Uncertainties in Quantitative Precipitation Estimation

JIAN ZHANG

NOAA/NATIONAL SEVERE STORMS LAB, NORMAN, OK

Outline

In the National Weather Service (NWS) operational radar QPE:

1) significant advances that have been made;
2) remaining issues need to be addressed;
3) challenges to solving the issues; and
4) What's needed to address the challenges.

Advancement of NWS Radar QPE

Single Radar

PPS (*Fulton et al. 1998*):
single radar, single-pol
single R(Z)/per radar; manually set

DPR (*Giangrande & Ryzhkov 2008*):
single radar, dual-pol
Hydrometeor classification
$R(Z)/R(Z,Z_{DR})/R(K_{DP})$ synthetic

CRAFT
(*Kelleher et al. 2007*)

Stage-II (*Baldwin & Mitchell 1996*):
multi-radar, single-pol
Inverse distance weighted (IDW) mosaicking
4km, hourly

MRMS-Q3RAD (*Zhang et al. 2016*):
Multi-radar, single-pol
dual-pol QC,
multi R(Z),
Precip classification
Bright band correction
Conditional IDW mosaicking
Canadian radar
1km, 2min

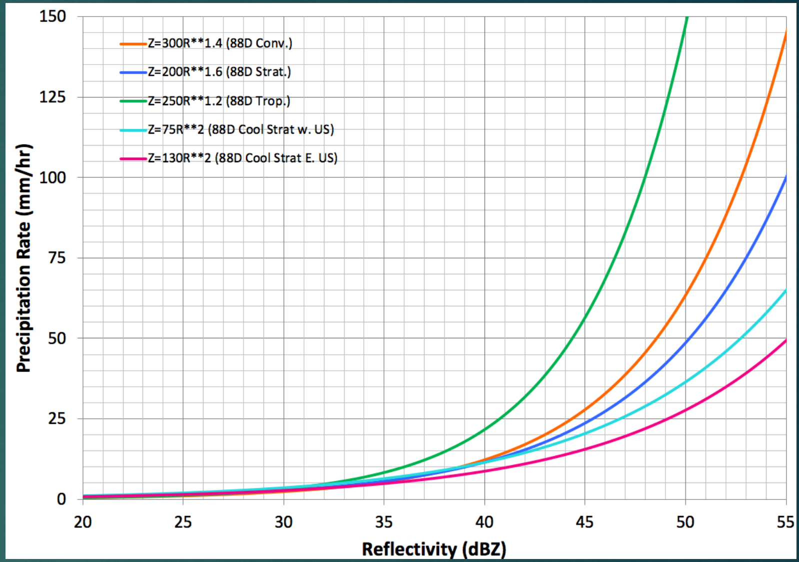
MRMS-Q3DP (Ryzhkov et al. 2014, *Zhang et al. 2017*):
Multi-radar, dual-pol
$R(A)/R(K_{DP})$ in rain and hail
Q3RAD in mixed and ice phase
Evaporation correction

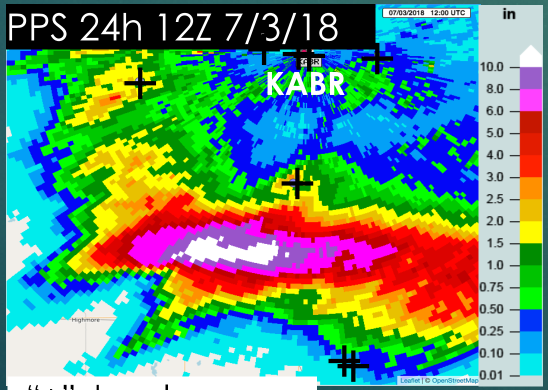
Multi-Radar Multi-Sensor (MRMS)

Z: reflectivity; Z_{DR}: differential reflectivity;
K_{DP}: specific differential phase; A: specific attenuation

Single-radar, Single-pol (PPS)

- **Methodology**
  - Single R(Z) per radar, set by forecasters and chosen from 5 pre-defined relations
  - Capped at 75 ~ 150mm/hr depending on locations
- **Advances (vs. gauge-based QPE):**
  - **Significantly improved resolution and coverage**
  - **A major improvement for flash flood warnings**





"+" hourly gauges

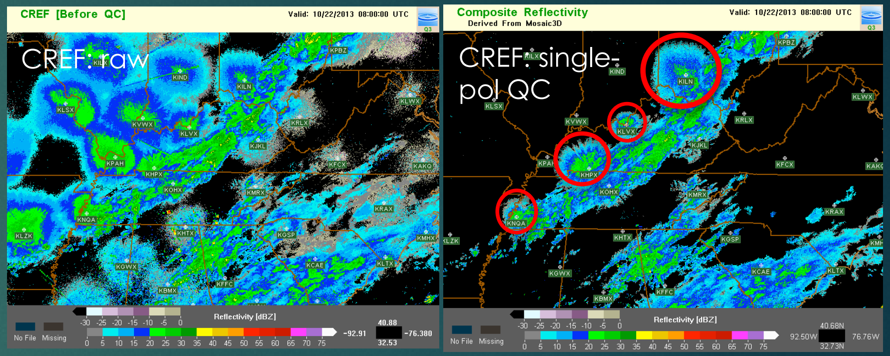
Hail and flash flood, Hand County, SD, 7/3/2018

Photos by *Alex Roeber*, Hand County emergency management director

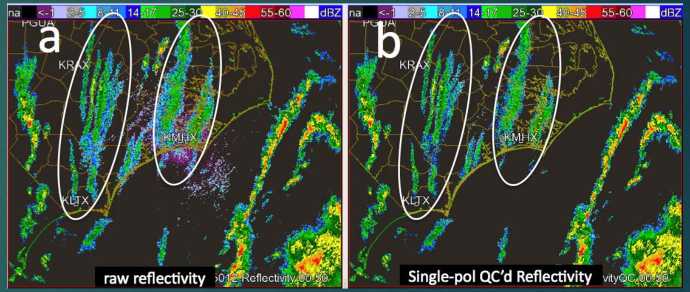
Single-Radar, Single-Pol (PPS)

- **Issues:**
  - Contamination of non-hydrometeor echoes
  - R(Z) uncertainties
  - Sensitivity to Z calibration bias
    - 0.5dBZ bias would cause 8.6 (10.1)% error in QPE based on continental (tropical) R(Z) relations
  - Range dependent errors
    - bright band
    - Overshooting of lower level precipitation processes
    - Evaporation below the lowest radar beam

Biological echoes ("blooms")/AP



Chaff



Single-Radar, Dual-Pol (DPR)

- **Methodology**
  - Hydrometeor Classification Algorithm (HCA)
  - $R(Z, Z_{DR})$, $R(K_{DP})$, and $R(Z)$ synthetic based on HCA

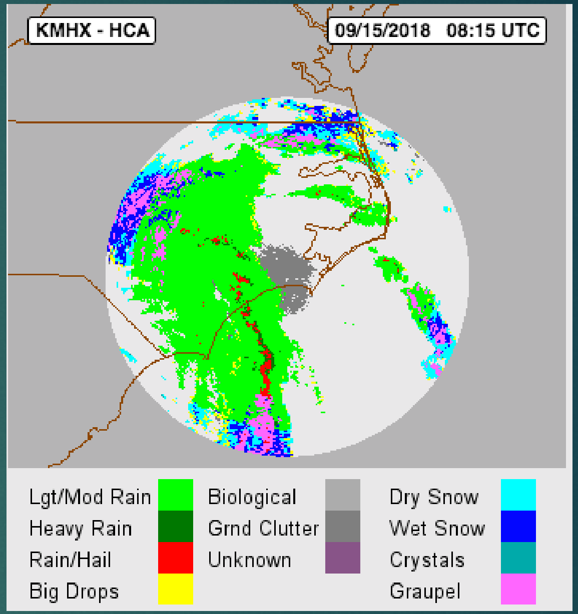
$R(Z, Z_{DR})$ for light/mod rain: 1) Continental: $R=0.007\ Z^{0.927}\ Z_{DR}^{-3.43}$

2) Tropical: $R=0.0142\ Z^{0.770}\ Z_{DR}^{-1.67}$

$R(K_{DP})$ for heavy rain and rain/hail mix: $R=44.0\,|K_{DP}|^{0.822}$

R(Z): $R = c*0.017\ Z^{0.714}$

Multiplier c is set to 0.6 for wet snow, 0.8 for graupel, and 2.8 for dry snow and crystals.



Single-Radar, Dual-Pol (DPR)

- **Methodology**
  - Hydrometeor Classification Algorithm (HCA)
  - $R(Z, Z_{DR})$, $R(K_{DP})$, and $R(Z)$ synthetic based on HCA

    $R(Z, Z_{DR})$ for light/mod rain: *1) Continental:* $R=0.007\ Z^{0.927}\ Z_{DR}^{-3.43}$

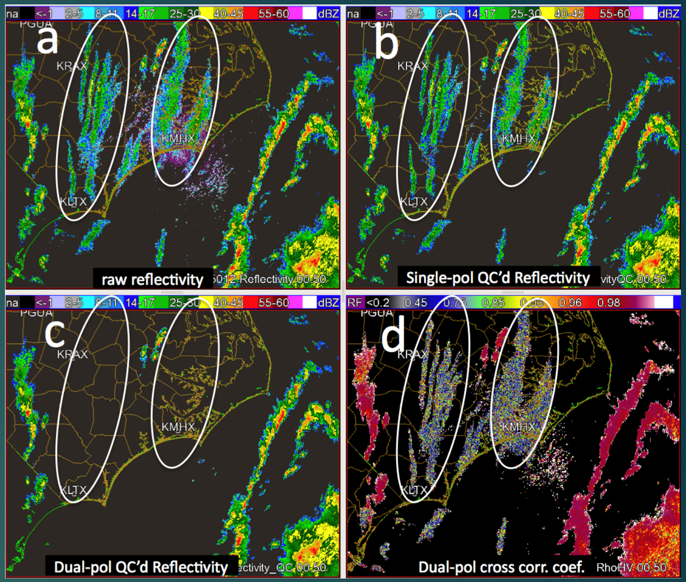
    2) Tropical: $R=0.0142\ Z^{0.770}\ Z_{DR}^{-1.67}$

    $R\ (K_{DP})$ for heavy rain and rain/hail mix: $R=44.0\,|K_{DP}|^{0.822}$

    R(Z): $R = c*0.017\ Z^{0.714}$

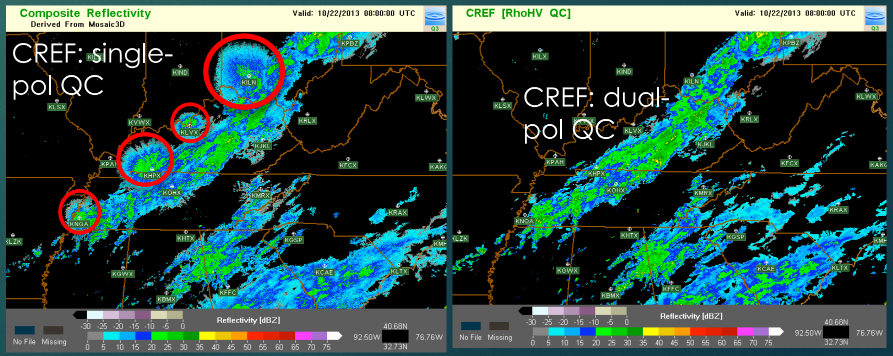
    Multiplier c is set to 0.6 for wet snow, 0.8 for graupel, and 2.8 for dry snow and crystals.

Chaff



- **Advances:**
  - **Major improvements in the identification of non-hydrometeor echoes**
  - **Improvements in convective storms**

Biological echoes ("blooms")/AP



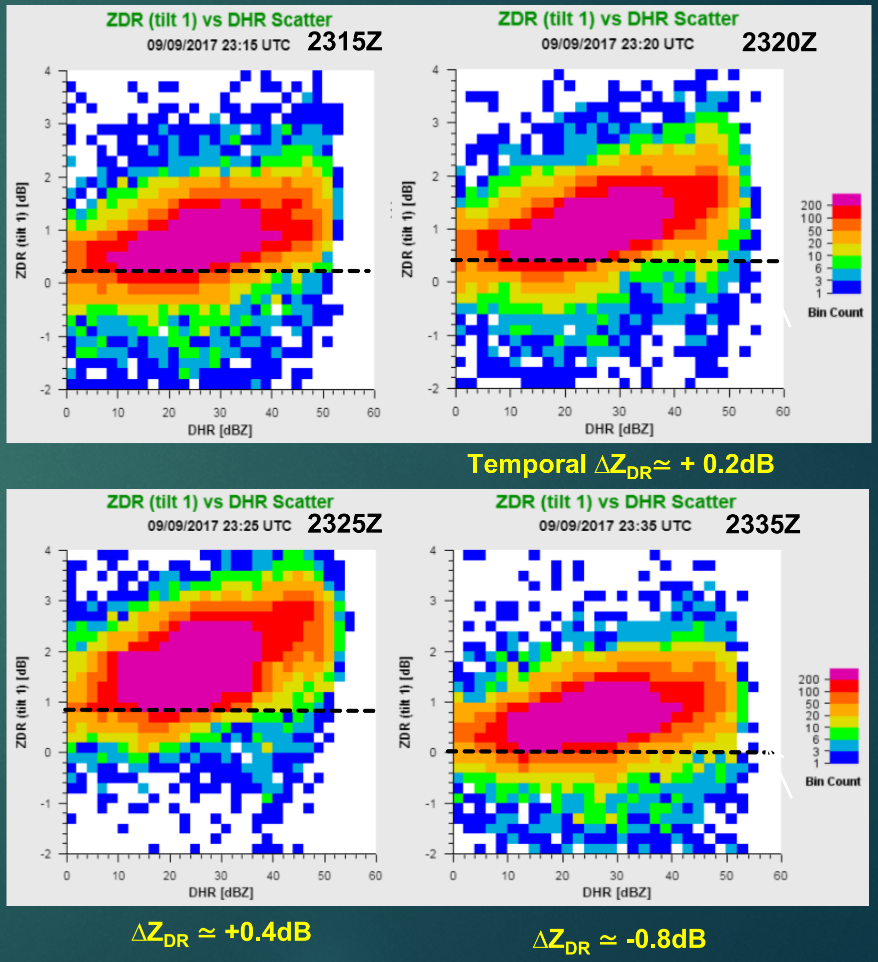
Single-Radar, Dual-Pol (DPR)

- **Issues:**
  - Sensitivity to Z & Z_{DR} calibration bias

dBZ	Z_{DR} (dB)	R (trop) (mm/hr)	R (cont) (mm/hr)
30	0.6	24.4	6.7
30	0.8 (+0.2)	9.1 (-63%)	4.1 (-39%)
40	1	35.7	16.8
40	1.2 (+0.2)	19.1 (-46%)	12.4 (-26%)

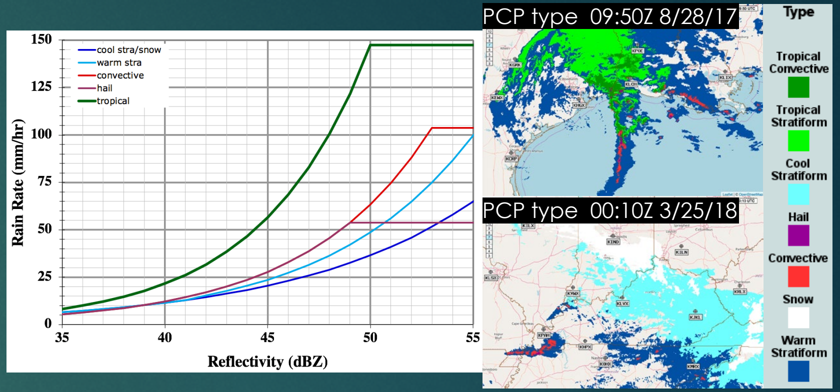
  - Underestimation in stratiform and tropical rain
  - Range dependent errors
    - Bright band
    - Overshooting of lower level precipitation processes
    - Evaporation below the lowest radar beam

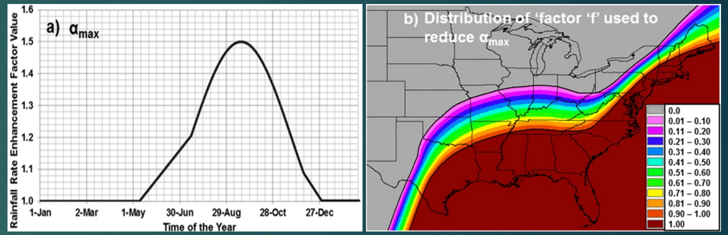
KAMX Z_{DR} bias 9/9/17



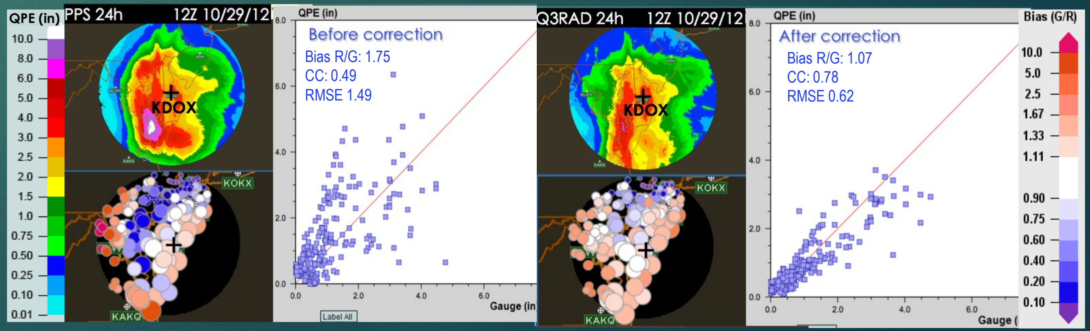
Multi-Radar, Single-Pol (Q3RAD)

- **Methodology**
  - Dual-pol QC
  - Multiple R(Z) based on precipitation classification
  - Tropical rain enhancement based on precip climatology ($R=\beta*2.447x10^{-3}*Z^{0.833}$, β: 1~1.5)
  - Vertical Profile of Refl (VPR) correction for bright band
  - Physically based mosaic to minimize impact of virga and beam overshooting





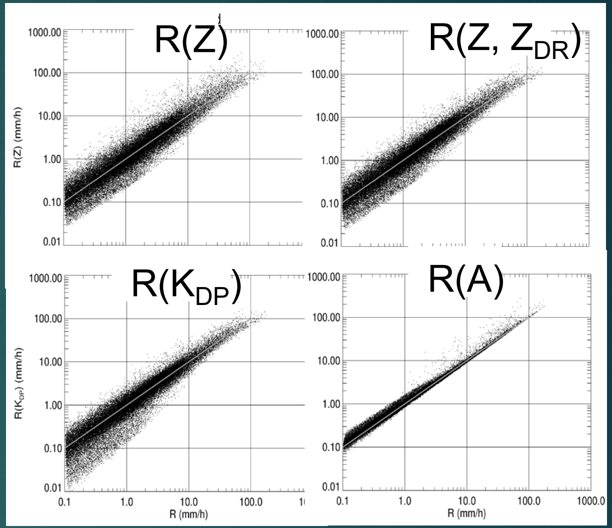
- **Advances**
  - **Improved QPE accuracy in bright band and at far ranges**
  - **Reduced underestimation bias in tropical and stratiform rain**



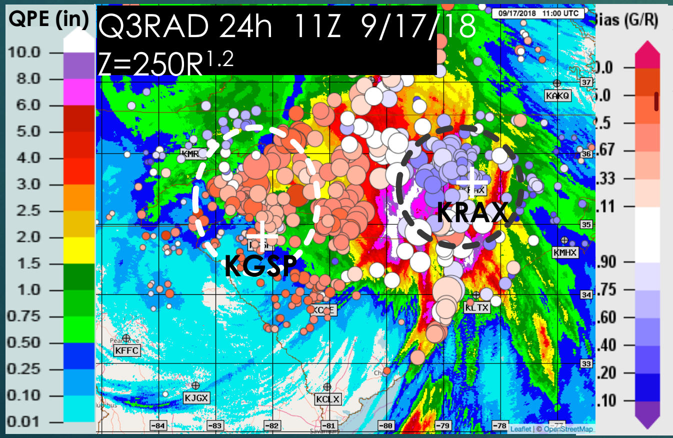
Multi-Radar, Single-Pol (Q3RAD)

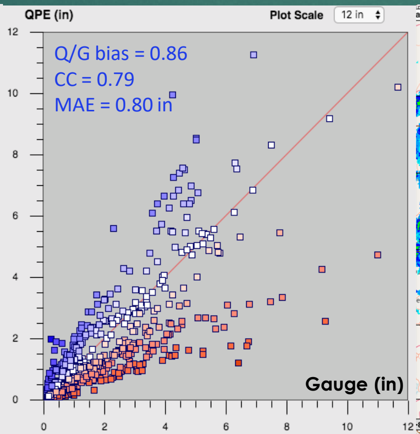
- **Issues**
  - Uncertainties in R(Z) relationships
  - Range dependent errors
    - Overshooting of lower level precipitation processes
    - Evaporation below the lowest radar beam

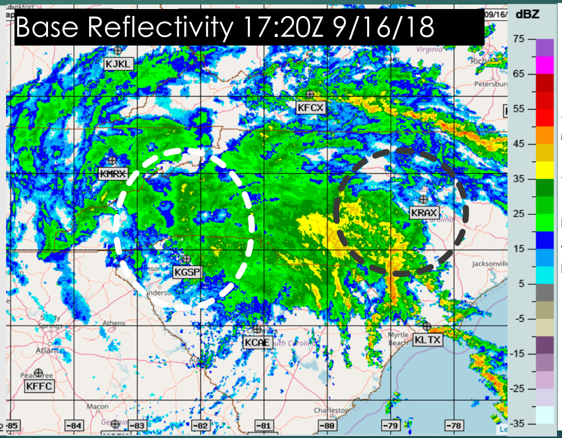
47144 DSDs collected in Oklahoma

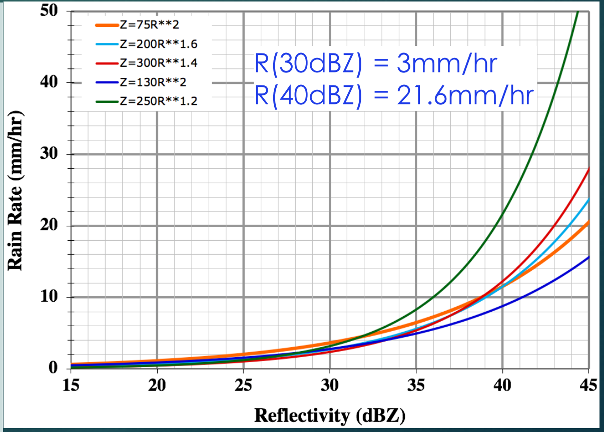


Ryzhkov et al. 2014; *JTECH*









Multi-Radar, Dual-Pol (Q3DP)

- **Methodology**
  - $R(A)$, $R(K_{DP})$ and $R(Z)$ synthetic based on hydrometeor phase and intensities

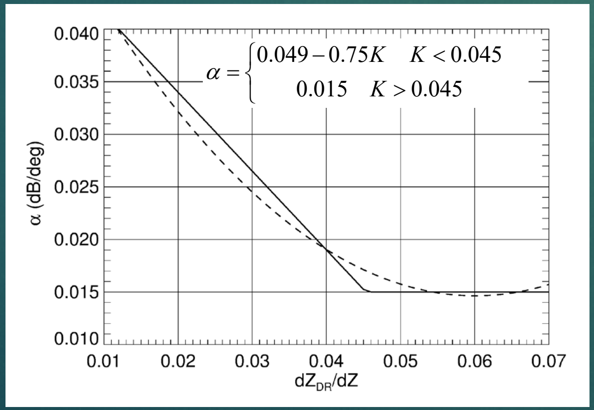
    In melting layer and above: Multiple R(Z) with VPR correction

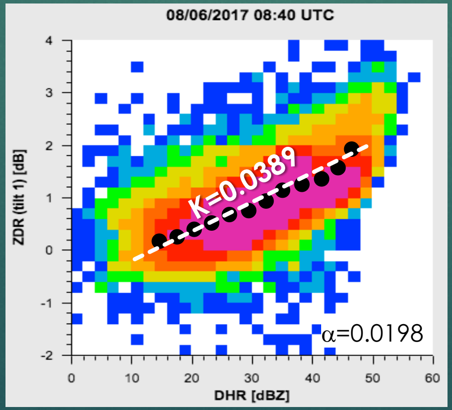
    Below melting layer:

    Z<48dBZ: R(A): $R = 4210\,A^{1.03}$

    Z≥48dBZ: $R(K_{DP})$: 1) $\rho_{HV}>0.9$: $R=44.0\,|K_{DP}|^{0.822}$

    2) $\rho_{HV} \le 0.9$: $R=29.0\,|K_{DP}|^{0.77}$
  - Evaporation correction





Zhang et al. 2017; AMS radar Conf

At S-band: $R=4210A^{1.03}$

$$A(r) = \frac{Z^b(r)C(b,PIA)}{0.46b\int_{r1}^{r2} Z^b ds + 0.46b\left(\int_{r}^{r2} Z^b ds\right)C(b,PIA)}$$

Z: attenuated reflectivity

r_1 & r_2: beginning and ending ranges of rain segments in a given radial

$$C(b,PIA) = \exp(0.23bPIA) - 1$$

$$PIA(r_1,r_2) = \alpha\left[\phi_{DP}(r_2) - \phi_{DP}(r_1)\right]$$

b: ≈ 0.62

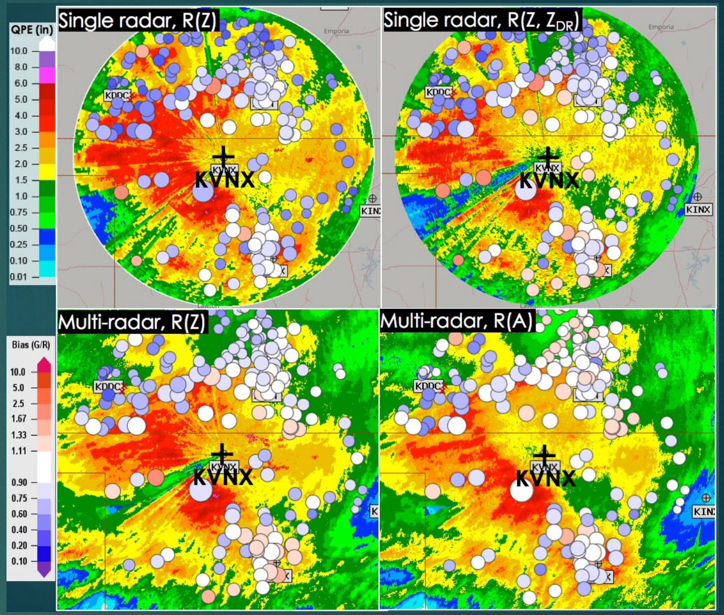
α: determined in real-time

Ryzhkov et al. 2014; *JTECH*

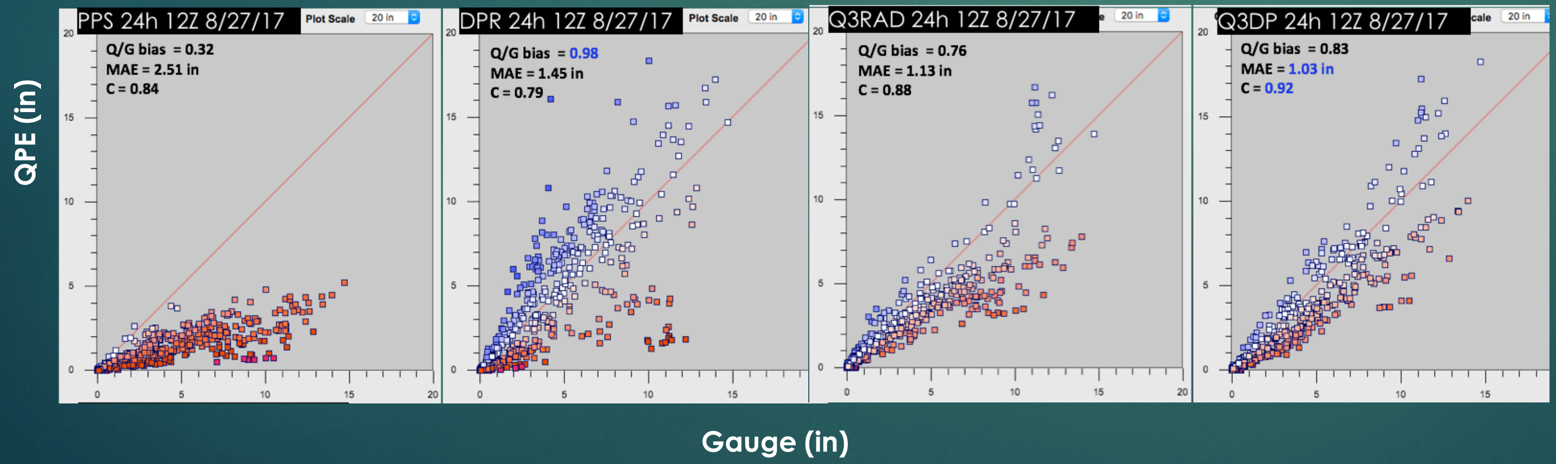
Multi-Radar, Dual-Pol (Q3DP)

- **Advances**
  - **insensitive to partial blockage**
  - **Insensitive to calibration errors in Z and Z_{DR}**
  - **Reduced overestimation in dry environment**
  - **Improved accuracy in extreme heavy rain**

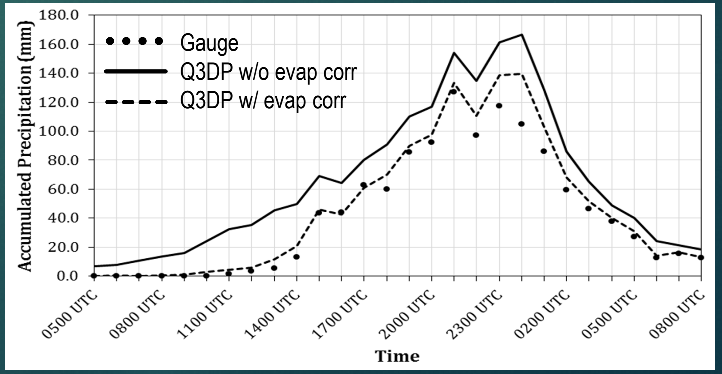
Blockages from trees



KGRK calibration issues: Z bias ≈ -4dBZ; Z_{DR} bias ≈ -1.8dB



Evaporation correction

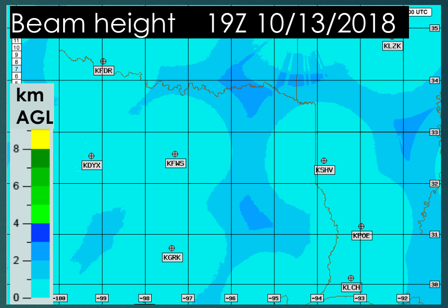


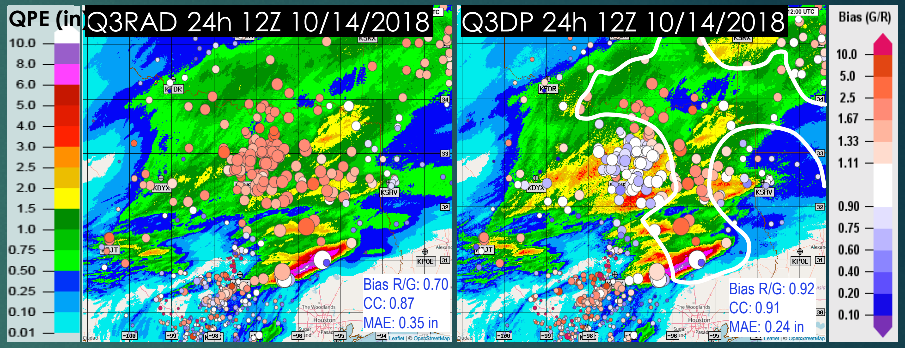
Martinaitis et al. 2018

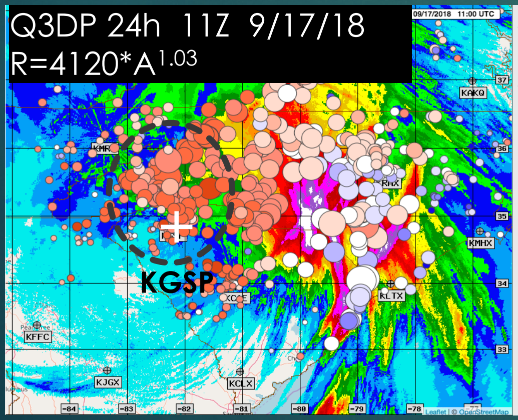
Multi-Radar, Dual-Pol (Q3DP)

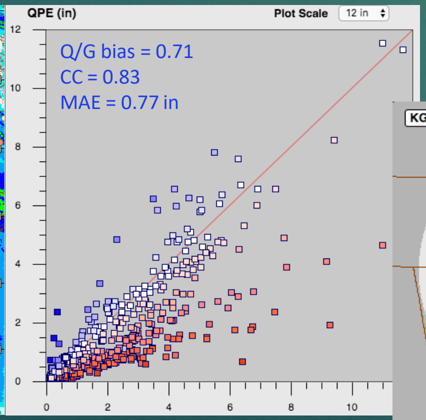
- **Issues**
  - Range dependent errors
    - Overshooting lower level precipitation enhancement due to warm rain or orographic processes
  - Underestimation in light *stratiform* rain

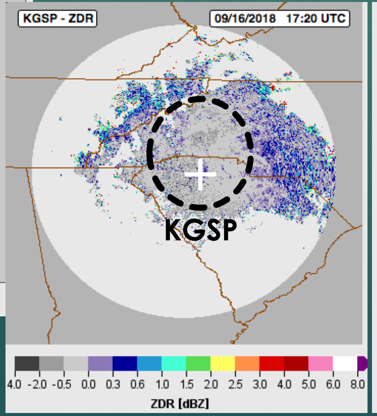
$Z_{DR} \approx 0$ & Z_{DR} slope ≈ 0

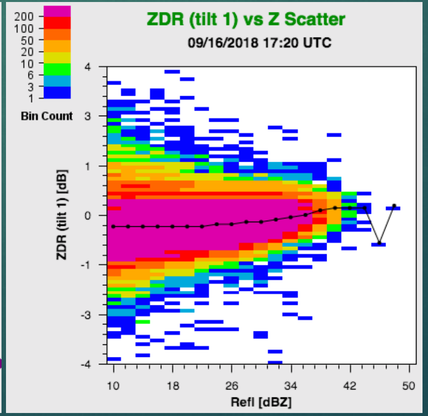


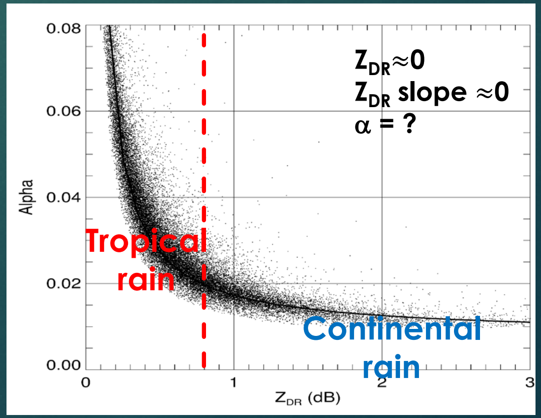












Advances at a Glance

Cocks 2018

QPE ↓	Gauge →	VL	L	M	H	E
Single radar Single-pol, **1 R(Z)**	VL	0.800	0.244	0.034	0.001	0
	L	0.196	0.658	0.402	0.041	0.007
	M	0.004	0.098	0.548	0.712	0.185
	H	0	0	0.013	0.181	0.308
	E	0	0	0.002	0.065	0.499
		VL	L	M	H	E
Single-radar Dual-pol **R(Z, Z_{DR}), R(K_{DP}), R(Z)**	VL	0.897	0.384	0.066	0.001	0
	L	0.102	0.565	0.495	0.070	0.001
	M	0.001	0.050	0.432	0.747	0.303
	H	0	0	0.007	0.169	0.445
	E	0	0	0	0.013	0.241
		VL	L	M	H	E
Multi-radar single-pol **Multiple R(Z)s, VPR corr**	VL	0.804	0.133	0.002	0	0
	L	0.194	0.790	0.353	0.018	0.004
	M	0.002	0.076	0.628	0.592	0.142
	H	0	0	0.015	0.324	0.344
	E	0	0	0.002	0.067	0.510
		VL	L	M	H	E
Multi-radar dual-pol **R(A), R(K_{DP}), R(Z), VPR & Evap corr**	VL	0.849	0.155	0.009	0	0
	L	0.149	0.753	0.286	0.010	0.002
	M	0.001	0.092	0.671	0.369	0.039
	H	0	0	0.031	0.488	0.307
	E	0	0	0.002	0.133	0.751

CONUS, May 2017 – Apr 2018
QPE/gauge pairs: ~122K

- '**Hit**' is when QPE category matched corresponding gauge category; otherwise, a '**Miss**'
- Multi-radar outperformed single-radar QPEs in the High to Extreme categories
- R(A) performed the best in moderate to extreme categories.

24hr Acc Categories:
*Very Lgt.(**VL**): G < 12.7mm*
*Lgt. (**L**): 12.7 ≤ G < 38.1mm*
*Mdt (**M**): 38.1 ≤ G < 101.6mm*
*Hvy (**H**): 101.6 ≤ G < 152.4mm*
*Ext (**E**): G ≥ 152.4mm*

Advances at a Glance

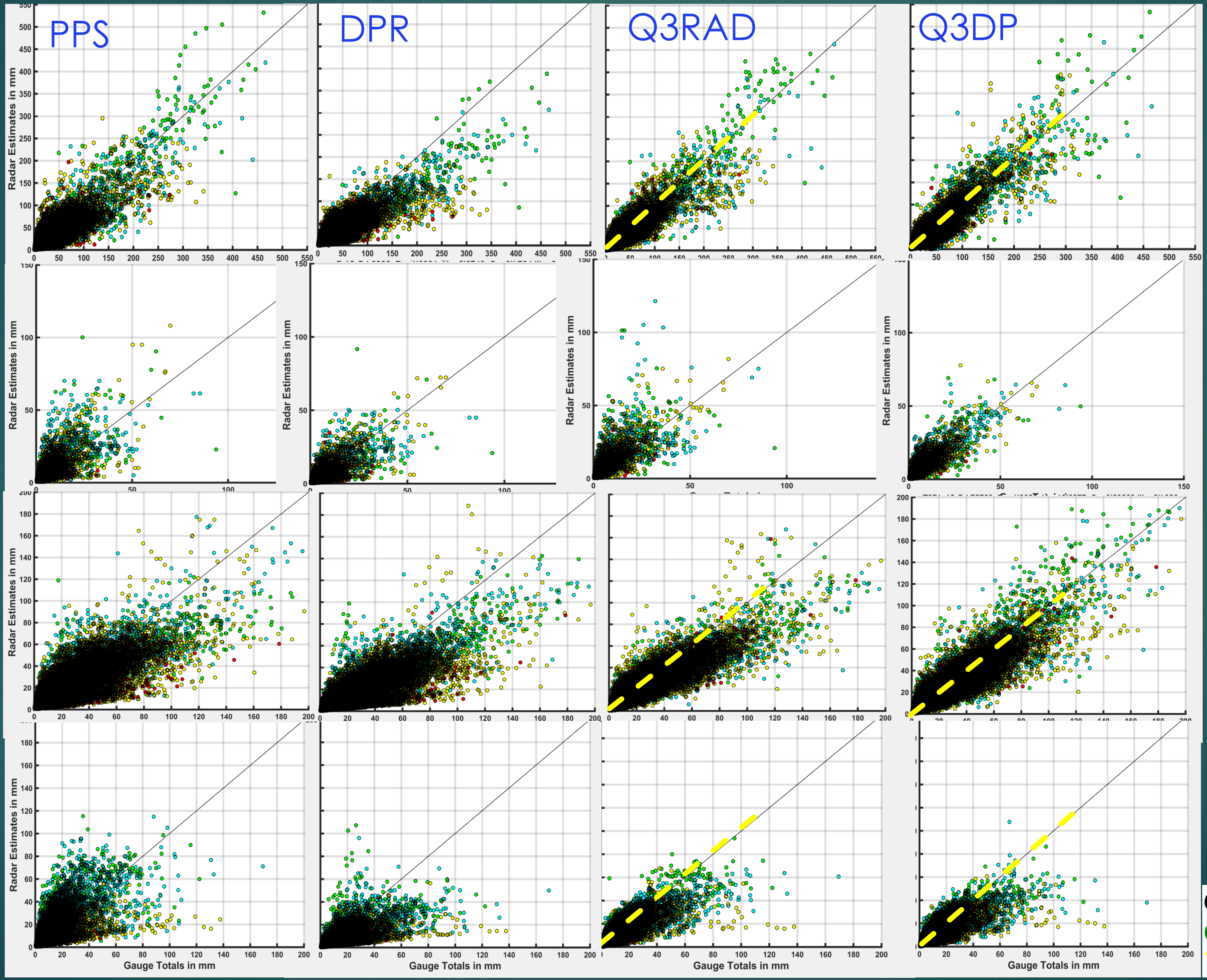
Cocks 2018

May-Sep 2017;
east of -105W
gauges: 41,750

May-Sep 2017;
west of -105W
gauges: 3,936

Oct 2017 – Apr 2018;
east of -105W
gauges: 25,259

Oct 2017 – Apr 2018;
west of -105W
gauges: 9,476



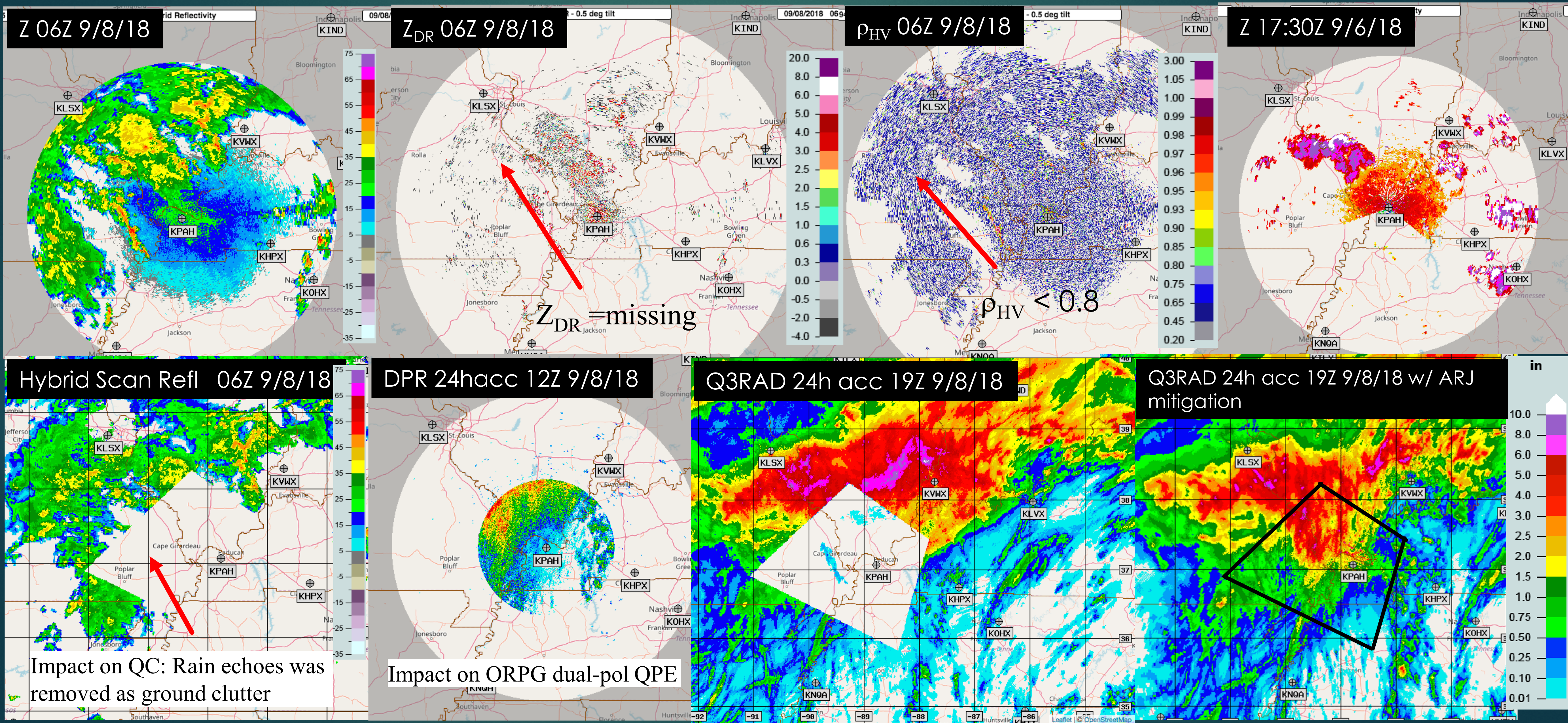
Prod	Q/G bias	CC	MAE (mm)
PPS	0.94	0.86	9.4
DPR	0.81	0.86	9.5
Q3RAD	0.99	0.90	7.5
Q3DP	1.02	0.92	7.1
PPS	1.25	0.69	4.9
DPR	0.99	0.73	3.9
Q3RAD	1.37	0.71	4.9
Q3DP	1.22	0.83	3.7
PPS	0.82	0.86	9.4
DPR	0.63	0.82	10.7
Q3RAD	0.88	0.89	7.2
Q3DP	0.93	0.90	6.7
PPS	1.11	0.63	8.5
DPR	0.56	0.65	8.0
Q3RAD	0.93	0.78	5.7
Q3DP	0.89	0.77	5.9

Color-coded range:
Green: ≤ 75 km; ***Blue : 75 – 150km***
Yellow: 150 – 225 km; ***Red: > 225 km***

Remaining Challenges

1) Radar data quality – calibration, hardware issues
2) Underestimation in light stratiform rain
3) Partial/complete overshooting of precipitation processes
4) Uncertainties in snow water equivalent estimation
5) Quality of validation data at hourly and sub-hourly scales, especially for snow

Challenges: Radar Hardware Problem

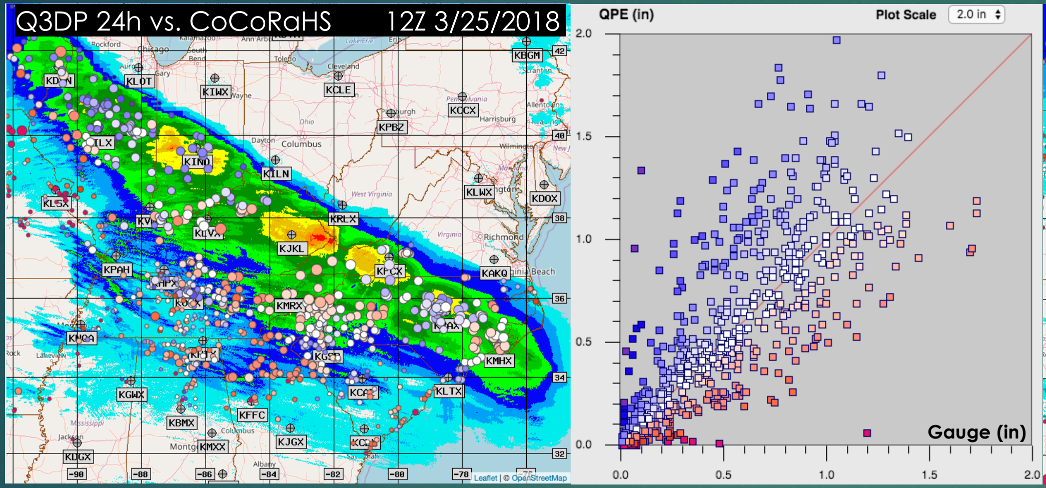


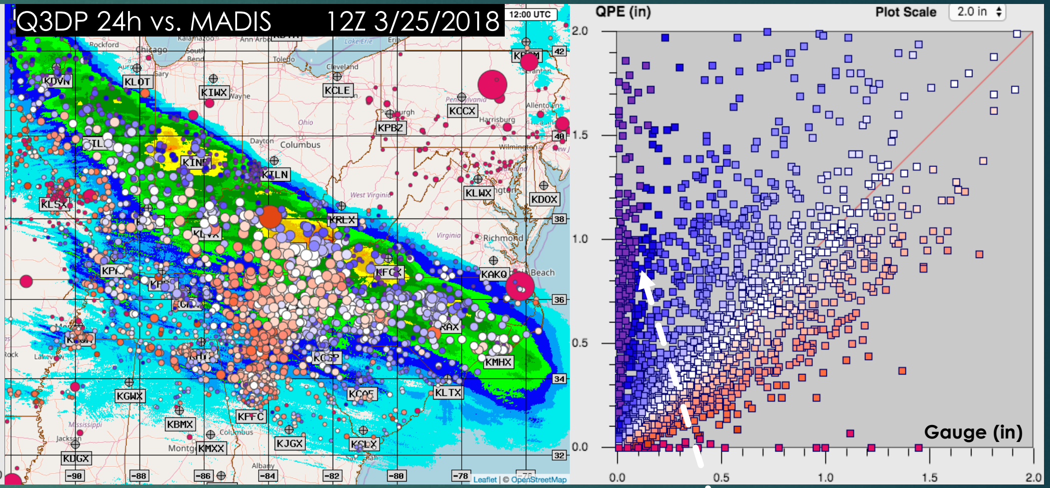
Challenges: Snow, Quality of Hourly Gauges

CoCoRaHS: daily, *manned* gauges by volunteers
https://www.cocorahs.org/

MADIS: hourly, *automated*, ASOS, local mesonets, gauges by state agencies, etc. https://madis.noaa.gov/

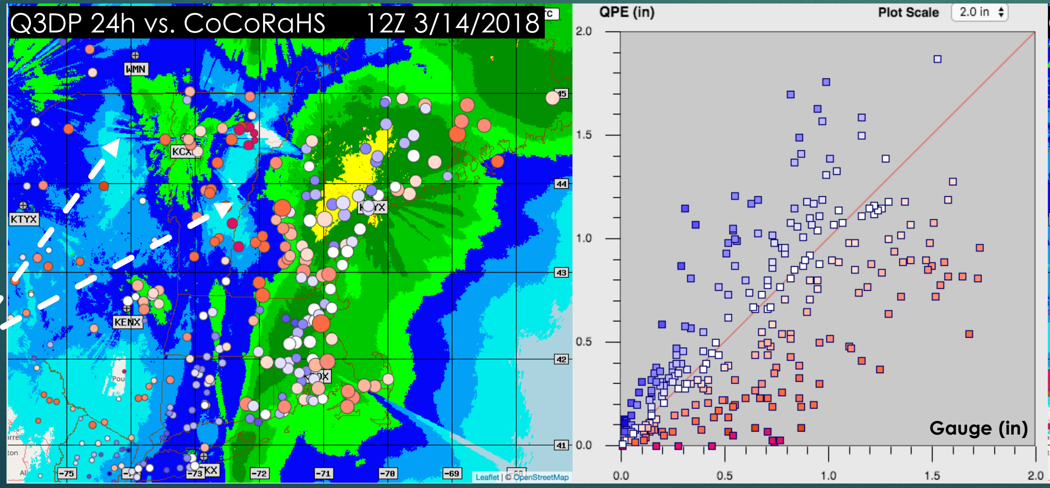
Snow/rain

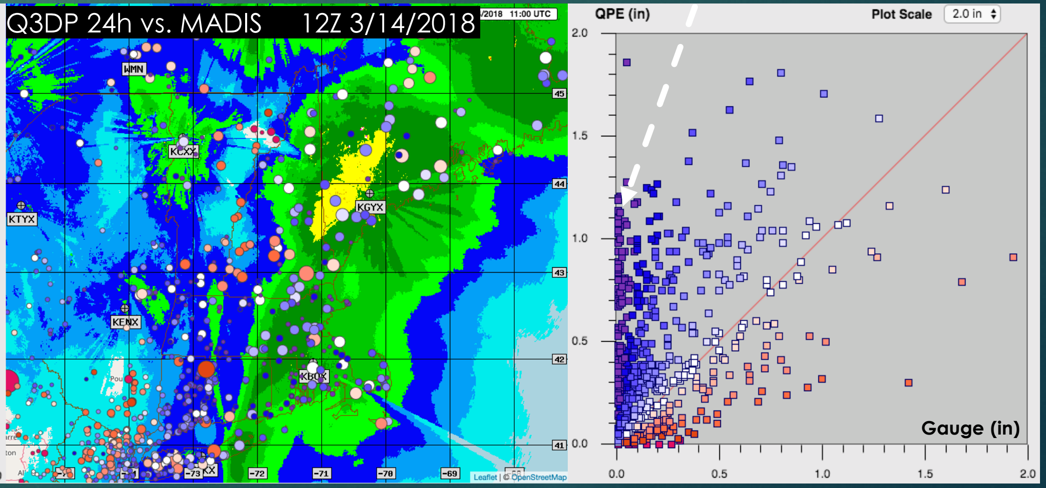




Frozen/stuck gauges?

Snow





Overshooting/
radar gaps

To Address the Challenges

1) Radar data quality – calibration, hardware issues
    - Radar hardware improvements
    - Software to mitigate the impact
2) Underestimation in light stratiform rain: more studies with radar data
3) Overshooting of precipitation processes at lower level and radar gaps:
    - VPR correction (for large scale, relatively homogenous systems)?
    - Gap-filling radars
    - Satellite and atmospheric models
4) Uncertainties in snow water equivalent (SWE) estimation
    - More basic studies
    - Initial experiment with WSR-88D dual-pol SWE estimation
5) Quality of validation data at hourly and sub-hourly scales, especially for snow
    - Multi-sensor gauge QC

Acknowledgment:

Steve Cocks, Steve Martinaitis, Lin Tang, Andrew Osborne, Micheal Simpson, Wolfgang Hanft, Carrie Langston, Brian Kaney and Ami Arthur

Thanks for your attention!

Acknowledgment: Steve Cocks, Steve Martinaitis, Lin Tang, Andrew Osborne, Micheal Simpson, Wolfgang Hanft, Carrie Langston, Brian Kaney and Ami Arthur