Threat Assessment

Advanced Warning Operations Course

IC Severe 2

Lesson 1

Outlook and Short-Term Assessment

Warning Decision Training Branch

The title for this Instructional Component (IC) is “Threat Assessment.” This is the 2nd instructional component for the AWOC Severe Track. Lesson 1 in this IC is on outlook and short-term assessment of hazards.

AWOC Severe Track Training Components

IC 1 – Conceptual Models

IC 2 – Threat Assessment

IC 3 – Storm Interrogation Strategies

IC 4 – Application and Review

This IC (one of 4 in Severe Track) is devoted to environmental threat assessment. There are 3 lessons in this IC.

The IC will address the process for evaluating the threat for severe weather hazards (hail ,high winds, flash flooding, and tornadoes). Background for this training is from PCUs 3 and 4 in the Severe Convection Forecasting and Warning PDS. See http://www.nwstc.noaa.gov/nwstrn/d.ntp/meteor/svrpds.html.

IC2 Performance Objective

- Demonstrate processes for continuous evaluation of hazardous weather threats (tornadoes, damaging winds, hail, and flash floods) to support effective warning methodologies.

The performance objective (the desired trainee behavior from training) for this IC is to demonstrate the ability to monitor the mesoscale environment to anticipate and identify storm types, storm evolutions, and hazardous severe weather threats to support severe weather warning methodologies. This would include some of the following:

1) Demonstrating ability to coordinate with SPC and adjacent WFOs on watch decisions (for ex. watch extensions and cancellations)
2) Demonstrate the ability to utilize full suite of products to issue short-term forecasts of convection.
3) Demonstrate ability to monitor mesoscale conditions (including near-storm environment) and provide input to warning decisions based on that data.

IC2 Outline

Lesson 1: Outlook and Short-term Assessment

Lesson 2: Lifting Mechanisms

Lesson 3: Updraft Persistence

These are are the 3 lessons in this IC.

Lesson 1 Learning Objectives

1. Identify purposes of threat assessment
2. Identify key job tasks for threat assessment for 0 to 24 hour time period
3. Identify 3 key job tasks for threat assessment in the 0 to 6 hour time period

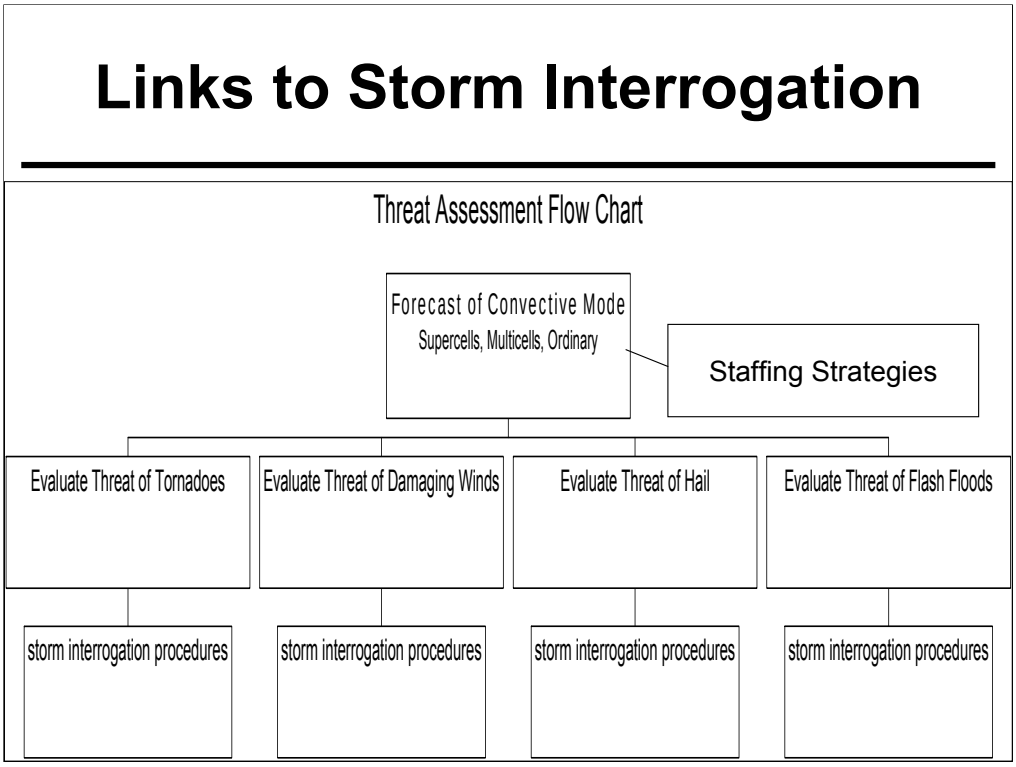
These are the learning objectives for lesson 1. The test will cover all objectives from all three lessons in the IC.

Purpose for Threat Assessment

- TA determines what products/procedures will be used in warnings
- TA is a key factor in establishing mental models for the entire event
- TA sets the tone for severe awareness (anticipation factor) in local office and user community

Threat assessment (TA) is an important part of an effective warning methodology. It is important in determining the tone of awareness for the subsequent event. This step enables the severe weather warning team to begin to focus on specific threat areas and specific storms within the CWA (how to initially sectorize the CWA for severe weather operations). By assessing the spatial and temporal evolution of the mesoscale convective environment, forecasters can improve their decision making skills because they can acquire an increasing knowledge of the perceived level of threat for each storm. Threat assessment is a continuous process, not a one-time action. Thus, many of the key job task skills presented here are applicable throughout the entire severe weather event, especially during warning mode, because forecasters often lose their situational awareness of the environment once warnings commence.

The assessment of potential hazards influences what radar products you might look at and how you will look at them , which is related to interrogation strategies (one of the steps in a warning methodology). One way to think about this is that there is a range of possibilities for all severe weather. After the synoptic and mesoscale assessment, you have narrowed down your expectations. When storms develop and you detect them on radar, you then compare that data to the mental images that have been processed in your brain. Even though the initial expectations provide an important working framework for subsequent warning sequences, individual and collective expectations must be re-evaluated during the event . This is another vital part of warning methodologies.



Environmental threat assessment influences subsequent actions in a warning methodology. There is an initial assessment of convective storm mode (supercells, multicells, or ordinary convection) , then an evaluation of specific hazards. These threats for each storm help determine interrogation procedures.

Threat Assessment
Outlook Phase (0 – 24 hr)

- Applies climatology and pattern recognition
- Includes synoptic/mesoscale analysis
- Evaluation of model signals and parameter output (forecast fields/soundings)
- Evaluate accuracy of model fields (impacts of convection)

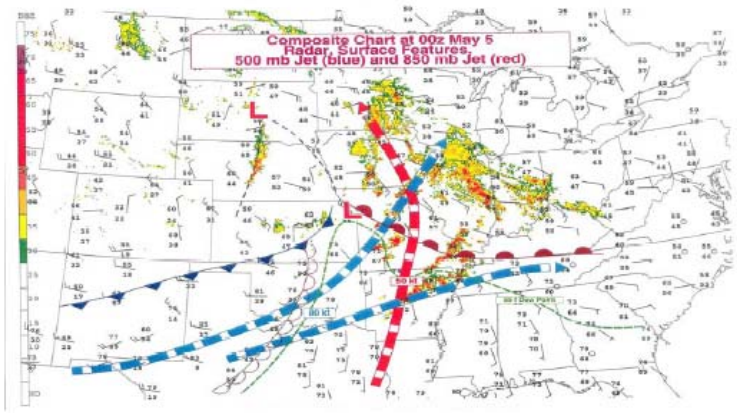
An important aspect of threat assessment is comparing observations to known patterns. The role of climatology is important in recognizing relative seasonal threats. As you analyze large scale features and make the forecast for potential severe weather, it is important to not get caught up in evolution of model details, but try to target relative threats from the potential convective storm types.

The evaluation of the quality of model fields, especially at 24 hrs, is an important factor in conducting threat assessment. Strong synoptically-forced events are often much better handled by the models than events where the synoptic forcing is weak and/or mesoscale is the critical aspect for the environment. Another important task in this phases is knowing how the model handles convection and the results of the convection on other fields.

Methodically, the process includes analyzing fields of shear, available potential buoyancy, potential storm/system movement, and all potential lifting mechanisms. These would help you define the highest threat areas within the CWA. Hourly model forecast soundings can help you to predict convective storm mode and evolution. Coordinate your forecasts with the SPC outlooks, mesoscale discussions and watches.

Pattern Recognition Ex. 1

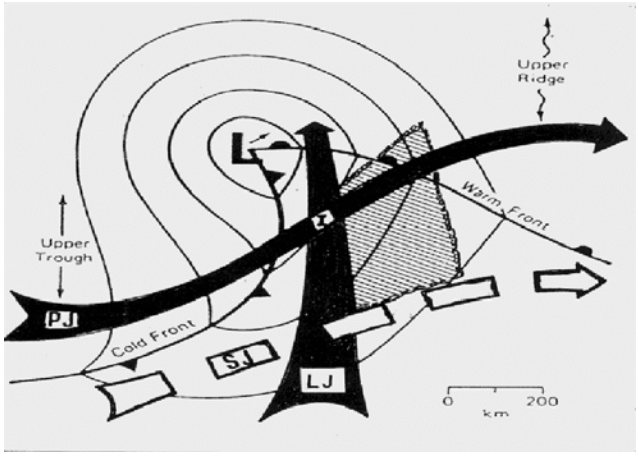
Does this …



It is important to compare synoptic patterns to analog events.

Pattern Recognition Ex. 1

Look like this?



Classic Tornado Outbreak Pattern
(from Newton, 1967)

This is a pattern well known to severe storm forecasters (see http://www.nwstc.noaa.gov/METEOR/SynPat/synpat_main_frm.htm).

Pattern Recognition Ex. 1

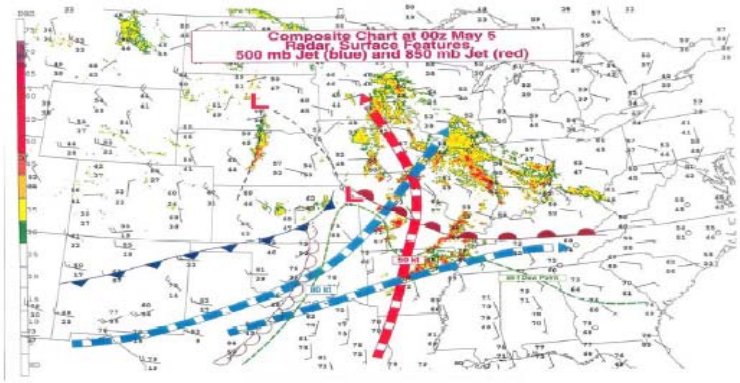
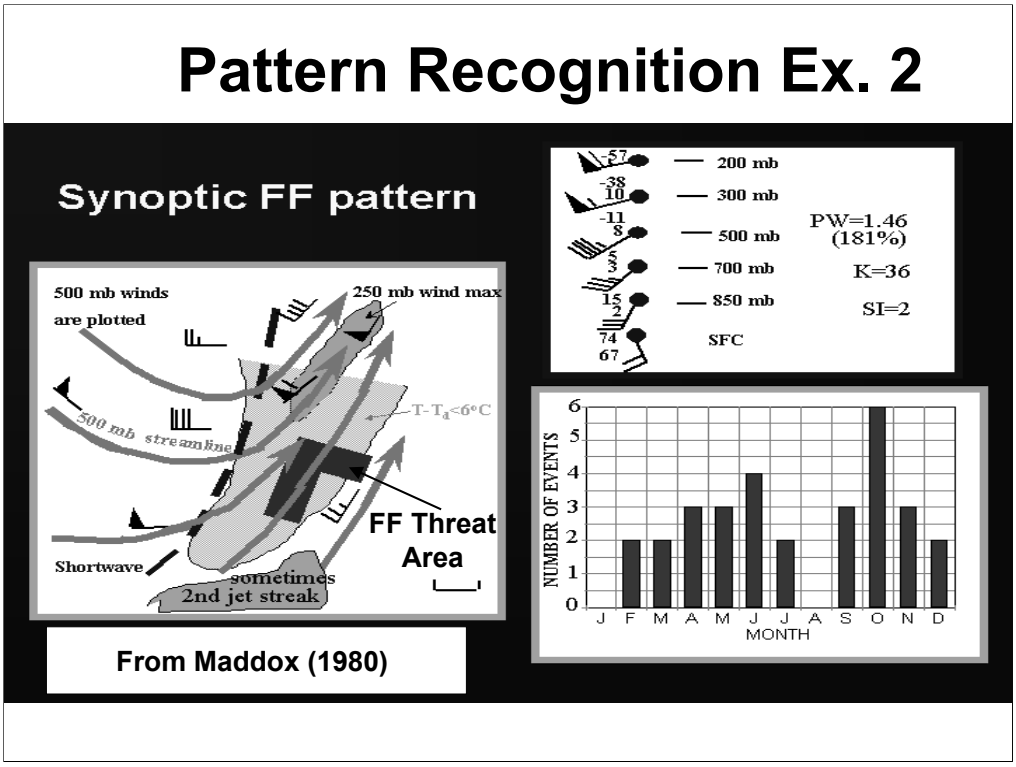


Figure 2. Composite Radar Reflectivity, Surface Fronts, 500 millibar and 850 millibar jet streams at 0000 UTC, (7:00 p.m. CDT May 4, 2003) May 5, 2003. Courtesy of SPC.

From NOAA/NWS Service Assessment of May 4-10, 2003 Tornado Outbreak

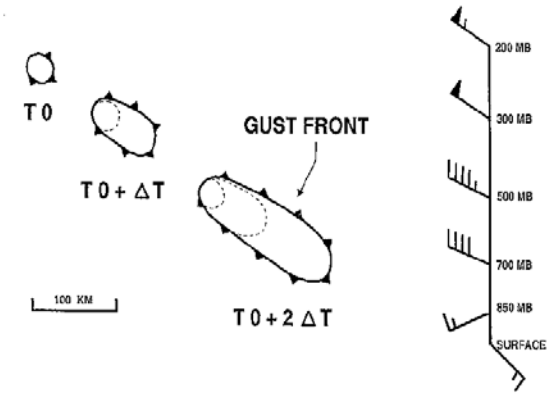
For more details on the May 4, 2003 tornado outbreak, which was a well forecast event, see http://www.noaanews.noaa.gov/stories/s1136.htm.



Another pattern to recognize, this one for heavy rain/flash floods events from Maddox (1980).

Pattern Recognition Ex. 3

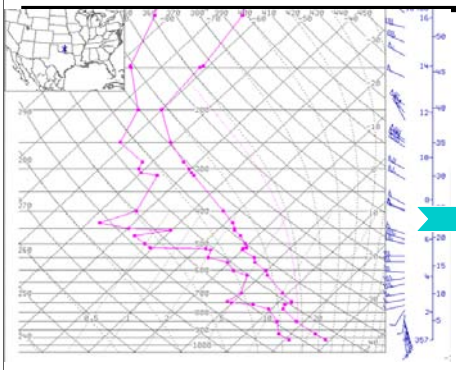
- For Forward Propagating MCSs (Corfidi, 2003)
  - System-relative convergence and instability present in downshear direction
  - Produces forced ascent along gust front
  - Propagation occurs in the downshear direction



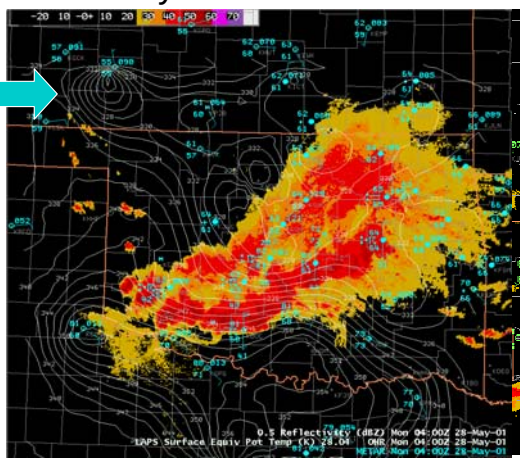
This one is for forward-propagating MCSs (Corfidi, 2003).

Pattern Recognition Ex. 3

Anticipating Forward Propagation



28 May 01 00 – 07Z



1) 50-60 kt WNW winds, dry air in midlevels (~ 500 mb)
2) Strong (3000-4000 J/Kg) downstream SBCAPE
3) Inflow vector ~180 deg of cloud bearing wind direction

There are 3 ingredients for forecasting the potential a downstream (or forward) propagating MCS motion based on Corfidi (2003):

1) Relatively dry conditions in midlevel and/or in the subcloud layer (to increase tendency to produce strong convective-scale downdrafts)
2) Storm-relative inflow strongest on the periphery of the cold pool (portions of gust front oriented parallel to the mean wind vector)
3) Surface-based instability is present downshear.

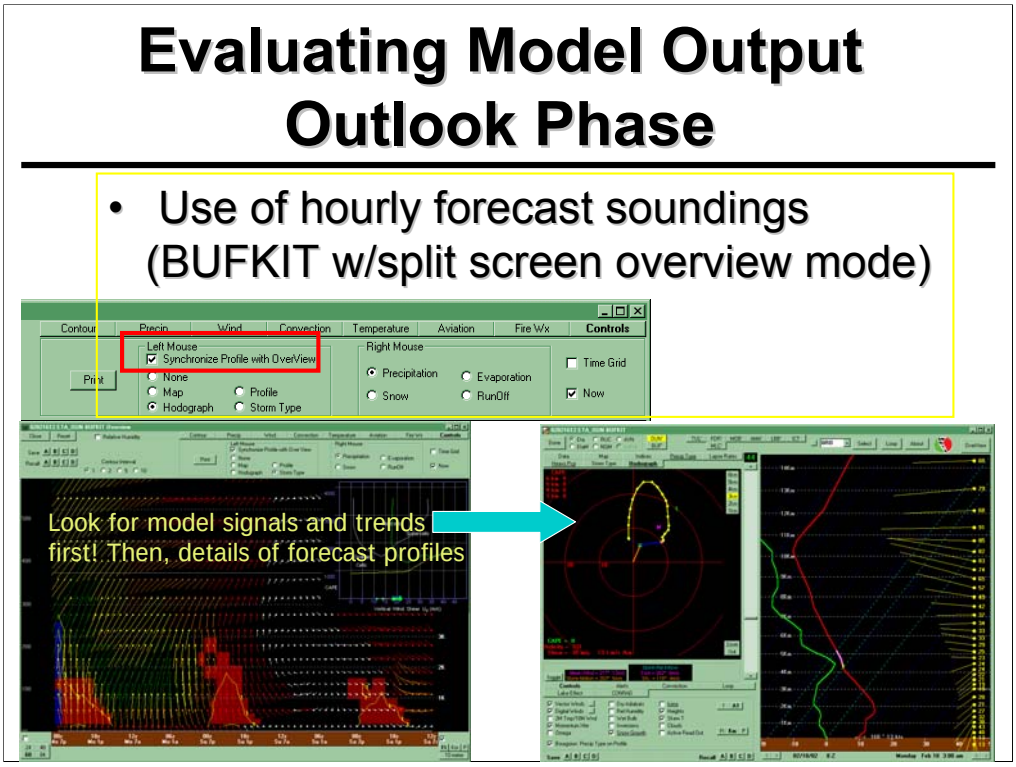
Evaluating Model Signals and Parameter Output

- Once confidence in model solution is established:
  - Evaluate output (from plan view plots and forecast profiles)
  - Verify threat assessment

Establishing confidence in the model solutions involves several components that include, but are not limited to, these factors:

1) Knowledge of the model characteristics (fundamentals, strengths and weaknesses)
2) Knowledge of the role of precipitation, cloud and convective parameterization schemes
3) Knowledge of post-processing of model data
4) Knowledge of model physics
5) Knowledge of model data assimilation and initialization problems

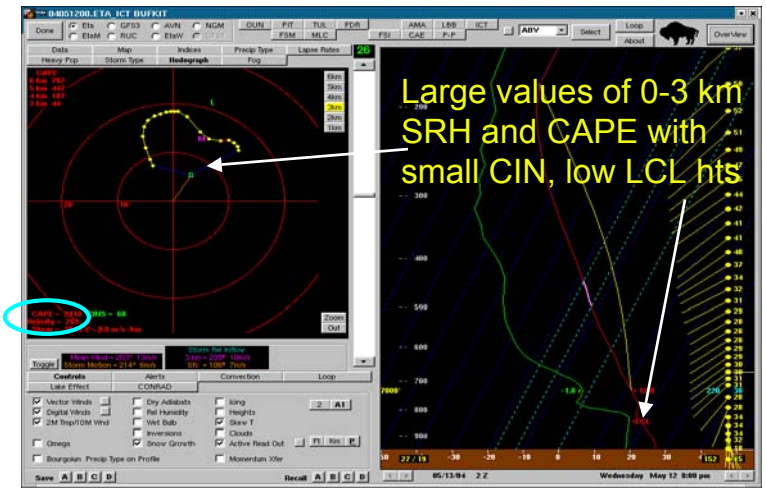
For example, model convective precip. can affect the model precip forecast and models soil moisture availability , which will affect evaporation and subsequent boundary-layer dewpoints and CAPE. Incorrect timing, placement, and amount of model precip can cause errors in the model forecast variables, even if they are treated in a consistent, physically realistic manner. Model soundings are affected where model convection occurs, and these effects are advected downstream. For more information on model precipitation and cloud parameterization issues, visit the COMET NWP web site at http://meted.ucar.edu/nwp/pcu1/ic3/index.htm.



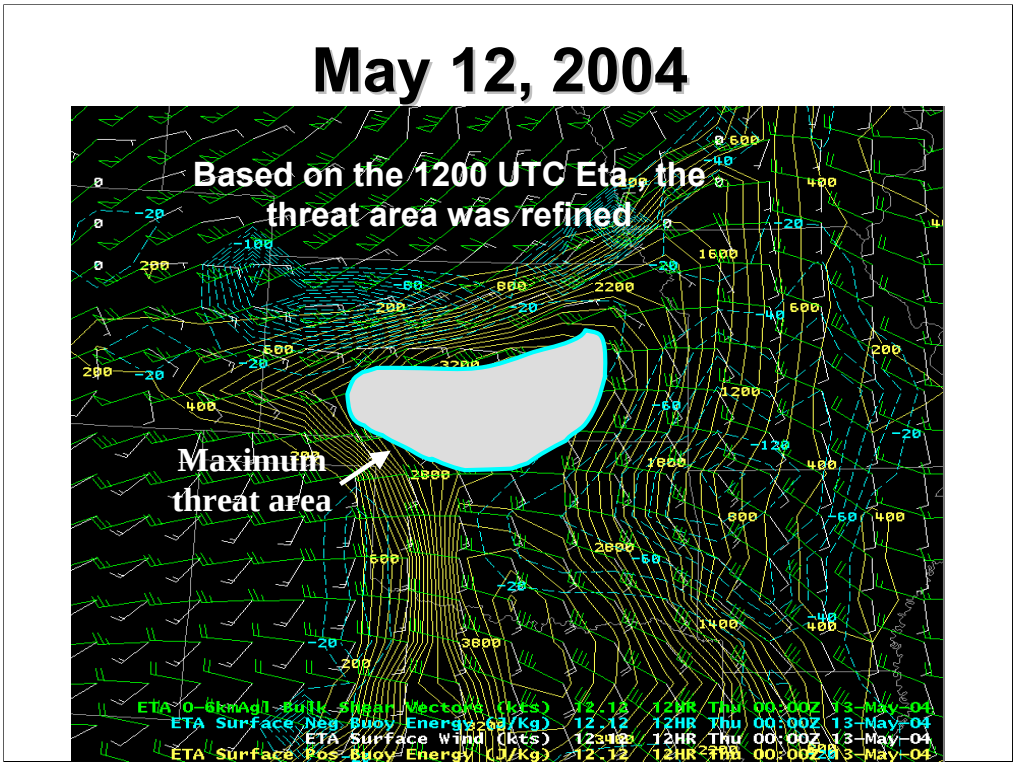
With the split screen mode and synchronized profile with overview option on BUFKIT, one can more easily analyze model signals and process single forecast profile output (See http://wdtb.noaa.gov/resources/projects/BUFKIT/index.html) for the latest version of BUKIT.

May 12, 2004

- **Model forecasts for 36 hours out indicated a high potential for tornadic supercell storms in Southern KS/Northern Oklahoma**

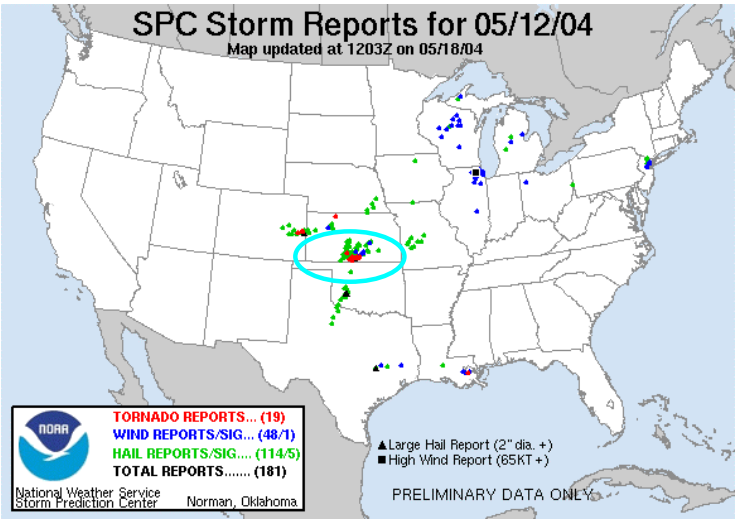


Note this is a 36 hr forecast!



The 12z Eta was suggesting a high potential for tornadic supercells in Southern KS by 00z

May 12 Results



Reports were concentrated in south central KS where the models were showing the highest threat would be.

Threat Assessment
Short-Term Forecast Phase (0 to 6 hrs)
3 Key Job Tasks

1. Initially define storm interrogation process
2. Analyze mesoscale environment to determine changes that may affect model and public forecasts
3. Determine representativeness of environmental data
4. Provide warning forecasters with continuous decision inputs of environmental data

Proper threat assessment on the mesoscale adds accuracy to the initial convective outlook process. The analysis of mesoscale data helps to determine when and where convection will develop, and, on some occasions, may yield clues to the probability of a specific hazard occurring. Since thunderstorms are a function of the environment within which it forms, if we can understand that environment, we have an advantage when it comes to accurately warning before events occur (i.e. increasing lead times). Thus, with environmental recognition of parameters we achieve heightened awareness of threats (for significant tornado events for example). The goals of these efforts are improved warning service. This phase is difficult because of the level of effort that must be made to ensure the assessment is thorough. It is also difficult because of the level of uncertainties in the data sets used in the analyses. How can forecasters provide useful information in a short-term threat assessment which supports the ongoing warning methodology? There are several ways. We will discuss briefly all 4 key tasks shown here.

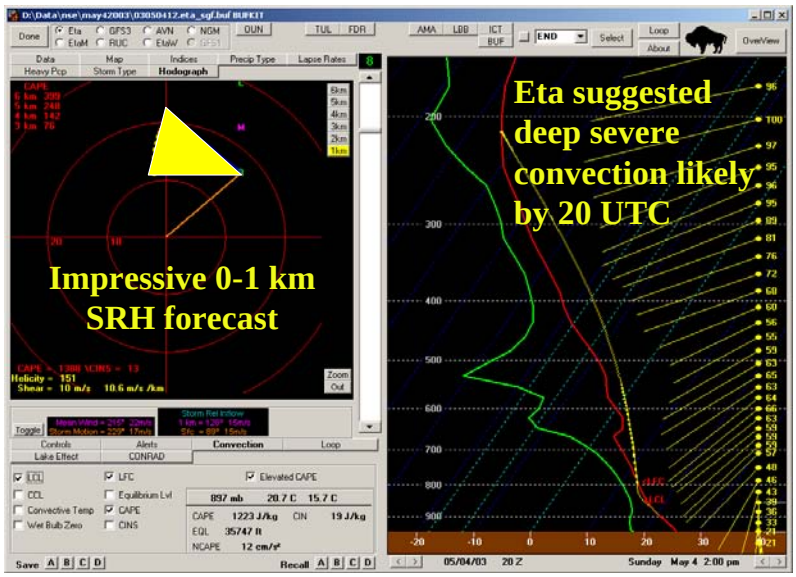
It is important to note that time and **data quality** are big factors in this process. How good are the objective analyses (OA) of thermodynamic and kinematic fields that are displayed on AWIPS? Are there observations to support the analysis? Important questions to ask as this component is performed in the warning methodology. Try to improve your local OA by getting more observations into the analysis. As time approaches the expected severe event, you will typically be analyzing mesoscale features using observed data and high-resolution models. Remember, this information will help you determine how you will interrogate these storms and can have a very strong influence effect on how you weigh radar and other information in the eventual warning decision.

Short-Term Assessment (0-6 hr) "Nowcasting"

- Determine mesoscale (or storm-induced) changes to current forecast
  - July 2, 1997 (Lower Michigan tornado outbreak)
  - April 21, 2001 (Hoisington, KS tornado)
  - May 31,1998 (NY tornado outbreak)
  - Check the WES Case Library

Many of these cases have been developed into good training cases and are available from the Convective PDS web site at http://www.nwstc.noaa.gov/nwstrn/d.ntp/meteor/svrpds.html.

May 4, 2003 12z Eta

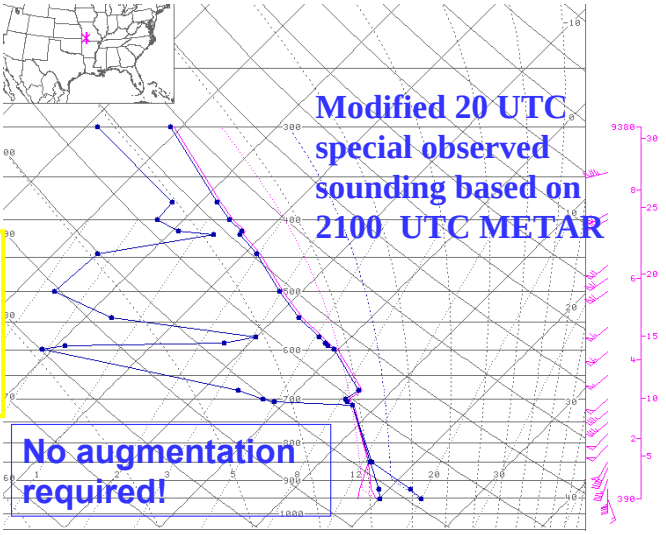


This is an example of short-term threat assessment. Based on the model forecasts, both the low-level CAPE (0-3 km CAPE = 76) and Shear (0-1 km SRH = 151 m2/s2) were very favorable for significant tornadic development. LCL height = 3137 ft (957 m) AGK, LFC = 4916 ft (1500 m) AGL.

The model signals were indicating increasing probability for tornadic supercells. But, could observations tell us even more?

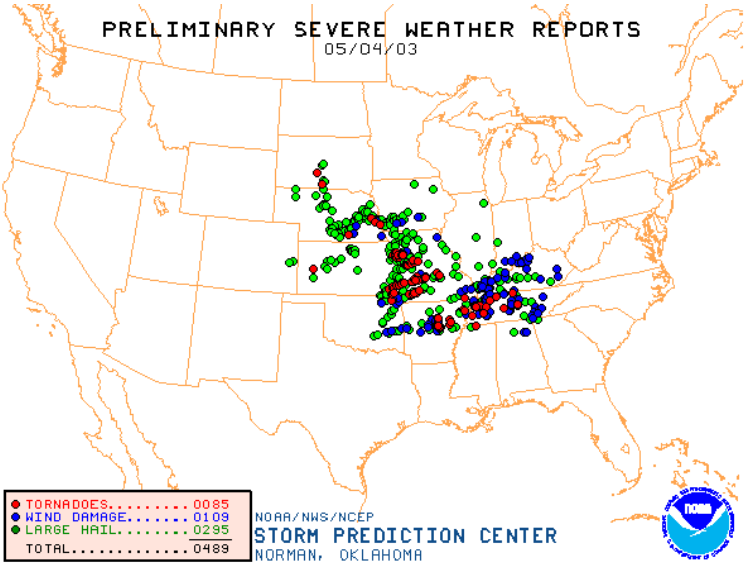
May 4, 2003 20z - Observed

- Turned out the moisture was even deeper than Eta forecasted and surface dew points 2-3 deg F higher.
- LCL ht = 2100 ft (640 m)
- CIN ~ 6 J/kg
- SBCAPE ~ 3068 J/kg
- SRH (0-3km) = 522 m2/s2



Much more impressive parameters from observed sounding (no storm influences either!). This mesoscale sounding indicated that conditions were already extremely high in terms of tornado potential, and that most storms that developed were going to be tornadic once they developed – and they did.

May 4, 2003 Results



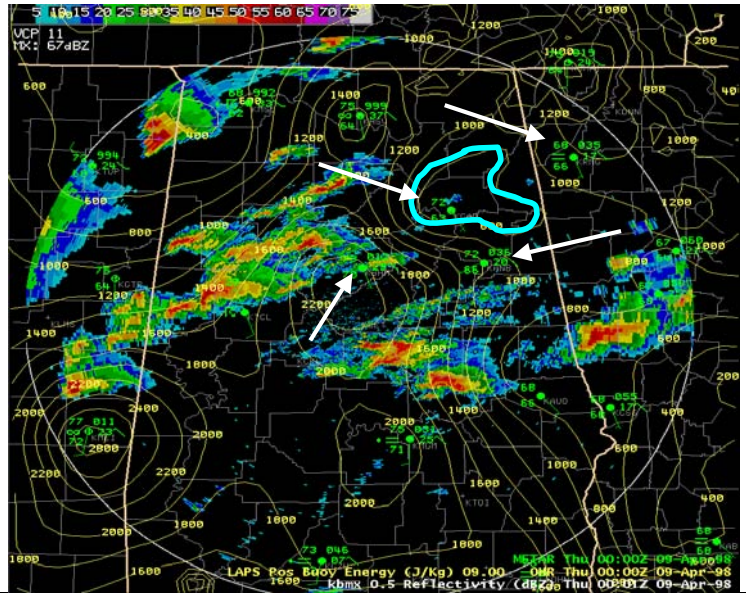
Short-Term Assessment (0-6 hr) "Nowcasting"

- Important to evaluate the representativeness of the data
  - How to "quality control" the model analysis
  - How to anticipate how convection will modify its environment

It is important to QC environment data because using "bad" data can be an impediment to effective warning methodologies. Misinterpreted or inappropriate data can mislead the warning team.

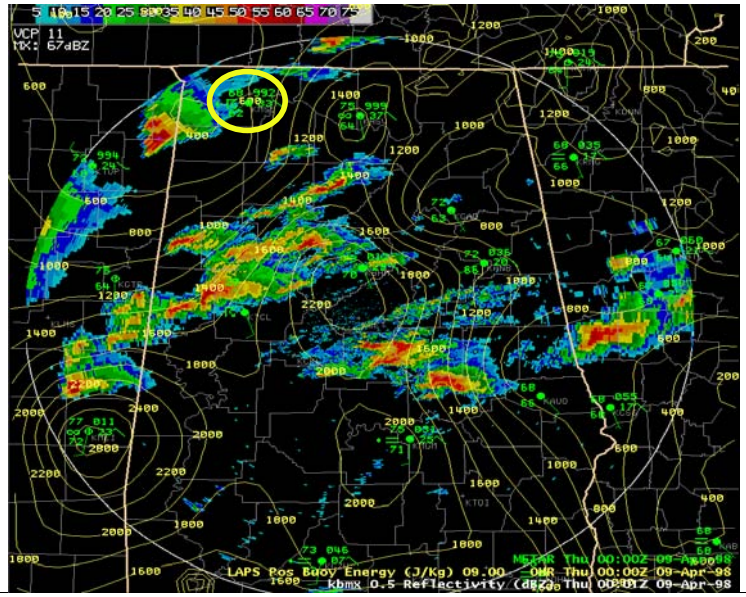
Most staffing strategies recommend a dedicated threat assessment forecaster, due to this reason.

QC-ing Model Forecast
April 8, 1998



Look at this area in northeast AL. How does the CAPE analysis compare to the observations?

April 8, 1998



Look at this area in northwest AL. How has CAPE LAPS analysis been affected by the 00z ob at MSL?

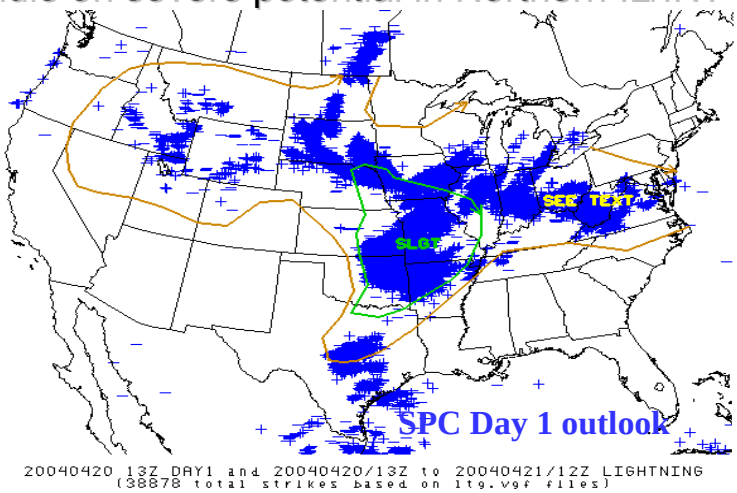
QC-ing Model Forecast

- LAPS and RUC often show spurious signals in CAPE fields
- April 8 ,1998 WES case is a good case to evaluate the “goodness” of the LAPS analysis from 22-01 UTC

Check out this WES case at
http://www.wdtb.noaa.gov/resources/docs/simulationguide/

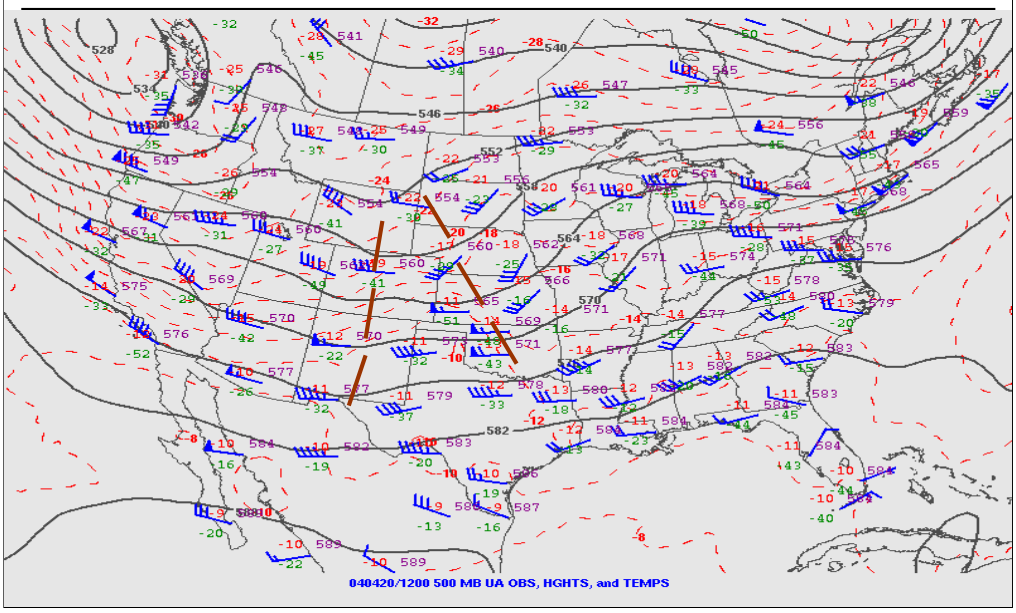
Evaluating Representativeness of Model Data – 4/20/04

- Did the models and current forecasts have a good handle on severe potential in Northern IL/IN?



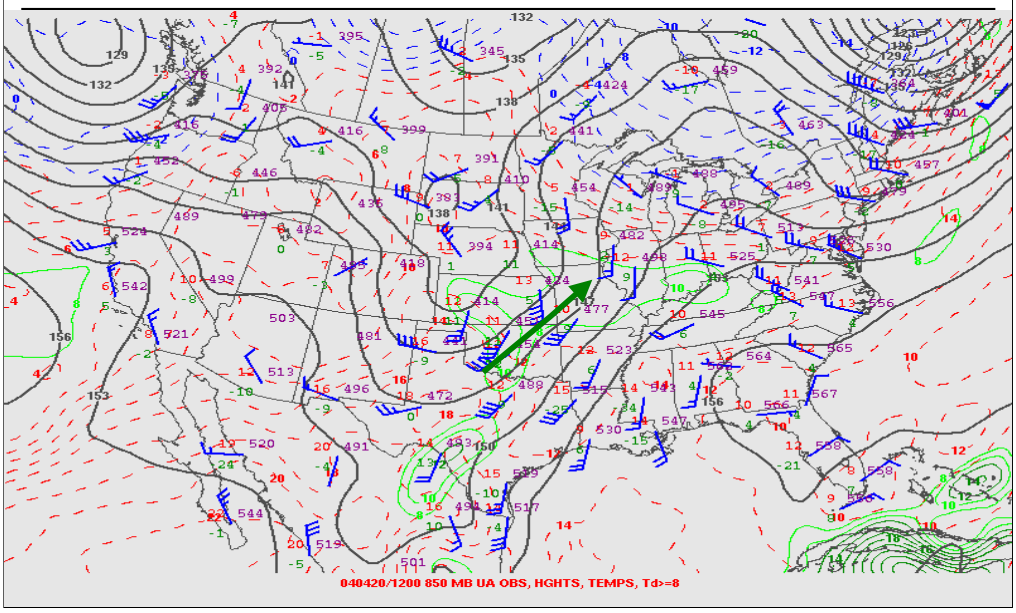
No risk of severe in northern IL/IN. Let's see what happened.

Evaluating Representativeness of Model Data – 4/20/04



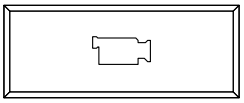
Satellite trends – large scale pattern indicating broad scale lift across central plains into the Ohio Valley (from distinct shortwave troughs).

Evaluating Representativeness of Model Data – 4/20/04



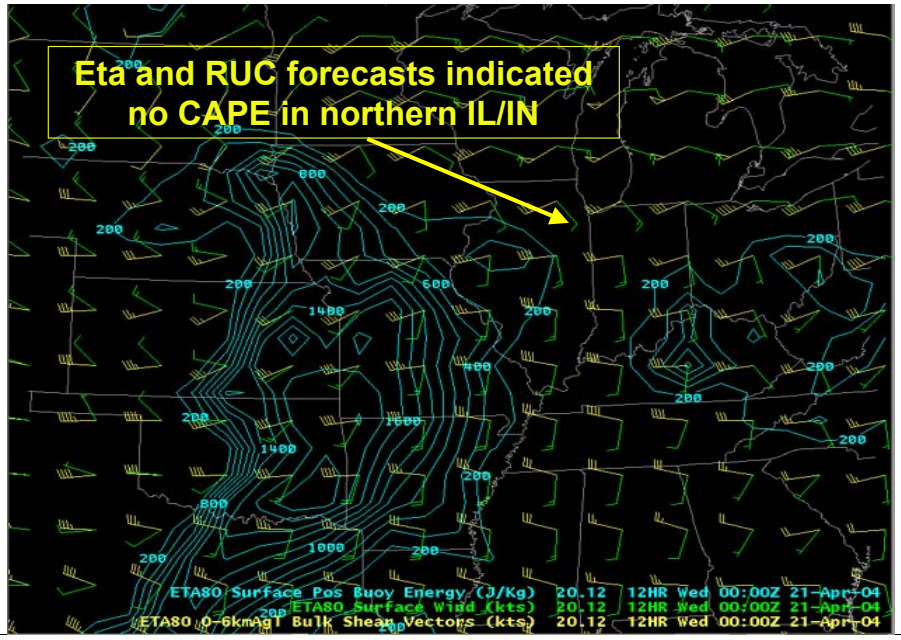
Strong H85 moisture advecting northward into Mid Ms Valley

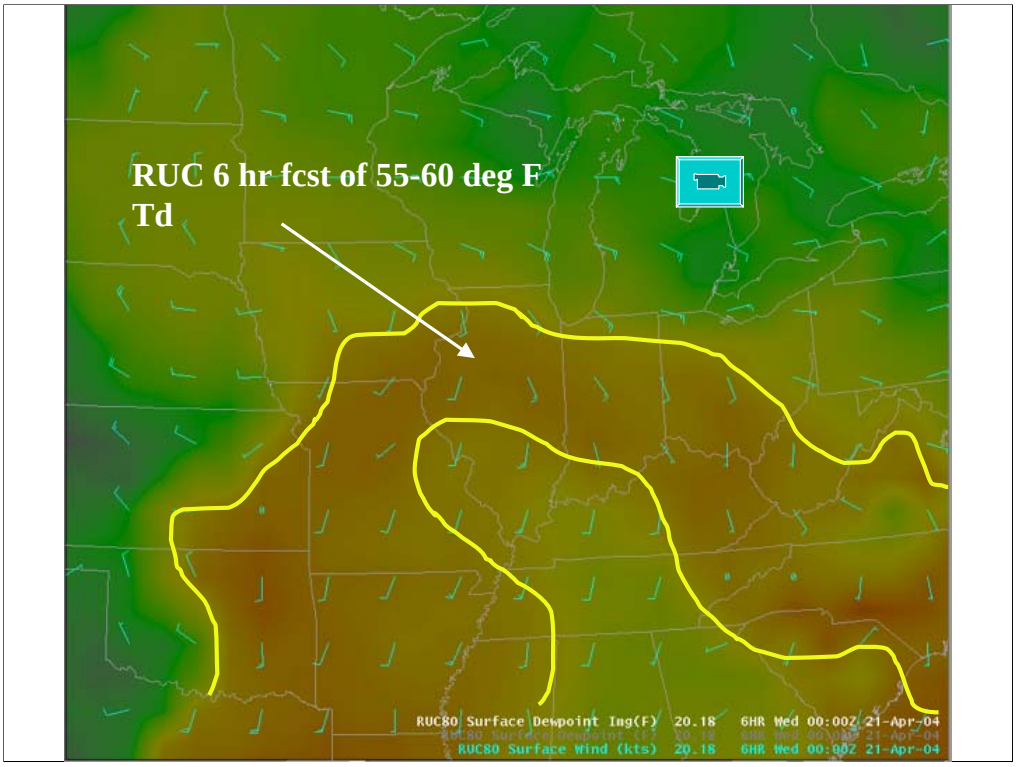
4/20/04 Satellite Loops



There are flash loops showing the satellite imagery.

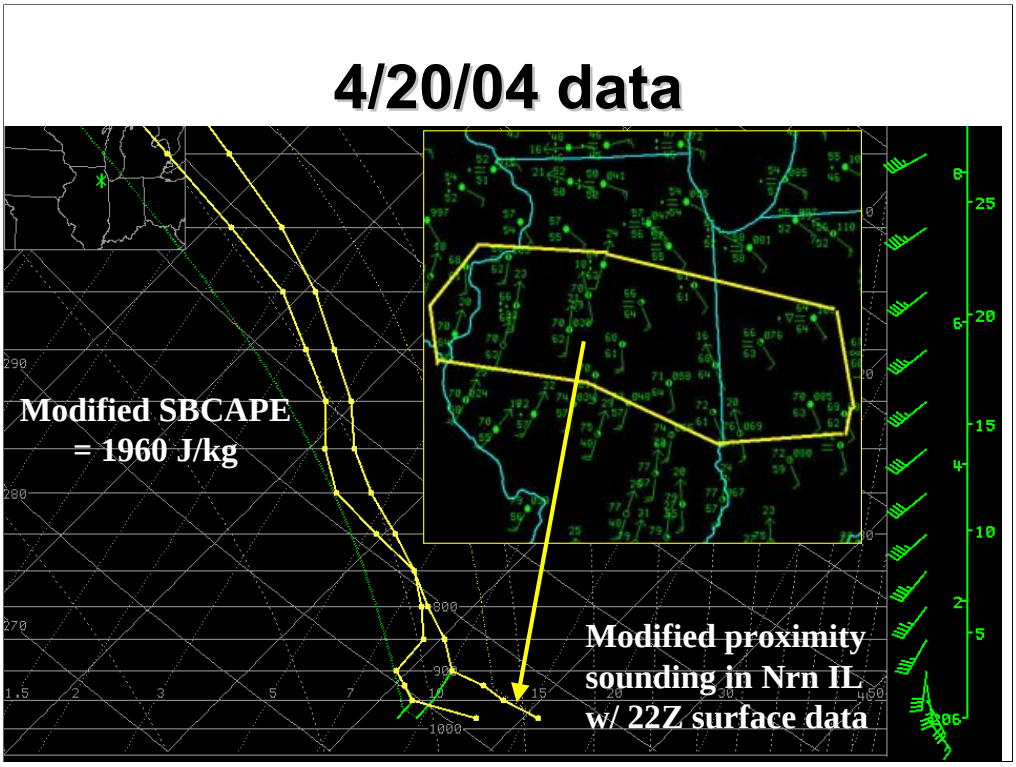
4/20/04 data


Eta and RUC forecasts indicated
no CAPE in northern IL/IN
ETA80 Surface Pos Buoy Energy (J/Kg) 20.12 12HR Wed 00:00Z 21-Apr-04
ETA80 Surface Wind (kts) 20.12 12HR Wed 00:00Z 21-Apr-04
ETA80 0-6kmAgl Bulk Shear Vectors (kts) 20.12 12HR Wed 00:00Z 21-Apr-04



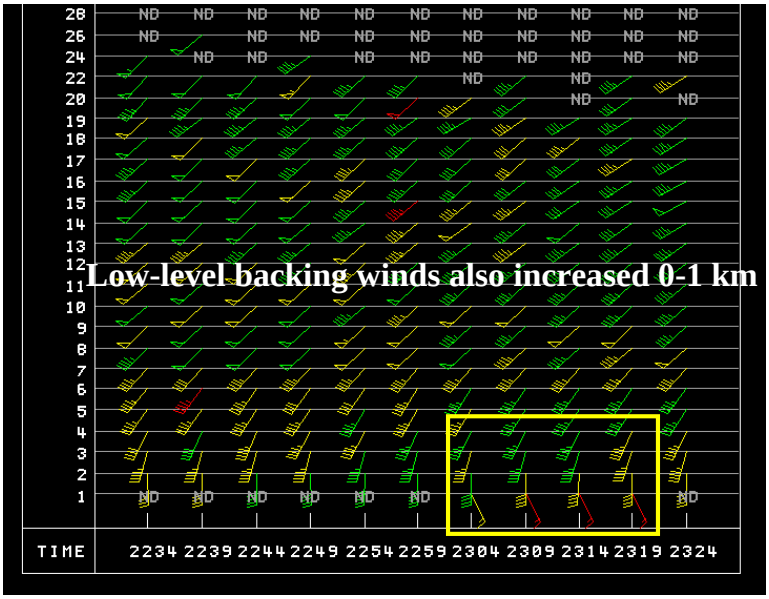
RUC dewpoint temps from 13z to 03z had forecast 60 deg F dewpoints increasing northward into central IL , but that was 5-6 deg less than what was indicated on Metars from 20-23z.

Note the animation of RUC model surface dewpoints

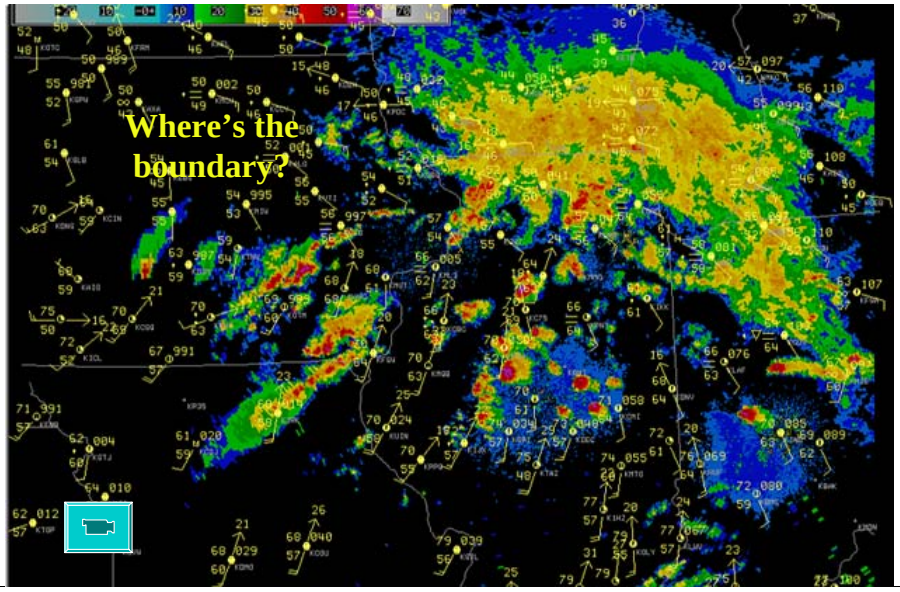


Low-level moisture was (Td > 60deg F) were starting to pool in this region.

4/20/04


Low-level backing winds also increased 0-1 km
TIME
2234 2239 2244 2249 2254 2259 2304 2309 2314 2319 2324

4/20/04



Play loop for evolution . Threat assessment helped forecasters see that the models were way underplaying the low level buoyancy and shear in northern IL/IN. The RUC was too cold and dry.

By the way, interesting supercell initiation along what? (ie. No boundary)

Short-Term Threat Assessment
Key Tasks

- Evaluating mesoscale environment to determine
  - Location of significant lifting mechanisms and associated character of lift
  - Location & timing of severe development
  - Likelihood and intensity of specific hazard (tornadoes, flash flooding, etc.)
  - Evolution of threat (especially movement)

These are some more tasks in general threat assessment, this time in the short-term and in some instances, nowcast phase.

We will discuss most of these in the next lesson.

Lesson 1 Summary

- Threat assessment is a key component in a warning methodology
  - Helps determine storm interrogation procedures
- Involves analyzing mesoscale environment
- Evaluating the “quality” of the environmental data (esp. models)

Threat Assessment

Advanced Warning Operations Course

IC Severe 2

Lesson 2

Lifting Mechanisms

Warning Decision Training Branch

The title for this instructional component is “Threat Assessment.” This is the 2nd instructional component for the AWOC Severe Track. This is lesson 2 on lifting mechanisms.

Lesson 2 Learning Objectives

1. Identify types of lifting mechanisms
2. Identify the factors in evaluating lift
3. Identify the effects of orientation of line of forcing and boundary-relative steering-layer flow on convective evolution

The detection and analysis of lifting mechanisms are crucial components in short-term threat assessment. We will describe types of lifting mechanisms, how to evaluate lift , and look at the details of the lift as it relates to boundary orientation.

Lifting Mechanisms

- Evaluation of lift involves 4 factors:
  - Type
  - Scale (intensity)
  - Duration
  - Details of lift (what is being lifted, how sounding will modify)
  - Orientation (Boundary relative flow, shear vector orientation with respect to boundary, cold pool shear balance)

All lifting mechanisms are not created equal. Boundaries with the greatest persistent convergence would have the highest potential for initiating convection given all other parameters being equal. But it is difficult to define persistence based on our limitations of the observing network. Often what may seem to be convergence could be a bad wind ob, or minor fluctuations in the reported winds. Persistence adds credibility that something is real there. So here are some cautions to evaluating strength of boundaries WRT convergence:

1) Most boundaries converge air on scales too small for even mesonetworks to resolve (Crook 1996).
2) Strength of convergence doesn't always mean deep convergence. A boundary may have strong convergence down low and be capped well below the LFC.

This is a problem especially when the LFC is high and/or if there's a significant capping layer below it. Drylines are notorious for exhibiting strong surface convergence and yet shallow circulations.

One thing to remember is that when looking at the vertical continuity equation, the vertical velocity at some level depends on the integrated values of convergence/divergence below. Vertical velocity is highest at the level of non-divergence where convergence resides below and divergence above. In most cases, the deeper the convergence, the higher the level of maximum vertical velocity will occur.

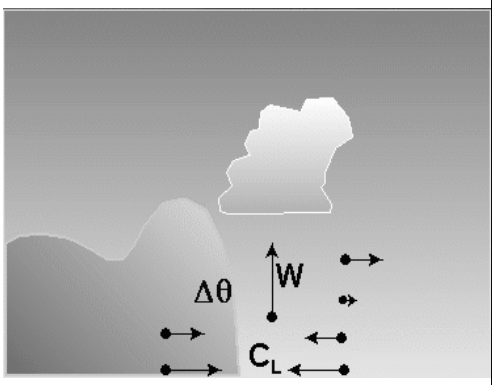
Types of Lift

- Boundaries
  - Evaluate strength by analyzing density gradient at surface and aloft (θ, T, Td, and P)
  - Evaluate convergence by analyzing moisture divergence
  - Best lift when coupled with jets

There are many types of lifting mechanisms, low-level boundaries being the most common. Depending on the scale, observable boundary attributes are location, density gradients, low-level convergence and ascending air. Density gradients produce direct mesoscale ascent, so that's why we analyze direct observables such as T, Td, q, P, and θ (actually θv is the best for density). Convergence can be estimated by calculating differential velocity across the width of the boundary (See http://www.nssl.noaa.gov/istpds/icu92/icu922web/ic922.html for more details). Ascending air, W, can be estimated by integrating values of convergence with height. Estimating one-dimensional convergence assumes a uniform airflow on either side. In other words, a front with no undulations or intersections with other boundaries. Convergence will be higher at intersections, mergers, collisions with other sources of ascent. Convergence is scale dependent. Data from METARs and mesonets will underestimate convergence in boundaries by 2 to 3 orders of magnitude. Model analysis will underestimate convergence similarly. All operational model resolutions are too poor to capture the true width of a boundary. Also, stormscale boundaries are typically unobserved by models. Typical boundaries are 3-10 km wide. Actual convergence will be occurring on these scales. Convergence will be higher at boundary intersections with other boundaries, circulations, rolls. Two dimensional convergence with boundary intersections becomes important since winds vary both along and normal to the boundary axis. Surface convergence may not always mean deep convergence/ascent . A capped atmosphere may limit the depth of even strong surface convergence. Therefore, the deeper the convergence zone relative to the LFC, the more likely initiation will occur.

Observable Boundary Attributes

- Location and movement
- Density gradient, Δθ
  - Except for troughs and HCRs
- Low-level convergence, C_L
  - Change with height
- Observing ascending air, W

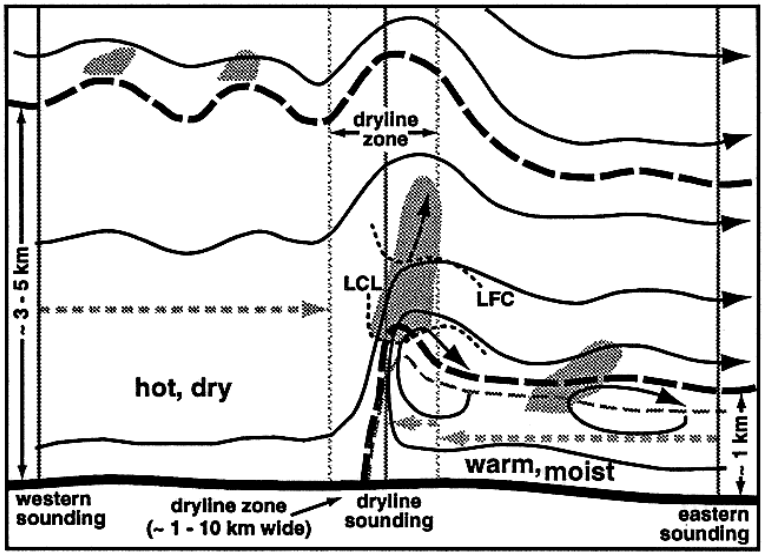


All of these are important when assessing lift

When analyzing boundaries as a potential lifting mechanism, try to evaluate the following:

1. Location and movement
2. Density gradients (which creates a thermally direct circulation and ascent on the least dense side of a boundary)
3. Low-level convergence (typically strongest near the surface)
4. Ascending air, W (even if you have convergence at the surface, it doesn't necessarily imply ascent). It has to be integrated values of convergence with height (decreasing convergence with height for example). Visual manifestation of moist W is cumulus clouds.

Lifting Along the Dryline



From Ziegler and Rasmussen (1998)

Moist boundary layer air parcels must be lifted to their LCL and LFC prior to leaving the mesoscale updraft to form deep convection. Cloud formation is predicted when the vertical mesoscale moisture flux predominates below the LCL, and deep convection is predicted if strong mesoscale lifting is deeper than the LFC.

A modification of proximity soundings to account for mesoscale lift, the across-dryline differences of environmental thermal stratification, and westerly wind shear effects can improve the diagnosis of the mesoscale dryline environment and the prediction of convective initiation at the dryline (Ziegler and Rasmussen, 1998).

Types of Lift

- Lower branch of indirect circulation
  - Enhances θ_e transport, low-level jet, convergence
- Upper divergence
  - From jet streaks, large scale ascent from Q-vector divergence
  - May be important to monitor when near-surface layer convergence is weak

In addition to boundaries, there are other lifting mechanisms like these shown here, which produce synoptic scale ascent. Most of these types of lifting can support the development of convection.

Types of Lift

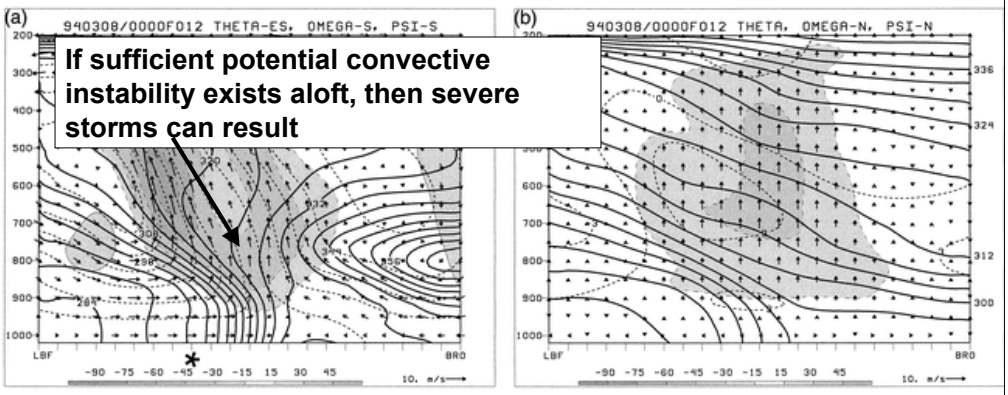
- Frontogenesis
  - Analyze incremental layers from 700 to 500 mb determined from AWIPS cross section drawn perpendicular to the temperature gradient
- Isentropic lift
  - Related to warm air advection and potential elevated convection if sufficient MUCAPE present

The diagnosis of frontogenesis will result in a diagnosis of the forcing for vertical motion on the frontal scale.
Ascent occurs on the warm side of a maximum of frontogenesis and on the cold side of a region of frontolysis (Schultz, 2001)

Elevated Convection and Frontogenesis

circulation **within** plane of cross section
(i.e., frontal circulation)

circulation **normal** to plane of cross section
(i.e., synoptic-scale circulation)



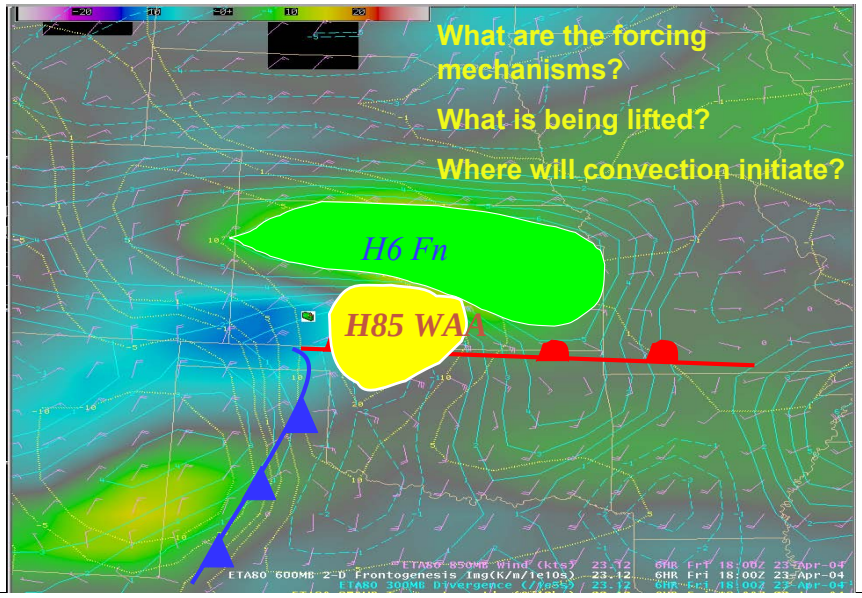
Vertical motion: shaded
Theta-Es: solid lines

Vertical motion: shaded
Theta: solid lines

From Trapp et al. (2000)

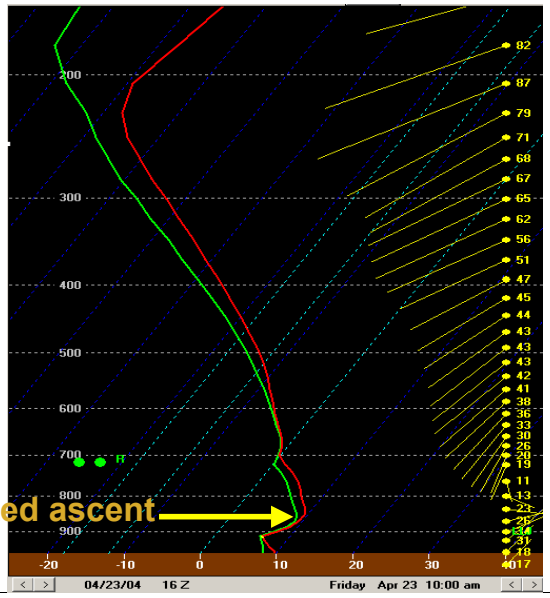
If sufficient instability is available aloft, severe elevated convection can result.

Combo of Lifting Example 4/23/04

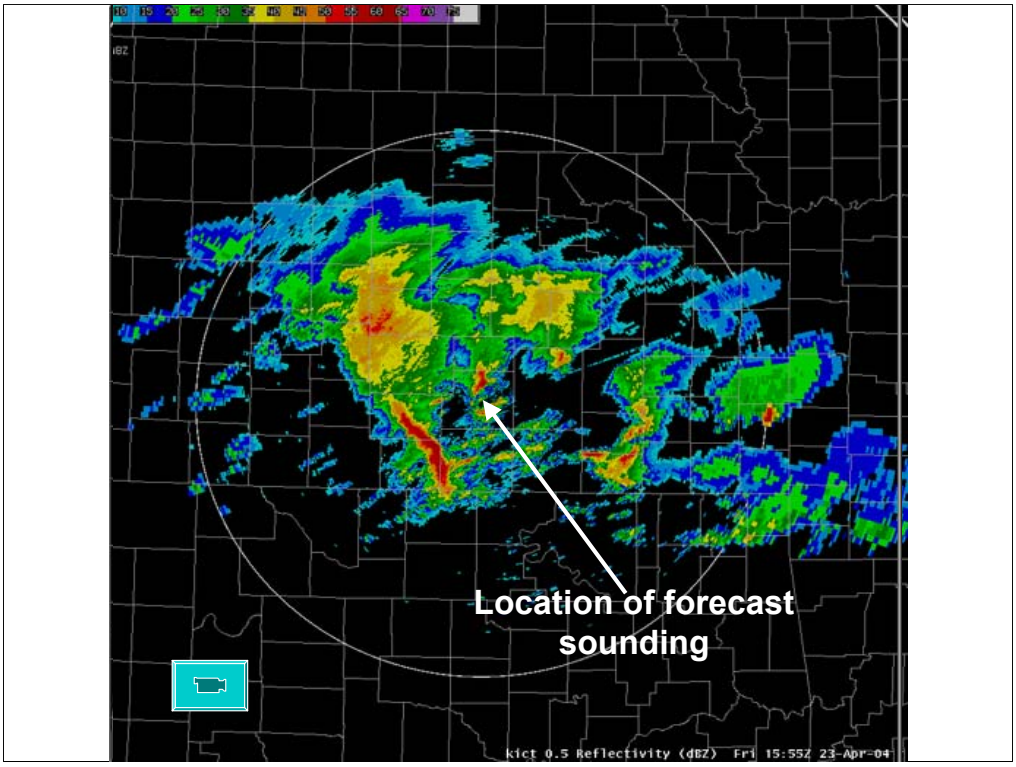


There were multiple contributions to upward motion indicated by the Eta across KS; all the convection which occurred, including the severe thunderstorm complex which developed and moved across KS during the morning hours was not surface based.

Sounding Showing Elevated Parcel Lifting Necessary



This is an Eta 4 hr forecast sounding for central KS - note the lifted parcel level (level where the parcel has the most unstable characteristics) is around 850 mb. CAPE when lifted from this level results in about 400 j/kg.



At this slide, you will want to play the flash movie showing the radar evolution. Note the convection developed into a forward propagating system – likely due to storm-relative winds from the east at low levels enhancing propagation effects.

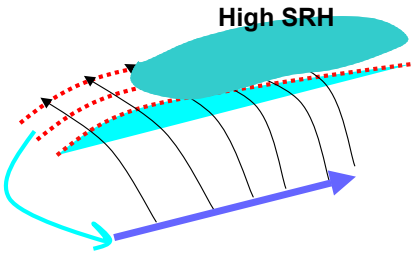
Types of Lift

- Differential heating
- Upslope winds

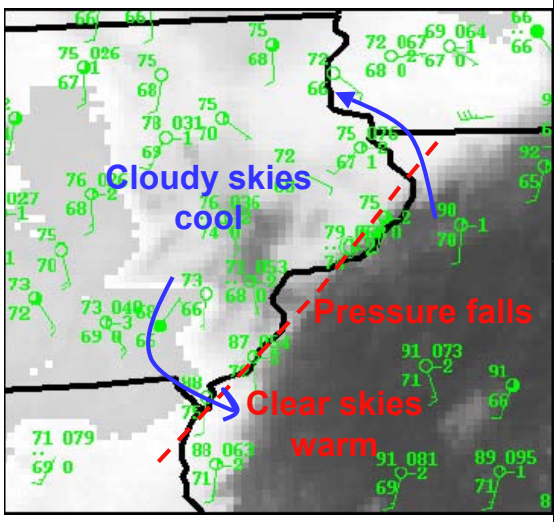
We'll take a look at lifting from differential heating.

Differential Heating

- **Over time differential ground heating will produce a solenoidal circulation**



- **Thermal gradient can also act to back low-level flow and increase near-ground SRH**



From Wolf (2002)

Pressure rises near the top of the boundary layer over the warmer air mass. This leads to divergence aloft and surface pressure falls within the warm sector. The adjacent cooler air subsequently flows toward the area of lowered pressure, and a direct circulation (warm air rising, cold air sinking) results. The increase gradient produces a solenoidal circulation, which depending on amount of CAPE/CIN and external lifting mechanisms, can help initiate severe convection.

Example at right is from 14 June 2001 (Wolf, AMS SLS conf.)

Upslope Lifting

- Terrain effects can aid boundary layer low-level jet characteristics
- Also, flow effects due to topography (see http://meted.ucar.edu/mesoprim/flowtopo/)

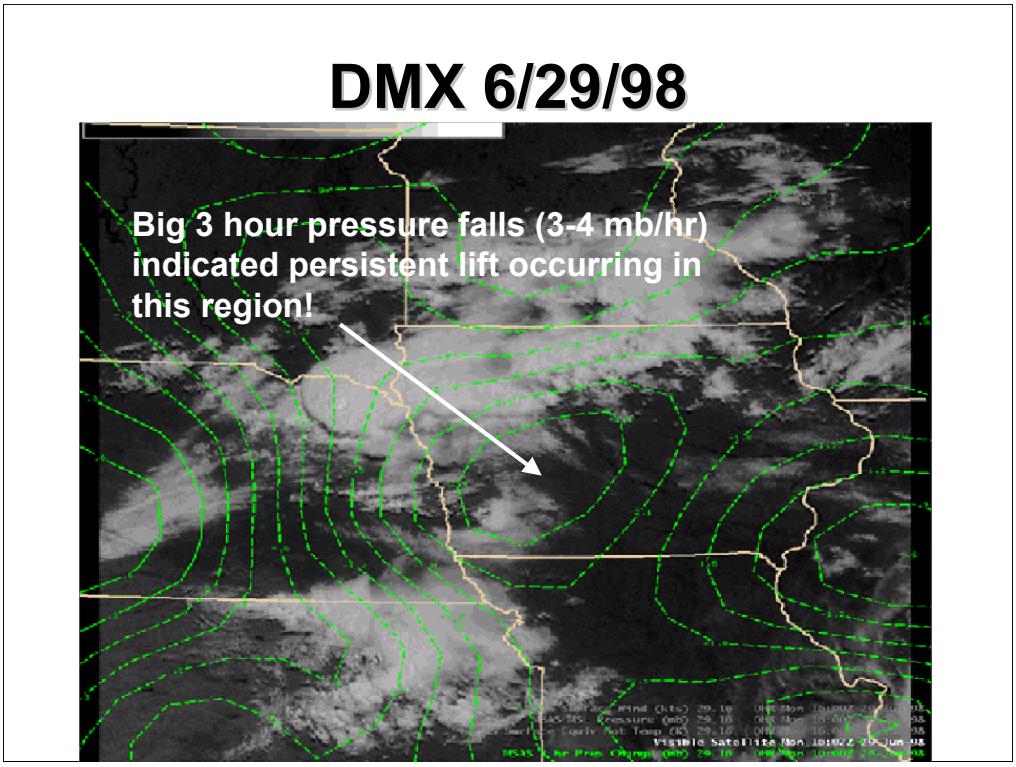
This is obviously an important consideration where there are significant changes in topography and wind flow.

Duration of Lift

- Surface pressure falls
  - 2 and 3 hour falls with continuity (often fall/rise couplets)
  - Location of fronts and movement of meso-lows by analyzing isallobaric pattern

In the DMX derecho event of 29 June 98, there were 3.6 mb/hr pressure falls in central IA for 3-4 hours prior to line intensifying and mesolow development.

One of the results was increased low level winds into the leading edge of the line, which increased vertical shear and updraft strength for storms which developed along the leading edge (some spawned tornadoes and 100 mph+ winds).



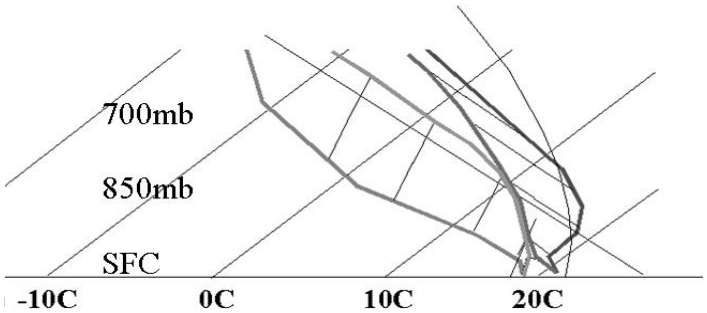
This event was analyzed in the DMX 29 June 1998 WES case.

Details of Lift

Synoptic scale lifting

With this unrealistically strong amount of lift for a 12-hour period, you saturate low-levels, and weaken cap sufficiently for moist convection.

In reality, vertical motion is substantially weaker, and varies in intensity with height, so sounding does not modify the same amount throughout.

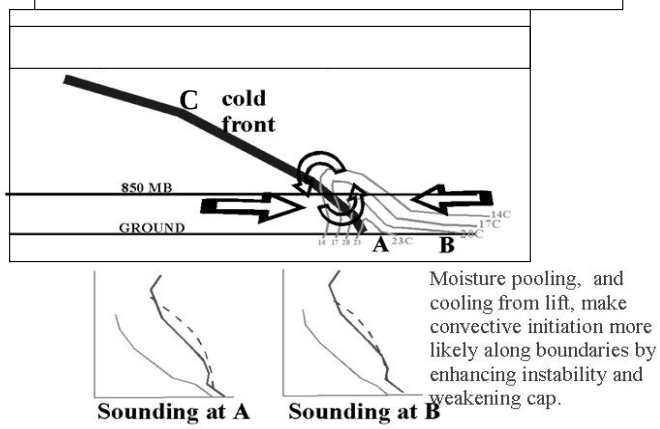


Graphics courtesy of Pete Wolf(ICT)

This is for synoptic scale layer lifting, which over a period time (0-12 hours) can act to significantly destabilize the atmospheric profile. This development of instability due to vertical motion on the large scale can contribute to convective development, but the instability alone provides inadequate mesoscale lifting for severe thunderstorms.

Details of Lift

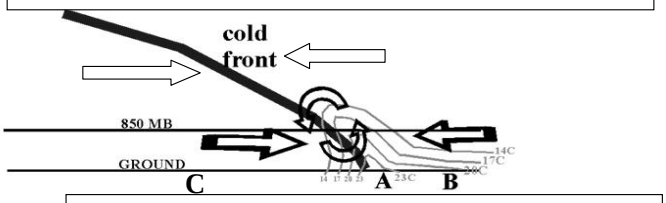
Determining what layer is being lifted



Use a surface based parcel along boundaries, a mixed layer parcel in warm sector, and a most unstable parcel north of a parcel (when instability is not rooted in boundary layer). Graphics courtesy of Pete Wolf (ICT).

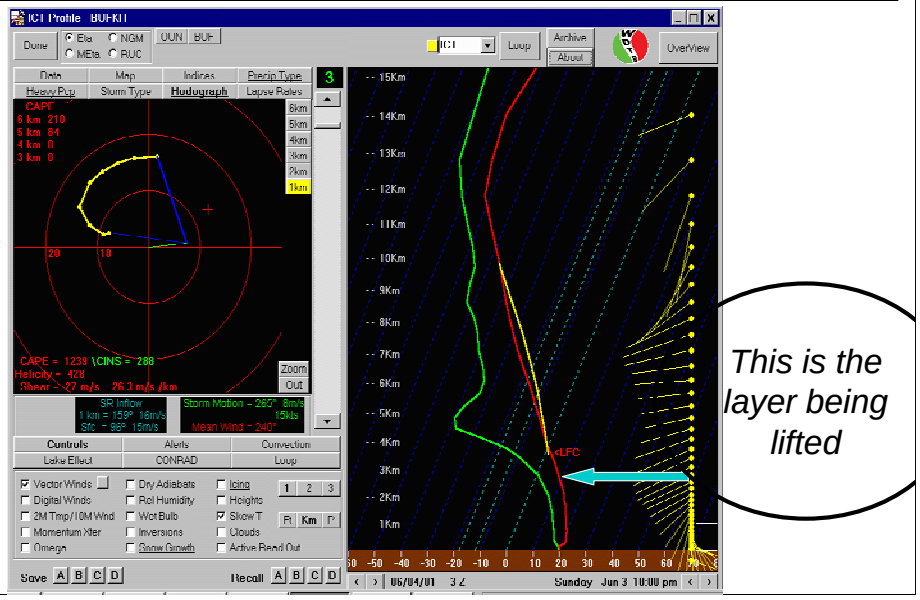
Details of Lift

- Now, let's look at a sounding at Point C



This sounding would be back in the colder air.

Elevated Convection
(sample sounding at Point C)

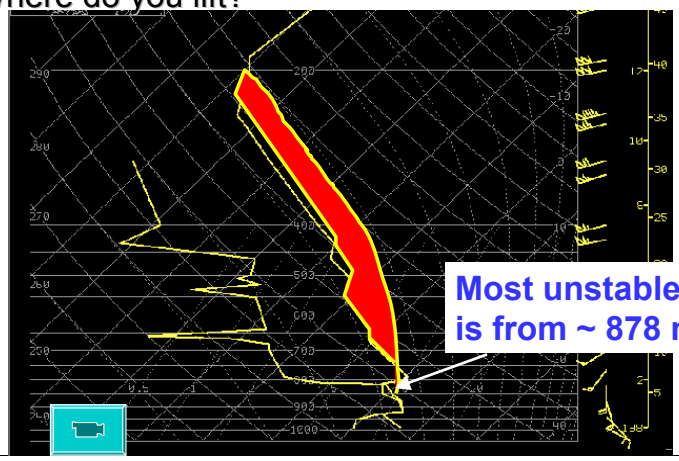


Look at lifting forces in the 2-4 km layer (6.5 – 13.1 kft) (800-625 mb), not surface to 850mb. That's why Warm Air advection centered around 850 mb is often a good correlation to lifting forces for elevated severe convection.

Important to assess convergence (theta-E convergence in 850-700 mb) and boundary relative flow. Also, frontogenesis in a 50-100 mb layer below the bottom level of positive buoyancy.

Details of Lift

- Consider this sounding…
  - How much lift is necessary for convection?
  - Where do you lift?



If you lift the parcel from 878 mb ,you get the most CAPE. This sounding was a proximity sounding for the big hailstorm that hit Dallas-Ft. Worth area.

For elevated convection , use the most unstable parcel (MUCAPE in SPC plots). Be aware of the limitations; it can overestimate the degree of instability and erode the cap too early before convection develops. Sometimes, it is better to use a lower mean layer for surface based convection.

There is an animation showing the effects of adjusting lifting parcel level with this sounding.

Orientation of Lift

- There are some additional factors to consider when evaluating how strong (and deep) the lift will be:
  - Boundary-relative flow (low-levels and steering layer)
  - Boundary-orthogonal shear (RKW Theory)

In addition to evaluating the individual details of parcels for lifting, we should look at the characteristics of lift associated with boundaries in terms of how strong and deep the lifting will be. Based on observations by Wilson and Megenhardt (1997), boundaries in FL were most active if cell motion -boundary motion was $\lesssim$ 5 m/s. Before storms, the 2 - 4 km mean wind = cell motion. Several observational studies including this one sampled the mean flow in a 2-4 km layer and found the boundaries were most convectively active when the boundary-normal flow was less than 5 m/s. The 2-4 km layer was chosen since it correlated best with new storm motion. Boundary-relative flows greater than 5 m/s exhibited less storm activity and those storms that did form on the boundary would quickly be left behind in less stable air and dissipate.

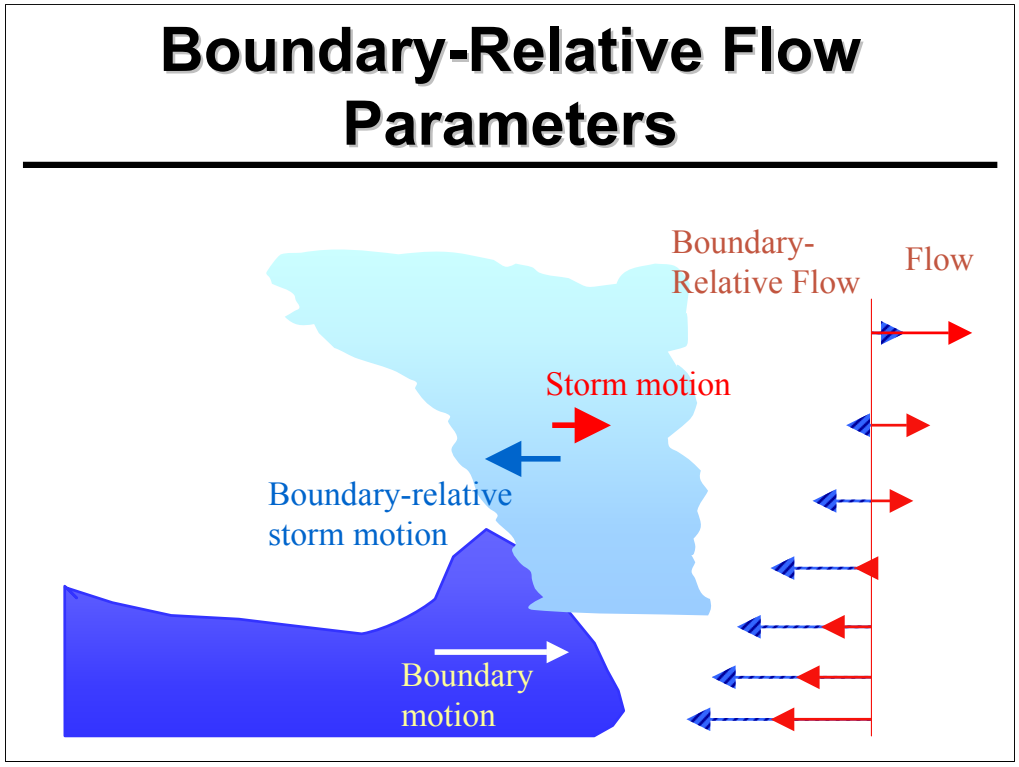
Note: This study was done during a field project around Cape Kennedy during the summer. Therefore the storms were mostly driven by surface-based phenomenon and there were small amounts of shear. Whether these findings can apply to stronger synoptically forced situations still remains a question worthy of testing at any of your locations.

Also note that not all storms will dissipate if the boundary-relative 2-4 km flow is high. Convection can persist or even thrive well after they leave the original boundary if there is still sufficient uncapped instability.

Boundary-Relative Flow Considerations

- Weak (0-5 m/s) boundary-relative (steering-layer) flow increases convective cell coverage
- Orientation of line of forcing can be as important as CAPE and shear in determining type of outbreak
  - Orientation WRT shear & wind vector
  - Boundary-relative supercell motion

Results of simulations (Bluestein and Weisman, 2000) suggest that when the deep-layer shear is normal to the line of forcing, isolated, cyclonically (anticyclonically) rotating, right-moving (left-moving) supercells develop at the end of the line to the right (left) of the deep-layer shear. A squall line having embedded, but distinct, intense cells develops in between. The squall line develops after neighboring right- and left-moving cells collide. The cells in the squall line have some supercellular characteristics, but the updrafts at midlevels are not very well correlated with vertical vorticity.

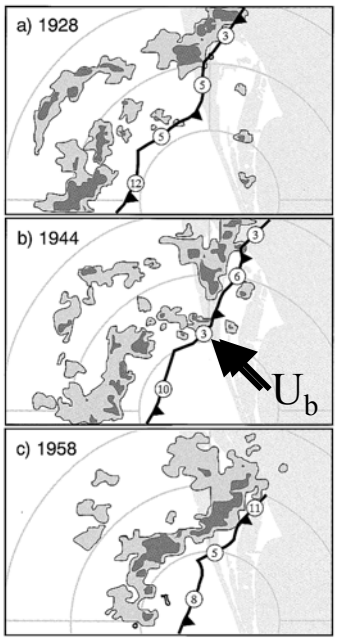


Graphic courtesy of Jim LaDue. These are theories that apply to density current boundaries:

1) A boundary-relative headwind (tailwind) increases (decreases) the depth of the ascending air column.
2) Based on numerical modeling of an outflow boundary, the boundary height increases when a boundary moves into a headwind.
3) Boundaries with a headwind move more slowly than those with a tailwind (from Moncrieff and Liu, 1999).

From these theoretical and numerical experiments, the ascending air column will be deeper for boundaries experiencing a significant headwind than for those following into a tailwind. It stands to reason that low-level convergence with headwind (tailwind) boundaries is higher (lower).

Boundary-Relative Flow



- Wilson and Megenhardt found the most coverage with boundary-relative storm motion (U_b) less than ± 5 m/s.

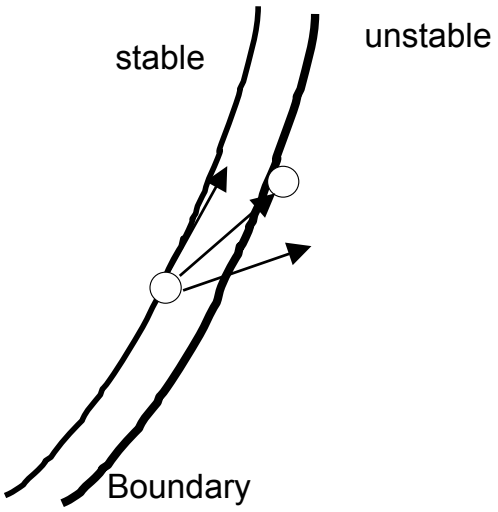
Wilson and Megenhardt (1997)

Wilson and Megenhardt (1997) found the most coverage with boundary-relative storm motion (U_b) less than ± 5 m/s.

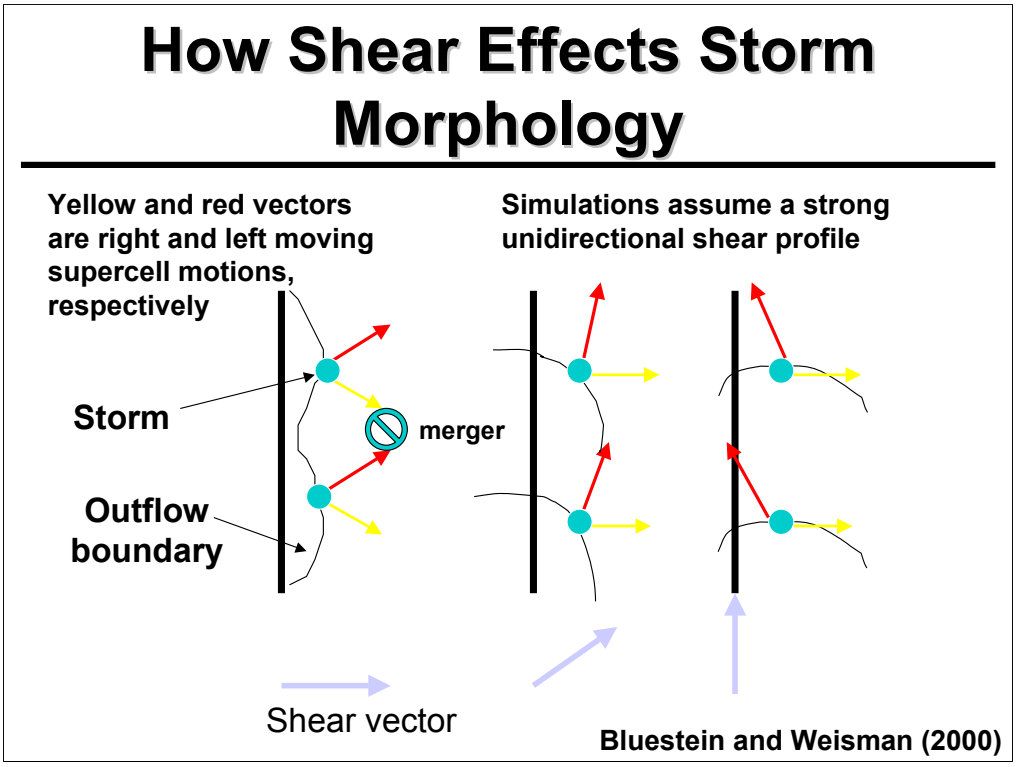
These storms occurred in weakly sheared environments.

Effects of Boundary-Relative Kinematics on Storm Morphology

- Steering flow
  - Is the storm going to remain on, fall behind, or overtake a boundary?
  - This may affect storm type in addition to CAPE and shear

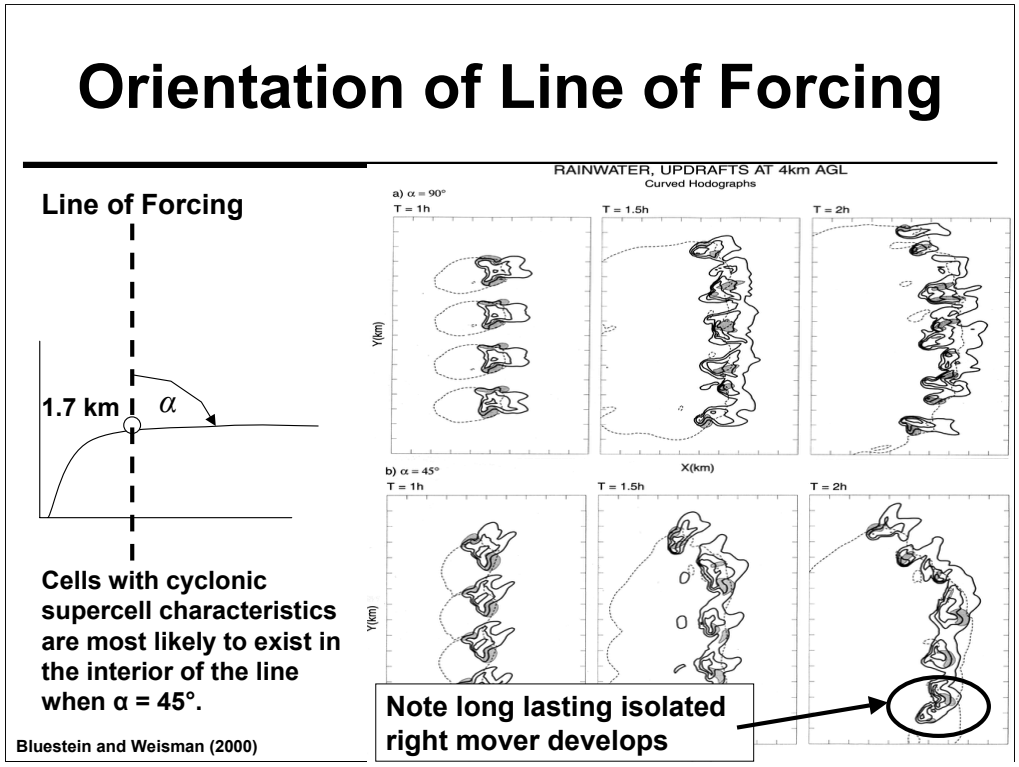


Based on boundary-relative considerations, the northward moving storm has the lowest boundary-relative flow which allows parcels to ride along the boundary and reach its LFC the fastest, thus maximizing lifting potential.



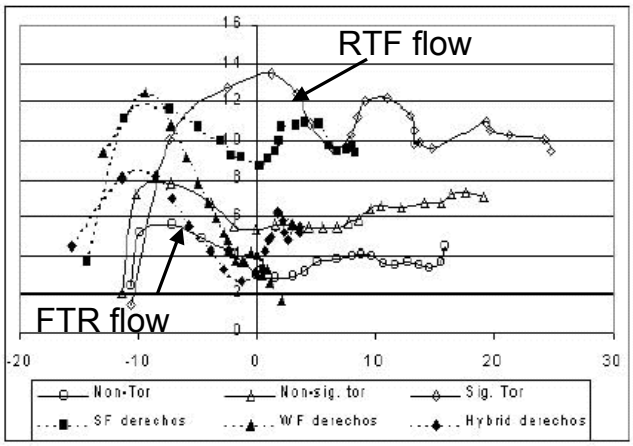
This is based on numerical simulation of storms (Bluestein and Weisman, 2000) where they looked at various orientations of the vertical shear vector with respect to the lines of forcing. The left-most example is of a shear vector oriented at a 90 deg. angle to the boundary. In this case, the right-mover will collide with the left-mover. In the middle situation, the shear vector is at a 45 deg. angle to the boundary. With the exception of the northernmost storm, the left-moving members will move across the outflow bndry generated by the right-moving neighbor to the north, and weaken, while the right movers will move away from the boundary and may not collide with their neighbors. The last case (far right) is where the shear vector is oriented parallel to the boundary. In this scenario, the left movers will move behind the boundary, while the right movers will slowly move ahead of the boundary. However, since there is also a component of storm motion parallel to bndry, the right movers might be able to catch up to the outflow bndrys generated by the adjacent right movers along the line, and weaken.

Thus, boundary-orthogonal shear (component of the shear vector normal to the boundary orientation) affects the motion of storms and thus, how long updrafts will stay on the boundary. The shear vector is drawn perpendicular to the gust front (thin lines), with right (yellow vectors) and left (red vectors) supercell storm motions based on Bunker's et al. (1999) method.



From Bluestein and Weisman (2000) , simulated fields for a line simulation, at 1, 1.5, and 2 h, of liquid-water mixing ratio (thick contours at 1, 4, and 8 g kg^{-1}) and vertical velocity (shaded region in excess of 8 m s^{-1}) at 4 km for the modified sounding and curved hodograph. Tick marks are spaced 10 km apart. Gust front at 0.25 km depicted by dashed line (perturbation temperature at 0.25 km, with respect to ambient environment, of −1°C). This simulation was for when alpha (angle between shear vector above 1.7 km AGL and line of forcing) was = 90 deg. In reality,this would be for a westerly shear and a north-south boundary.

Storm-Relative Winds Affect Mode of Convection

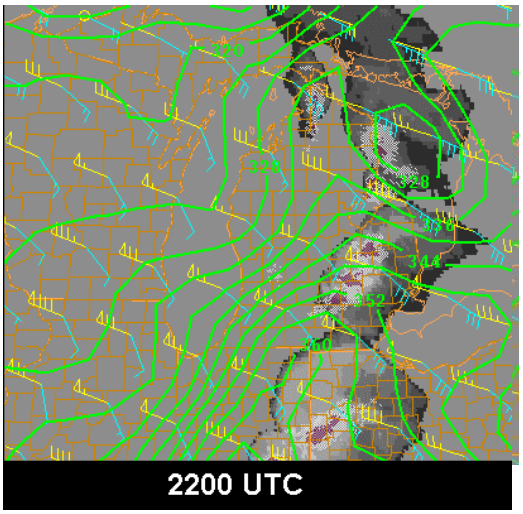


From Evans and Doswell (2002)

When storm-relative winds are examined (as in this figure from Evans and Doswell, 2002) it is apparent that the derechos yield the strongest inflow in the lowest 1 km. In addition, weakly forced events develop and persist in environments with deep storm relative inflow (front-to-rear flow) from the surface through 8-9 km. In contrast, the supercell dataset reveals pronounced rear-to-front flow above 2-3 km , especially the significantly tornadic events. This is really evident above 4 km, where only the supercells indicate rear-to-front storm-relative flow increasing through 10 km. These results were consistent with other studies that found the distribution of hydrometers and precipitation largely due to the mid- and upper-level wind fields *relative* to storms.

Boundary-Relative Flow
7/2/97– Michigan Tornadoes

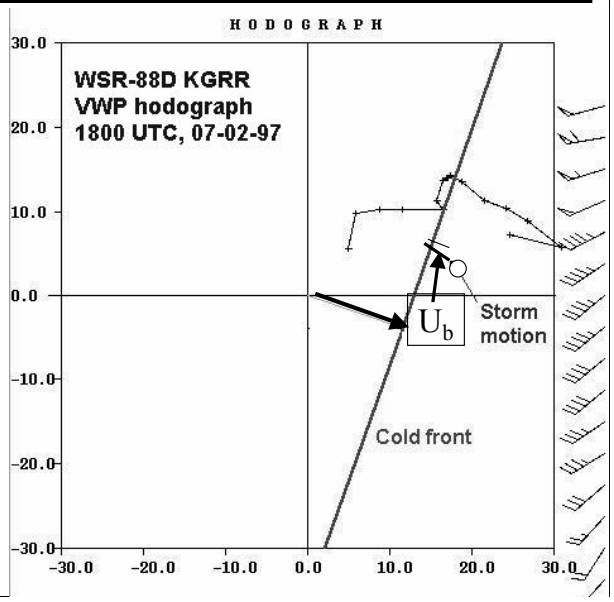
- Strong synoptic forcing and favorable CAPE/shear for tornadic supercells
- Boundary-relative flow in mid to upper levels was rear-to-front



The blue vectors are 850 mb boundary orthogonal winds, the yellow vectors are anvil level (~ 250) boundary orthogonal winds (after LaDue, 1998).

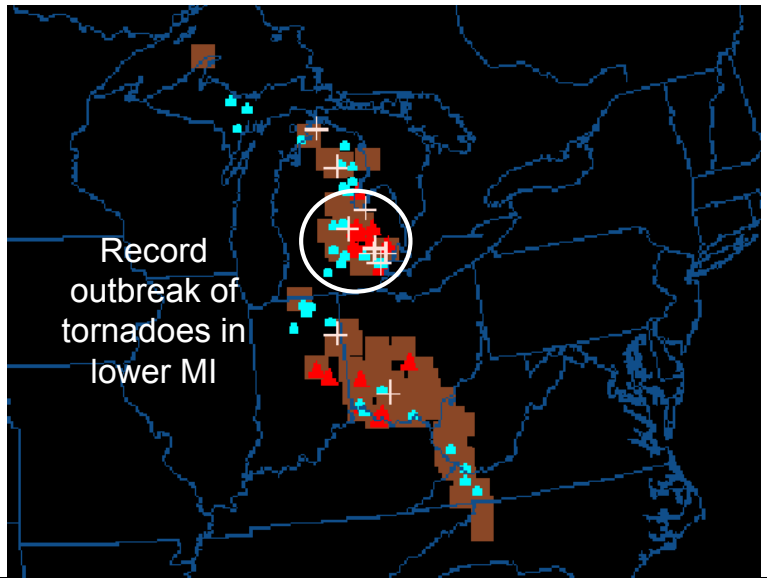
7/2/97 Michigan Tornadoes

- VWP hodograph shows observed storm motion pulling ahead of front



The blue dot is the storm motion vector. Boundary relative flow is the blue vector (~ 280 deg, 5 m/s).

7/2/97 Storm Summary

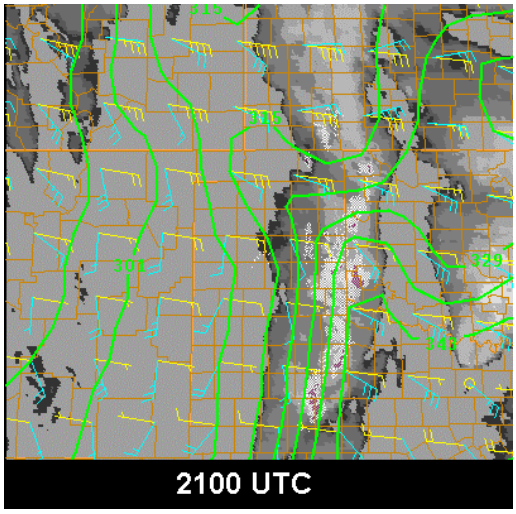


Severe weather reports from 1200 to 2300 UCT 02 July 1997. Small blue square-like symbols are hail >= 0.75 inches in diameter, red triangles are tornadoes, large brown squares are wind damage, white crosses are reported wind gusts >= 50 knots.

See http://www.wdtb.noaa.gov/resources/cases/jul02case/torcase.htm for more information on this event.

May 5, 1995 – TX PH Tornado Null Case

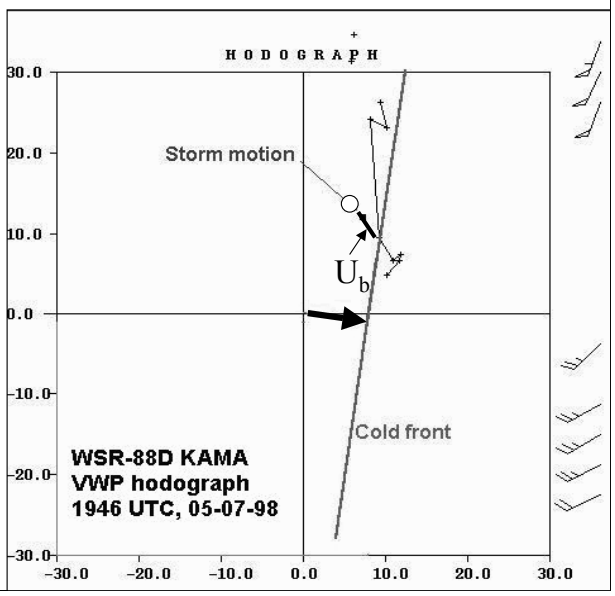
- As in 7/2/97 case, shear and buoyancy were in range of supercell tornadoes
- However, boundary-relative upper level flow was front-to-rear



Same vector notation as previous example.

May 05, 1995 – TX PH tornado null case

- VWP hodograph shows observed storm motion falling behind front



Same color convention as previous example.

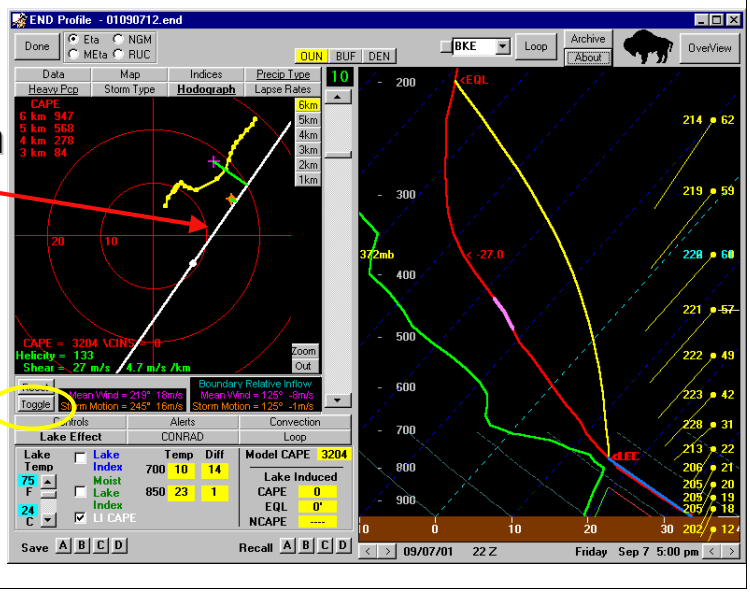
Visualizing Boundary-Relative Flow/Shear

- Line of forcing can be viewed as another axis on a hodograph
- Winds and shear can be interpreted with respect to the line of forcing
- The line of forcing can be displayed with the BUFKIT hodograph

The best way to view orientations of line of forcing and shear is through a hodograph like what is available on BUFKIT.

Visualizing in BUFKIT

- Boundary Orientation

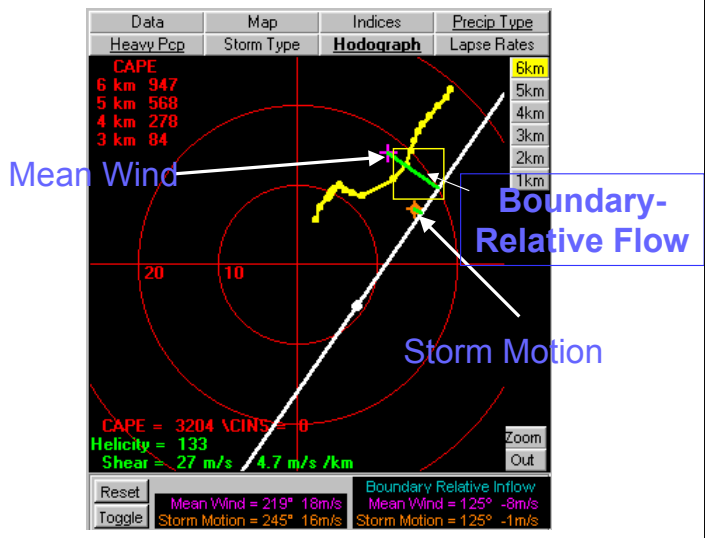


Use the toggle button to go from hodograph display to B-R coordinates

This hodograph is from a Eta forecast profile at Enid, OK.

Visualizing in BUFKIT

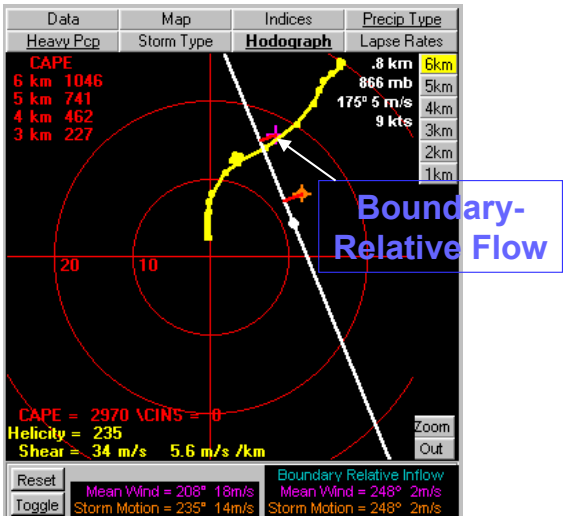
- 10 hr Eta forecast for END
- Storms forecast to fall behind boundary



This shows storms falling behind the boundary due to BRF considerations. On BUFKIT, the green vector is the Boundary-relative flow vector.

Visualizing in BUFKIT

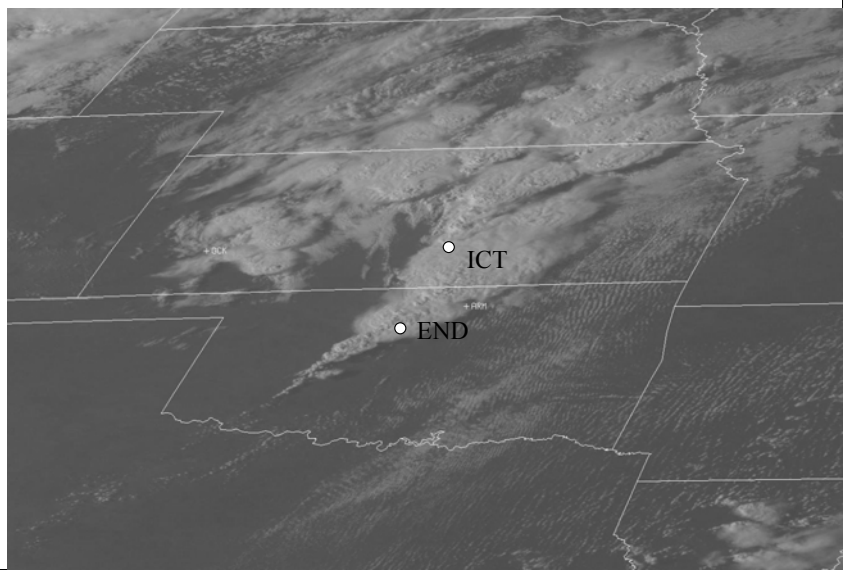
- 10 hr Eta forecast for ICT
- Storms forecast to stay just ahead of boundary



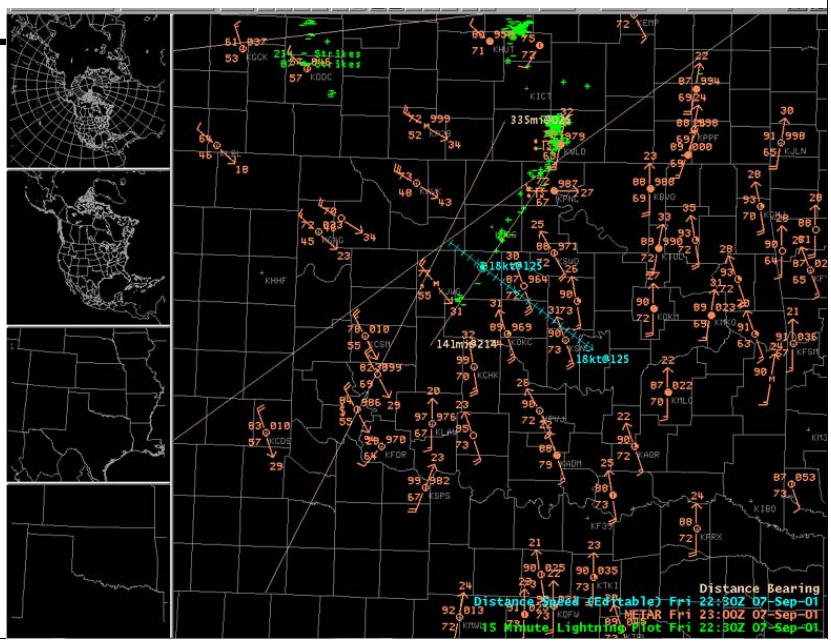
This forecast shows storms staying out ahead of the boundary in the warmer air.

Sept 07, 2001 case

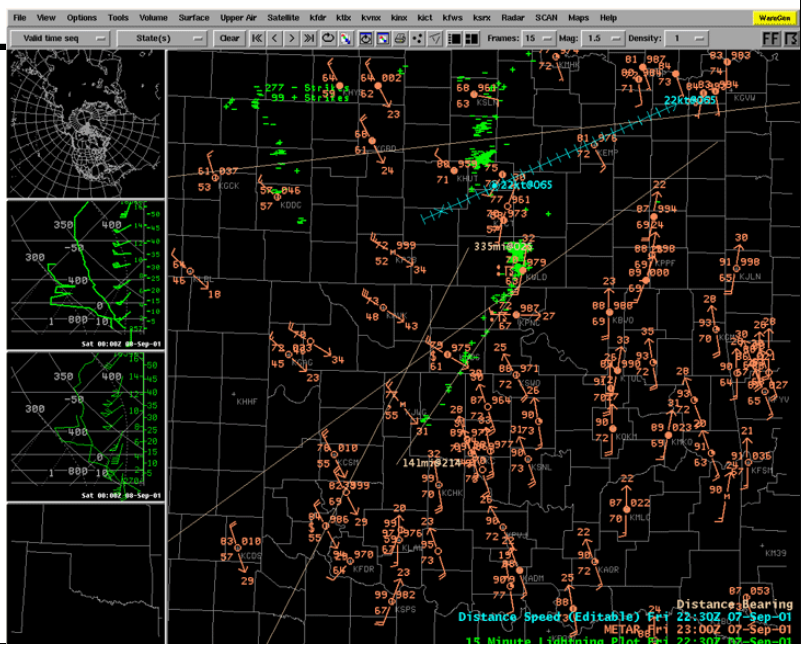
GOES-8
2200 UTC



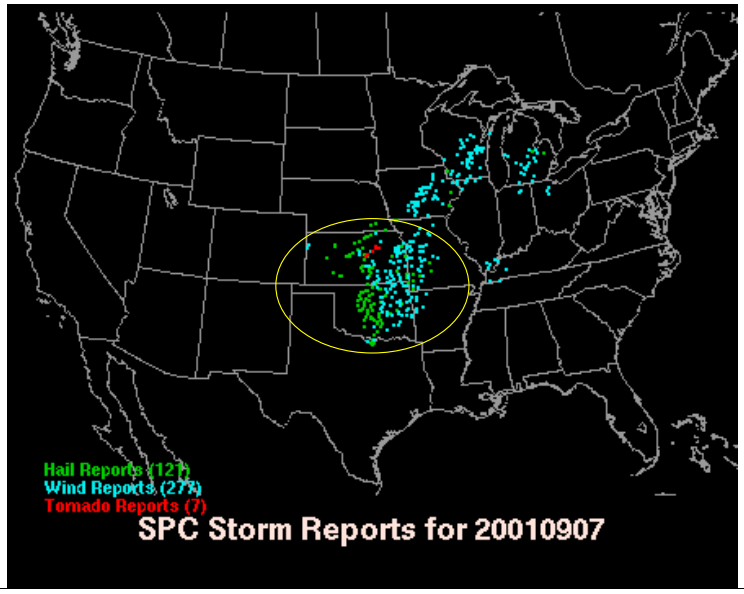
Sept 07, 2001 case



Sept 07, 2001 case



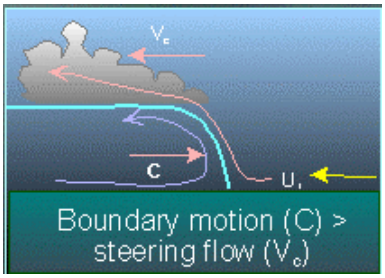
Sept 07, 2001 case



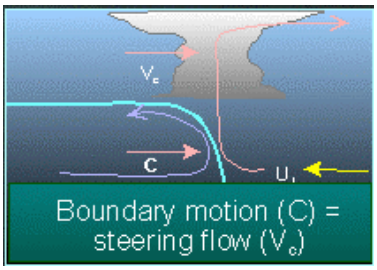
Boundary orientation relative to mean wind and shear appeared to influence convective mode, another consideration to lifting characteristics and your threat assessment.

Depth of Ascent Zone

- Key is to maximize residence time of parcel in ascent zone to ensure parcel reaches the LFC
  - Related to deep layer shear but also could be any boundary
  - Small (≤ 5 m/s) boundary-relative motion



Destructive to lifting



Promotes deeper lifting

This theory is based on Rotunno, Klemp, and Weisman (RKW) numerical simulation studies from the 80s and early 90s. It is based on horizontal vorticity arguments. The key to maximizing residence time of a parcel in the ascent zone is to ensure it reaches the LFC. (See http://meted.ucar.edu/mesoprim/shear/frameset.htm). These theories apply to density current boundaries. Density current boundaries include strong fronts, seabreeze boundaries and outflow boundaries. Deepest ascent occurs when boundary orthogonal environmental shear balances cold pool vorticity (Rotunno et al. 1988), or when the boundary speed (C) cancels out positive shear magnitude (U_L). C/ U_L ~ 1. When the boundary-normal (or orthogonal) component of the shear is oriented forward away from the cold side of the boundary (positive shear) and it has the same magnitude as the forward speed of the boundary, the conditions are optimal for the strongest, most vertically oriented ascent zone. That is C/ Delta U_L ~ 1. This is graphically shown in the right side schematic. What often occurs is shown in the left side figure where the shear vector is directed front to rear of the boundary (negative shear). In that case, no balance occurs in C/ UL and the ascent zone becomes much shallower. When a boundary does not have any density current characteristics, the shear considerations do not apply in the sense in which they were presented. In some sense shear is still important since boundary-normal shear can be too strong potentially ripping apart an ascending zone of air before it can reach the LFC.

Determining Depth of Ascent Zone – 3 main factors

1. Maximize low-level headwinds
   - Applies to density current boundaries
   - Not necessarily strong convergence
2. Boundary-orthogonal shear
   - For isolated storms (eg. supercells), like to see rear-to-front flow from 2-3 km through 10 km equal to boundary motion
3. Boundary-orthogonal mean flow
   - For isolated storms, best if this value is $\leq$ 5 m/s

This is a summary of topics covered related to determining the ascent zone.

Summary
Lesson 2

- Factors in assessing lift
  - Boundary-relative flow, shear/cold pool relationships
- Types of lifting
  - Synoptic or mesoscale
- Orientation of lines of forcing
  - Can affect intensity and longevity of storms

Threat Assessment

Advanced Warning Operations Course

IC Severe 2

Lesson 3

Updraft Persistence

Warning Decision Training Branch

The title for this instructional component is “Threat Assessment.” This is the 2nd instructional component for the AWOC Severe Track. This is Lesson 3.

Lesson 3 Learning Objectives

1. Identify some considerations for determining updraft persistence.
2. Determine movement and evolution of severe threats.

There are 3 objectives in lesson 3. We will discuss moisture pooling and horizontal rolls as they pertain to updraft persistence. In addition, we look at movement of convective systems, in particular, MCSs.

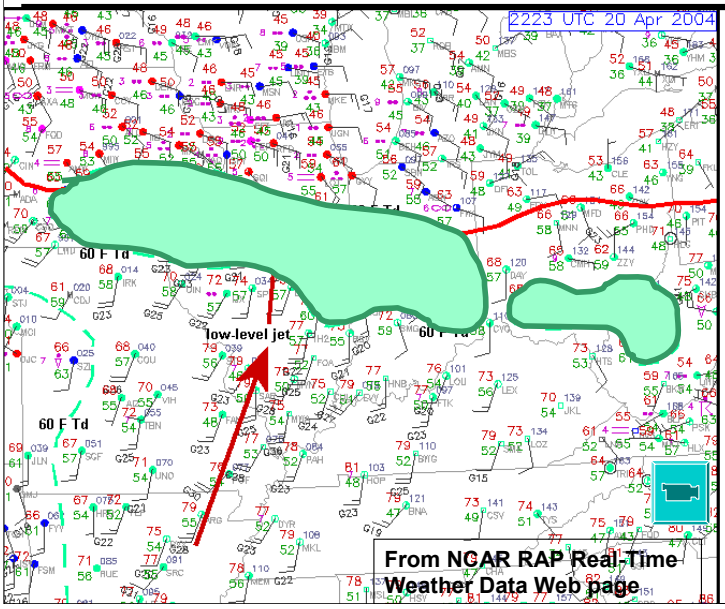
Considerations for Updraft Persistence

- Low-level moisture pooling, persistence
- Satellite indications of rolls, streets

Low-level moisture is an important source for low-level buoyancy and can help sustain updrafts when shear is constant. Numerical models often underestimate moisture in the vicinity of boundaries so satellite data can help locate cloud streets, or horizontal rolls. Horizontal rolls fit the definition of cloud streets as long-narrow lines of cumulus clouds that form due to shear and instability in the boundary layer, and align themselves with the integrated boundary shear vector. In most cases, and when there is sufficient moisture, there are numerous cloud streets, separated more or less equidistant from one another.

Moisture Pooling

April 20, 2004



Axis of >60F Td led to increased SBCAPE to ~ 1500 J/kg by 2200 UTC

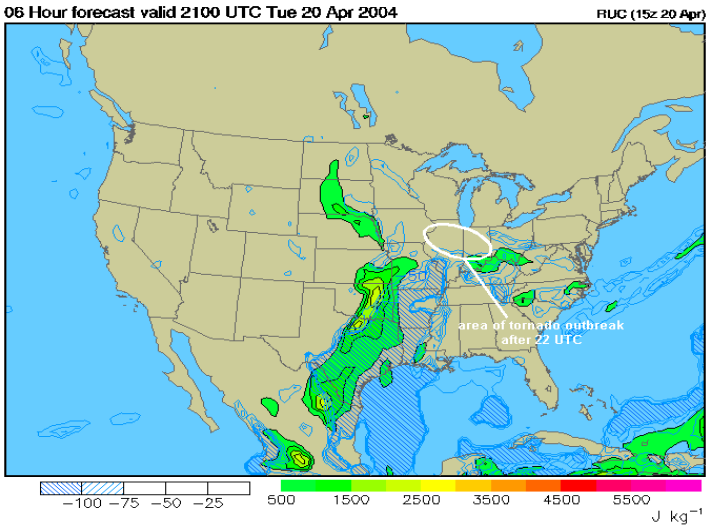
By the way, RUC and Eta both had CAPES ~ 0

This is an example where moisture pooling might have played a part in severe storm development. Area shaded in green are Td > 60 deg F. There are two satellite animations (water vapor and visible) that can be played with this slide to show how portions of northern IL/IN were able to clear out and destabilize during the afternoon.

Moisture Pooling

What the Models Showed

CAPE / CIN (J/kg)



From UCAR RAP page

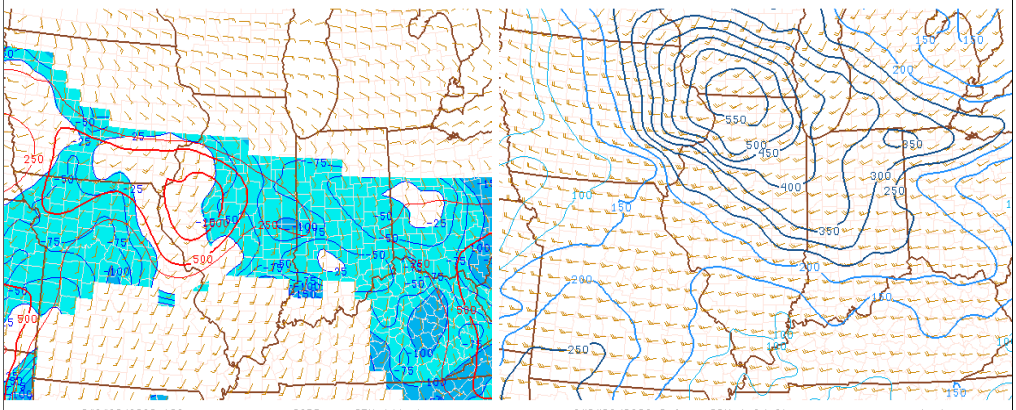
Both RUC and Eta indicated no CAPE across northern IL/IN.

Moisture Pooling

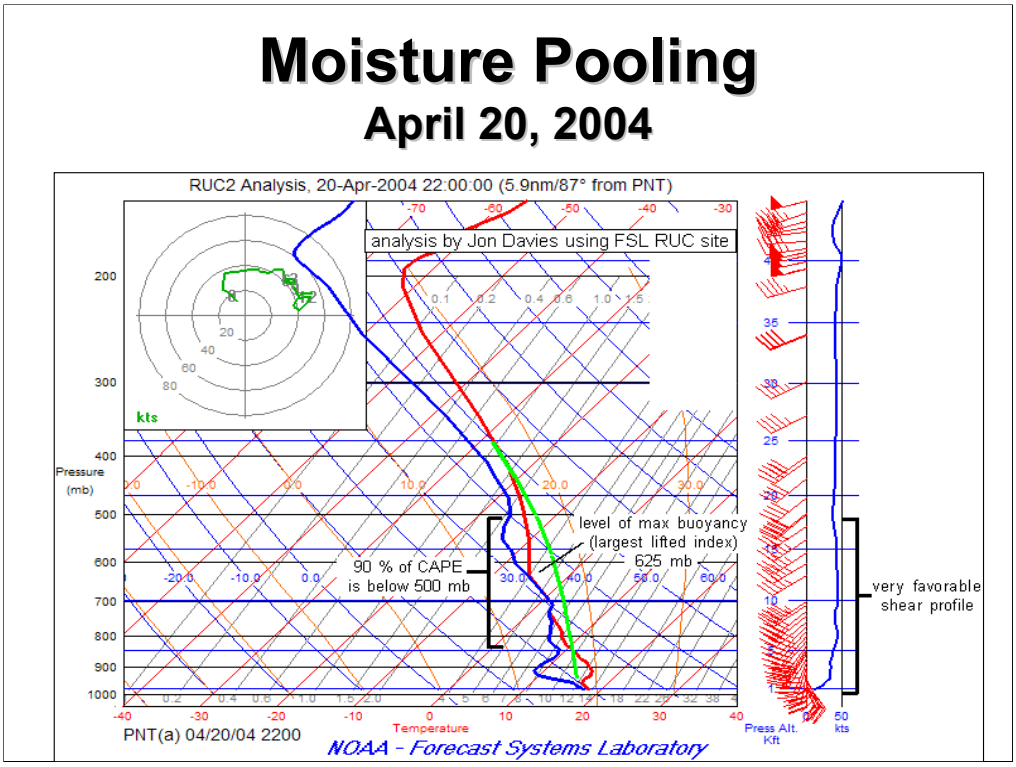
What the Models Showed

From SPC Mesoanalysis Page (RUC-based)

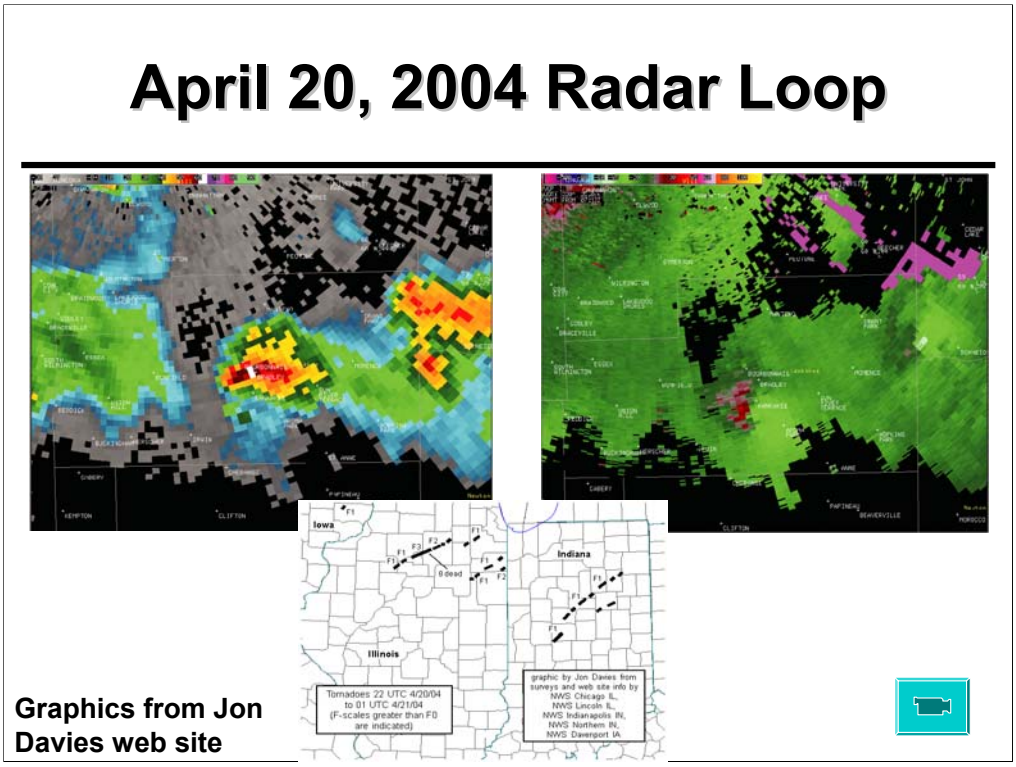
MLCAPE 2300z **SRH (0-1 km) 2300z**



There is a loop of RUC surface dew points on this slide.



This modification of a RUC forecast sounding at Pontiac, MI (PNT) just north of the warm front. In northern IL shows how quickly the environment could change from no CAPE to positive CAPE as the warm front approached. Just as important, notice on the modified profile how much of the CAPE would be located relatively low in the profile. This is a favorable "small CAPE" tornado profile with nearly all the CAPE below 500 mb and the level of maximum buoyancy centered below 600 mb. This is very different from typical spring tornado environments in the plains where only around a third of the CAPE is below 500 mb, and the maximum buoyancy is centered much higher (usually near 400 mb). These results are from a recent case study by Jon Davies (see http://members.cox.net/jondavies3/042004ilin/042004ilin.htm).



To summarize, here are key points from Jon Davies on this case study of April 20, 2004 , and others like it:

1) Model forecasts using lowest 100 mb CAPE largely overlooked and misrepresented the instability for this event.

2) Surface-based or shallower mixed parcels worked better when assessing relevant CAPE from model-derived products..

3) CAPE was located unusually low in the environment profiles for this event, suggesting the setting to be thermodynamically more favorable for tornadoes than total CAPE alone would indicate.

4) The "low-profile" CAPE in this event appeared to be ideally co-located in the vertical with available shear, possibly increasing tornado potential.

5) Monitoring of the rapidly advancing warm front was of key importance in anticipating rapid thermodynamic environment changes favorable for tornadoes.

Davies has noted (see his web site at http://members.cox.net/jondavies3/042004ilin/042004ilin.htm) in small CAPE tornado cases, around 50% or more of the CAPE is typically located below 500 mb, and the level of maximum buoyancy (most unstable lifted index) is centered below 500 mb. This matches nicely a detailed modeling study by McCaul and Weisman (*Monthly Weather Review*, April 2001) that found when shear was sizable and held constant, surface vorticity in simulated storms increased as *CAPE* was compressed into lower levels of the environment profile.

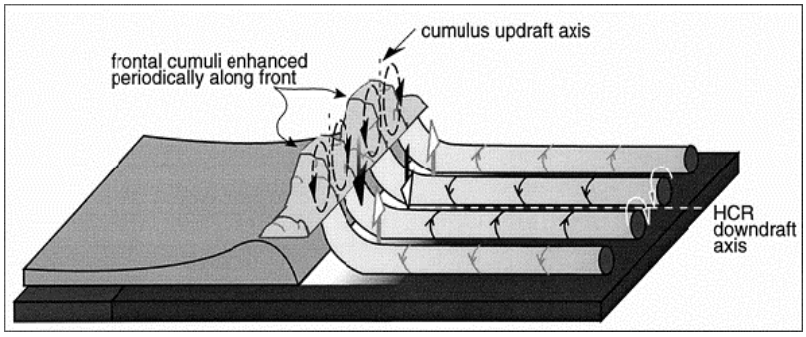
Determining Updraft Persistence

- Evaluate buoyancy via sounding analysis
- Assess large scale lifting (destabilizing effects)
- Assess intensity of mesoscale lift
- Identify horizontal rolls (cloud streets)

Initiation is favored where roll updrafts intersect another boundary, especially for large rolls or rolls with the largest cumulus street.

Horizontal Rolls and Lift

- Initiation often favored where large roll updrafts intersect another boundary (such as a large cumulus street)



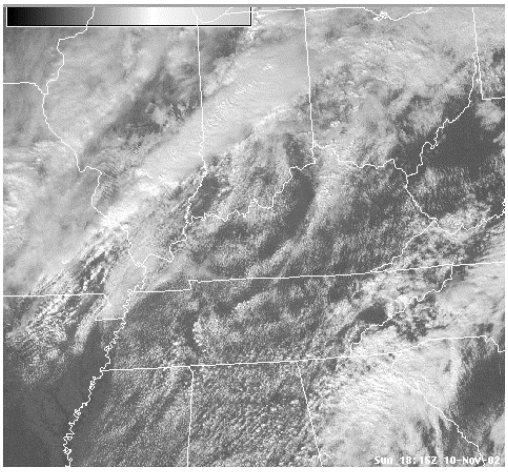
After Dailey and Fovell (1998)

These are some factors for initiation due to roll updrafts intersecting another boundary.

1) Applies best for large rolls or rolls with the largest cumulus street.
2) Note schematic figure from Dailey and Fovell (1998) which shows how the updraft axis of the rolls becomes superimposed on the ascending zone of the boundary to create enhanced regions of updraft. Conversely, the downdraft axis of the rolls will negate or cancel out the boundary ascending air to limit the potential for convection in these areas.
3) Most average roll spacing is only about 4km, the scale of cumulus clouds. There is not much room for enhanced cumulus to grow at the intersection points along a boundary. Occasionally, large or enhanced rolls exist with an aspect ratio of greater than 7. These rolls exhibit greater depths of circulations and will be even more likely areas of initiation where they intersect boundaries.

The initiation of GOES rapid scan (RSO) for severe weather operations is an important tool in diagnosing subtle boundary interactions like those shown in next example.

Roll Example



There is an animation from 10 Nov 2002 showing interaction of horizontal rolls or cloud street into the pre-frontal convective initiation.

Short-Term Threat Assessment
Key Tasks

- Evaluating mesoscale environment to determine
  - Location of significant lifting mechanisms and associated character of lift
  - Location & timing of severe development
  - Likelihood and intensity of specific hazard (tornadoes, flash flooding, etc.)
  - Evolution of threat (especially movement)

Next we will discuss the last 2 bullets.

Likelihood and Intensity of Specific Hazard

- Assessing the threat of a particular hazard
  - Related to conceptual models (See Severe IC1)
- Also,see http://wdtb.noaa.gov/DLCourses/dloc/ic57/ic57-1-screen.pdf (DLOC IC 5.7)

When determining the relative threats associated with a particular hazard, it is important to know the process associated with development - See IC 1. We also cover the hazardous threats in the Distance Learning Operations Course (DLOC), see

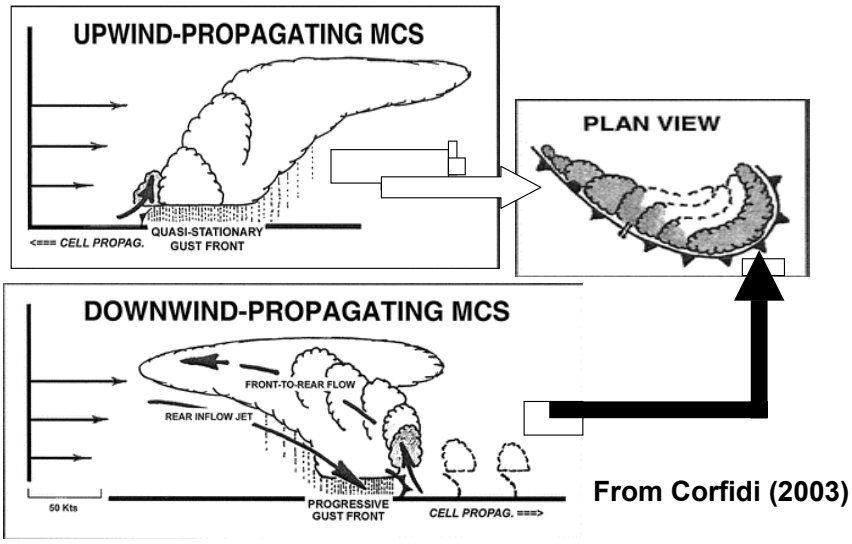
http://wdtb.noaa.gov/DLCourses/dloc/dlocmain.html.

Determining the Evolution of Threats (Especially Movement)

- Use storm/system motion estimate techniques (Bunker's ID method for supercells)
- Look at downstream buoyancy and storm relative inflow (will storms increase or decrease updraft potential)
- Evaluate multicell motion via Corfidi MBE vectors

For supercells, you can use the linear motion tool using motion on Bunker's ID method (See IC 1). For ordinary convection (pulse storms) storms usually move with the mean wind (0-12 km). For the next bullet, downstream buoyancy often, but not always – (see Richardson's (1999) study) influences movement and resulting longevity. Consider Oct.9, 2001 tornadic storms in west central OK (a DLOC mini-exercise) . We know the importance of instability and propagation on multicell motion and longevity (again IC 1) . Now you can use AWIPS or BUFKIT (better) to evaluate multicell propagation effects. But multicell system motion, especially in the early stages, is often quite complicated.

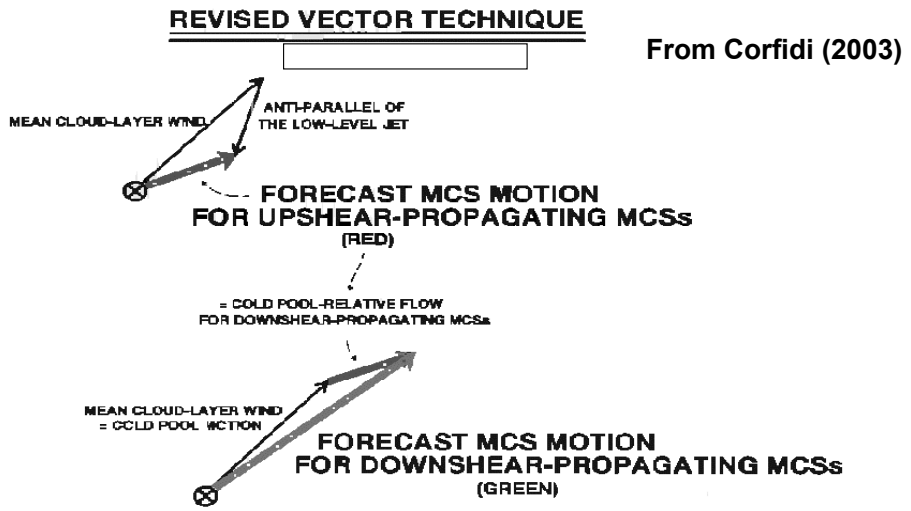
Downwind – Developing MCSs



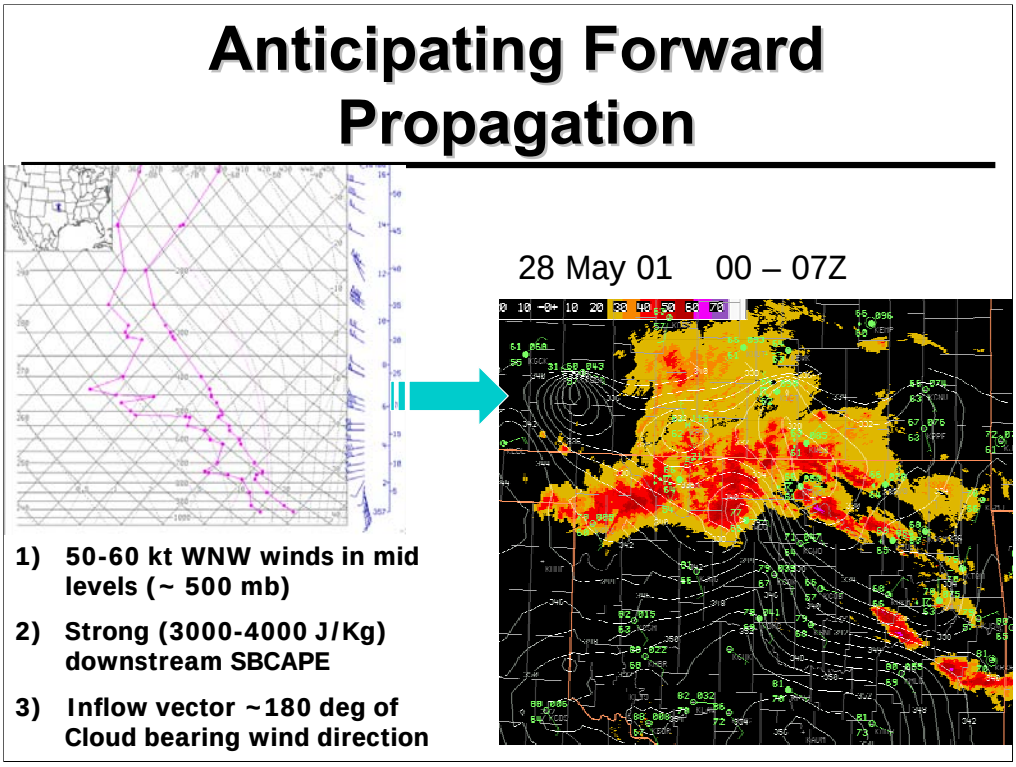
From Corfidi (2003)

Based on Corfidi's (2003) study, a cold pool will elongate in the direction of the mean cloud-layer wind as a result of momentum transfer. The degree of elongation increases as the wind profile becomes more unidirectional, and this effect occurs on all time and space scales. Propagation, or new cell development relative to existing storms, occurs most readily on the periphery of the cold pool (i.e., along those portions of the gust front), where the relative inflow is strongest and where surface-based convective instability is present . Upwind-developing MCSs are most favored along quasi-stationary (mean flow parallel) portions of the gust front, and downwind-developing MCSs are favored on the more progressive (mean flow perpendicular) parts of the boundary. Thermodynamic factors modulate the role played by gust-front orientation and motion. Upwind-developing environments are characterized by comparatively moist conditions through the low to midtroposphere and, therefore, relatively weak convective-scale downdrafts, and downwind-developing environments are characterized by comparatively dry conditions at midlevels and/or in the subcloud layer and, therefore, a tendency to produce strong convective-scale downdrafts.

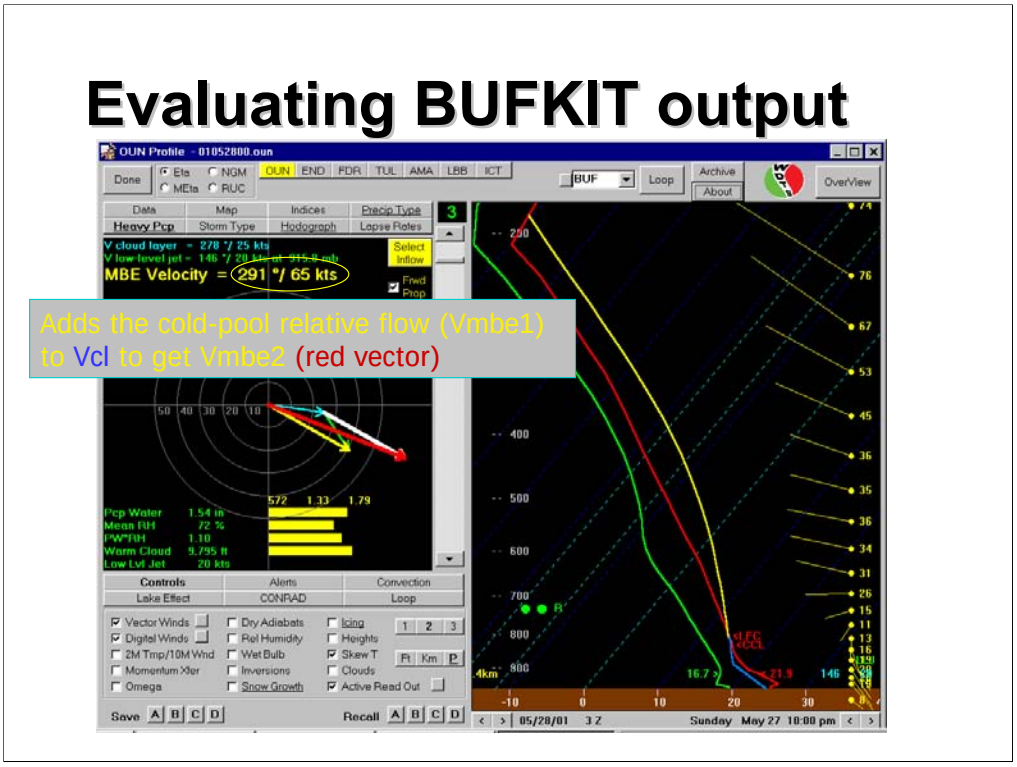
Revised MCS Vector technique



This is a technique from Corfidi (2003) . You can apply this in BUFKIT and AWIPS Volume Browser.

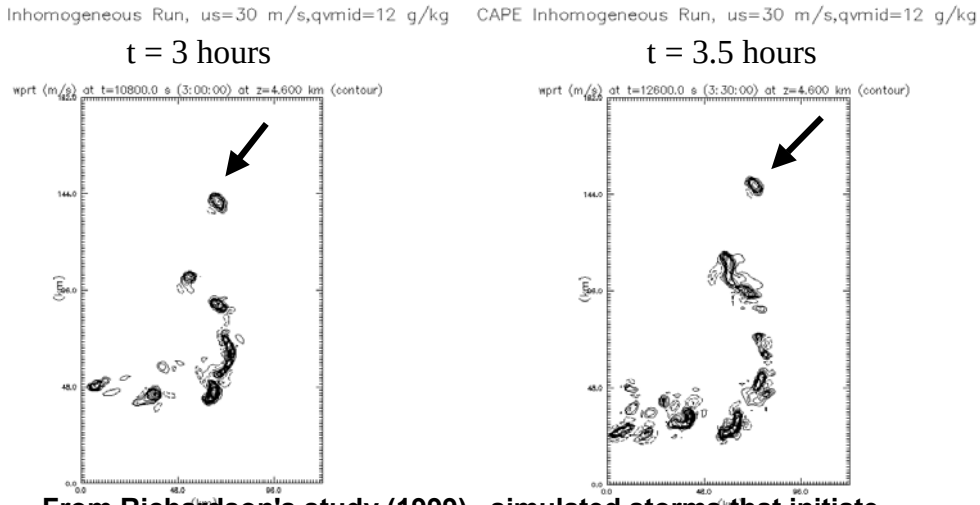


This was a case in OK in May of 2001. Over 100 reports of wind damage across the central and western parts of the state from this forward propagating MCS.



Using Corfidi's technique described in the WAF article, the MBE motion computed in BUFKIT (see vector magnitude circled in yellow and red vector on hodograph display – accessed from heavy pcp button) for a 3 hr Eta forecast sounding was 291 deg, 65 kts. Observed (radar) system motions on along the line were probably closer to 300 deg at 55 kts.

Storm Longevity vs. Environmental Constraints



From Richardson's study (1999), simulated storms that initiate in greater moisture can continue to exist as they move into unfavorable environments

There are also considerations of adjacent storms affecting the environment and subsequent movements. Richardson's study (1999) indicated that simulated storms initiated in greater moisture may continue to exist as they move into an environment that would not support a cell from inception. Split cell motion only mildly influenced by moisture distribution. Updraft strength and mid level rotation are enhanced by increased moisture. Complex cell interactions make definitive conclusions regarding low level rotation difficult. Thus, uncertainties regarding storm/system influences on the environment.

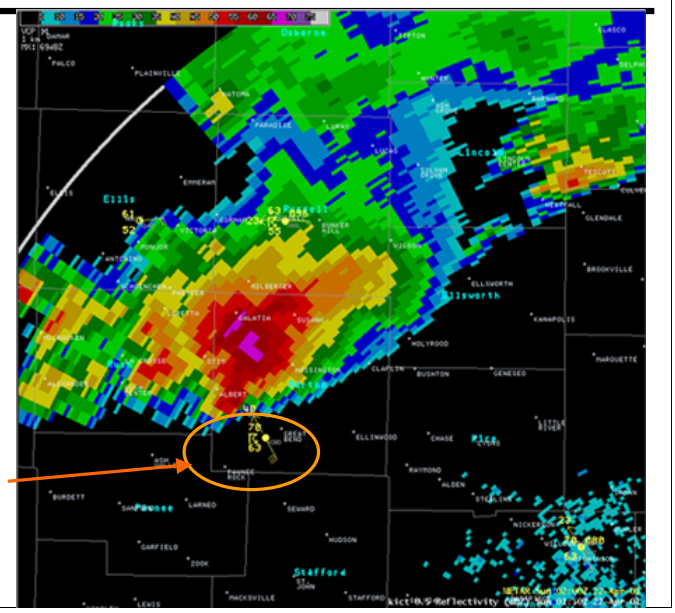
Storm Scale Effects

- How does the storm scale affect the environment (and vise versa?)
  - Anvil-induced shadows
  - Increased accelerations/shear in inflow region (within 30 km)

From Weisman (1998 SLS Preprint), there are significant enhancements in shear and SRH near the storm (10-50% of the environment) due to parcel accelerations in inflow region. To determine a mesoscale sounding that is not storm influenced, consider the effects of the storm in modifying the environment. This influence likely extends out to 30 km (15 mi) from the storm.

Evaluating Storm Scale Effects

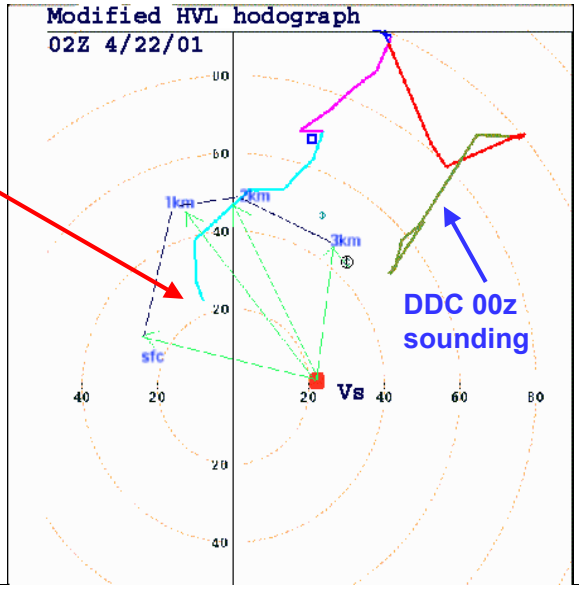
- KICT 0.5 deg. Z product , 20 min. prior to tornado touchdown



This was from the April 21, 2001 tornado near Hoisington, KS.

Determining Storm Induced Changes in Mesoscale

- Profiler at HVL showed large changes in 0-1 km SRH due to storm inflow prior to tornadic supercell development

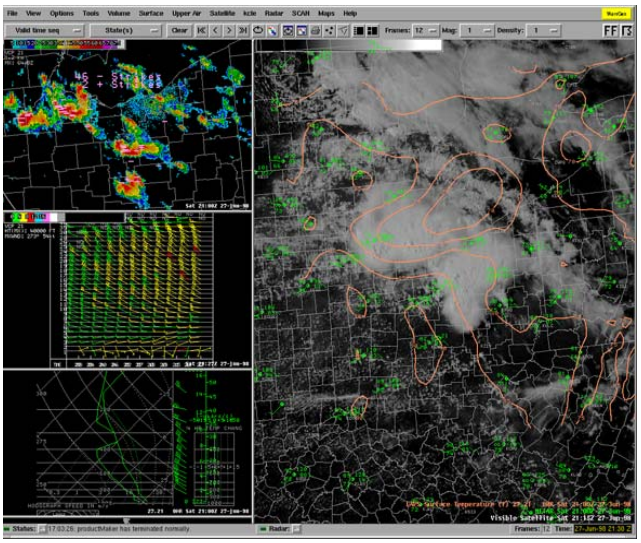


Diagnosing storm-induced changes in the environment (such as this) can provide considerable weight to warning decisions.

By the way, a large tornado (rated F4 damage) developed in Hoisington , KS in this environment

Threat Assessment
Sample AWIPS Layout

- Should include the ability to monitor convective storm development and evolution on the mesoscale throughout the lifetime of event



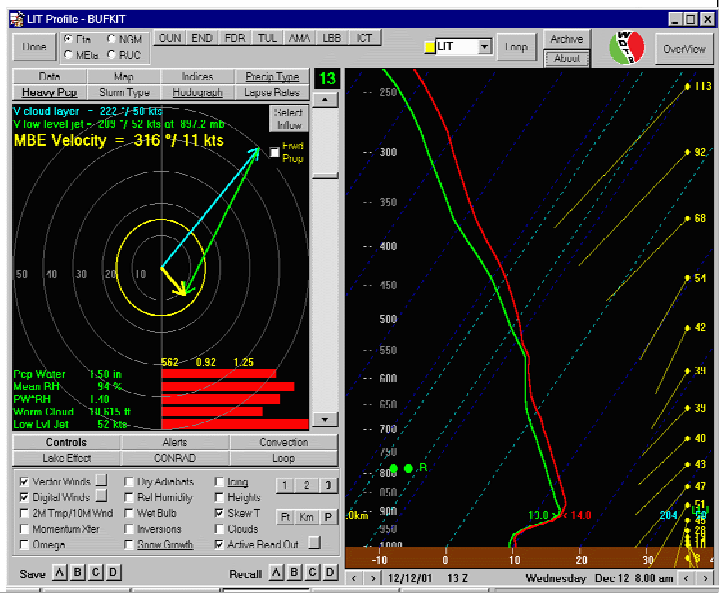
If a dedicated *Meso-analyst* is not available, we recommend **at least one** monitor on your AWIPS warning workstation dedicated to mesoanalysis for all situations when severe weather is expected. The Warning Met should utilize some panes on the AWIPS D2D workstation for proper mesoanalysis. In moderate to outbreak severe weather events, an entire AWIPS workstation position may be needed to perform the duties. It depends on staffing strategies, but some offices may combine the Mesoscale Analyst position with other positions (eg., HMT, long-term, aviation, short-term forecaster, etc.) .

There is a lot of room for personal preference here, but for any situation , the AWIPS workstation layout should provide the opportunity for the mesoscale analyst position to monitor storm development and evolution. Multiple AWIPS datasets providing routine and continuous analysis of the convective environment include GOES and POES satellite imagery, upper-air data, surface data, profiler data, model data, and radar data. In terms of radar data, the mesoscale threat assessment D2D layout should incorporate a **multi-state scale view** of the data so the forecaster can keep abreast of the “big picture”. This analysis is important for the warning Met as he/she often loses track of the big picture during the storm scale interrogation process.

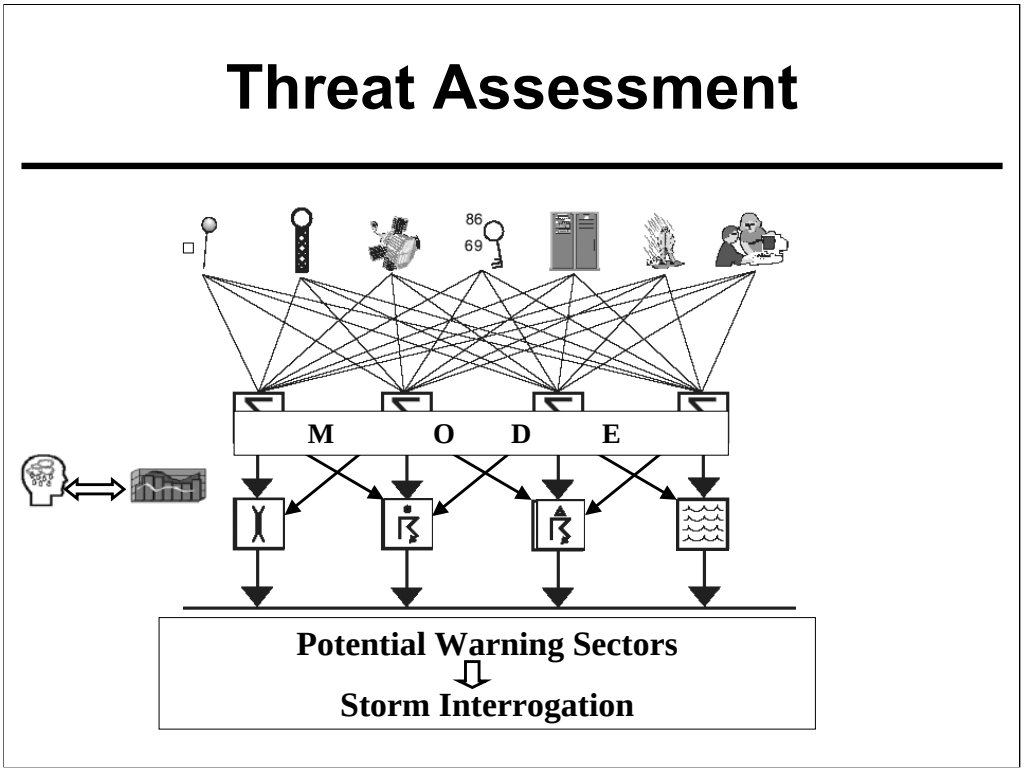
Threat Assessment Layout

- Include a PC box for BUFKIT

- Offers ability to forecast convective mode and motion using various techniques



The ability to recognize potential severe weather types and evolutions is crucial to maintaining situational awareness in a warning methodology. The mesoanalyst position is a vital link in the warning process. The use of hourly forecast profiles offers an excellent way to visualize spatial and temporal changes in the mesoscale.



To summarize the threat assessment process in warning methodology, you could envision an integrated synthesized approach of all synoptic and mesoscale data into a summative forecast of convective storm type. The little head symbol and bar graph on the left of the represent the pattern recognition process. The initial forecast of convective mode (supercells, multicells, pulse) should contain (if possible) an additional probability forecast of tornado, damaging winds, severe hail, and/or flash flooding (note, often multiple types of severe weather are associated with the same convective mode, so this process is often quiet difficult). The type of severe weather that we expect based on the environment gives the warning team initial thoughts for the warning strategy, such as determination of any needs to sectorize warning operations, what procedures, etc. This leads to interrogation process, which is the next step in the warning process.

Summary

- Threat Assessment
  - Outlook
  - Short-term
  - Continuous

Threat assessment is a continuous process on various time and space scales.

References

- See the reference page handout

Contact Information

- For questions on this IC
  - Contact your SOO
  - WDTB focal points for Severe Track IC2
    - icsvr2@wdtb.noaa.gov

There are some instructors at WDTB that can help you with questions on this IC. Send any questions to this e-mail address.

Severe Track IC 2
References

Bluestein, H. B., and M. L. Weisman (2000): The Interaction of Numerically Simulated Supercells Initiated along Lines. *Monthly Weather Review*: Vol. 128, No. 9, pp. 3128–3149.

COMET, 1996: Anticipating convective storm structure and evolution. CD-ROM.

COMET, 1999: Mesoscale Convective Systems: Squall Lines and Bow Echoes. Online training module, http://www.meted.ucar.edu/convectn/mcs/index.htm.

COMET, 2001: Understanding NWP Models and Their Processes, A Distance Learning Course, available at http://www.meted.ucar.edu/nwp/course/index.htm

Corfidi, S.F., 2003: Cold Pools and MCS Propagation: Forecasting the Motion of Downwind-Developing MCSs. *Wea. Forecasting.* Vol. 18, No. 6, 997-1017.

Crook, N. A., 1996: Sensitivity of moist convection forced by boundary layer processes to low- level thermodynamic fields. *Mon. Wea. Rev.*, 124, 1767-1785.

Davies, J., 2004: Tornadoes in a deceptively small CAPE setting: The "surprise" 4/20/04 outbreak in Illinois and Indiana. Web article at http://members.cox.net/jondavies3/042004ilin/042004ilin.htm.

Diagnosing the Potential for Surface Boundaries to Initiate Convection, A VISIT training session produced by WDTB (Jim LaDue, primary author), 2001. Available at http://www.nssl.noaa.gov/istpds/icu92/icu922web/ic922.html

Evans, J.S. and C. A. Doswell III, 2002: Investigating Derecho and Supercell Proximity Soundings**.** Preprints, 21st Conf. Severe Local Storms, San Antonio.

LaDue, J. L., 1998: The influence of two cold fronts on storm morphology. *Preprints*, 19th Conf. On Severe Storms, Minneapolis, MN, Amer. Meteor. Soc., 324-327.

Maddox, R.A., 1980: Mesoscale convective complexes. *Bull. Amer. Meteor. Soc*., 61, 1374-1387.

McCaul, E. W., and M. L. Weisman, 2000: The sensitivity of simulated storm structure and intensity to variations in the shapes of environment buoyancy and shear profiles. Mon. Wea. Rev., 129, 664-687.

Moncrieff, M. W., and C. Liu, 1999: Convection Initiation by Density Currents: Role of Convergence, Shear, and Dynamical Organization. *Monthly Weather Review*, 127, No. 10, pp. 2455–2464.

NWS Professional Development Series (PDS), *Forecasting and Warning Severe Convection*, available at http://www.nwstc.noaa.gov/nwstrn/d.ntp/meteor/svrpds.html

Newton, C. W., 1967: Dynamics of severe convective storms, *Met. Monographs*, 5, 33-58.

Richardson, Y.P., 1999: The Influence of horizontal variations in vertical shear and low-level moisture on numerically simulated convective storms. Ph.D. Dissertation, School of Meteorology, University of Oklahoma - Norman, 236 pp.

Rotunno, R., J. B., Klemp, and M. L. Weisman, 1988: A Theory for Strong, Long-Lived Squall Lines**.** *Journal of the Atmospheric Sciences*: Vol. 45, No. 3, pp. 463–485.

Rutledge, S. A., and R.A. Houze, 1987: A Diagnostic Modelling Study of the Trailing Stratiform Region of a Midlatitude Squall Line. *Journal of the Atmospheric Sciences*: Vol. 44, No. 18, pp. 2640–2656.

Schultz, D. M., 2001: Winter Weather Forecasting Topics at the WDTB Winter Weather Workshop, presentation available at http://wdtb.noaa.gov/workshop/WinterWxIV/presentations/SCHULTZ_.PPT

Trapp, J., R. D., M. Schultz, A. V. Ryzhkov, and R. L. Holle, 2000: Multiscale Structure and Evolution of an Oklahoma Precipitation Event , *Mon. Wea. Rev*., 129, 3, 486-501.

Using AWIPS to Detect Surface Boundaries, A VISIT training session produced by WDTB, 2000. Available at http://www.nssl.noaa.gov/istpds/icu92/ic921.html

Weaver, J. F., 1979: Storm Motion as related to boundary-layer convergence. *Mon. Wea. Rev.,* 107**,** 612-619.

Weisman, M. L., M.S. Gilmore, and L. J. Wicker, 1998: The Impact of Convective Storms on their Local Environment: What is an Appropriate Ambient Sounding? Preprints, 19th Conf. on Severe Local Storms, MPLS, 238-245.

____, 1993: The genesis of severe, long-lived bow echoes. *J. Atmos. Sci.,* 50, 645–670.

Wilson, J. W., and D. L. Megenhardt, 1997: Thunderstorm initiation, organization, and lifetime associated with Florida boundary layer convergence lines. *Mon. Wea. Rev.*, 125, 1507-1525.

Wolf, R. 2002: Doppler radar observations of squall line tornadogenesis near the KDVN WSR-88D. Preprints. 21st Conf. on Severe Local Storms, San Antonio, 507-510.

Ziegler, C. L., and E. N. Rasmussen, 1998: The Initiation of Moist Convection at the Dryline: Forecasting Issues from a Case Study Perspective**.** *Weather and Forecasting*: Vol. 13, No. 4, 1106–1131.