Assimilation of Polarimetric Radar Data into Stormscale Models with a Variational Scheme for Improving Short-term Severe Weather Forecasts

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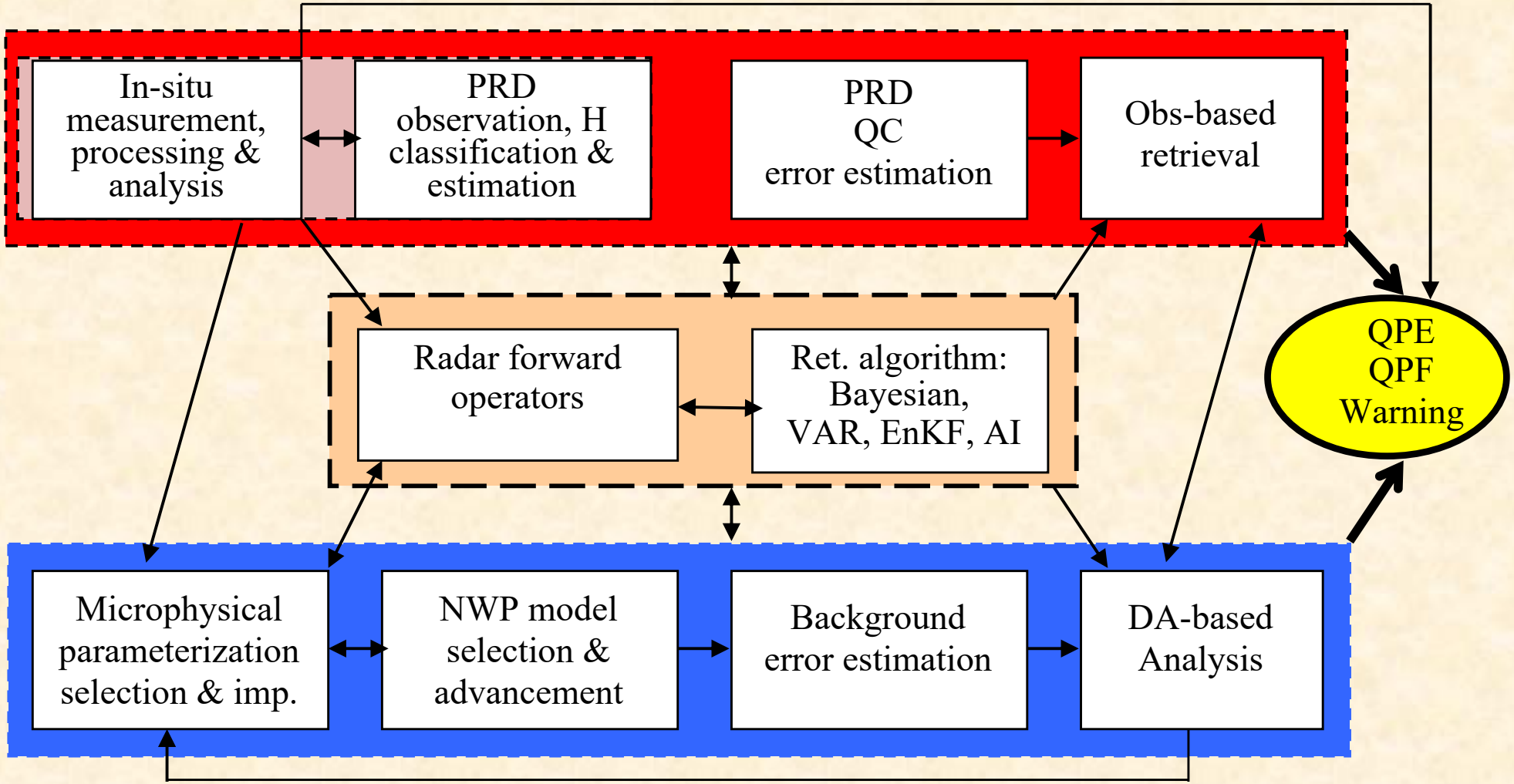
Acknowledgements: Guifu Zhang, Jacob Carlin, Muyun Du, Yunheng Wang, Pam Heinselman, Jeff Synder, Alexander Ryzhkov

Challenging research question

Assimilation of tradition 88D radar data like reflectivity and radial velocity is yet to be optimized. **How can PRD (polarimetric radar data) be exploited to improve stormscale quantitative precipitation and severe weather model forecasts?**

The answer: **Optimally combining knowledge from radar community and NWP community could help**. (Dr. Zhang's vision)

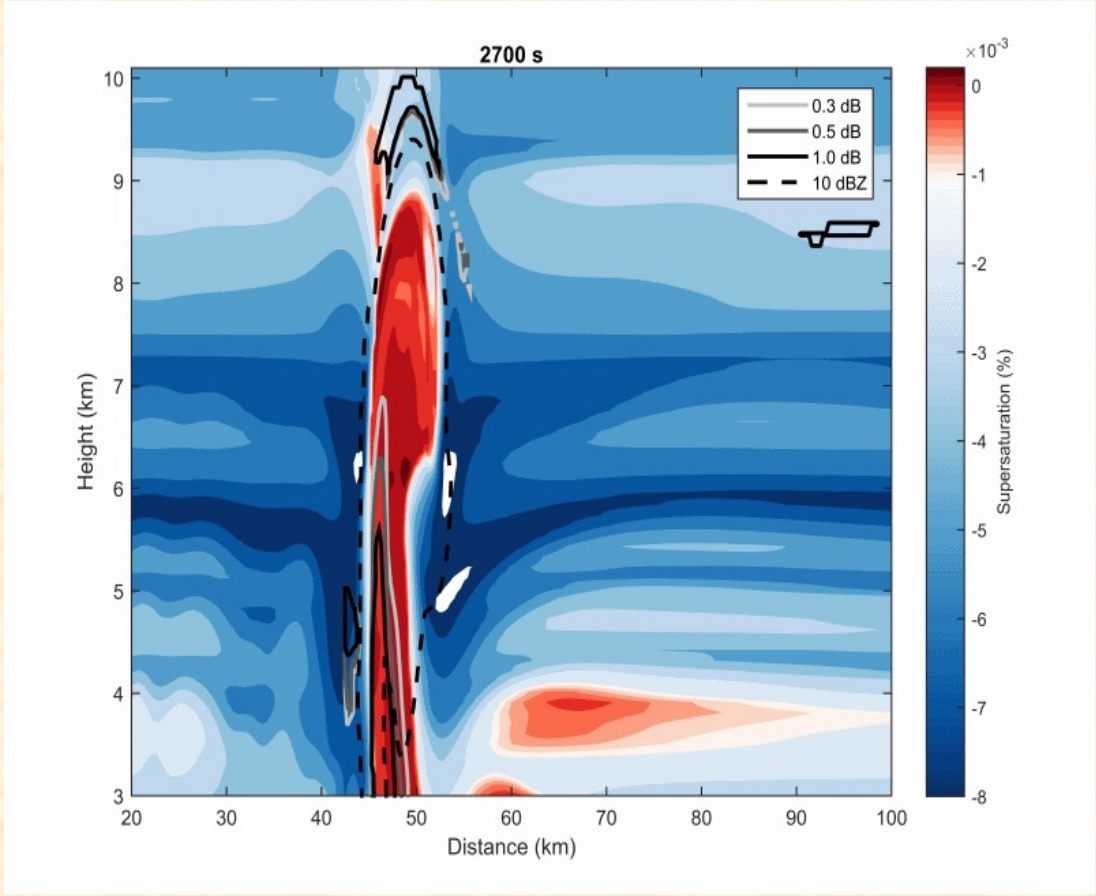


Zhang, G., and Coauthors, 2019: Current status and future challenges of weather radar polarimetry: Bridging the gap between radar meteorology/hydrology/engineering and numerical weather prediction. ***Adv. Atmos. Sci., 36(6)***, 571–588.

1: The impact of Obs. based retrieval & DA analysis: proof of concept

Part of Jacob Carlin's PhD study:

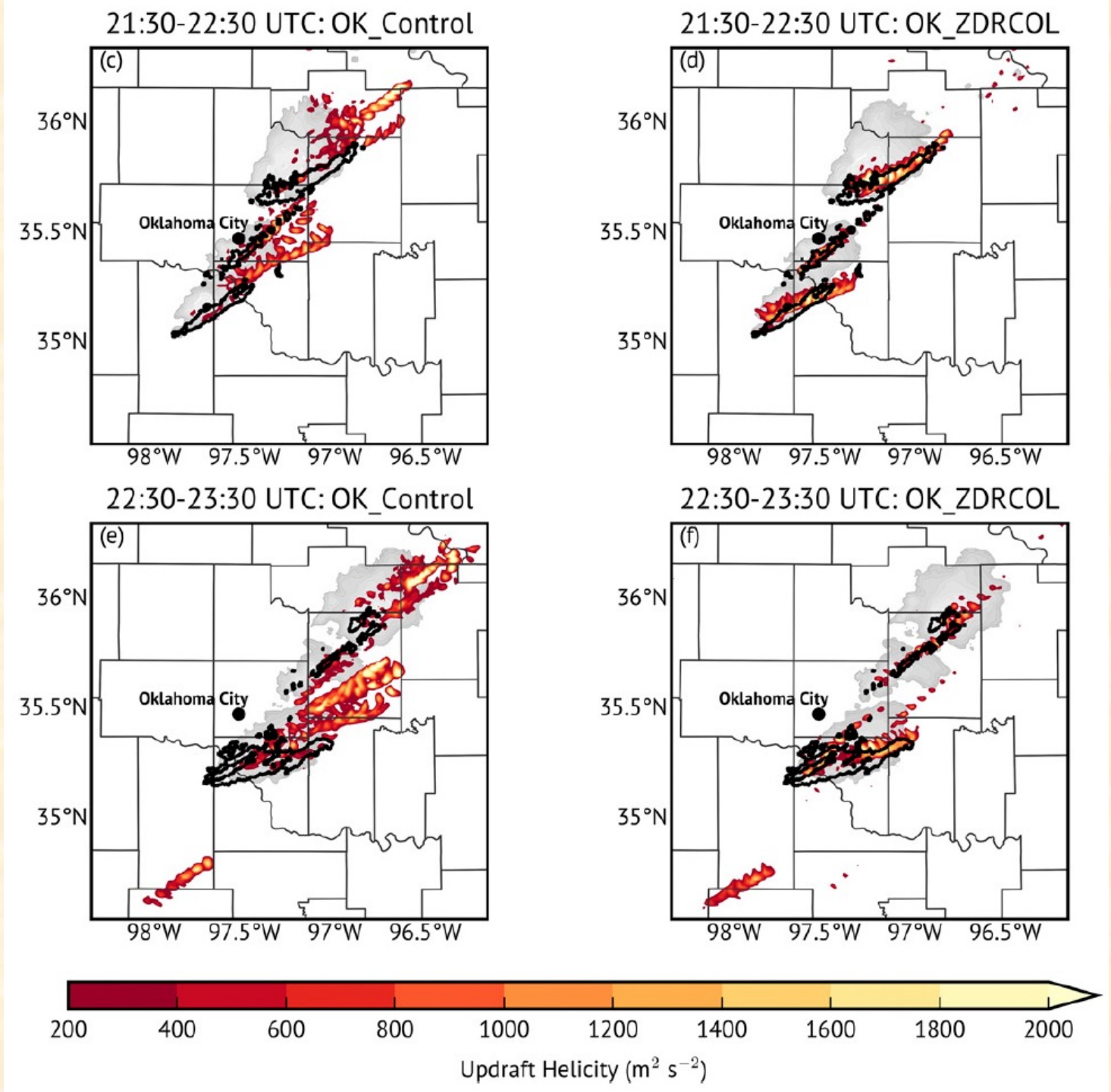
- Many difficulties remain with directly assimilating observed PRD.
- 88D radars do not directly observe moisture field & clouds, but moisture & clouds very important to stormscale modeling. Is it possible to retrieve qv first from Zdr?
- 2D cloud model simulation. The evolution of relative humidity (color shaded) and calculated Zdr columns (contours).
- Main areas of saturation (red color area) are coincident with Z_{DR} columns throughout the life cycle of storm.



Carlin, J. T., J. Gao, J. C. Snyder and V. Ryzhkov, 2017: Assimilation of ZDR Columns for Improving the Spin-Up and Forecast of Convective Storms in Storm-Scale Models: Proof-of-Concept Experiments. ***Mon. Wea. Rev.***, **144**, 2981-3001.

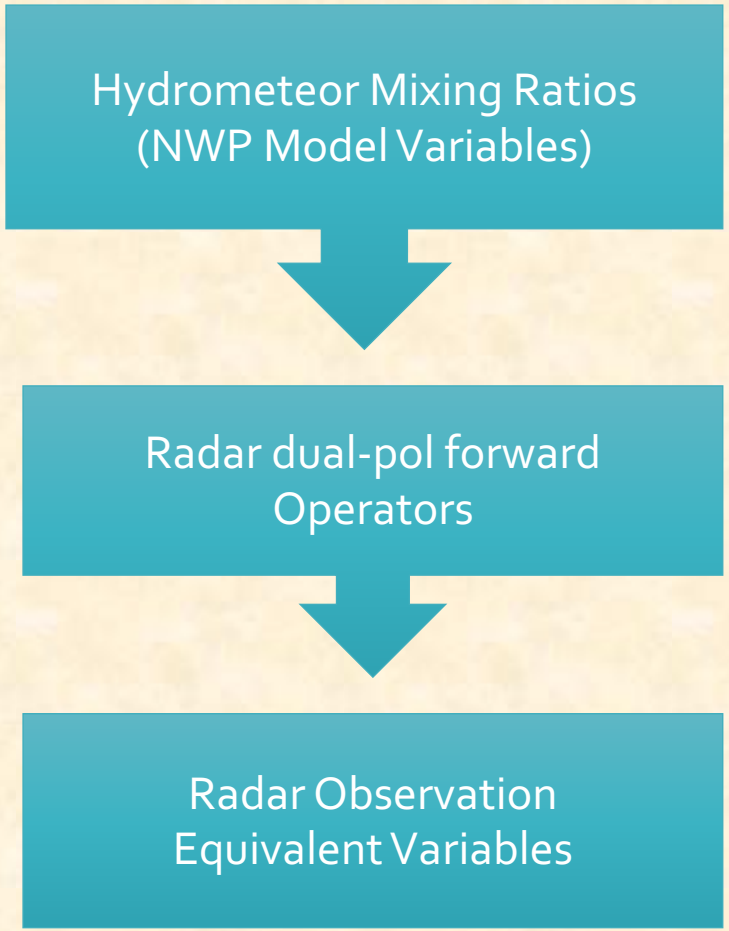
May 19, 2013 Shawnee tornado Case:

- Used ARPS 5.3.6 with 1km resolution ($\Delta x = \Delta y = 1$ km, 53 vertical levels).
- Assimilated OK Mesonet and 88D radar data (KTLX) every 15-min for 1 hour before launching 1-hr forecast. The results from two 1-hour forecasts are shown here.
- Left (Control): Assimilate Vr, Z only
  Right(Zdr Col): Assimilate both Vr, Z& Zdr col.
- Observed **MRMS** azimuthal shear tracks (**black**) and 1 hr forecasted 1-6 km AGL UH tracks (color shaded).
- For both 1 hour forecast, the predicted UH tracks from Zdr column Exp. match with the MRMS azimuthal shear tracks very well for all three storm tracks!



2: DA based Analysis and Forecast

DA methods exist &mature, develop suitable dual-pol Forward Operators first!



- Accurate radar forward operators make quantitative comparison between radar observations and model output feasible
- Inaccurate radar operators can lead to errors in simulations of radar variables, parameter retrievals and also model forecast

One example of existing dual-pol operators

$$Z_x = \frac{4\lambda^4}{\pi^4 |K_w|^2} \int_0^\infty |S(\pi)|^2 N(D) dD \qquad Z_H = 10 \log_{10}(Z_r + Z_s + Z_g + Z_h)$$

(Jung et al. 2008, 2010, *Mon. Wea. Rev.*
& many other research)

- Advantages
  - ✓Allows for particle scattering calculated using T-matrix method
  - ✓More accurate for large particles, like hail and melting snow
  - ✓Can generate realistic dual-pol variables
- Shortcomings
  - ✓Computationally expensive
  - ✓Non-differentiable
  - ✓Numerical integration makes the applications of these operators more difficult.

So I raised these shortcomings for NWP application to Dr. Guifu Zhang several years ago.

New Simplified Dual-Pol Operators

For a given DSD model, hydrometeor mixing ratio (q_x) and the number concentration N_{tx} can be converted to mass-weighted diameter D_{mx}=f(q_x, N_{tx}). Radar variables can be parameterized in terms of a polynomial function of D_{mx}.

As an example, for rain we have:

$$Z_h \approx \rho_a q_r \left(-1.725 + 28.49 D_m + 36.046 D_m^2 - 1.746 D_m^3 - 0.4899 D_m^4\right)^2$$ reflectivity

$$Z_{dr} \approx 1.019 - 0.143 D_m + 0.317 D_m^2 - 0.065 D_m^3 + 0.00416 D_m^4$$ differential reflectivity

$$K_{DP} \approx \rho_a q_r \left(-0.0356 D_m + 0.132 D_m^2 + 0.00320 D_m^3 - 0.00302 D_m^4\right)$$ specific differential phase

$$\rho_{hv} \approx 0.999 + 0.00826 D_m - 0.0117 D_m^2 + 0.00361 D_m^3 - 0.000344 D_m^4$$ correlation coefficient

For contributions from snow, graupel, similar formulations have been developed as well.

Features of New Dual-Pol Radar Operators

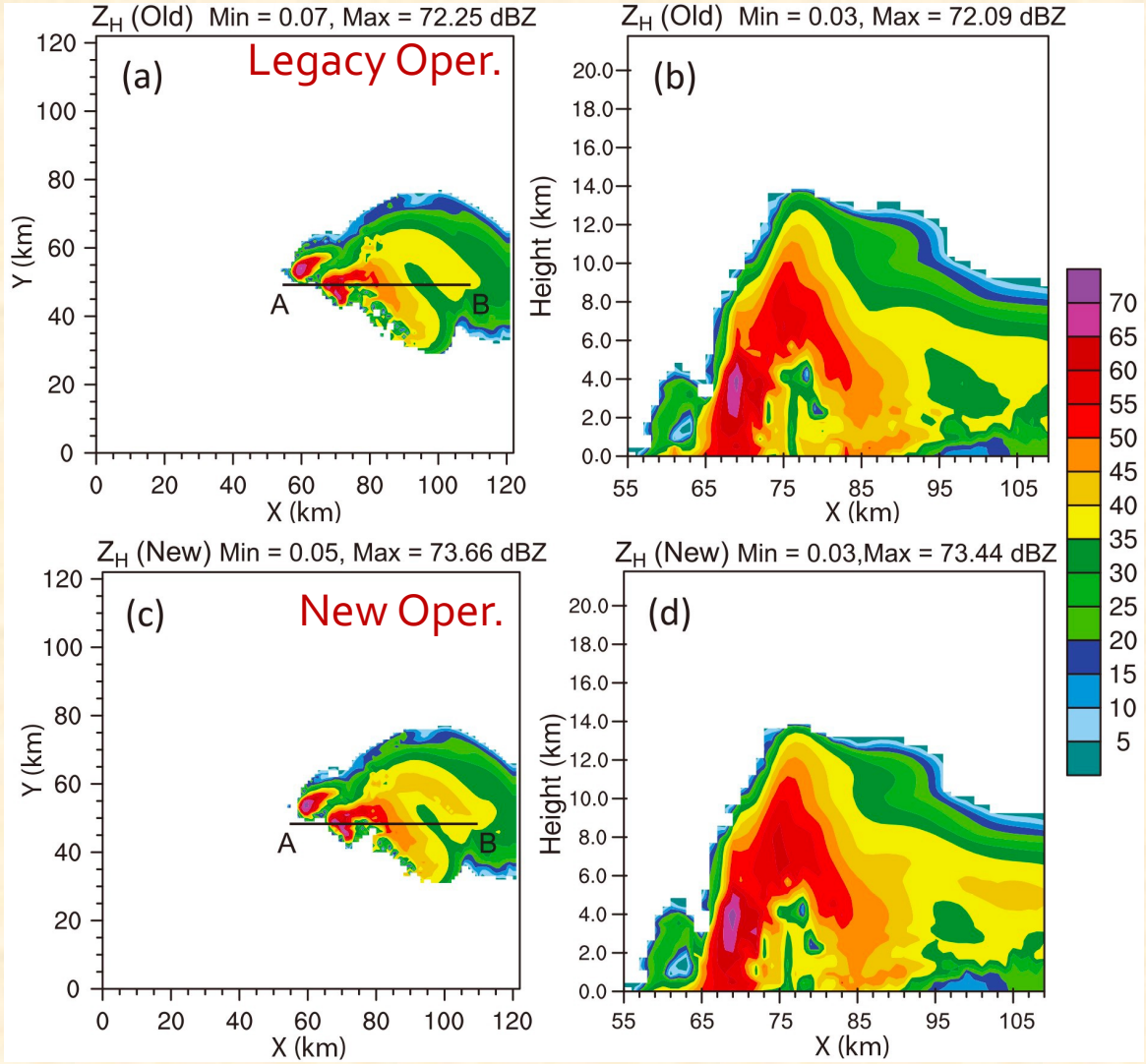
- Run much faster than the forward operators developed by using numerical integration.
- The new operators are differentiable so that they can be easily used in any DA schemes, including variational DA methods.

Zhang, G., J. Gao, and M. Du, 2021: Parameterized Forward Operators for Simulation and Assimilation of Polarimetric Radar Data with Numerical Weather Predictions, *Adv. Atmos. Sci.* **38**, 737-754.

Idealized case study with the dual-pol operators:

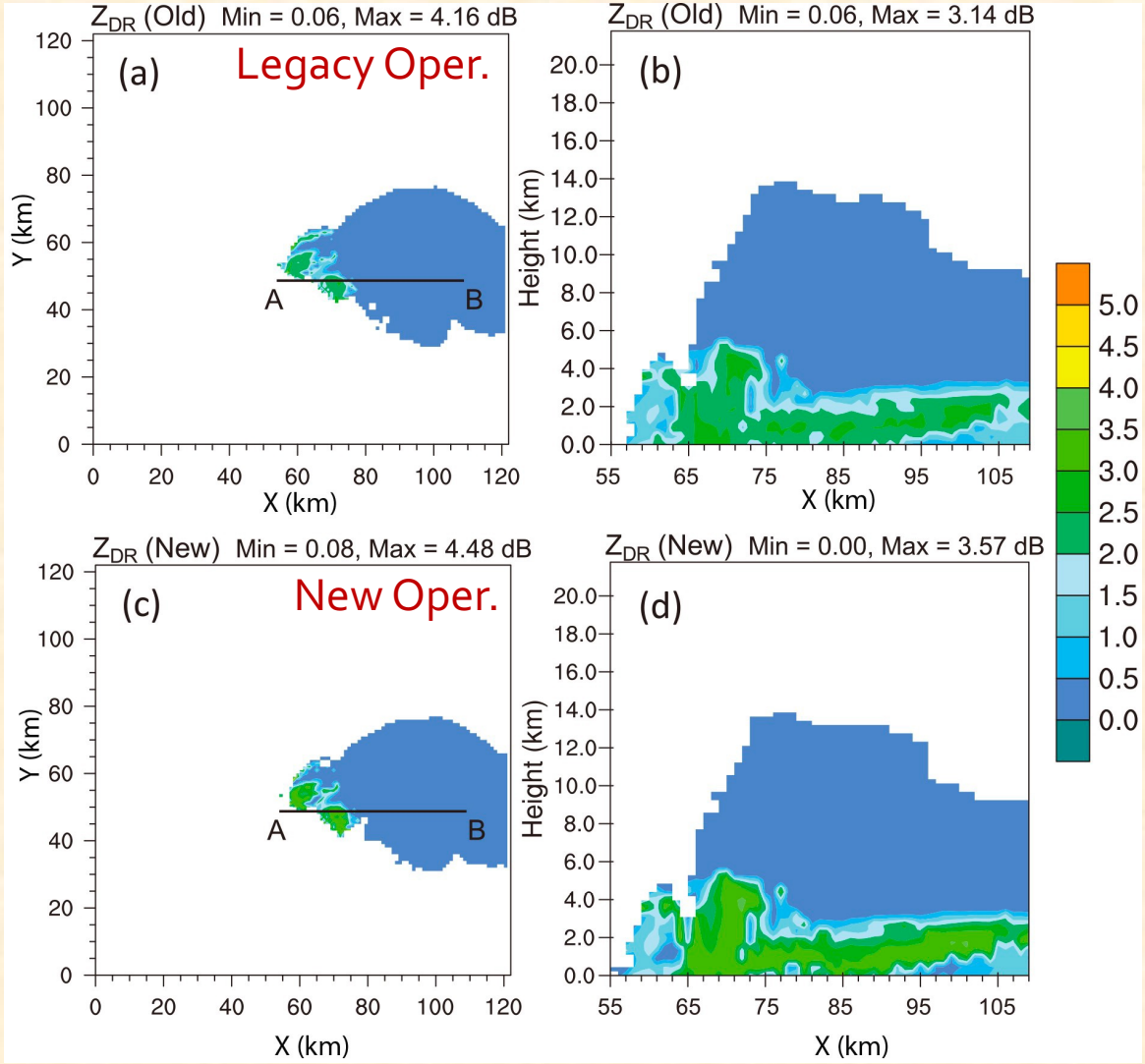
horizontal reflectivity

- Use WRF model 3.7.1 to generate a supercell storm with the Milbrandt-Yau 2-moment microphysics scheme.
- Model parameters: dx = dy = 1 km, dz = 500 m; nx = ny = 121; nz = 51.
- simulated-obs. for V_r, Z_H, Z_{DR}, K_{DP}, ρ_{HV} are generated from model output.

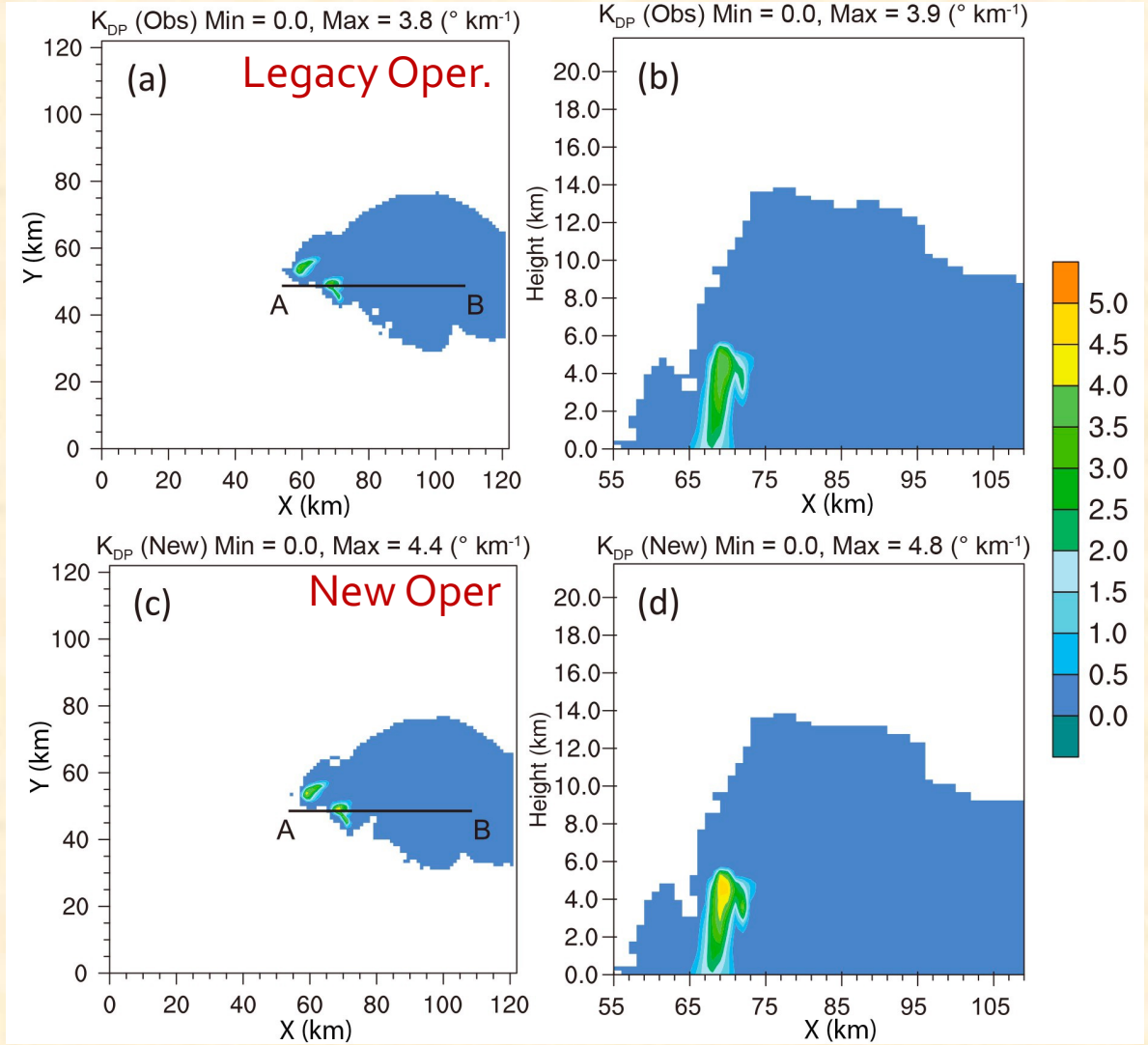


The legacy operators developed and released by CAPS (Jung et al. 2008, Mon. Wea. Rev.)

differential reflectivity (ZDR)



specific differential phase (Kdp)



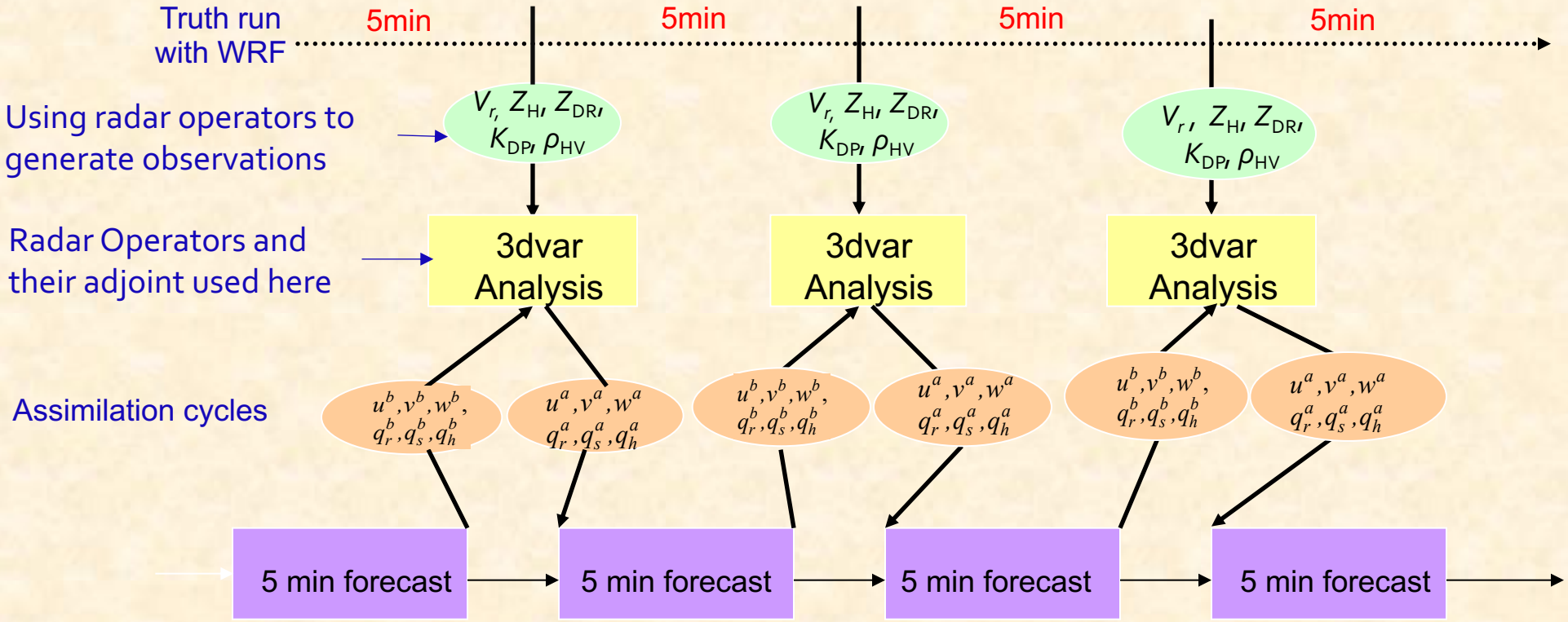
How efficient of the new PRD forward operators?

Table 5. List of computational CPU time (seconds) used for calculating radar variables from WRF model hydrometeor output (domain size is different for idealized and real data cases).

Event	Idealized case	Real data case
Old numerical integration operators	10.55	243.1
New parameterized operators	0.098	2.287

The new operators are 100x faster than the legacy ones, good enough for DA applications.

Continuous cycles of a radar DA scheme (3dvar)



Each DA cycle includes two steps: analysis and forecast.

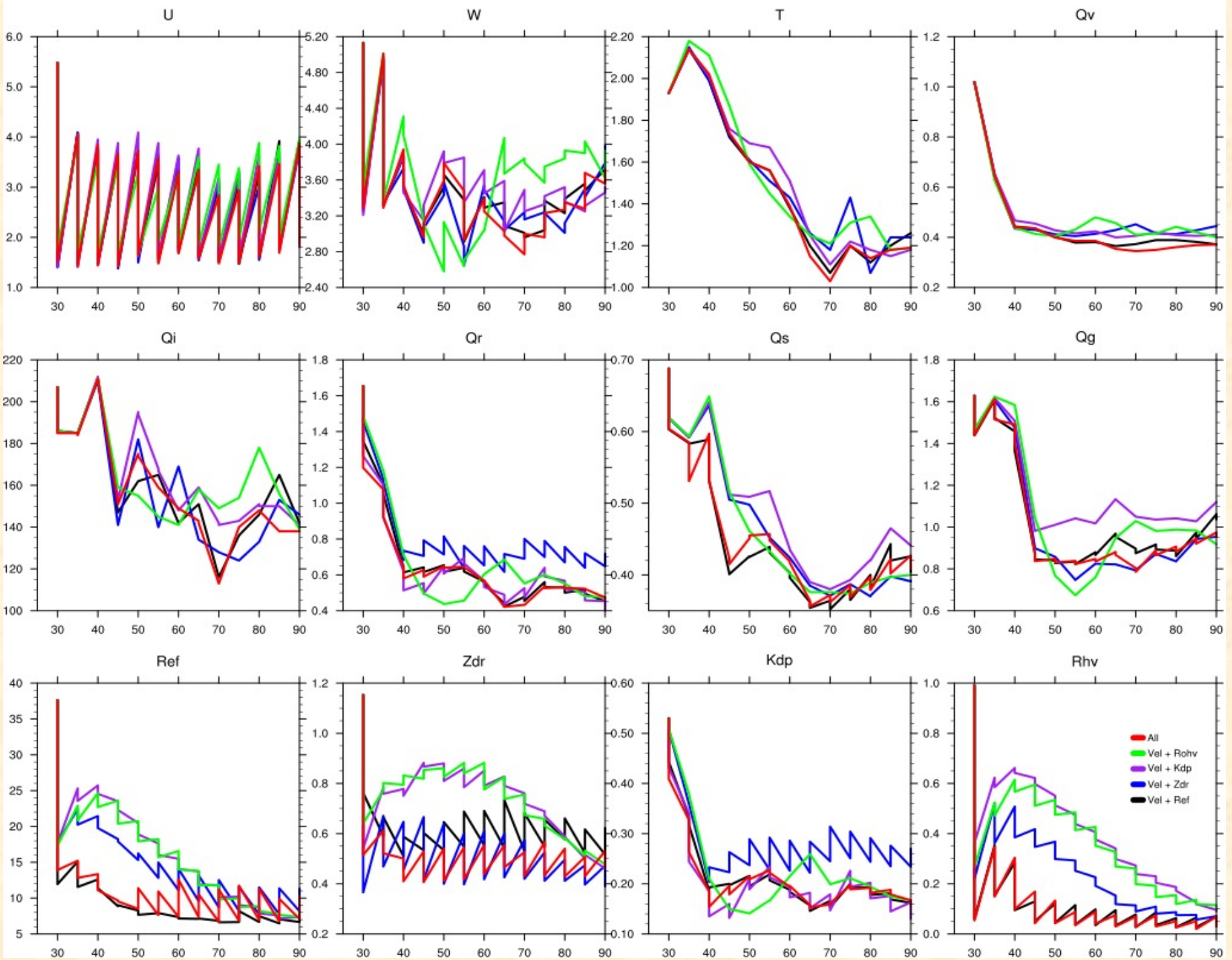
Du, M., J. Gao, Y. Wang, P. L. Heinselman, and C. Cui, 2021: Assimilation of Polarimetric Radar Data in Simulation of a Supercell Storm with a Variational Approach and the WRF Model, *Remote Sensing*. 13, 3060.

Exp. with an idealized supercell storm

Five DA Experiments:

(1) V_r+Z_h: black curve
(2) V_r+Z_{dr}: blue
(3) V_r+K_{dp}: purple
(4) V_r+Rhv: green
(5) V_r+Z_h+Z_{dr}+K_{dp}+Rhv: red

Variations of RMS errors for selected model & radar variables with time (minutes)



3: Future Work

New NSF grant: Hybrid Ensemble Variational Analysis of Polarimetric Radar Data to Improve Microphysical Parameterization and Short-term Weather Prediction. **PIs:** Guifu Zhang(SoM); Jacob Carlin(CIWRO) & Jidong Gao(NSSL), 3 years, $655K (Collaborations inside NWC)

- Further develop PRD forward operators for different microphysics schemes (i. e, link with NSSL 2-moment scheme);
- Quantify both PRD measurement errors and forward operator errors;
- Simulation severe storms using convective-scale NWP models with PRD operators, and do comparison with real radar PRD;

Future Work (cont'd)

- To use the new operators in Hybrid Variational & EnKF DA and try to see if these data can help improve severe weather forecast.
- To combine research on Zdr column based retrievals and DA based analysis with multiple radars.
- Do research to see if these operators are useful to the WoF applications.