Analysis of Three-Body Scattering Signatures for Use in Hail Size Estimation

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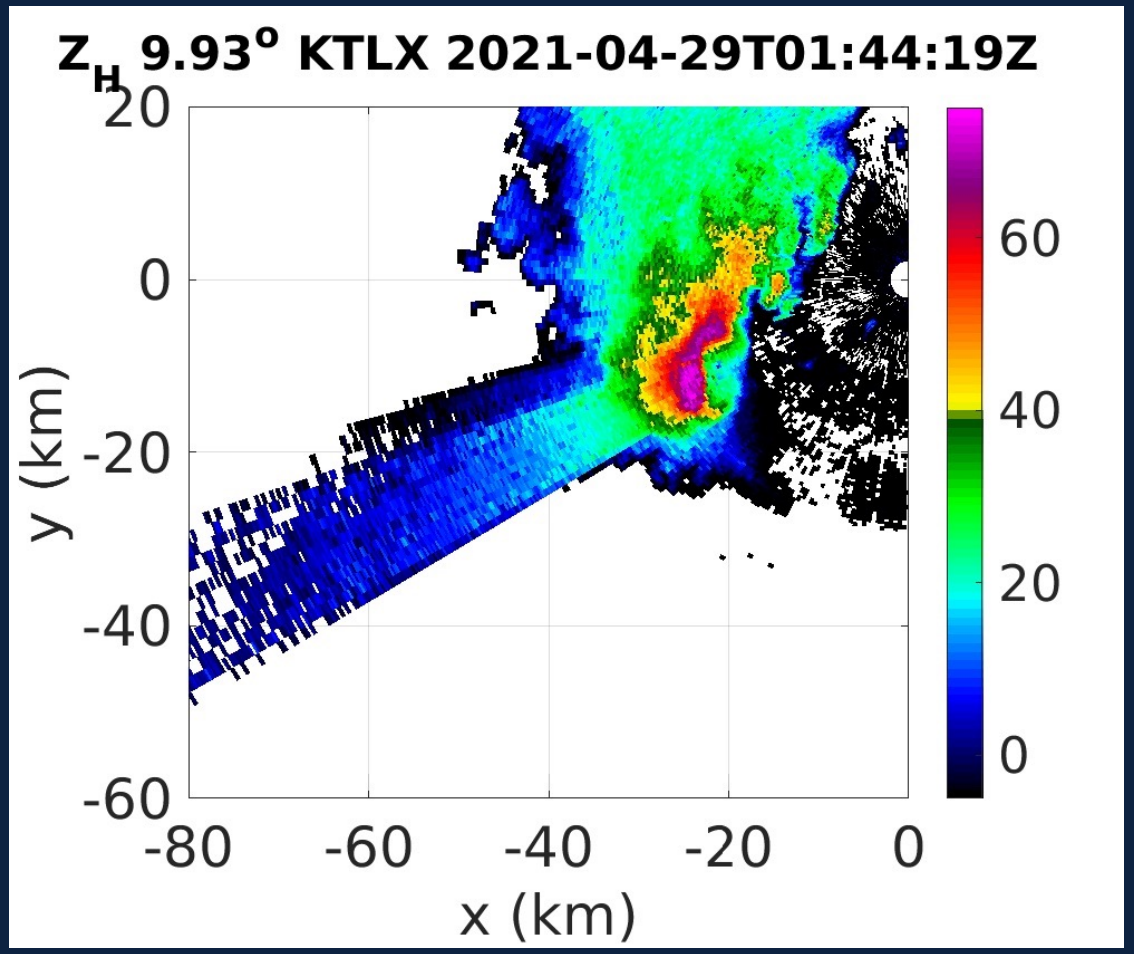
Three-Body Scattering Signature (TBSS; Zrnić 1987)

- Weak reflectivity “spike” or “flare”
- Colloquially referred to as “hail spike”
- Often used to infer the existence of severe hail for NWS forecasting



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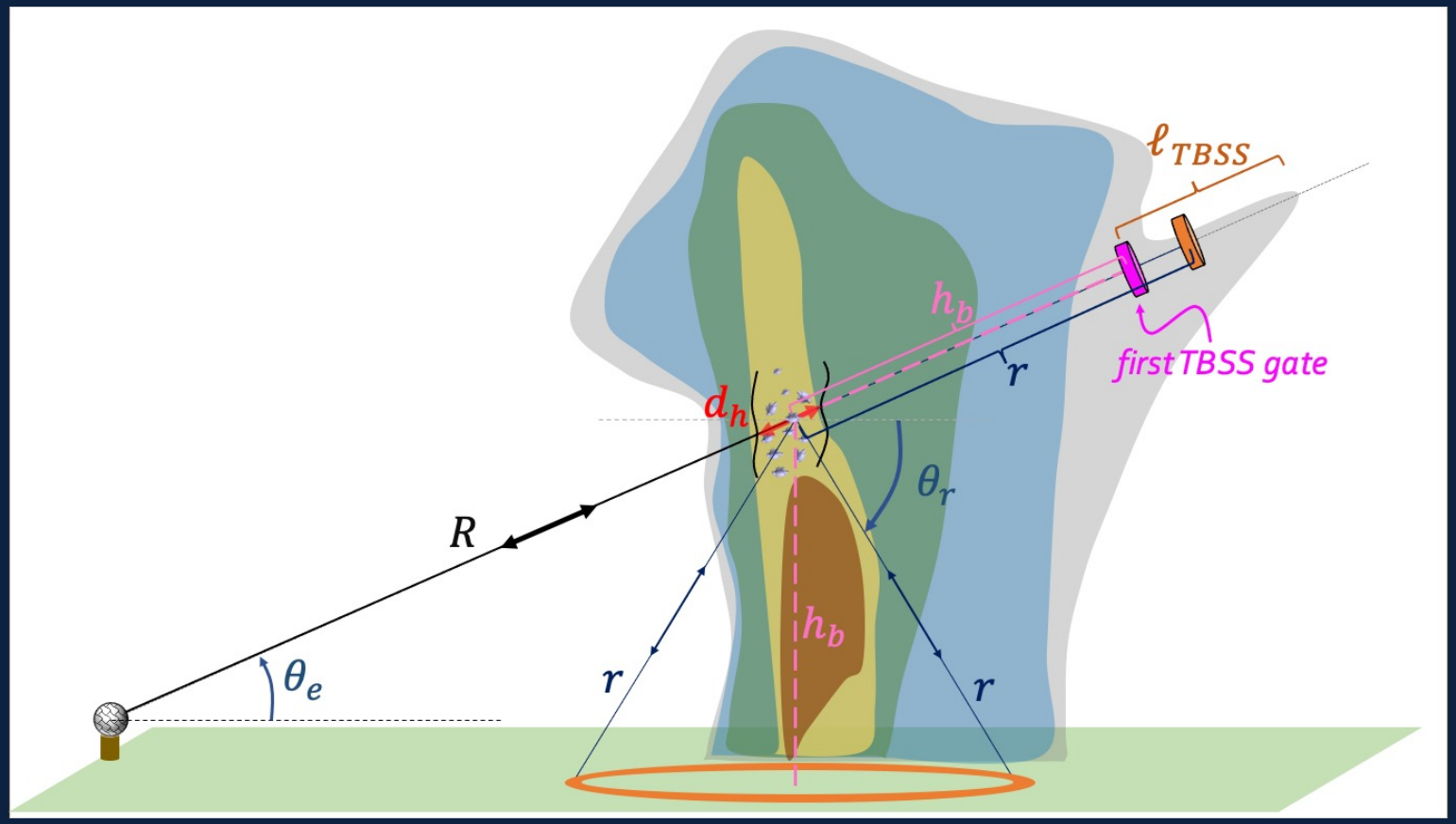
Schematic of Three-Body Scattering Signature

TBSS is EM radiation scattered:

(1) from high-reflectivity core to the ground,

(2) from the ground back to the high-reflectivity core, and then

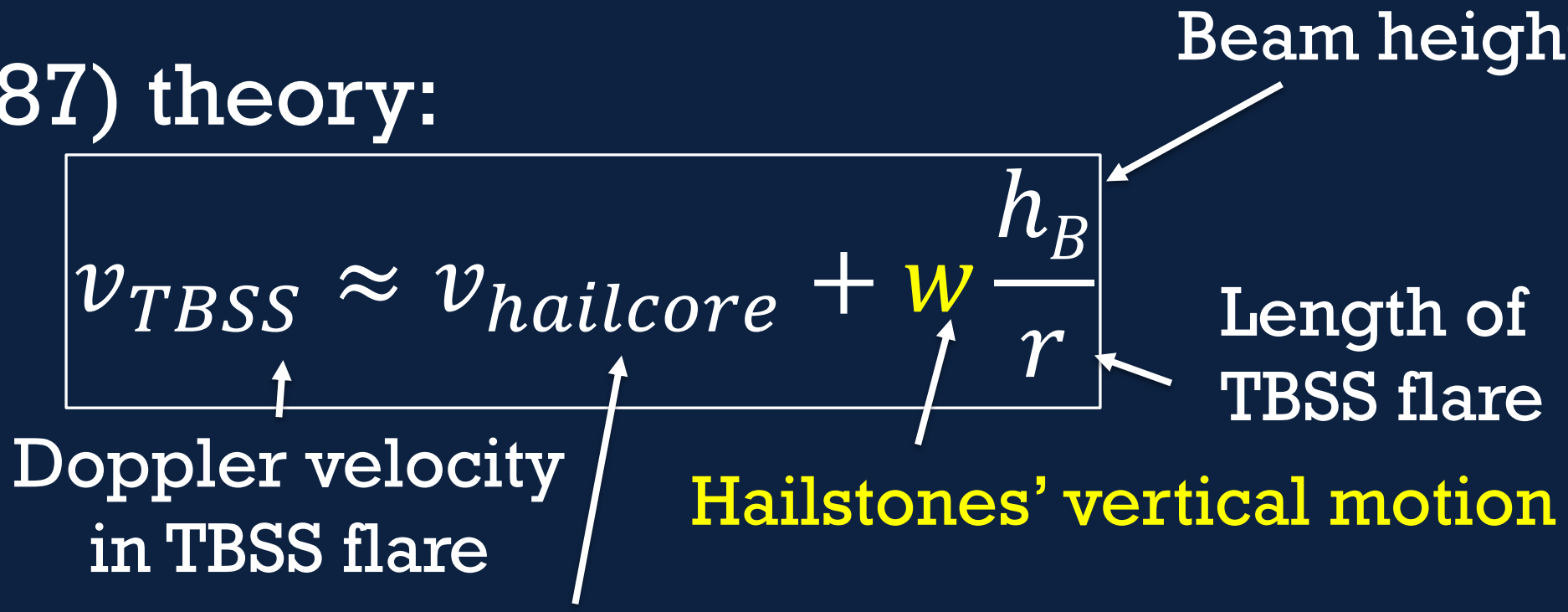
(3) from high-reflectivity core back to radar antenna.



(VanAlstine & Kumjian 2022)

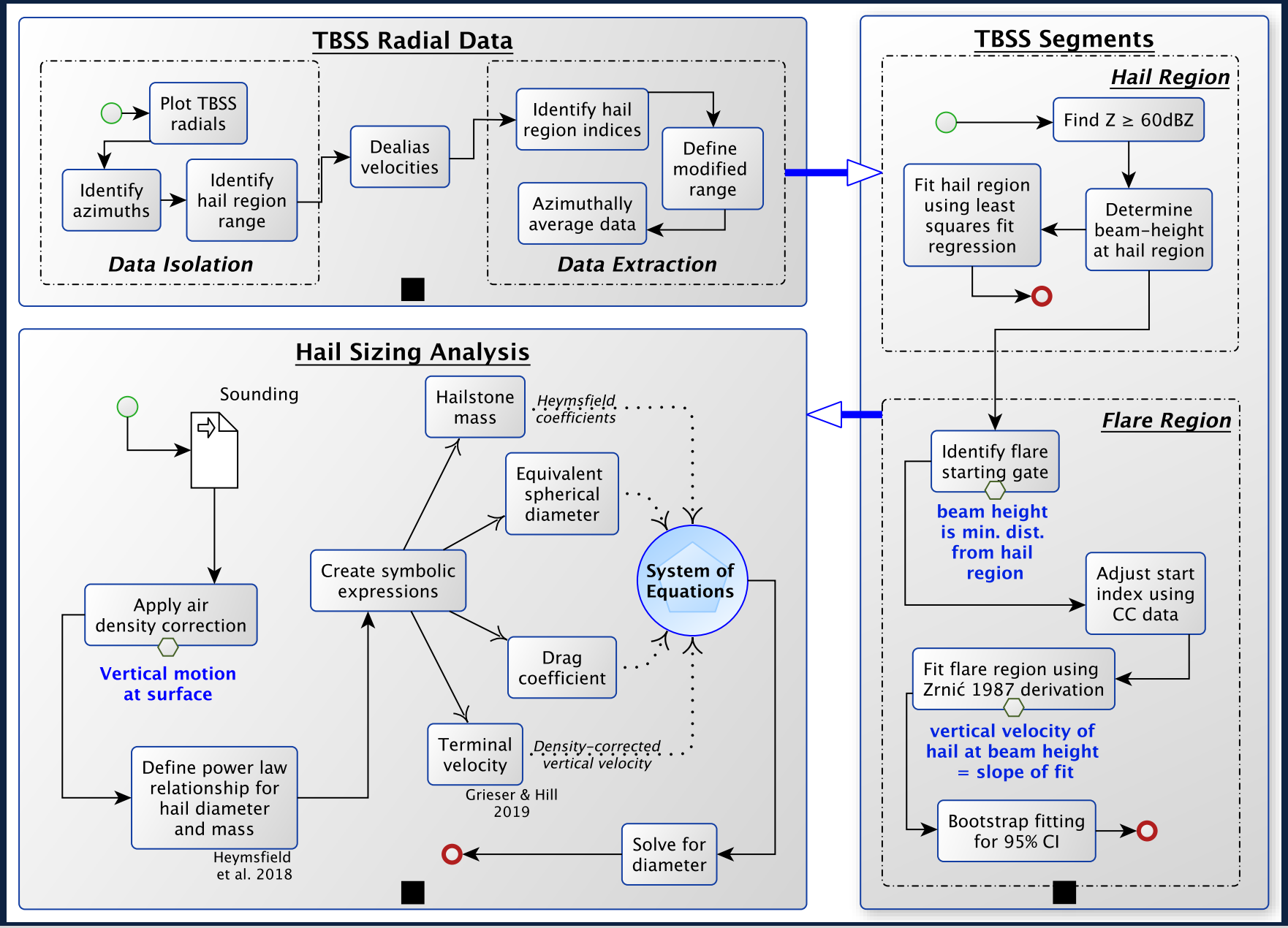
Utility of TBSS to estimate hail size?

Zrnić (1987) theory:



Hailstone fall speed increases monotonically with size (e.g., Heymsfield et al. 2018)

HYPOTHESIS: The Doppler velocity in TBSS is related to hailstone size


TBSS Radial Data
Plot TBSS radials
Identify azimuths
Identify hail region range
Data Isolation
Dealias velocities
Identify hail region indices
Define modified range
Azimuthally average data
Data Extraction
TBSS Segments
Hail Region
Find Z ≥ 60dBZ
Determine beam-height at hail region
Fit hail region using least squares fit regression
Flare Region
Identify flare starting gate
beam height is min. dist. from hail region
Adjust start index using CC data
Fit flare region using Zrnić 1987 derivation
vertical velocity of hail at beam height = slope of fit
Bootstrap fitting for 95% CI
Hail Sizing Analysis
Sounding
Apply air density correction
Vertical motion at surface
Define power law relationship for hail diameter and mass
Heymsfield et al. 2018
Create symbolic expressions
Hailstone mass
Heymsfield coefficients
Equivalent spherical diameter
Drag coefficient
Terminal velocity
Density-corrected vertical velocity
Grieser & Hill 2019
System of Equations
Solve for diameter

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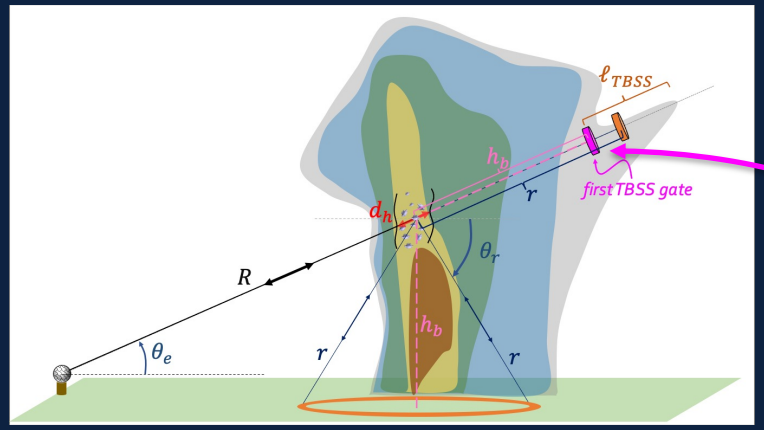
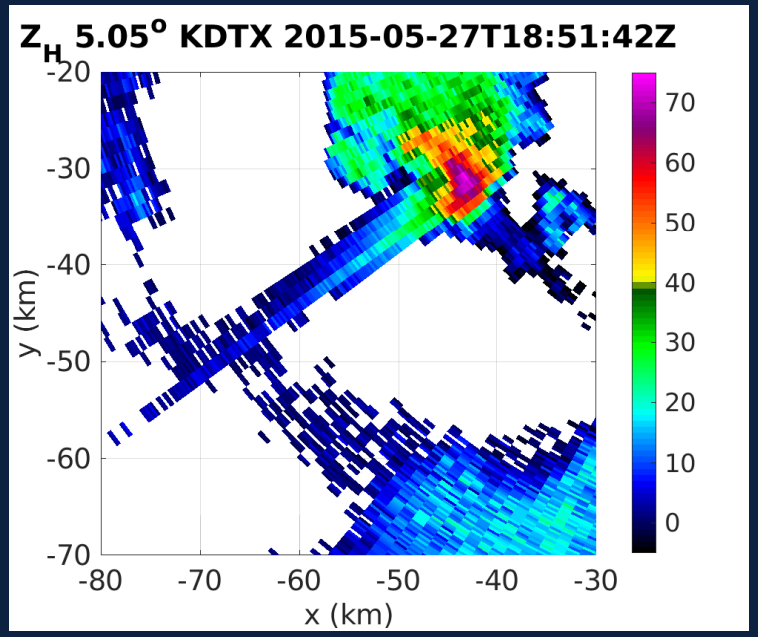
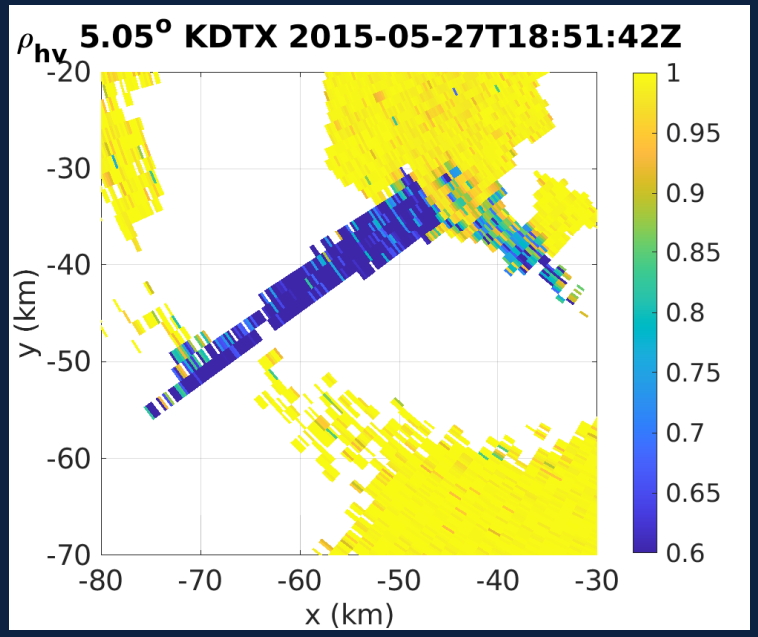
Detroit, Michigan

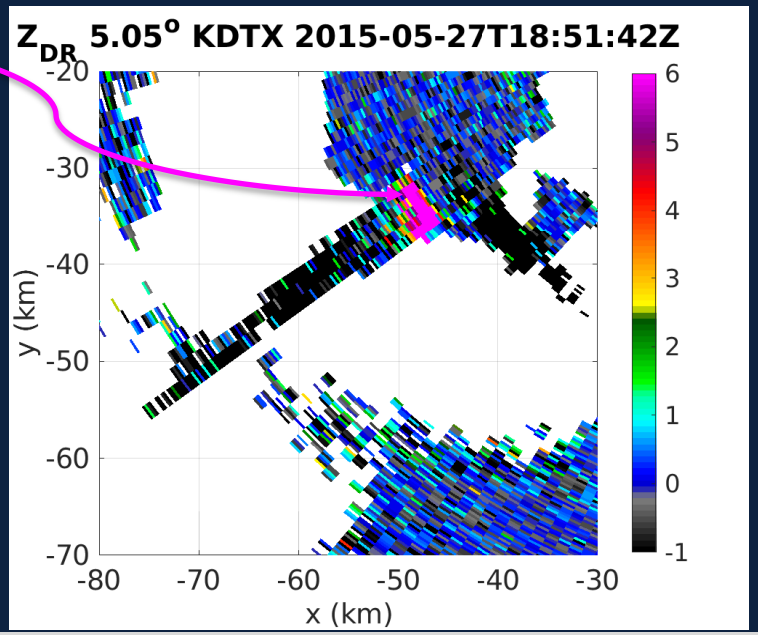
2015 – 05 – 27

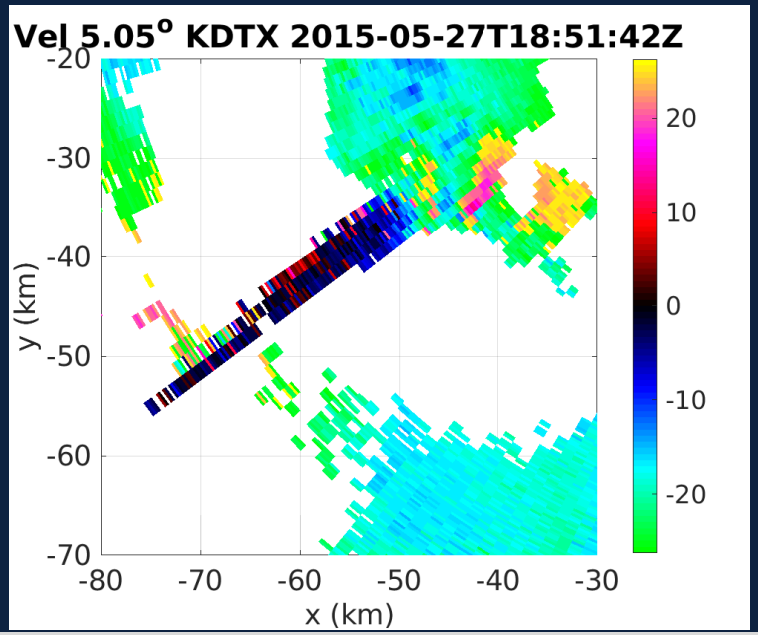
Marginally Severe ≤ 5 cm.







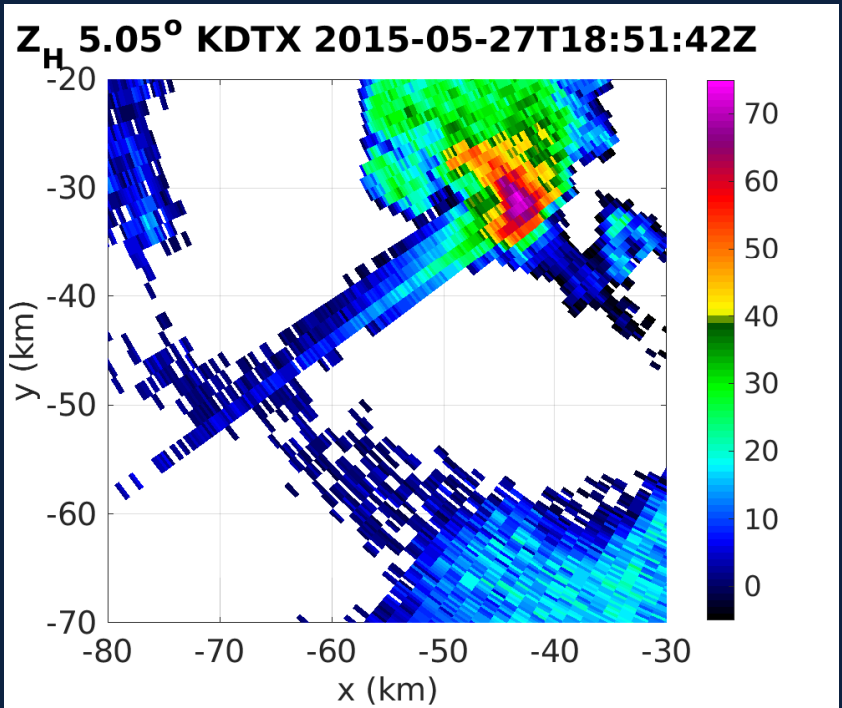


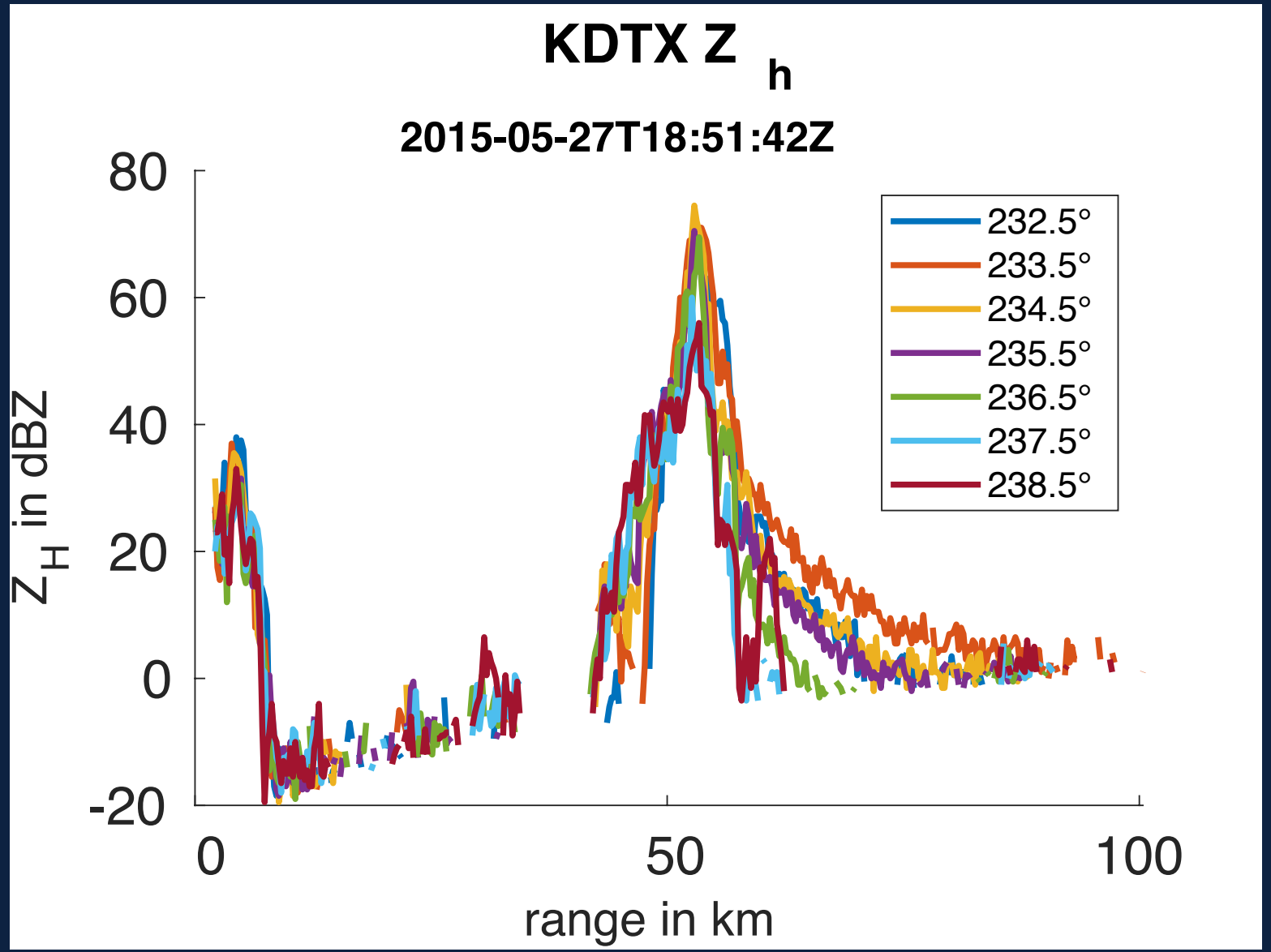


Detroit, Michigan

2015 – 05 – 27

Marginally Severe ≤ 5 cm.





Detroit, Michigan

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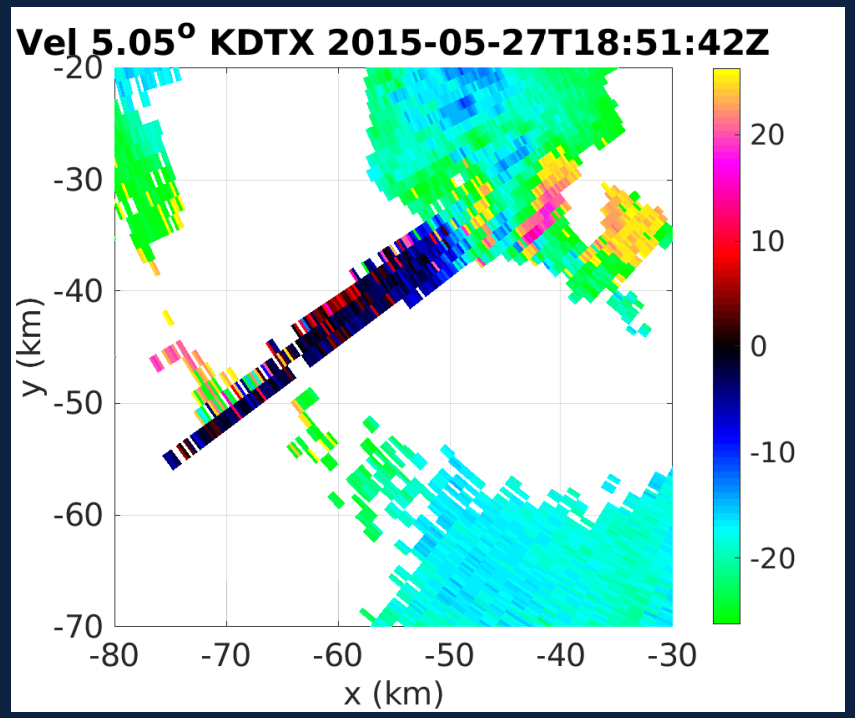
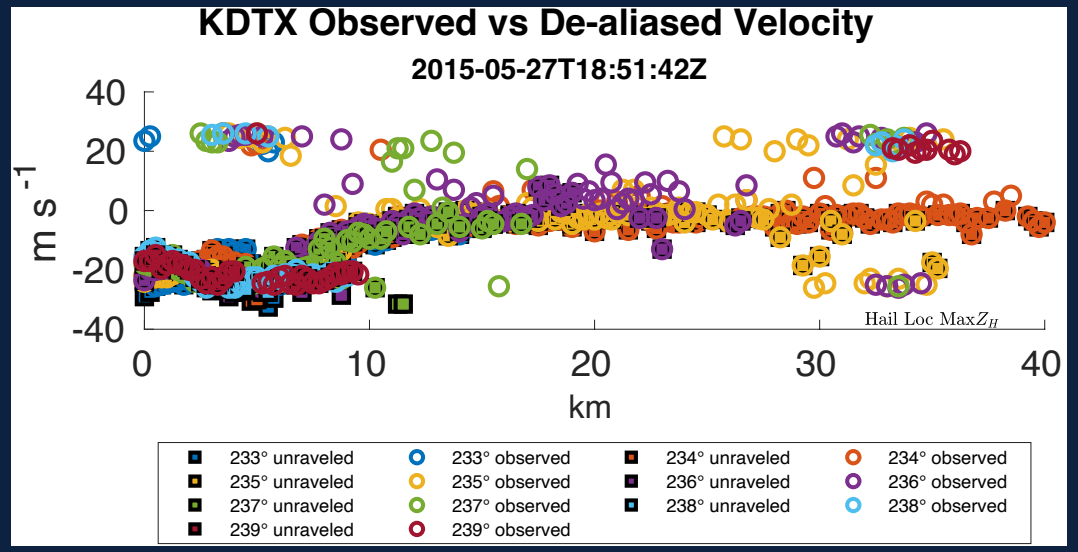
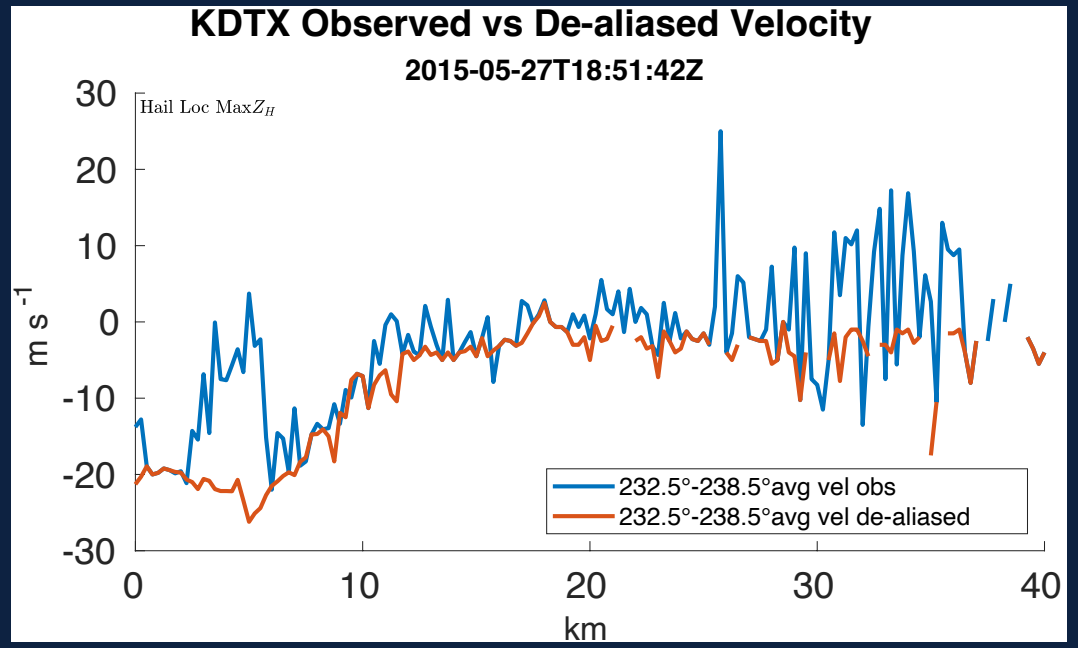


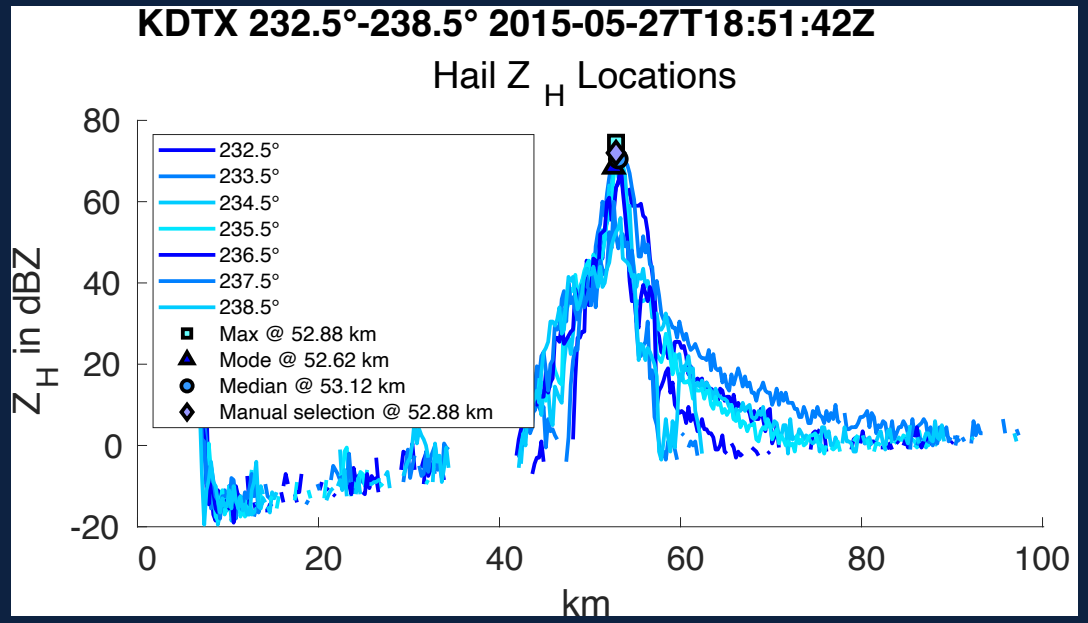


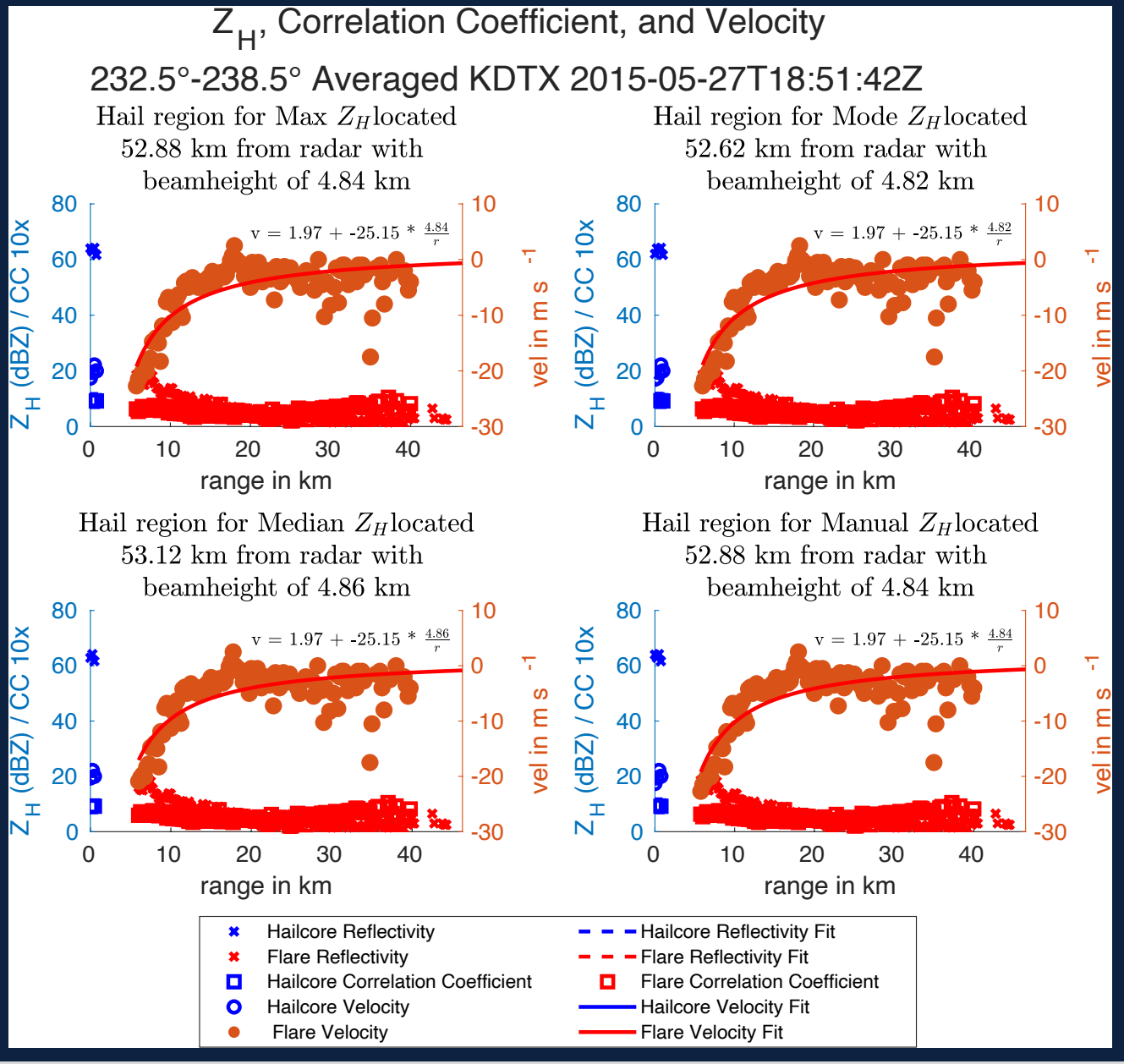


Detroit, Michigan

2015 – 05 – 27

Marginally Severe ≤ 5 cm.





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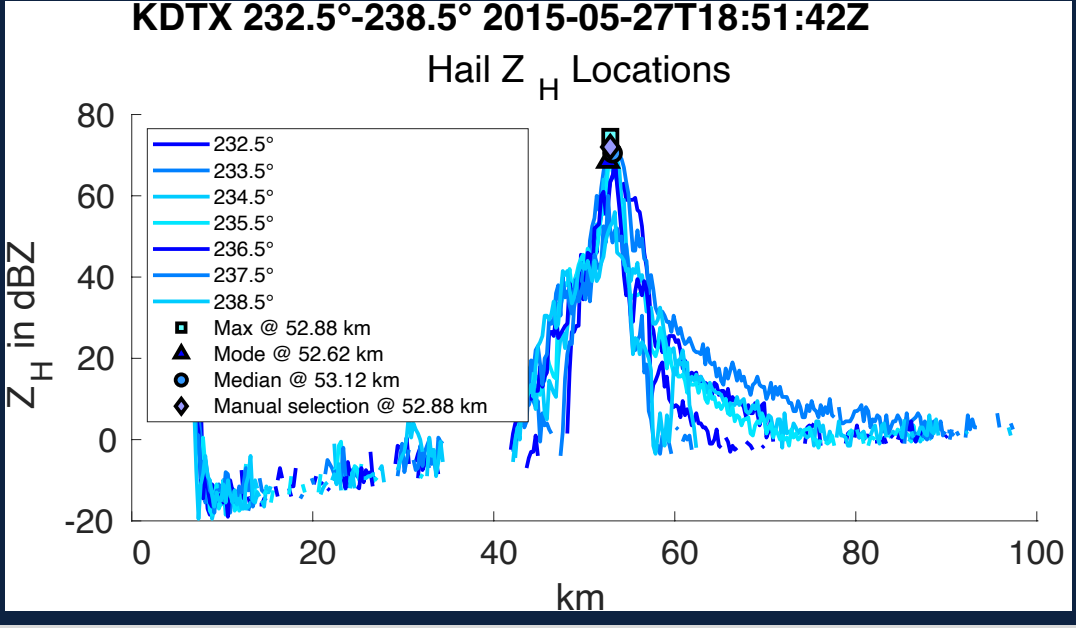
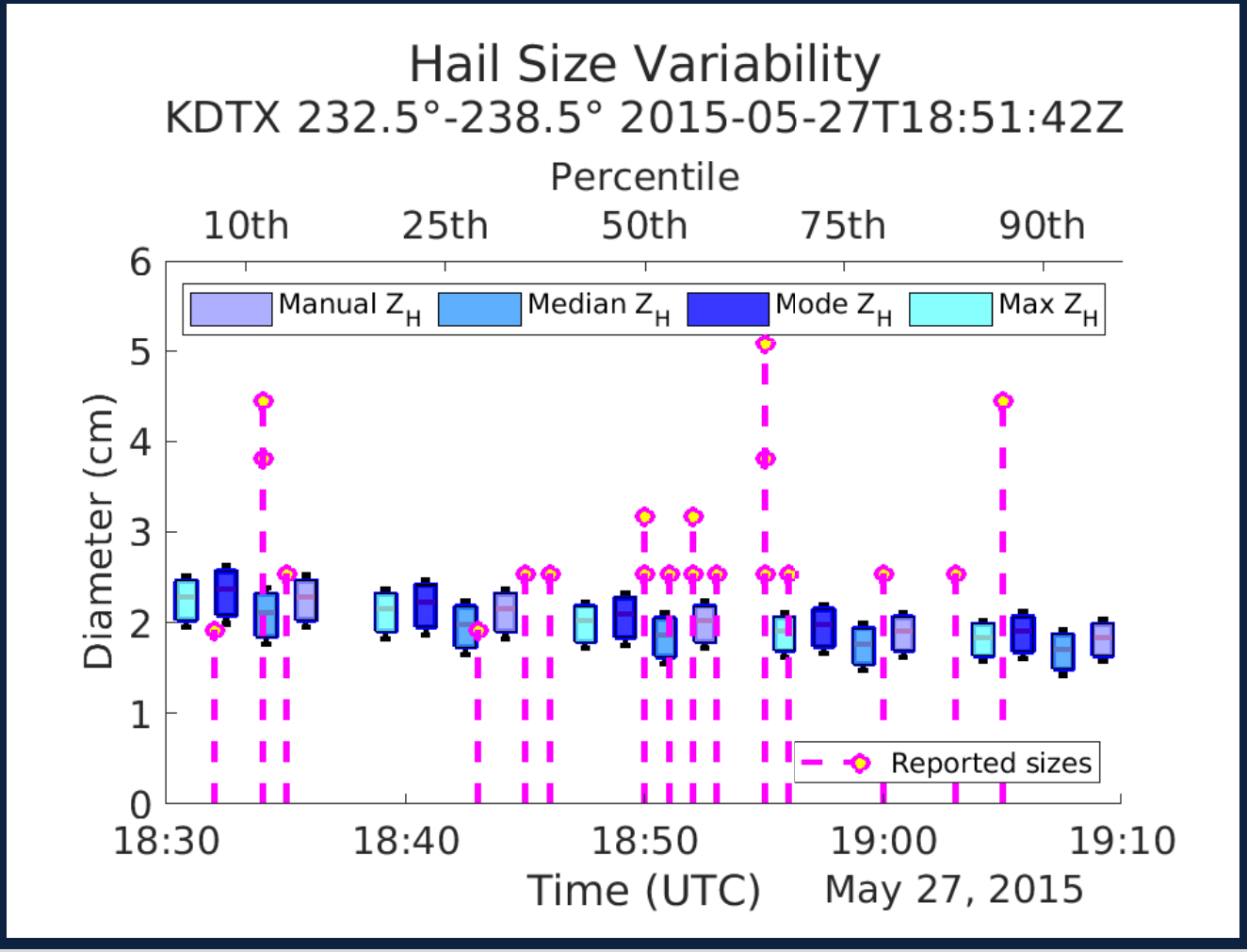
Marginally Severe ≤ 5 cm.

Est. Hail Sizes [cm] for Hail Regions & Mass-Diameter Power Fit					
	10th	25th	50th	75th	90th
Max ZH	2.28	2.15	2.02	1.91	1.84
Mode (ZH ≥ 60 dBZ)	2.37	2.23	2.10	1.98	1.91
Median (ZH ≥ 60 dBZ)	2.11	1.98	1.86	1.76	1.70
Manually Selected	2.28	2.15	2.02	1.91	1.84





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KUDX 2015-07-15

KOAX 2022-06-11

KTLX 2021-04-29

KARX 2017-07-07

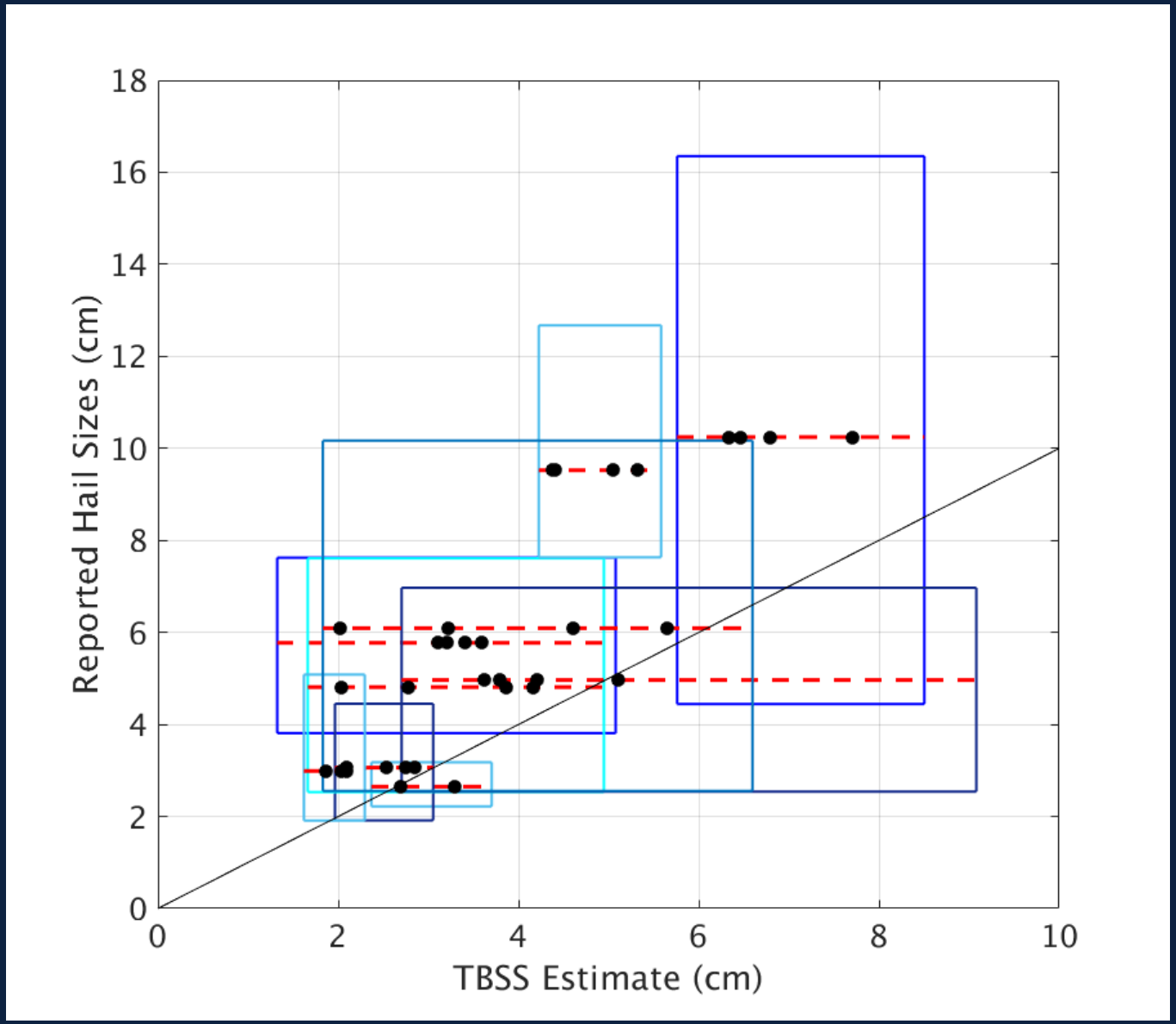
KMAF 2022-05-01

KDTX 2015-05-27

KDVN 2014-04-03

KEWX 2016-04-13

KEWX 2021-04-29



Key Takeaways

- Does it work?
  - To an extent… There are a few cases where it not perform well, but overall, it does show to be promising.
- Future improvements?
  1. More dual-pol variables brought into analysis for evaluating observed TBSS properties and sensitivity of hail size estimates.
  2. Evaluation of the environmental conditions
  3. Comprehensive analysis at each radar elevation angle for detecting strong convective storm updraft's influence on the hailstone vertical motion.
- Limited by scattering physics.

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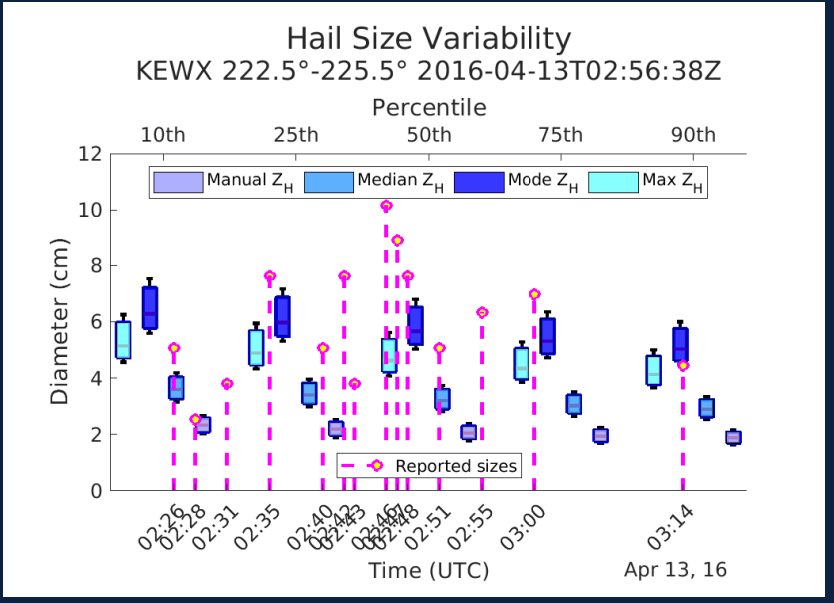
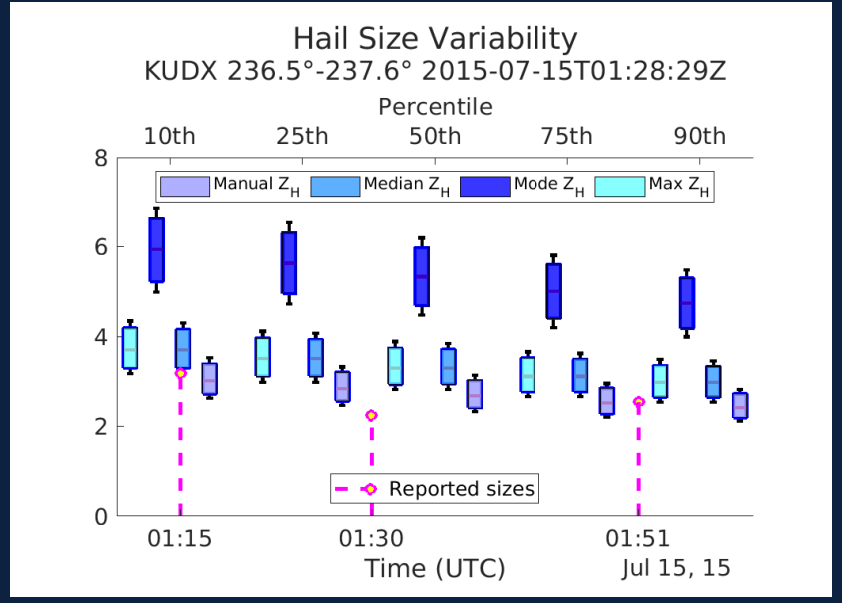
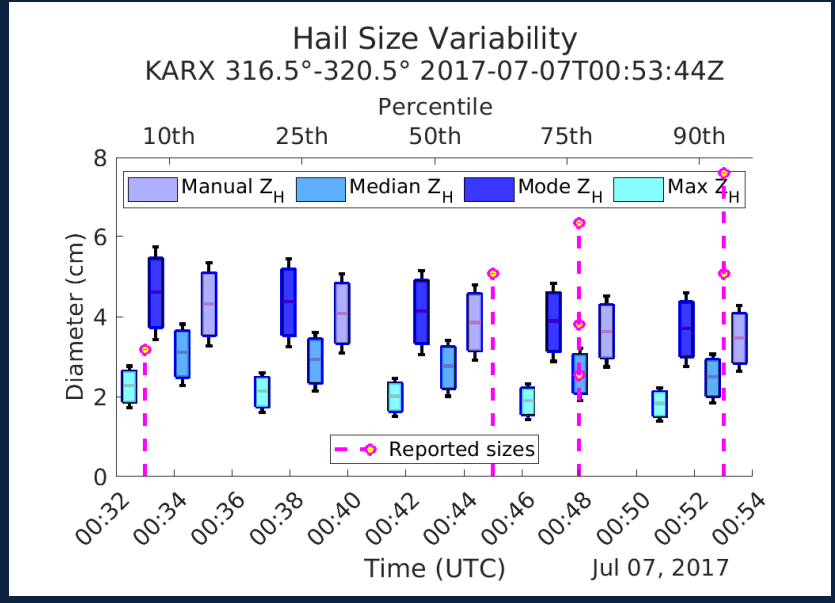
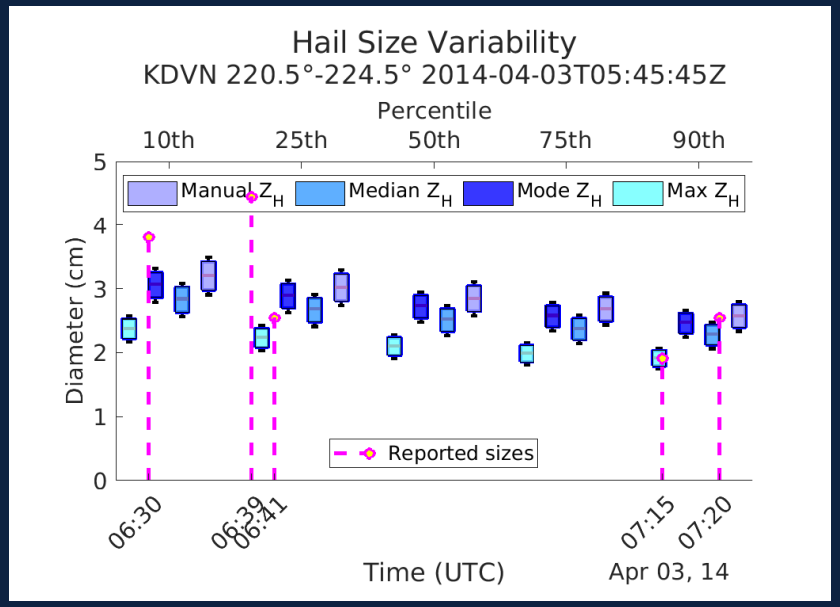
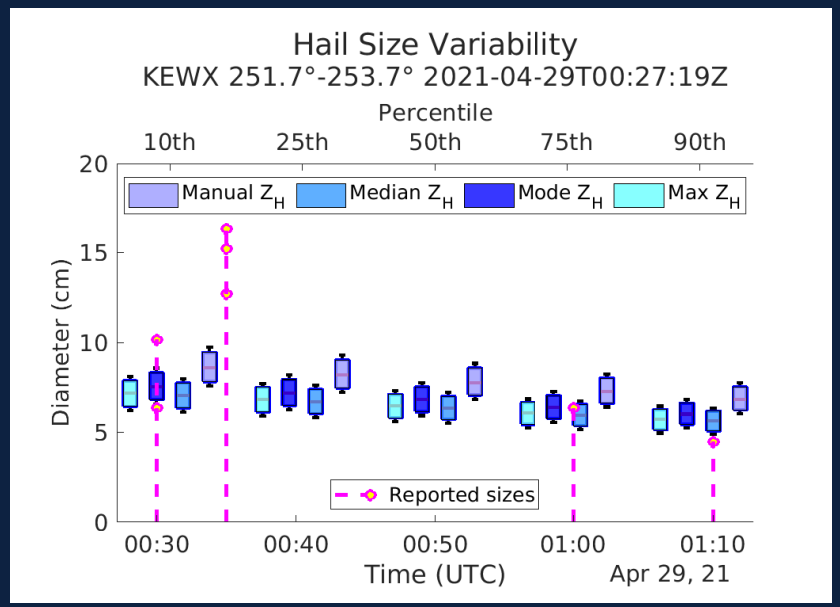

Hail Size Variability
KEWX 222.5°-225.5° 2016-04-13T02:56:38Z
Percentile
10th
25th
50th
75th
90th
Manual Z_H
Median Z_H
Mode Z_H
Max Z_H
Diameter (cm)
Reported sizes
Time (UTC)
Apr 13, 16


Hail Size Variability
KUDX 236.5°-237.6° 2015-07-15T01:28:29Z
Percentile
10th
25th
50th
75th
90th
Manual Z_H
Median Z_H
Mode Z_H
Max Z_H
Reported sizes
01:15
01:30
01:51
Time (UTC)
Jul 15, 15


Hail Size Variability
KARX 316.5°-320.5° 2017-07-07T00:53:44Z
Percentile
10th
25th
50th
75th
90th
Manual Z_H
Median Z_H
Mode Z_H
Max Z_H
Diameter (cm)
Reported sizes
Time (UTC)
Jul 07, 2017


Hail Size Variability
KDVN 220.5°-224.5° 2014-04-03T05:45:45Z
Percentile
10th
25th
50th
75th
90th
Manual Z_H
Median Z_H
Mode Z_H
Max Z_H
Diameter (cm)
Reported sizes
06:30
06:39
06:41
07:15
07:20
Time (UTC)
Apr 03, 14


Hail Size Variability
KEWX 251.7°-253.7° 2021-04-29T00:27:19Z
Percentile
10th
25th
50th
75th
90th
Manual Z_H
Median Z_H
Mode Z_H
Max Z_H
Diameter (cm)
Reported sizes
00:30
00:40
00:50
01:00
01:10
Time (UTC)
Apr 29, 21

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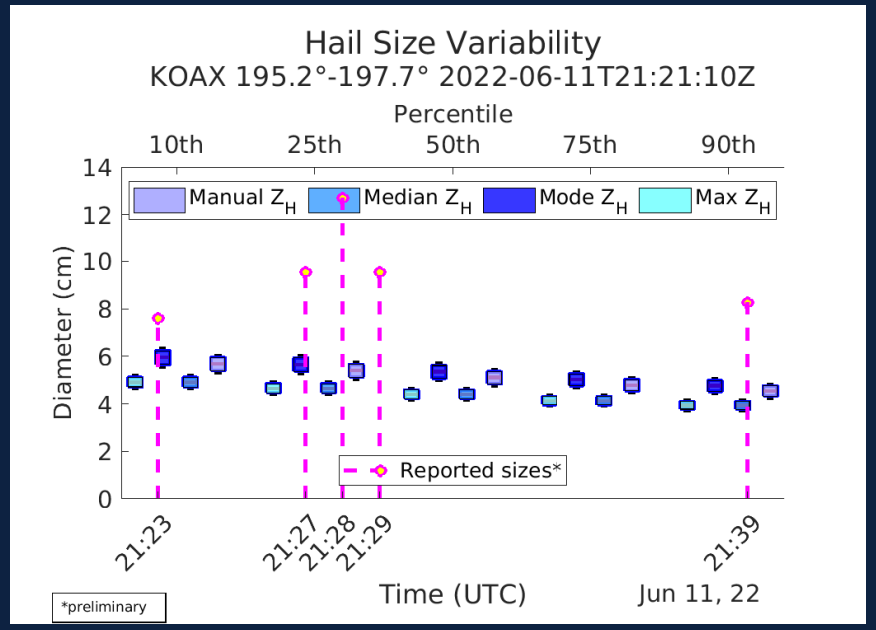
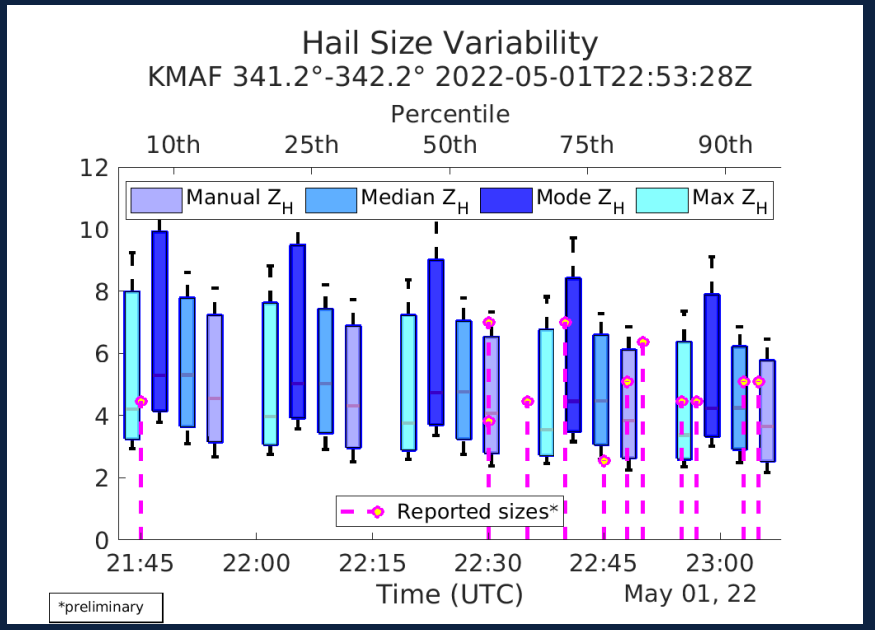
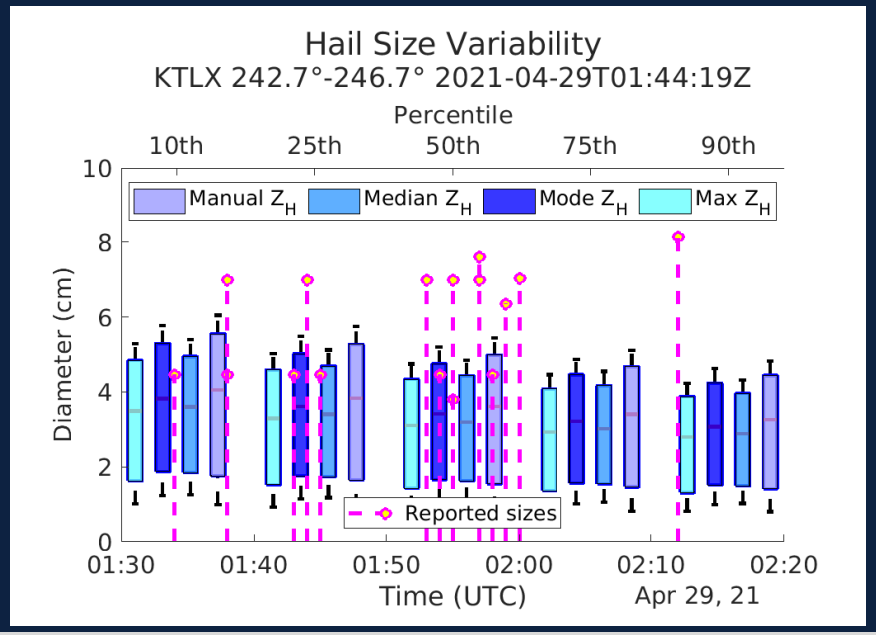
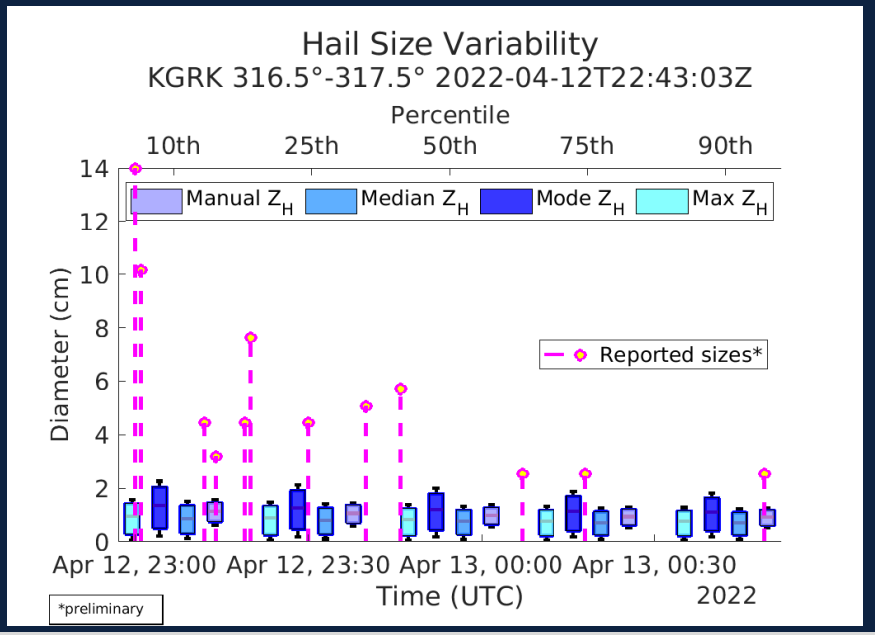
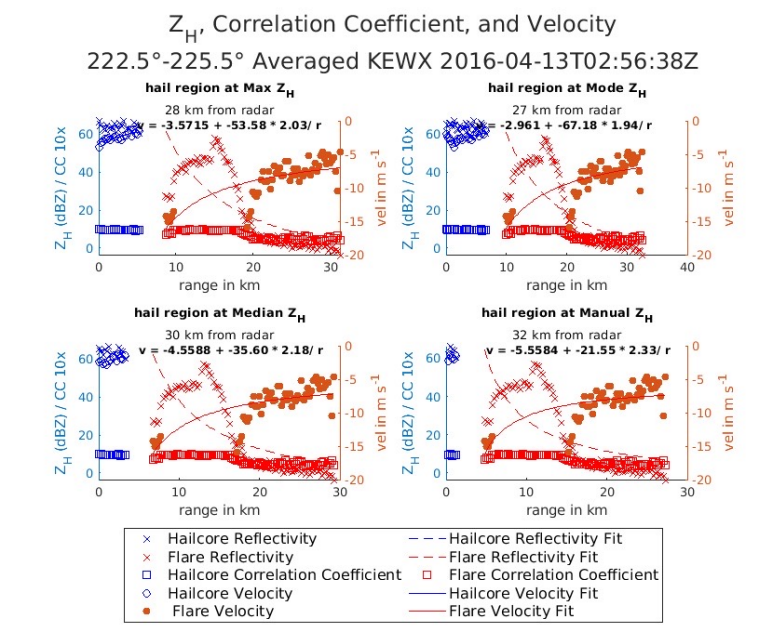
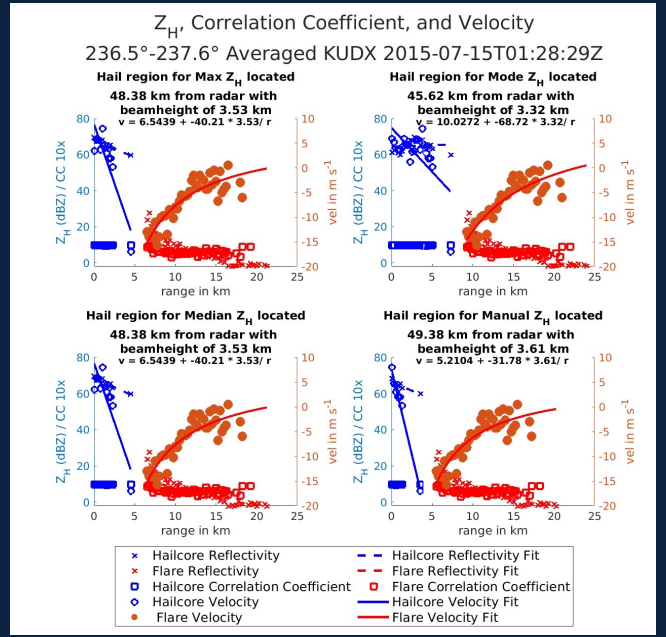

Hail Size Variability
KOAX 195.2°-197.7° 2022-06-11T21:21:10Z
Percentile
10th
25th
50th
75th
90th
Manual Z_H
Median Z_H
Mode Z_H
Max Z_H
Diameter (cm)
Reported sizes*
21:23
21:27
21:28
21:29
21:39
Time (UTC)
Jun 11, 22
*preliminary

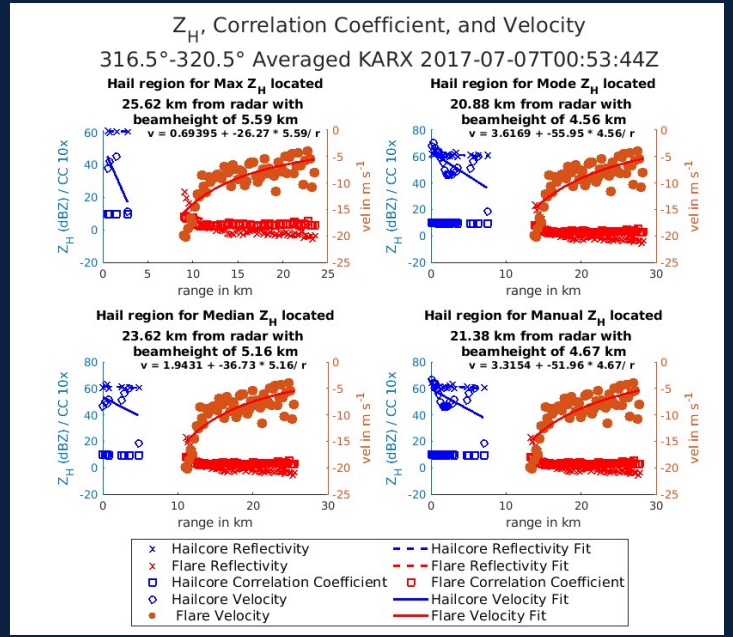

Hail Size Variability
KMAF 341.2°-342.2° 2022-05-01T22:53:28Z
Percentile
10th
25th
50th
75th
90th
Manual Z_H
Median Z_H
Mode Z_H
Max Z_H
Reported sizes*
21:45
22:00
22:15
22:30
22:45
23:00
Time (UTC)
May 01, 22
*preliminary

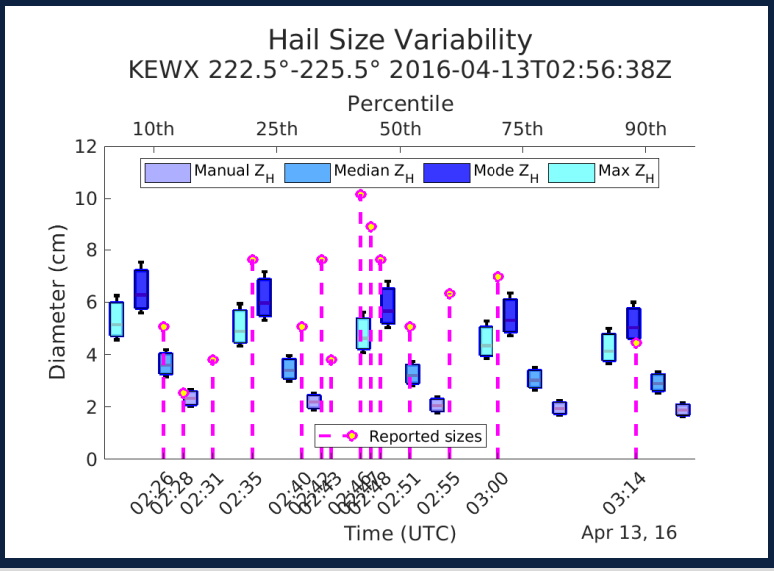

Hail Size Variability
KTLX 242.7°-246.7° 2021-04-29T01:44:19Z
Percentile
10th
25th
50th
75th
90th
Manual Z_H
Median Z_H
Mode Z_H
Max Z_H
Diameter (cm)
Reported sizes
01:30
01:40
01:50
02:00
02:10
02:20
Time (UTC)
Apr 29, 21

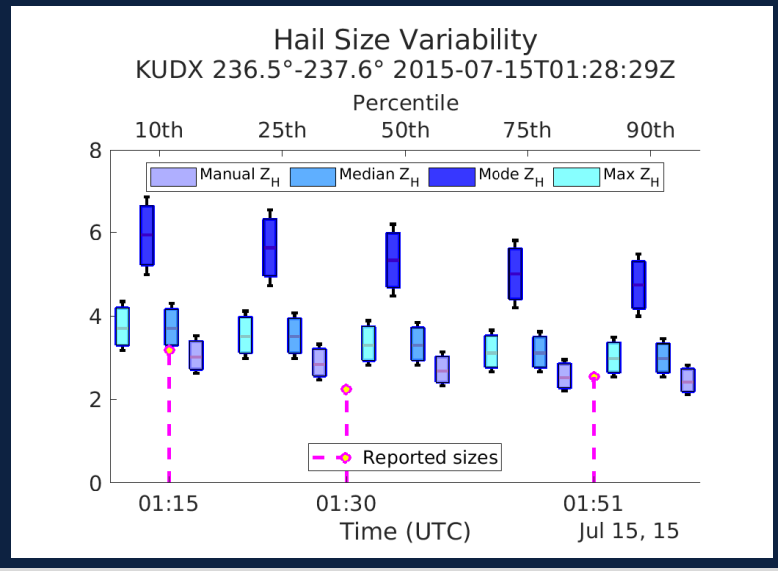

Hail Size Variability
KGRK 316.5°-317.5° 2022-04-12T22:43:03Z
Percentile
10th
25th
50th
75th
90th
Manual Z_H
Median Z_H
Mode Z_H
Max Z_H
Diameter (cm)
Reported sizes*
Apr 12, 23:00
Apr 12, 23:30
Apr 13, 00:00
Apr 13, 00:30
Time (UTC)
2022
*preliminary

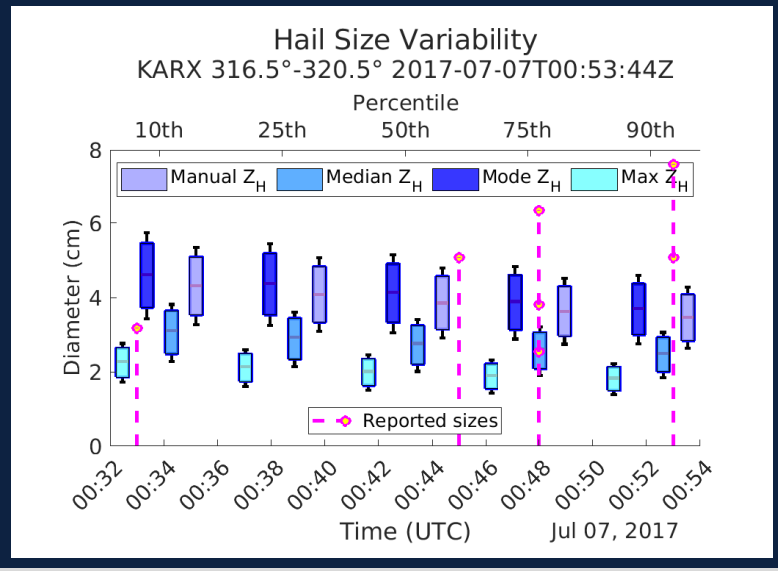

Z_H, Correlation Coefficient, and Velocity
222.5°-225.5° Averaged KEWX 2016-04-13T02:56:38Z
hail region at Max Z_H
28 km from radar
v = -3.5715 + -53.58 * 2.03/ r
hail region at Mode Z_H
27 km from radar
v = -2.961 + -67.18 * 1.94/ r
hail region at Median Z_H
30 km from radar
v = -4.4588 + -35.60 * 2.18/ r
hail region at Manual Z_H
32 km from radar
v = -5.5584 + -21.55 * 2.33/ r
Z_H (dBZ) / CC 10x
vel in m s^{-1}
range in km
Hailcore Reflectivity
Flare Reflectivity
Hailcore Correlation Coefficient
Hailcore Velocity
Flare Velocity
Hailcore Reflectivity Fit
Flare Reflectivity Fit
Flare Correlation Coefficient
Hailcore Velocity Fit
Flare Velocity Fit


Z_H, Correlation Coefficient, and Velocity
236.5°-237.6° Averaged KUDX 2015-07-15T01:28:29Z
Hail region for Max Z_H located
48.38 km from radar with beamheight of 3.53 km
v = 6.5439 + -40.21 * 3.53/ r
Hail region for Mode Z_H located
45.62 km from radar with beamheight of 3.32 km
v = 10.0272 + -68.72 * 3.32/ r
Hail region for Median Z_H located
48.38 km from radar with beamheight of 3.53 km
v = 6.5439 + -40.21 * 3.53/ r
Hail region for Manual Z_H located
49.38 km from radar with beamheight of 3.61 km
v = 5.2104 + -31.78 * 3.61/ r
Z_H (dBZ) / CC 10x
vel in m s^{-1}
range in km
Hailcore Reflectivity
Flare Reflectivity
Hailcore Correlation Coefficient
Hailcore Velocity
Flare Velocity
Hailcore Reflectivity Fit
Flare Reflectivity Fit
Flare Correlation Coefficient
Hailcore Velocity Fit
Flare Velocity Fit

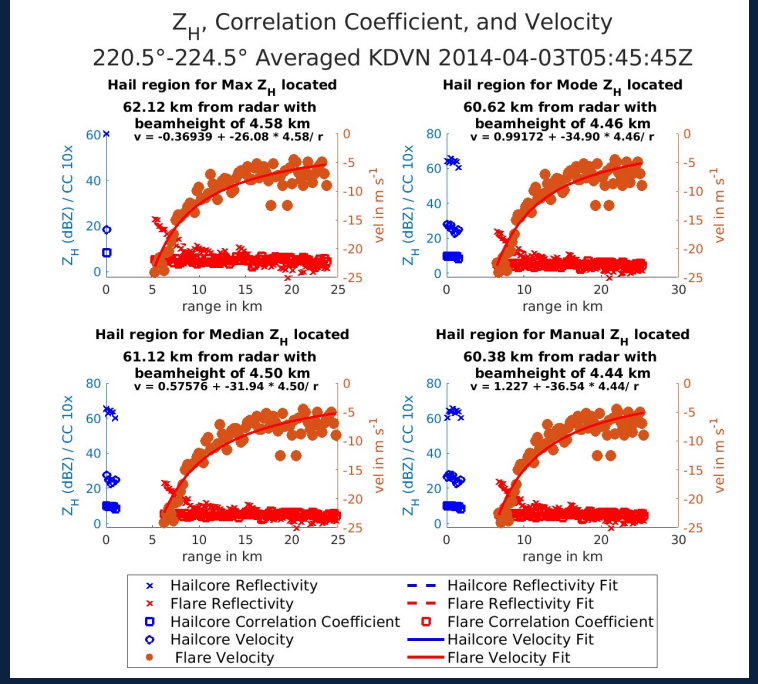

Z_H, Correlation Coefficient, and Velocity
316.5°-320.5° Averaged KARX 2017-07-07T00:53:44Z
Hail region for Max Z_H located
25.62 km from radar with beamheight of 5.59 km
v = 0.69395 + -26.27 * 5.59/ r
Hail region for Mode Z_H located
20.88 km from radar with beamheight of 4.56 km
v = 3.6169 + -55.95 * 4.56/ r
Hail region for Median Z_H located
23.62 km from radar with beamheight of 5.16 km
v = 1.9431 + -36.73 * 5.16/ r
Hail region for Manual Z_H located
21.38 km from radar with beamheight of 4.67 km
v = 3.3154 + -51.96 * 4.67/ r
Z_H (dBZ) / CC 10x
vel in m s^{-1}
range in km
Hailcore Reflectivity
Flare Reflectivity
Hailcore Correlation Coefficient
Hailcore Velocity
Flare Velocity
Hailcore Reflectivity Fit
Flare Reflectivity Fit
Flare Correlation Coefficient
Hailcore Velocity Fit
Flare Velocity Fit

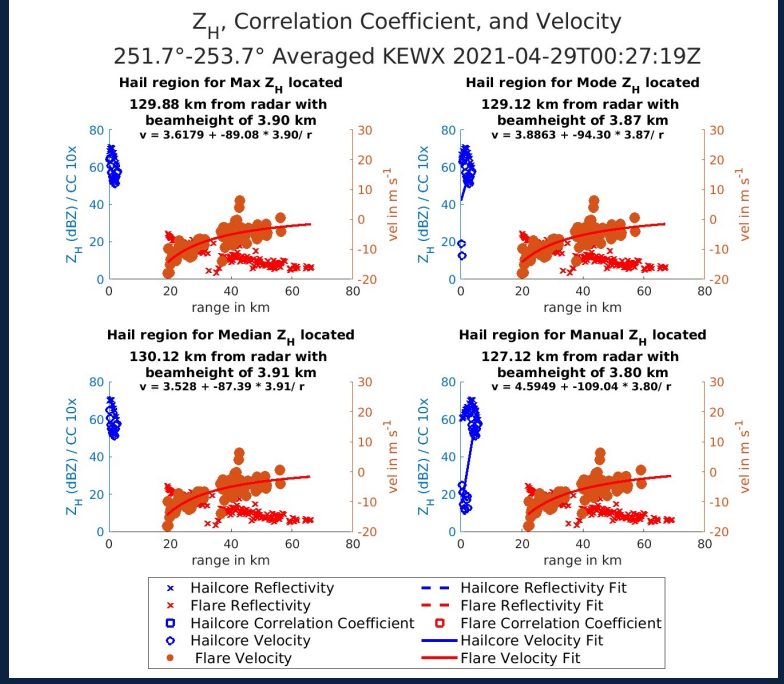

Hail Size Variability
KEWX 222.5°-225.5° 2016-04-13T02:56:38Z
Percentile
10th
25th
50th
75th
90th
Manual Z_H
Median Z_H
Mode Z_H
Max Z_H
Diameter (cm)
Reported sizes
Time (UTC)
Apr 13, 16

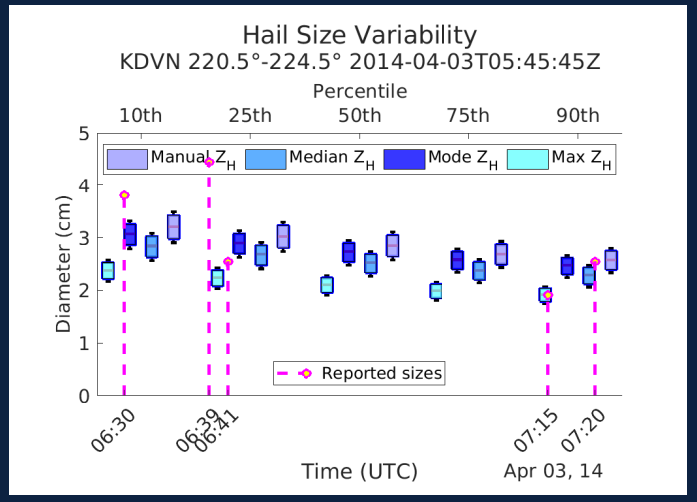

Hail Size Variability
KUDX 236.5°-237.6° 2015-07-15T01:28:29Z
Percentile
10th
25th
50th
75th
90th
Manual Z_H
Median Z_H
Mode Z_H
Max Z_H
Reported sizes
01:15
01:30
01:51
Time (UTC)
Jul 15, 15

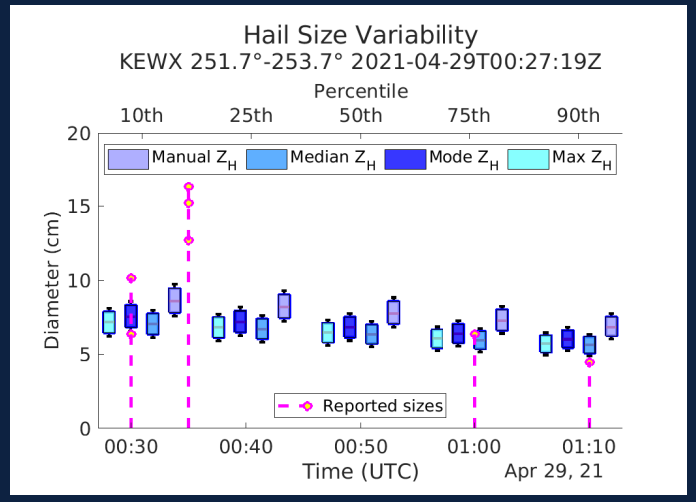

Hail Size Variability
KARX 316.5°-320.5° 2017-07-07T00:53:44Z
Percentile
10th
25th
50th
75th
90th
Manual Z_H
Median Z_H
Mode Z_H
Max Z_H
Diameter (cm)
Reported sizes
Time (UTC)
Jul 07, 2017

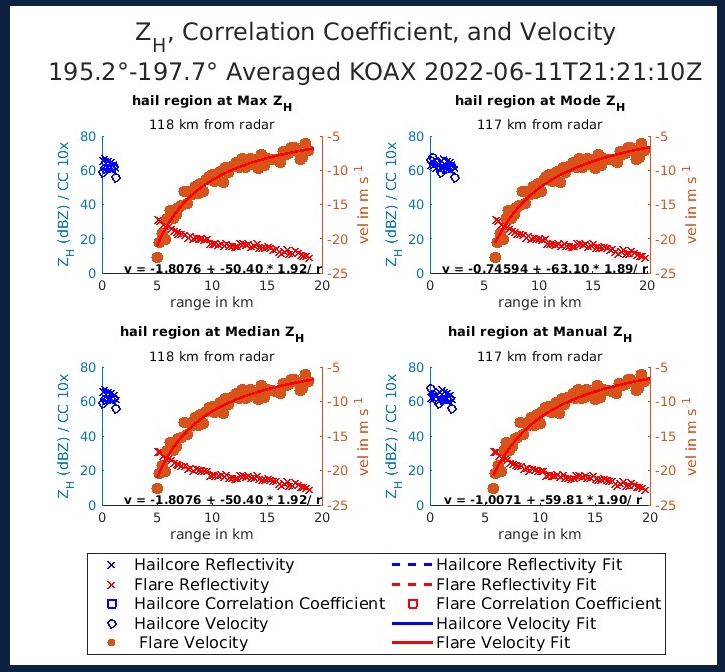
PennState

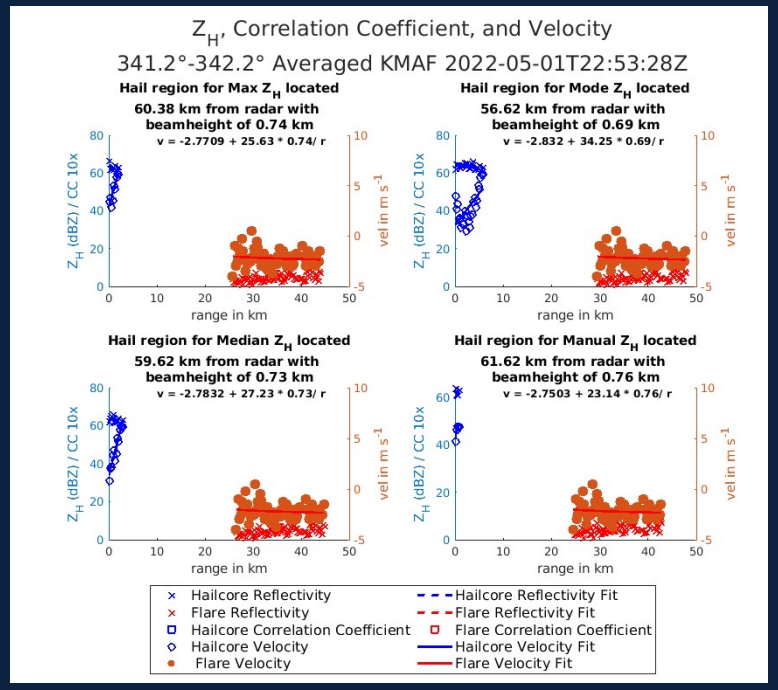

Z_H, Correlation Coefficient, and Velocity
220.5°-224.5° Averaged KDVN 2014-04-03T05:45:45Z
Hail region for Max Z_H located
62.12 km from radar with beamheight of 4.58 km
v = -0.36939 + -26.08 * 4.58/ r
Hail region for Mode Z_H located
60.62 km from radar with beamheight of 4.46 km
v = 0.99172 + -34.90 * 4.46/ r
Hail region for Median Z_H located
61.12 km from radar with beamheight of 4.50 km
v = 0.57576 + -31.94 * 4.50/ r
Hail region for Manual Z_H located
60.38 km from radar with beamheight of 4.44 km
v = 1.227 + -36.54 * 4.44/ r
Z_H (dBZ) / CC 10x
vel in m s^{-1}
range in km
Haircore Reflectivity
Flare Reflectivity
Haircore Correlation Coefficient
Haircore Velocity
Flare Velocity
Haircore Reflectivity Fit
Flare Reflectivity Fit
Flare Correlation Coefficient
Haircore Velocity Fit
Flare Velocity Fit

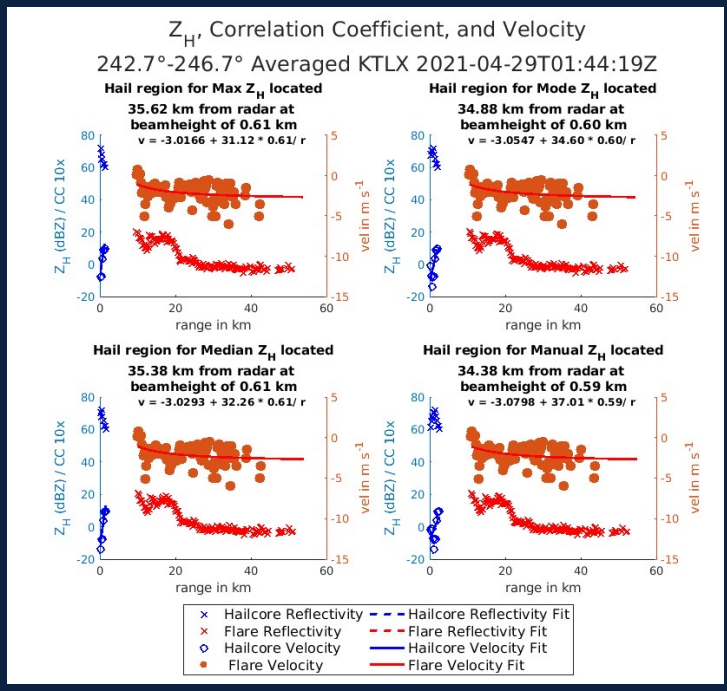

Z_H, Correlation Coefficient, and Velocity
251.7°-253.7° Averaged KEWX 2021-04-29T00:27:19Z
Hail region for Max Z_H located
129.88 km from radar with beamheight of 3.90 km
v = 3.6179 + -89.08 * 3.90/ r
Hail region for Mode Z_H located
129.12 km from radar with beamheight of 3.87 km
v = 3.8863 + -94.30 * 3.87/ r
Hail region for Median Z_H located
130.12 km from radar with beamheight of 3.91 km
v = 3.528 + -87.39 * 3.91/ r
Hail region for Manual Z_H located
127.12 km from radar with beamheight of 3.80 km
v = 4.5949 + -109.04 * 3.80/ r
Z_H (dBZ) / CC 10x
vel in m s^{-1}
range in km
Haircore Reflectivity
Flare Reflectivity
Haircore Correlation Coefficient
Haircore Velocity
Flare Velocity
Haircore Reflectivity Fit
Flare Reflectivity Fit
Flare Correlation Coefficient
Haircore Velocity Fit
Flare Velocity Fit

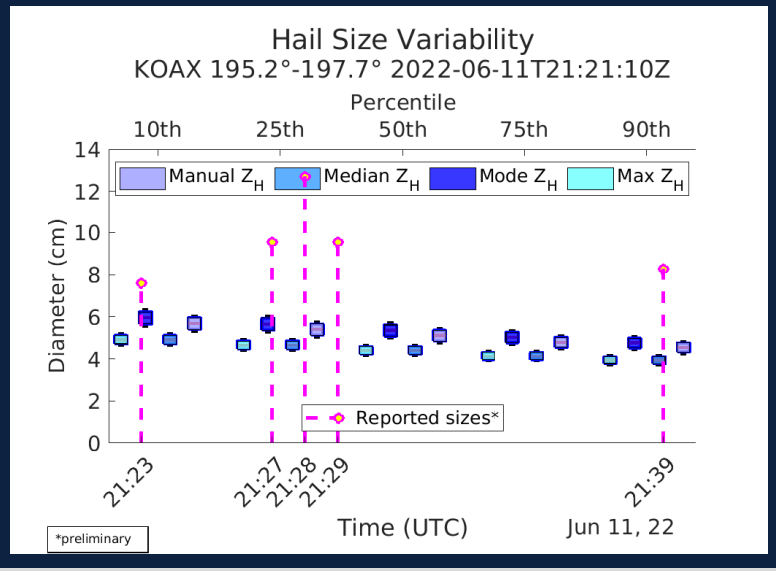

Hail Size Variability
KDVN 220.5°-224.5° 2014-04-03T05:45:45Z
Percentile
10th
25th
50th
75th
90th
Manual Z_H
Median Z_H
Mode Z_H
Max Z_H
Diameter (cm)
Reported sizes
06:30
06:39
06:41
07:15
07:20
Time (UTC)
Apr 03, 14

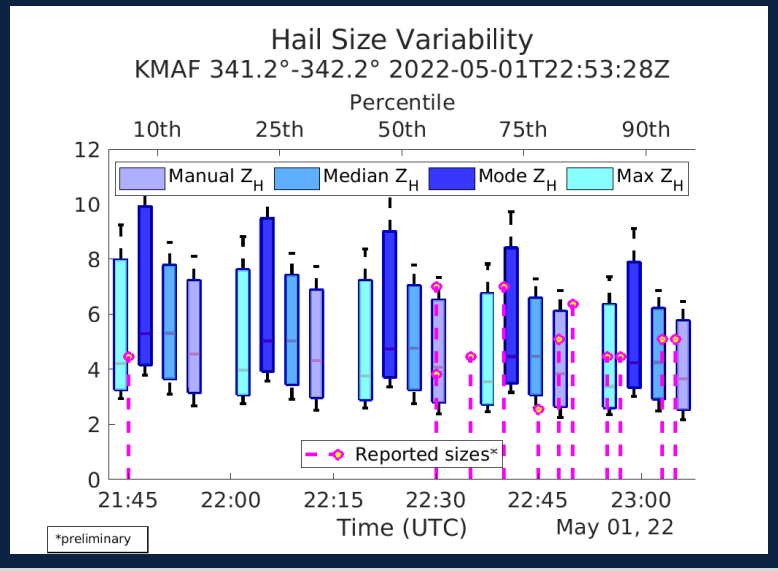

Hail Size Variability
KEWX 251.7°-253.7° 2021-04-29T00:27:19Z
Percentile
10th
25th
50th
75th
90th
Manual Z_H
Median Z_H
Mode Z_H
Max Z_H
Diameter (cm)
Reported sizes
00:30
00:40
00:50
01:00
01:10
Time (UTC)
Apr 29, 21

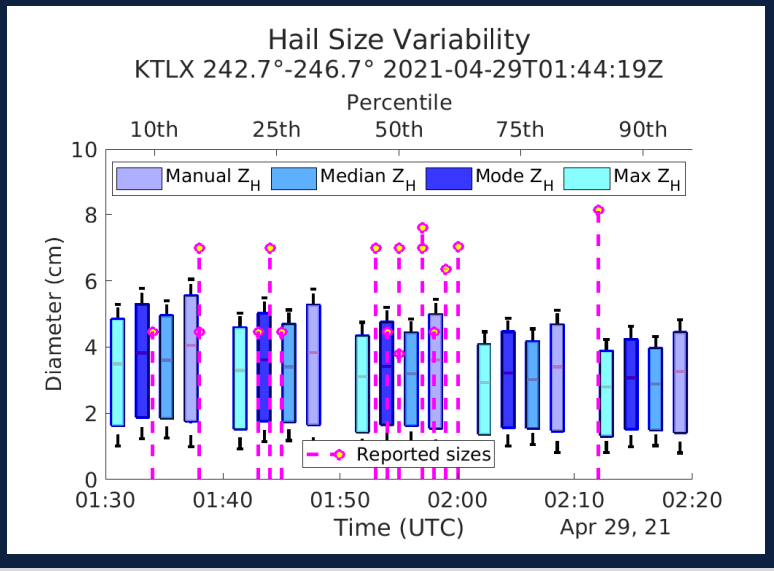

Z_H, Correlation Coefficient, and Velocity
195.2°-197.7° Averaged KOAX 2022-06-11T21:21:10Z
hail region at Max Z_H
118 km from radar
v = -1.8076 + -50.40 * 1.92/ r
hail region at Mode Z_H
117 km from radar
v = -0.74594 + -63.10 * 1.89/ r
hail region at Median Z_H
118 km from radar
v = -1.8076 + -50.40 * 1.92/ r
hail region at Manual Z_H
117 km from radar
v = -1.0071 + -59.81 * 1.90/ r
Z_H (dBZ) / CC 10x
vel in m s^{-1}
range in km
Hailcore Reflectivity
Flare Reflectivity
Hailcore Correlation Coefficient
Hailcore Velocity
Flare Velocity
Hailcore Reflectivity Fit
Flare Reflectivity Fit
Flare Correlation Coefficient
Hailcore Velocity Fit
Flare Velocity Fit


Z_H, Correlation Coefficient, and Velocity
341.2°-342.2° Averaged KMAF 2022-05-01T22:53:28Z
Hail region for Max Z_H located
60.38 km from radar with beamheight of 0.74 km
v = -2.7709 + 25.63 * 0.74/ r
Hail region for Mode Z_H located
56.62 km from radar with beamheight of 0.69 km
v = -2.832 + 34.25 * 0.69/ r
Hail region for Median Z_H located
59.62 km from radar with beamheight of 0.73 km
v = -2.7832 + 27.23 * 0.73/ r
Hail region for Manual Z_H located
61.62 km from radar with beamheight of 0.76 km
v = -2.7503 + 23.14 * 0.76/ r
Z_H (dBZ) / CC 10x
vel in m s^{-1}
range in km
Hailcore Reflectivity
Flare Reflectivity
Hailcore Correlation Coefficient
Hailcore Velocity
Flare Velocity
Hailcore Reflectivity Fit
Flare Reflectivity Fit
Flare Correlation Coefficient
Hailcore Velocity Fit
Flare Velocity Fit


Z_H, Correlation Coefficient, and Velocity
242.7°-246.7° Averaged KTLX 2021-04-29T01:44:19Z
Hail region for Max Z_H located
35.62 km from radar at beamheight of 0.61 km
v = -3.0166 + 31.12 * 0.61/ r
Hail region for Mode Z_H located
34.88 km from radar at beamheight of 0.60 km
v = -3.0547 + 34.60 * 0.60/ r
Hail region for Median Z_H located
35.38 km from radar at beamheight of 0.61 km
v = -3.0293 + 32.26 * 0.61/ r
Hail region for Manual Z_H located
34.38 km from radar at beamheight of 0.59 km
v = -3.0798 + 37.01 * 0.59/ r
Z_H (dBZ) / CC 10x
vel in m s^{-1}
range in km
Hailcore Reflectivity
Flare Reflectivity
Hailcore Velocity
Flare Velocity
Hailcore Reflectivity Fit
Flare Reflectivity Fit
Hailcore Velocity Fit
Flare Velocity Fit


Hail Size Variability
KOAX 195.2°-197.7° 2022-06-11T21:21:10Z
Percentile
10th
25th
50th
75th
90th
Manual Z_H
Median Z_H
Mode Z_H
Max Z_H
Diameter (cm)
Reported sizes*
21:23
21:27
21:28
21:29
21:39
Time (UTC)
Jun 11, 22
*preliminary


Hail Size Variability
KMAF 341.2°-342.2° 2022-05-01T22:53:28Z
Percentile
10th
25th
50th
75th
90th
Manual Z_H
Median Z_H
Mode Z_H
Max Z_H
Reported sizes*
21:45
22:00
22:15
22:30
22:45
23:00
Time (UTC)
May 01, 22
*preliminary


Hail Size Variability
KTLX 242.7°-246.7° 2021-04-29T01:44:19Z
Percentile
10th
25th
50th
75th
90th
Manual Z_H
Median Z_H
Mode Z_H
Max Z_H
Diameter (cm)
Reported sizes
01:30
01:40
01:50
02:00
02:10
02:20
Time (UTC)
Apr 29, 21

PennState