect vertical moisture, temperature, and wind shear profiles
  - Weaken the convective inhibition (the cap)

Next, assess the mesoscale (the smaller picture):

- Perform mesoanalyses of surface, upper air, LAPS/MSAS, sounding, satellite, and radar (reflectivity and precipitation estimate) data.

- Identify surface boundaries, fronts aloft, convergence/frontogenetical zones, enhanced inflow channels, etc. and their relationship to changing fields of moisture, instability, and lift.

Finally, assess the storm-scale (the smallest picture):

- If convection is ongoing, analyze temporal changes in storm structure, including the existence and effect of outflow boundaries, colliding boundaries, cell mergers, the convective cold pool, and preferred locations for new cell development (i.e., propagation characteristics).

Integrated scale analysis will help the forecaster assess what will cause or is causing convective precipitation, and enhance the ability to produce short-term forecasts of future precipitation amounts, locations, and movements.

Parameters Useful in Assessing Heavy Rain Potential

Moisture:

High values of ambient or upstream surface to 850 mb dewpoints (above seasonal normal)

Surface to 500 mb relative humidity:

- High RH better for precipitation efficiency due to less dry air entrainment & evaporation

Precipitable water and percent of normal:

- Warm season ambient or upstream values about 1.5 inches or more; lower values possible in cool season (but still near relative max); values well over 100 % of normal

Instability:

CAPE:

- Surface-based storms: CAPE values can vary significantly and still result in heavy rain
- Elevated storms: May be little or no low-level CAPE, but elevated CAPE present
- Shape of CAPE: long, narrow positive area conducive to better precipitation efficiency; “fat” positive area promotes intense updraft, severe weather, but less efficiency

Lifted index:

- Warm sector convection: ambient LI < 0
- Elevated convection: ambient LI may be > 0 (stable boundary layer below frontal inversion) but unstable values exist upstream along the low-level jet axis

K index:

- Ambient or upstream values above 30 in the warm season; lower values possible in cool season (but still near relative max or within a ridge axis)

Parameters Useful in Assessing Heavy Rain Potential

Low-level features:

Low-level jet:

- Normally along or west of jet axis, or within jet exit region

Equivalent potential temperature (theta-e) and theta-e advection:

- Warm sector convection: along or just to north or west side (gradient) of 850 mb ridge axis, but often just downstream from max values
- Elevated convection: in downstream gradient zone of 850 mb theta-e (perhaps near 700 mb theta-e max)
- Theta-e advection: positive advection zones, especially useful for elevated convection in warm advection/isentropic lift regimes

Moisture transport vectors and moisture convergence:

- Often just downstream from maximum moisture transport vectors and near maximum area of moisture convergence

Strong warm advection/isentropic lift:

- Promotes broad forcing conducive to elevated MCSs; less important for surface-based storms

Warm cloud depth (temperature of cloud > 0 C):

- Greater depth promotes higher moisture content of air and enhances collision-coalescence process to increase precipitation efficiency

Parameters Useful in Assessing Heavy Rain Potential

Mid-level features:

500 mb flow:

- Broad south to west flow in mid-levels, perhaps near a broad ridge axis, with only weak shortwaves present promotes higher potential for regenerative MCS; strong mid-level systems favor faster movement and shorter duration rainfall

Upper-level features:

300/200 mb jet streak/divergence:

- Jet streak exit and entrance regions, especially those which exhibit substantial along-stream wind variation; anticyclonically-curved entrance; cyclonically-curved exit regions
- Area of upper-level divergence (convection can occur within or south and/or east of maximum divergence area)

Thickness gradient considerations:

Tight gradient:

- Baroclinic regime favors forward propagation along/right of 850-300 mb thickness grad

Moderate gradient:

- Tendency for forward cell movement, but with possible cell regeneration upstream assuming favorable low-level inflow; often present for elevated convection

Weak gradient:

- Weak winds and weak thermal gradient typical of warm sector, warm season convection; storms may develop or propagate backwards within a thickness diffluent area

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Important Processes Related to Heavy Rain Production

Upper-Level Jet

Boundaries

Frontogenesis

Low-Level Jet

The Low-Level Jet:
Formation Mechanisms

The low-level jet (LLJ) can form in 3 primary ways:

- Beneath exit region of upper-level jet streak (ULJ), where LLJ slopes toward divergence maximum on north (left) side of ULJ; isallobarically forced (responds to height/pressure falls); LLJ increases as exit region of ULJ approaches
  - Cool season heavy stable precipitation
  - Northwest flow convective events
  - Tendency for forward MCS propagation and shorter duration of heavy rainfall
- Beneath entrance region of ULJ, where LLJ slopes towards divergence maximum on south (right) side of ULJ; isallobarically forced; LLJ increases as entrance region isotach gradient (along stream variation) increases
  - Very important to heavy rainfall (and snowfall) production
  - Forcing is more closely located to warm, moist inflow and maximum instability
  - Better chance for slow-moving, backward propagating, and/or regenerative convection
- Forms as an “inversion wind maximum” in late spring and summer in Plains at night at top of nocturnal inversion during apparent benign synoptic conditions
  - Important component of nocturnal elevated MCS and heavy rainfall production in Plains states

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The Low-Level Jet:
A Key Component of a Heavy Rainfall Event

- The LLJ is crucial to the initiation and sustenance of MCSs and heavy rain

- Heavy rainfall often occurs near the nose (exit region) and/or left (west) side of the LLJ axis where speed convergence, confluent flow, frontogenesis, and lift are maximized

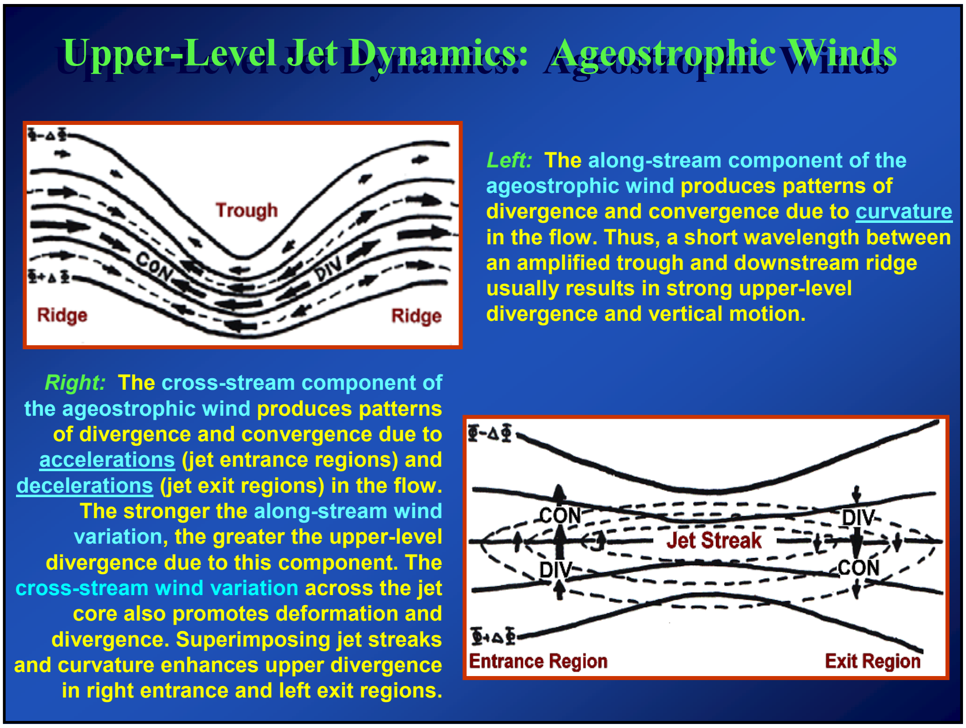
- Horizontal and vertical flux (transport) of moisture is related to the strength of LLJ

- Differential advection of moisture, temperature, and high theta-e air can lead to air mass destabilization

- A strong LLJ in a baroclinic regime can lead to significant isentropic lift and production of elevated convection and heavy rainfall north of a surface boundary

- A quasi-stationary LLJ supports the regeneration of convective cells and/or cell training, which accentuates heavy rainfall amounts

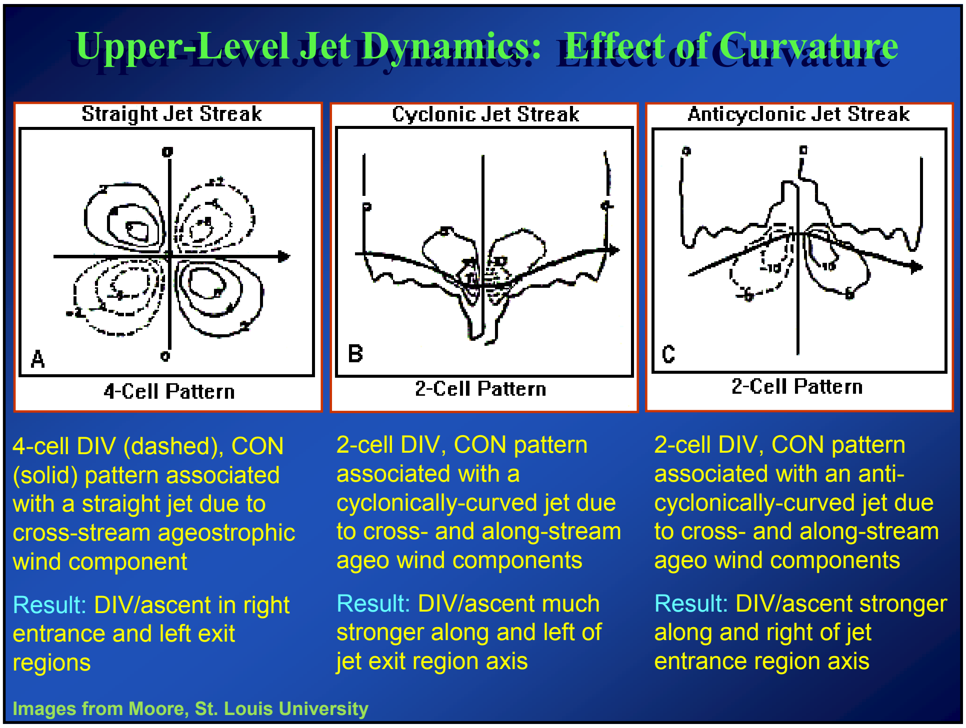
- LLJ usually is positioned on southwest or west flank of a backward propagating MCS and along or ahead of a forward propagating system



Upper-Level Jet Dynamics: Ageostrophic Winds

Left: The along-stream component of the ageostrophic wind produces patterns of divergence and convergence due to curvature in the flow. Thus, a short wavelength between an amplified trough and downstream ridge usually results in strong upper-level divergence and vertical motion.

Right: The cross-stream component of the ageostrophic wind produces patterns of divergence and convergence due to accelerations (jet entrance regions) and decelerations (jet exit regions) in the flow. The stronger the along-stream wind variation, the greater the upper-level divergence due to this component. The cross-stream wind variation across the jet core also promotes deformation and divergence. Superimposing jet streaks and curvature enhances upper divergence in right entrance and left exit regions.



Upper-Level Jet Dynamics: Effect of Curvature

4-cell DIV (dashed), CON (solid) pattern associated with a straight jet due to cross-stream ageostrophic wind component

Result: DIV/ascent in right entrance and left exit regions

2-cell DIV, CON pattern associated with a cyclonically-curved jet due to cross- and along-stream ageo wind components

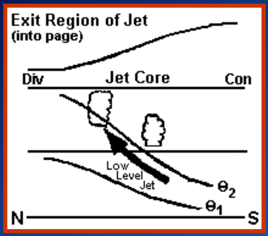
Result: DIV/ascent much stronger along and left of jet exit region axis

2-cell DIV, CON pattern associated with an anti-cyclonically-curved jet due to cross- and along-stream ageo wind components

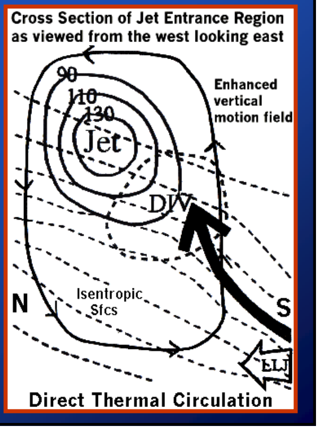
Result: DIV/ascent stronger along and right of jet entrance region axis

Images from Moore, St. Louis University

Upper-Level Jet Dynamics: Sloped Response of LLJ

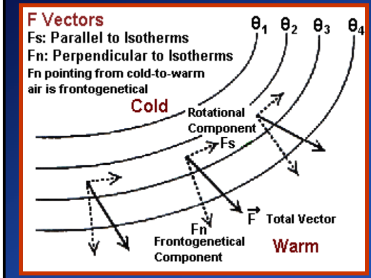


Left: The LLJ often exhibits a sloped response roughly along isentropic surfaces to upper-level divergence in jet exit and entrance regions. Thus, convection can develop south or east of the maximum upper divergence that occurs in the left exit and right entrance regions, depending on the moisture and instability profile of the rising low-level air.



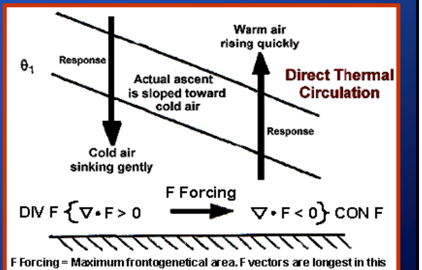
Right: Jet streak entrance region cross-section (looking west to east) reveals its secondary ageostrophic direct thermal circulation (outer circle/box with arrows). Isentropes slope upward from south to north toward jet streak. An enhanced LLJ rises quasi-isentropically toward divergence region in right entrance region. Lower branch of ageostrophic circulation "flows" from colder to warmer air counteracting the ambient southerly low-level flow. This creates convergence and frontogenesis in the low-to-middle levels beneath the entrance region. The resultant smaller-scale frontogenetical circulation complements the jet streak dynamics. This can lead to banded heavy precipitation, including snow in winter and a heavy rainfall producing MCS in the warm season.

Frontogenesis



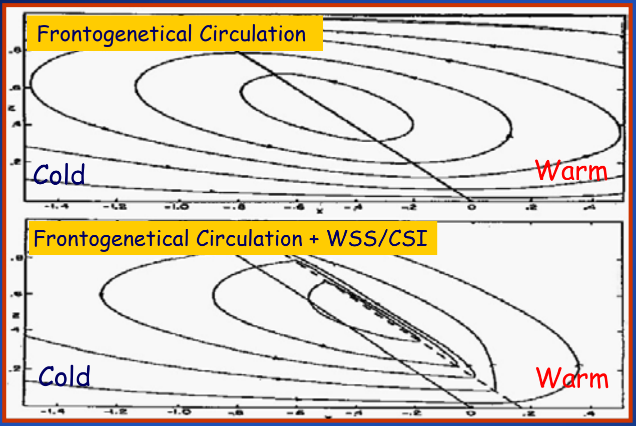
Frontogenesis refers to a strengthening thermal gradient, and can be evaluated using F vectors. F_n and F_s = components directed perpendicular and parallel to isotherms, respectively. F vectors describe changes in the magnitude and orientation of a thermal gradient. F pointing from cold to warm air implies frontogenesis. F_s describes temperature advection patterns, and forces ascent on the synoptic scale. Usually the dominant term and available on AWIPS, F_n describes how the magnitude of a thermal gradient is changing, i.e., either strengthening (frontogenesis) via confluence and deformation, or weakening (frontolysis) via difluence. F_n vectors are longest where the thermal gradient is changing the most. Convergence of F_n represents forcing for mesoscale ascent possibly leading to banded heavy precipitation or convection given sufficient moisture.

Frontogenesis produces a mesoscale direct thermal circulation that is sloped with height toward cold air. F vector convergence (forcing for lift) occurs on southern/eastern periphery of the maximum frontogenesis area. A steeply sloped frontogenetical zone in low-to-mid levels can produce a definitive mesoscale band of heavy precipitation superimposed on broader, lighter precipitation. Low-level frontogenesis also can force the lift needed to initiate deep convection and subsequent heavy rainfall.



F Forcing = Maximum frontogenetical area. F vectors are longest in this area. DIV/CON F is occurs on the flanks of the maximum frontogenesis, and is forcing for ascent.

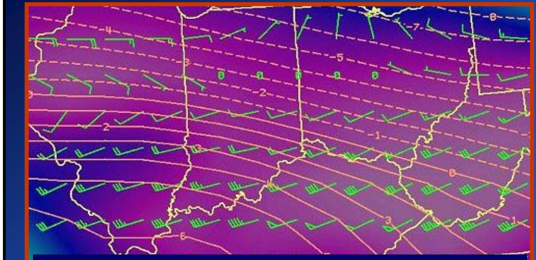
Frontogenesis



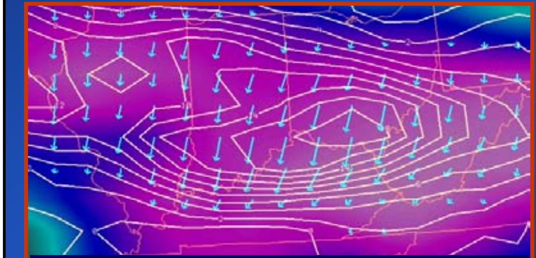
The importance of assessing static stability:

Top: **Broad frontogenetical circulation associated with a stable environment.**
Bottom: **In the presence of a less stable atmosphere, i.e., weak symmetric stability (WSS), conditional symmetric instability (CSI), or elevated convective instability (CI), the updrafts of the frontogenetical circulation become stronger and more concentrated than in a stable environment. Thus, one MUST assess stability when considering forcing, subsequent lift, and heavy precipitation potential.**

Frontogenesis



850-700 mb winds (kts) and temps, and 1000-500 mb RH image (purple=highest RH)



850-700 mb 2-D frontogenesis (contours), F_n vectors (blue arrows), and 1000-500 mb RH image

Example Case: February 15, 2003

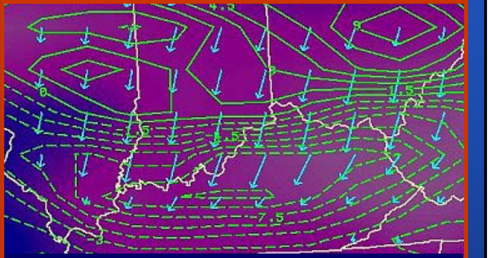
A rough assessment of horizontal frontogenesis can be made by viewing winds and isotherms in a layer or level. At left, 850-700 mb layer frontogenesis is implied over central/southern IN and OH, northern KY, and central IL where winds indicate convergence superimposed on and directed nearly perpendicular to an existing tight thermal gradient.

A better assessment can be made by viewing 2-D frontogenesis and F_n vectors in AWIPS (left). In this case, the implied frontogenesis above is quantified with a frontogenetical situation shown over the Ohio Valley (maximum over southern OH, southern IN, and northern KY). F_n vectors are longest where the frontogenesis is greatest.

Frontogenesis

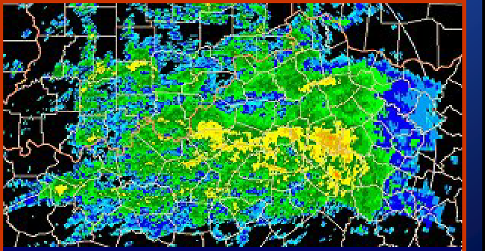
Example Case: February 15, 2003

Fn vector convergence represents forcing for ascent. At right, a concentrated axis of F_n vector convergence in the 850-700 mb layer indicated forcing for strong ascent over central KY. This axis was on the southern edge of the maximum frontogenetical area shown on the previous slide.



850-700 mb F_n vectors & F_n vector divergence (green; dashed=convergence), and RH image

Given air mass saturation (purple RH area above), banded heavy rainfall resulted (right), which matched up very well with the frontogenetical forcing shown above.

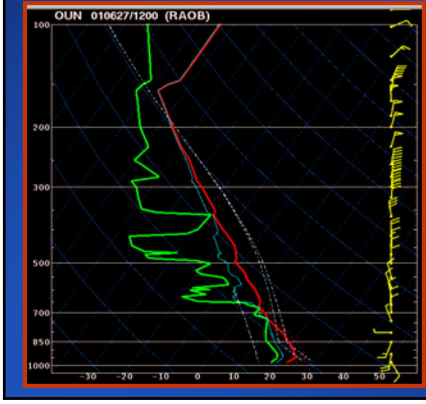


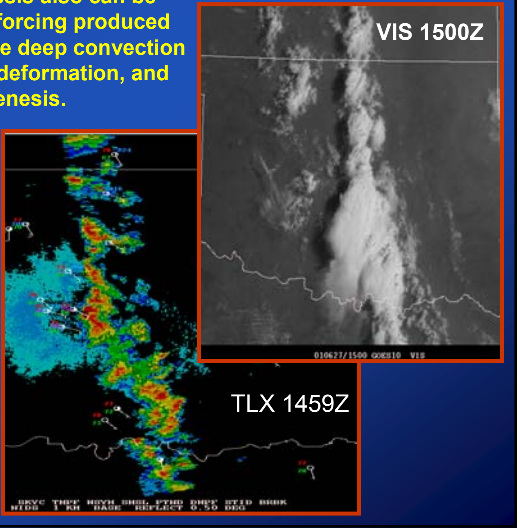
KLVX radar 0.5 deg reflectivity image over central KY at 06 utc Feb 15

Warm Season Frontogenesis

Example Case: June 27, 2001

While most important during the cool season when baroclinicity is greatest, low-level and surface frontogenesis also can be important in the convective season. The forcing produced by frontogenesis may be enough to initiate deep convection given adequate instability. Convergence, deformation, and diabatic heating contribute to the frontogenesis.

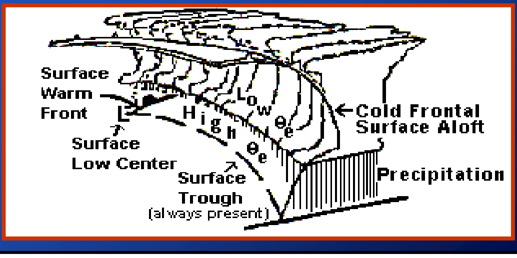




Importance of Boundaries

- Boundaries have a profound effect on convective initiation and maintenance.
- Boundaries can be synoptic scale (fronts/troughs), mesoscale (rain-no rain, cloudy-clear boundaries; frontogenetical zones; horizontal convective rolls), and storm-scale (outflow boundaries).
- Boundaries can be surface-based (important in warm season convection) or elevated (fronts/frontogenetical zones aloft, which are important in cool and warm season where precipitation field bares little resemblance to surface frontal positions).
- Models have difficulty in resolving mesoscale and especially storm-scale boundaries. Thus, model precipitation locations and amounts likely will be wrong.
- Diligent analysis is critical to resolve boundaries in surface, satellite, and radar data and their effect on heavy precipitation. Some boundaries and convergence zones are not resolvable in surface or even mesonet data due to spatial scales of only a few kms.

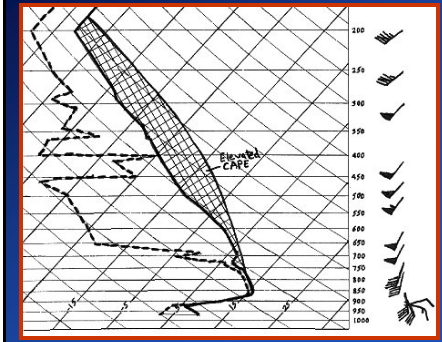
Example of a front or frontogenetical zone aloft initiating deep convection ahead of the relatively inactive surface boundary.



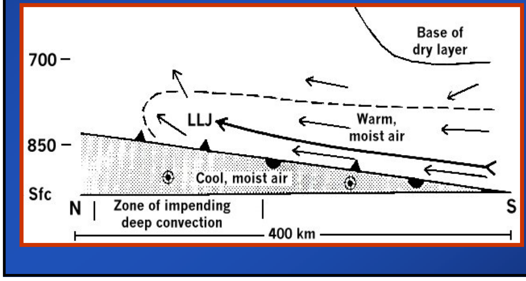
Elevated Convection

- Definition of elevated convection: thunderstorms that form above (north or east of) a frontal zone inversion or outflow boundary (on cool side) and are associated with 1) elevated convective instability released by isentropic lift or 2) near neutral stability (CSI) and frontogenetical forcing.
- Conceptual model for elevated storms with convective instability includes:
  - **No positive boundary layer CAPE and ambient LI values > 0**
  - **Elevated instability present above frontal inversion; elevated CAPE (parcels lifted from level of max theta-e) more representative with values > 0; SI values may be < 0**
  - **High values of boundary layer-based CAPE and LI values < 0 typically located upstream in inflow air originating south of boundary**
  - **MCS forms approximately 100-200 km north of surface boundary; surface winds often from northeast or east with south or southwest flow above inversion**
  - **Moderate-to-strong warm air advection and isentropic lift present aloft (baroclinic atmosphere)**
  - **Storms form in or near maximum zone of 850 mb positive theta-e advection (downstream from maximum theta-e values); storms may be closer to maximum 700 mb theta-e values**
  - **Storms located near maximum 925 and 850 mb moisture convergence zone associated with exit or left exit region of low-level jet**
  - **MCS tends to form along an inflection point in the 500 mb height field, about 500-1000 km downstream from a weak short-wave trough**
  - **Storms may occur within right entrance region of upper-level jet streak near or south of upper-level divergence maximum and in area of sloped frontogenetical forcing**

Elevated Convection: Sounding/Schematic Drawing

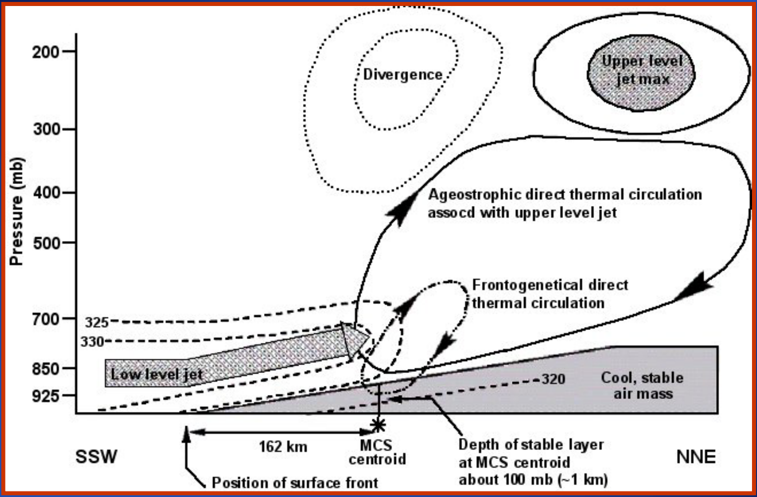


Example sounding in a pronounced elevated convective environment. The boundary layer is very stable and cool (LI = +7) due to a significant frontal inversion (note easterly winds below and southwesterly winds above). However, the air mass is unstable above the inversion as SI = -6, TT = 56, and KI = 33. Also note that conventional CAPE = 0, but CAPE calculated from the level of maximum theta-e (i.e., elevated CAPE) is nearly 2500 J/kg.



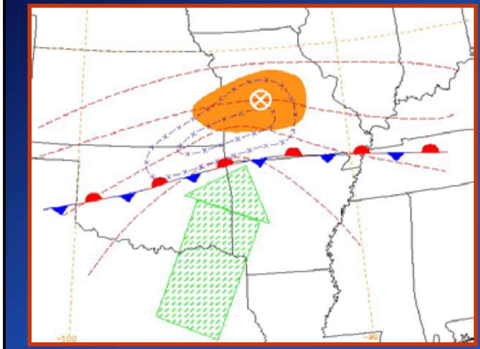
Idealized south-north cross-section showing structure just prior to development of deep elevated convection above a wedge-shaped cool air mass. The arrows and dashed line represent a wedge of warm, moist air flow rising isentropically from south to north above the frontal surface. The long arrow is the low-level jet. The dots inside the circles in the cool air mass represent easterly flow (out of the page).

Elevated Convection: Schematic Drawing

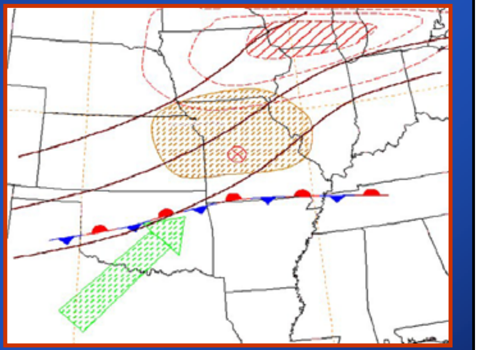


Cross-section looking basically east to west into page. MCS centroid often is located north of the warm front near the exit region of low-level jet (and theta-e gradient zone) where warm advection and convergence lead to frontogenetical forcing and resultant direct thermal circulation. This enhances the large scale ageostrophic circulation associated with the right entrance region of the upper-level jet streak.

Elevated Convection: Composite Drawings



Shaded orange: max 925-850 mb 2$_e$ advection; dashed lines = 925-850 mb 2$_e$; dashed-X lines = 925-850 mb mstr convergence; green arrow = low-level jet (LLJ); white circled X = active MCS site

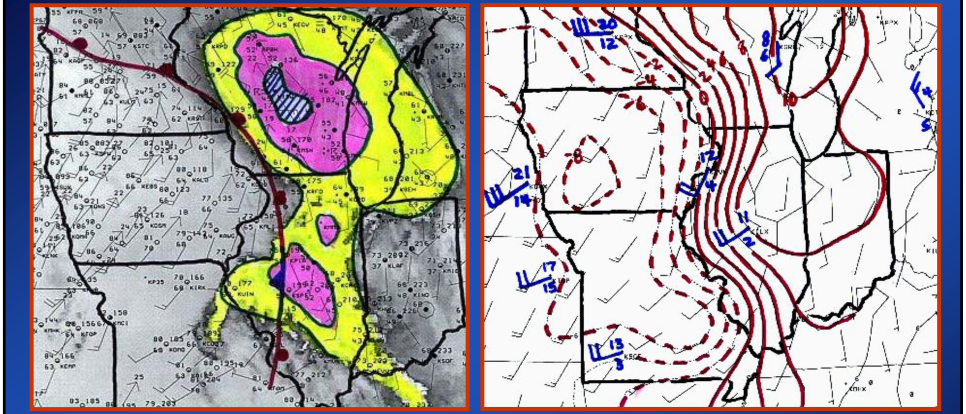


Solid lines = 500 mb heights; dashed red lines = 200 mb isotachs; stippled area = surface-500 mb mean RH > 70%; green arrow = 700 mb jet; red circled X = active MCS site

Based on 21 cases from 1993-1998, composite drawings of elevated thunderstorm events over the mid Mississippi Valley. The average active MCS location occurs roughly 100-200 km north of the warm/stationary front in/near exit region of low-level jet, near low-level moisture convergence maximum, generally within southern portion of surface-500 mb mean relative humidity, and in the right entrance region of upper level jet streak.

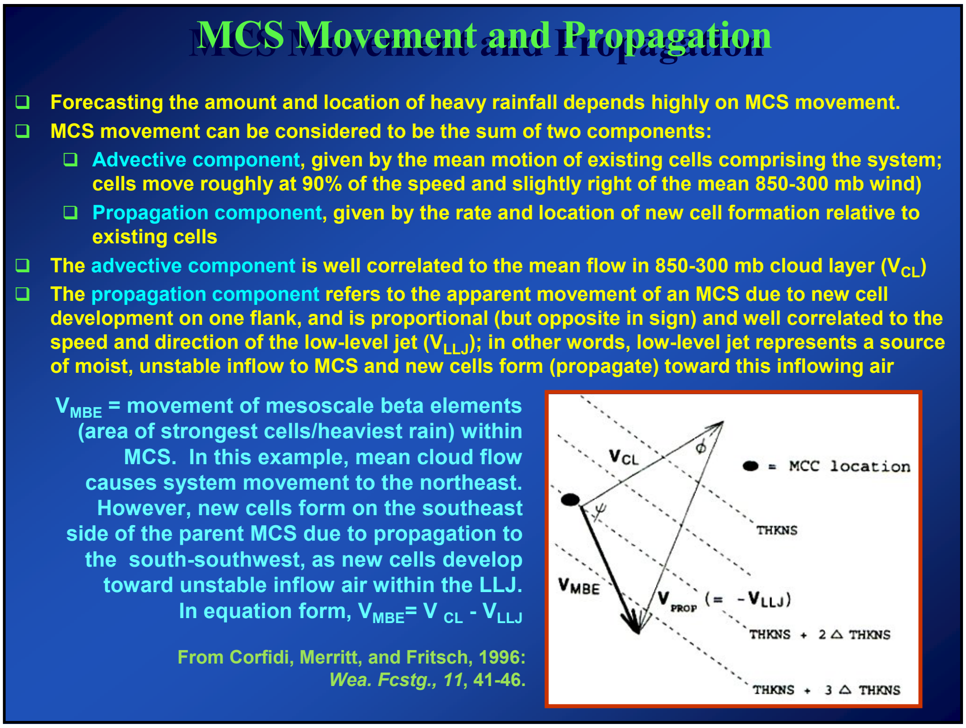
From Moore et al., COMET Hydrometeorology Course, 14-21 August 1993.

Elevated Convection: Example on May 14, 2001



Left: **Cold cloud tops (colored shading/hatching) on IR satellite imagery showing an MCS over WI and weakening storms over IL; surface plot and warm front at 1700 UTC.**

Right: **MSAS LIs (dashed red: LI < 0; solid red: LI > 0) and surface winds; 850 mb plot at 1200 UTC (blue). Note that elevated MCS is occurring east of warm front in area of stable LIs. However, a tight LI gradient exists to the west with advection of warm, moist, unstable air by the LLJ into the MCS area. Air mass is capped west of front, despite the ambient unstable air mass.**

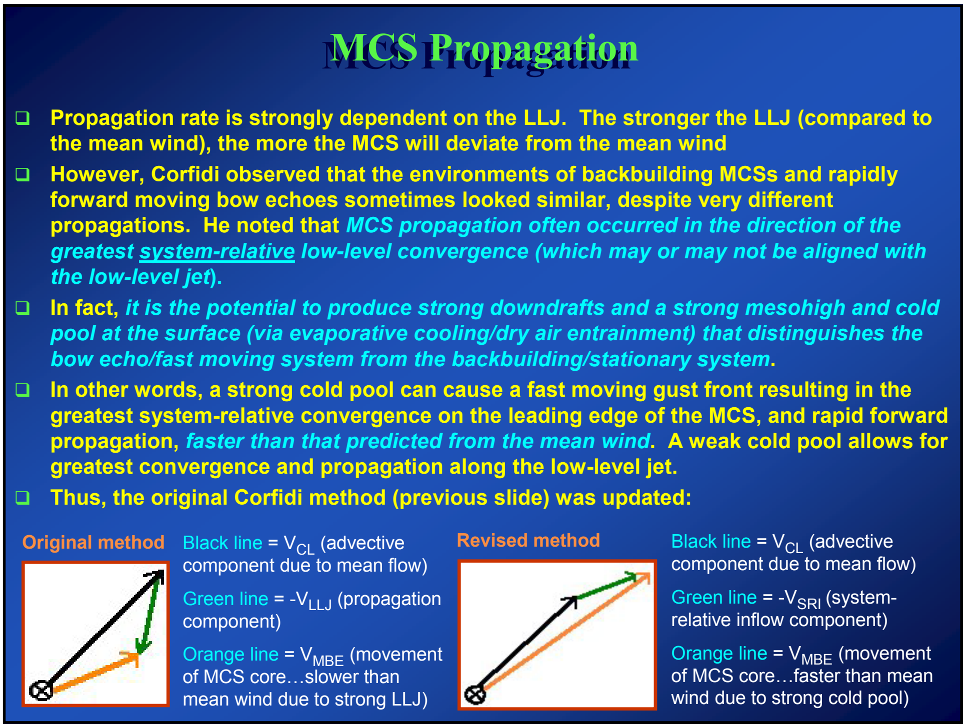


MCS Movement and Propagation

- Forecasting the amount and location of heavy rainfall depends highly on MCS movement.
- MCS movement can be considered to be the sum of two components:
  - Advective component, given by the mean motion of existing cells comprising the system; cells move roughly at 90% of the speed and slightly right of the mean 850-300 mb wind)
  - Propagation component, given by the rate and location of new cell formation relative to existing cells
- The advective component is well correlated to the mean flow in 850-300 mb cloud layer (V_{CL})
- The propagation component refers to the apparent movement of an MCS due to new cell development on one flank, and is proportional (but opposite in sign) and well correlated to the speed and direction of the low-level jet (V_{LLJ}); in other words, low-level jet represents a source of moist, unstable inflow to MCS and new cells form (propagate) toward this inflowing air

V_{MBE} = movement of mesoscale beta elements (area of strongest cells/heaviest rain) within MCS. In this example, mean cloud flow causes system movement to the northeast. However, new cells form on the southeast side of the parent MCS due to propagation to the south-southwest, as new cells develop toward unstable inflow air within the LLJ. In equation form, $V_{MBE} = V_{CL} - V_{LLJ}$

From Corfidi, Merritt, and Fritsch, 1996: *Wea. Fcstg., 11*, 41-46.



MCS Propagation

- Propagation rate is strongly dependent on the LLJ. The stronger the LLJ (compared to the mean wind), the more the MCS will deviate from the mean wind
- However, Corfidi observed that the environments of backbuilding MCSs and rapidly forward moving bow echoes sometimes looked similar, despite very different propagations. He noted that *MCS propagation often occurred in the direction of the greatest system-relative low-level convergence (which may or may not be aligned with the low-level jet)*.
- In fact, *it is the potential to produce strong downdrafts and a strong mesohigh and cold pool at the surface (via evaporative cooling/dry air entrainment) that distinguishes the bow echo/fast moving system from the backbuilding/stationary system*.
- In other words, a strong cold pool can cause a fast moving gust front resulting in the greatest system-relative convergence on the leading edge of the MCS, and rapid forward propagation, *faster than that predicted from the mean wind*. A weak cold pool allows for greatest convergence and propagation along the low-level jet.
- Thus, the original Corfidi method (previous slide) was updated:

Original method

Black line = V_{CL} (advective component due to mean flow)

Green line = $-V_{LLJ}$ (propagation component)

Orange line = V_{MBE} (movement of MCS core…slower than mean wind due to strong LLJ)

Revised method

Black line = V_{CL} (advective component due to mean flow)

Green line = $-V_{SRI}$ (system-relative inflow component)

Orange line = V_{MBE} (movement of MCS core…faster than mean wind due to strong cold pool)

MCS Propagation

- ❑ The main types of propagation include:
  - ➢ *Forward* (fast forward and slow forward propagation and movement)
  - ➢ *Quasi-Stationary* (little overall propagation and movement)
  - ➢ *Backward* (MCS appears to move backward due to new cell development on upwind flank even if individual cell movement is slowly forward)
  - ➢ *Regenerative* (MCS and cells within MCS move forward, but new cells and/or other MCSs develop upwind and move forward over the same location)
- ❑ Prolonged heavy rainfall and a flash flood threat are due mainly to quasi-stationary, backward, and/or regenerative convection
- ❑ Short duration heavy rainfall (that could also be a severe threat) is due to fast forward movement (e.g., a bow echo)
- ❑ However, even a forward propagating MCS (e.g., bow echo) that contains either significant leading or trailing stratiform precipitation still could pose a flood threat, depending on system speed, soil conditions and type, and terrain

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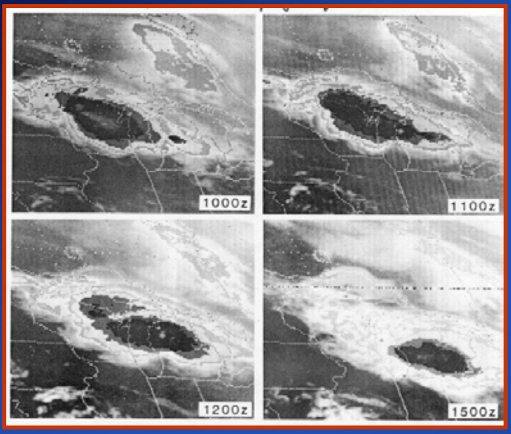
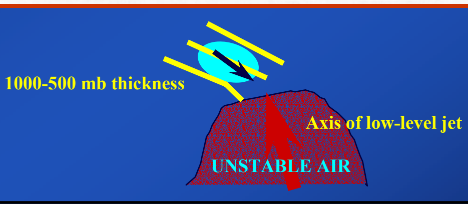
MCS Propagation: Forward in Satellite



Example of a forward propagating MCS in IR satellite imagery (Mb enhancement curve). In 5 hours, the MCS progresses from Wisconsin to the southern Lower Peninsula of Michigan. Note that the preferred flank for new cell development is on the leading (downwind) edge of the parent MCS. New cells then merge with the MCS keeping it moving forward along the low-level unstable inflow zone. Meanwhile, older cells in the upwind portion of the system weaken.



1000-500 mb thickness

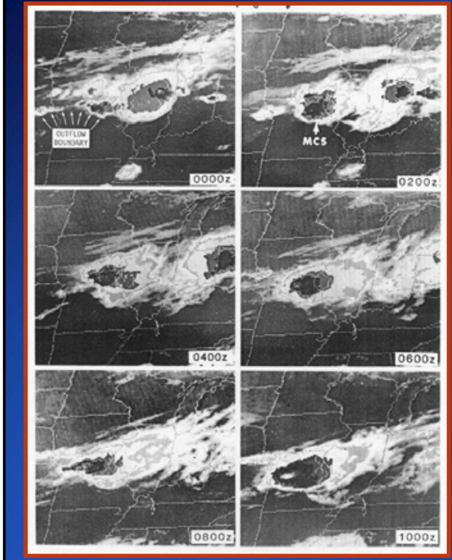
Axis of low-level jet

UNSTABLE AIR

→ = Direction of propagation

● = MCS location

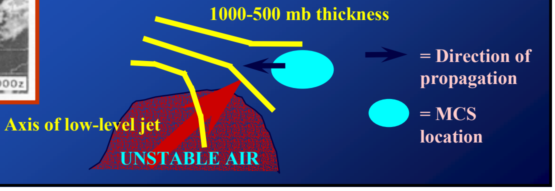
MCS Propagation: Backward in Satellite



An MCS over central IL at 0000 UTC moved east while new cells developed and propagated backward within the preferred low-level moist, unstable inflow zone along an outflow boundary west of the MCS. Thus, by 1000 UTC, strongest cells in the new MCS were located over west-central MO.

Meanwhile, the initial MCS over IL propagated forward while new cells downstream were stationary near the east-central IN/west-central OH border. These cells then merged with the forward propagating MCS from IL which swept the system east.

Both MCS areas (MO and IN/OH border) represent potential flash flood locations.



1000-500 mb thickness

➔ = Direction of propagation

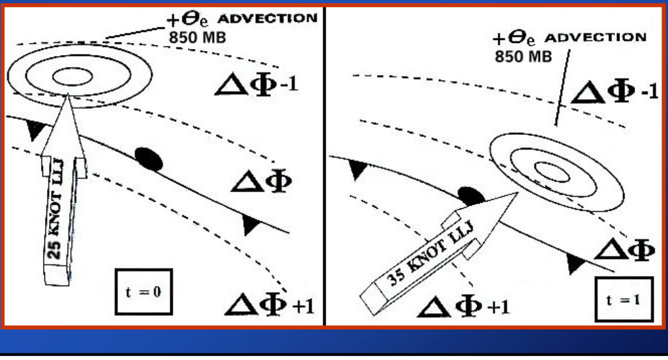
● = MCS location

Axis of low-level jet

UNSTABLE AIR

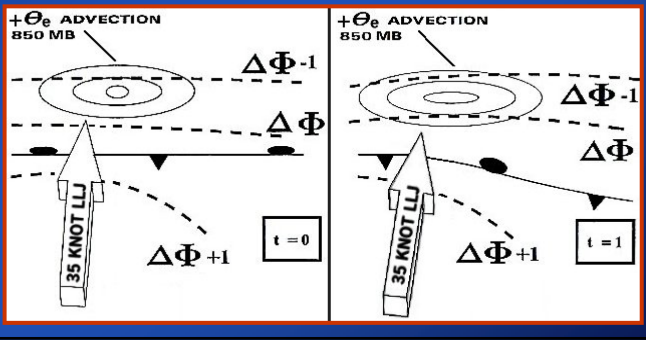
Characteristics of Forward Propagating MCS's

- ❑ Forward Propagating MCSs:
  - ❑ Maximum CAPE downstream or coincident with MCS
  - ❑ 850 mb theta-e ridge axis downstream or coincident with MCS
  - ❑ LLJ and strongest low-level moisture transport and convergence coincident with or downstream from MCS
  - ❑ Moderate-to-strong 850-300 mb mean winds and thickness gradient
  - ❑ MCS usually moves along or just right of 850-300 mb thickness contours
  - ❑ Progressive shortwave present which keeps MCS moving forward



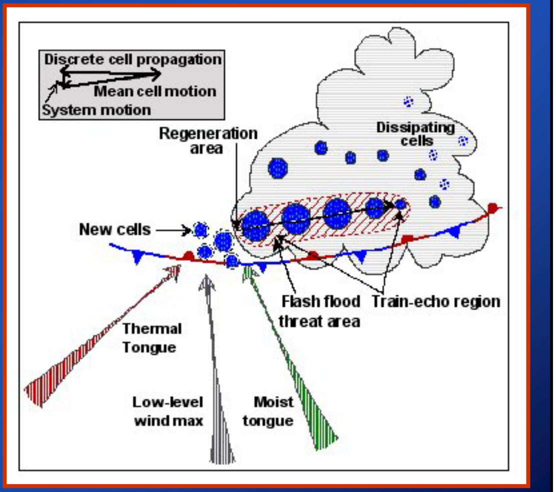
Characteristics of Backward Propagating MCS's

- Backward Propagating/Quasi-Stationary MCSs:
  - Maximum CAPE along and upstream from MCS (typically to W or SW)
  - Quasi-stationary east-west surface boundary (front or outflow boundary) present
  - 850 mb theta-e ridge axis along and upstream from MCS (typically to W or SW)
  - LLJ & strongest low-level moisture transport & convergence upstream from MCS
  - Relatively weak 850-300 mb mean winds and thickness gradient (although regenerating cells can occur when winds and gradient are stronger)
  - Possible diffluent thickness pattern aloft
  - May be near mean upper-level ridge aloft; weak shortwave aloft present if any
  - Veering winds with height, but limited speed shear



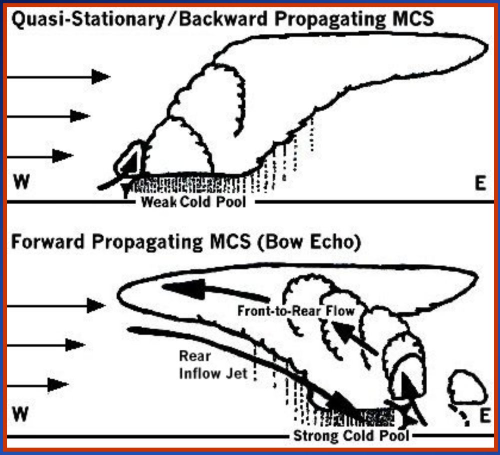
Characteristics of Regenerative Convection

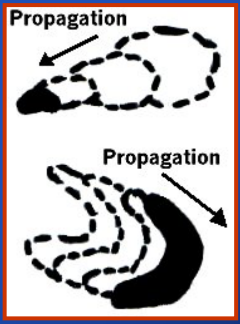
- Regenerative Convection:
  - Often near or within the upper ridge; relatively weak flow
  - Steering flow carries new echoes slowly away from regeneration area
  - Watch for intersection of low-level jet with pre-existing boundary and storm-generated boundary
  - Consider whether regeneration will be fast enough to balance cell movement
  - An approaching shortwave causes surface pressure falls, which helps enhance local low-level flow that supplies the storm



From Kelsch, 2001; COMAP Symposium 02-2

MCS Propagation: Different Storm Structure

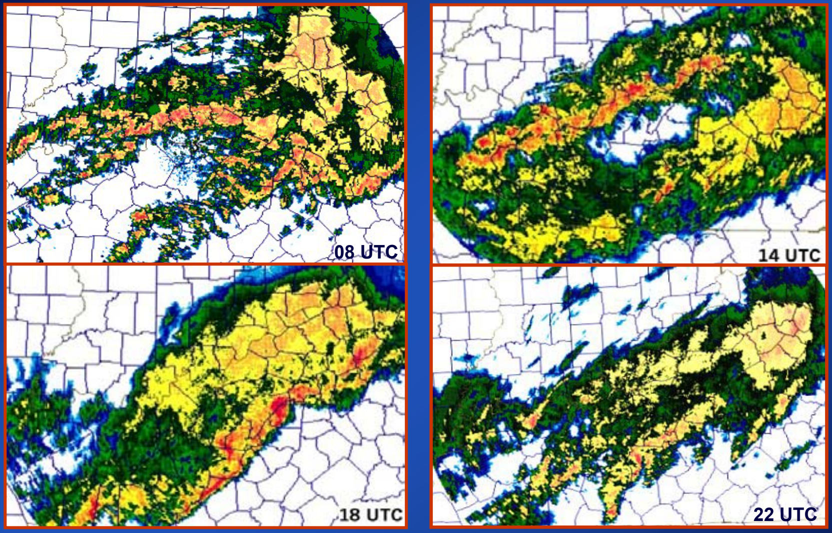




Top: **Quasi-stationary/backward propagating MCS due to preferred inflow and new cell development on upwind end of MCS; flash flood threat.**

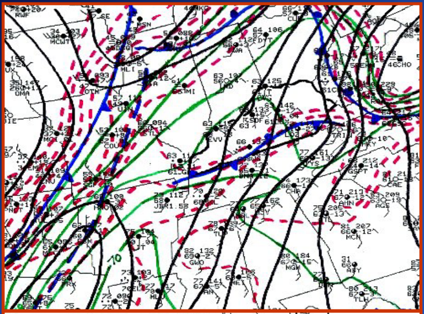
Bottom: **Fast forward propagating MCS (bow echo); new cells develop on leading edge where rear inflow jet converges with storm-relative inflow; wind damage threat; could be flash flood threat if rainfall rates are high enough and if trailing stratiform precip exists**

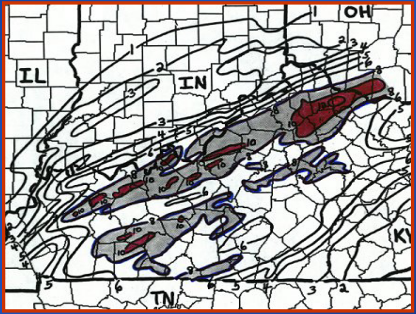
MCS Propagation: March 1, 1997 Record Rain Event

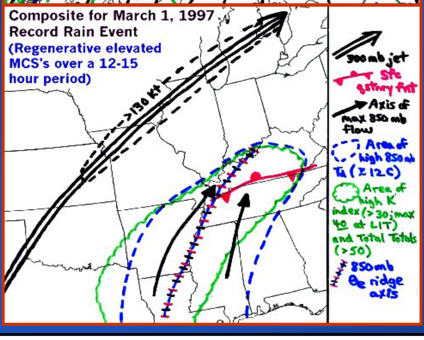


The above KLVX radar images show a persistent area of rain and convection that trained from southwest to northeast over central Kentucky on March 1, 1997. Coupled with additional heavy rain after these images, a total of 6-12 inches of rain fell in less than 24 hours. Widespread flooding and flash flooding occurred.

MCS Propagation: March 1, 1997 Record Rain Event



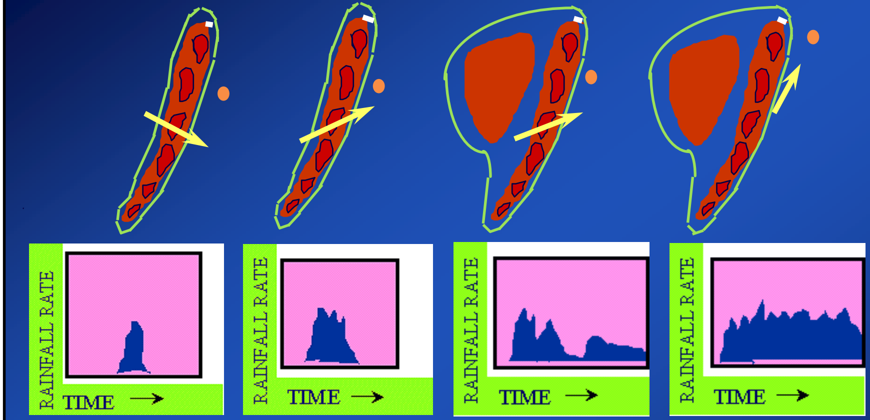




Composite for March 1, 1997 Record Rain Event
(Regenerative elevated MCS's over a 12-15 hour period)

Representative surface map (upper left) during the record rain event showed a stationary front near the KY-TN border, north of which elevated convection trained producing 6-12 inches of rain (max amounts shaded; above). At bottom left is the composite synoptic chart for the event. Low-level moist, unstable inflow along the axis of the low-level jet remained very persistent over the lower Mississippi and lower Ohio Valleys, resulting in preferred new cell development on the upwind portion of the rain and thunderstorm complex. Aloft, the area was south of an anticyclonically curved jet, although no significant shortwaves were present.

Effect of System Shape on Rainfall



- ❑ The graphs show rainfall rate and duration that would occur at the orange dots above depending on MCS shape (outlined by green lines) and movement (yellow arrows).
- ❑ A narrow squall line moving perpendicular to its major axis produces only a brief period of heavy rain at any one location, but is more likely to produce wind damage.
- ❑ A squall line with significant trailing rainfall moving nearly parallel to its major axis produces prolonged heavy rainfall, and an increased flash flood threat.

Precipitation Efficiency

Precipitation Efficiency is defined as the ratio of the precipitation that occurs at the surface over the lifetime of an MCS to the water vapor (moisture) ingested into the MCS updraft during the same period.

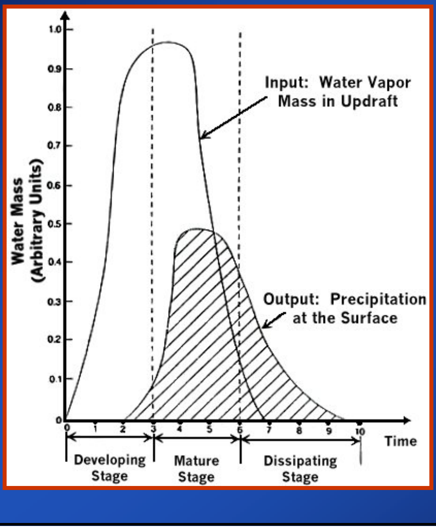


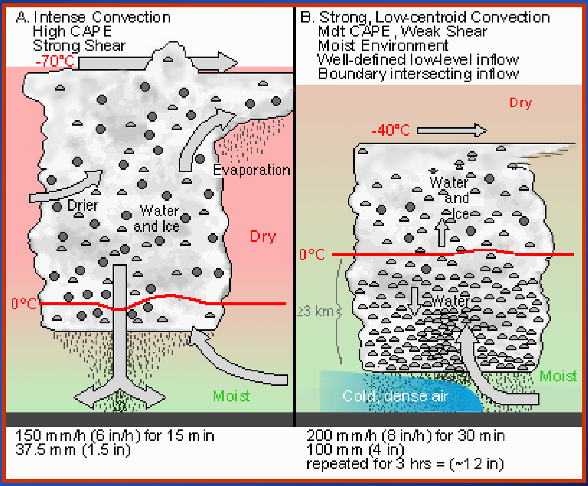
Diagram illustrating the input of water vapor to a thunderstorm versus output of rainfall at the surface. During the developing stage, input is very high with little or no surface precipitation. In the mature stage, water vapor is still being supplied within the updraft while heavy rain reaches the surface. The storm rains itself out in the dissipation stage (no input, only output). The "taller" the output curve versus input curve, the greater the precipitation efficiency.

Factors Affecting Precipitation Efficiency

- Moderate to high environmental relative humidity (> 70%); moisture/high RH throughout sounding (no dry air aloft); less dry air entrainment into storm
- High precipitable water (1.5 to 2.5 inches...warm season)
- Low cloud base height which decreases evaporation in sub-cloud layer
- Vertically deep warm cloud layer (T_{cloud} > 0 C) greater than 3-4 km; higher cloud liquid water content which enhances collision-coalescence process
- Low centroid storm (highest reflectivity in lower half of cloud)
- Strong storm-relative high theta-e inflow and mixing ratios in low levels (0-2 km) to enhance moisture convergence
- Weak-to-moderate vertical wind shear in mid and upper levels; yields slower system movement and decreased entrainment
- Moderate values of CAPE (~2000 J/kg or less), i.e., moderate updraft; long, relatively "skinny" positive area on sounding to promote slow vertical acceleration; this increases residence time of droplets in cloud to increase growth with less condensate loss near top of storm; a "fatter" area of positive energy promotes an intense updraft which increases severe threat but generally decreases precipitation efficiency
- A broad spectrum of cloud droplet sizes to enhance collision-coalescence (occurs when air mass has long trajectory over water, e.g., strong inflow from Gulf of Mexico)

Factors Affecting Precipitation Efficiency

A low-centroid storm, often associated with moderate CAPE, relatively weak vertical wind shear, and deep-layered moisture, is more efficient in rainfall production due to warm rain processes (collision-coalescence) than high CAPE, strongly sheared (severe) storms. Low-level inflow intersecting a boundary usually also enhances storm efficiency.

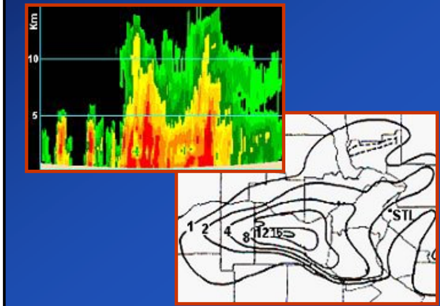


From Kelsch, 2001; COMAP Symposium 02-2

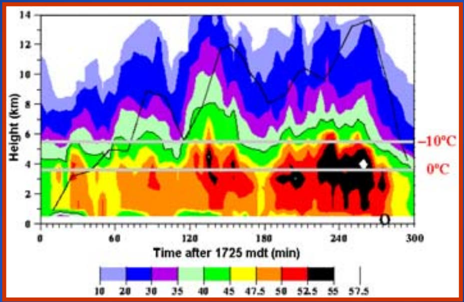
Factors Affecting Precipitation Efficiency

Warm cloud processes:

Beware of a deep low-level warm cloud layer containing the majority of a storm's high reflectivity values!!



Flash flooding rains produced over one foot of rain west of St. Louis during early morning of May 7, 2000. ***Note highest reflectivity in lower half of cloud. Radar would likely underestimate rates!***

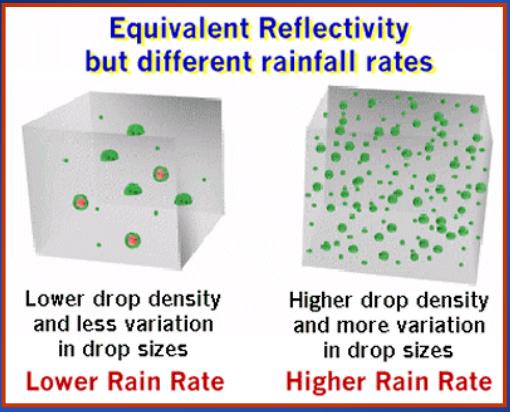


Time-height cross-section of reflectivity for convection near Ft. Collins, CO. Nothing noteworthy in terms of severe weather potential is evident. However, two very important aspects must be recognized: 1) Cells trained over same location for several hours; and 2) majority of reflectivity was below -10 C, so collision-coalescence produced very high precipitation efficiency and high rainfall rates. Thus, significant flash flooding occurred, despite no severe weather and limited CG strikes.

In such situations, coordinate with the RFC and consider a change to the radar's Tropical Z-R relationship.

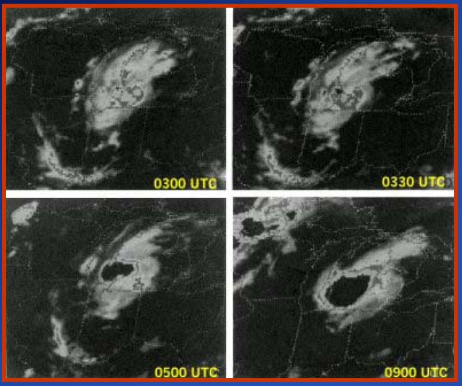
Factors Affecting Precipitation Efficiency

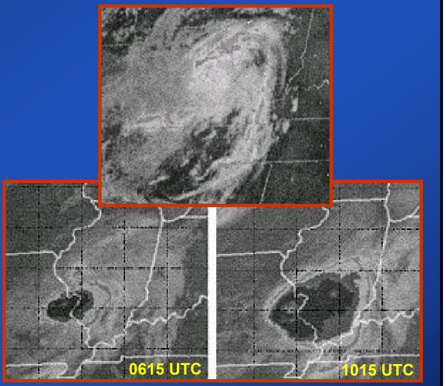
Not all reflectivity is created equally.



Equivalent radar reflectivity values can be generated from 1) a few large drops (or hail) but with a low droplet density and size distribution, and 2) many small drops with a high density and size distribution. However, the second scenario (typical in a maritime tropical air mass) would result in higher rainfall amounts. Thus, when evaluating reflectivity for precipitation estimates, know the environment the storm is within to help determine the efficiency of the storm.

Mesoscale Convective Vortices (MCV)

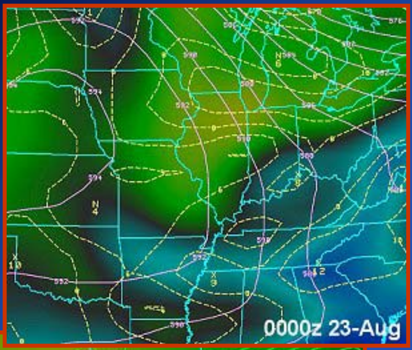


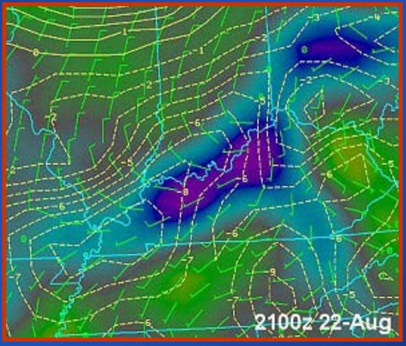


Due to large amounts of latent heat released within a large MCS, a mid-level low (mesoscale convective vortex) and increased winds on northern edge of MCS can develop in its latter stages. When MCS dissipates, these features can move downstream into an unstable air mass and produce convection where model data showed little or no QPF.

During afternoon, convection typically develops on periphery of MCV due to differential heating. At night, peripheral convection may dissipate, but deep convection/very heavy rain may develop near MCV center within area of max moisture convergence (similar to remnants of tropical storms).

Flash Flood Event: Aug. 22, 2003





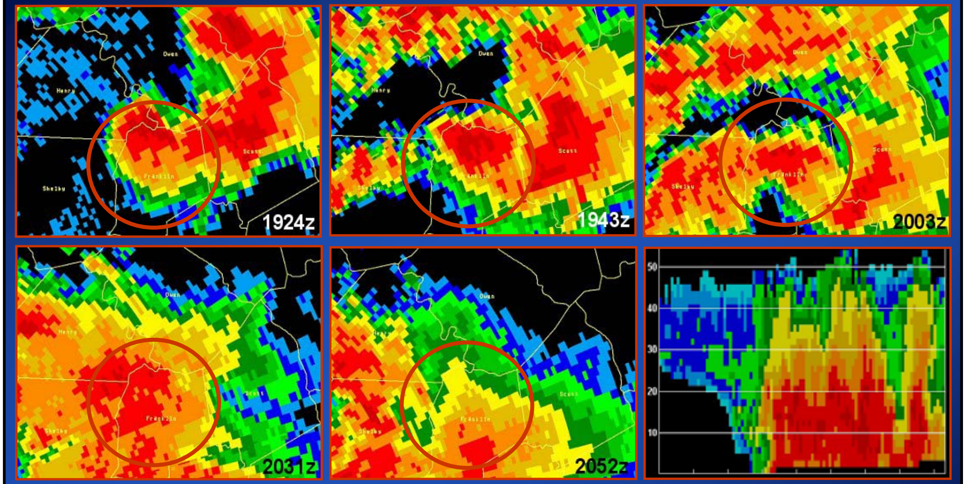
Synoptic Pattern:

500 mb (upper left): Nothing distinct: upper ridge over Plains; weak northerly flow/weak shortwaves across OH Valley; 1000-500 mb moisture near OH River (image).

Surface (upper right): Winds depict a cold front along OH River where surface-based LIs from MSAS are -6 to -10. Image shows axis of moisture flux convergence along OH River (blue/purple colors).

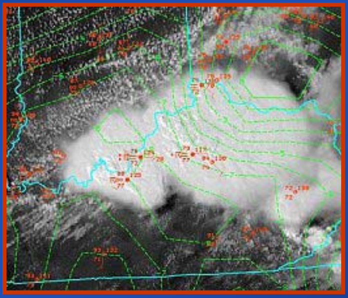
925 mb (lower left): Pronounced 2-D frontogenetical axis present where F_n vectors were longest. Resulting forcing was along southern edge near OH River.

Flash Flood Event: Aug. 22, 2003



The 0.5 deg base reflectivity images from the KLVX radar indicated training convection over northern Franklin county in central KY (within circle). From 1924- 2003 utc, thunderstorms producing torrential rain moved little as redevelopment occurred rapidly on the northern end of the storm area. By 2031 utc, additional upstream storms (at 2003 utc) had moved into the county resulting in more heavy rain and flash flooding. Rain began to diminish after 2052 utc. A vertical cross-section (lower right) showed a series of cells with their highest reflectivity in the lower part of the cloud. Given a deep warm cloud depth, this indicated storms with very efficient rainfall production.

Flash Flood Event: Aug. 22, 2003

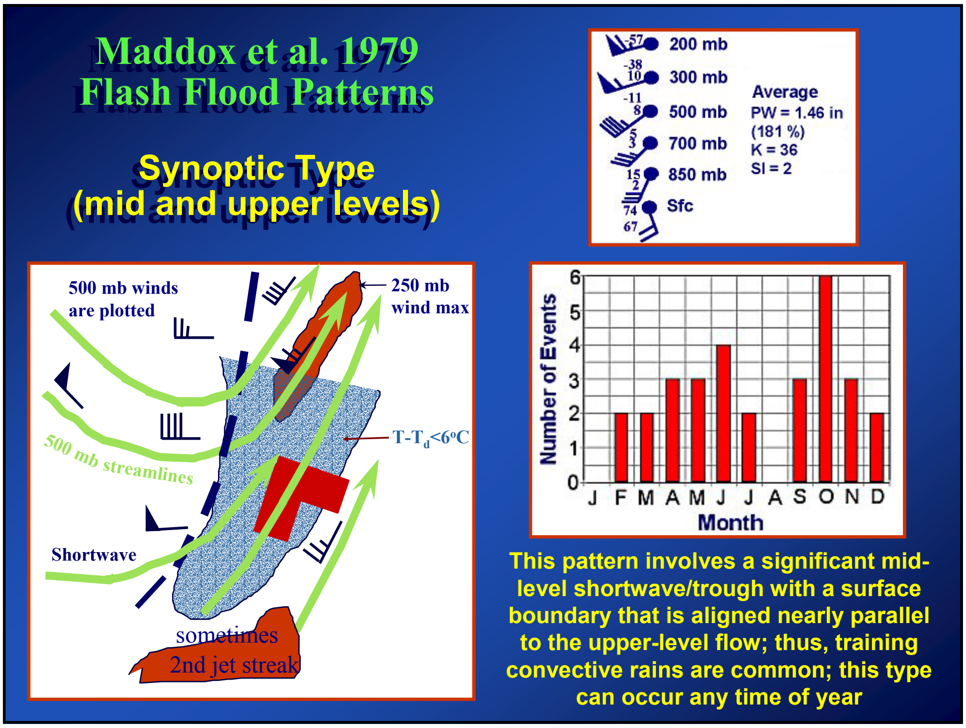


Visible satellite imagery showed a blossoming MCS that produced torrential rain and wind damage as it moved slowly southward into mid 70 dewpoint air where surface LIs were -6 to -10.

One hour radar estimated precipitation (top left) revealed 3-4 inches over northern Franklin and Scott counties in central KY. Estimated storm totals were from 5-6 inches, which generally were accurate (little or no hail contamination).

Flash flooding occurred resulting in 2 deaths in Franklin County. Flash Flood Warnings were issued in advance, *despite initial reports of no flooding in the area*.

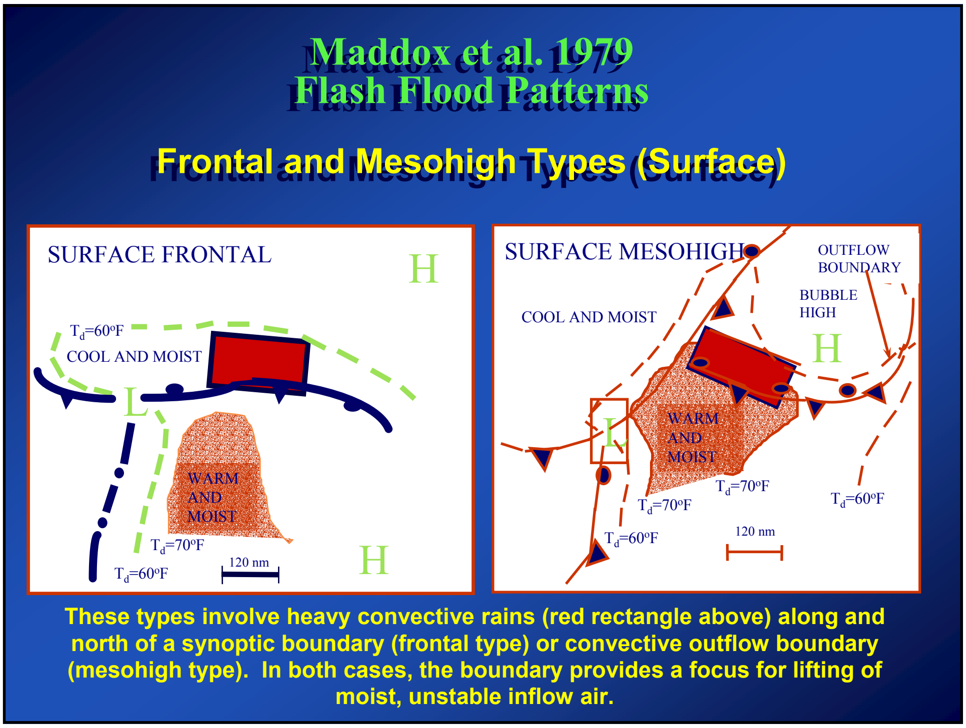
Synoptic and Mesoscale Patterns and Climatology Associated with Heavy Convective Rainfall Across the Central U.S.



Maddox et al. 1979
Flash Flood Patterns

Synoptic Type
(mid and upper levels)

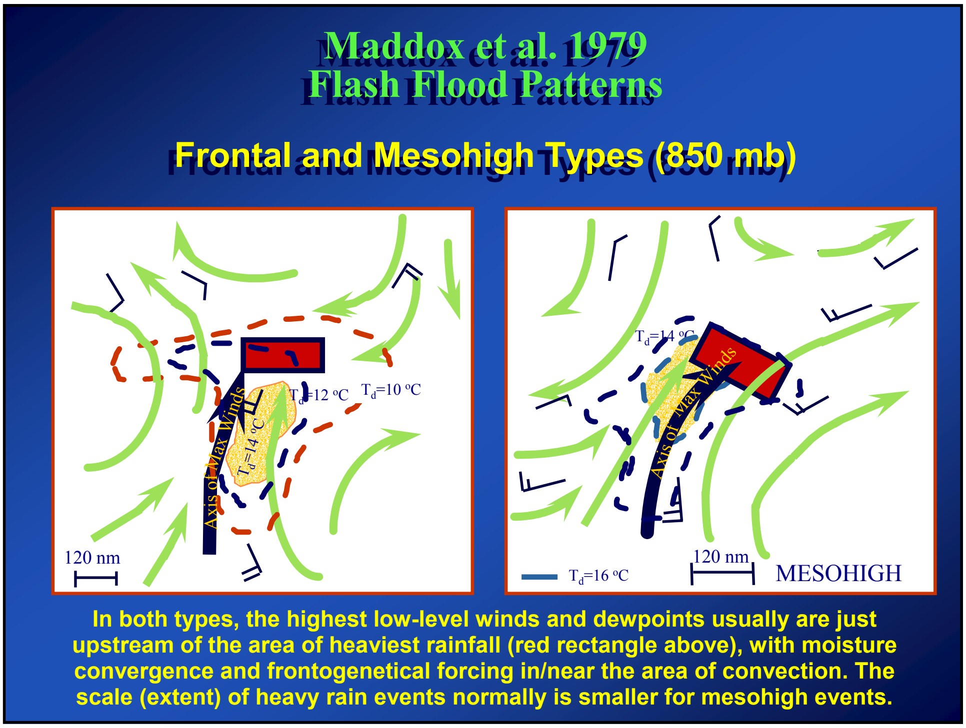
This pattern involves a significant mid-level shortwave/trough with a surface boundary that is aligned nearly parallel to the upper-level flow; thus, training convective rains are common; this type can occur any time of year



Maddox et al. 1979
Flash Flood Patterns

Frontal and Mesohigh Types (Surface)

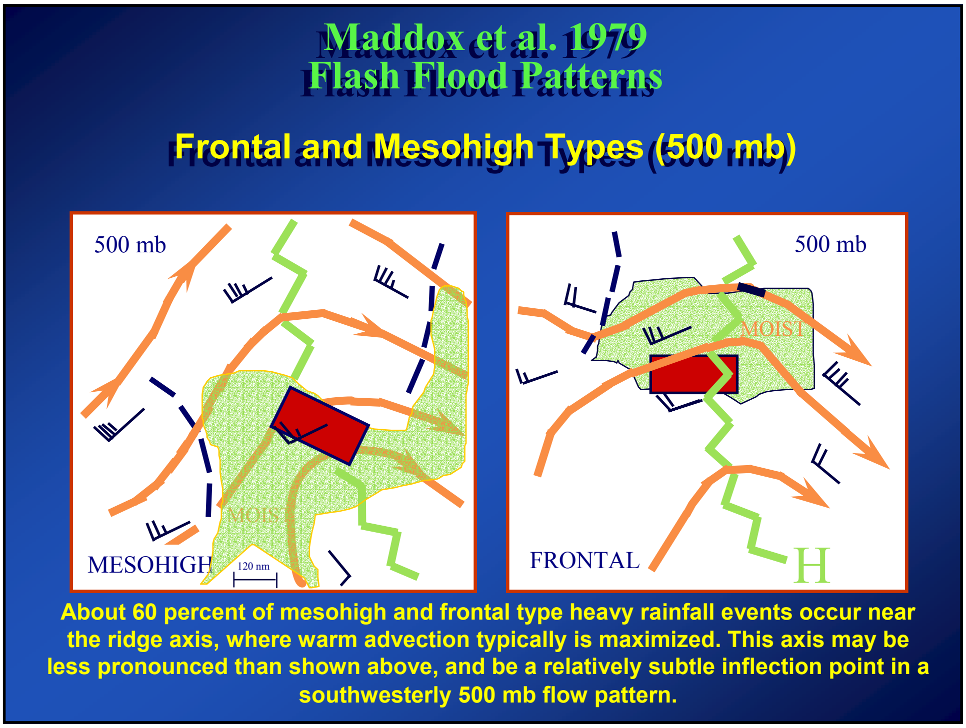
These types involve heavy convective rains (red rectangle above) along and north of a synoptic boundary (frontal type) or convective outflow boundary (mesohigh type). In both cases, the boundary provides a focus for lifting of moist, unstable inflow air.



Maddox et al. 1979
Flash Flood Patterns

Frontal and Mesohigh Types (850 mb)

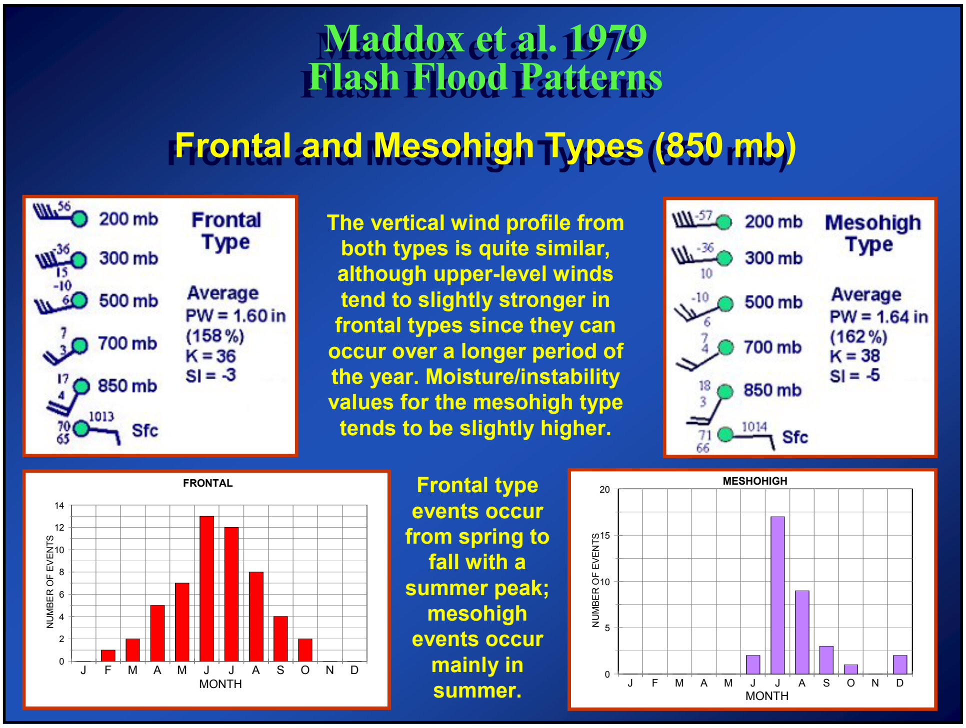
In both types, the highest low-level winds and dewpoints usually are just upstream of the area of heaviest rainfall (red rectangle above), with moisture convergence and frontogenetical forcing in/near the area of convection. The scale (extent) of heavy rain events normally is smaller for mesohigh events.



Maddox et al. 1979
Flash Flood Patterns

Frontal and Mesohigh Types (500 mb)

About 60 percent of mesohigh and frontal type heavy rainfall events occur near the ridge axis, where warm advection typically is maximized. This axis may be less pronounced than shown above, and be a relatively subtle inflection point in a southwesterly 500 mb flow pattern.



Maddox et al. 1979
Flash Flood Patterns

Frontal and Mesohigh Types (850 mb)

Frontal Type

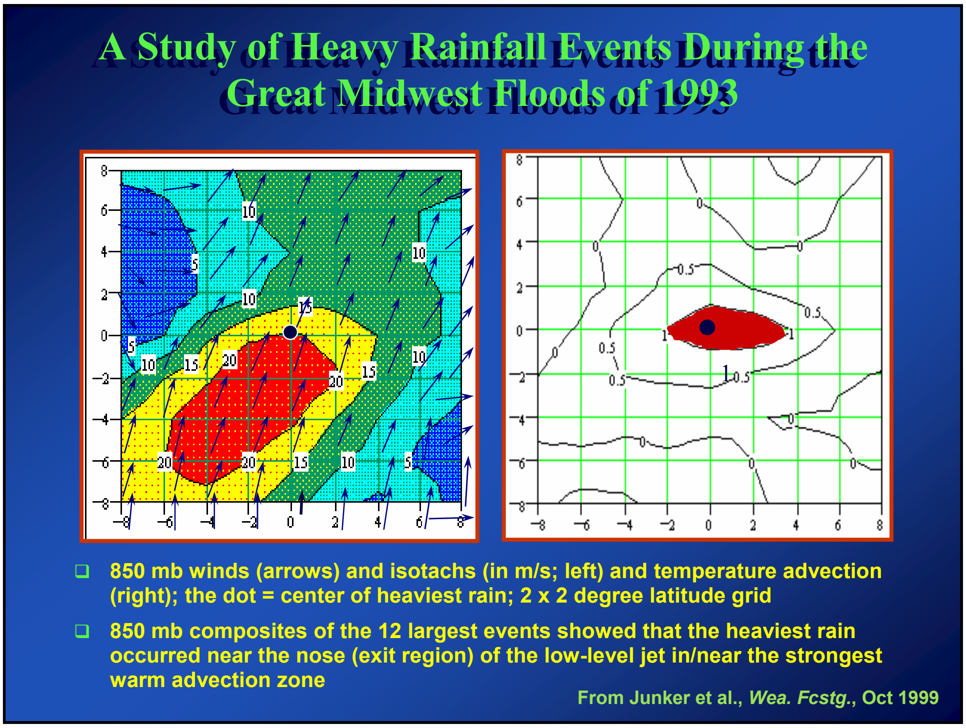
Average
PW = 1.60 in
(158 %)
K = 36
SI = -3

The vertical wind profile from both types is quite similar, although upper-level winds tend to slightly stronger in frontal types since they can occur over a longer period of the year. Moisture/instability values for the mesohigh type tends to be slightly higher.

Mesohigh Type

Average
PW = 1.64 in
(162 %)
K = 38
SI = -5

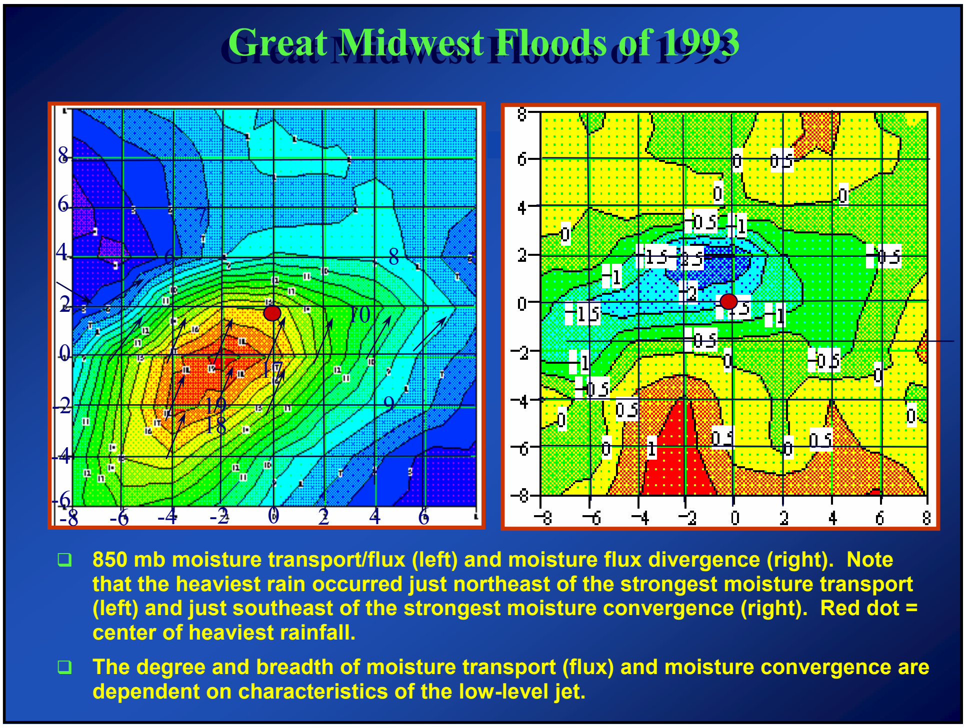
Frontal type events occur from spring to fall with a summer peak; mesohigh events occur mainly in summer.



A Study of Heavy Rainfall Events During the Great Midwest Floods of 1993

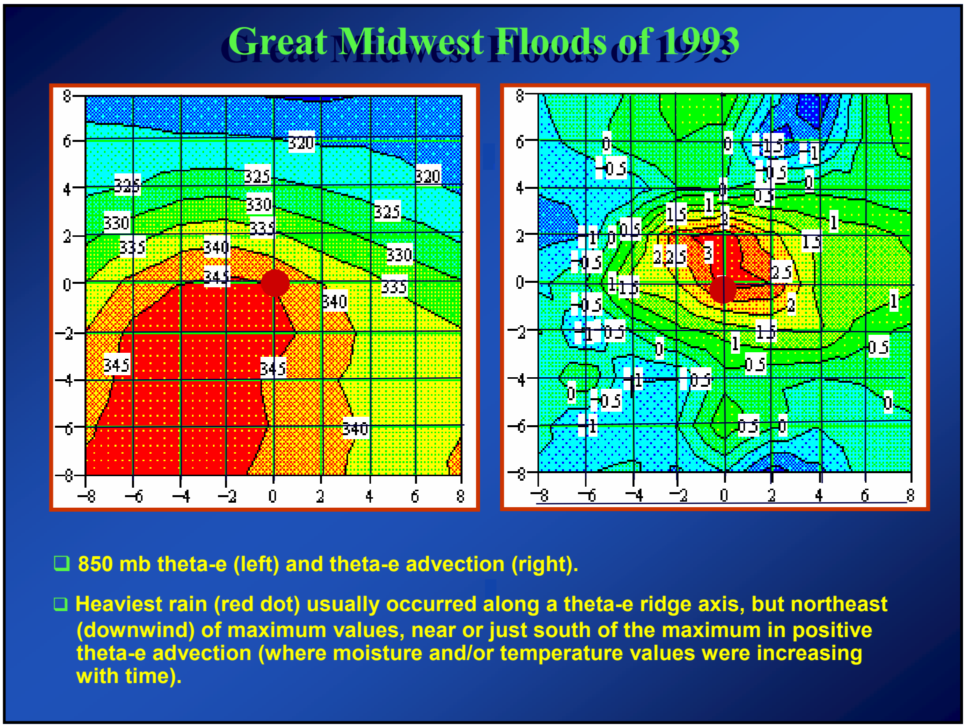
- ❑ 850 mb winds (arrows) and isotachs (in m/s; left) and temperature advection (right); the dot = center of heaviest rain; 2 x 2 degree latitude grid
- ❑ 850 mb composites of the 12 largest events showed that the heaviest rain occurred near the nose (exit region) of the low-level jet in/near the strongest warm advection zone

From Junker et al., *Wea. Fcstg.*, Oct 1999



Great Midwest Floods of 1993

- 850 mb moisture transport/flux (left) and moisture flux divergence (right). Note that the heaviest rain occurred just northeast of the strongest moisture transport (left) and just southeast of the strongest moisture convergence (right). Red dot = center of heaviest rainfall.
- The degree and breadth of moisture transport (flux) and moisture convergence are dependent on characteristics of the low-level jet.

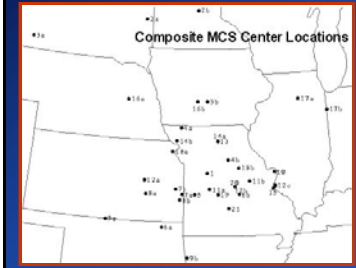


Great Midwest Floods of 1993

- 850 mb theta-e (left) and theta-e advection (right).
- Heaviest rain (red dot) usually occurred along a theta-e ridge axis, but northeast (downwind) of maximum values, near or just south of the maximum in positive theta-e advection (where moisture and/or temperature values were increasing with time).

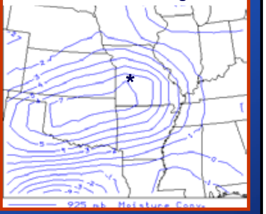
Climatology of Elevated Convection over Central U.S.

Based on a study of 21 separate cases (including 35 events) of warm season elevated MCSs from 1993-1998 in the central U.S.; some cases involved multiple time periods. Rainfall criteria: >4 inches within 24 hours over at least a 100 km x 100 km sized area.

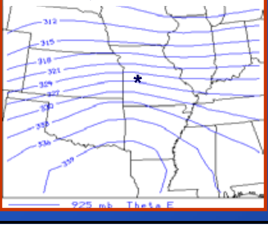


Composite MCS centroid about 162 km north of sfc front

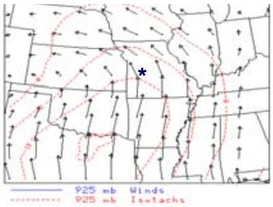
MCS north/east of max 925 mb moisture convergence



MCS in gradient of 925 mb theta-e, well north of max



MCS downwind from max winds at 925 mb



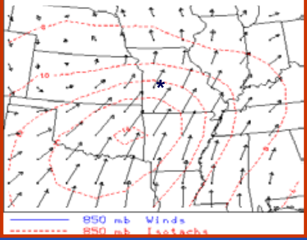
Star (*) = Composite MCS centroid for all events versus each parameter

Study performed by Moore and Graves, St. Louis Univ; Glass, WFO St. Louis; Rochette, SUNY Brockport; and Singer, Aviation Weather Center. Presented at COMET Hydrometeorology Course: 14-21 August 2003

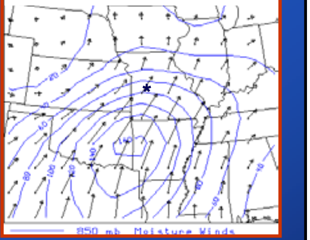
Climatology of Elevated Convection over Central U.S.

MCS vs. 850 mb height and temp fields (in gradient zone of temps)

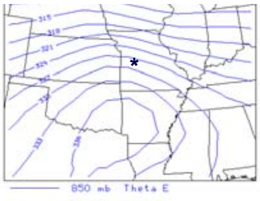
MCS downwind from max winds at 850 mb (in exit region)



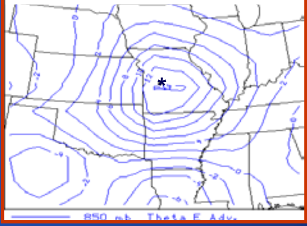
MCS downwind from max 850 mb moisture transport vectors



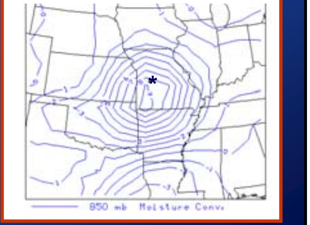
MCS in gradient of 850 mb theta-e but near ridge axis downwind from max values



MCS coincident with or near max 850 mb positive theta-e advection



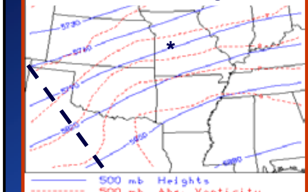
MCS near max of strong 850 mb moisture convergence



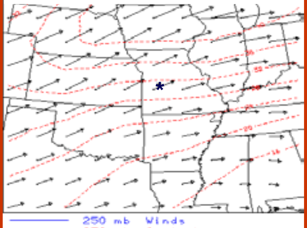
From Moore, Glass, Graves, Rochette, and Singer.

Climatology of Elevated Convection over Central U.S.

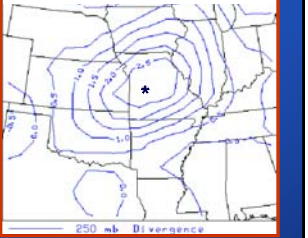
500 mb heights/vorticity; MCS in southwest flow near shortwave ridge & downstream from weak shortwave trough



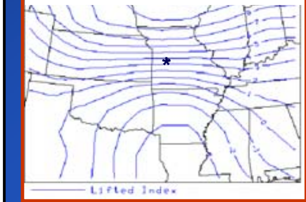
MCS in/near right entrance region of 250 mb jet streak



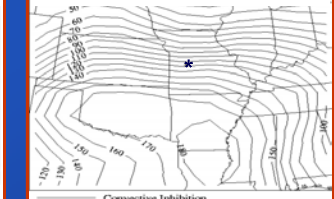
MCS within/near max 250 mb divergence



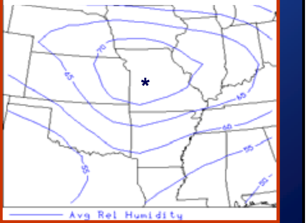
MCS in area of positive LIs but in tight gradient zone with negative LIs within inflow air; CAPE similar



High mean parcel CIN south (air capped); less capping in MCS area, with even lower max theta-e CIN



MCS within but near southern edge of max 1000-500 mb RH

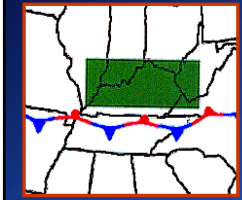


From Moore, Glass, Graves, Rochette, and Singer.

Heavy Rainfall Climatology: Patterns Across Kentucky and Southern Indiana (Ohio River Valley)

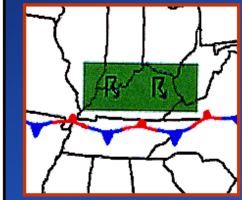
- A study of heavy rainfall events, defined as >2 inches in 24 hours, from 1982-1996 across Kentucky and southern Indiana (155 events total) resulted in identification of several patterns to enhance the forecast process and ability to determine rainfall potential.
- Patterns included:
  - **Frontal Stable**
  - **Frontal Unstable**
  - **Frontal Warm**
  - **Synoptic Maddox**
  - **Synoptic Warm**
  - **Synoptic Cold**
  - **Mesohigh**
  - **SHARS (subtle heavy rainfall signature)**
- The most predominant patterns were Frontal Stable/Unstable and Synoptic Maddox, which can result in heavy rainfall anytime in the year.

Heavy Rainfall Surface Patterns (most common types)
Number of Events per Pattern



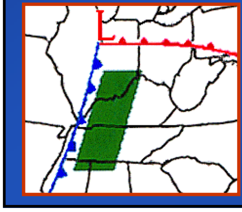
Frontal Stable:

E-W stationary or warm front present with heavy rain north of front; no elevated convection; usually lower pressure to the west



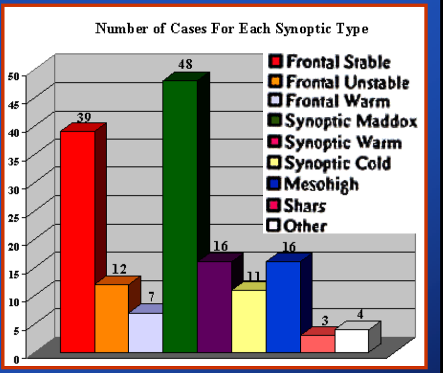
Frontal Unstable:

Similar to Frontal Stable except elevated convection is present north of front due to influx of higher instability from the south; usually lower pressure to the west



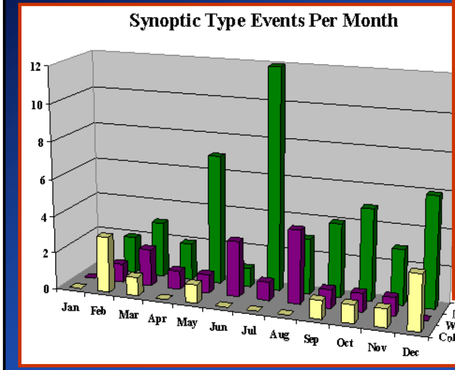
Synoptic Maddox:

Heavy rain occurs along and just ahead of a slow moving cold front; convection may or may not be present



The **Frontal Stable** (red) and **Unstable** (orange) and **Synoptic Maddox** (green) types make up about two-thirds of the total number of heavy rainfall events across Kentucky and the southern third of Indiana.

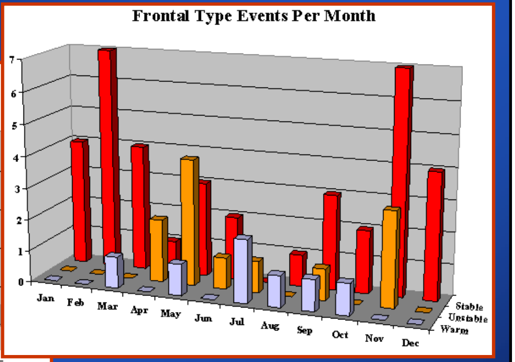
Frontal and Synoptic Events per Month



Synoptic Maddox events (green) can occur anytime during year, including winter.

Synoptic Cold events (yellow) (post cold frontal heavy rain) most common in winter.

Synoptic Warm (purple) (heavy rain within warm sector ahead of cold front) most prevalent in spring and summer.

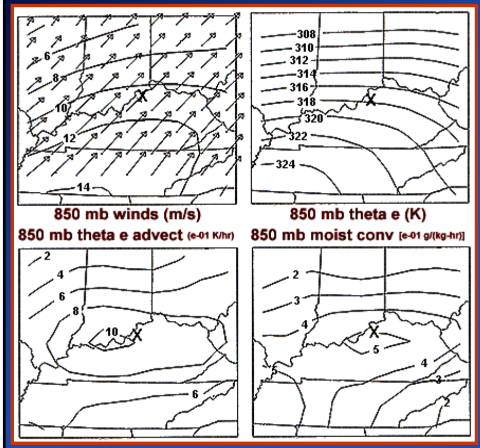


Frontal Stable events (red) common in fall, winter, and early spring.

Frontal Unstable events (orange) most common in spring and fall, when elevated instability results in elevated convection.

Frontal Warm events (lavender) (heavy rain in warm sector south of warm front) occurs in summer.

Frontal Stable: 850 mb & Mid/Upper Level Pattern

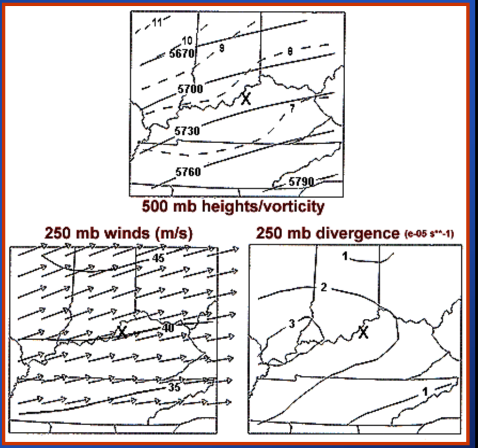


850 mb winds (m/s)

850 mb theta e (K)

850 mb theta e advect (e-01 K/hr)

850 mb moist conv [e-01 g/(kg-hr)]



500 mb heights/vorticity

250 mb winds (m/s)

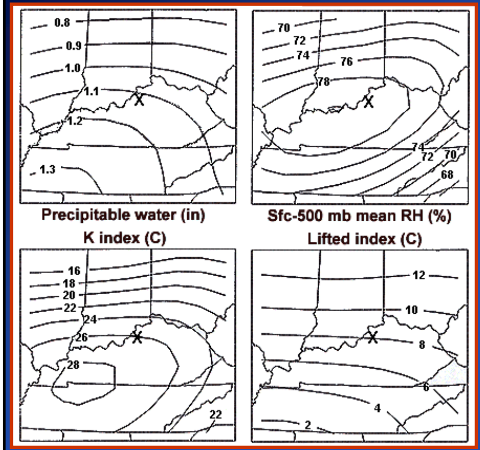
250 mb divergence (e-05 s**-1)

"X" = composite location of centroid of heavy rainfall versus various parameters

850 mb: Heavy rain typically falls just downwind of low-level maximum wind flow (within exit region) in area of 850 mb moisture convergence and positive theta-e advection, downwind from highest theta-e values.

Mid/Upper-levels: Occur within broad southwest flow at 500 mb and absence of strong shortwave. Heavy rain occurs south of strongest 250 mb winds within/near right entrance region of jet, where upper-level divergence is present.

Frontal Events: Moisture/Instability Pattern

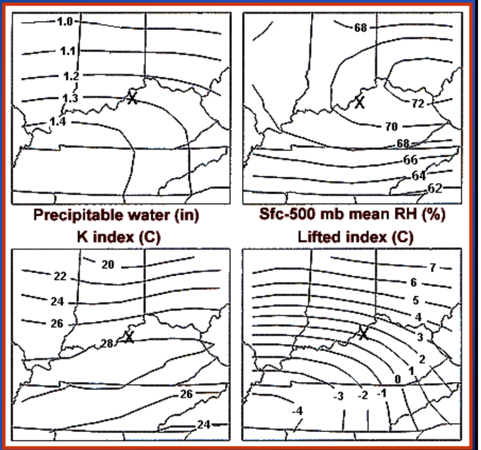


Precipitable water (in)

Sfc-500 mb mean RH (%)

K index (C)

Lifted index (C)



Precipitable water (in)

Sfc-500 mb mean RH (%)

K index (C)

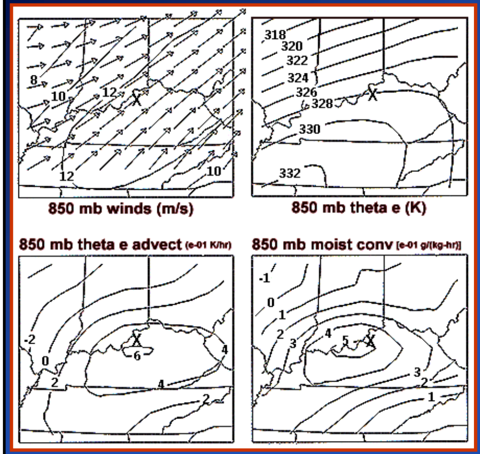
Lifted index (C)

"X" = composite location of centroid of heavy rainfall versus various parameters

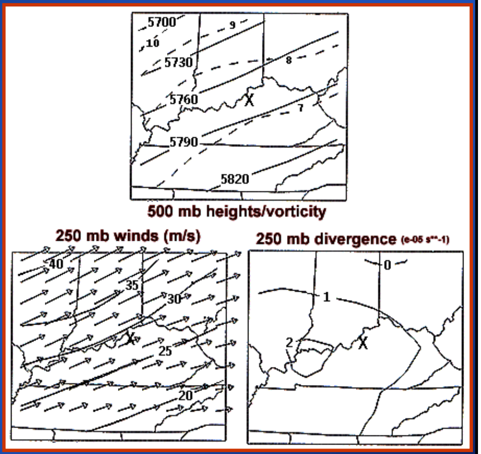
Frontal Stable: Heavy rain occurs just downwind of max values of PW and K index, but within highest mean RH. Events associated with stable ambient LI values, with lower, but still stable values upstream.

Frontal Unstable: Differ from Frontal Stable as ambient/upstream instability is higher, resulting in elevated storms. Also, moisture values often are higher in Frontal Unstable events, which are displaced slightly from maximum mean RH area.

Synoptic Maddox: 850 mb & Mid/Upper Level Pattern



850 mb winds (m/s)
850 mb theta e (K)
850 mb theta e advect (e-01 K/hr)
850 mb moist conv (e-01 g/(kg-hr))



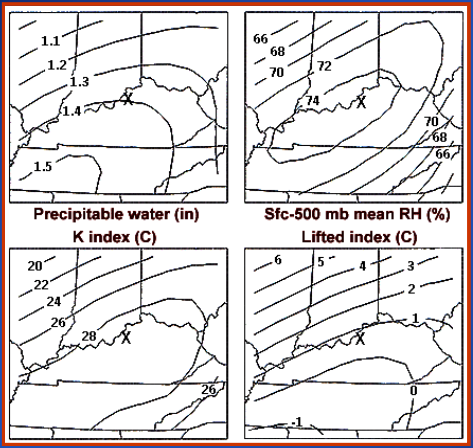
500 mb heights/vorticity
250 mb winds (m/s)
250 mb divergence (e-05 s**-1)

"X" = composite location of centroid of heavy rainfall versus various parameters

850 mb: Heaviest rain occurs within axis of 850 mb jet and along/just left of pronounced ridge axis in theta-e. Theta e values generally are higher than in frontal events. Moisture convergence and positive theta-e advection also are common.

Mid/Upper levels: Flow aloft southwesterly and nearly parallel to low-level front; allows for slow system movement and prolonged period of heavy rain. Rain positioned south/ east of upper-level jet, within/near right entrance region where divergence prevalent.

Synoptic Maddox: Moisture/Instability Pattern

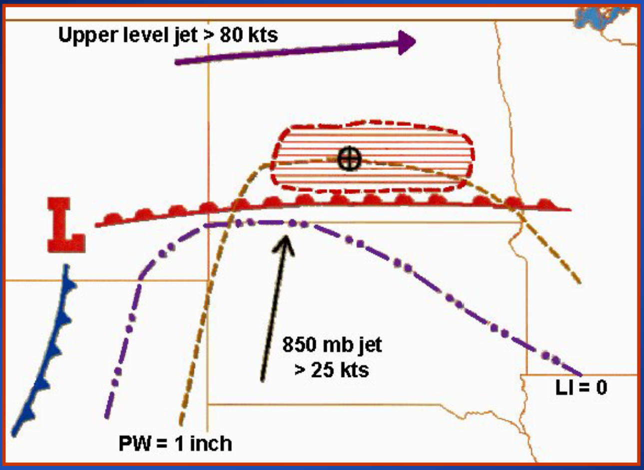


Precipitable water (in)
Sfc-500 mb mean RH (%)
K index (C)
Lifted index (C)

"X" = composite location of centroid of heavy rainfall versus various parameters

Synoptic Maddox: Heaviest rain occurs along a pronounced ridge axis in moisture (PW), K index, and mean RH. Ridge axis is oriented nearly parallel to low-level front and mid and upper-level flow. Varying degrees of instability are present in individual events, depending on time of year.

Heavy Rain Pattern in the Northern Plains



A common heavy rain pattern in the Northern Plains is elevated convection, where the MCS centroid (black plus sign) is north of a warm/stationary front with moist, unstable inflow feeding the MCS from the south, and a jet streak north of the area of heavy rain (red hatched area).

From Vic Jensen, WFO Bismarck

Why Numerical Models Have Forecast Problems

- Initialization and quality control smoothes data fields; some of the lost detail may be important
- Small changes in initial conditions can lead to large forecast variations with time; this is the basis for ensemble forecasting which offers a way to judge some of the uncertainty in initial conditions
- Lack of data over the oceans
- Atmospheric processes are non-linear
- Small-scale processes can affect the larger scale, thus hampering a model's solution with time
- Terrain may not have sufficient resolution in the model
- Model physics are approximations: for lower resolution models, convection is parameterized (since grid spacing to too large to handle convection explicitly); for higher resolution models, microphysical processes are parameterized
- When convective parameterization kicks in, it changes the vertical stability, redistributes and generates heat, redistributes and removes moisture, redistributes momentum, and makes clouds; parameterization problems also can lead to erroneous latent heat feedback and precipitation bulls eyes
- Radiational processes, evapotranspiration, and some boundary layer processes also are parameterized in some models, which can affect temperature, moisture, and therefore, stability

Numerical Model Handling of MCSs and QPF

- Numerical models DO NOT handle MCS and convective QPF well; some reasons why include:
  - Lack of resolution
  - Convective parameterization schemes have weaknesses
  - Lack of explicit handling of convection
  - The scale of convergence and lifting associated with low-level boundaries (that may be important for convective development) may be too small to be resolved well by model forecasts
  - Instability/CAPE and convective inhibition are not predicted well by models
  - Current models have a very difficult time handling convective cold pools, outflow boundaries from storms, and subsequent propagation
  - Models’ convective QPF is even more suspect given weak synoptic scale forcing
- Thus, concentrate on which model appears to be best handling the mass and wind fields, then modify its QPF based on pattern recognition, expected processes, known model biases, expected movement and propagation, and your knowledge of the mesoscale environment

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Rules of Thumb for Predicting Heavy Rainfall

Rules of thumb are based on experience and subjective analysis of heavy rain events. You must know the meteorological reasoning that supports the rule! No rule of thumb will apply to all situations, and should NOT be used in lieu of a thorough scale analysis and application of processes appropriate to the individual situation.

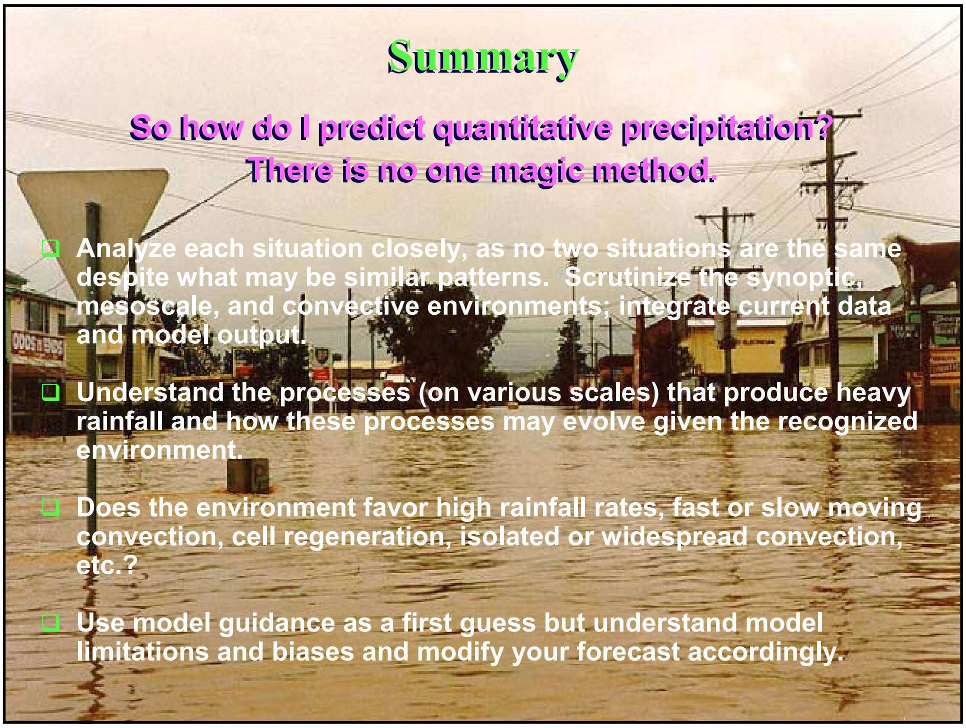
- Be aware of features that will increase the intensity, duration, and area of heavy precipitation; e.g., need plentiful moisture and rapid replenishment of that moisture
- Rainfall maximum often occurs along or near the low-level theta-e ridge axis just north or northeast of maximum theta-e values (best low-level thermal forcing)
- Inverted isobars along a front (inverted trough) can signal heavy rainfall potential, given sufficient moist inflow; usually associated with low-to-mid-level warm advection with lower surface pressure upstream
- Heavy convective rainfall can occur within a thickness difluence area along or ahead of a cold front, implying an upper-level jet exit region or the southern edge of the westerlies; heavy rain also can occur within a thickness gradient zone for elevated convection north of a west-east warm/stationary front
- Beware of thickness lines or temperatures that hold steady or sink southward in the face of southerly low-level warm advection and inflow; this indicates strong adiabatic cooling from strong ascent that could result in heavy warm/cool season precipitation

Rules of Thumb for Predicting Heavy Rainfall

- K indices are a good measure of deep moisture; values above 35 show very good potential for heavy rainfall; even in winter, a ridge axis of relatively higher values may signal heavy precipitation potential
- Beware of tropical connections as observed in water vapor imagery as moist mid and upper levels can result in higher precipitation efficiency (increases collision/ coalescence); also reduces the need for low-level moisture to seed (moisten) mid and upper levels during ascent
- Strong height falls/shortwaves and/or fast moving systems usually preclude prolonged heavy rainfall amounts, although rainfall rates still could be high; instead, a large area of moderate rainfall amounts is more likely; weak/no height falls/ shortwaves aloft may be more conducive to prolonged heavy rainfall so that significant low-level moist inflow and forcing are not interrupted
- A favorable upper-level jet structure can enhance heavy rainfall rate potential, especially within cyclonically-curved exit regions, and anticyclonically-curved right entrance regions; actual amounts depend on storm propagation
- Rainfall efficiency from one storm to the next on the same day can be different depending on storm-scale processes and boundary/cell interactions
- The maximum rainfall usually occurs where the center of the strongest inflow intersects a boundary, resulting in strong low-level moisture convergence

Rules of Thumb for Predicting Heavy Rainfall

- MCSs often form near a mid-level ridge axis where warm advection is maximized and where neutral inertial stability or instability exists; also beware of a jet streak approaching a ridge axis
- In summer, heaviest rainfall often occurs along/near outflow boundaries, which can exist south of a warm front; denser convective cold pool has an easy time pushing into the warm/less dense air mass south of front, thus outflow boundary becomes effective focusing mechanism
- Watch for convection behind a weak mid-level vorticity maximum or near a vorticity minimum if low-level thermal ridging and moisture convergence remains, which can allow convective to reform despite the lack of mid/upper-level support
- Beware of slow moving synoptic circulation elevated convective events, often within or on the southern edge of a comma type satellite signature associated with deformation/frontogenesis within a strong low and mid-level system
- Due to organized moisture convergence, the maximum convective rainfall usually occurs within the core/center of the remnant of a tropical system at night, rather than daytime peripheral activity
- Numerical models often forecast the synoptic pattern, low-level jet, and moisture distribution reasonably well, but normally cannot handle mesoscale details and outflows that dictate convective locations, propagation, and rainfall amounts



Summary

So how do I predict quantitative precipitation? There is no one magic method.

- Analyze each situation closely, as no two situations are the same despite what may be similar patterns. Scrutinize the synoptic, mesoscale, and convective environments; integrate current data and model output.
- Understand the processes (on various scales) that produce heavy rainfall and how these processes may evolve given the recognized environment.
- Does the environment favor high rainfall rates, fast or slow moving convection, cell regeneration, isolated or widespread convection, etc.?
- Use model guidance as a first guess but understand model limitations and biases and modify your forecast accordingly.