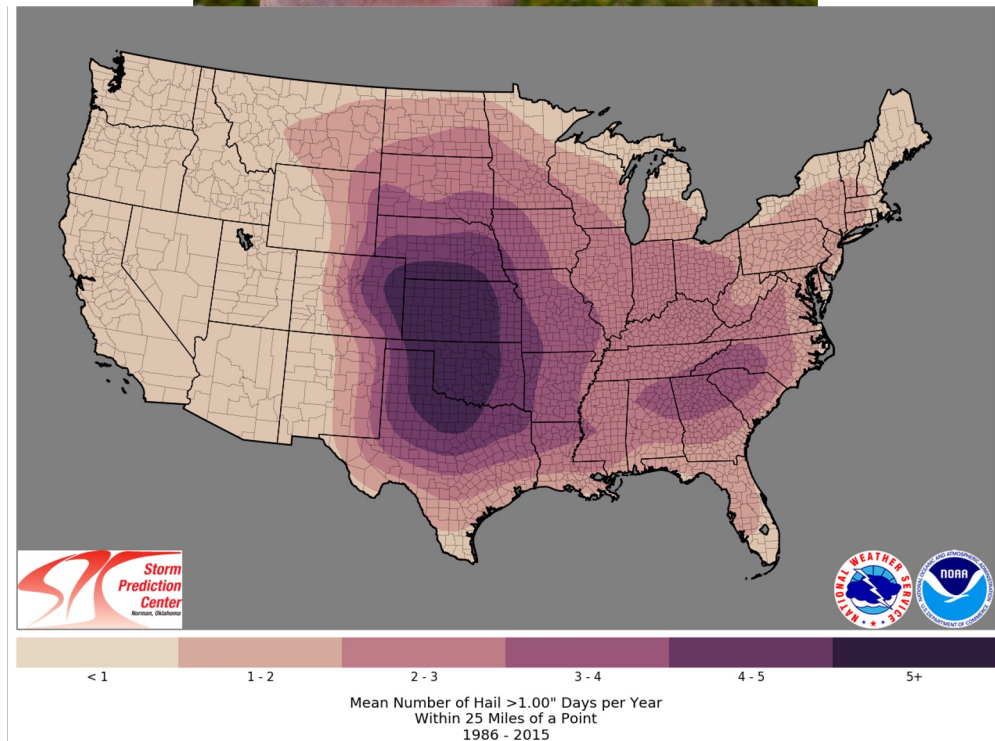


Hail Forecasting



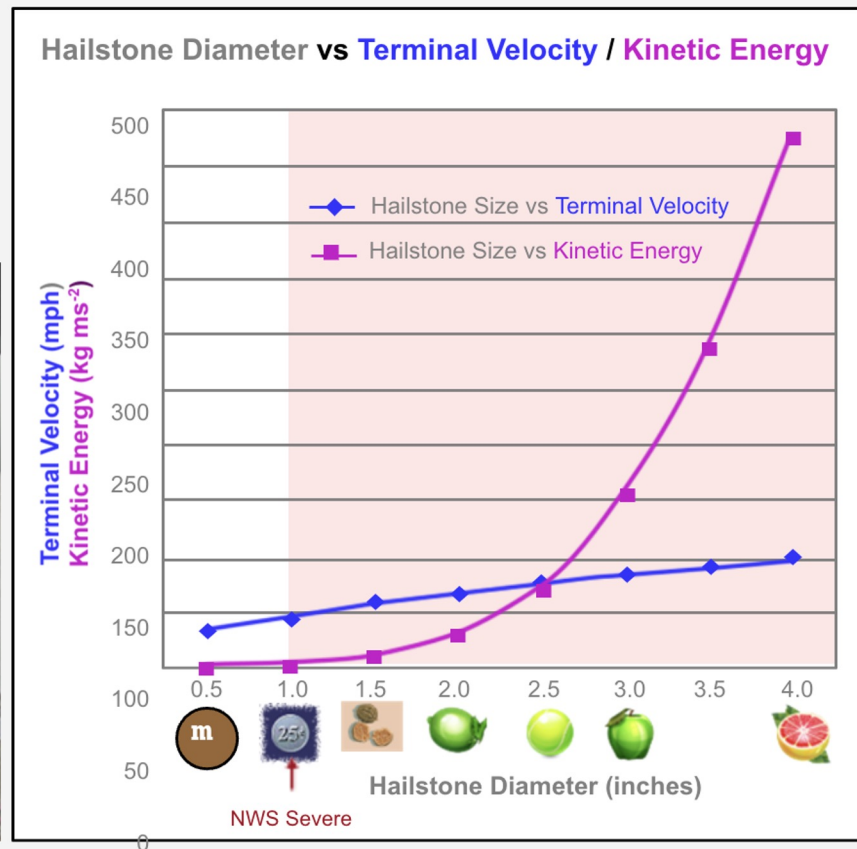
Background

- 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.



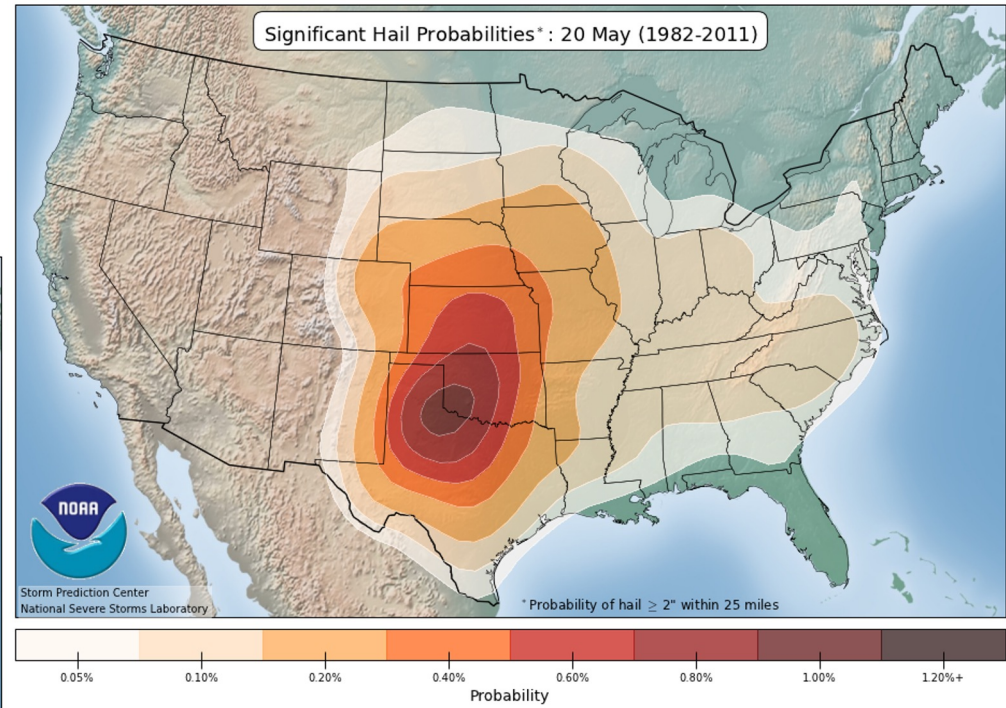
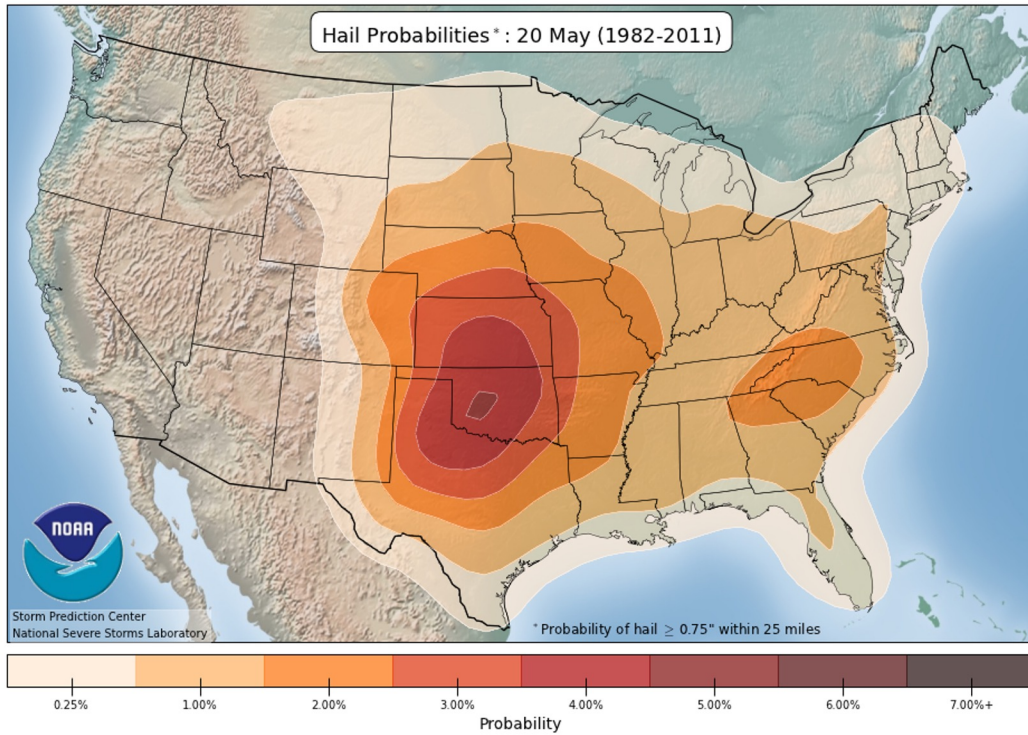
Motivation

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.

Sun Mar 31, 2024 12:30 PM

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

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.,

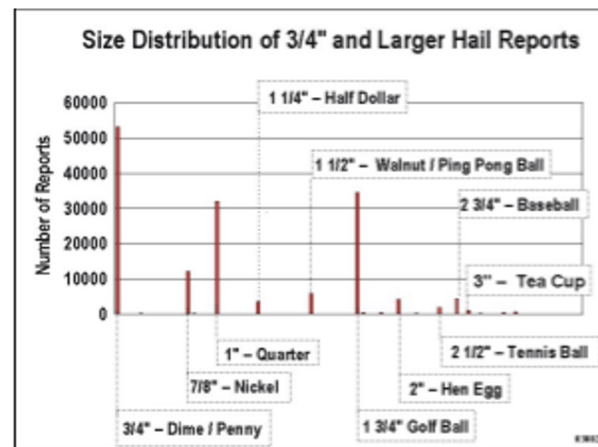
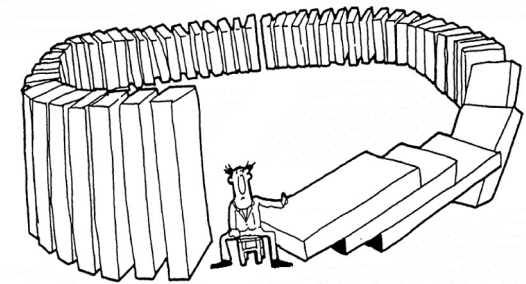


Figure 1: Size distribution of severe hail reports (1955 – 2002)

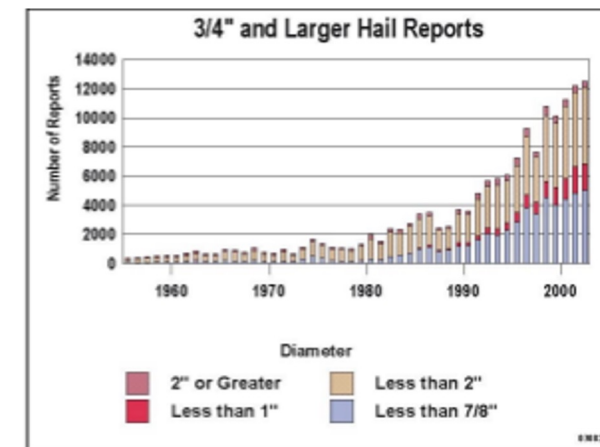
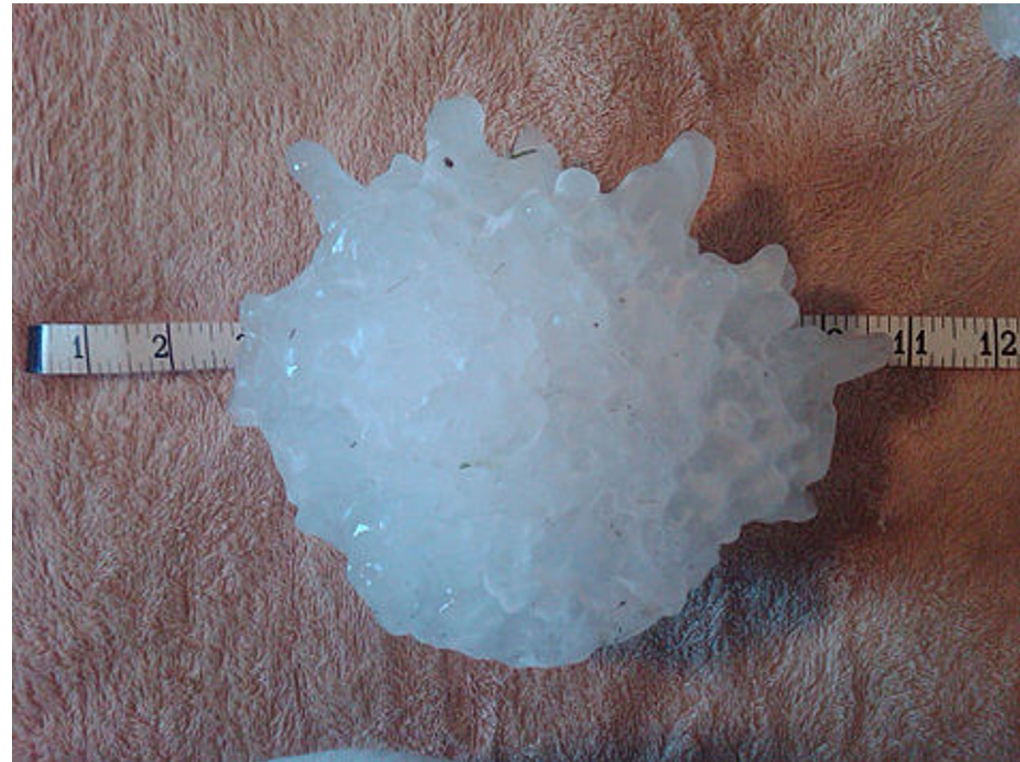


Figure 2: Growth of hail reports with time

Records

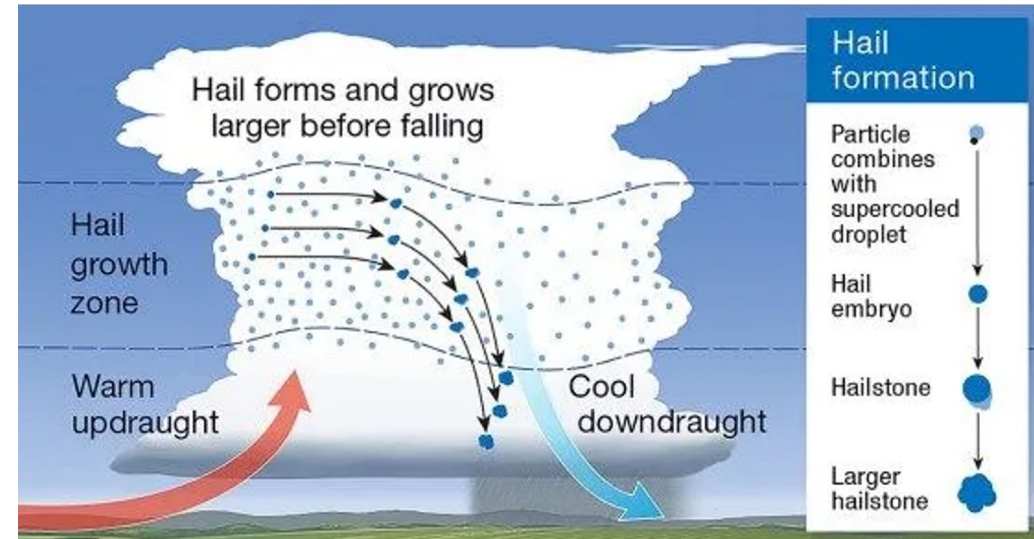
- Us record for diameter is from Vivian, SD July 23rd of 2010
 - 7.9 inches (20 cm) in diameter and weighed nearly 2 lbs.
- **Heaviest:** 1.02 kg (2.2 lb); [Gopalganj District](#), Bangladesh, 14 April 1986.^{[43][44]}
- **Largest diameter officially measured:** 7.9 in (20 cm) diameter, 18.622 in (47.3 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
- 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.
 - $v_t = \sqrt{(2 \times M \times G) / (A \times C_d \times \rho)}$



$$C_d=0.47 \quad A=0.031 \text{ m}^2 \quad \rho=1.3$$

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

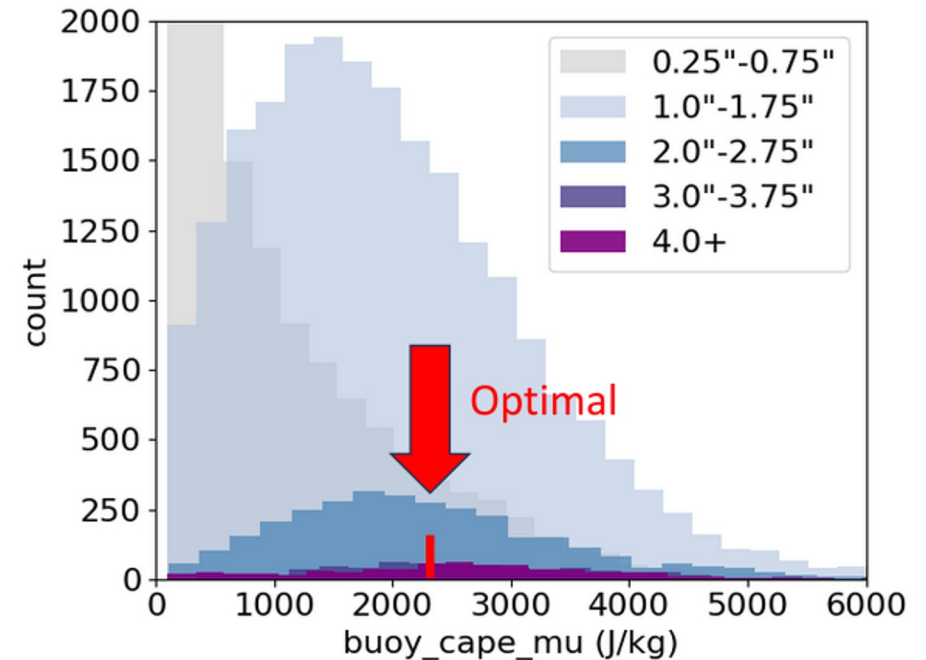
Basic ingredients for Hail and Significant Hail (Updrafts)

- 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 $W_{MAX} = \sqrt{2 \times CAPE}$
 - 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!)



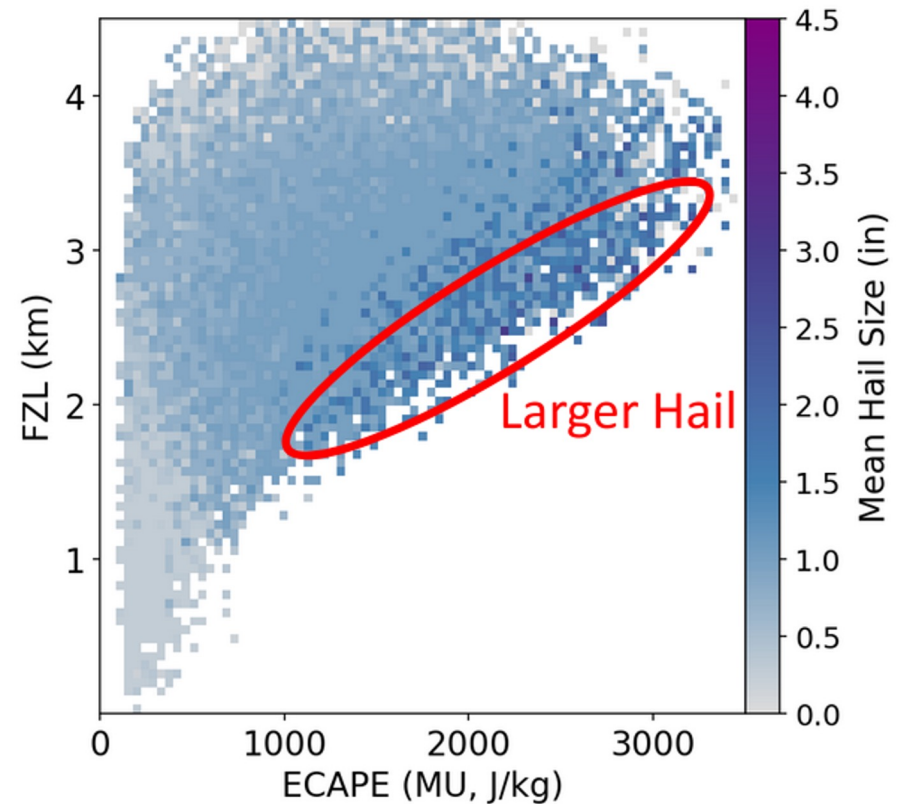
But a word of caution...

- 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
- Why?
 - Higher cape environments are less common.
 - measurement bias
 - ect.



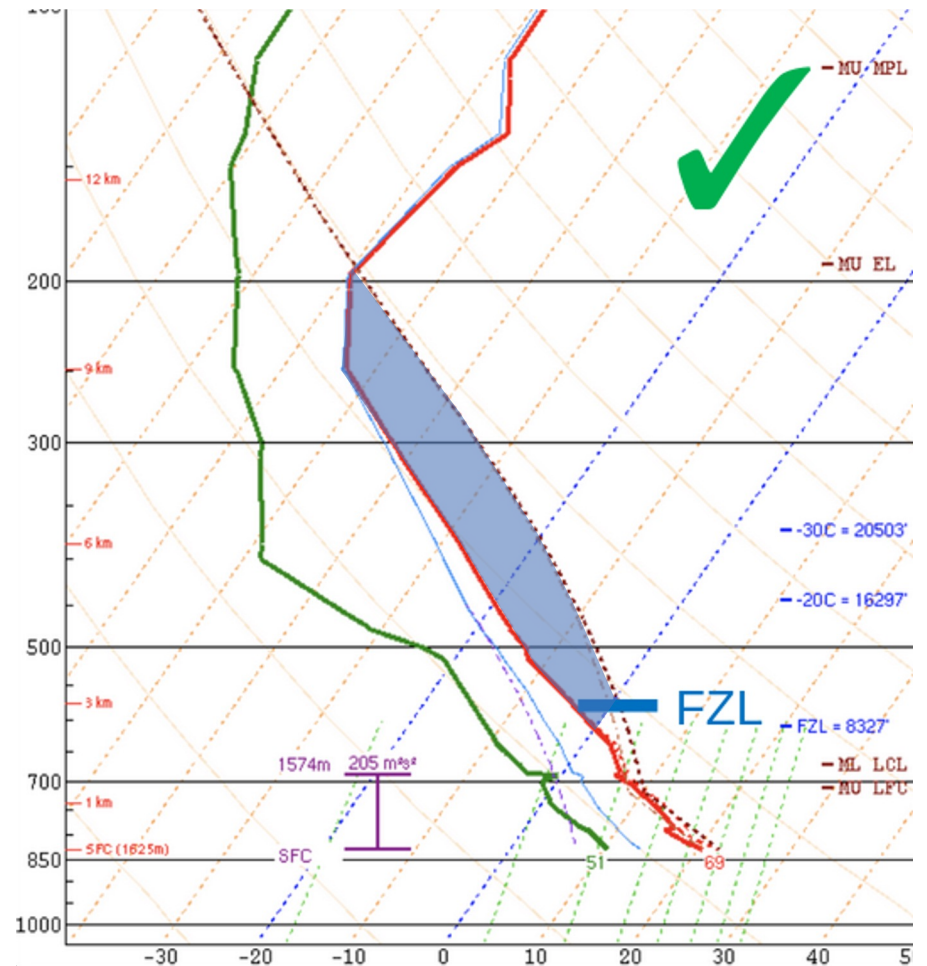
The Freezing Level and Hail

- 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



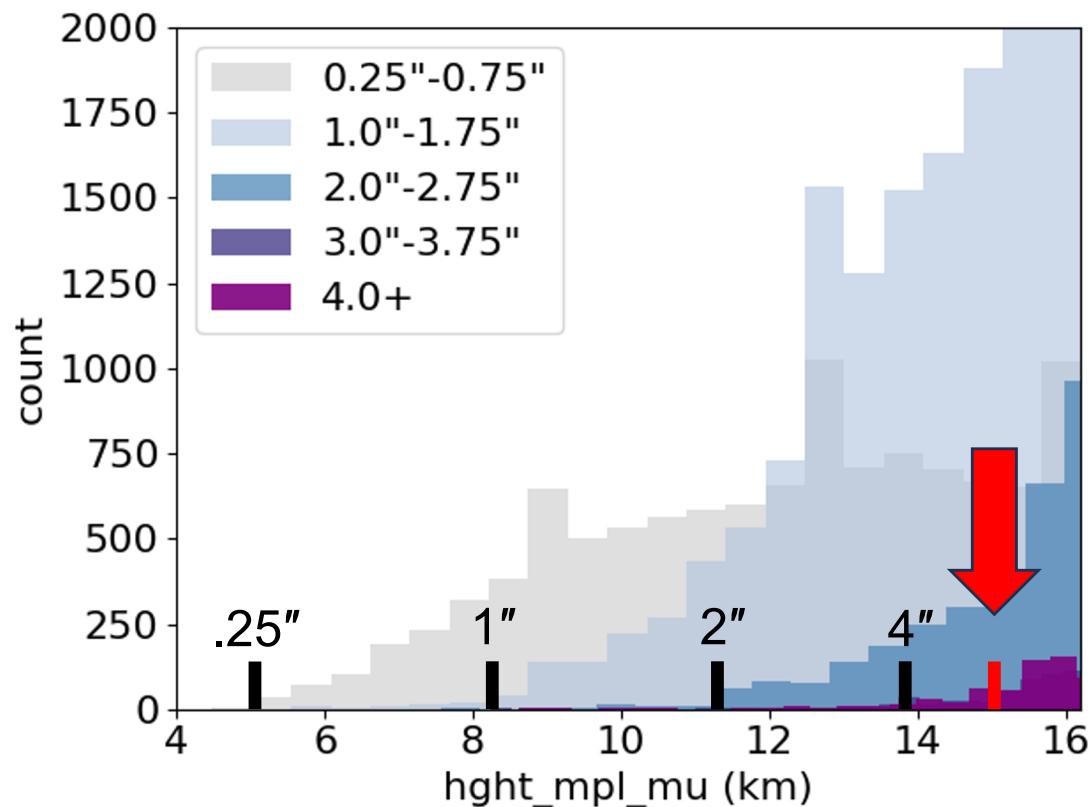
Lapse rates and Hail

- 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



2. Storm depth

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



(Nixon 2025)

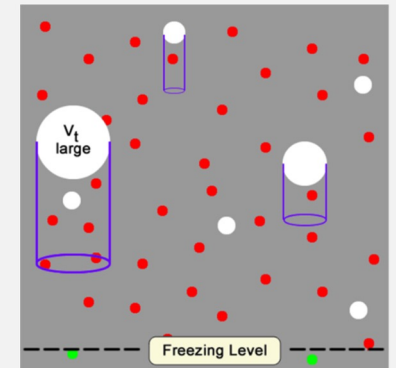
Hail Forecasting Saturation

- Hailstone formation and growth requires enough supercooled water to support accretion.
- **Goldilocks problem.** 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.

Hail Formation and Growth Process

Embryo accretes ice due to collisions with supercooled liquid water (SLW) droplets within a CB

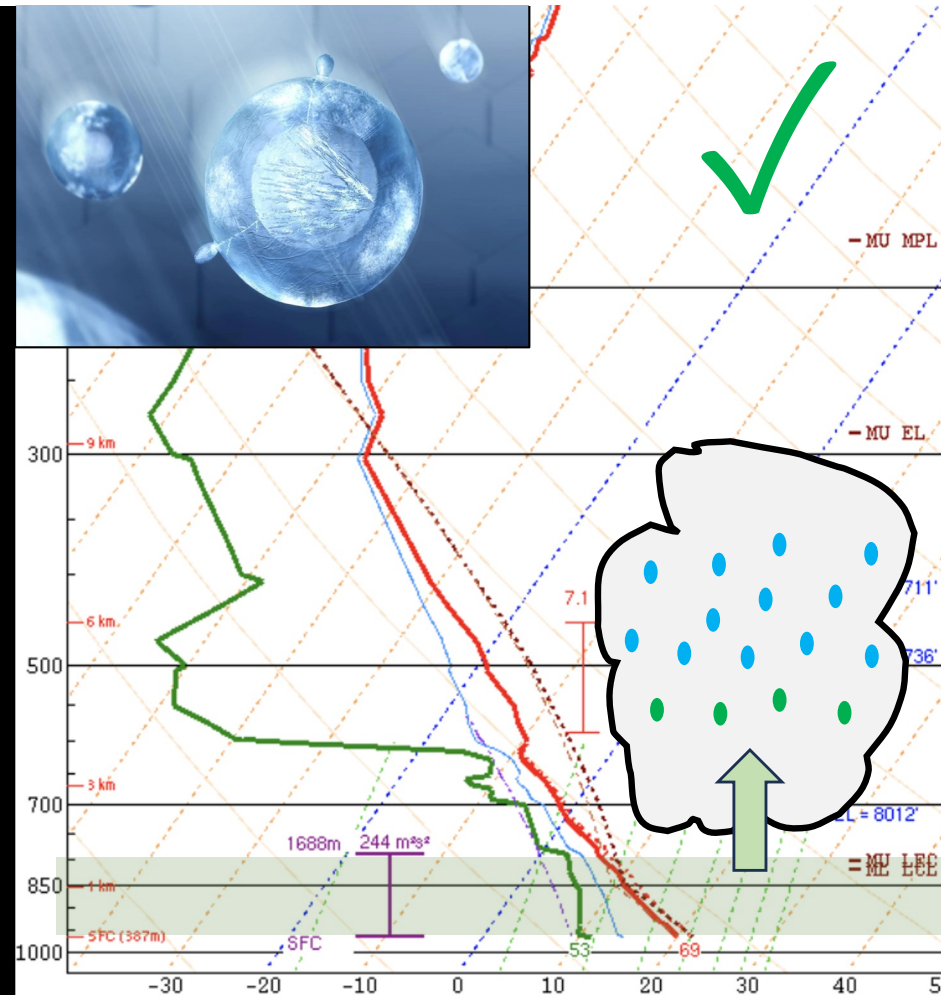
- Embryo becomes heavier than SLW droplets and falls
- Hailstone “sweeps up” SLW droplets along its path
- Process takes 15-20 minutes
 - Longer for larger hailstones



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**

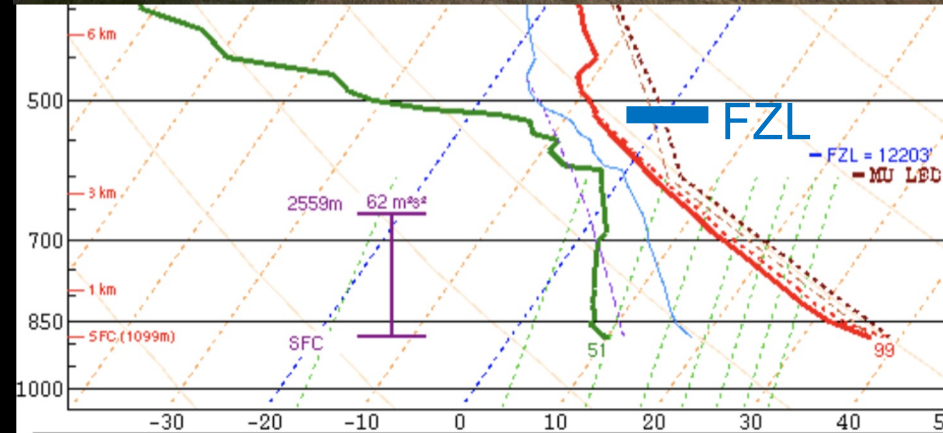


Summary:

Many ways to get **efficient** hailstorms:

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

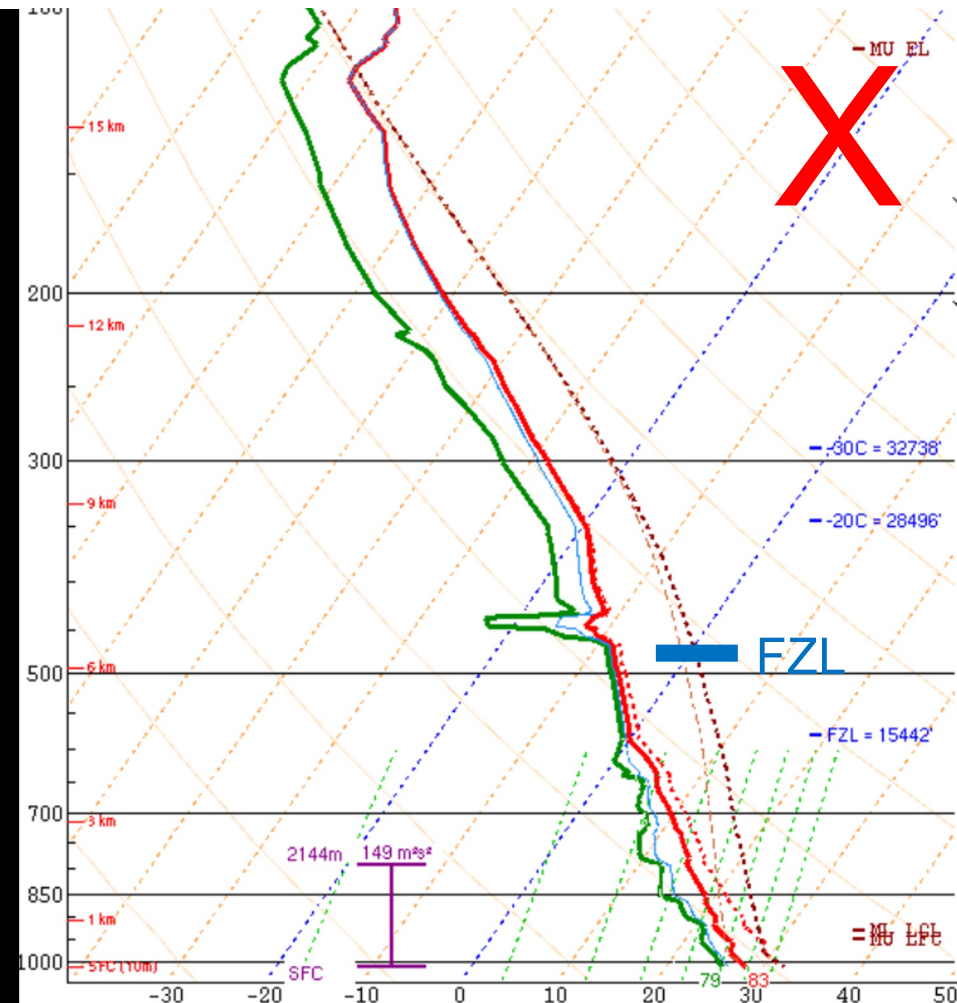
high-based



Summary:

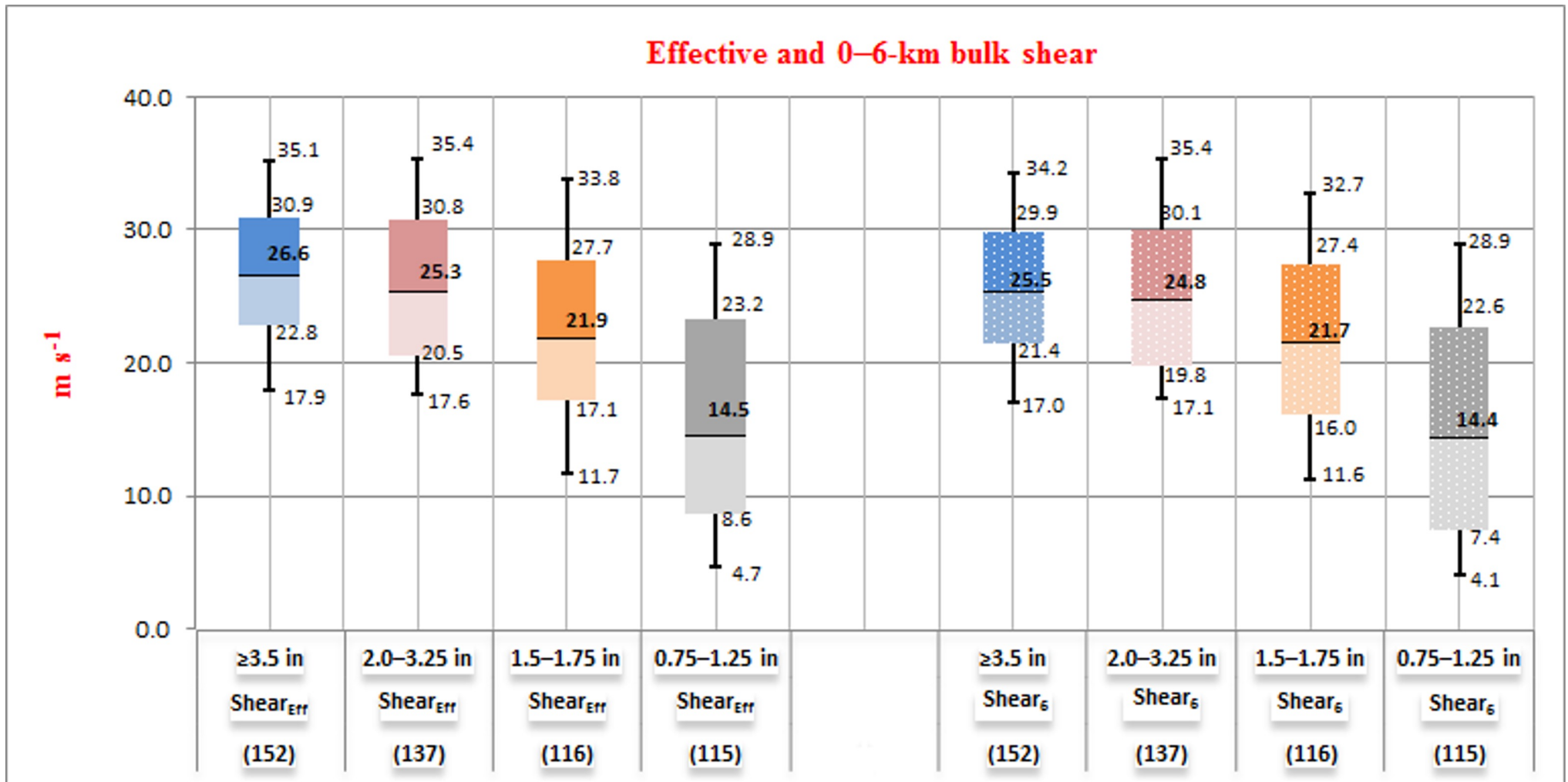
Hail efficiency is poor with:

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



(Johnson & Sugden 2021)

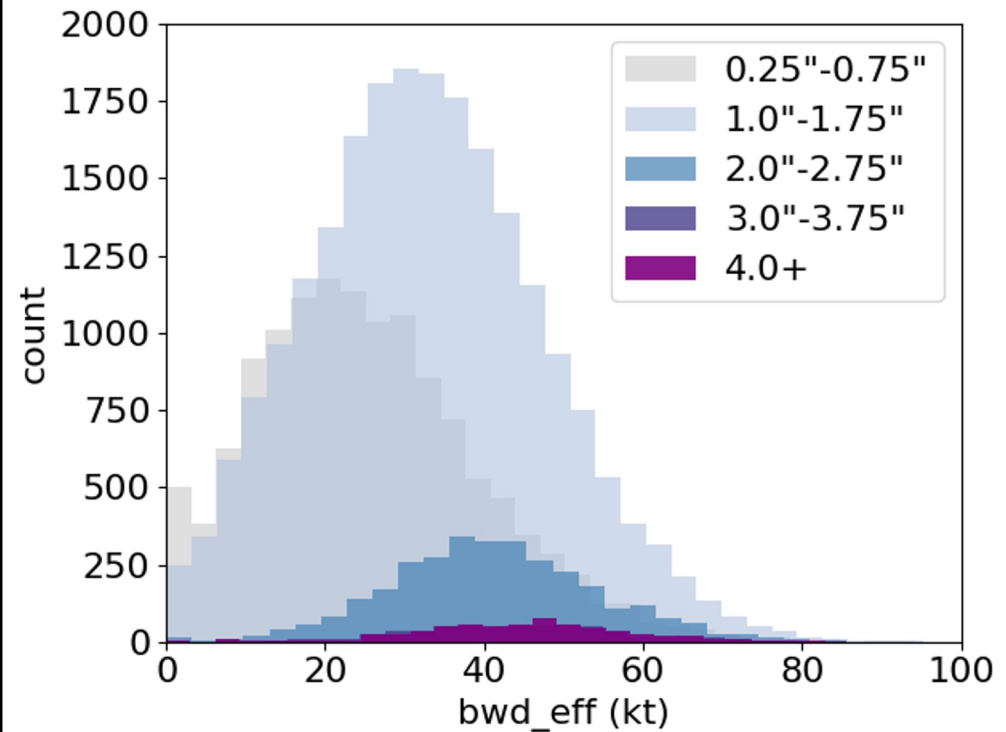
Vertical Shear



4. Wind Shear

Effective shear/SRW is most skillful, likely because many hailstorms are elevated¹

SHIP/LHP do not take this into account!

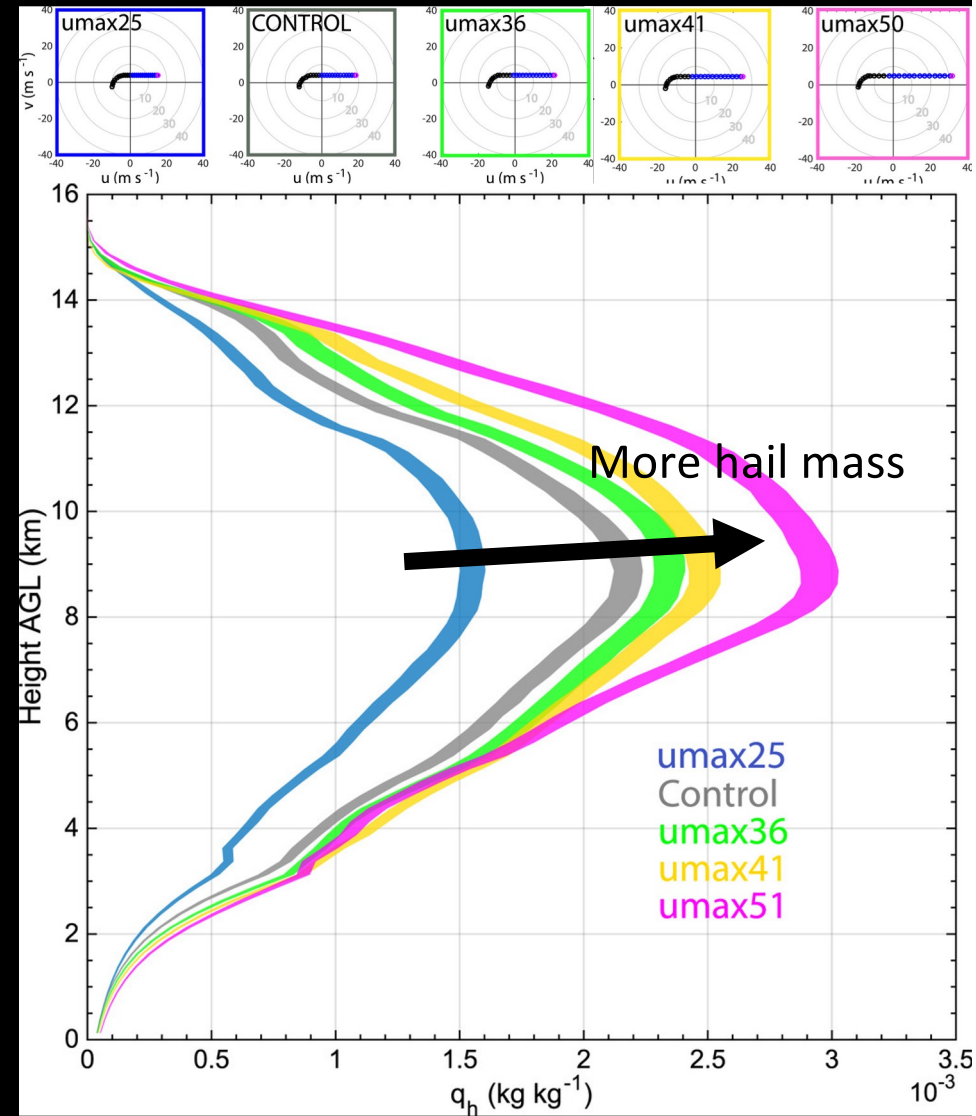


1 – Nixon & Allen (2023)

4. Wind Shear

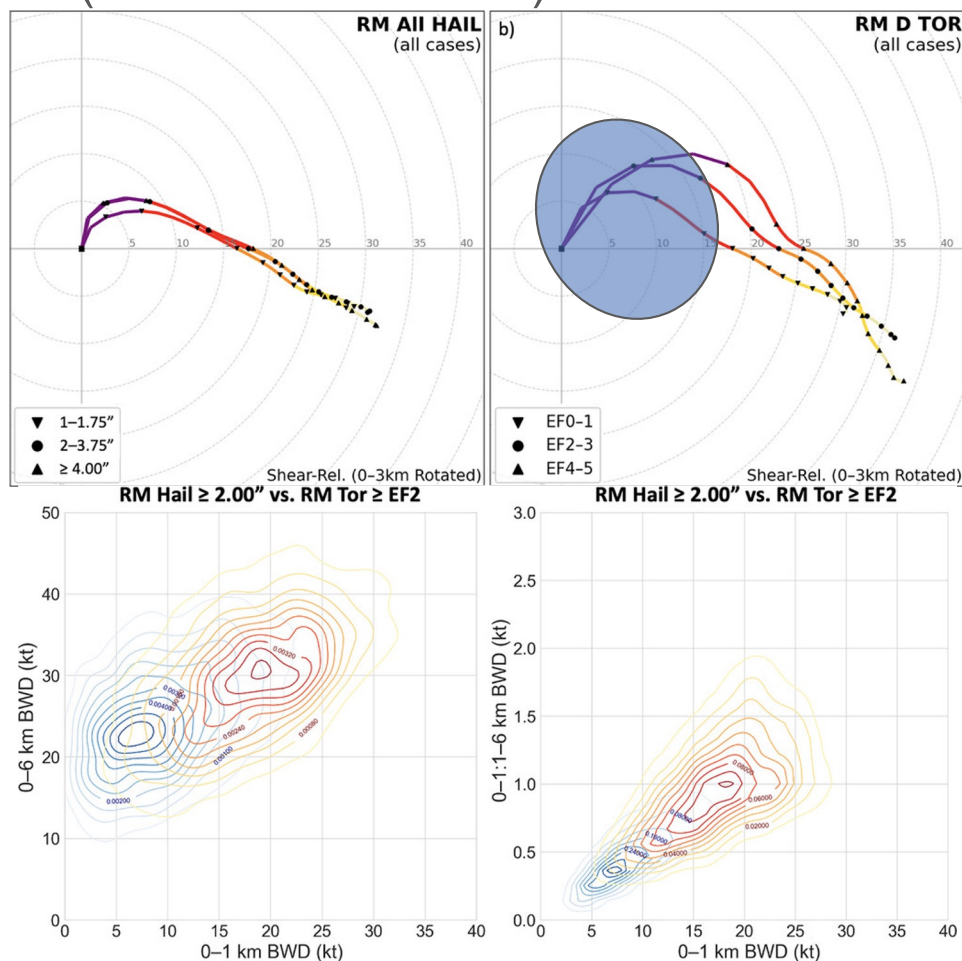
Stronger deep-layer shear can support wider updrafts that produce more hail^{1,2}

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



Hail Favoring Hodographs

(Nixon & Allen 2022)



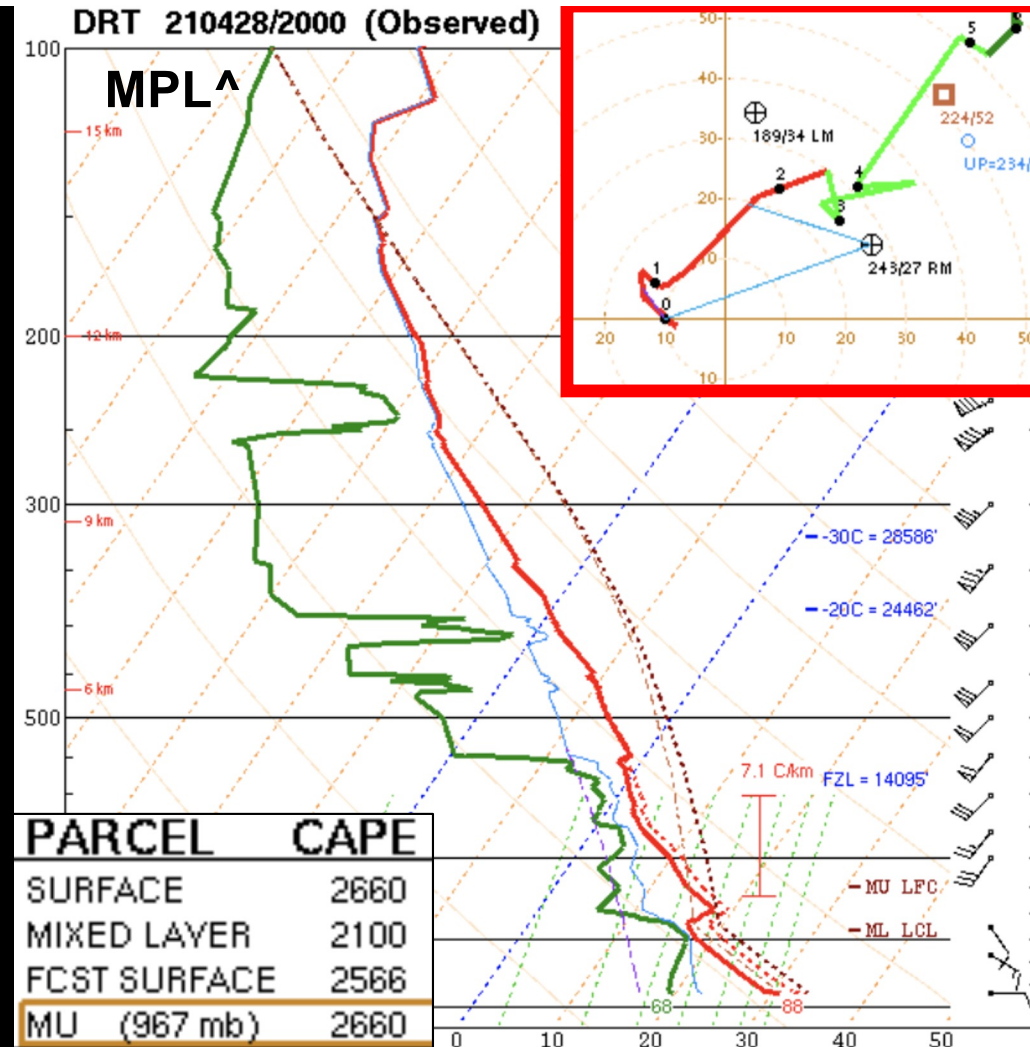
- Moderate to strong mid-level shear
- Upper-level flow not too strong to limit residence time.
- Strong enough low-level SRW to support broad updraft and supercells.
- But not too strong to displace hail embryos.
- Weaker low-level shear compared to tornadic cases but still significant overlap.

Cool stable layer at the surface
Effective straight line hodo aloft

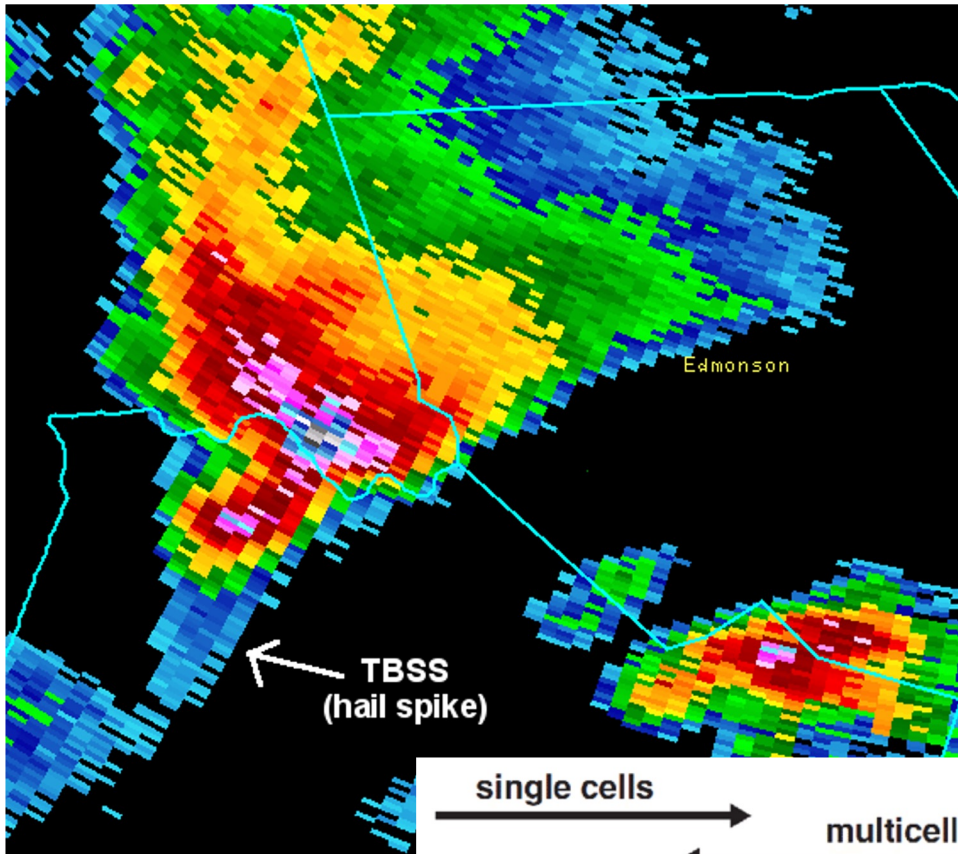
Summary:

How to get the **largest** hailstones:

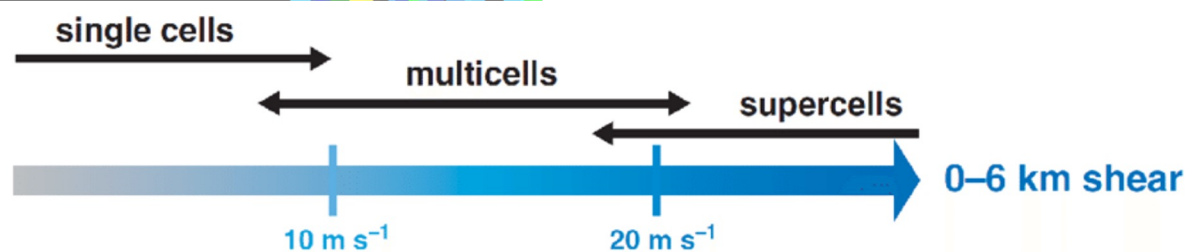
- Moderate CAPE
- Higher MPL
- Stronger Eff. Shear



Updrafts (Storm Mode)

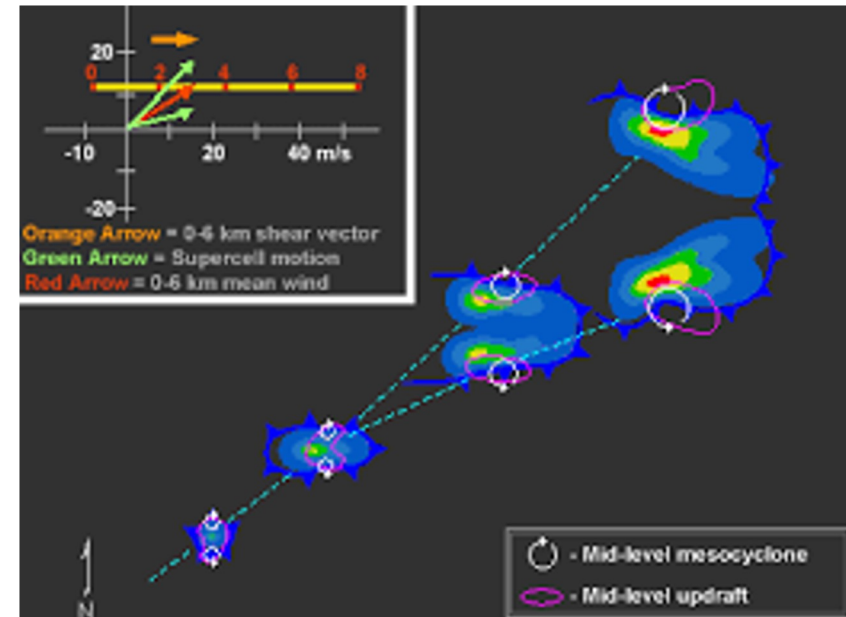


- The majority of prolific hail events are produced by supercells.
- Storm mode plays a significant role. Hail more likely with discrete or cluster types. Less likely with lines.
- Vertical shear strong enough to supports supercells can be a significant predictor for hail.
- Storm interactions can also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

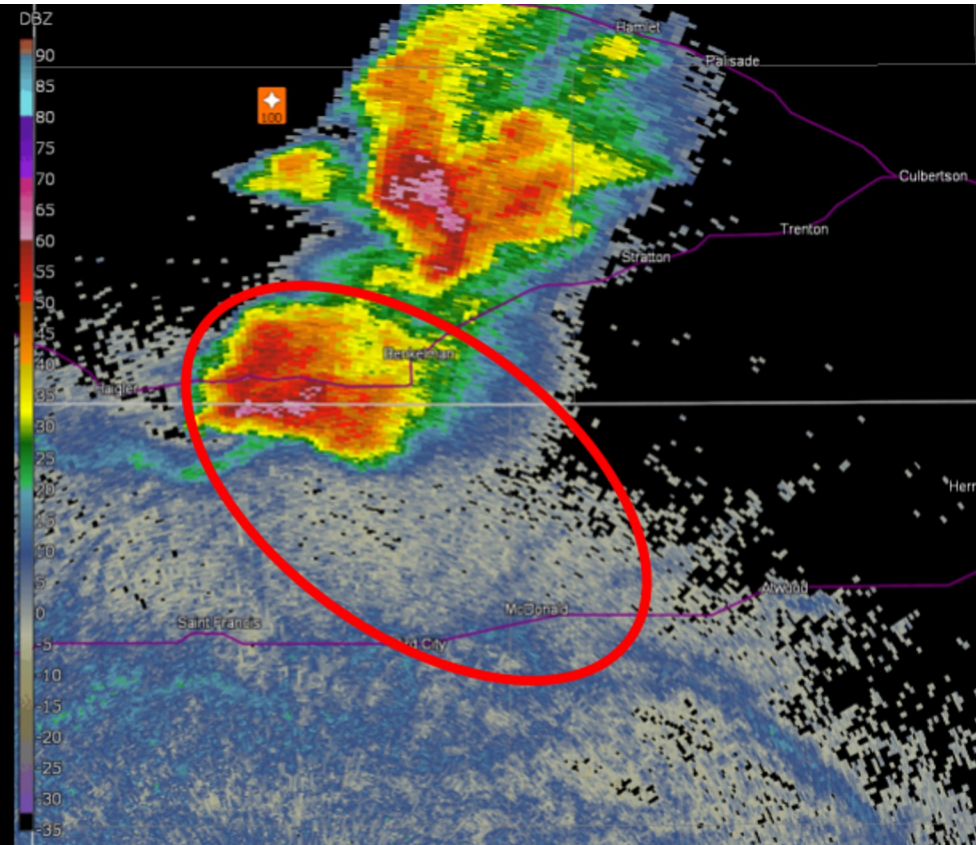


3. Eff. Inflow Base

Many hailstorms are “elevated”:

Over **25%** of all 3"+ hailstorms occur behind outflow boundaries and cold fronts¹

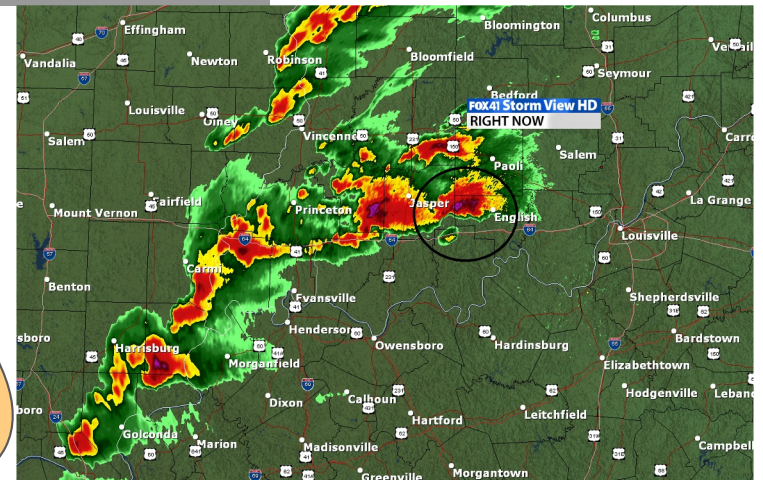
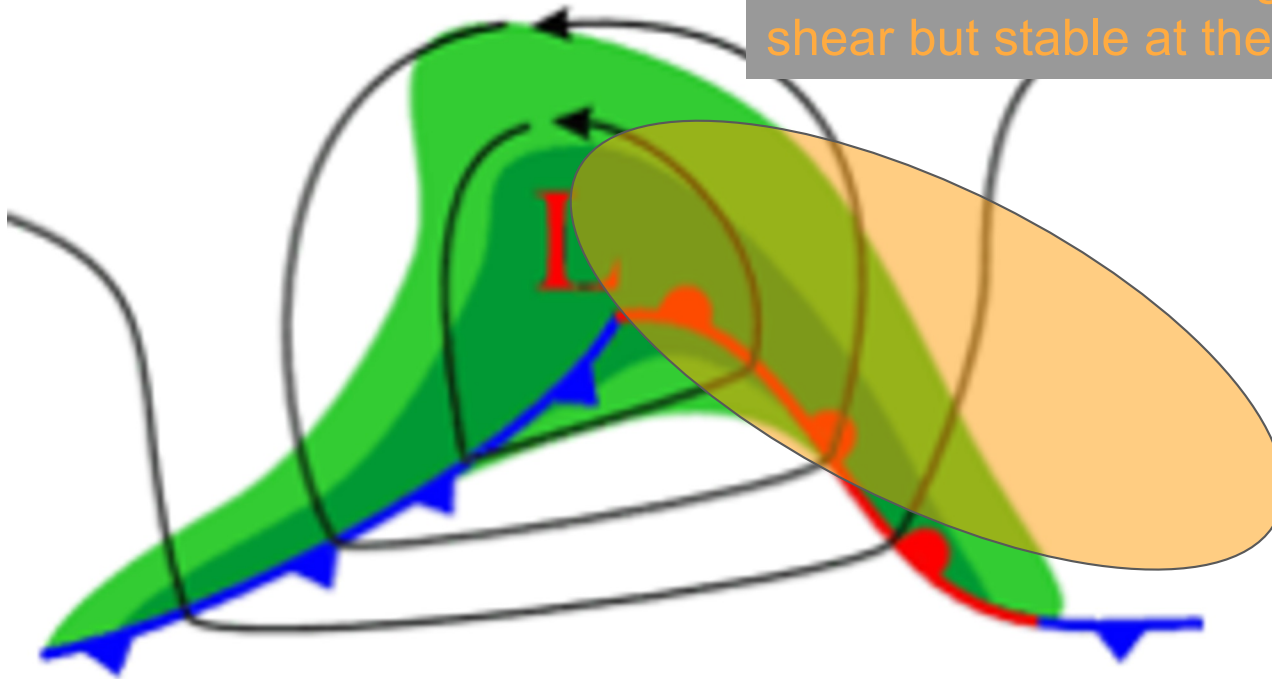
Over **20%** occur in the outflow of other supercells¹



1 – Nixon et al. (2024)

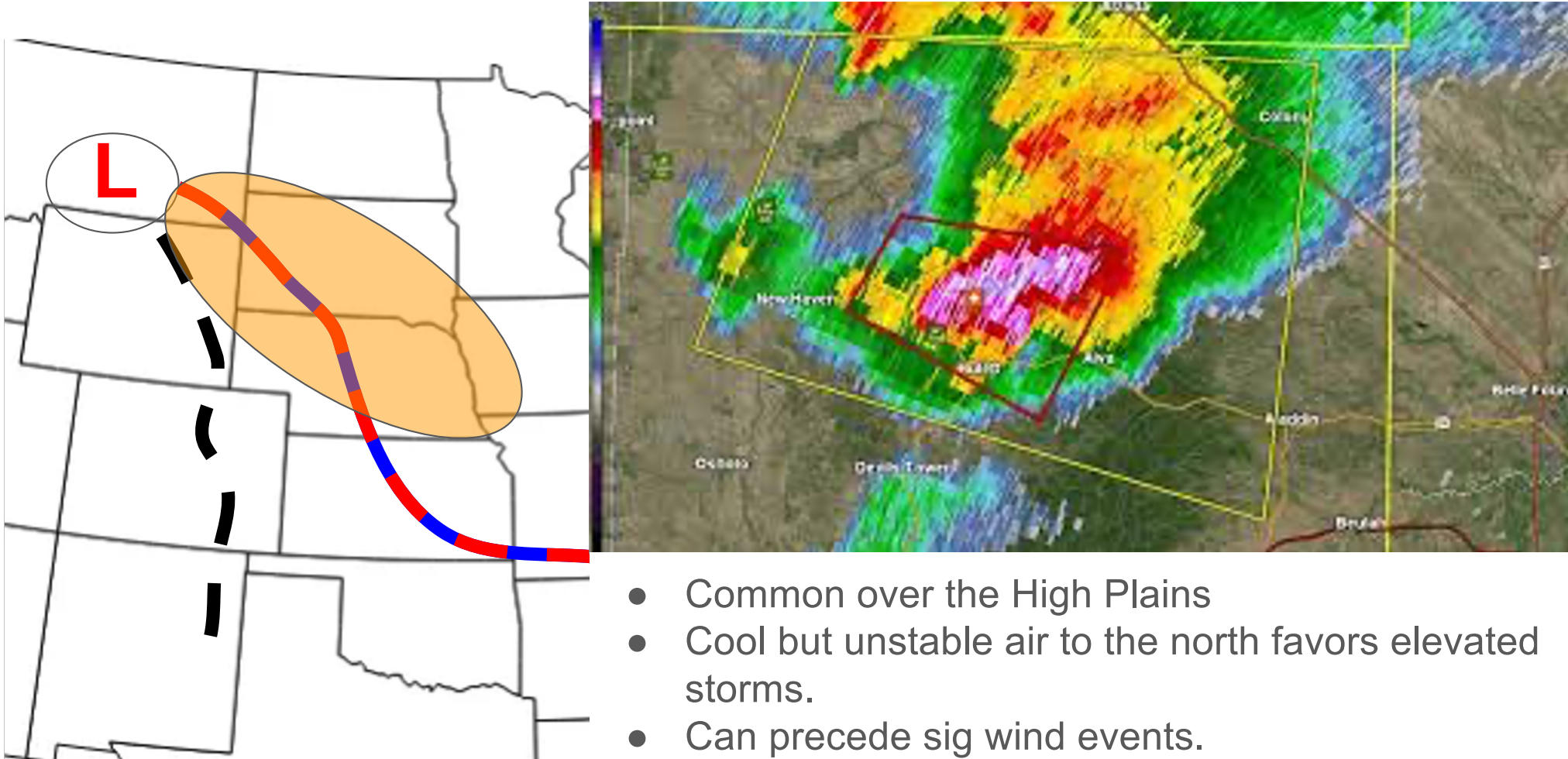
Setups Favoring Hail (Warm Front)

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

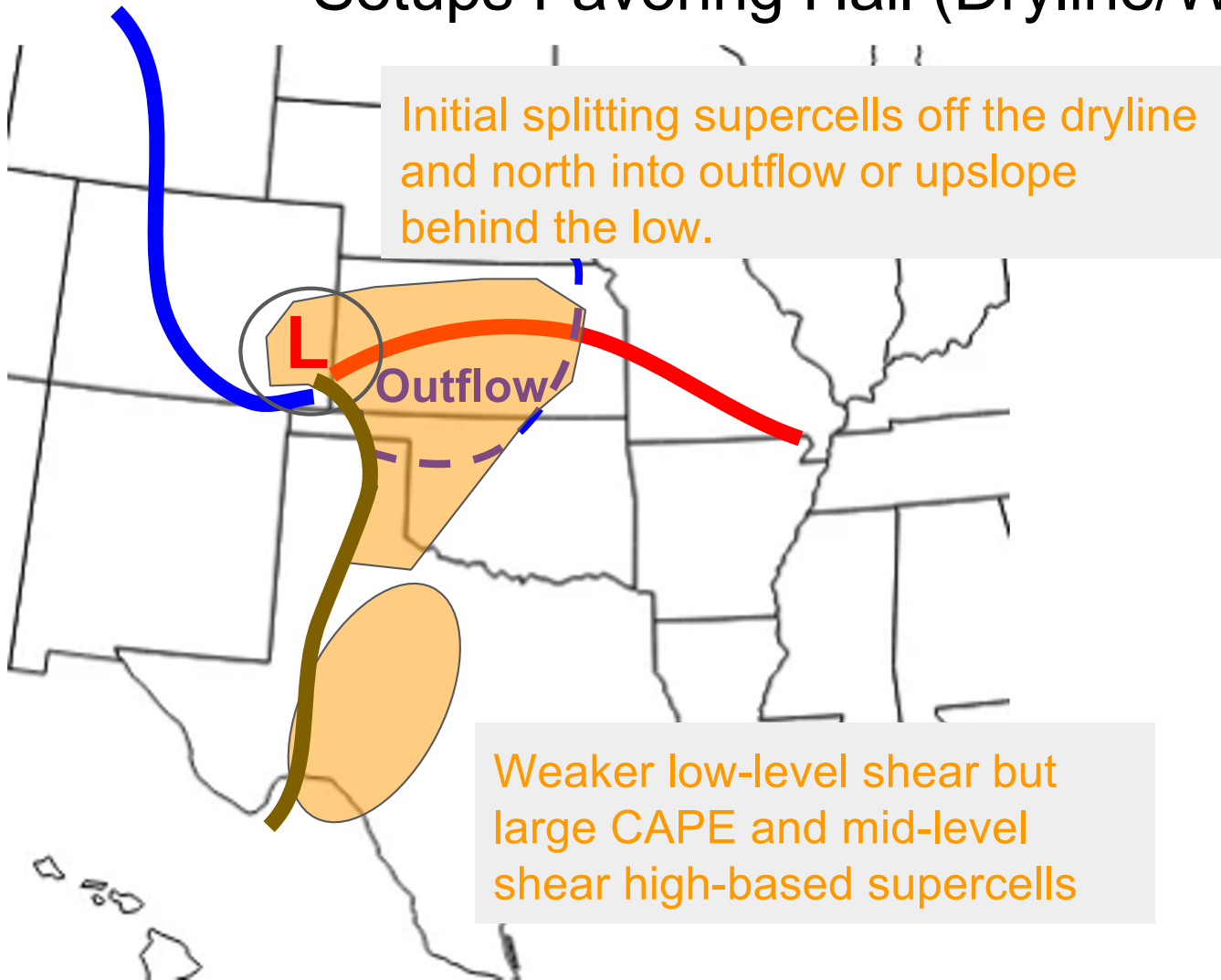


- Very classic setup for large hail along and north of the WF

Setups Favoring Hail (Stationary Front/Northwest Flow)



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.

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].

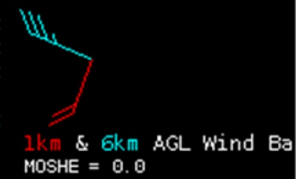
If $0-6 \text{ km BWD} < 14 \text{ m s}^{-1}$ or $\text{MUCAPE} < 400 \text{ J kg}^{-1}$, $\text{LHP} = 0$. If both the shear and MUCAPE are \geq to the above conditions (a loose supercell check):

$$\text{LHP} = (\text{TERM A} * \text{TERM B}) + 5$$

$\text{TERM A} = (((\text{MUCAPE}-2000)/1000) + ((3200-\text{THK}_{\text{HGZ}})/500) + ((\text{LR}_{75}-6.5)/2))$ 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.

$\text{TERM B} = (((\text{Shear}_{\text{EL}}-25)/5) + ((\text{GRW}_{\text{dirEL}}+5)/20) + ((\text{SRW}_{\text{dirMID}}-80)/10))$ 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, $\text{GRW}_{\text{dirEL}}$ 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 $\text{SRW}_{\text{dirMID}}$ is the directional difference between the mean storm-relative winds in the 3-6 km and 0-1 km layers.

PARCEL	CAPE	CIN	LCL	LI	LFC	EL	Sum2	SRH(m ² /s ²)	Shear(kt)	MnWind	SRW
SURFACE	6762	0	1021m	-13	1021m	47060'	SFC-1km	44	11	192/17	169/19
ML 100 mb	4505	-30	1251m	-10	2168m	45243'	SFC-2km	138	23	203/19	179/19
FCST SFC	5046	-1	1512m	-11	1935m	46114'	SFC-3km	186	27	216/20	193/19
MJ (973 mb)	6762	0	1021m	-13	1021m	47060'	Eff Inflow	157	26	209/19	187/19
EFF LAYER	2394	-87	2150m	-6	3107m	43550'	SFC-6km		40	240/21	218/17
USER DEF	2229	-112	2087m	-5	3168m	43550'	SFC-8km		45	250/20	233/15
PW = 1.751n	SCAPE = 44J/kg	WBZ = 12848'	WNDG = 0.76				LCL-EL(Cloud Layer)		40	271/24	265/17
K = 36	DCAPE = 1423J/kg	FZL = 14122'	ESP = 0.27				Eff Shear(EBWD)		41	246/20	226/16
MidRH = 56%	DownT = 62F	ConvT = 93F	MMP = 0.97				BRN Shear =		37 m ² /s ²		
LowRH = 64%	MeanW = 17.1g/kg	MaxT = 93F	NCAPE = 0.51				4-6km SR Wind =		274/24 kt		
sfc-3km Agl LapseRate=	22C/7.3C/km						Corfidi Downshear =		296/52 kt		
3-6km Agl LapseRate=	22C/7.2C/km						Corfidi Upshear =		314/29 kt		
850-500mb LapseRate=	30C/6.9C/km						Bunkers Right =		285/7 kt		
700-500mb LapseRate=	20C/7.3C/km						Bunkers Left =		243/34 kt		
							STP(eff)LR =		0.0		
							Supercell=		21.3		
							STP(eff)=		2.6		
							STP(fixed)=		1.3		
							SHIP=		2.7		
							LGHAIL =		25.0		



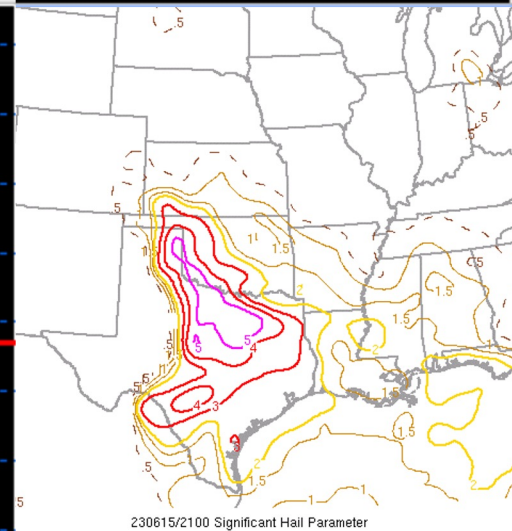
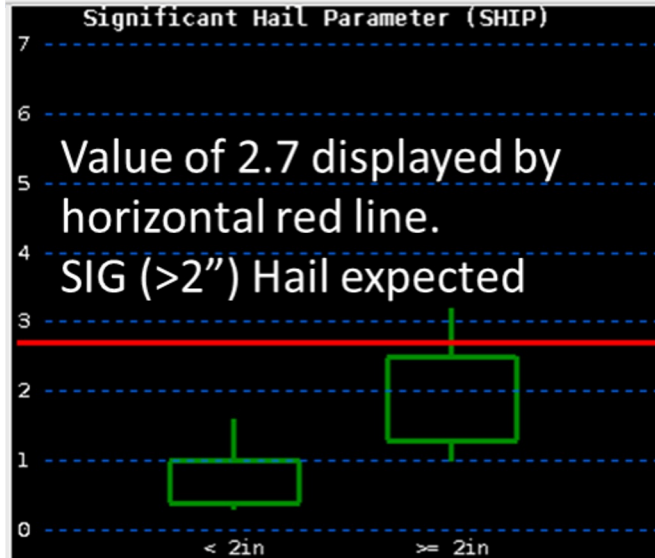
Hail Parameters

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 ($\geq 2''$ diameter) and NON-SIG ($< 2''$ diameter) hail environments.

PARCEL	CAPE	CIN	LCL	LI	LFC	EL	Sum2	SRH(m ² /s ²)	Shear(kt)	MnWind	SRW
SURFACE	6762	0	1021m	-13	1021m	47060'	SFC-1km	44	11	192/17	169/19
M_100 mb	4505	-30	1251m	-10	2168m	45243'	SFC-2km	138	23	203/19	179/19
FCST SFC	5046	-1	1512m	-11	1935m	46114'	SFC-3km	186	27	216/20	193/19
MU (973 mb)	6762	0	1021m	-13	1021m	47060'	Eff Inflow	157	26	209/19	187/19
EFF LAYER	2394	-87	2150m	-6	3107m	43550'	SFC-6km	40	40	240/21	218/17
USER DEF	2229	-112	2087m	-5	3168m	43550'	SFC-8km	45	45	250/20	233/15
PW = 1.751n	SCAPE = 44J/kg	WBZ = 12848'	WINDG = 0.76				LCL-EL(Cloud Layer)	40	40	271/24	265/17
K = 36	DCAPE = 1423J/kg	FZL = 14122'	ESP = 0.27				Eff Shear(EBWD)	41	41	246/20	226/16
MidRH = 56%	DownT = 62F	ConvT = 93F	MMP = 0.97				BRN Shear =		37 m ² /s ²		
LowRH = 64%	MeanW = 1.7g/kg	MaxT = 93F	NCAPE = 0.51				4-6km SR Wind =		274/24 kt		
sfc-3km Agl LapseRate=	22C/7.3C/km	Supercell=	21.3				Corfidi Downshear =		296/52 kt		
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850-500mb LapseRate=	30C/6.9C/km	STP(fixed)=	1.3				Bunkers Right =		285/7 kt		
700-500mb LapseRate=	20C/7.3C/km	SHIP=	2.7				Bunkers Left =		243/34 kt		
							STP(eff)LR =		0.0		
							LGHAIL =		25.0		

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



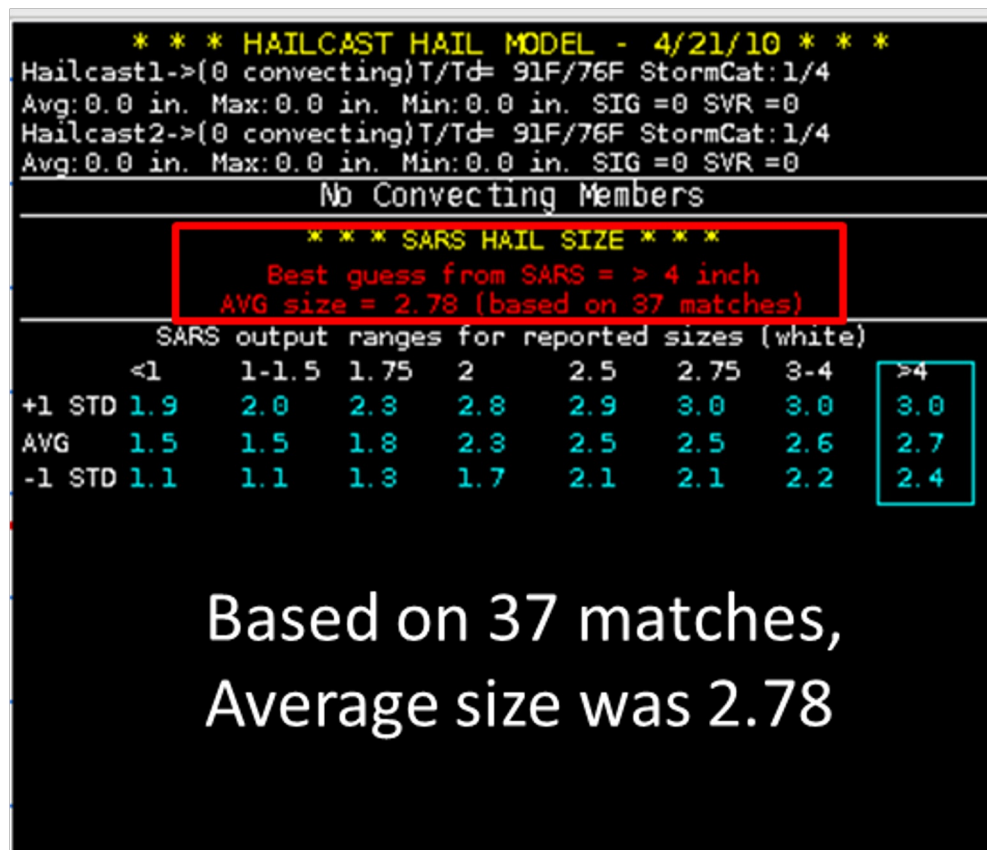
Hail Parameters

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.

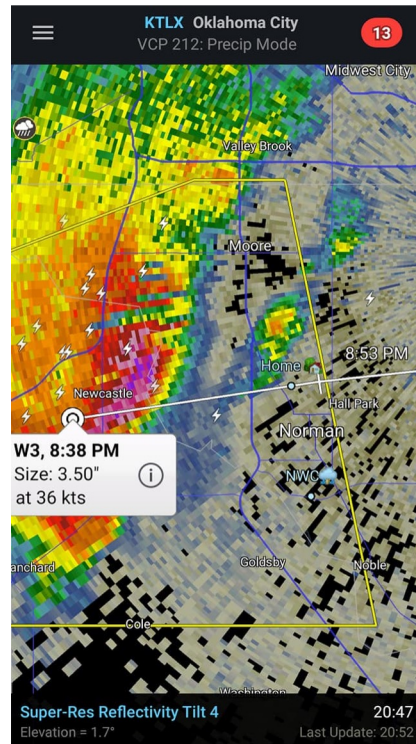
This graphic shows the "best guess" maximum hail report.

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.



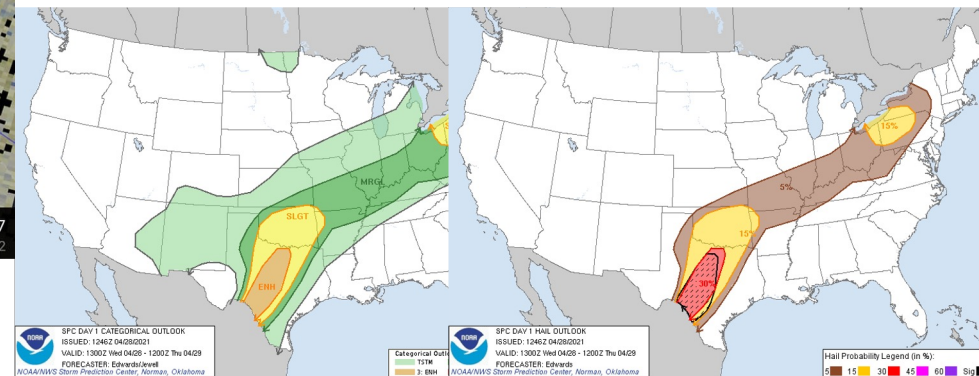
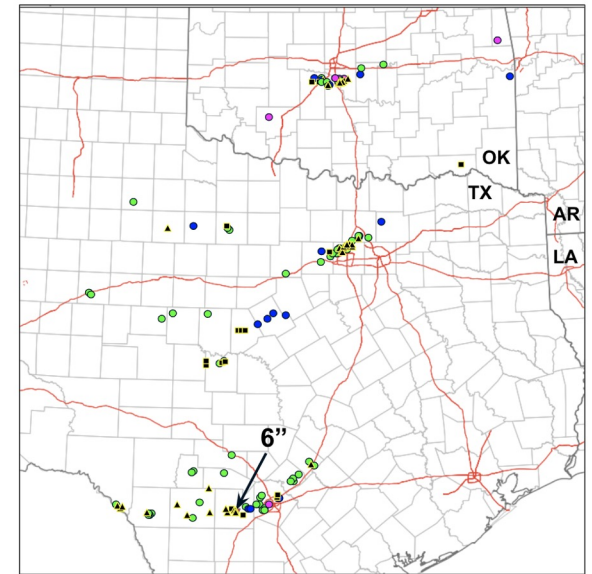
April 28 2021 Norman Hail Storm

- 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!

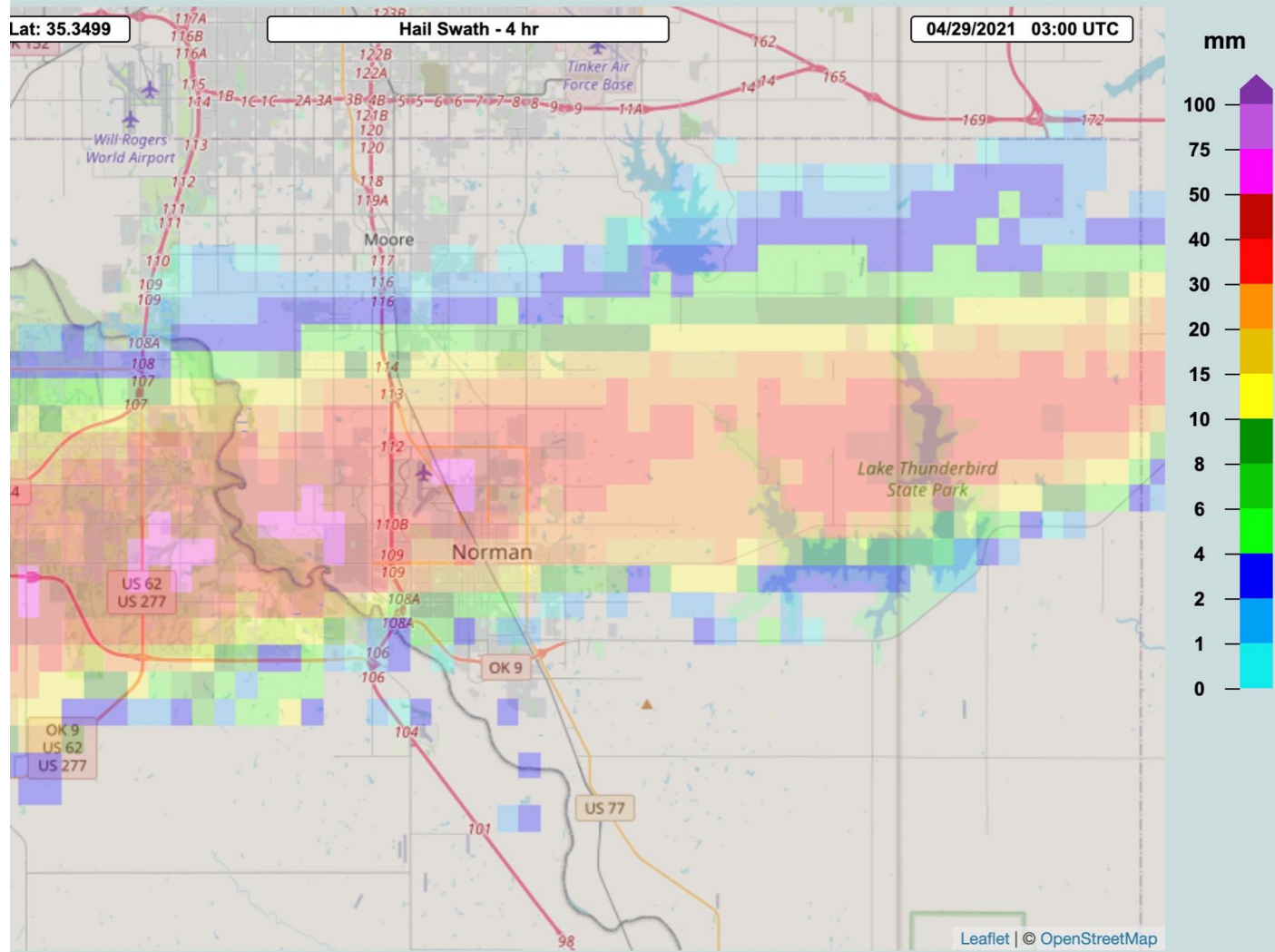


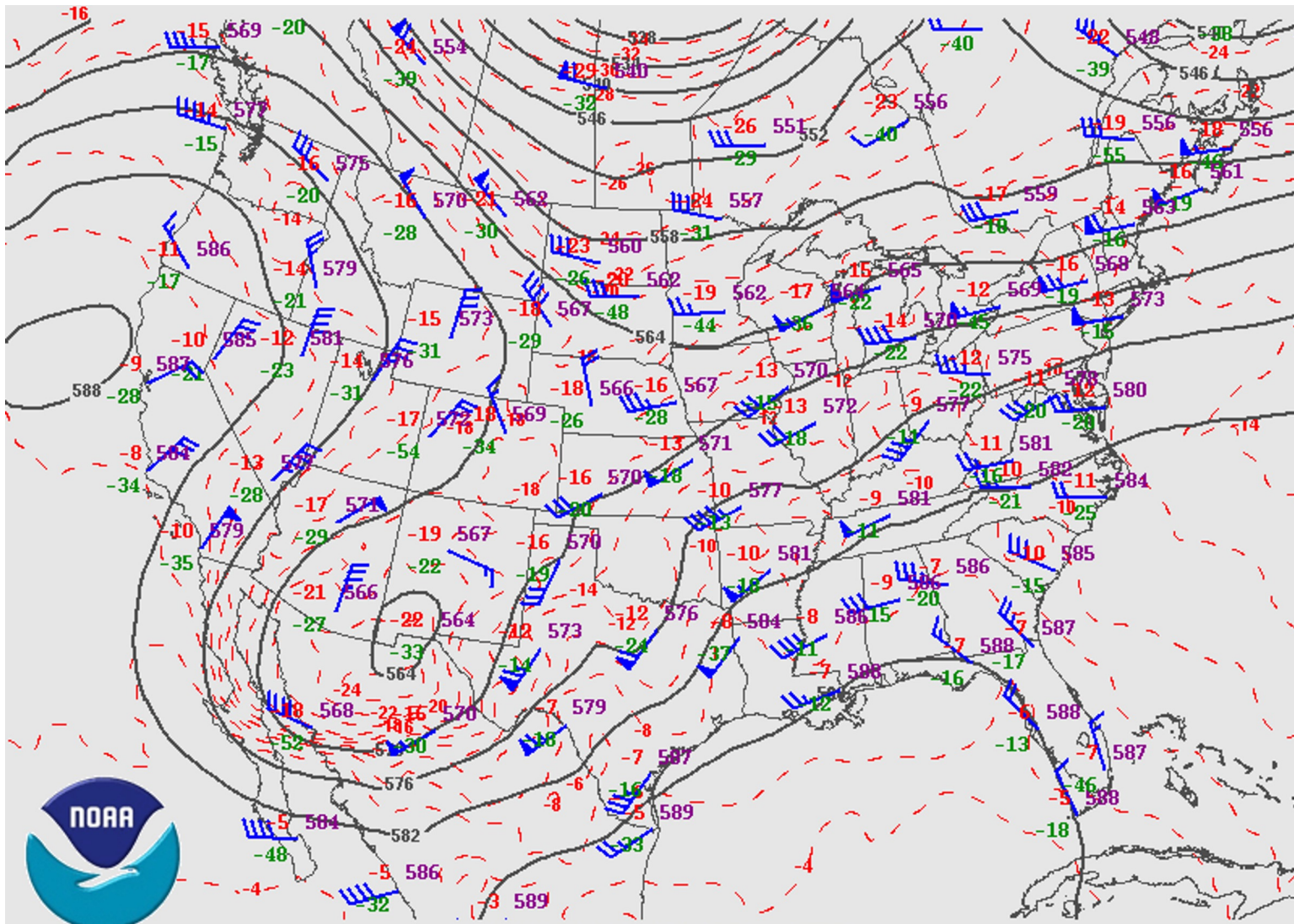
Local Storm Reports in the WoFS domain (4/28/21)

- Severe Hail
- ▲ Significant Severe Hail (> 2 inch diameter)
- Severe Wind
- Significant Severe Wind (> 65 knots)
- ▼ Tornado
- Flash Flooding



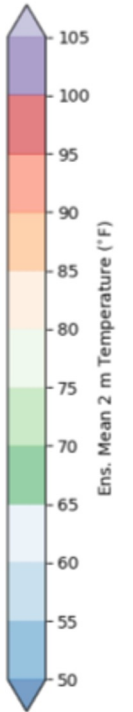
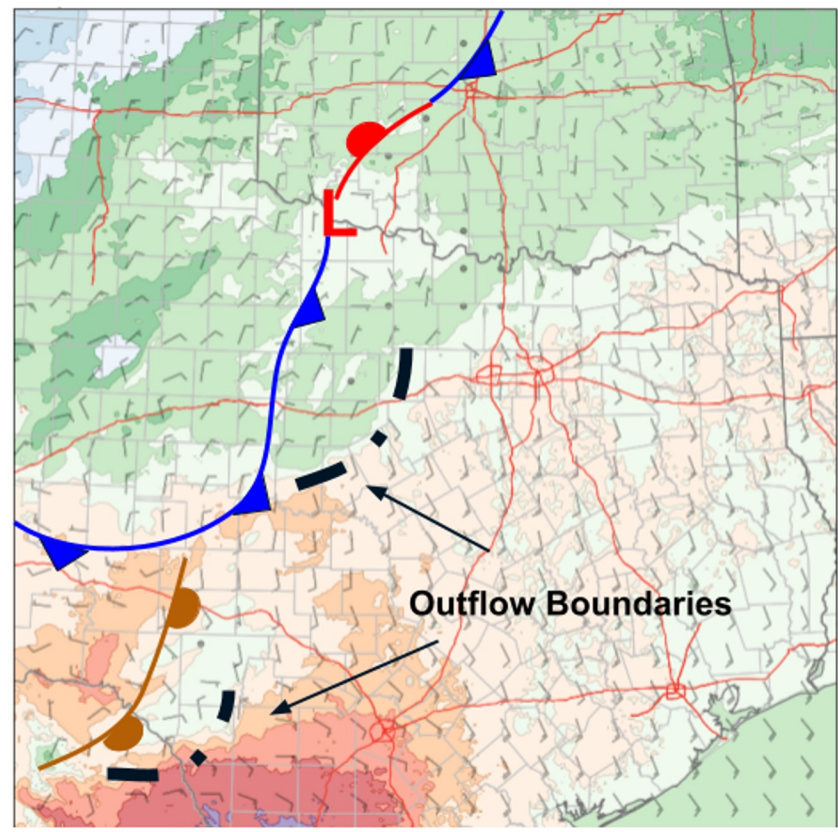
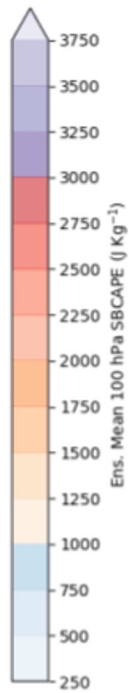
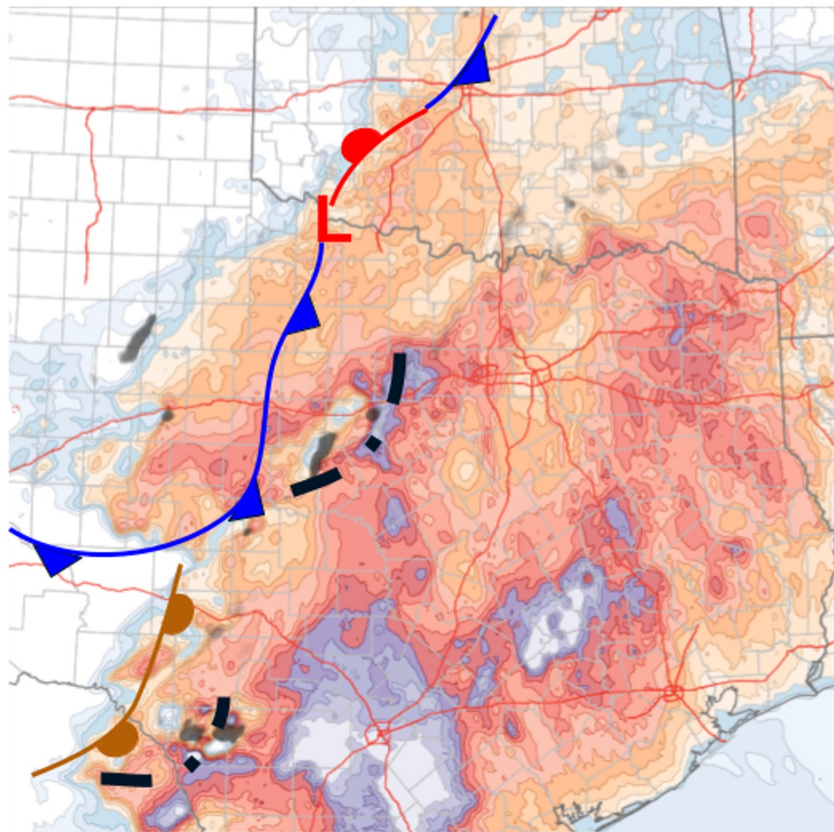
Operational Product Viewer

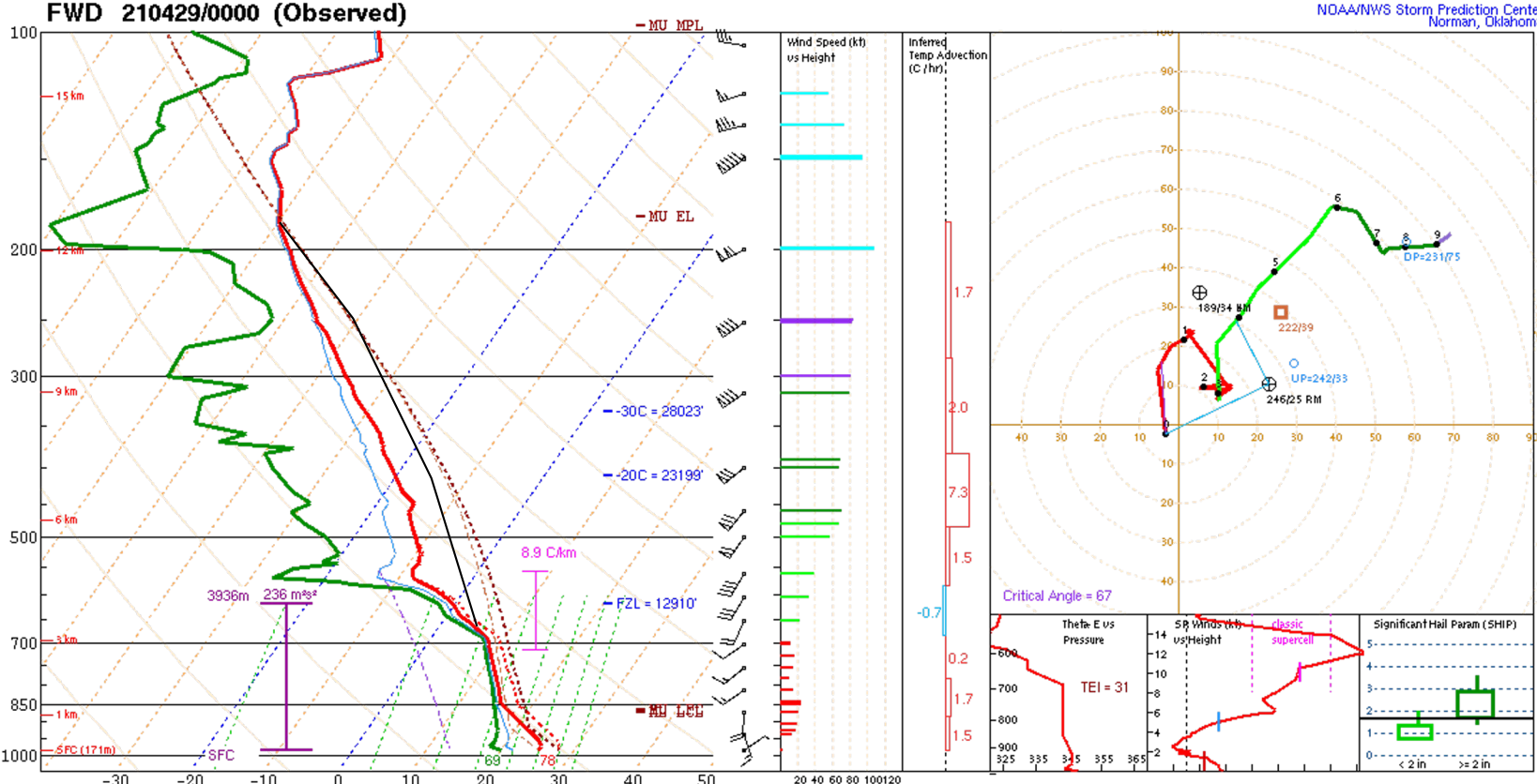




National Weather Service
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210429/0000 500 MB UA OBS, HGHTS, and TEMPS





Storm was potentially elevated!

OUN sounding missing I wonder why :)

PARCEL	CAPE	CINH	LCL	LI	LFC	EL
SURFACE	2176	-40	666m	-8	1147m	41619'
MIXED LAYER	1782	-13	1044m	-7	1286m	40840'
FCST SURFACE	2496	0	1404m	-9	1404m	42191'
MU (983 mb)	2176	-40	666m	-8	1147m	41619'

PW = 1.79 in	3CAPE = 22 J/kg	WBZ = 12387'	WINDG = 0.0
K = 42	DCAPE = 1483 J/kg	FZL = 12910'	ESP = 0.0
MidRH = 94%	DownT = 56 F	ConvT = 82F	MMP = 0.94
LowRH = 81%	MeanW = 14.2 g/kg	MaxT = 86F	NCAPE = 0.19
SigSevere = 66487 m3/s3			

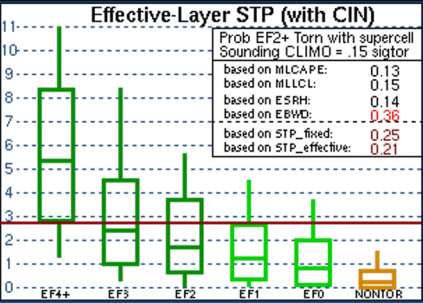
3fc-3km Agl Lapse Rate = 5.8 C/km	
3-6km Agl Lapse Rate = 7.2 C/km	
850-500mb Lapse Rate = 6.4 C/km	
700-500mb Lapse Rate = 7.5 C/km	

Supercell = 10.3
Left Supercell = -0.4
STP (eff layer) = 2.7
STP (fix layer) = 2.7
Sig Hail = 1.6

SRH(m2/s2)	Shear(kt)	MnWind	SRW
SFC - 1 km	187	24	168/13
SFC - 3 km	159	17	197/13
Eff Inflow Layer	236	34	200/15
SFC - 6 km	72	206/21	117/17
SFC - 8 km	77	212/26	141/15
LCL - EL (Cloud Layer)	98	220/36	180/17
Eff Shear (EBWD)	74	207/22	126/16
BRN Shear = 44 m/s²			
4-6km SR Wind = 182/28 kt			
Storm Motion Vectors			
Bunkers Right = 246/25 kt			
Bunkers Left = 189/34 kt			
Corfidi Downshear = 231/75 kt			
Corfidi Upshear = 242/33 kt			

*** BEST GUESS PRECIP TYPE ***
Rain.
 Based on sfc temperature of 77.7 F.

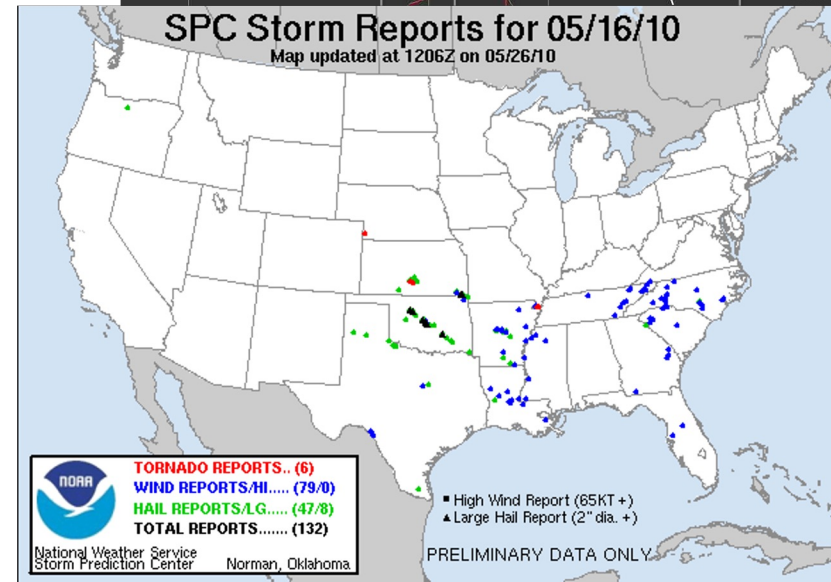
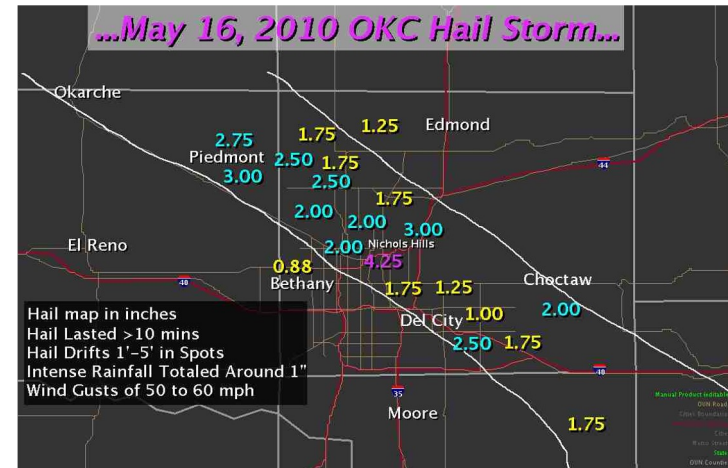
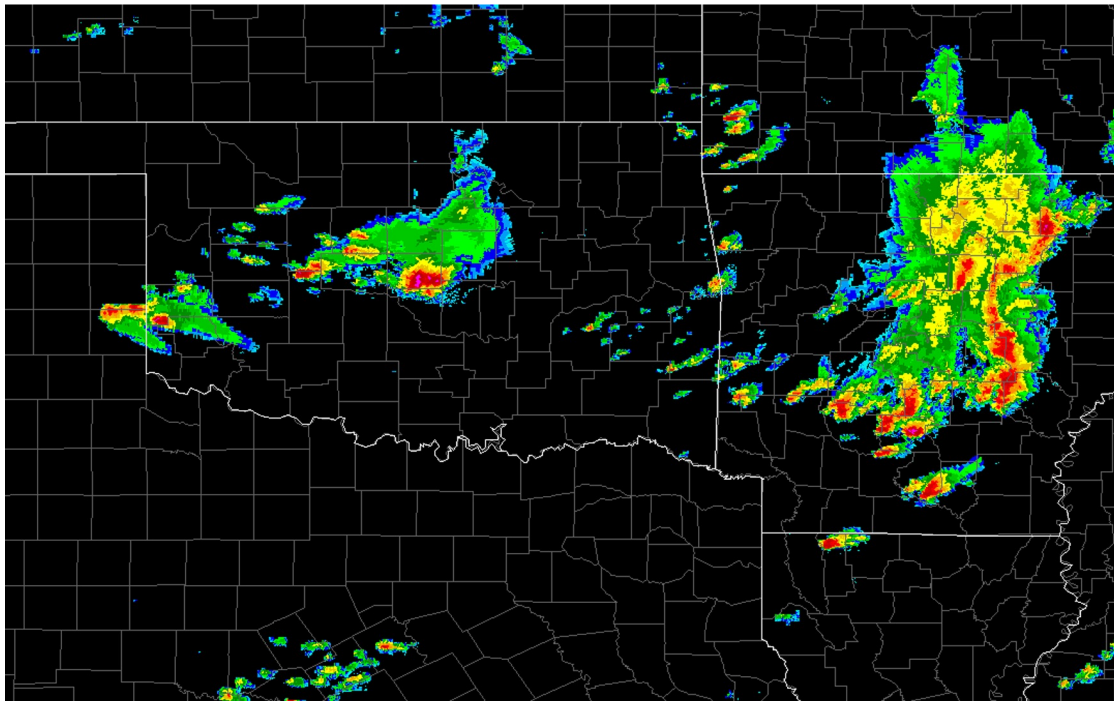
SARS - Sounding Analogs	
SUPERCELL	SGFNT HAIL
No Quality Matches	No Quality Matches
(5 loose matches) SARS: 100% TOR	(9 loose matches) SARS: 67% SIG



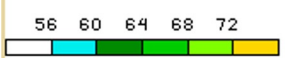
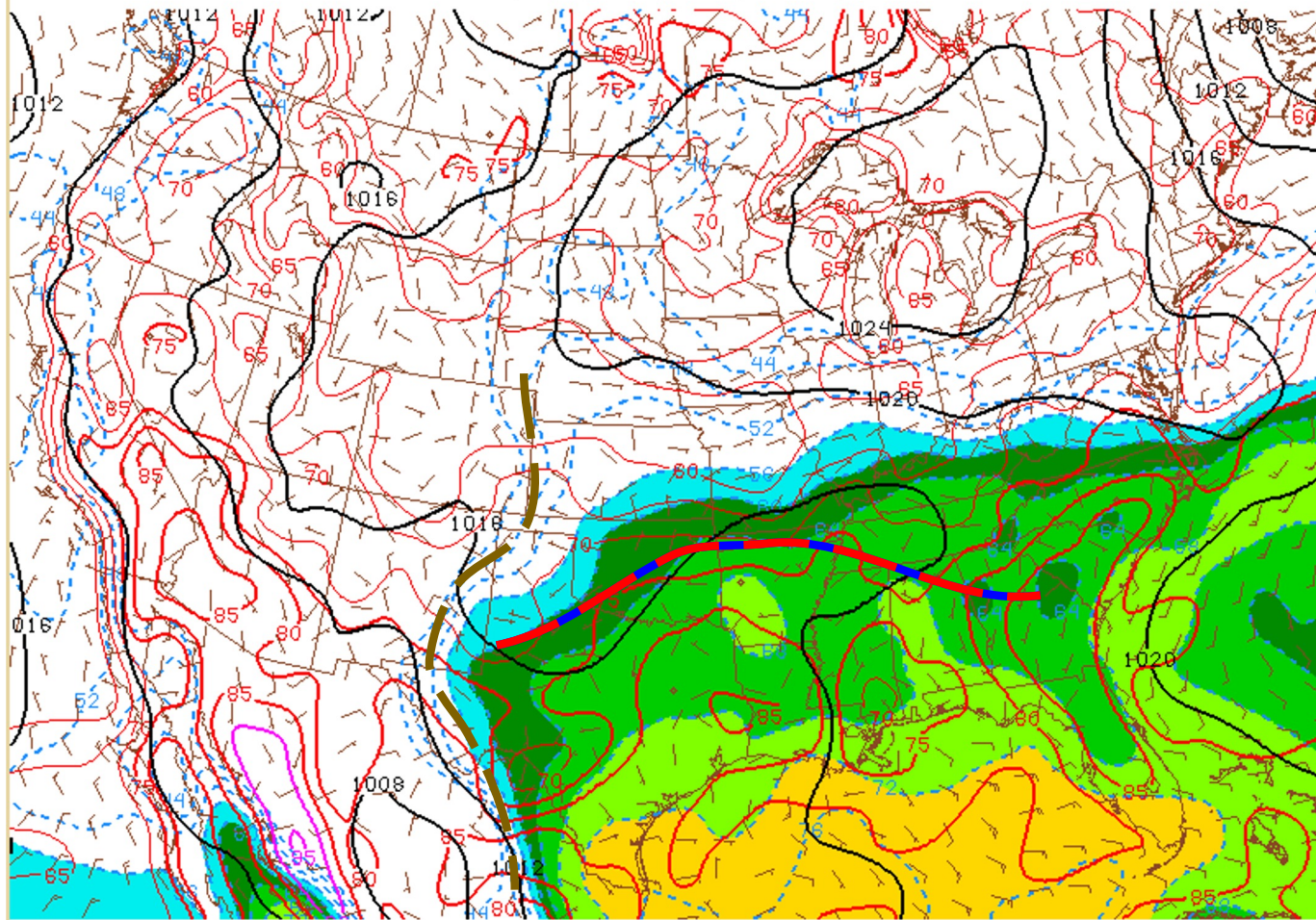


May 16, 2010 OKC Hail Storm

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



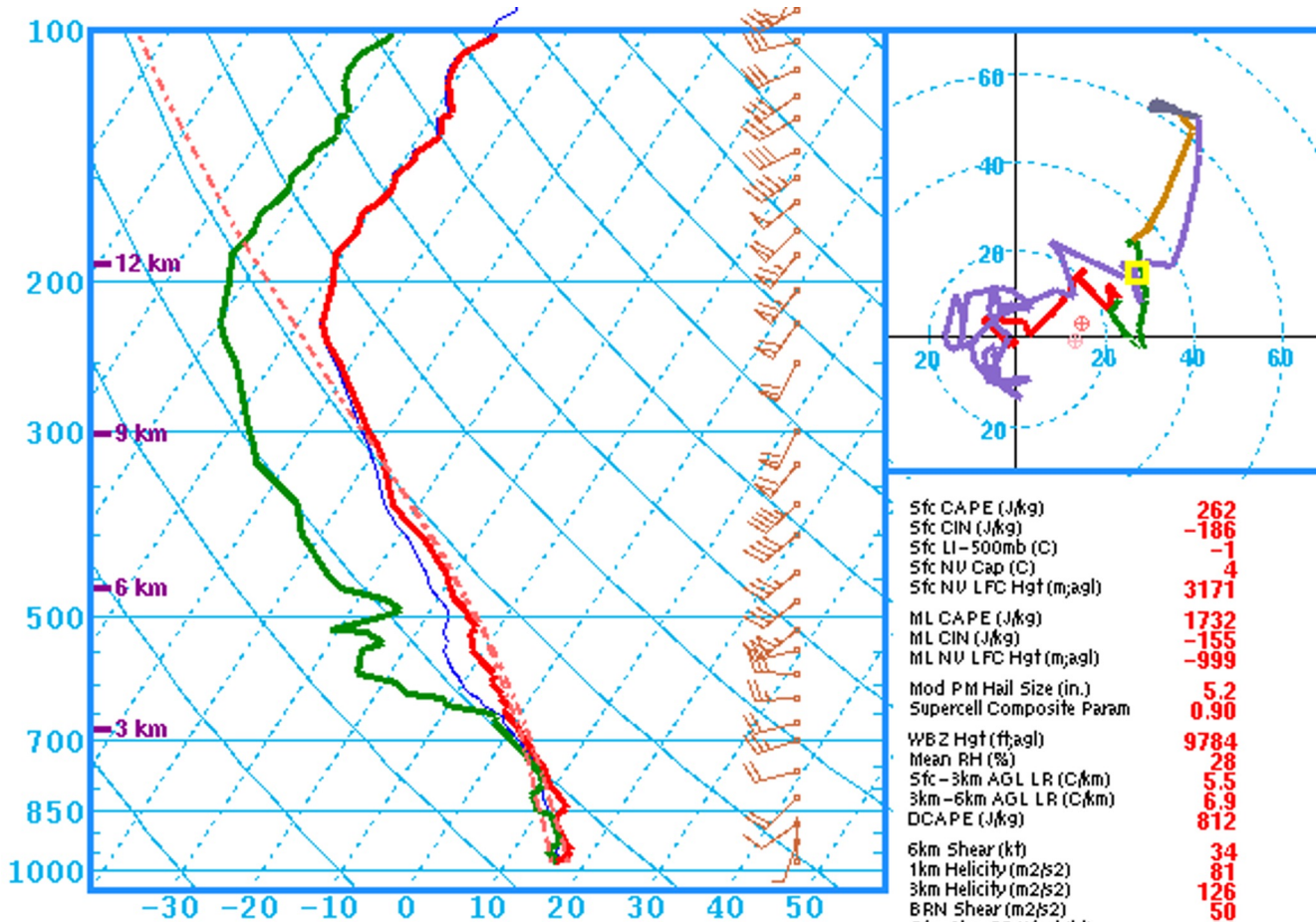
< > Start Rock Refresh



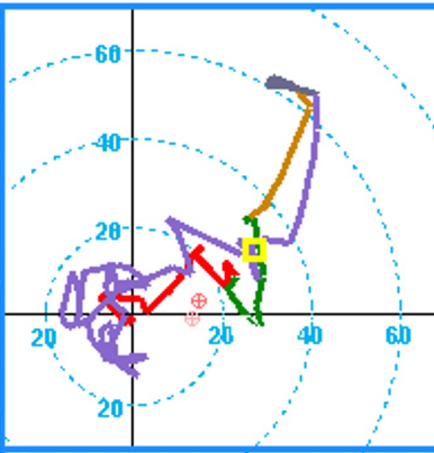
100516/1800 Surface temp, dewpoint, and pms1

- + Zoom

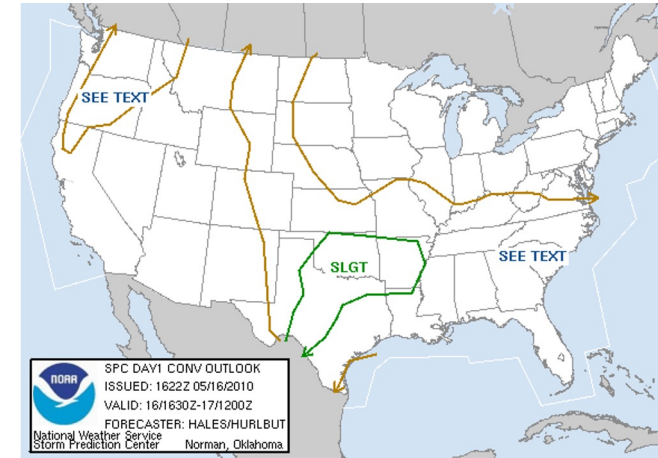




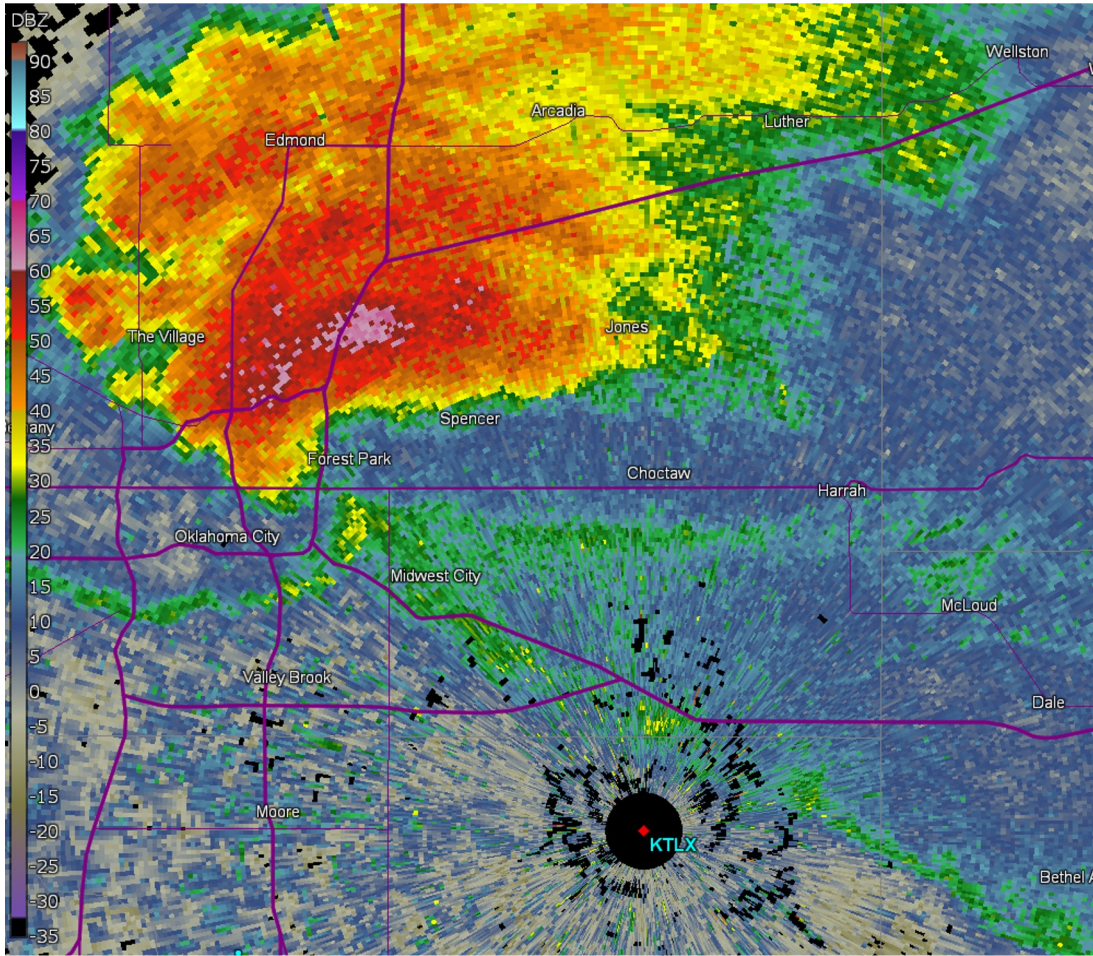
OUN – 100516/1200
OBSERVED Sounding



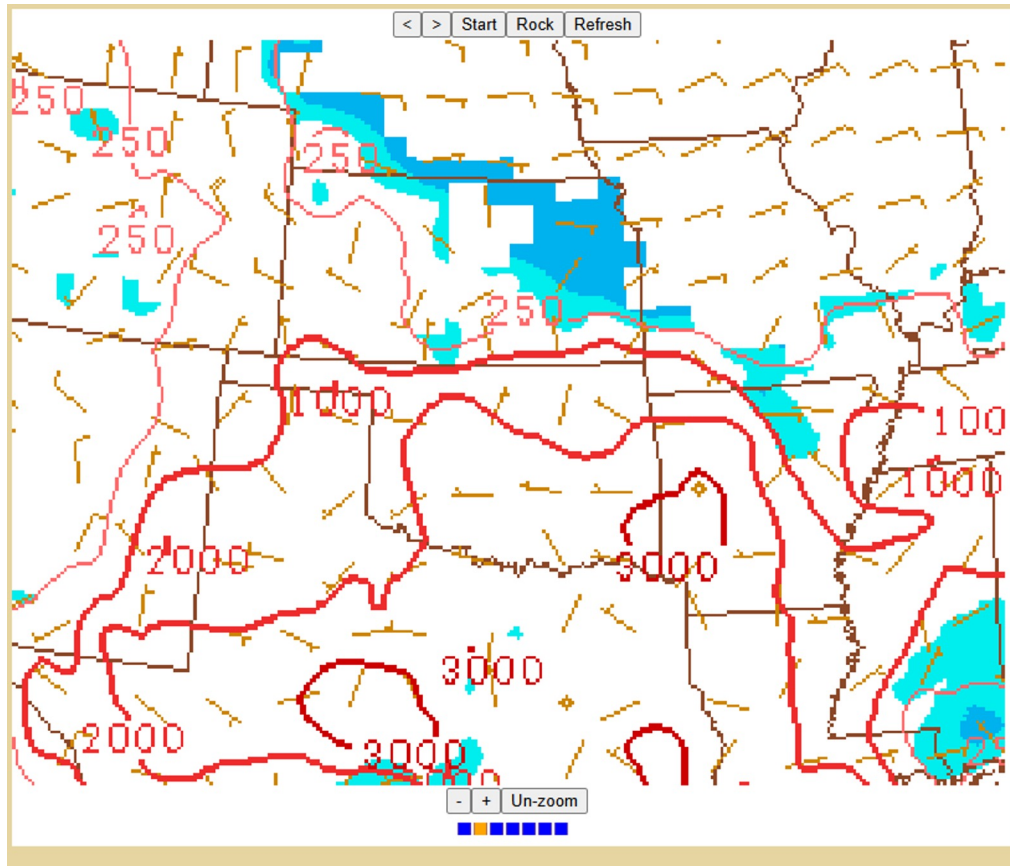
Sfc CAPE (J/kg)	262
Sfc CIN (J/kg)	-186
Sfc LI-500mb (C)	-1
Sfc NU Cap (C)	4
Sfc NU LFC Hgt (m;agl)	3171
ML CAPE (J/kg)	1732
ML CIN (J/kg)	-155
ML NU LFC Hgt (m;agl)	-999
Mod PM Hail Size (in.)	5.2
Supercell Composite Param	0.90
WBZ Hgt (ft;agl)	9784
Mean RH (%)	28
Sfc-3km AGL LR (C/km)	5.5
3km-6km AGL 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

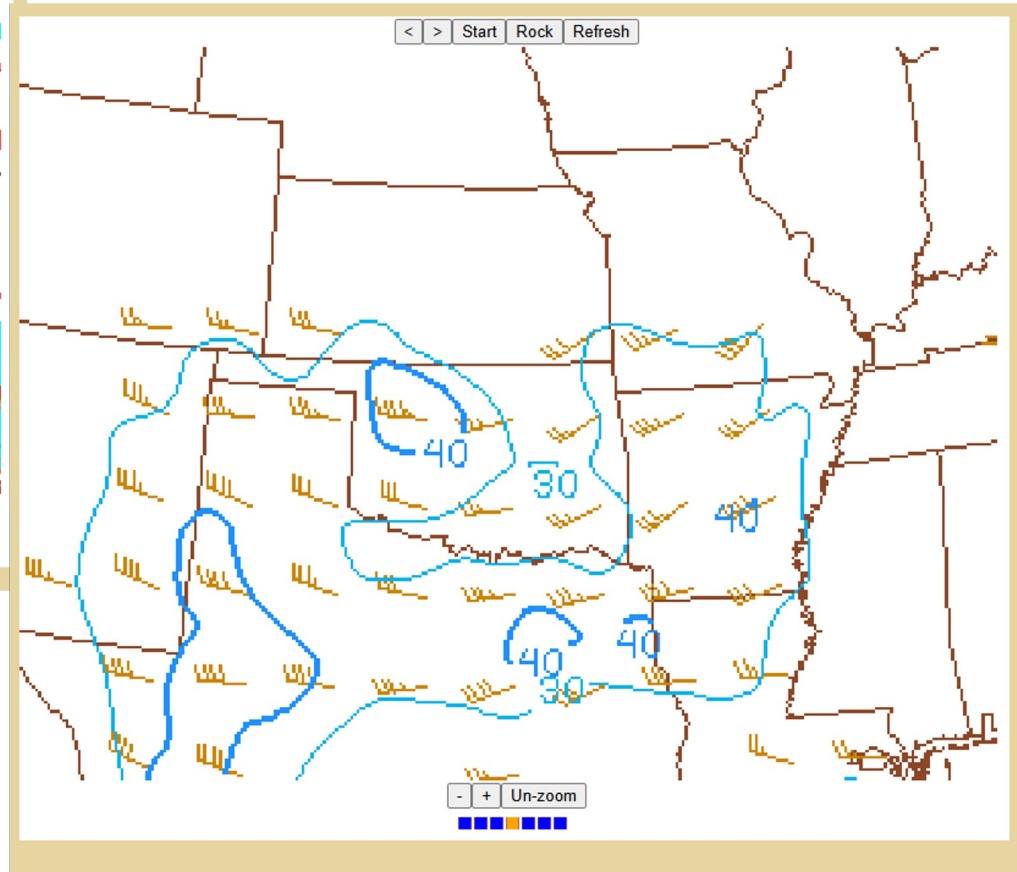


- Storm was elevated north of the front!!



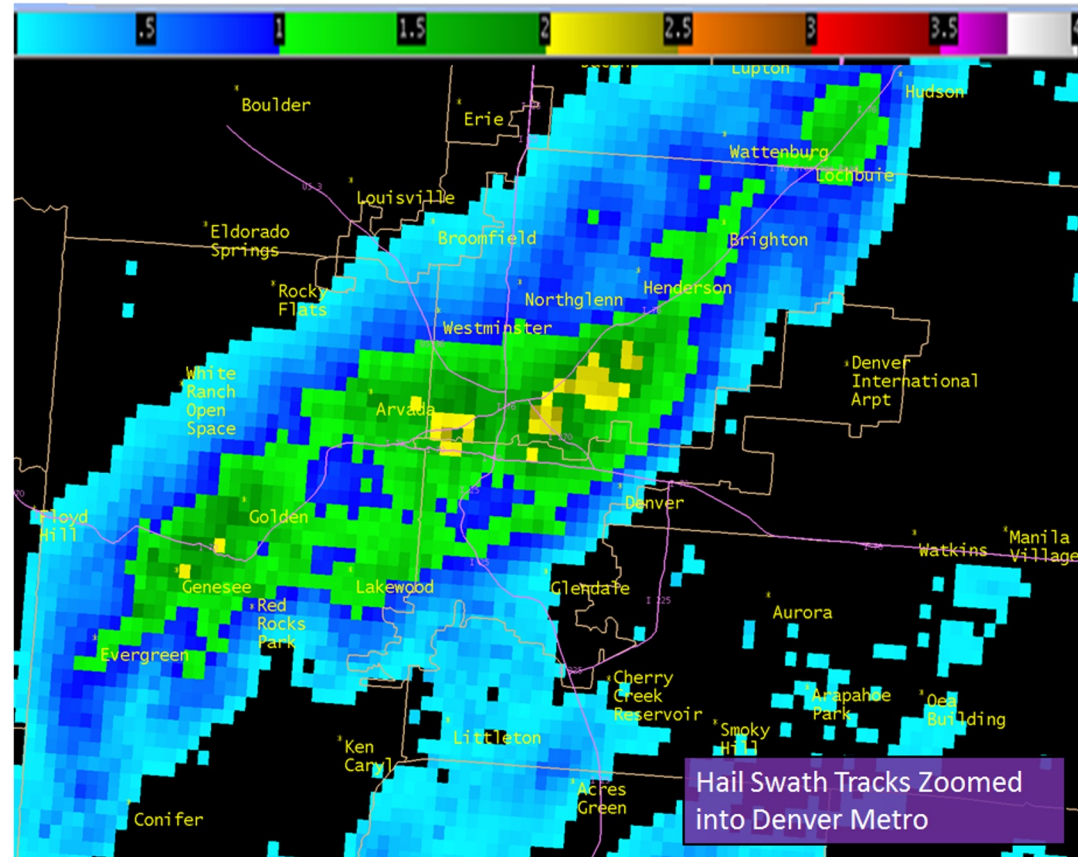
SBCAPE

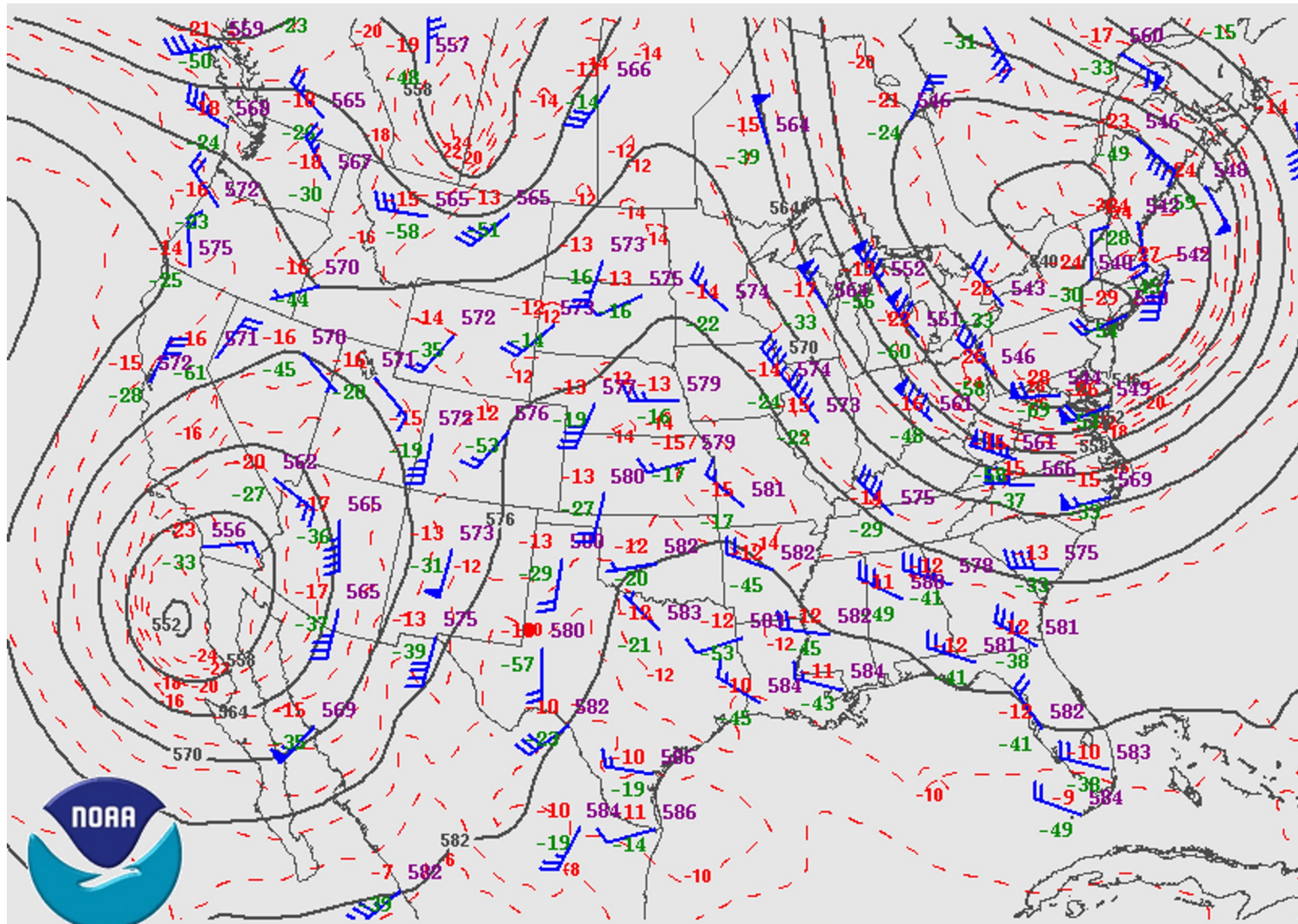
EFFECTIVE SHEAR



May 8, 2017 Denver Hail Storm

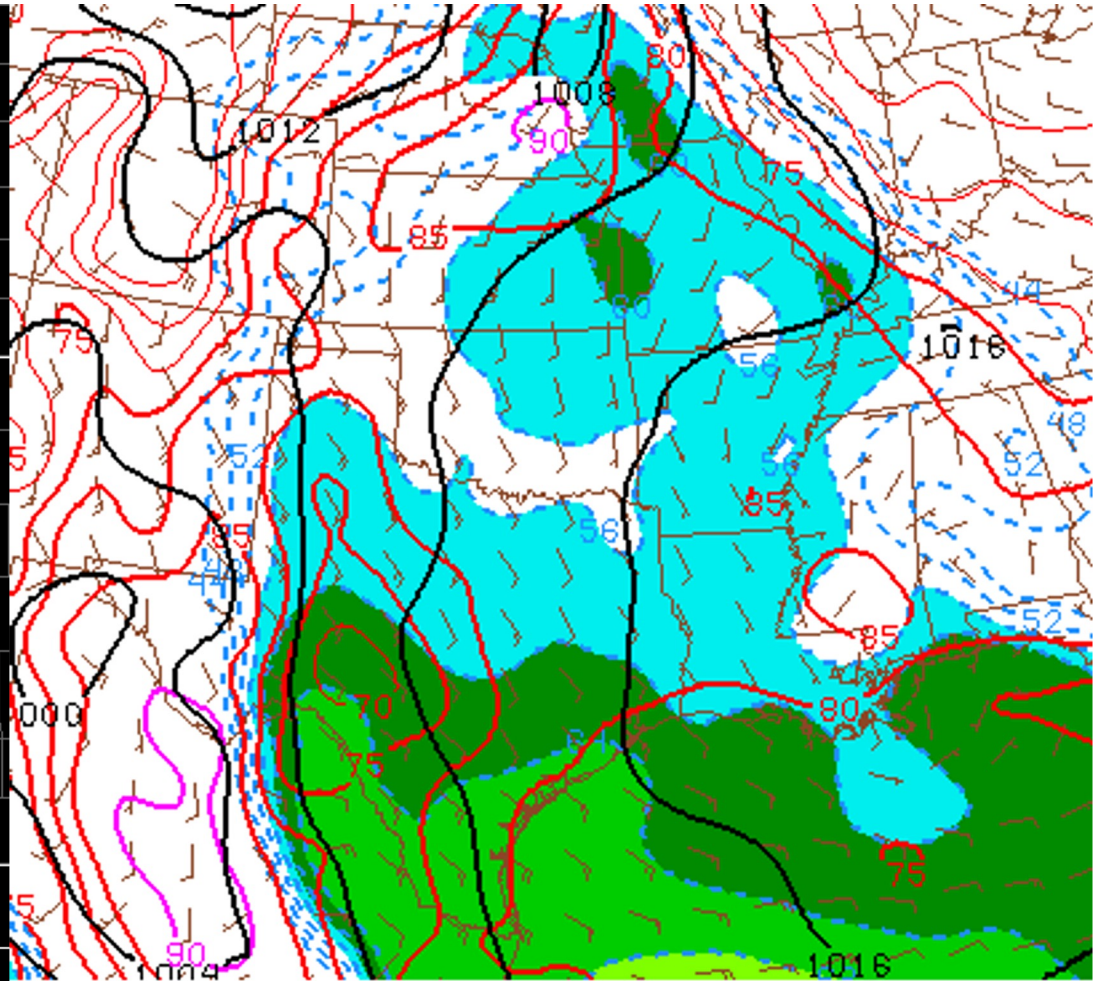
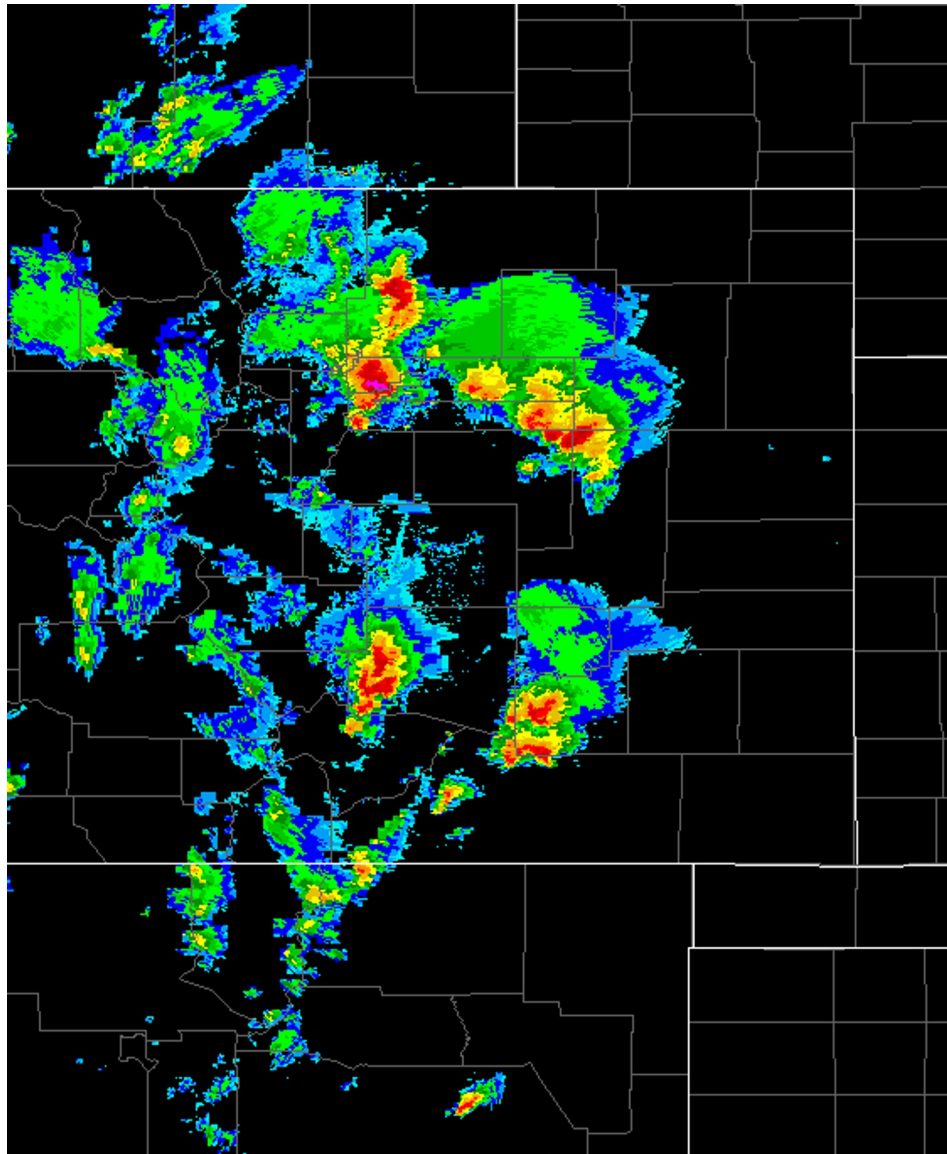
- \$2.3 Billion dollars in damage through the heart of downtown Denver.
- Several elevated supercells north of a stationary front.
- Numerous reports of golf ball and 2 inch wind driven hail.





National Weather Service
Storm Prediction Center

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



170508/2100 Surface temp, dewpoint, and pmsl

- + Zoom