Tornado Forecasting Class Notes - Handout

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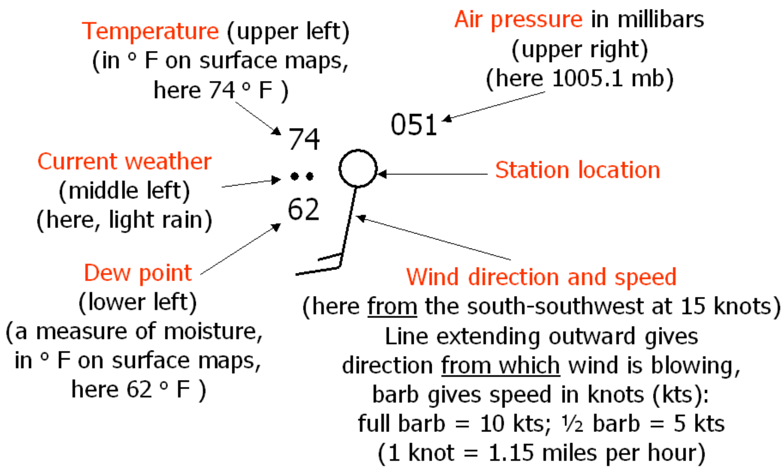
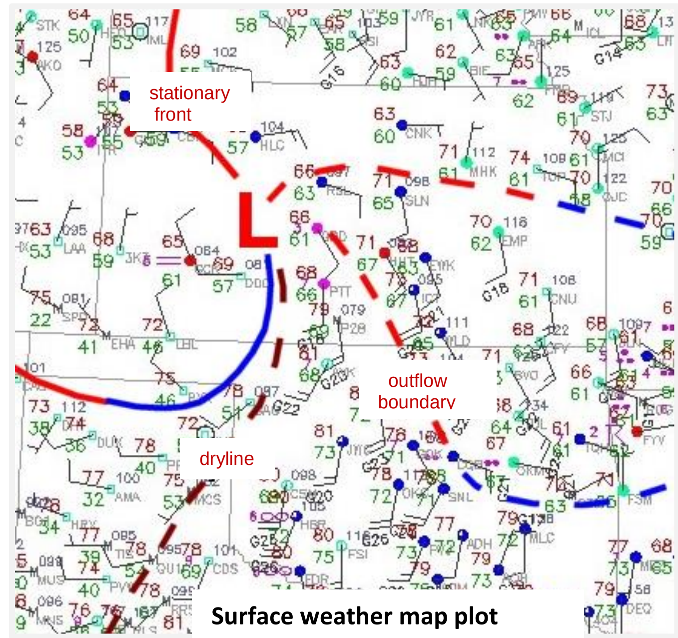
Some Basic Meteorology Background -

Surface weather map observation station plots:



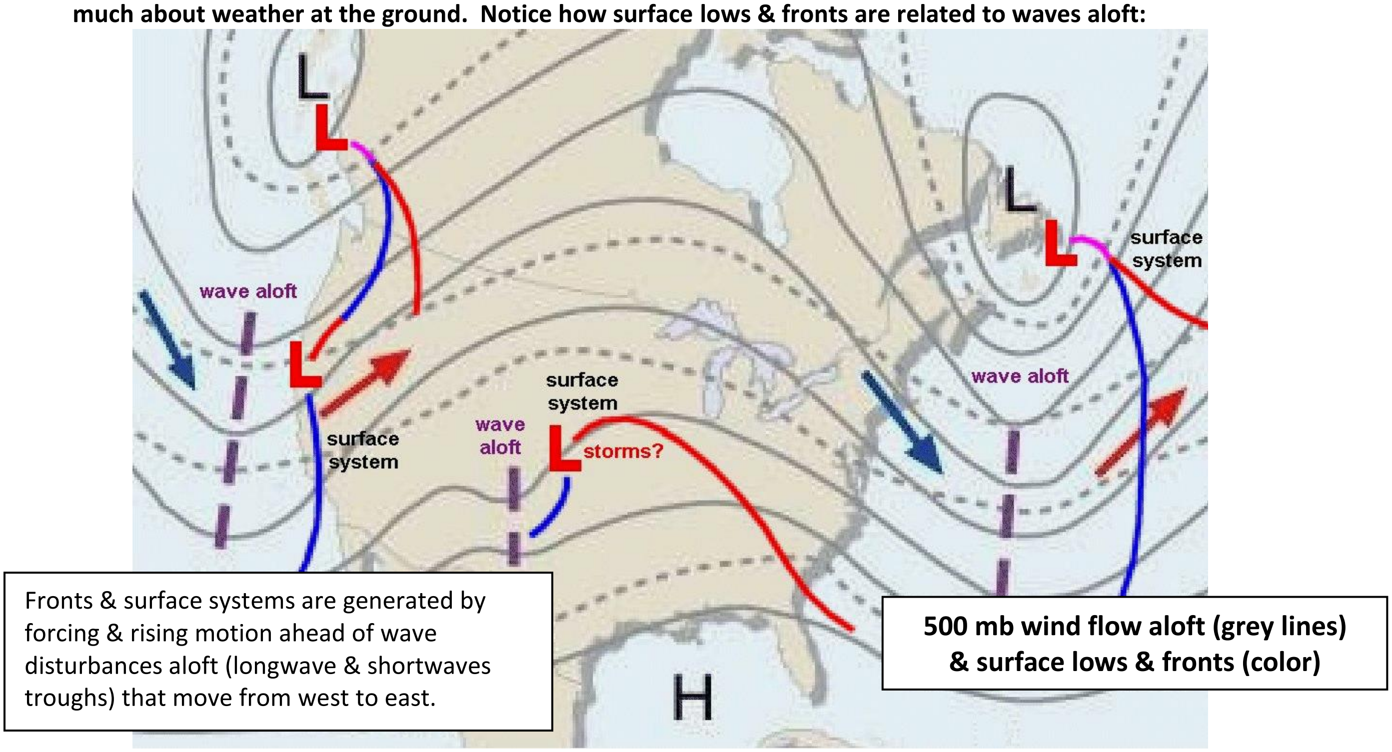


Surface weather map plot

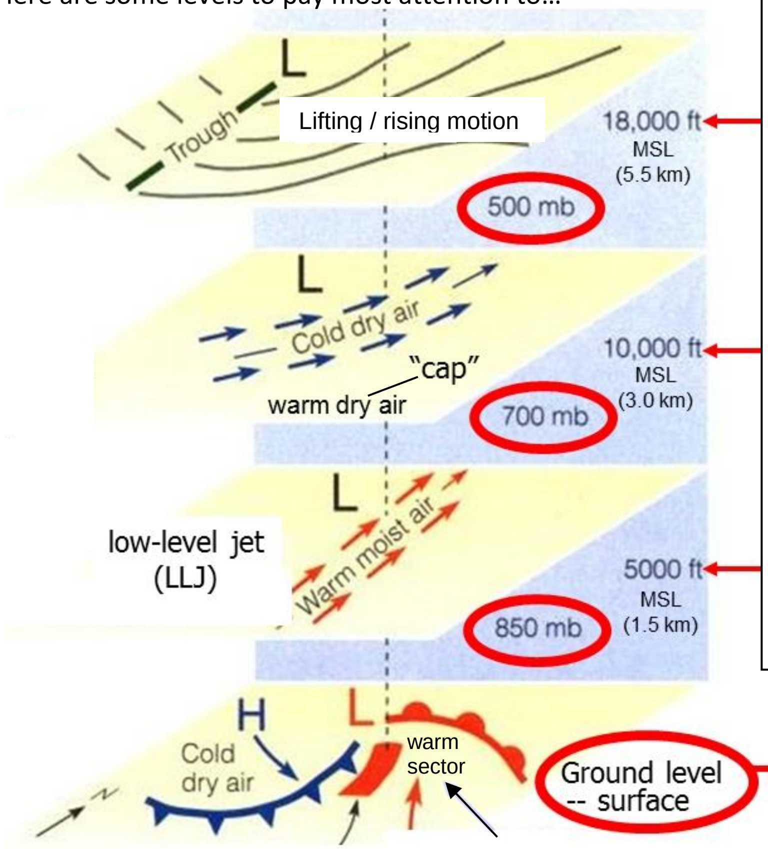
Surface maps are the most basic weather map. Boundaries/wind shifts such as cold fronts (blue)/warm fronts (red)/stationary fronts (red & blue)/drylines (dashed brown)/storm outflow (dashed red & blue) can help generate thunderstorms through converging winds & lift. These boundaries are located by looking carefully for any of the following, organized along a line or curve:

- Sharp temperature changes over a short distance
- Significant changes in moisture content (dew point)
- Significant changes in wind direction

Weather maps above ground (this is a 500 mb map – roughly 18,000 ft MSL) are important because they tell us much about weather at the ground. Notice how surface lows & fronts are related to waves aloft:



Learn to read upper air maps, which are slices through the atmosphere at increasing elevations above ground. Here are some levels to pay most attention to…



Some things to look for regarding severe weather on upper air maps from computer model forecasts:

500 mb map (approx. 18,000 ft MSL):
- use this level to check for wave / trough disturbances aloft that force air upward & can trigger thunderstorms.
- also check for stronger wind speeds aloft (30-35 knots or greater) that can organize storms into supercells.

700 mb map (approx. 10,000 ft MSL):
- use this level to check for areas of warm air aloft that can "cap" and inhibit thunderstorm development.

850 mb map (approx. 5,000 ft MSL):
- use this level to check for stronger winds 1-2 km above ground (the **low-level jet**) that contribute to low-level wind shear & storm-relative helicity [SRH] that can help generate tornadoes.

Surface map (ground level):
Look for lows, fronts, wind shifts, areas of converging winds, heating, and moisture (dew points in the 50s/60s/70s° F) to locate where organized thunderstorms might form.

Forecasts of surface & upper air maps and various parameters are available from computer models that are run and maintained by the National Weather Service (NWS). These are used by meteorologists to make weather forecasts, including severe weather. Computer models such as the **NAM** and **RAP** have higher resolution & more detail than the **GFS**; the **HRRR** model has very high resolution and the most detail. A summary of these models:

- **GFS (Global Forecast System):** goes out to 16 days & is run 4 times per day (12z am & 00z pm runs are most accurate as they use new sounding observations).
- **NAM (North American Mesoscale):** goes out to 3.5 days (84 hours), is run 4 times per day.
- **RAP (Rapid Refresh):** goes out to 18 hours (out to 48 hours at 15z/21z/03z/09z), is run hourly.
- **HRRR (High Resolution Rapid Refresh):** goes out to 18 hours (out to 48 hours at 12z/18z/00z/06z) is run hourly. Has highest resolution detail, best for 1-2 day convective/thunderstorm forecasting.

The **GFS** is used to look farther ahead (out to 16 days), but it is very unreliable beyond 5-7 days. The early panels can be used as a comparison to the NAM, but it is the lowest resolution and least detailed of all the models.

The **NAM** is used to look out to 3 days or so, and is more detailed than the GFS. The panels out to 18 or 48 hours can also be used as a comparison to the RAP.

The **RAP** and **HRRR** are short-range models used mostly within 1-2 days of an impending event. The HRRR is updated frequently with available current observations for even more detail.

The **HRRR** with its frequent updating and high resolution is good for convective and thunderstorm forecasting. It has products such as **updraft helicity**, "rotation" tracks on radar forecast panels that suggest where supercell storms may develop. Be careful not to read these too literally, as they suggest storm mode in general areas, but can vary on specifics from hour to hour.

Sites with real-time weather information & computer model forecasts:

- College of DuPage:

weather.cod.edu/forecast (HRRR, RAP, NAM, & GFS – also European model)
also has archive of model runs past 1-3 days; and recent surface, satellite, & radar at **weather.cod.edu/analysis** & **weather.cod.edu/satrad**

- Pivotal Weather:

www.pivotalweather.com/model.php (HRRR, RAP, NAM, & GFS - also European model)

- TwisterData:

www.twisterdata.com (RAP, NAM, & GFS models)

- UCAR / NCAR weather (University Center for Atmospheric Research):

weather.rap.ucar.edu/model (RAP, NAM, & GFS) – also excellent source for current & recent **surface, satellite, & radar** data **–** also see archives at **www.mmm.ucar.edu/imagearchive**

- Storm Prediction Center (SPC) mesoanalysis:

www.spc.noaa.gov/exper/mesoanalysis – real-time severe weather fields from 1-hr **RAP** forecasts updated by surface obs, along with RAP model 2 to 6 hour forecasts of these fields

IMPORTANT NOTES about computer models:
- Computer models, at best, are only an approximation & estimation of the atmosphere. They make assumptions that may not always apply well, and initialization in sparse data areas can create forecast problems.
- As models go farther out in time, errors amplify to make large inaccuracies.
- Use computer models only as an "opinion" to be considered and compared with other information & experience.

*** **Reading UTC time:** computer models & most weather maps use "UTC" or "Z" time stamps (note: '0300 UTC' & '03 UTC' & '03z' & '0300z' are all different ways of displaying the same time). **Learn to read these time labels!**

Table converting Universal Time (UTC) to Central Time (CST or CDT):

0000 UTC =	**6:00 p.m. CST**	**= 7:00 p.m. CDT**
0300 UTC =	**9:00 p.m. CST**	**= 10:00 p.m. CDT**
0600 UTC =	**midnight CST**	**= 1:00 a.m. CDT**
0900 UTC =	**3:00 a.m. CST**	**= 4:00 a.m. CDT**
1200 UTC =	**6:00 a.m. CST**	**= 7:00 a.m. CDT**
1500 UTC =	**9:00 a.m. CST**	**= 10:00 a.m. CDT**
1800 UTC =	**noon CST**	**= 1:00 p.m. CDT**
2100 UTC =	**3:00 p.m. CST**	**= 4:00 p.m. CDT**

- Add 1 hour to CDT & CST to get Eastern Time (EDT & EST).
- Subtract 1 hour from CDT & CST to get Mountain Time (MST & MDT).
- Subtract 2 hours from CDT & CST to get Pacific Time (PDT & PST).

- NOTE: Remember that dates "jump ahead" a day in the evening hours starting at 0000 UTC:
2100 UTC **1 May** 2018 is **4:00 pm CDT** 1 **May** 2018, **BUT** 0000 UTC **1 May** 2018 is actually **7:00 pm CDT 2 May** 2018,
and 0000 UTC **1 Feb** 2018 is actually **6:00 pm CST 2 Feb** 2018

Some meteorological concepts to be familiar with for supercell tornado forecasting:

Tornadoes like certain types of boundaries:

- Warm fronts are very supportive of tornadoes, particularly for supercells that are directly on or very near the warm front.
- Stationary fronts can also support tornadoes, particularly if a supercell is moving along the front.
- Outflow boundaries can also be supportive of tornadoes, similar to stationary fronts.
- The warm sector, away from boundaries & just east of drylines, can support supercell tornadoes, but combinations of wind shear (SRH) & buoyancy (CAPE) must be large.
- Cold fronts aren't usually supportive of supercell tornadoes, due to cold air undercutting of supercells that are directly on the cold front. A tornadic supercell must be ahead of the front.

The **low-level jet** (LLJ, around the 850 mb level) is important for creating wind shear that supports supercell tornadoes in the Plains. It increases dramatically near & just after dark, sometimes creating a "window of opportunity" for tornadoes before nighttime cooling sets in.

The "**cap**" is a layer of hot, dry air from the desert southwest of the U.S. & Mexico that can move out northeastward over the top of moist, unstable air in the Plains when winds aloft at the 700 mb level are from a southwesterly direction. This cap of hot, dry air can act like a "lid", suppressing thunderstorm development. Assessing whether there is a cap and where it might be located is important for thunderstorm forecasting. Here's a rough guide for locating the cap using **700 mb** temperature at different times of the year:

Spring		Fall	
March	approx $\geq$ 5-6° C	August	approx $\geq$ 12° C
April	approx $\geq$ 7-8° C	September	approx $\geq$ 9-11° C
May	approx $\geq$ 9-11° C	October	approx $\geq$ 7-8° C
June	approx $\geq$ 12-13° C	November	approx $\geq$ 5-6° C

NOTE: This chart does not work well in the High Plains of eastern NM-CO-WY-MT, far western NE-SD, etc., due to elevation issues. Also, strong surface heating (90's° F to 100's° F) can initiate very high-based storms in otherwise "capped" areas that will usually dissipate after sunset.

Factors that relate more directly to the possibility of supercell tornadoes, (if storms are expected to develop):

- **sizable CAPE**
- **sizable low-level wind shear (SRH)**

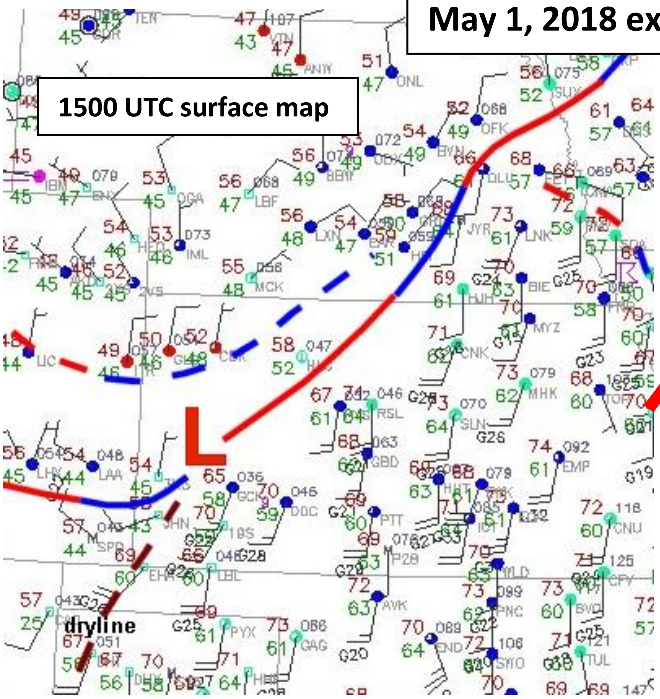
} *Combinations of these 2 ingredients are very important for supercell tornadoes*

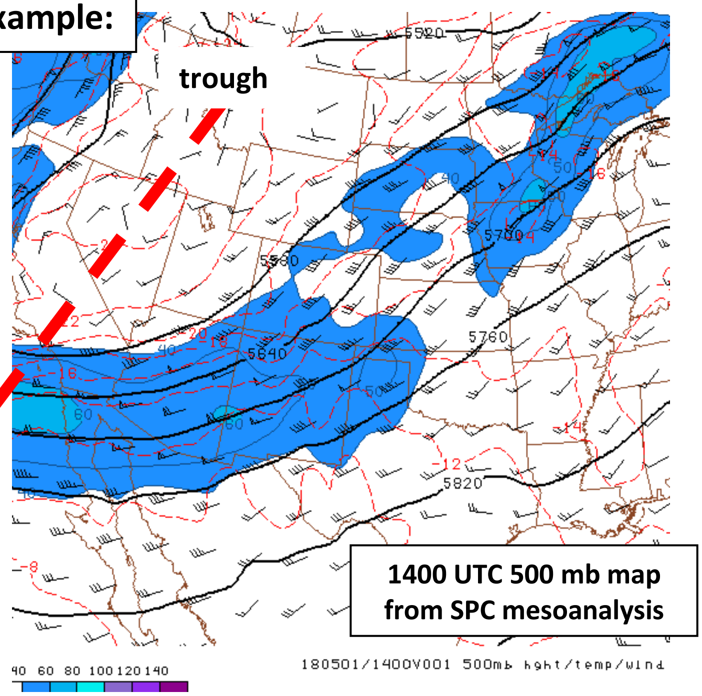
- **sizable deep-layer wind shear (500 mb winds > 30-35 kt)**
- **relatively low cloud bases – low lifting condensation level (LCL) heights**

Weather forecasting amounts to two basic steps:

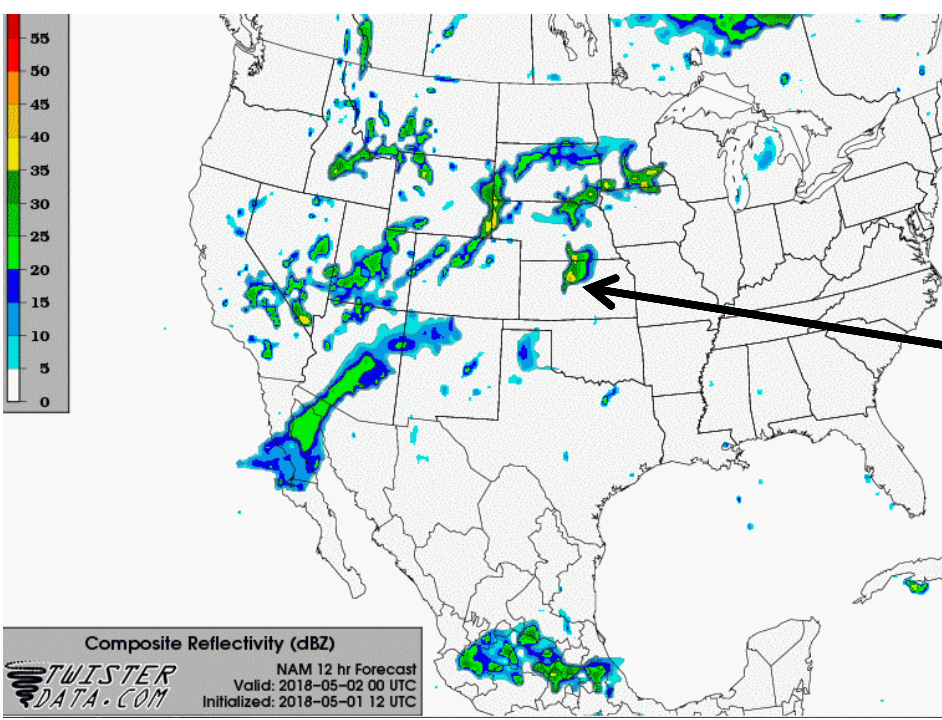
1) **Diagnosis** – getting an understanding of current weather features the morning of a chase using surface maps, radar, satellite and upper air data.
2) **Prognosis** - making a projection of how these weather features and processes will evolve during the day using computer model forecasts and knowledge of weather processes from experience.

May 1, 2018 example:

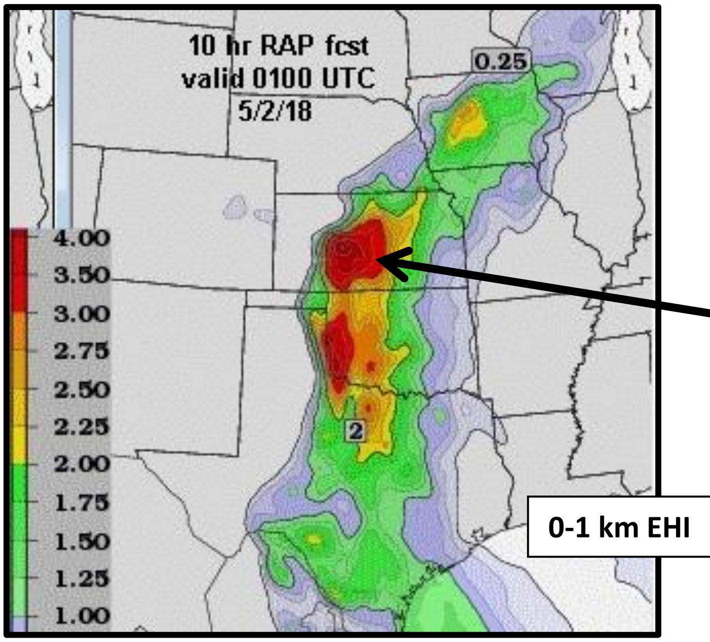




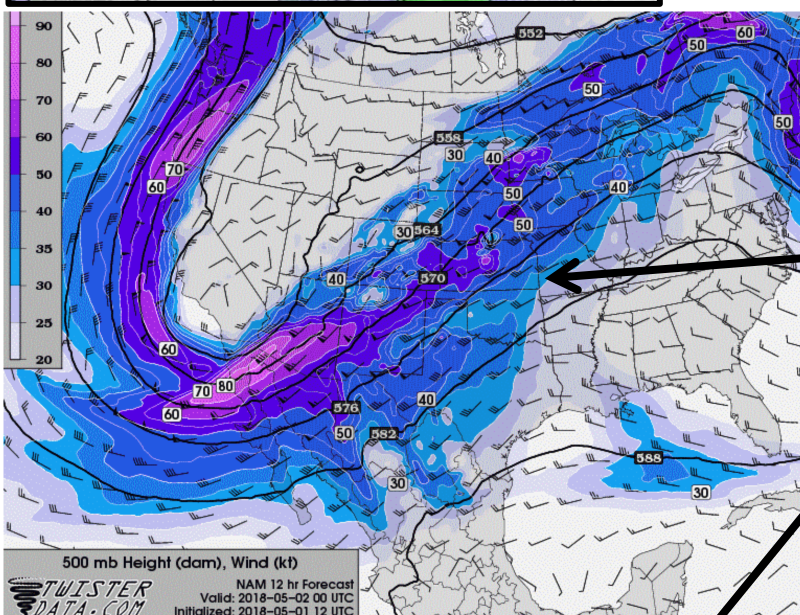
Above are mid-morning analysis maps to make a ***diagnosis*** of morning weather. On the surface map, a stationary front and low are over western and north-central Kansas with dew points in the 60's^{o} F. Aloft at 500 mb (roughly 18,000 ft MSL), a large trough is over the western U.S., with strong winds extending northeastward over Kansas. This is a common setting for severe weather in the Plains northeast of the Kansas surface low. Now, on to ***prognosis*** & computer model forecasts for the afternoon & evening:



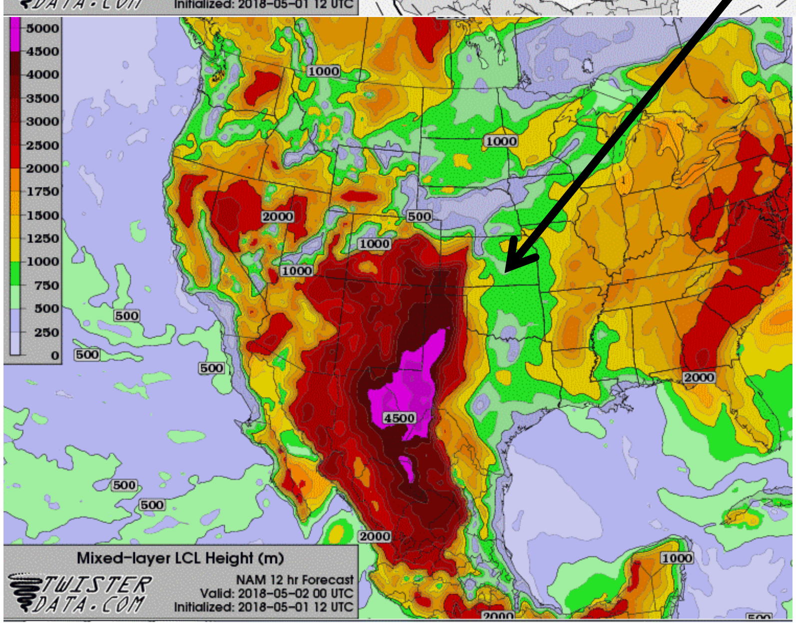
12 hour forecast showing the NAM model's "opinion" of what radar reflectivity will look like at 7 pm CDT (early evening). Note the cluster of storms forecast in central Kansas. This fits with the NAM model forecast of the "cap" at 700mb (not shown), where temperatures in central & northern Kansas were expected to be < 9^{o} C. using the cap guide from the previous page.



10 hour forecast showing the RAP model's "opinion" of where combinations of CAPE and low-level wind shear (SRH) will be largest at 8 pm CDT, using the 0-1 km energy-helicity index (EHI). Notice the red area in central Kansas near where the NAM model forecasts a thunderstorm cluster (previous page).



Finally, here are the 12 hour NAM model's forecasts of winds at 500 mb, and LCL heights, valid at 7 pm CDT. Notice how strong the 500 mb winds are over Kansas (blues & purples), good for organizing & supporting supercell storms, & notice that the LCL heights are relatively low (green) over central Kansas where the NAM also forecasts a storm cluster



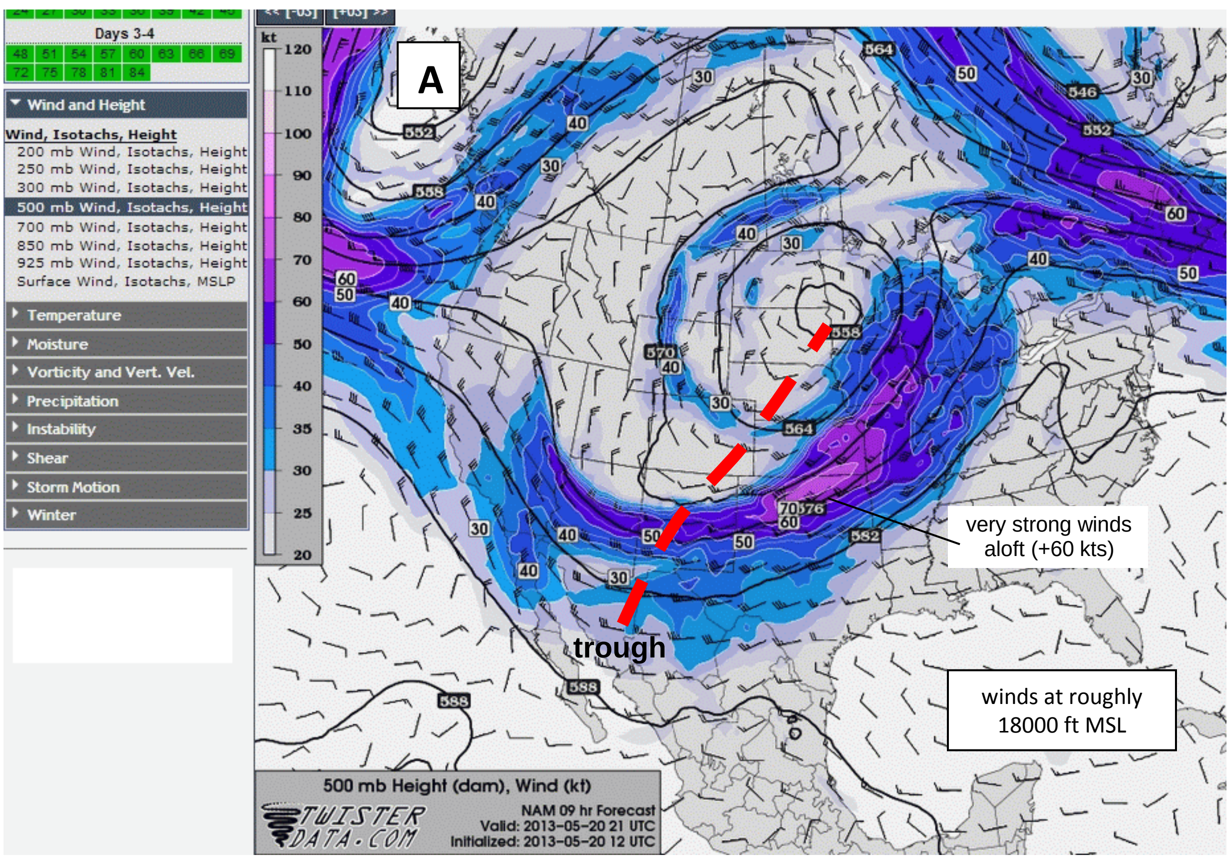
So, this abbreviated look at the model forecasts makes some sense, given the features from our morning analysis and **diagnosis**. And our **prognosis** is that the main factors relating to supercell tornadoes (sizable CAPE and SRH, strong deep-layer shear, and low LCL heights) appear like they will all be present over central Kansas where thunderstorms are forecast. It therefore is reasonable to expect that evening tornadoes will be possible over central Kansas, which indeed is what happened near Salina.

Forecasting supercell tornadoes: Basic requirements – a sort of "checklist"

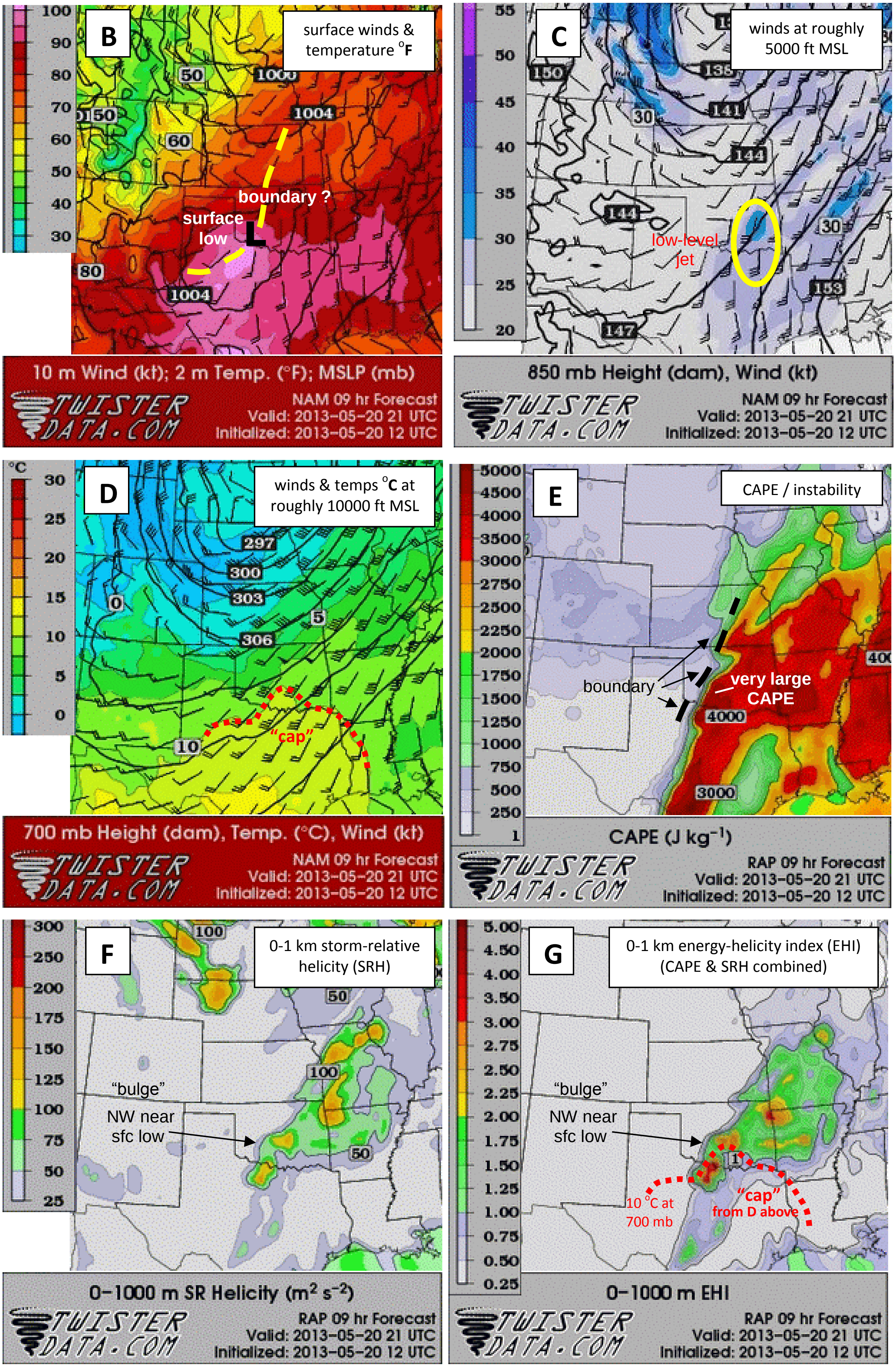
- **Moisture & instability**
  - look for CAPE (instability) to support thunderstorms
- **Forcing & upward motion to trigger storms**
  - wave disturbances aloft (around 500 mb) for lift & rising motion
  - surface boundaries for wind convergence & lift; daytime heating helps
  - absence of a "cap" (a warm layer around 700 mb that inhibits storms)
- **Strong winds aloft (at 500 mb)**
  - 30-35 kt winds or more at 500 mb help organize storms into supercells
- **Significant wind shear near the ground**
  - winds veering from southerly to westerly & increasing with height in the lowest 1 km or so provide horizontal "spin" that can help supercell thunderstorms to generate tornadoes

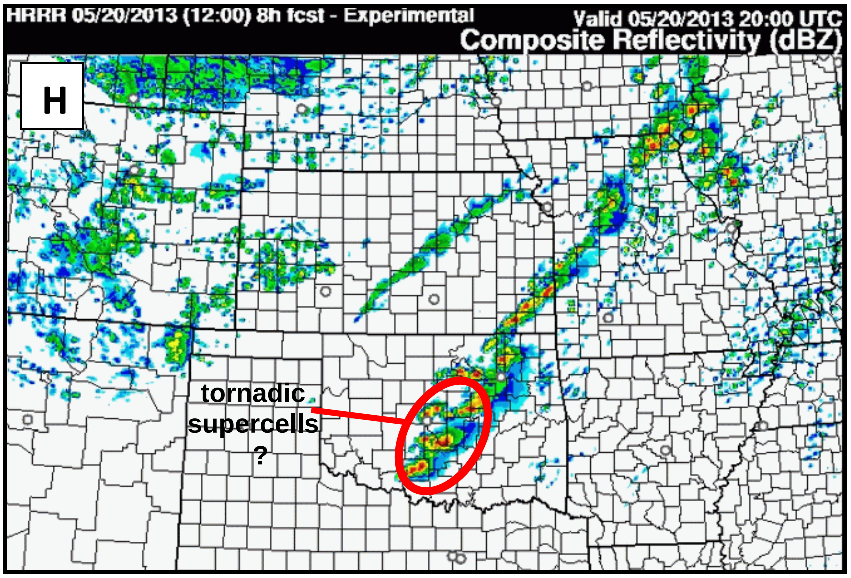
CASE STUDY – a case example applying the above "checklist"

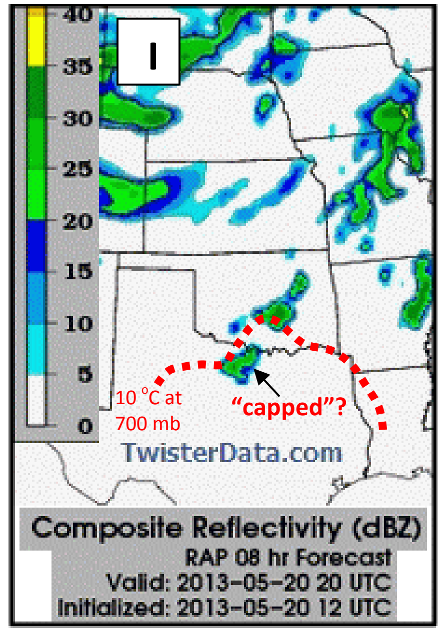
Using the above information, let's analyze some forecast maps (below, on pg. 5, and at top of pg. 6) from the Twisterdata site using the 12 UTC NAM, RAP, & HRRR model forecasts valid for mid-pm on 20 May 2013, the day of the deadly Moore OK tornado. A detailed analysis/forecast discussion is given on pages 6, 7, and 8.



The 500 mb map above is shown full screen; the remaining maps on the following page will be shown "cropped" over the central U.S. so more maps can be displayed on a page.


B
surface winds & temperature °F
boundary ?
surface low
L
10 m Wind (kt); 2 m Temp. (°F); MSLP (mb)
TWISTER DATA.COM
NAM 09 hr Forecast
Valid: 2013-05-20 21 UTC
Initialized: 2013-05-20 12 UTC
C
winds at roughly 5000 ft MSL
low-level jet
850 mb Height (dam), Wind (kt)
TWISTER DATA.COM
NAM 09 hr Forecast
Valid: 2013-05-20 21 UTC
Initialized: 2013-05-20 12 UTC
D
winds & temps °C at roughly 10000 ft MSL
"cap"
700 mb Height (dam), Temp. (°C), Wind (kt)
TWISTER DATA.COM
NAM 09 hr Forecast
Valid: 2013-05-20 21 UTC
Initialized: 2013-05-20 12 UTC
E
CAPE / instability
boundary
very large CAPE
CAPE (J kg⁻¹)
TWISTER DATA.COM
RAP 09 hr Forecast
Valid: 2013-05-20 21 UTC
Initialized: 2013-05-20 12 UTC
F
0-1 km storm-relative helicity (SRH)
"bulge"
NW near sfc low
0-1000 m SR Helicity (m² s⁻²)
TWISTER DATA.COM
RAP 09 hr Forecast
Valid: 2013-05-20 21 UTC
Initialized: 2013-05-20 12 UTC
G
0-1 km energy-helicity index (EHI) (CAPE & SRH combined)
"bulge"
NW near sfc low
10 °C at 700 mb
"cap" from D above
0-1000 m EHI
TWISTER DATA.COM
RAP 09 hr Forecast
Valid: 2013-05-20 21 UTC
Initialized: 2013-05-20 12 UTC





Moisture & instability – Looking at graphic E on pg. 5, there's plenty of CAPE / instability forecast over central Texas (TX), Oklahoma (OK), southeast Kansas (KS) & eastward, with over 4000 J/kg of CAPE (a very large amount) expected over parts of central and southern OK and north TX. The sharp western edge of the CAPE field also suggests a boundary (focus for storms?) from north central OK to northwest TX.

Forcing & upward motion to trigger storms – Figuring out where storms will develop is one of the more difficult tasks in forecasting, and involves assessing several factors:

Looking at the 500 mb level forecast aloft (graphic A back on pg. 4), there's a large wave/trough in the jet stream winds (blues & purples) moving out into the central plains that will provide broad energy and lifting there.

On graphic B (pg. 5), the surface map forecast suggests a northeast-southwest boundary similar to that indicated on the CAPE forecast (graphic E, pg. 5), along with a surface low & heating over southwest OK. This should provide strong focus for thunderstorms at the west edge of the large CAPE area over OK when combined with the strong system aloft at 500 mb in graphic A on pg. 4.

Graphic D on pg. 5 shows temperatures at the 700 mb level. In mid May (see the chart below), temperatures around 10°C are a rough indicator of the north edge of the "cap" (warm air aloft from the desert southwestern U.S. & Mexico that inhibits thunderstorms). Using 10°C as a guide, notice that graphic D suggests the south edge of thunderstorm potential will be somewhere over southern OK or northwest TX.

700 mb temperature estimations of areas that are "capped" (too warm aloft for thunderstorms):

Spring		Fall	
March	approx ≥ 5-6° C	August	approx ≥ 12° C
April	approx ≥ 7-8° C	September	approx ≥ 9-11° C
May	approx ≥ 9-11° C	October	approx ≥ 7-8° C
June	approx ≥ 12-13° C	November	approx ≥ 5-6° C

*This chart doesn't work well in the western High Plains due to elevation (e.g., eastern NM, eastern CO, far western NE, etc.).

The last thing we'll look at regarding forcing & upward motion to trigger thunderstorms is computer forecasts of radar / precipitation. Graphics H & I on pg. 6 are 8 hour radar forecasts valid at mid-pm from the HRRR (highest resolution) and the RAP. Notice that the HRRR forecast is very aggressive initiating storms relatively early in the pm from central OK to southeast Iowa, with the most impressive cells in central OK along the boundary discussed earlier (graphics B & E on pg. 5) where the RAP forecast of CAPE (graphic E on pg. 5) was largest (> 4000 J/kg). The RAP radar forecast in graphic I (pg. 6) is lower in resolution, but shows roughly the same thing, except that storms are also Indicated in northwest TX where the atmosphere may actually be "capped" (graphic D on pg. 5).

Based on all the above information, it looks like the best forecast for the **strongest storms** is in **central & southern OK** where CAPE is large just **east of the surface low**, which from experience is often **a favored location**.

Strong winds aloft at 500 mb – Going back to graphic A on pg. 4, winds aloft at 500 mb are very strong (near 60 kts, purples & pinks) in central OK, which is excellent for supporting organized thunderstorms & supercells (30-35 kts is typically the minimum speed required).

Significant wind shear near the ground – This is what often makes the most difference between tornadic & non-tornadic supercell settings.

Winds from a southerly or easterly direction veering with height to become stronger & more southwesterly or westerly create rolling motions of slow horizontal "spin" in the lowest 1 lm or so above ground. This "spin" can then be ingested into thunderstorms to be tilted upward & stretched, creating low-level rotations that may generate supercell tornadoes if other factors such as updrafts & downdrafts come together properly.

This potential for horizontal "spin" is estimated by a parameter called **storm-relative helicity (SRH)** in the **0-1 km** layer. Areas of stronger southerly 850 mb winds (25-30 kts or more, as seen over south & southeast OK in graphic C, pg. 5) may also indicate good potential for this "spin". Favorable values of SRH for supercell tornadoes depend on amount of CAPE available for storm updraft strength & stretching (stronger low-level wind shear will also help enhance updraft strength). Smaller SRH values (roughly 100-150 m^2/s^2) require much larger amounts of CAPE (3000-5000 J/kg) than SRH values of roughly 200-300 m^2/s^2 or more (CAPE of 1500-2500 J/kg). A parameter called the **0-1 km energy-helicity index (EHI)** combines SRH with CAPE to suggest favorable values for tornado potential; EHI values of 2.0-3.0 or more in the spring, summer, and early fall suggest increased potential for supercell tornadoes:

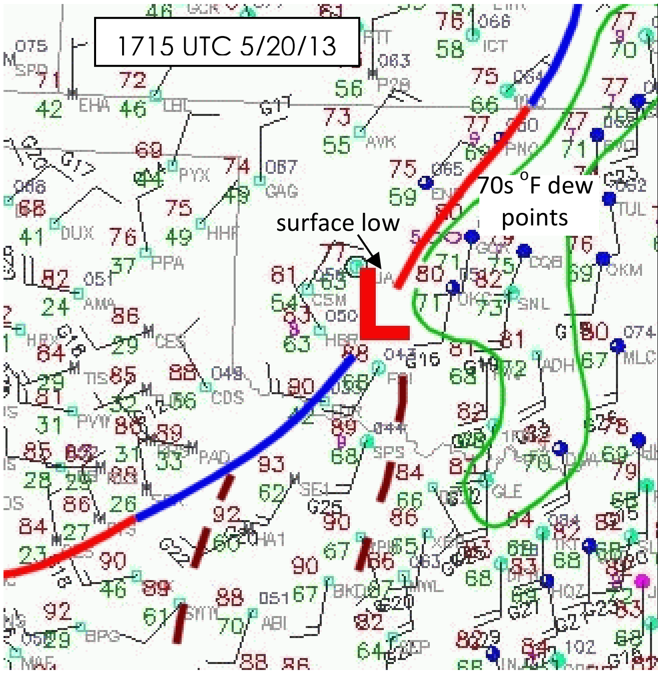
Some favorable parameter values for assessing settings that may support significant supercell tornadoes:

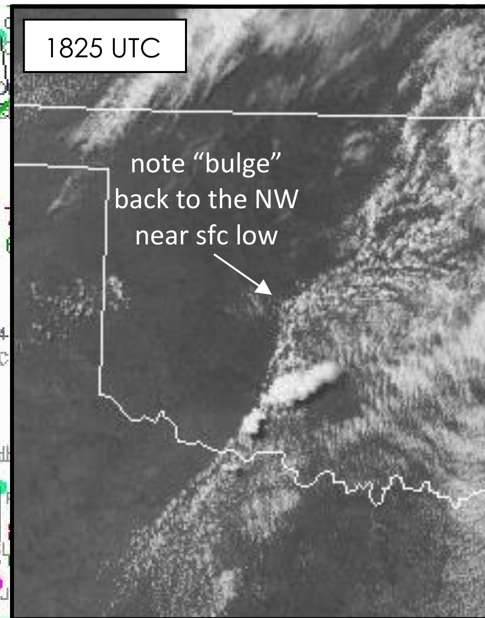
- **Low-level wind shear & CAPE:**
  - **0-1 km EHI of 2 – 3 or more (1 or more in cool season Oct.-Mar.)**
  - **SRH of 100-150 m^2/s^2 or more when CAPE* is large, 3000-5000 J/kg**
  - **SRH around 200-300 m^2/s^2 or more when CAPE* is roughly 1500-2500 J/kg**
  - **SRH around 400-500 m^2/s^2 or more when CAPE* is small, 500-1000 J/kg**
- **Strong winds aloft: 500 mb winds around 30-35 knots (near 40 knots or more for stronger tornadoes)**
- **Surface temperature (T) – dew point (T_d) spreads 20°F or less (reduces evaporative cooling that can hinder low-level rotation)**

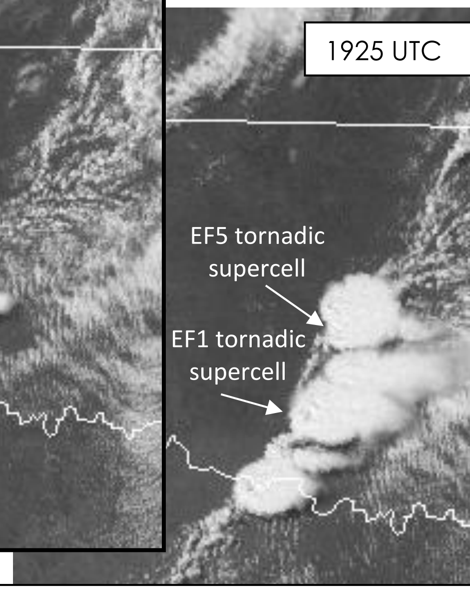
*** Largest CAPE of either: surface-based (SBCAPE), or lowest 100mb mixed-layer parcel (MLCAPE)**

So, **back to our analysis** & using the table above, graphic F (pg. 5) forecasts **0-1 km SRH values of around 100 m^2/s^2** over central OK where storms are expected and no "cap" is indicated. Combined with **CAPE greater than 4000 J/kg** forecast in the same area (graphic E, pg. 5), **0-1 km EHI values more than 2.0** (graphic G, pg. 5, yellow colors east /northeast of the surface low location) suggest that **central OK** may be a favored location for supercell tornadoes. Also, just look at the surface pattern that is forecast back on pg. 5… a surface low is over southwest OK with large CAPE to its east (a favored location for tornadoes), with radar forecasts (pg. 6) showing storms firing up there… these factors alone point to central OK having strong potential for severe weather, if not tornadoes.

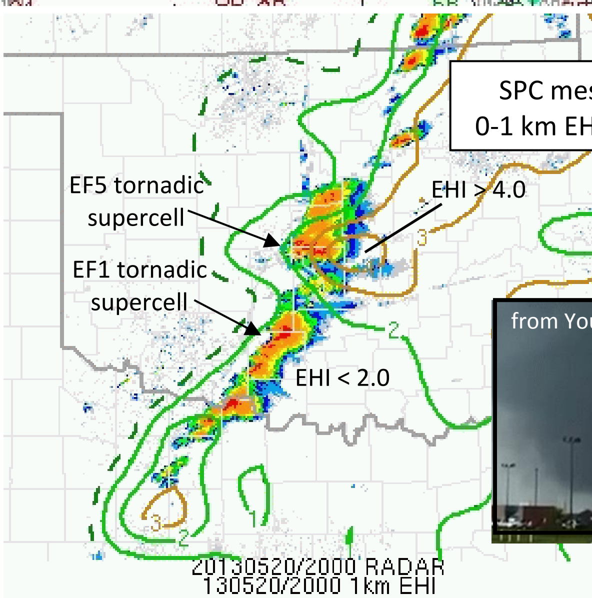
Here's what actually happened on 20 May 2013 from surface, satellite. radar, & SPC mesoanalysis data at early to mid pm:

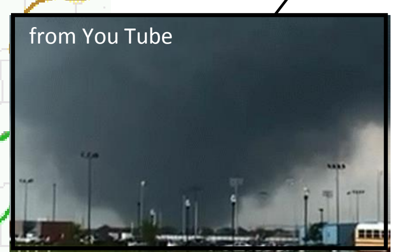






These maps suggest how you might refine a forecast as the day progresses if you have ongoing access to data.





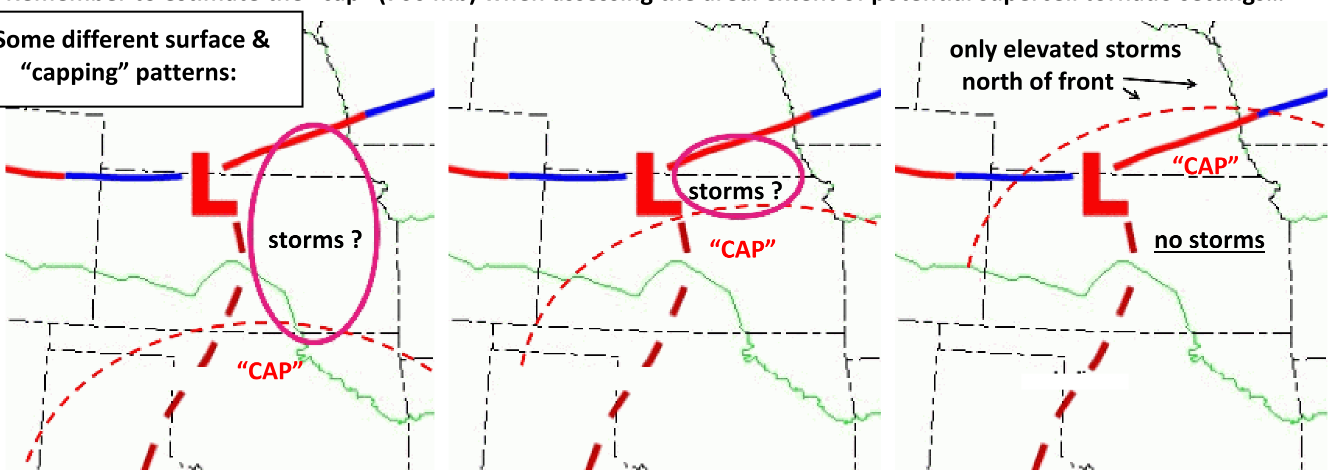
Sadly, the EF5 tornado that struck Moore in central OK shortly after 2 pm CDT killed 24 people.

Even though 0-1 km SRH values forecast over central OK were not overly impressive that afternoon (only 100-125 m^2/s^2, graphic F, pg. 5), when combined with CAPE values over 4000 J/kg & unusually strong wind flow at 500 mb (over 60 knots) for the time of year, the setting was explosively supportive of a deadly tornado.

Other tornadoes of lesser intensity developed with cells that moved into northeastern OK later in the afternoon, where EHI values were also sizable.

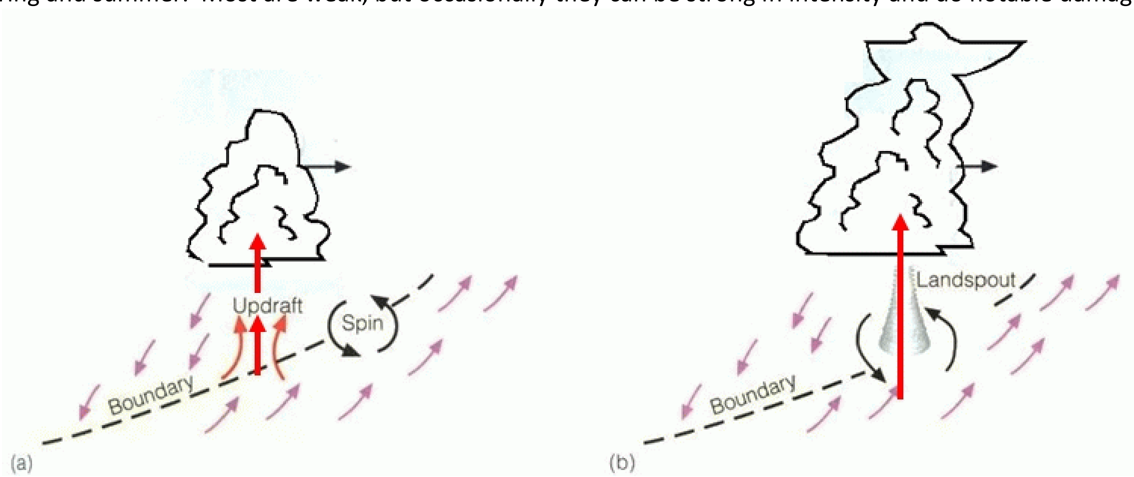
Remember to estimate the "cap" (700 mb) when assessing the areal extent of potential supercell tornado settings…

Some different surface & "capping" patterns:



Non-supercell tornadoes:

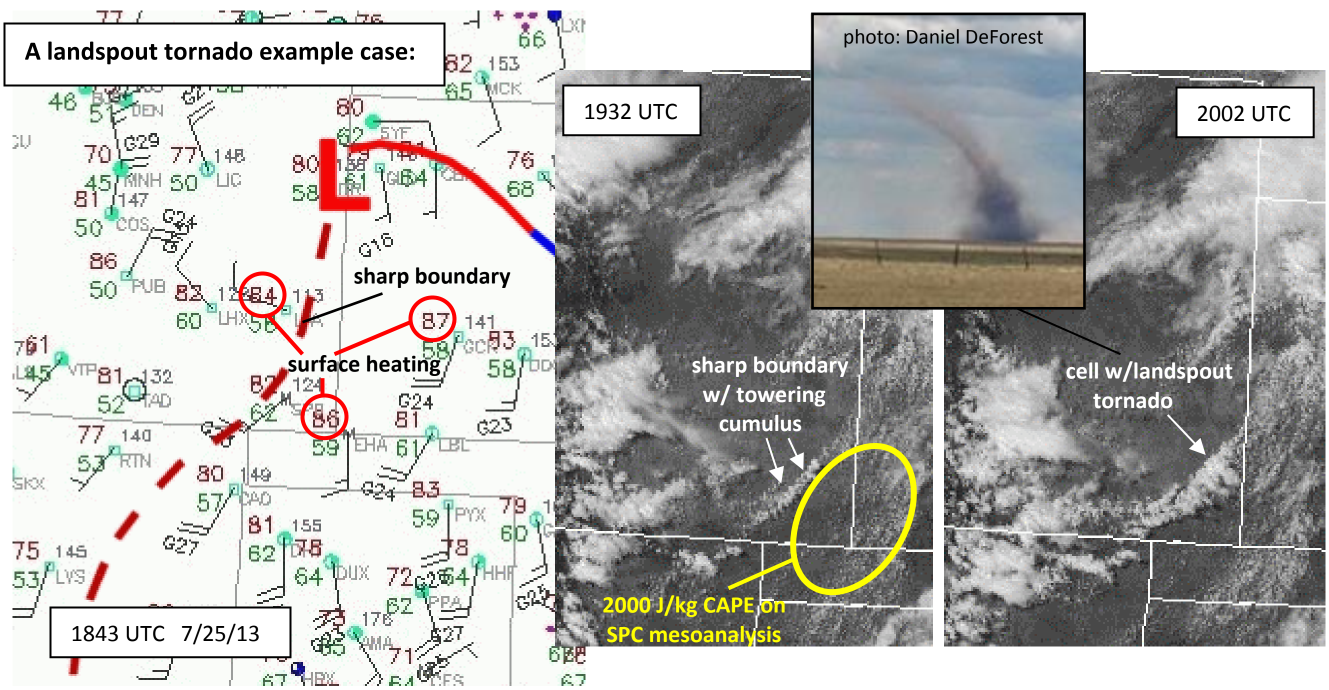
Landspouts are most common in the High Plains of eastern CO, western KS & NE, and the TX panhandle, but can happen anywhere in the central U.S. if the right ingredients come together during peak afternoon heating in late spring and summer. Most are weak, but occasionally they can be strong in intensity and do notable damage.



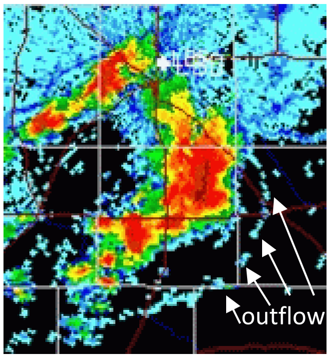
Pockets of slow vertical "spin" can be present on a sharp slow-moving wind shift boundary before storms form. If storm updrafts develop directly over the boundary & stretch one of the pockets of "spin" (vertical vorticity), a landspout tornado can develop.

Landspouts are difficult to forecast, but one might see ingredients coming together to increase the chances of a mesoscale "accident" a few hours in advance of an event. On a hot day in the central or high plains in late spring or summer, watch for:

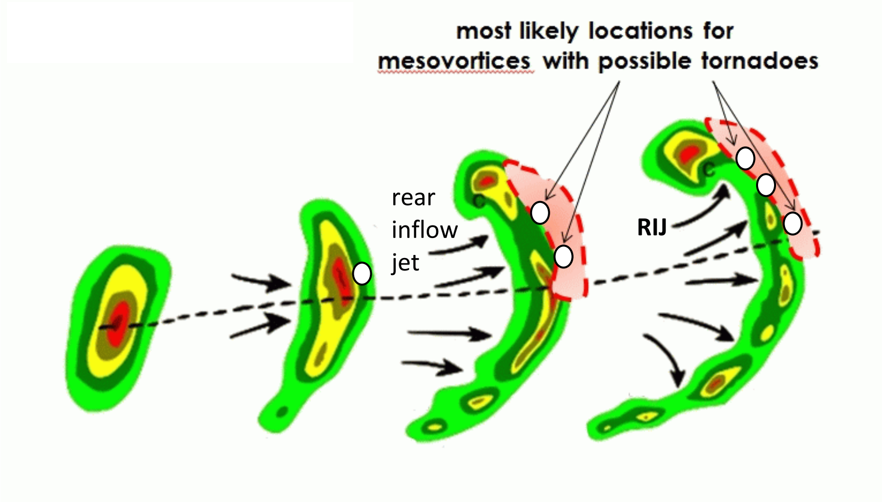
- A sharp northeast-southwest surface wind shift boundary that is slow-moving with little temperature contrast across it
- Significant CAPE / instability along & near the boundary
- Strong surface heating & steep low-level temperature lapse rates near the boundary



Gustnadoes aren't considered tornadoes, but are shallow vortices that "spin up" along gust front outflow from thunderstorms. They are possible with any thunderstorm, but are most likely on hot afternoons with storms in the central U.S. during spring and summer:



Bow echo tornadoes are non-supercell tornadoes that form from circulations called **mesovortices** along and north of the center of a bow echo or what is called a "quasi-linear convective system (QLCS)". They are not well understood, and are generally short-lived and weak, but once in a while they can be marginally strong in intensity and do brief but notable damage. Their formation appears to relate to a **rear-inflow jet (RIJ)** of air flow that descends at the back of the bow, and its interaction with vorticity ("spin") along the bow-echo gust front near the leading edge of the bow. Settings with large low-level shear (SRH) ahead of the bow can also help with these "spin ups". Such tornadoes are difficult if not impossible to forecast, but can occur with any bow echo thunderstorm complex at any time of year if there is some CAPE present to support and maintain the thunderstorm line:



So… That's a really broad summary of basic meteorological data & sources, and how some of that applies to supercell tornado forecasting, along with brief material about non-supercell tornadoes.

When forecasting, do what works for you and have fun with it!

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