4D-Var Data Assimilation of Radar Observations for Short-term Prediction Of Convective storms

Juanzhen Sun

National Center for Atmospheric Research
Boulder, CO, USA

Collaborators: Ying Zhang, Guifu Zhang, Andrew Crook, and Ed Brandes
OUTLINE

• Background: radar data assimilation and the VDRAS 4D-Var system

• Assimilation of multiple Doppler observations for an IHOP squall line case

• Use of radar data to improve microphysics
  a. Microphysical parameter retrieval
  b. Improving microphysical parameterization

• Assimilation of refractivity data

• Summary
Why was VDRAS developed

• Radars provide high-resolution observations that are able to sample the structure of convective storms

• A fundamental question for the effective use of these observations for the initialization of a high-resolution model is whether the unobserved variables can be retrieved

• The Variational Doppler Radar Analysis System (VDRAS) was initially developed as a research tool to answer this fundamental question

• Studies have shown that the 3D wind, temperature, and microphysics can be obtained with reasonable accuracy with the 4D-Var technique in VDRAS

• VDRAS was used as a real-time low-level wind analysis system since 1998 at a number of sites for nowcasting purposes
Main Features of VDRAS

• A 4D-Var system with the full adjoint of an anelastic cloud-scale model with Kessler-type warm rain parameterization

• Radar data are assimilated with a 4D-Var cycling procedure which has a 12 minutes assimilation cycle (three radar volumes) and a short forecast cycle

• Surface data, VAD analysis, and soundings extracted from a mesoscale model are analyzed using a Barnes scheme to provide a mesoscale background for the 4D-Var radar data assimilation

• A recursive filter is used for preconditioning and background error correlation

• Radar data quality control and interpolation from the radar coordinates \((r, \phi, \theta)\) to a PPI coordinates \((x, y, \theta)\) are performed prior to the data assimilation
Cost Function

\[ J = J_b + J_o + J_{mb} + J_p \]

Background term:

\[ J_b = (x_0 - x_b)^T B^{-1} (x_0 - x_b) \]

Observation term:

\[ J_o = \sum_{\sigma, t} \left[ \eta_v (v_r - v_r^o)^2 + \eta_z (q_r - q_r^o)^2 \right] \]

Penalty term:

\[ J_p = \sum_{\sigma, t, i, j} \alpha_{1i} \left( \frac{\partial^2 A_j}{\partial x_i^2} \right)^2 + \alpha_{2i} \left( \frac{\partial^2 A_j}{\partial t^2} \right)^2 \]
Cost Function

\( v_r - (u,v,w) \) Relation:

\[
v_r = \frac{x - x_r}{r} u + \frac{y - y_r}{r} v + \frac{z - z_r}{r} (w - V_T)\]

\( Z - q_r \) Relation

\[
Z = 43.1 + 17.5 \log_{10} (\rho q_r)
\]
Assimilation of multiple radars for an IHOP squall line case (June 12, 2002)
IHOP domain and observations

Red letters: NEXRAD
White letters: RAOB
Wind barb: Metars
IHOP June 12-13 Squall Line

Column maximum reflectivity (hourly)

24 hour accumulated precipitation
Three hour forecast compared with observations
Frame interval is 15 Min.
Cold pool evolution

Forecasts of temperature perturbation

$t = 0$

$t = 1.5$ hr

$t = 3$ hr
Vertical velocity at $z = 5.25$ km
Use of radar data to improve microphysics

• Microphysical parameter retrieval
• Improving microphysical parameterization
Microphysical parameter retrieval through 4D-Var radar data assimilation

• Traditionally these parameters were tuned empirically

• They were not optimal in terms of producing the best forecast

• 4D-Var and radar observations provide a possibility to optimally tune these parameters

• Whether one can optimally determine them depends on their sensitivity relative to that of the initial conditions

• We have found the terminal velocity and the evaporation rate are the two most sensitive parameters in our model
Rain-drop terminal velocity:

\[ V_{Tm} = V_0 a (\rho q_r)^{0.125} \]

Evaporation rate of rain:

\[ R_e = \beta_e (q_v - q_{vs})(\rho q_r)^{0.65} \]
Simulated data experiments

Change of the parameters with respect to iteration number
Real data experiments of a supercell storm (STEPS June 29, 2000)

Optimal estimation of the terminal velocity resulted in the improvement of the forecast.
Can we improve the microphysical parameterization using polarimetric radar observations?

**Marshal-Palmer rain DSD model**: \( N(D) = N_0 \exp(-\Lambda D) \), \( N_0 = 8 \times 10^6 \, \text{m}^{-4} \)

\[ Z_H \rightarrow W \]

**Constrained-Gamma rain DSD model**: \( N(D) = N_0 D^\mu \exp(-\Lambda D) \)

\[ (Z_H, Z_{DR}) \rightarrow (W, D_0) \]

Resulting parameterization schemes:
- **M-P DSD model**: power law relations
- **C-G DSD model**: polynomial relations

Parameterization schemes based C-G model agree better with observations and present less nonlinearity
Comparison of model parameterizations with disdrometer observations

Evaporation

Accretion

Terminal velocity
Comparison of the M-P and C-G schemes and their derivatives

Parameterized Process

Derivative
Comparison of model simulations with observations using M-P and C-G schemes

\[ t = 0 \text{ min.} \]

Observation  |  M-P  |  C-G
---|---|---

\[ t = 30 \text{ min.} \]

Observation  |  M-P  |  C-G
Assimilation of refractivity observations

What impact of the refractivity data have on convective initiation?
A new term in the cost function and the adjoint

Refractivity is related some model variables through:

\[ N = 77.6 \frac{P}{T} + 3.73 \times 10^5 \frac{e}{T^2} \]

\[ e \uparrow 1\,mb \iff N \uparrow 5 \]

Sensitivity of each variable:

\[ T \uparrow 1^\circ C \iff N \downarrow 0.5 \]

\[ P \uparrow 1\,mb \iff N \uparrow 0.26 \]

Assimilate \( q_v \) instead of \( N \):

\[ N \rightarrow e \rightarrow q_v \]

Cost function:

\[ J_{\text{new}} = J_{\text{old}} + \sum_{t,\sigma} \eta_r (q_v - q_v^{ob})^2 \]
An storm was initiated at the intersection of two convergence lines and the region of high refractivity values.
Analysis of relative humidity and velocity convergence fields

Relative Humidity

Without Refractivity

With Refractivity

Velocity Convergence

Without Refractivity

With Refractivity
30 min. forecast of rain water mixing ratio

With Refractivity

Without Refractivity
Summary

• The simulation of an IHOP squall line initialized by multiple radar data and a 4D-Var scheme showed promise and the 3 hour forecast agrees well with observations

• Preliminary results from a study on the optimal tuning of the parameters in microphysical schemes showed encouraging results, but more studies with real data are necessary to draw solid conclusions

• Microphysical parameterization schemes based on the constrained-gamma DSD model resulted in better analysis and forecast for the stratiform rain region.

• Refractivity data provide observations of low-level moisture variability and these data can be used through data assimilation to improve the forecast of initiation of individual convection. Further studies are needed to determine their effectiveness.
Three Hour Forecast of the June 12, 2002 Squall Line Observed During IHOP

The forecast was performed using a cloud model initialized by data from four NEXRADs using a 4D-Var radar data assimilation system.

Data assimilation of multiple radars to improve short-term QPF
WRF low-level
Rain water mixing ratio

Radar observation

WRF Forecast (12h and 15h)