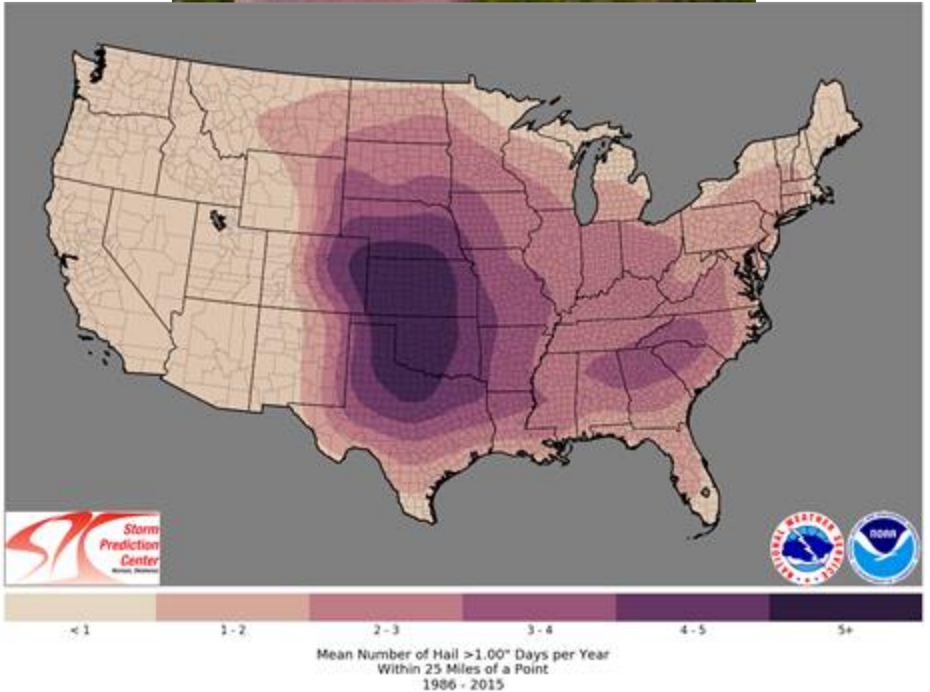
Hail Forecasting

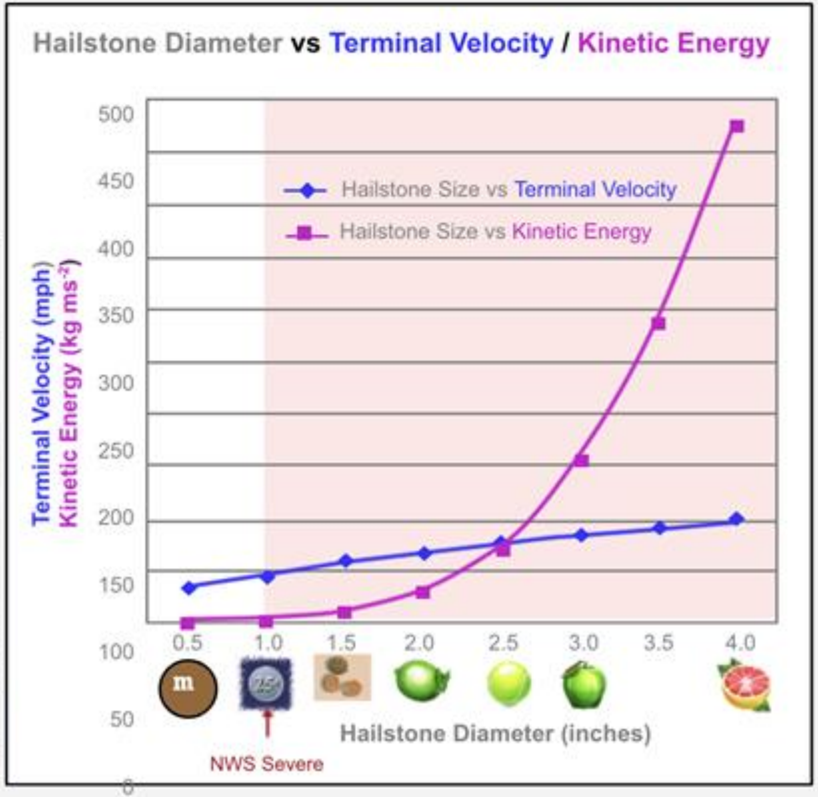
Background

- Severe hail is any hail greater than 1” in diameter after 2010.
    - Sig Hail > 2” in diameter
    - *Prior to 2010 it was 0.75”*
- Around 5,000 Severe hail reports on average in the us every year.
    - Numerous cases of sub-severe hail
    - Accumulating hail also a growing area of study.
- Most common over the Great Plains states
- One of the most costly hazards associated with severe thunderstorms
    - Billion dollar hail storms becoming more frequent.



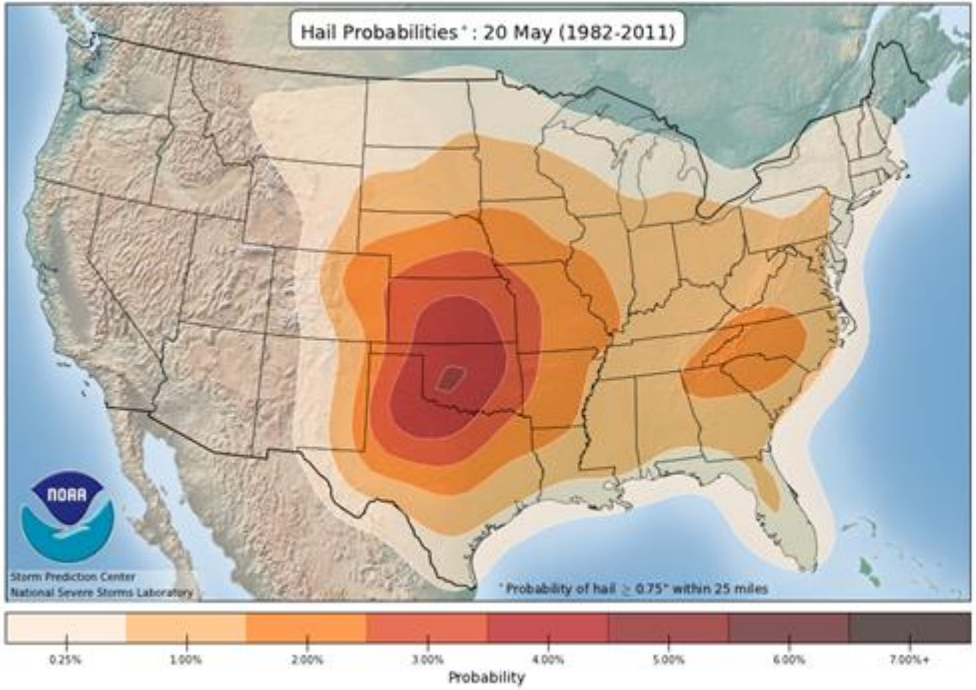
Motivation

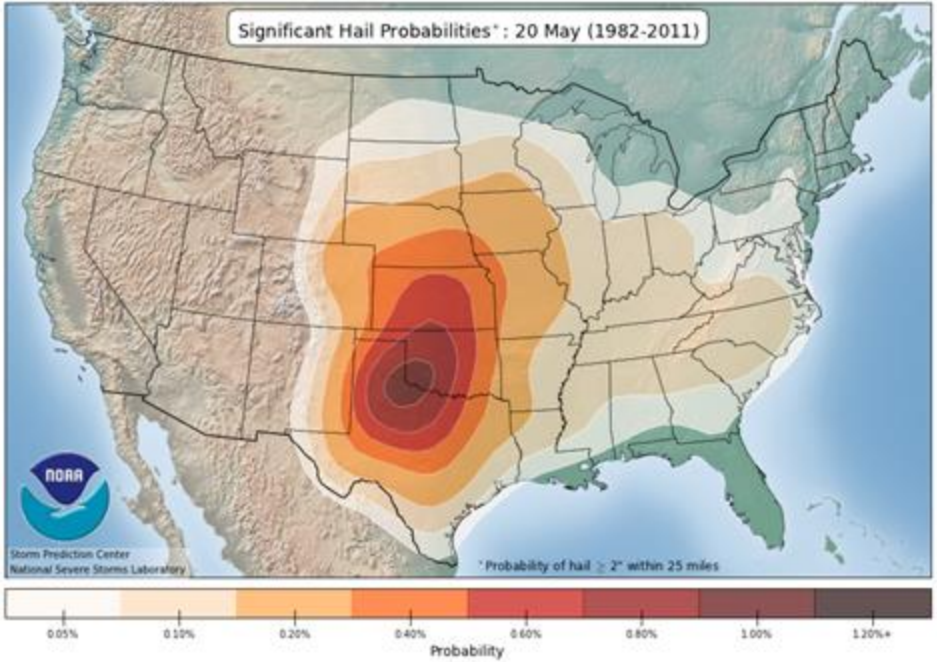
A hailstone's destructive potential increases dramatically with diameter



https://www.spc.noaa.gov/new/SVRclimo/climo.php?parm=allHail

https://www.spc.noaa.gov/new/SVRclimo/climo.php?parm=sigHail





Hail Size Chart

NWS Quad Cities IA / IL

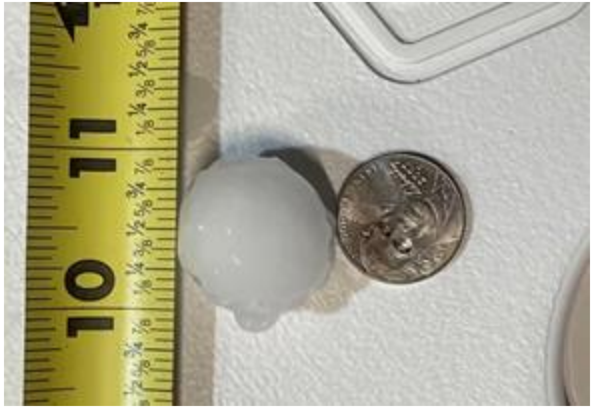
While the National Weather Service encourages the actual measurement of hail size, oftentimes, an object-to-size conversion can provide important information about hail that fall from thunderstorms. Here is a list of common objects used to describe the diameter of observed hail.

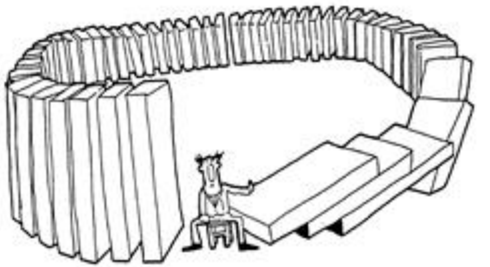
Size	Object
0.25 inches	Pea
0.75 inches	Penny
1.00 inches	Quarter
1.50 inches	Ping Pong Ball
1.75 inches	Golf Ball
2.00 inches	Lime
2.50 inches	Tennis Ball
2.75 inches	Baseball
4.00 inches	Softball
4.50 inches	Grapefruit

Sun Mar 31, 2024 12:30 PM

How its messed stuff up…

- Size discretization of hail from coins and objects has resulted in unrealistic distributions of reported sizes.
- Hail size should generally decrease in frequency (exponential) but we see a multimodal distribution.
- Hail size cluster around common objects and sizes
  - Quarter
  - Golf Ball
  - Baseball
- It's gotten much easier to report hail
  - MPING
  - Spotter network
  - Twitter
  - but perhaps not the true size…





Schafer et al.,

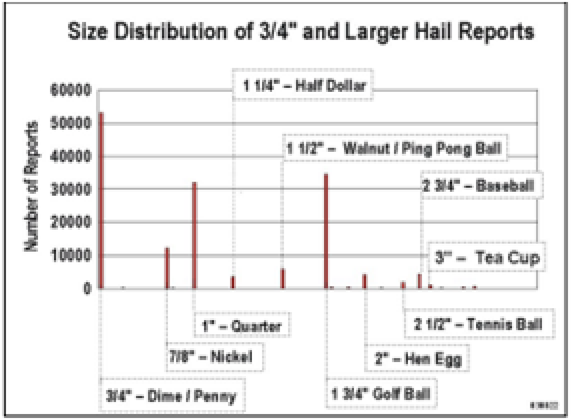


Figure 1: Size distribution of severe hail reports (1955 – 2002)

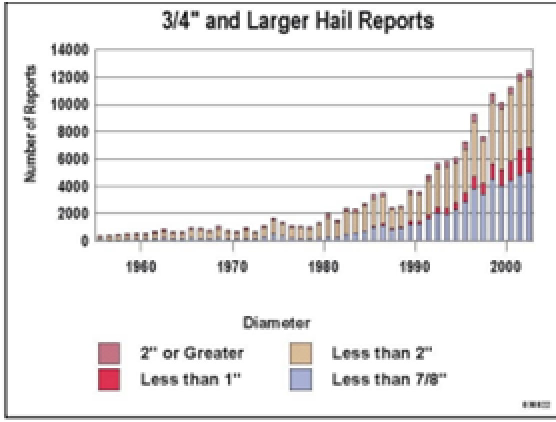


Figure 2: Growth of hail reports with time

Records

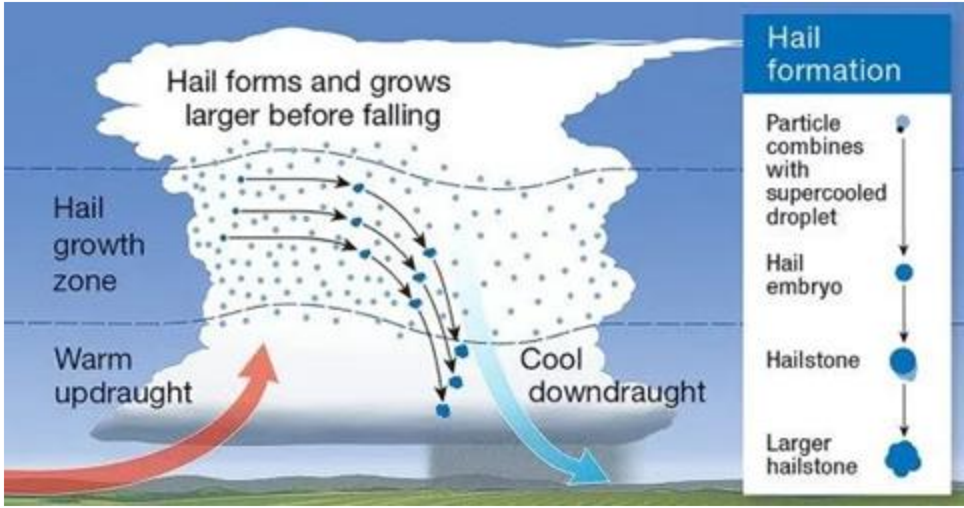
- Us record for diameter is from Vivian, SD july 23rd of 2010
  - 7.9 inches (20 cm) in diameter and weighed nearly 2 lbs.

- **Heaviest:** 1.02 kg (2.2 lb); Gopalganj District, Bangladesh, 14 April 1986.[43][44]
- **Largest diameter officially measured:** 7.9 in (20 cm) diameter, 18.622 in (47.3 cm) circumference; Vivian, South Dakota, 23 July 2010.[45]
- **Largest circumference officially measured:** 18.74 in (47.6 cm) circumference, 7.0 in (17.8 cm) diameter; Aurora, Nebraska, 22 June 2003.[44][46]
- **Greatest average hail precipitation:** Kericho, Kenya experiences hailstorms, on average, 50 days annually.

https://en.wikipedia.org/wiki/File:Record_hailstone_Vivian,_SD.jpg

Basics of Hail Formation: Ingredients

- Hail requires 3 ingredients.
- Hail Embryo
  - An ice nuclei that begins the freezing process.
- A *moderately* strong updraft.
  - The updraft must be strong enough to suspend large and heavy hailstones, but not too strong to maximize residence time
  - ~~and to provide a continuous flux of water vapor~~.
- Moisture or saturation
  - Supercooled liquid water (SLW) is required for accretion to build large hailstones.
  - As stones grow their terminal velocity increases until it surpass the updraft speed.
  - $v_t = \sqrt{(2 \times M \times G) / (A \times C_d \times \rho)}$



$C_d=0.47$ $A=0.031$ m2 $\rho=1.3$

$v_t = \sqrt{(2 \times M\textit{(0.87 kg)} \times G) / (A\textit{(3.14 x .1**2)} \times C_d \textit{(0.47)} \times \rho)}$ == **35 m/s (80 mph!)**

Hail Ingredients Summary

Ingredients Favorable for Larger Hailstone Sizes	
Microphysics	Kinematics
High supercooled liquid water content	Light storm-relative flow though updraft
Wet growth in mixed phase region	Large contiguous updraft of 20-40 m/s (39-78 kt)
Low density growth	Optimal trajectories
Large embryos	Favorable horizontal updraft gradients

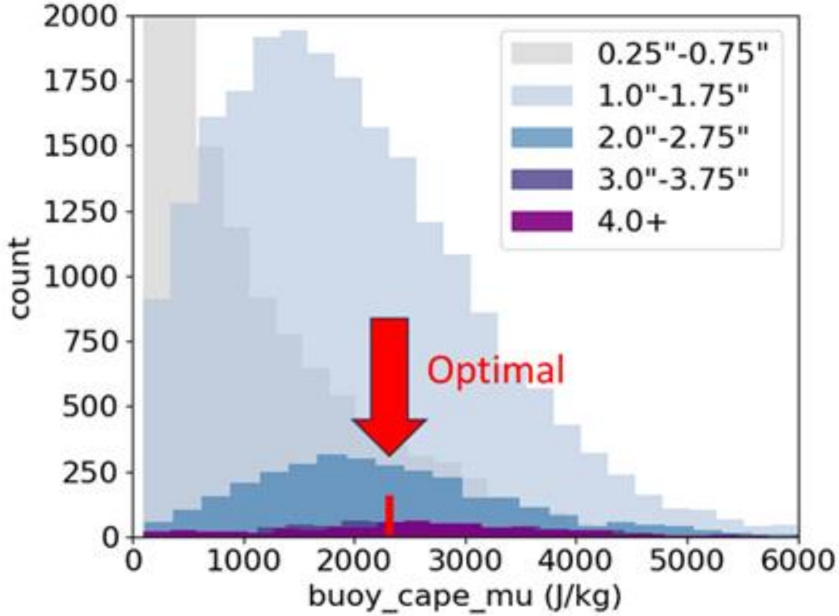
Ingredients Favorable for Larger Amounts of Hail	
Microphysics	Kinematics
High embryo concentration	Large contiguous updraft of 20-40 m/s (39-78 kt)
Ample supercooled liquid water content	Flow that injects embryos across a broad updraft front

Basic ingredients for Hail and Significant Hail (Updrafts)

- The largest contributors to the development of severe hail are strong convective updrafts
- Best way to get strong updrafts?
  - Lots of ways but having more CAPE helps a lot!
  - Bigger CAPE (with some caveats) = stronger updrafts $WMAX = \sqrt{(2 \times CAPE)}$
  - Wider updrafts (stronger storm relative inflow) can be stronger and longer-lived
- Strong vertical shear supports stronger and longer lived updrafts
  - Storm organization (downdraft separation)
  - Stronger storm relative flow (kinetic energy)
  - Dynamical effects and pressure perturbations *(More on this later!)*

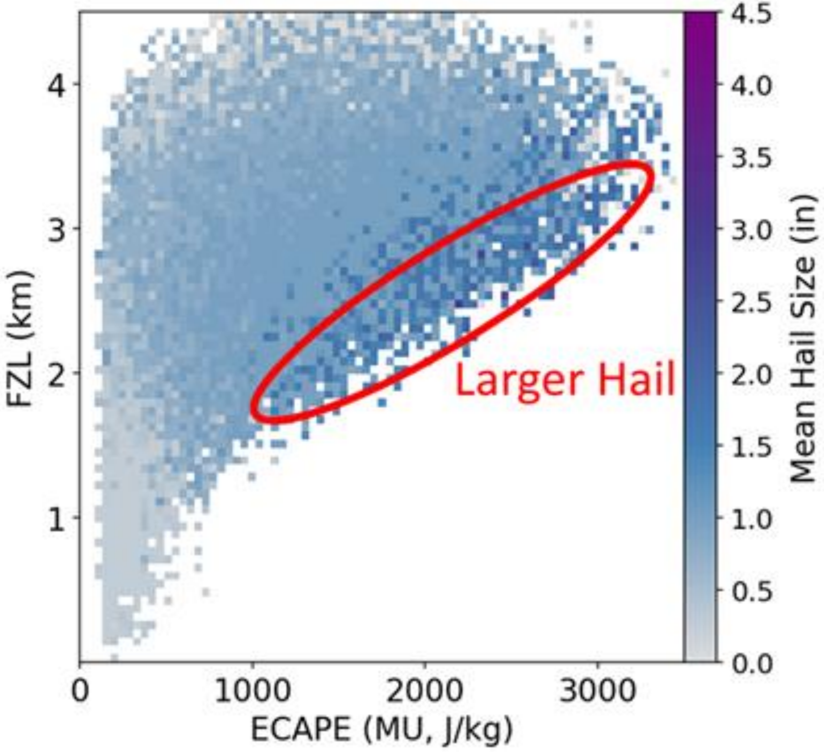
But a word of caution…

- More CAPE does not always mean larger hail!
- Simulations have found CAPE between 2000-2400 J/kg to be “optimal”
- Giant hail is occasionally recorded with CAPE <1000 J/kg
- Stronger shear can make up for this



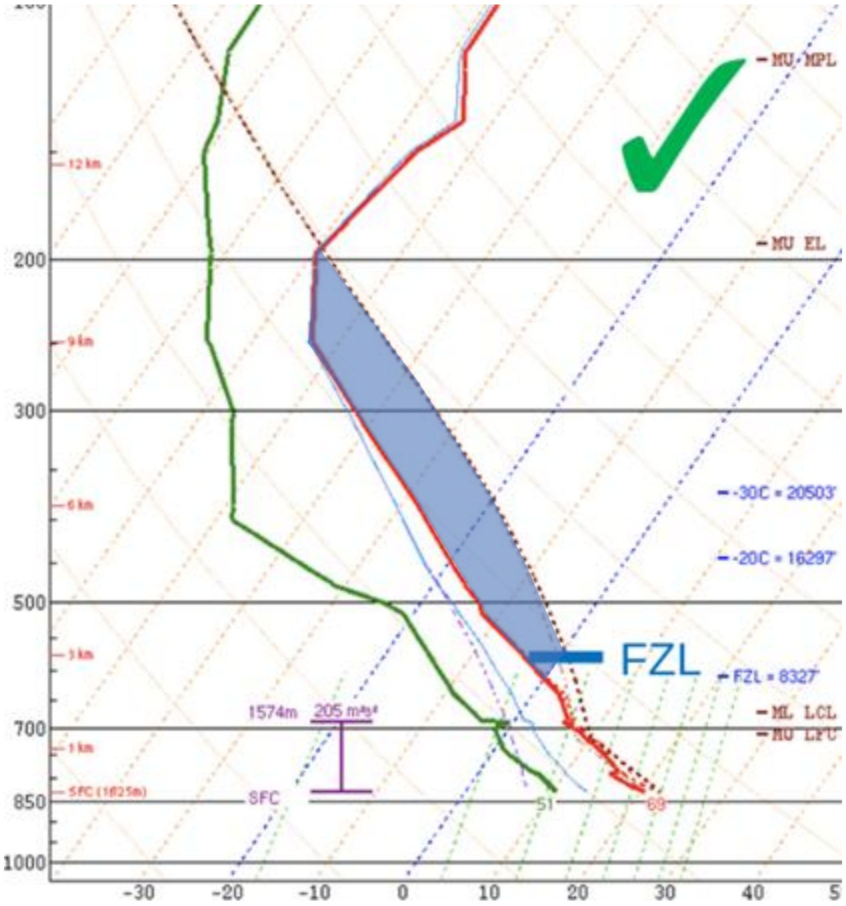
The Freezing Level and Hail

- Hail potential is intrinsically related to the freezing level
- Steeper lapse rates contribute to more CAPE and can support stronger updrafts.
- Large hail is more likely with lower freezing levels for any CAPE
- Steeper lapse rates can also mean lower freezing levels as temperature decreases more quickly with height.
- Higher elevation locations are closer to the freezing layer and closer to EML source
- Large to very large hail is more common in high mid-level lapse rate environments. Hence the climatology



Lapse rates and Hail

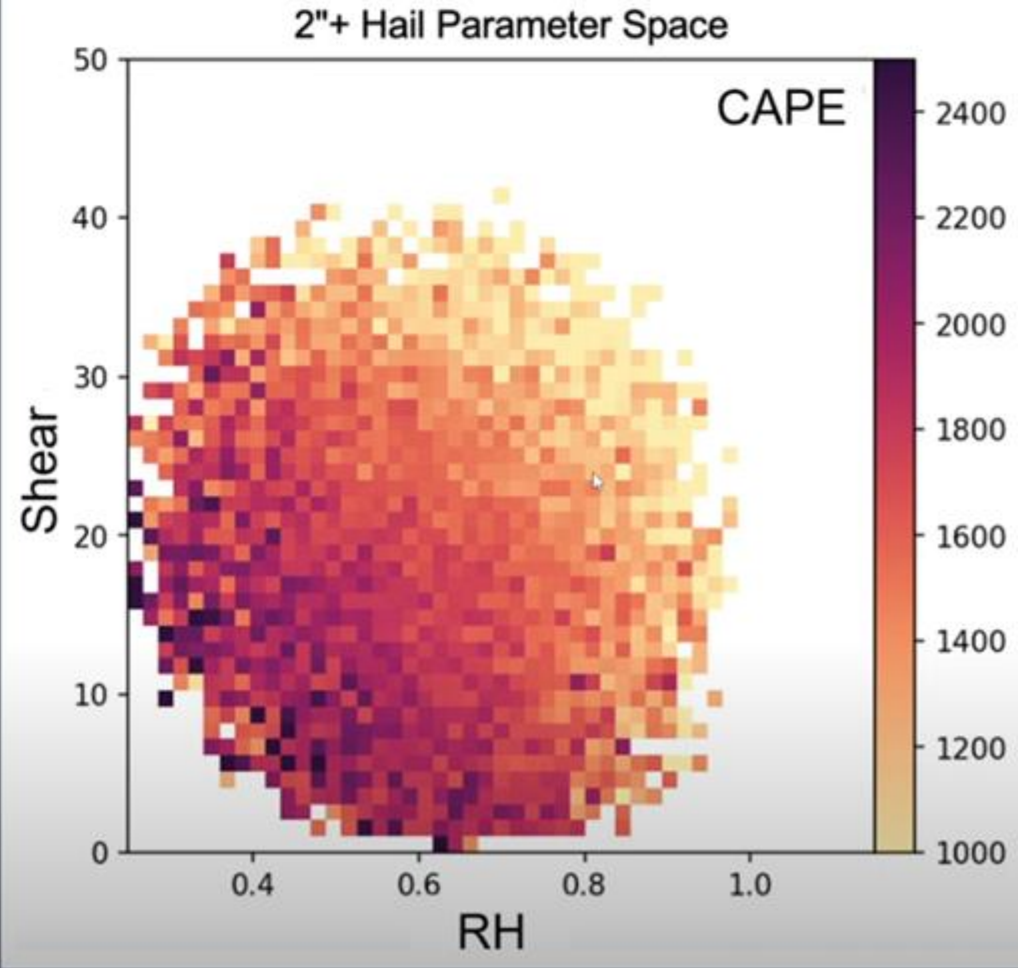
- Generally, we want a greater portion of CAPE *above* the freezing level
- Steep lapse rates help achieve this!
- Steeper lapse rates contribute to more CAPE and can support stronger updrafts.
- Steeper lapse rates can also mean lower freezing levels as temperature decreases more quickly with height.
- Higher elevation locations are closer to the freezing layer and closer to EML source



1. Buoyancy

The "Goldilocks" Problem:

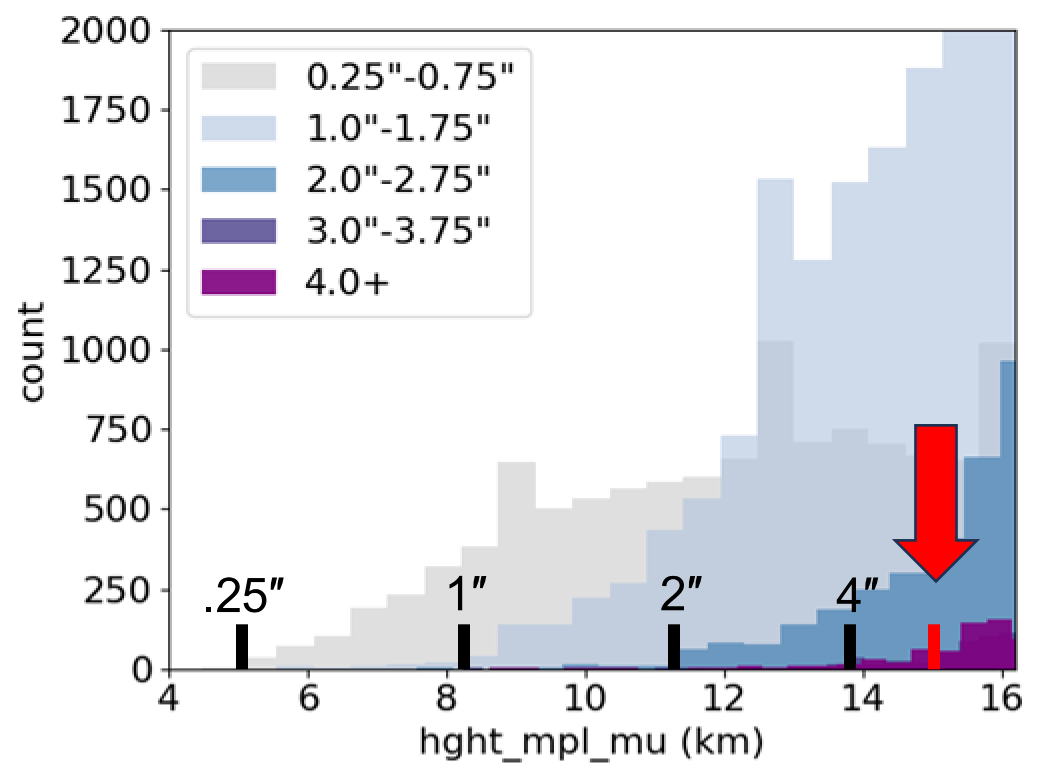
- Favorable CAPE depends on shear and RH![1,2]



(Nixon & Allen 2023)

2. Storm depth

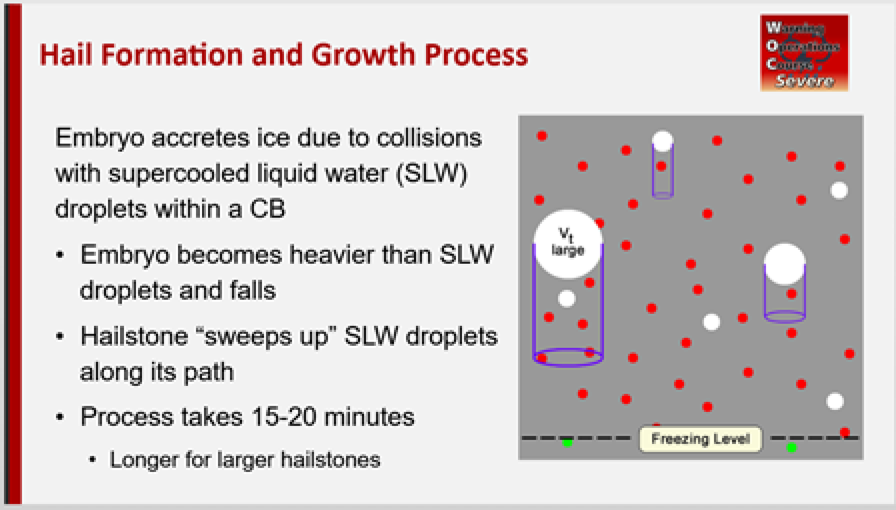
MPL is a good indicator of the ceiling for hail size!



(Nixon 2025)

Hail Forecasting Saturation

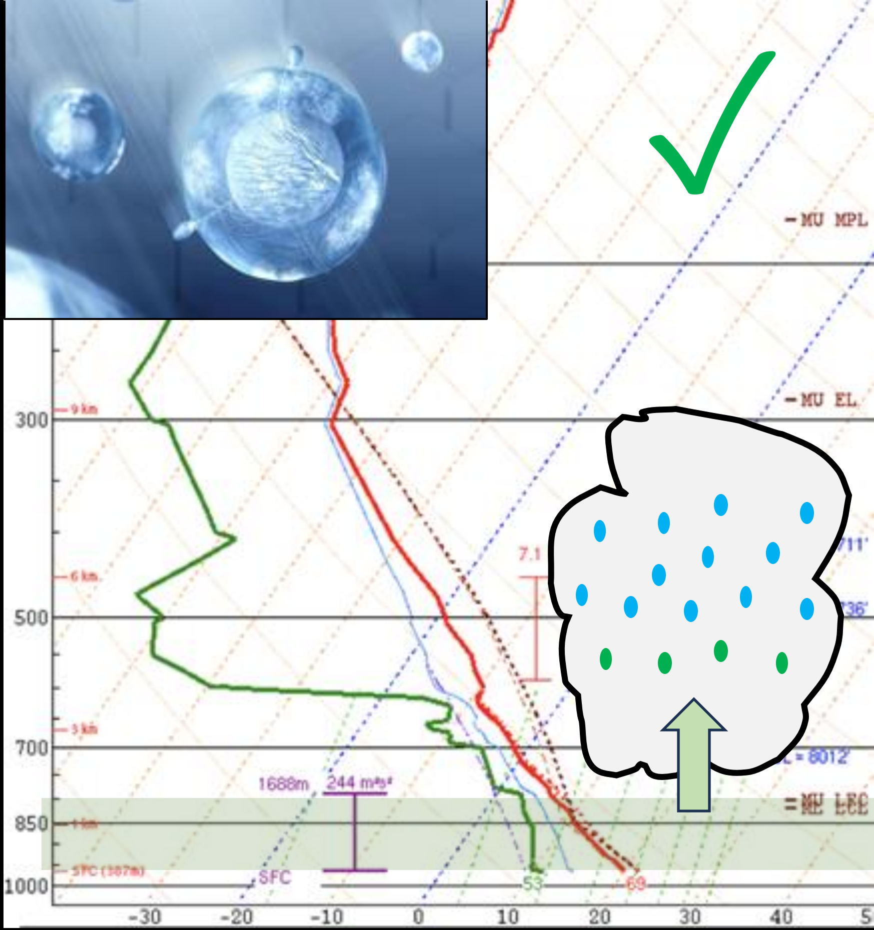
- Hailstone formation and growth requires enough supercooled water to support accretion.
- **<u>Goldilocks problem.</u>** Need enough water to support formation and growth, but not too much
  - Water-loading of the updraft
  - Too much latent heat raises the freezing level and causes more water release from rain
  - Too saturated also weakens lapse rates
- Too little saturation in the mid-levels can weaken updrafts via dry air entrainment.



2. Temp/Humidity

Cloud microphysics:

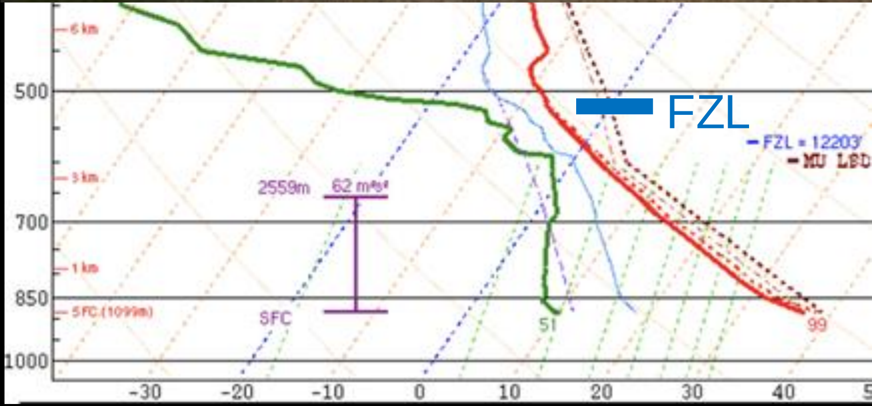
- Colder, drier clouds produce smaller droplets
- More droplets are lighter, and can be lofted higher, into colder temperatures
- More droplets can go towards graupel and supercooled water



Summary:

Many ways to get efficient hailstorms:

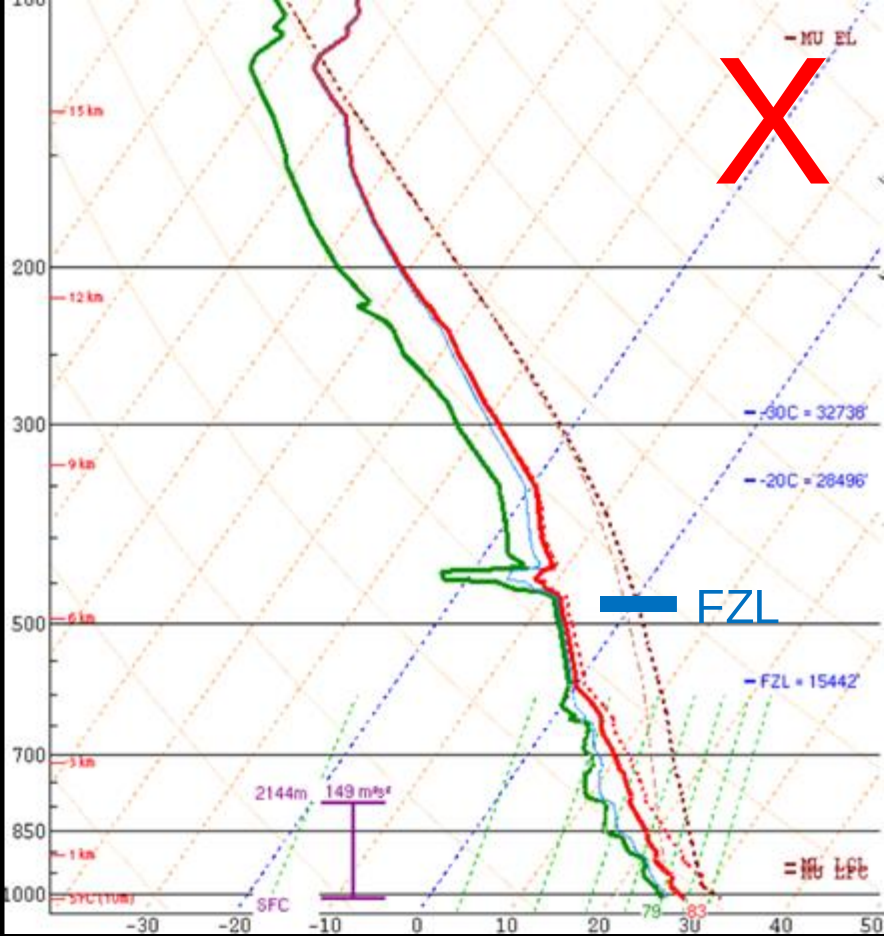
- Low freezing level
- High elevation
- Elevated inflow base
- High cloud base



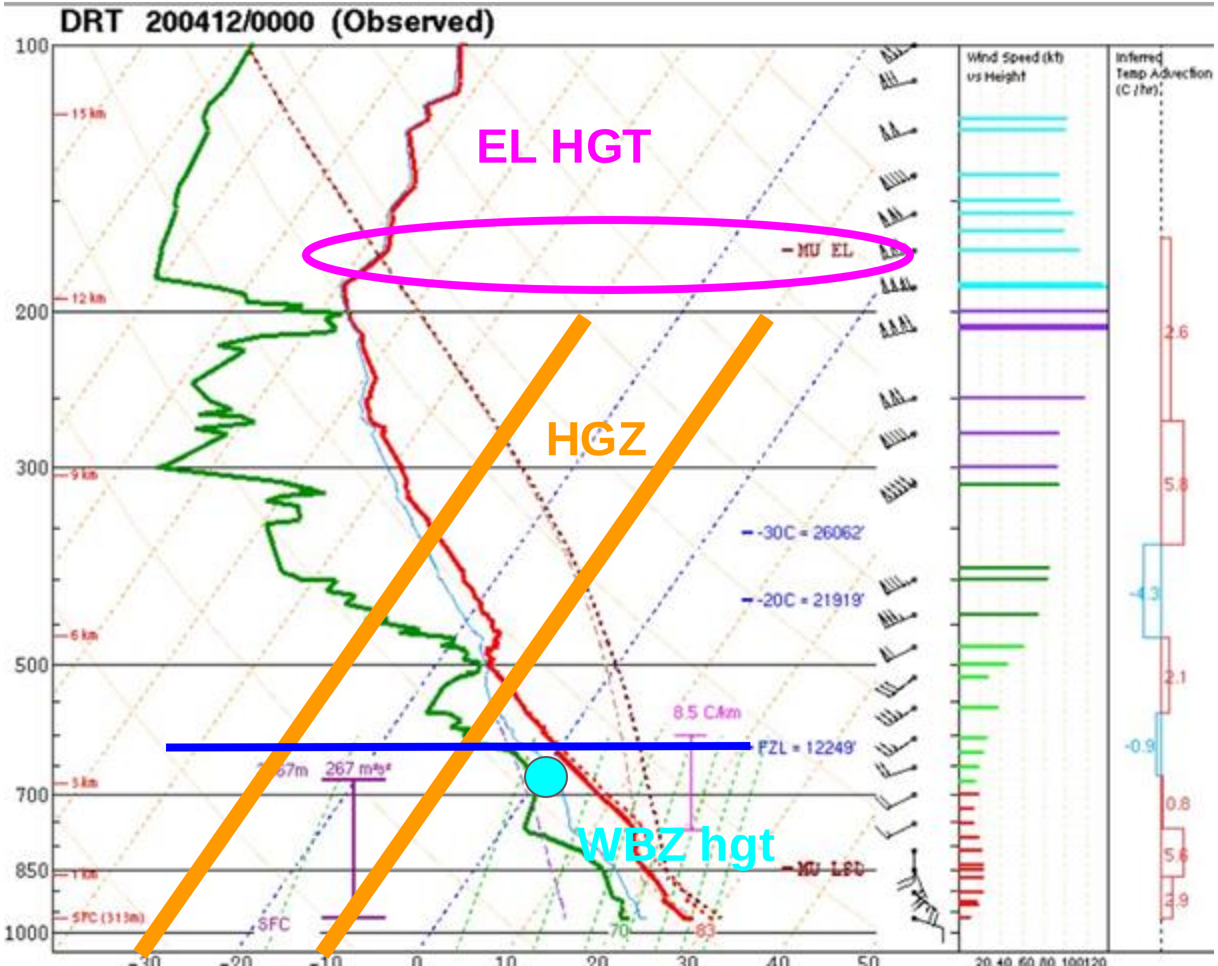
Summary:

Hail efficiency is poor with:

- Deep, warm, moist inflow layer
- High freezing level
- Low elevation / tropical



Hail forecasting with Skew-Ts

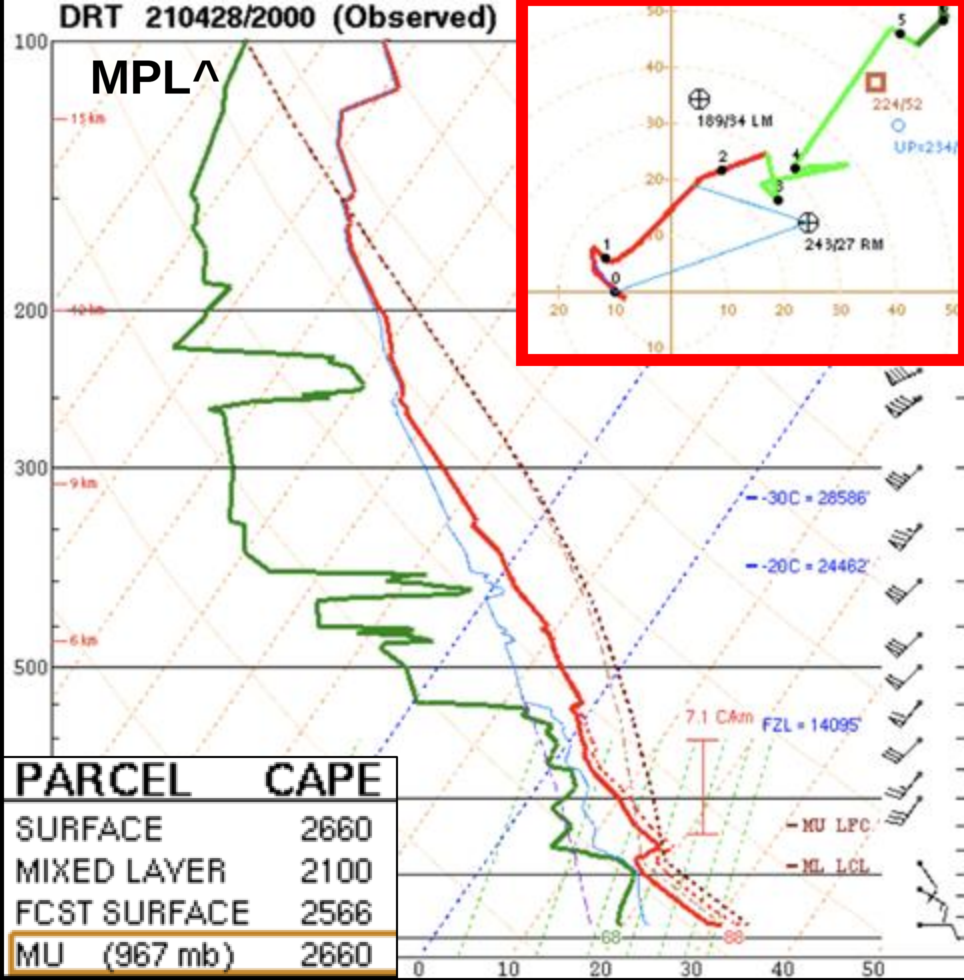


- Large CAPE in the hail growth zone supports strong updrafts and residence time below freezing. (-10 to -30 C)
- Steep mid-level lapse rates favorable for more cape, lower FZ Level
- Low FZ Level or WBZ height also supports more time below freezing.
- High Equilibrium height favors *deeper* updrafts.

Summary:

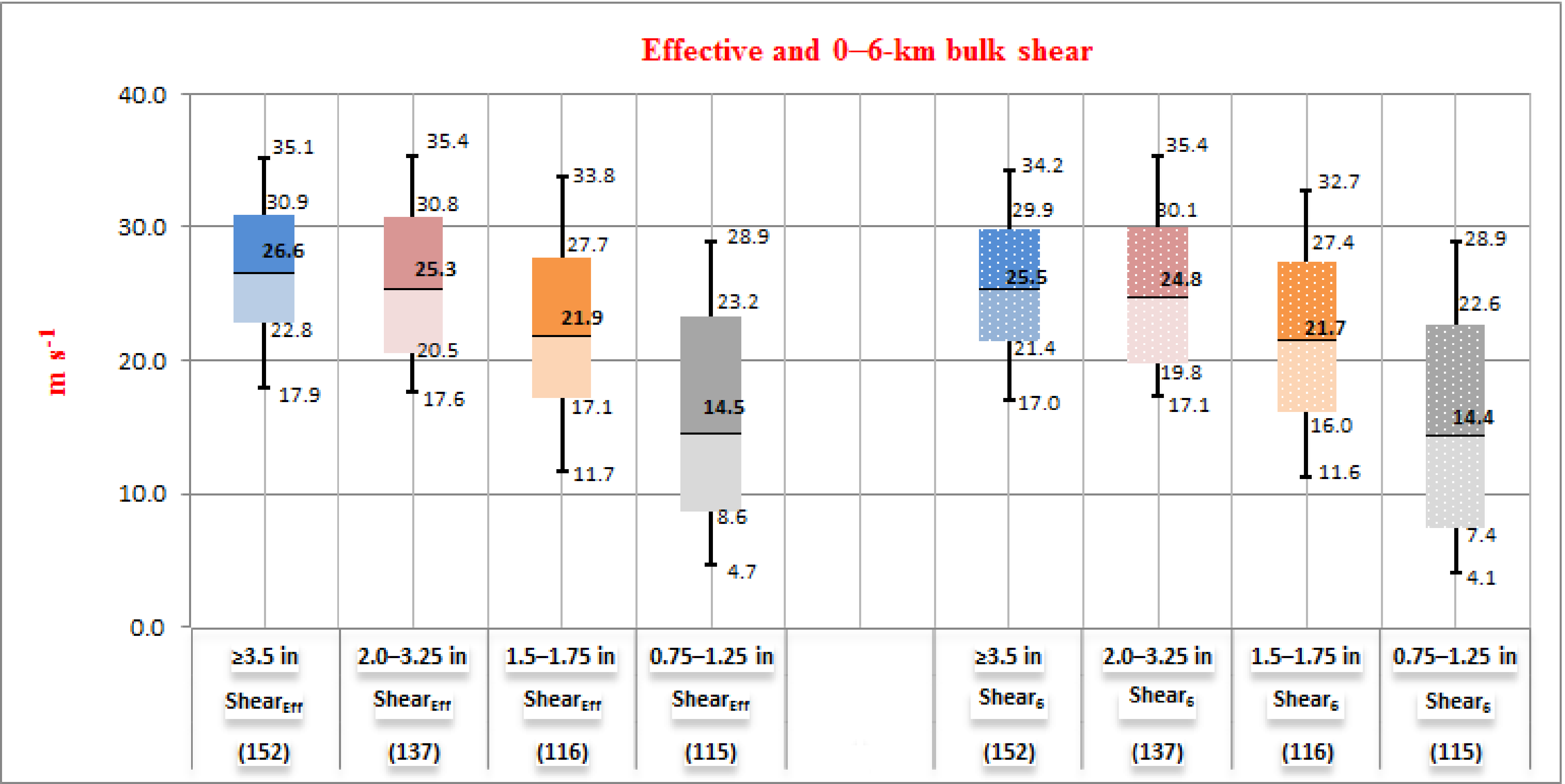
How to get the largest hailstones:

- Moderate CAPE
- Higher MPL
- Stronger Eff. Shear



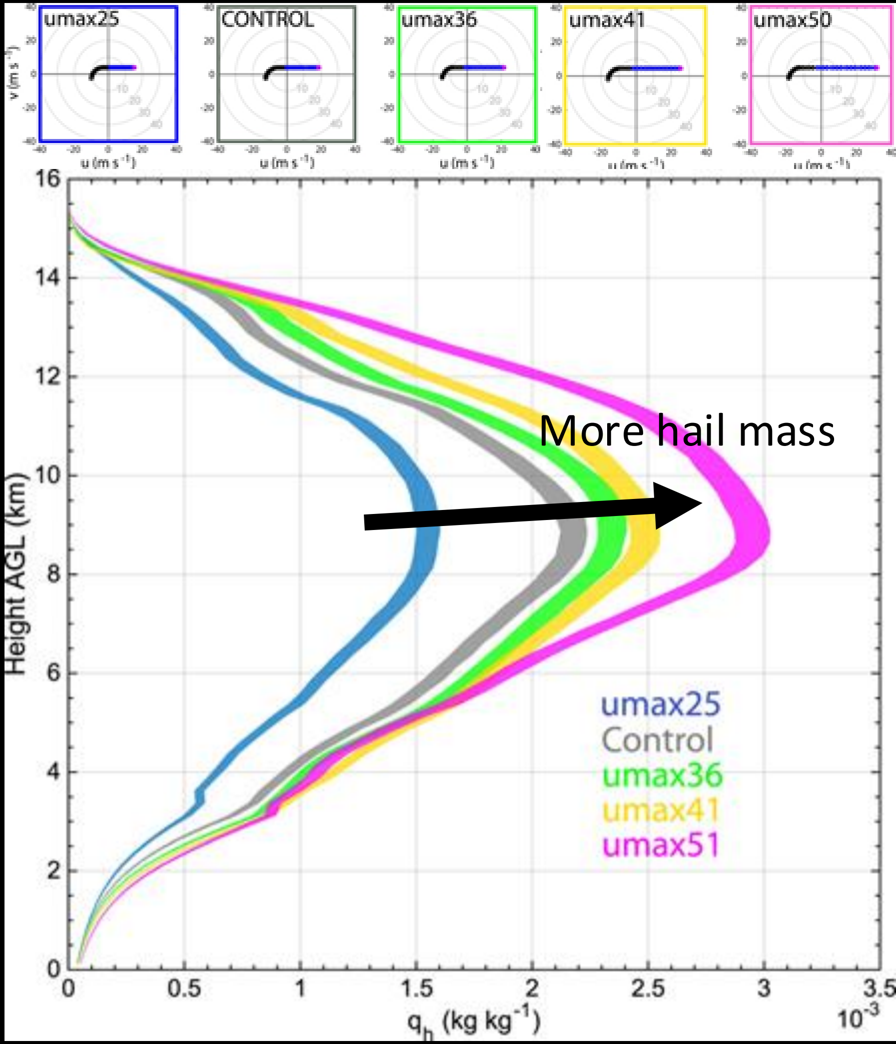
(Johnson & Sugden 2021)

Vertical Shear



4. Wind Shear

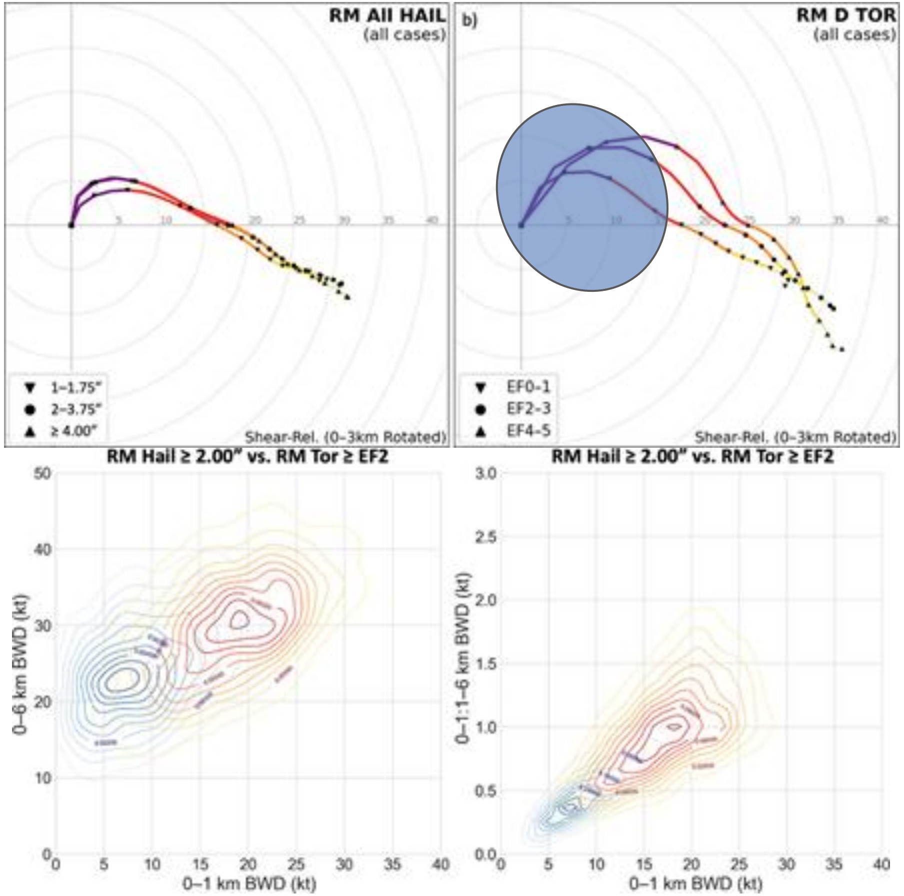
Stronger deep-layer shear can support wider updrafts that produce more hail[1,2]



1 – Dennis & Kumjian (2017)
2 – Nixon et al. (2023)

Hail Favoring Hodographs

(Nixon & Allen 2022)



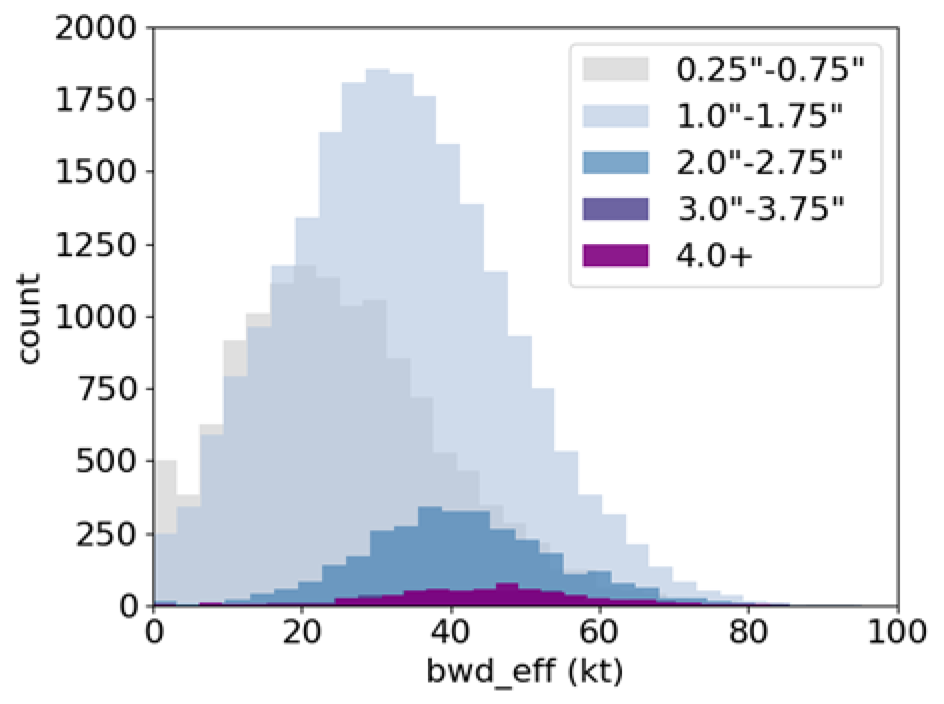
- Moderate to strong mid-level shear
- Upper-level flow not too strong to limit residence time.
- Strong enough low-level SRW to support broad updraft and supercells.
- But not too strong to displace hail embryos.
- Weaker low-level shear compared to tornadic cases but still significant overlap.

Cool stable layer at the surface
Effective straight line hodo aloft

4. Wind Shear

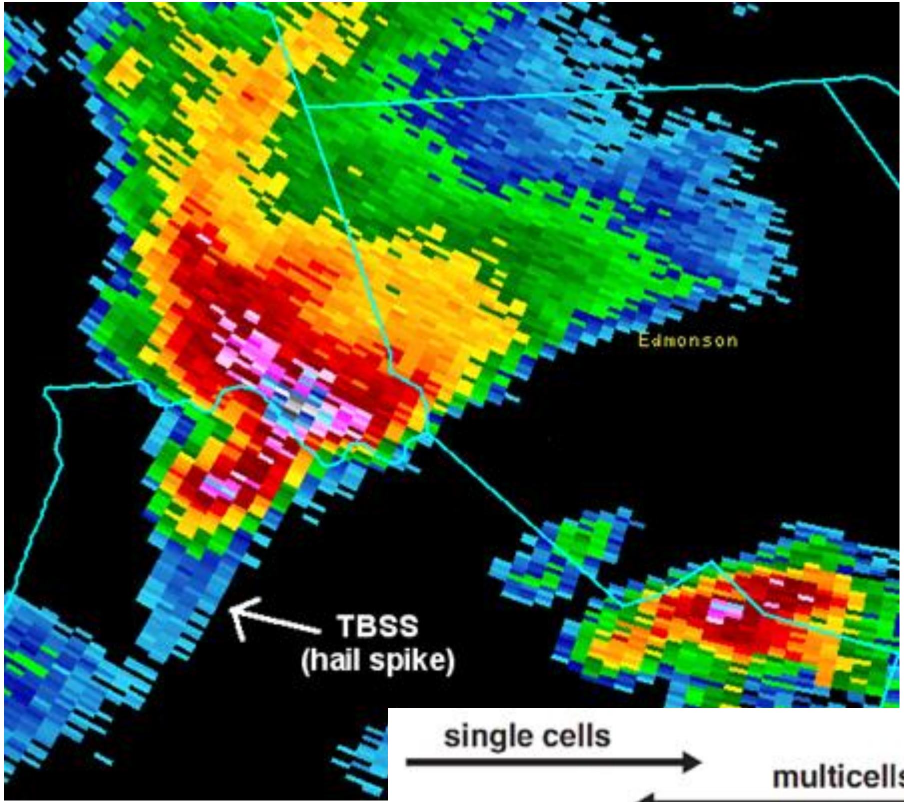
Effective shear/SRW is most skillful, likely because many hailstorms are elevated[1]

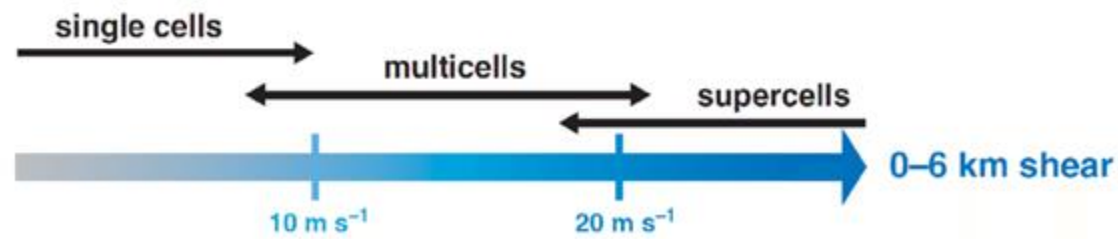
SHIP/LHP do not take this into account!



1 – Nixon & Allen (2023)

Updrafts (Storm Mode)

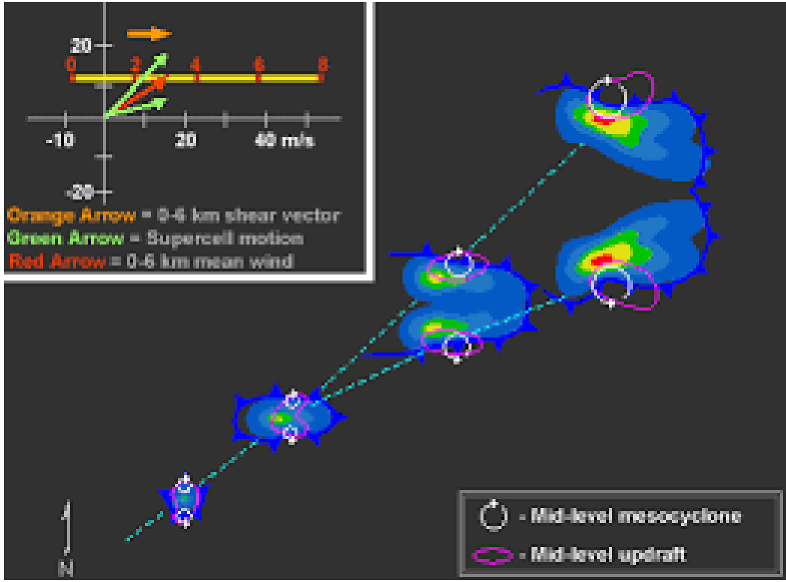




- The majority of prolific hail events are produced by supercells.
- Storm mode plays a significant role. Hail more likely with discrete or cluster types. Less likely with lines.
- Vertical shear strong enough to supports supercells can be a significant predictor for hail.
- Storm interactions can also favor hail.
- Splitting storms and left movers.

Splitting Supercells

- Relatively straight hodographs that favor splitting supercells can produce large hail.
- Left split storms can be dynamically suppressed by vertical shear favorable for RM.
  - Less favorable for tornadoes
  - But still strong enough updraft to produce large hail.
- Splitting storms can occur near boundaries with elevated features.

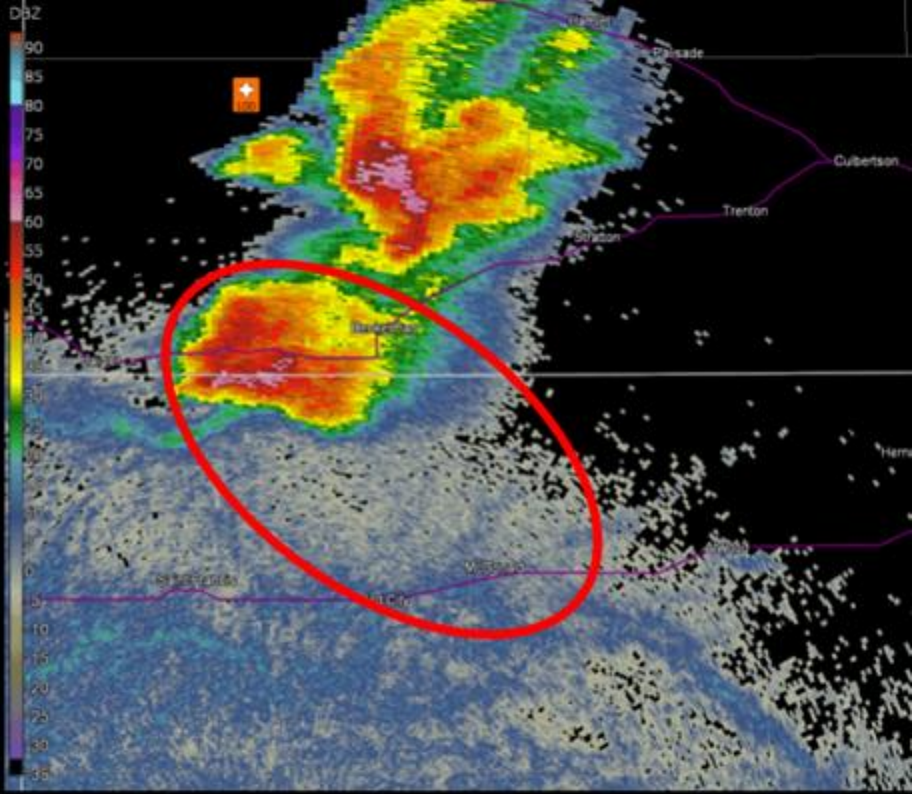


3. Eff. Inflow Base

Many hailstorms are “elevated”:

Over 25% of all 3"+ hailstorms occur behind outflow boundaries and cold fronts[1]

Over 20% occur in the outflow of other supercells[1]



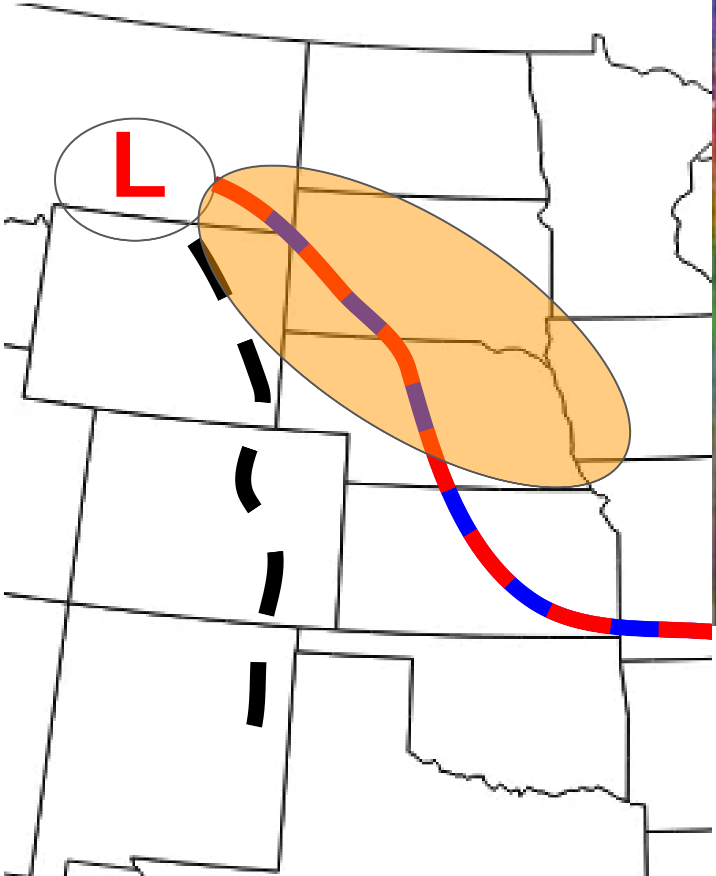
1 – Nixon et al. (2024)

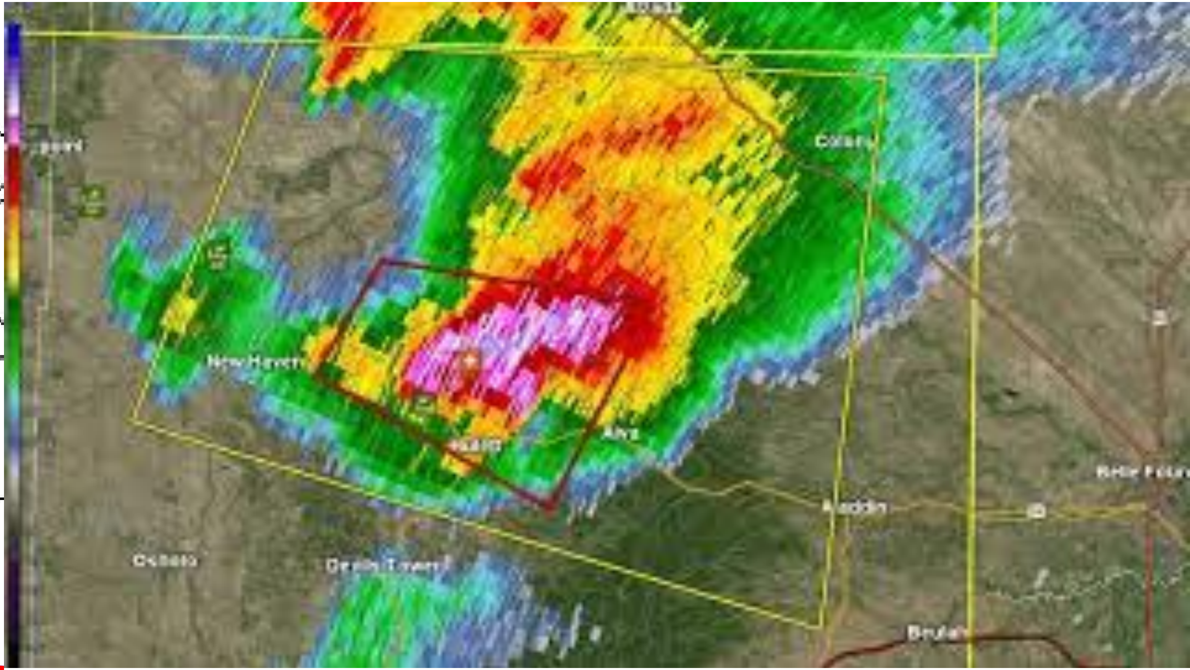
Setups Favoring Hail (Warm Front)

Elevated supercells within WAA Elevated CAPE Strong effective shear but stable at the surface

- Very classic setup for large hail along and north of the WF

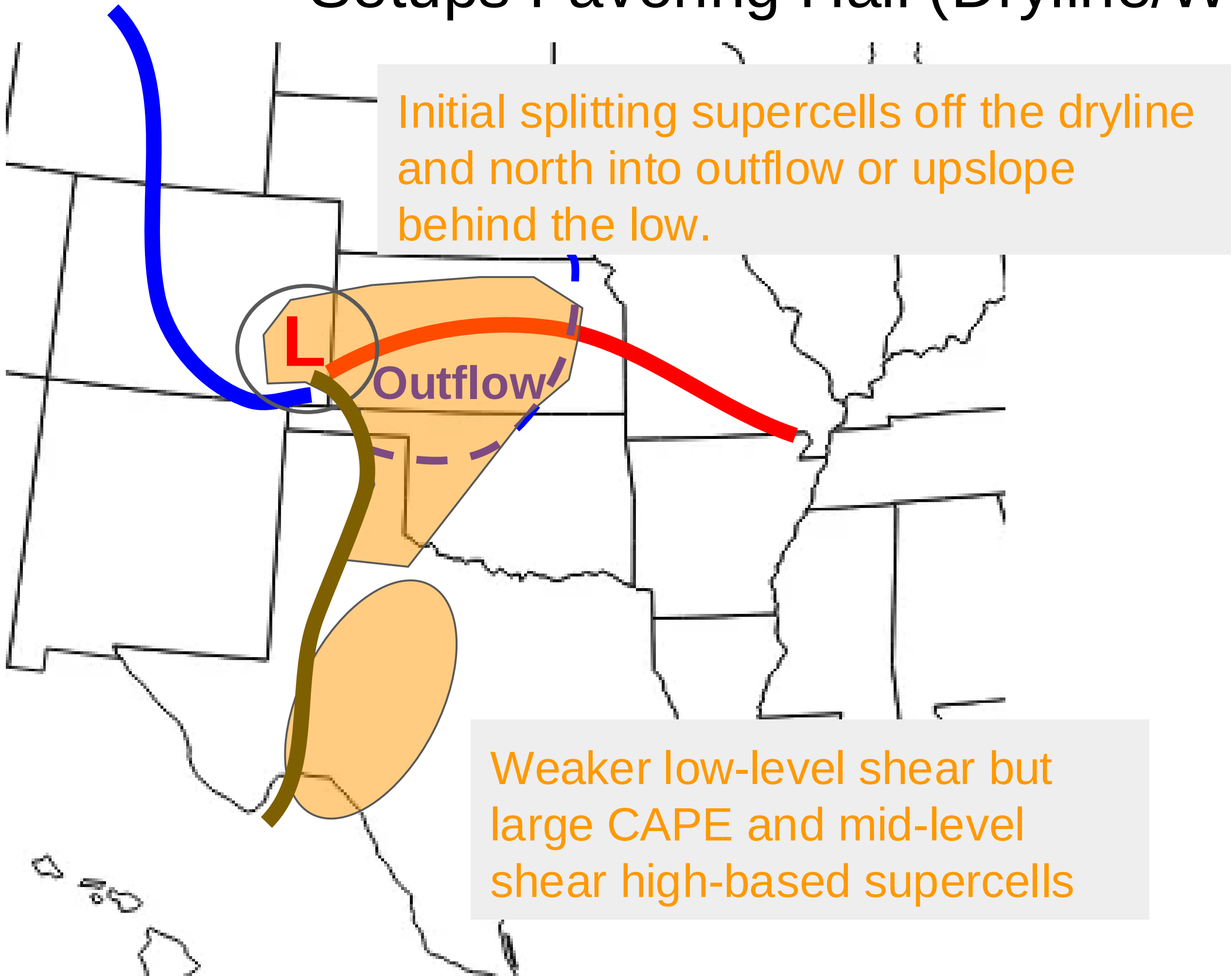
Setups Favoring Hail (Stationary Front/Northwest Flow)





- Common over the High Plains
- Cool but unstable air to the north favors elevated storms.
- Can precede sig wind events.

Setups Favoring Hail (Dryline/Warm sector)



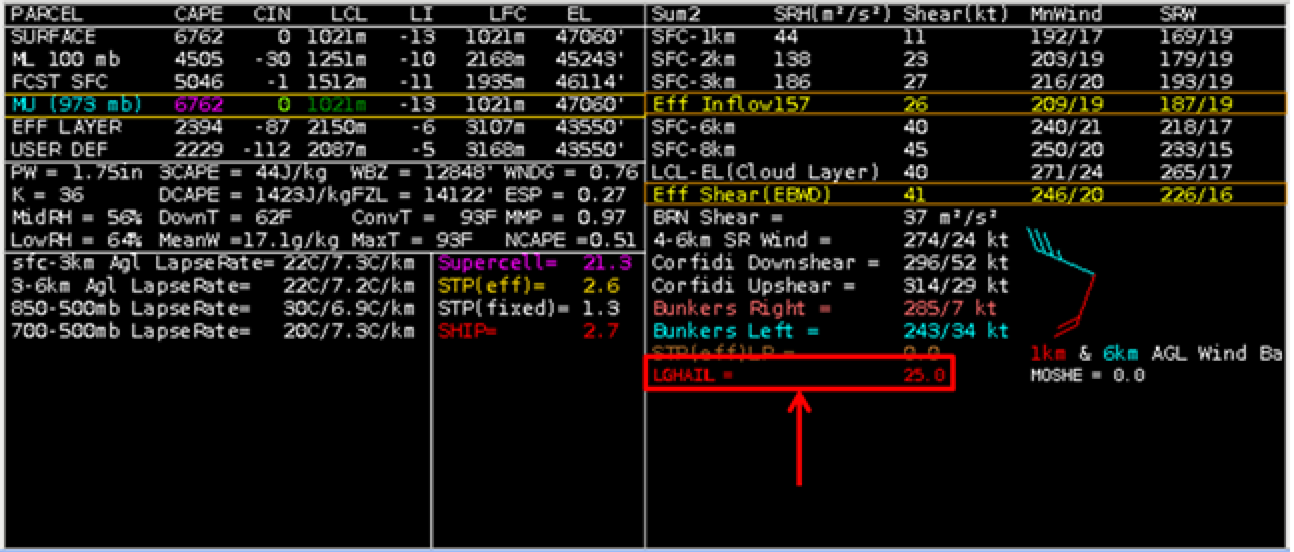
- Hail very common with the initial development stages of supercells off the dryline
- Possible even into cooler air or wrap around upslope into the high plains.
- Warmer temperatures farther south force higher-based storms
- Hail threat still possible farther east with strong supercells.


EARTH FROM ORBIT
TEXAS DRY LINE
DRIVES STORMS

Hail Parameters

Large Hail Parameter

A multiple ingredient, composite index that includes three thermodynamic components [MUCAPE, 700-500 mb lapse rates, the depth of the hail growth zone (-10 to -30 C)], as well as three vertical shear components [surface to EL bulk shear, the direction difference between the ground-relative winds at the EL and in the 3-6 km layer, and the direction difference between the storm-relative winds in the 3-6 km and 0-1 km layers].



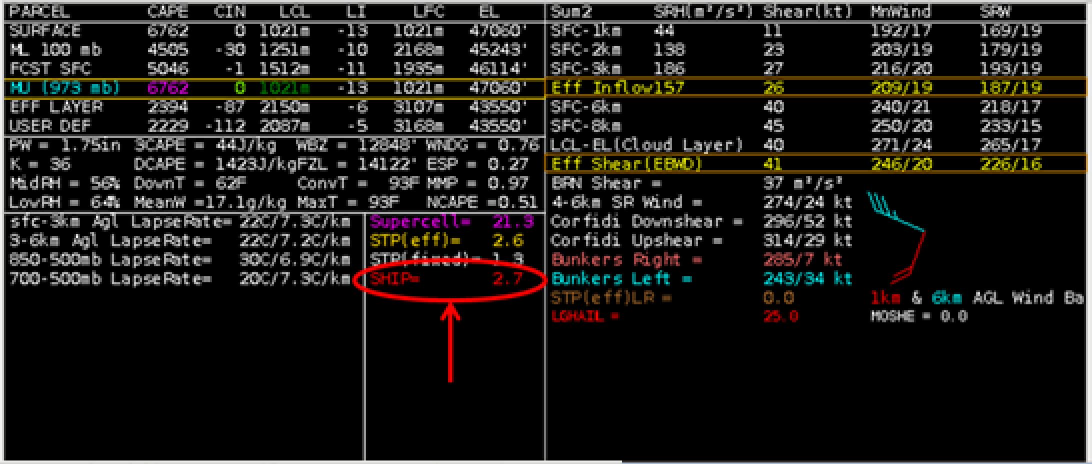
If if 0-6 km BWD < 14 m s $^{-1}$ or MUCAPE < 400 J kg^{-1}, LHP = 0. If both the shear and MUCAPE are >= to the above conditions (a loose supercell check):

LHP = (TERM A * TERM B) + 5

TERM A = (((MUCAPE-2000)/1000) + ((3200-THK_{HGZ})/500) + ((LR_{75}-6.5)/2)) where THK_{HGZ} is the depth of the hail growth zone (the -10 to -30 C layer), and LR_{75} is the 700-500 mb temperature lapse rate.

TERM B = ((($Shear_{EL}$-25)/5) + ((GRW_{dirEL}+5)/20) + ((SRW_{dirMID}-80)/10)) where $Shear_{EL}$ is the magnitude of the vector wind difference between the surface wind and the mean wind in the 1.5 km layer immediately below the EL height for the MU parcel, GRW_{dirEL} is the directional difference between the ground-relative mean wind in the 1.5 km layer below the EL and the mean wind in the 3-6 km layer AGL, and SRW_{dirMID} is the directional difference betweem the mean storm-relative winds in the 3-6 km and 0-1 km layers.

Hail Parameters



PARCEL	CAPE	CIN	LCL	LI	LFC	EL
SURFACE	6762	0	1021m	-13	1021m	47060'
ML 100 mb	4505	-30	1251m	-10	2168m	45243'
FCST SFC	5046	-1	1512m	-11	1935m	46114'
MU (973 mb)	6762	0	1021m	-13	1021m	47060'
EFF LAYER	2394	-87	2150m	-6	3107m	43550'
USER DEF	2229	-112	2087m	-5	3168m	43550'

PW = 1.75in 3CAPE = 44J/kg WBZ = 12848' WNDG = 0.76
K = 36 DCAPE = 1423J/kgFZL = 14122' ESP = 0.27
MidRH = 56% DownT = 62F ConvT = 93F MMP = 0.97
LowRH = 64% MeanW =17.1g/kg MaxT = 93F NCAPE =0.51

sfc-3km Agl LapseRate= 22C/7.3C/km
3-6km Agl LapseRate= 22C/7.2C/km
850-500mb LapseRate= 30C/6.9C/km
700-500mb LapseRate= 20C/7.3C/km

Supercell= 21.3
STP(eff)= 2.6
STP(fixed)= 1.3
SHIP= 2.7

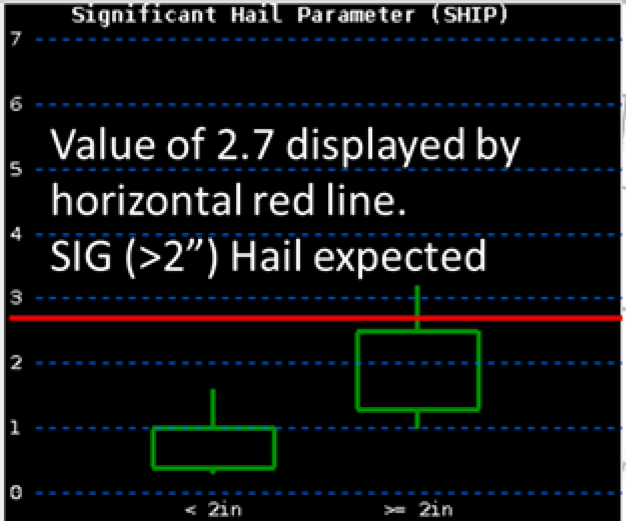
Sum2	SRH(m²/s²)	Shear(kt)	MnWind	SRW
SFC-1km	44	11	192/17	169/19
SFC-2km	138	23	203/19	179/19
SFC-3km	186	27	216/20	193/19
Eff Inflow	157	26	209/19	187/19
SFC-6km		40	240/21	218/17
SFC-8km		45	250/20	233/15
LCL-EL(Cloud Layer)		40	271/24	265/17
Eff Shear(EBWD)		41	246/20	226/16

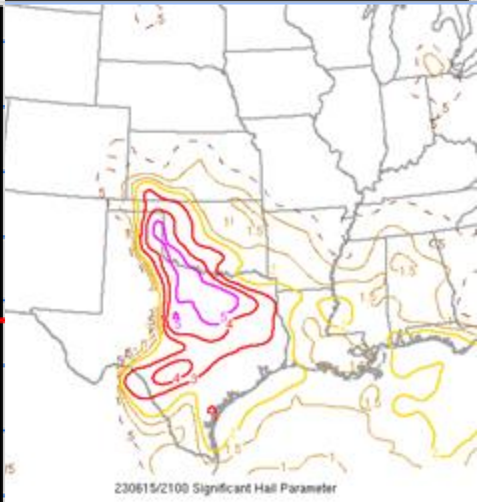
BRN Shear = 37 m²/s²
4-6km SR Wind = 274/24 kt
Corfidi Downshear = 296/52 kt
Corfidi Upshear = 314/29 kt
Bunkers Right = 285/7 kt
Bunkers Left = 243/34 kt
STP(eff)LR = 0.0
LGHAIL = 25.0
1km & 6km AGL Wind Ba
MOSHE = 0.0

Significant Hail Parameter

The Sig. Hail Parameter (SHIP) was developed using a large database of surface-modified, observed severe hail proximity soundings. It is based on 5 parameters, and is meant to delineate between SIG (>=2" diameter) and NON-SIG (<2" diameter) hail environments.

SHIP = [(MUCAPE j/kg) * (Mixing Ratio of MU PARCEL g/kg) * (700-500mb LAPSE RATE c/km) * (-500mb TEMP C) * (0-6km Shear m/s)] / 42,000,000





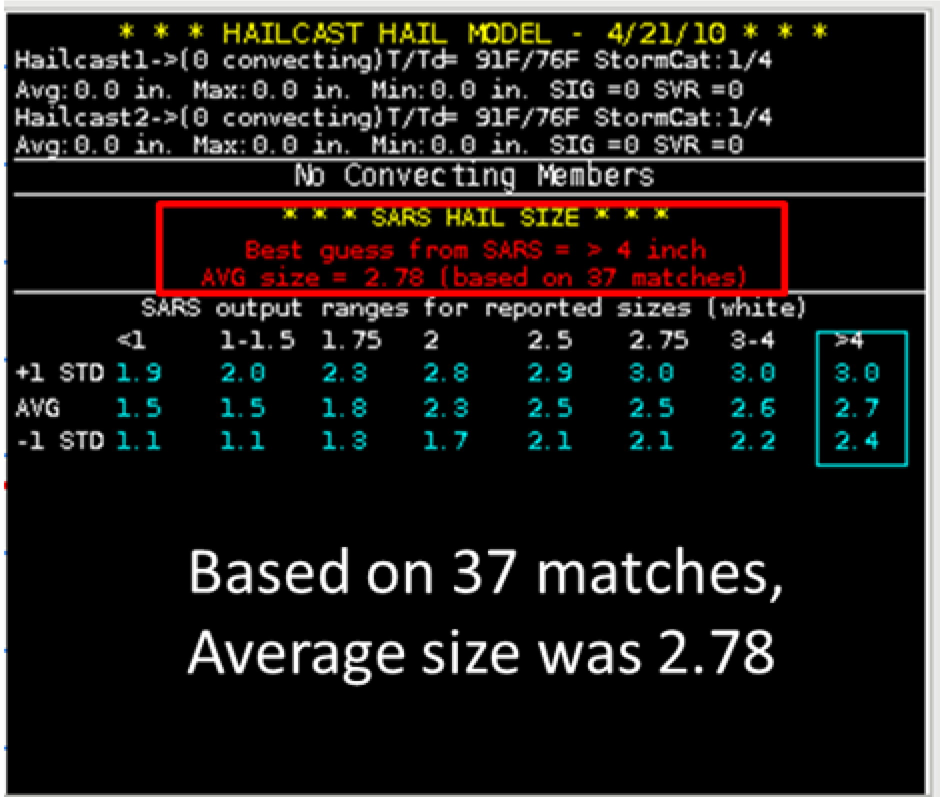
Hail Parameters

SARS Hail Size

The SARS method returns a maximum expected hail report by matching existing environmental conditions to historic severe hail cases. These forecast maximum sizes are conditional on severe hail of any size occurring.

This graphic shows the "best guess" maximum hail report.

Hailcast is a 1D model developed by SPC forecaster ryan Jewel to estimate the maximum hail size based on a supplied model or observed sounding.



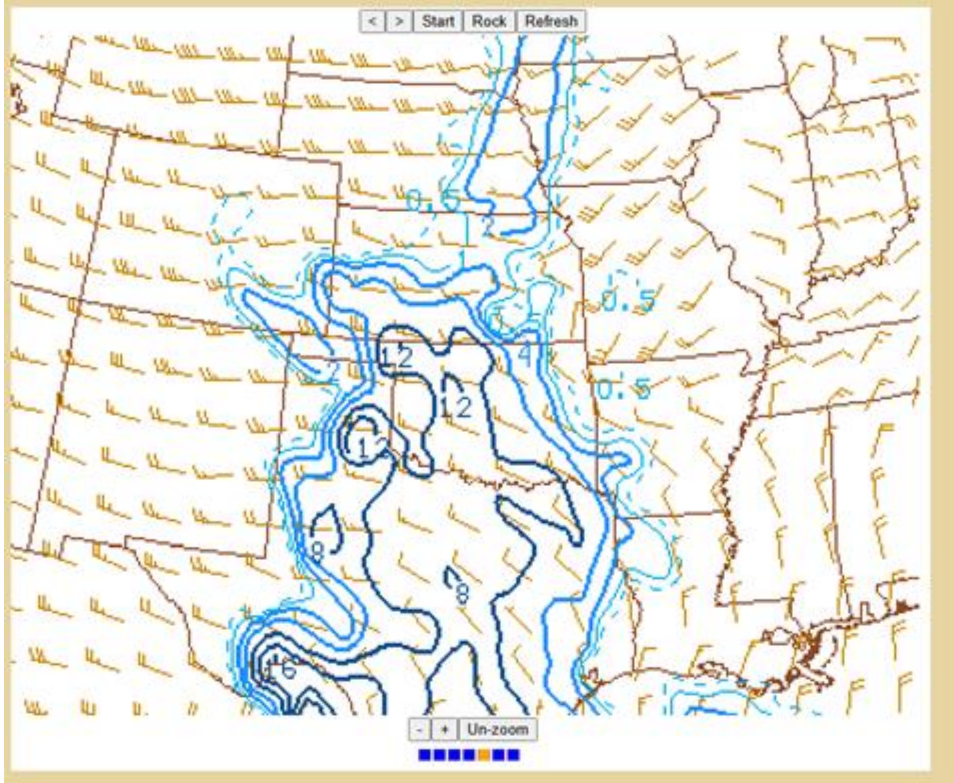
Hail Parameters

Supercell Composite Parameter

A multiple ingredient, composite index that includes effective storm-relative helicity (ESRH, based on Bunkers right supercell motion), most unstable parcel CAPE (muCAPE) and convective inhibition (muCIN), and effective bulk wind difference (EBWD). Each ingredient is normalized to supercell "threshold" values, and larger values of SCP denote greater "overlap" in the three supercell ingredients. Only positive values of SCP are displayed, which correspond to environments favoring right-moving (cyclonic) supercells.

SCP = (muCAPE / 1000 J kg^{-1}) * (ESRH / 50 m^2 s^{-2}) * (EBWD / 20 m s^{-1}) * (-40 J kg^{-1} / muCIN)

EBWD is divided by 20 m s^{-1} in the range of 10-20 m s^{-1}. EBWD less than 10 m s^{-1} is set to zero, and EBWD greater than 20 m s^{-1} is set to one. The muCIN term is based on work by Gropp and Davenport (2018), and it is set to 1.0 when muCIN is greater than -40 kg^{-1}.



Not a direct hail forecast but can be useful.

Hail Forecasting Cheat Sheet

Large Hail
- -10 to -30° C layer is the hail growth zone; look for a large CAPE within -10 to -30° C layer
- Rotating updraft – the longer hail resides within hail growth zone, the greater the potential for large hail

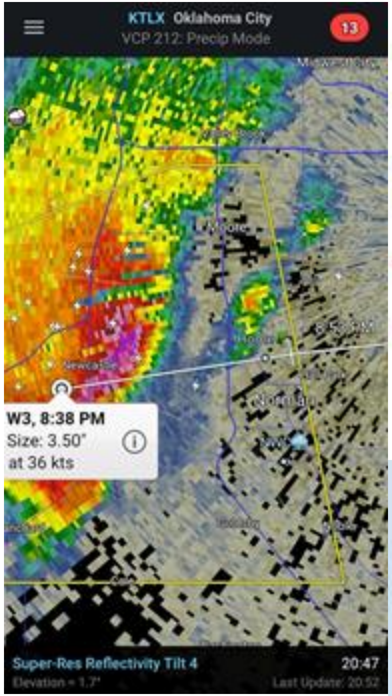
Supercells & Hail
- Large boundary layer moisture
- 700-500 mb lapse rates > 7.0 C km^{-1}
- Moderate to large CAPE, including "fat" CAPE for rapid acceleration
- 0-6 km shear > 40-50 kts (includes speed and directional)
- 0-3 km SRH > 150-200 m^2 s^{-2}

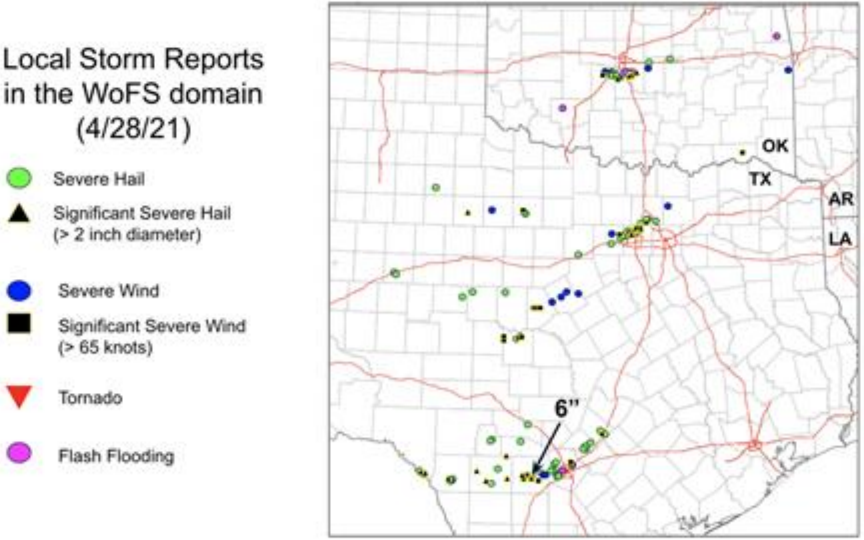
Non-supercell hail events
- Large boundary layer moisture
- 700-500 mb lapse rates > 7.0 C km^{-1}
- Large CAPE, including within hail growth zone
- Freezing level and Wet Bulb Zero level < 10500 ft

Melting issues
- Large depth between LCL and freezing level (i.e., deep warm cloud zone to promote melting)
- Freezing level and wet-bulb zero levels are > 10500 ft
- High RH in the lowest several km's
- Lapse rates 850-500 mb are moist adiabatic
- Hail falling within heavy rain core; limited vertical wind shear

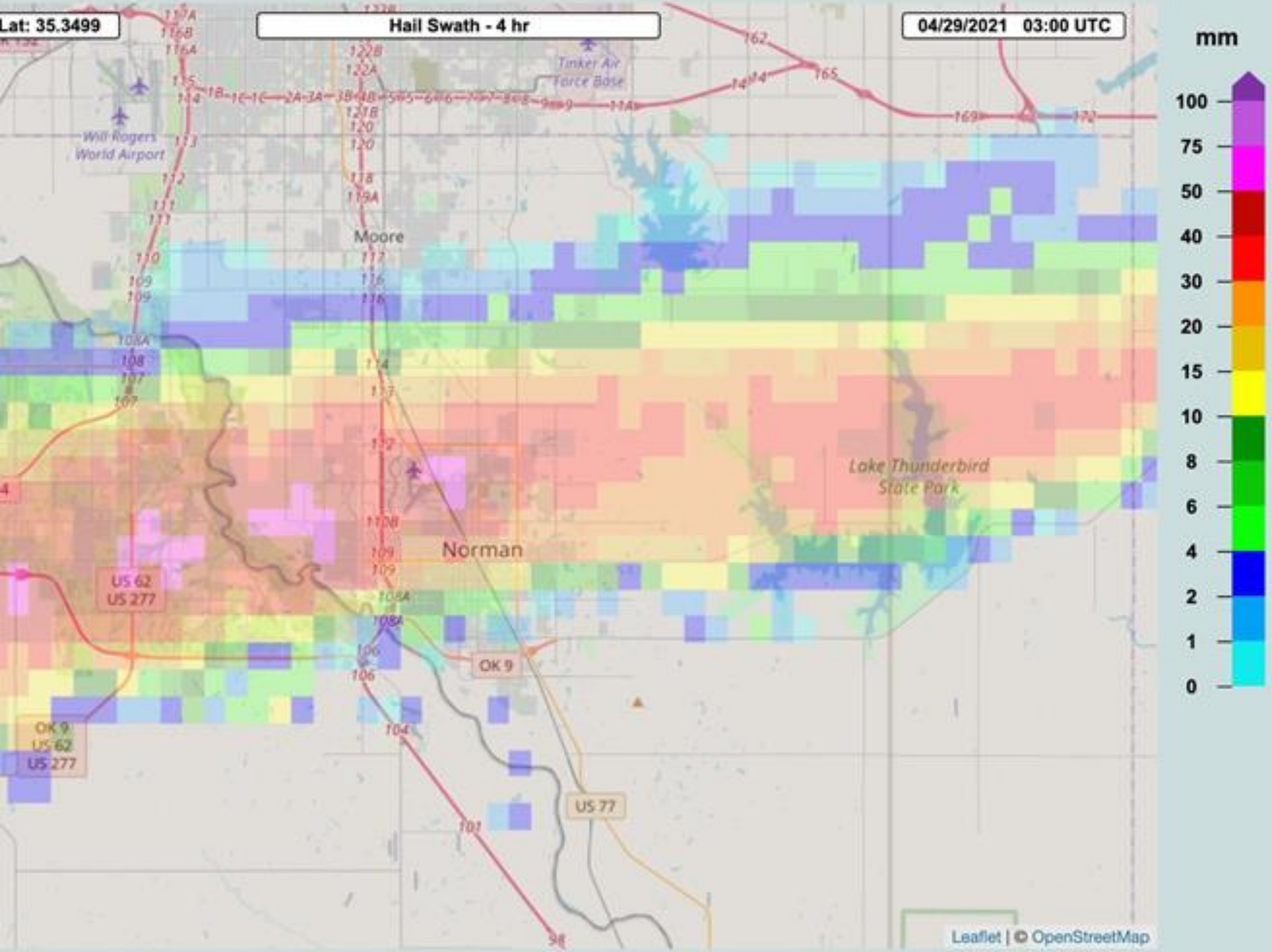
April 28 2021 Norman Hail Storm

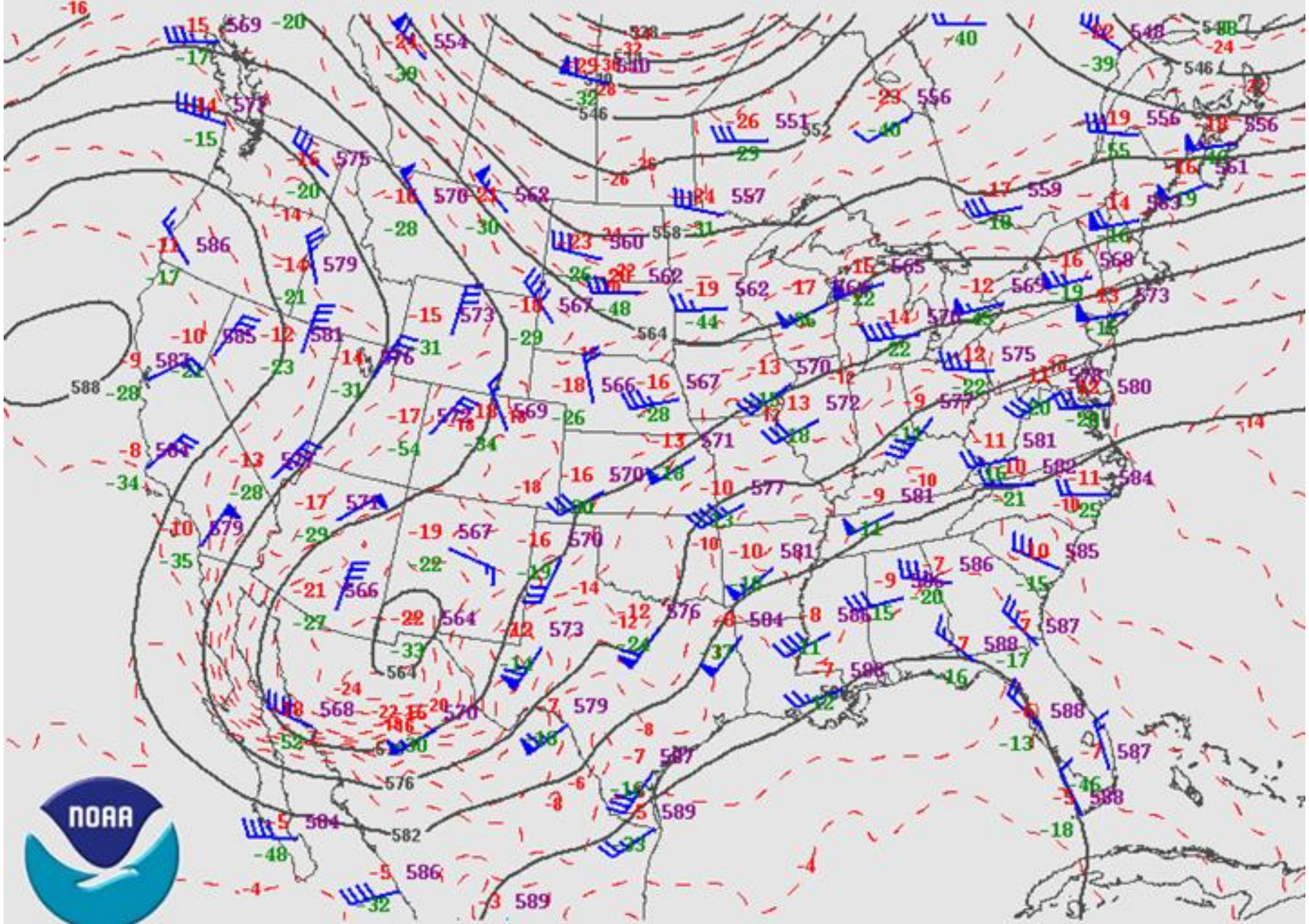
- Swath of 2-2.75 inch hail through Norman. Including my house…
- Millions in damage thousands of cars dented.
- Not overly well forecast
- Audible hail roar!





Operational Product Viewer





National Weather Service
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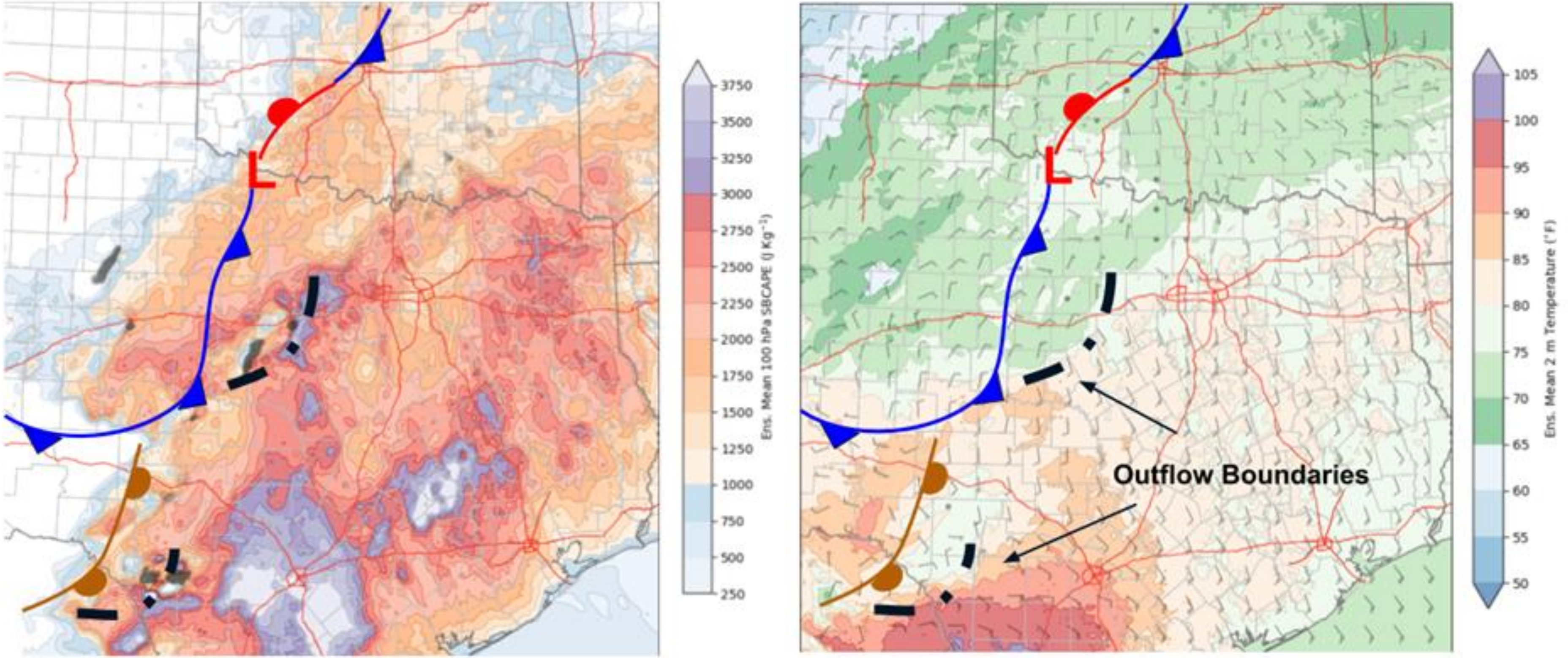
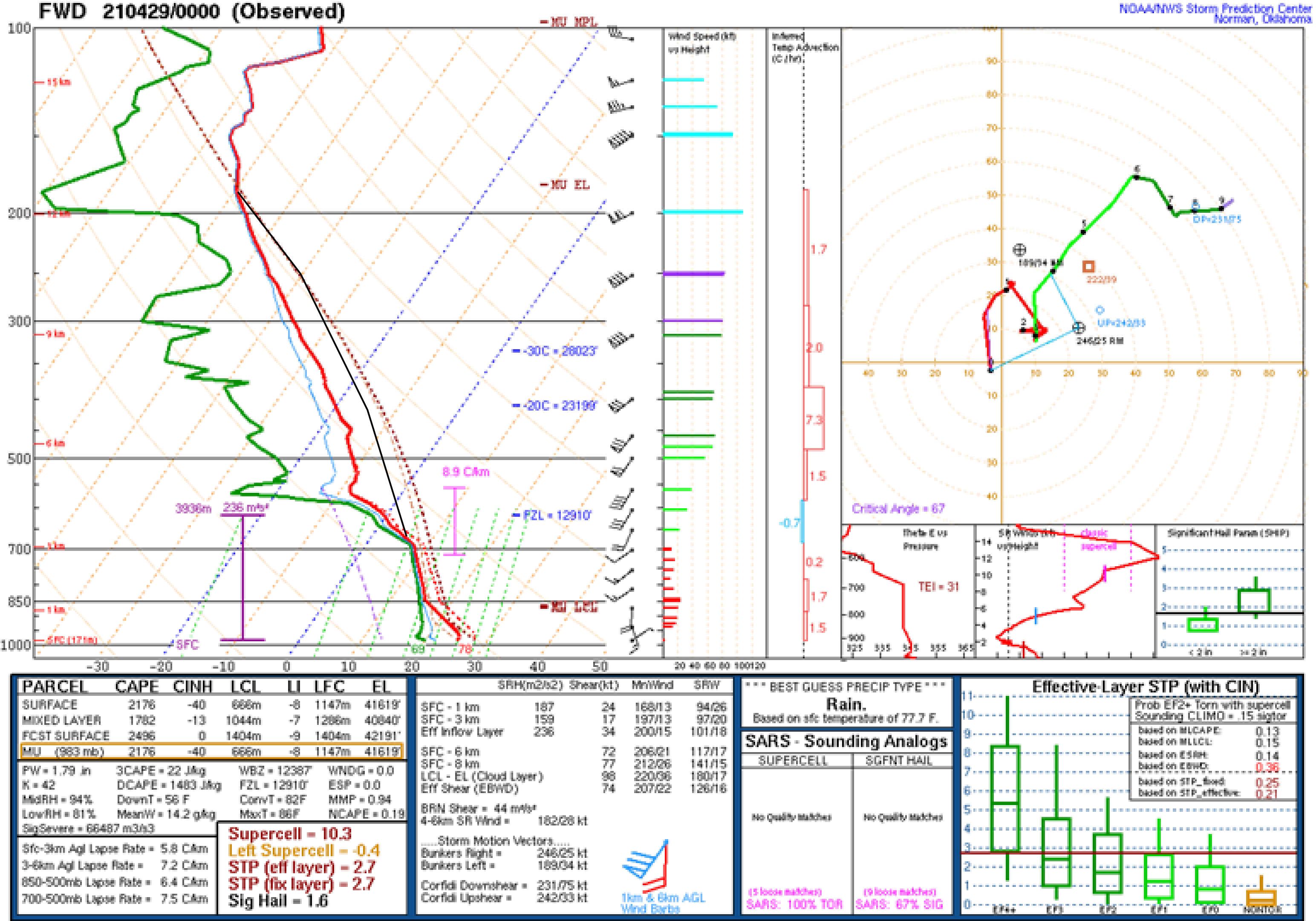
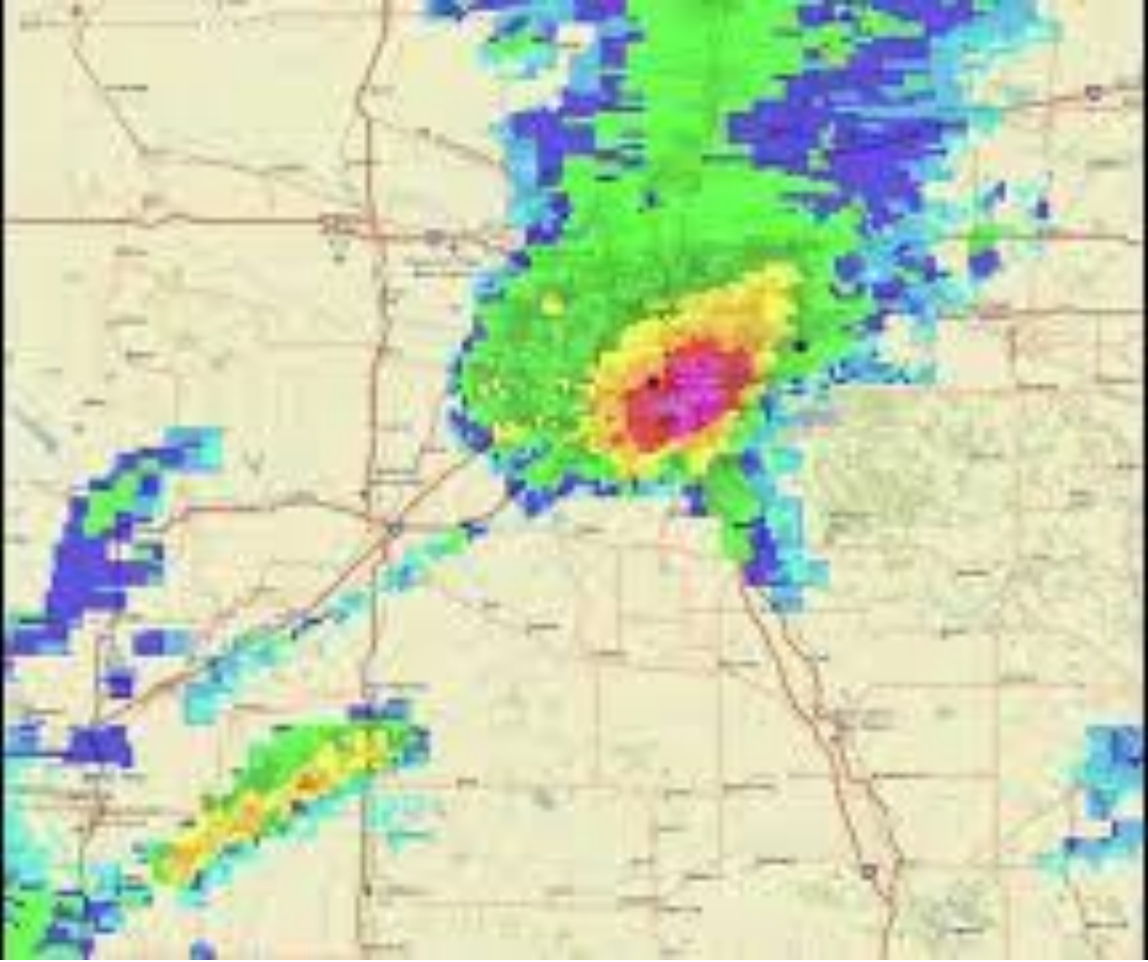
210429/0000 500 MB UA OBS, HGHTS, and TEMPS


3750
3500
3250
3000
2750
2500
2250
2000
1750
1500
1250
1000
750
500
250
Ens. Mean 100 hPa SBCAPE (J Kg^{-1})
Outflow Boundaries
105
100
95
90
85
80
75
70
65
60
55
50
Ens. Mean 2 m Temperature (°F)



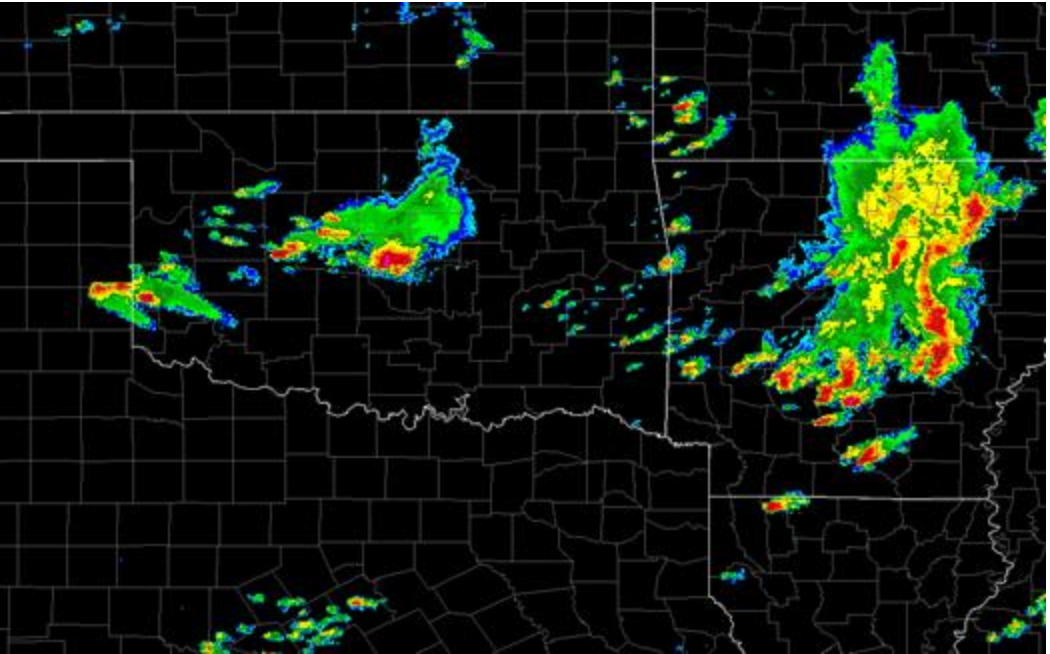
Storm was potentially elevated!

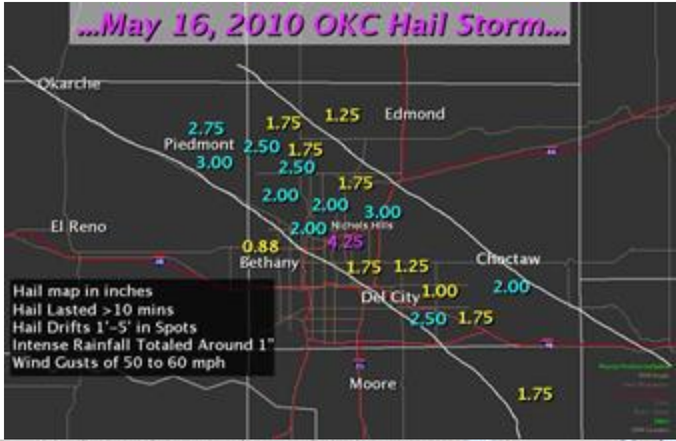
OUN sounding missing I wonder why :)

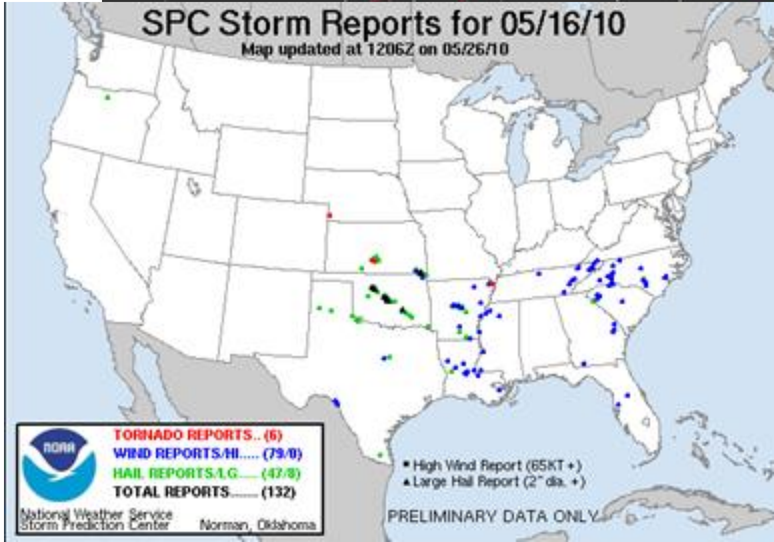


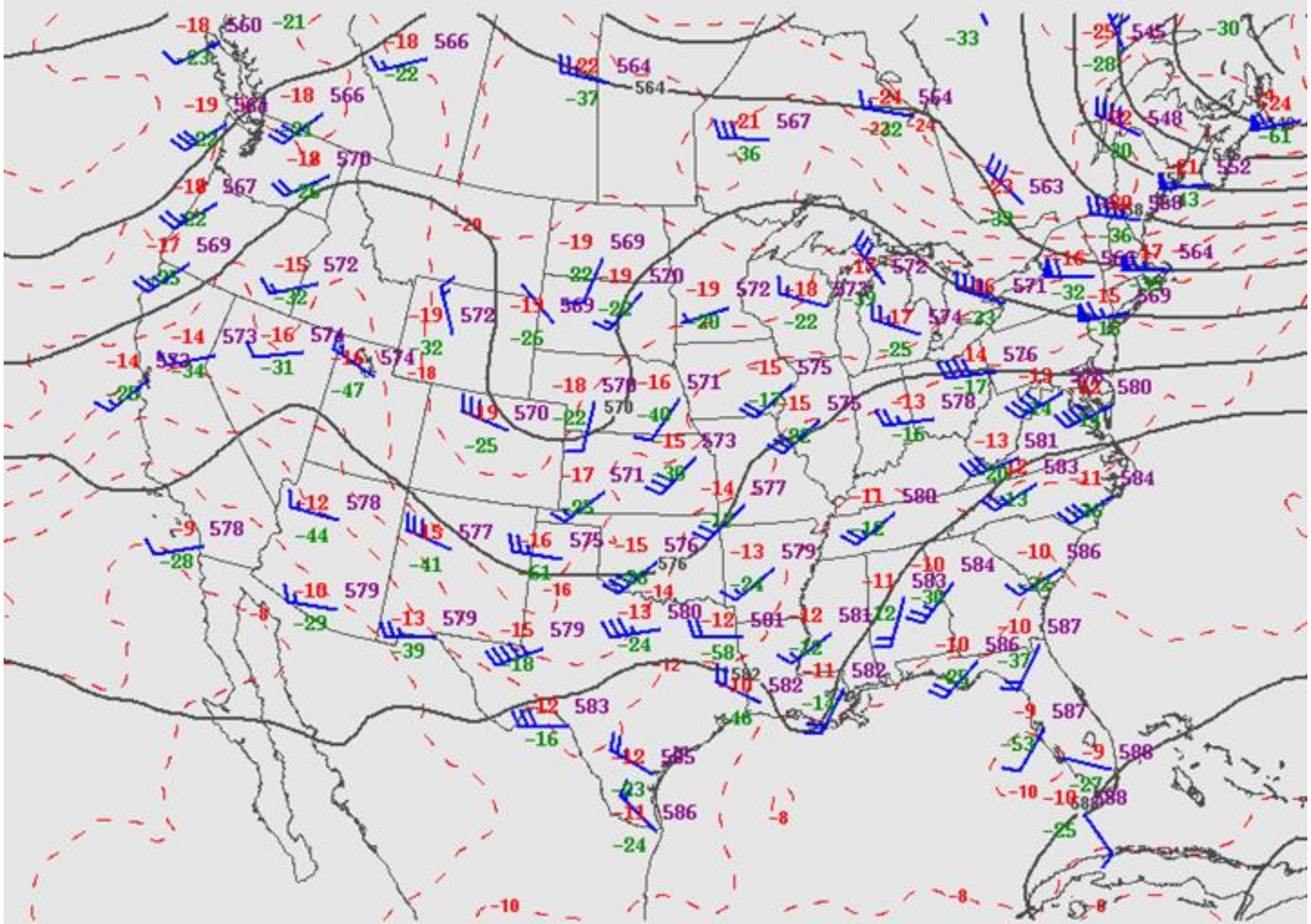
May 16, 2010 OKC Hail Storm

- Significant spring hail storm over parts of the southern Plains.
- A relatively benign pattern without strong surface features but still supported giant hail.



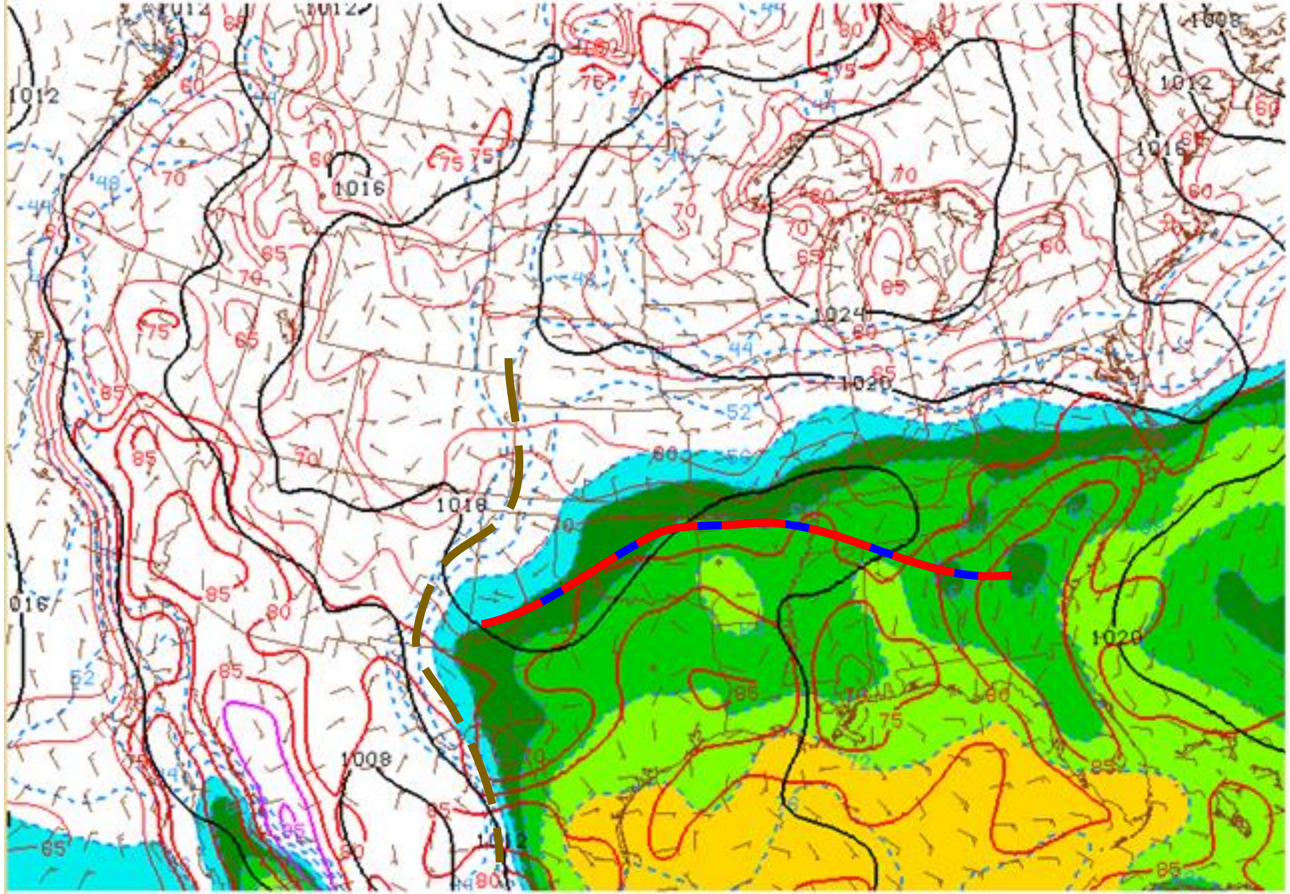






100516/1200 500 MB UA OBS, HGHTS, and TEMPS

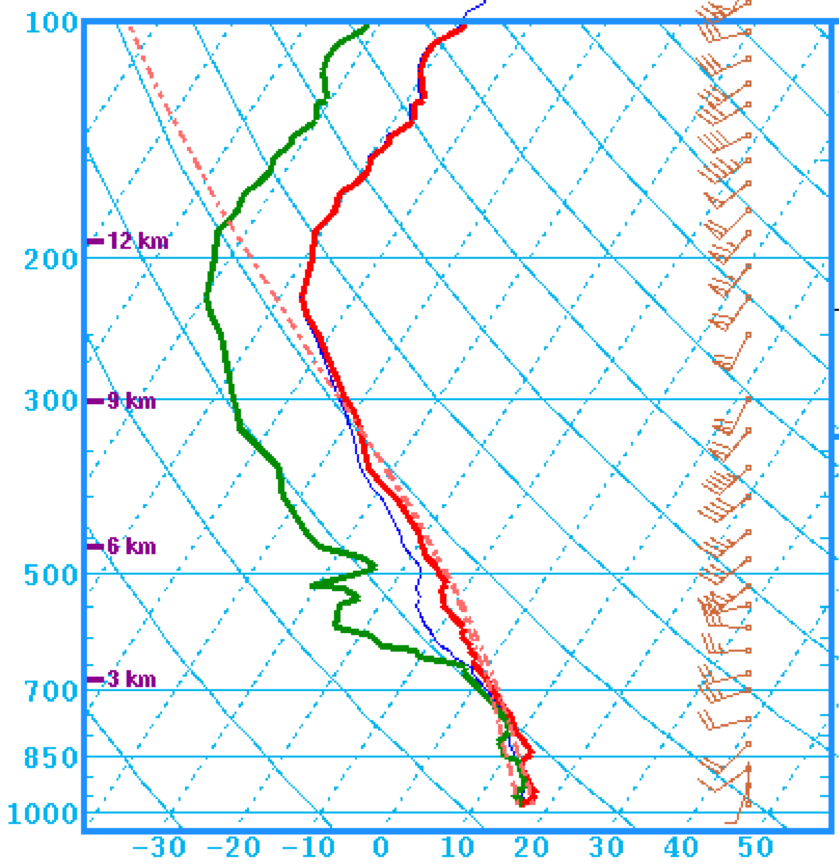
< > Start Rock Refresh



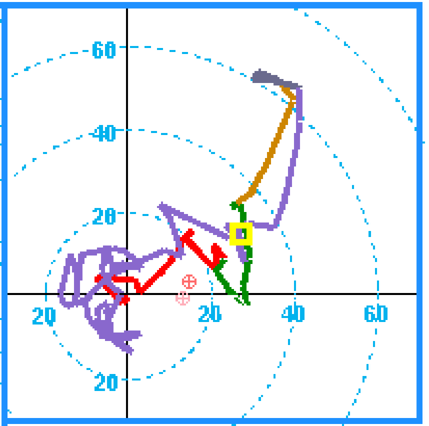
56 60 64 68 72

100516/1800 Surface temp, dewpoint, and pmsl

- + Zoom



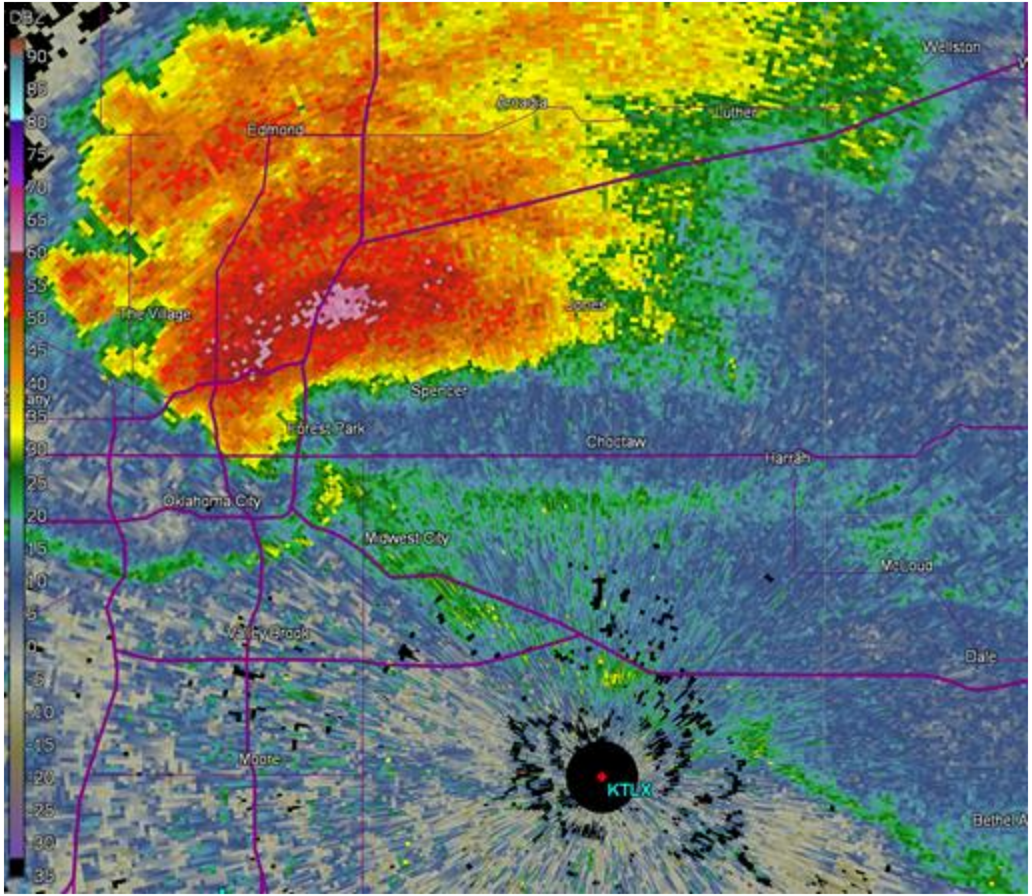
OUN – 100516/1200
OBSERVED Sounding



Sfc CAPE (J/kg)	262
Sfc CIN (J/kg)	-186
Sfc LI-500mb (C)	-1
Sfc NV Cap (C)	4
Sfc NV LFC Hgt (m;agl)	3171
ML CAPE (J/kg)	1732
ML CIN (J/kg)	-155
ML NV LFC Hgt (m;agl)	-999
Mod PM Hail Size (in.)	5.2
Supercell Composite Param	0.90
WBZ Hgt (ft;agl)	9784
Mean RH (%)	28
Sfc-3km AGL LR (C/km)	5.5
3km-6km AGL LR (C/km)	6.9
DCAPE (J/kg)	812
6km Shear (kt)	34
1km Helicity (m2/s2)	81
3km Helicity (m2/s2)	126
BRN Shear (m2/s2)	50
Sfc-2km SR Wind (kt)	21
4-6km SR Wind (kt)	15
Estimated Storm Motion (kt)	277/25

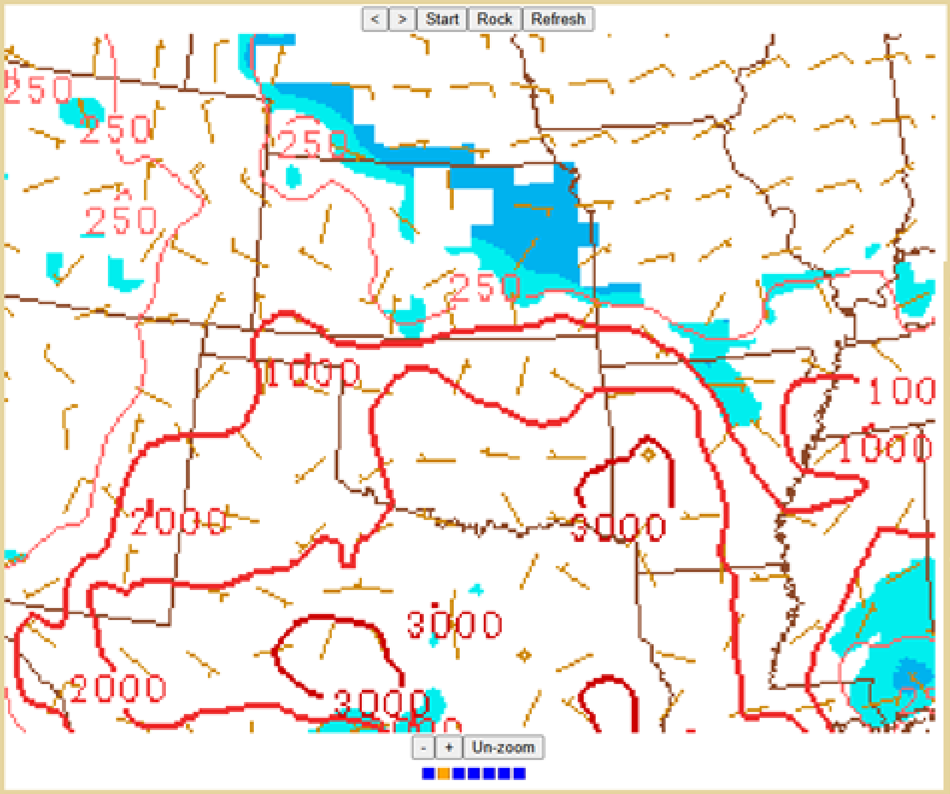
- Warming would support moderate CAPE with moderate deep-layer shear
- Probable supercell storm mode.
- Supercells can produce extremely large hail

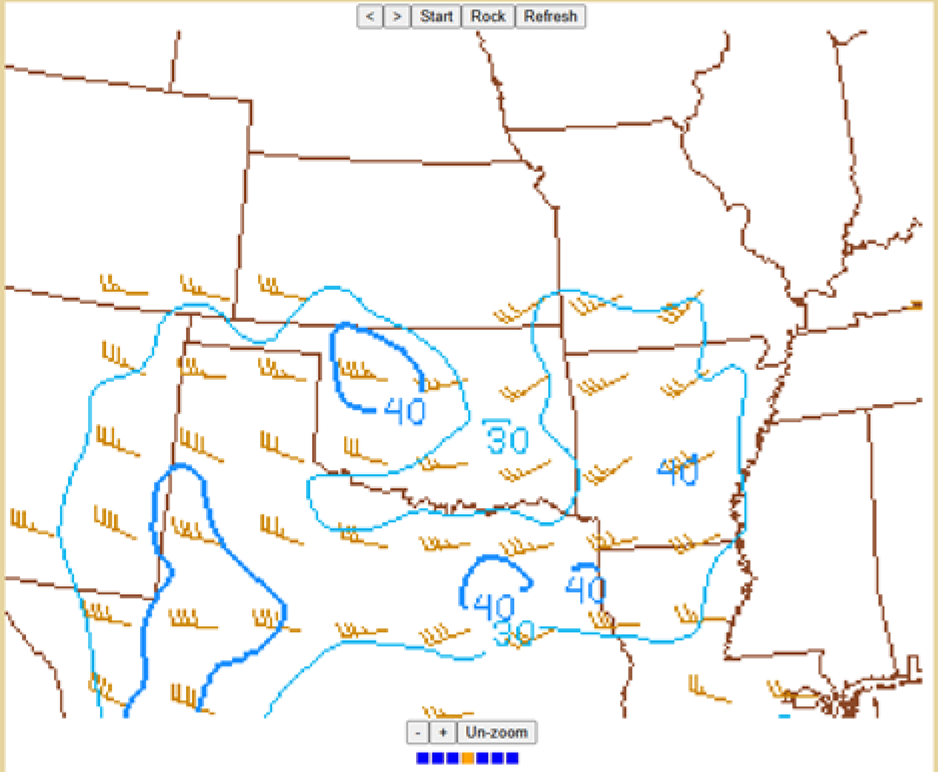
NWS/NCEP/SPC



- Storm was elevated north of the front!!

EFFECTIVE SHEAR

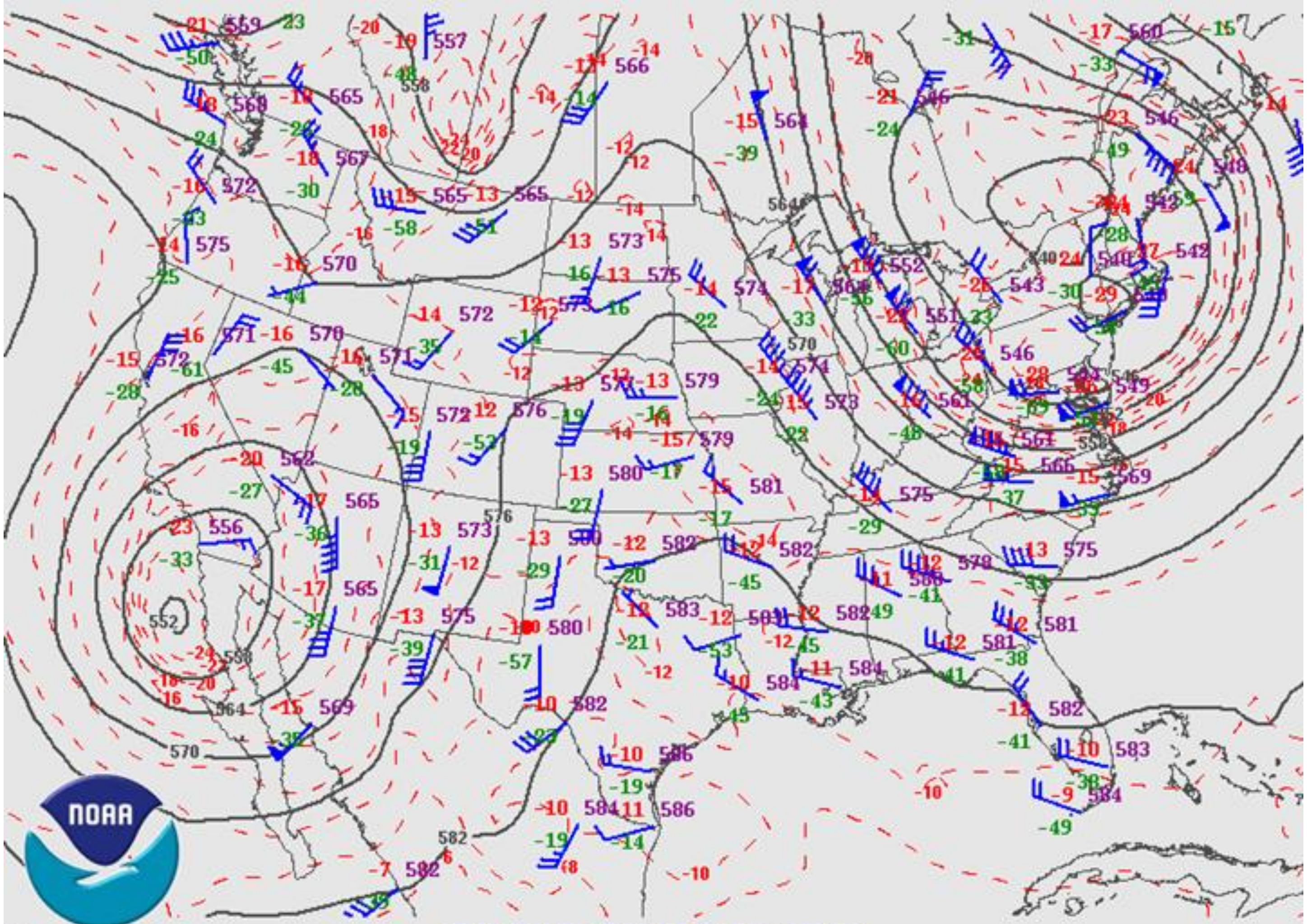




SBCAPE

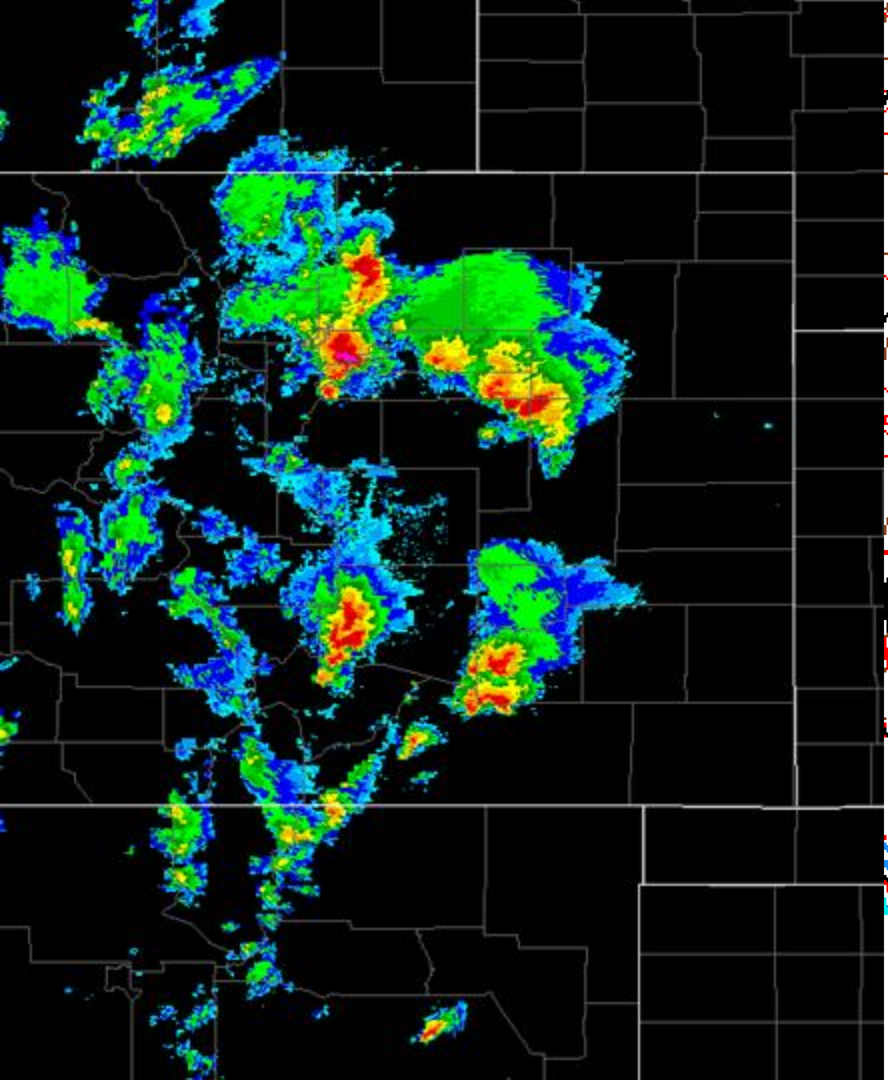
May 8, 2017 Denver Hail Storm

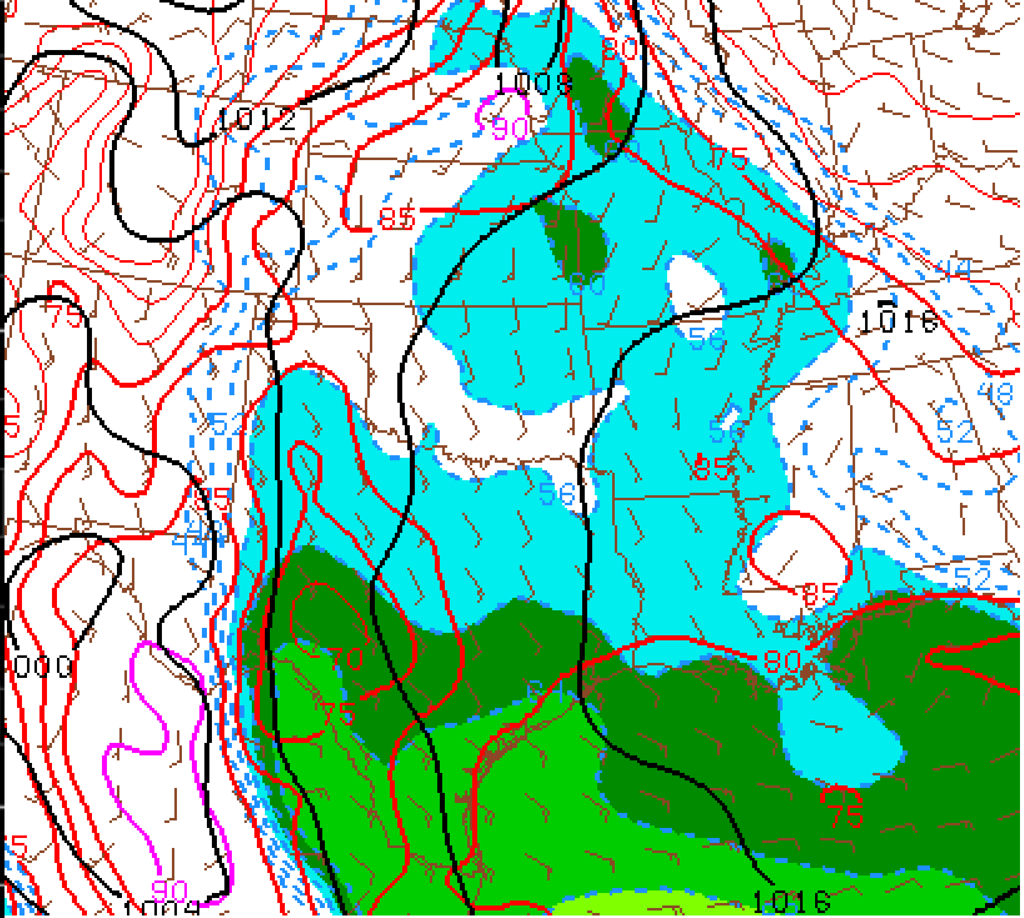
- $2.3 Billion dollars in damage through the heart of downtown Denver.
- Several elevated supercells north of a stationary front.
- Numerous reports of golf ball and 2 inch wind driven hail.



National Weather Service
Storm Prediction Center

170508/1200 500 MB UA OBS, HGHTS, and TEMPS





170508/2100 Surface temp, dewpoint, and pmsl

- + Zoom