NRL Four-dimensional Variational Radar Data Assimilation for Improved Near-term and Short-term Storm Prediction

Allen Zhao, Teddy Holt, Paul Harasti, Amerault Clark, Liang Xu, Nancy Baker, James Doyle, Yi Jin, Hao Jin, Mike Frost

Marine Meteorology Division, Naval Research Laboratory (NRL), Monterey, CA

Qin Xu

National Severe Storms Laboratory (NSSL), Norman, Oklahoma

Hway-Jen Chen

Naval Postgraduate School (NPS), Monterey, CA

Boon Chua, Dan Geiszler

Science Applications International Corporation (SAIC), San Diego, CA

Introduction

- Naval Research Laboratory (NRL) recently developed a four-dimensional variational (4DVar) radar data assimilation technique for the Navy's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®) to improve near-term (0-6h) and short-term (0-72h) forecasts of maritime storms.
- The objective of this development is to provide the model initial fields with improved depiction of storm structures as well as the mesoscale and large-scale environment for storm development.
- COAMPS®-4DVar recently developed at NRL is used as the framework for the assimilation of Doppler radar data along with conventional and satellite observations.
- Storm observations from weather Doppler radars along US coastal lines and tactical Doppler radars onboard US Navy ships have been used to develop and test the radar data assimilation system.
- The study is to investigate the impact of Doppler radar observations of storms on improved forecasts of severe weather events over oceans and in coastal regions.

NRL 4DVar Radar Data Assimilation

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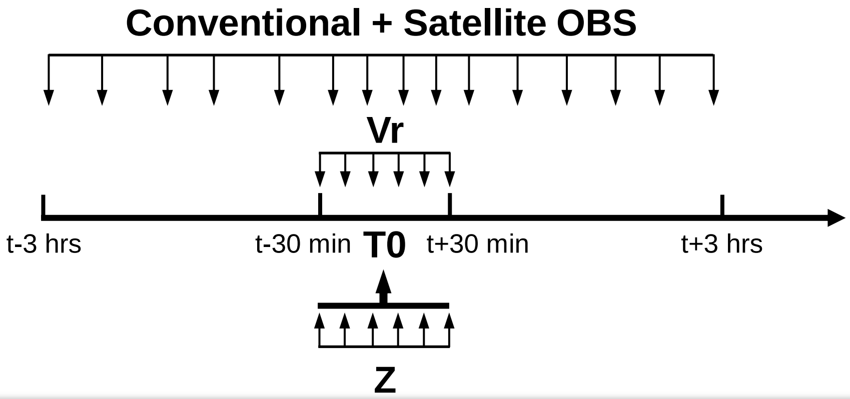
Linear operator for Doppler velocity (V_r):

$$V_r = \frac{1}{S}[(x_d - x_r)u + (y_d - y_r)v + (z_d - z_r)(w - V_t)]$$

$$S = \sqrt{(x_d - x_r)^2 + (y_d - y_r)^2 + (z_d - z_r)^2}$$

Where

- (x_d, y_d, z_d) is obs location
- (x_r, y_r, z_r) is the radar location
- V_t is the terminal velocity of precipitation



Nonlinear operator for radar reflectivity (Z):

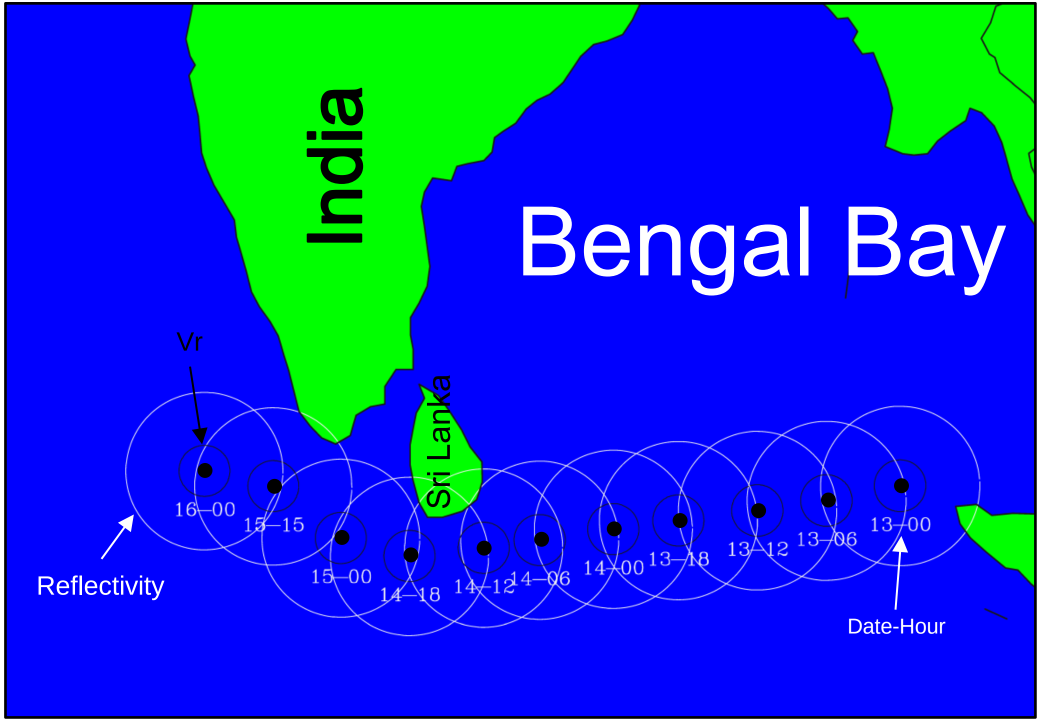
$$Z = 10 * \log(a_r M_r^{b_r} + a_s M_s^{b_s} + a_g M_g^{b_g})$$

Where

- M_r, M_s, and M_g are water content of rain, snow, and graupel
- a_r, b_r, a_s, b_s, a_g, and b_g are the parameters determined by Marshall and Palmer (1948), Gun and Marshall (1958) and Douglas (1964) for rain, snow, and graupel

- 4DVar techniques are used for assimilating V_r data along with conventional and satellite obs
  a. A super-obs algorithm for V_r
  b. DA windows: **1**-hr for Vr, **6**-hr for conventional+satellite data
- An innovative approach was developed to assimilate radar reflectivity (Z) within COAMPS®-4DVar framework
  a. Share the major DA procedures and I/O with the 4DVar except a separate 3DVar cost function minimization procedure
     - Avoid the need for adjoint/TLM of COAMPS microphysics
  b. Improve consistency between storm dynamics and physics in model initial fields
  c. Effective and efficient

Test with Single Shipboard Doppler Radar Data



- A US Navy ship (the black dot) encountered strong convective storm systems on October 13-15, 2012 near the tip of India while traveling across Indian Ocean
- The shipboard Doppler radar continuously observed the storm system every 10 minutes
- Radar data coverage:
  - Z – 261 km data cut off, 22 tilts (0.1 - 22.0 degrees, large white circles)
  - V_r – 81 km data cut off, lowest 3 tilts (small black circles)

Three experiments:

CNTL – Conventional+Satellite

Vr – Conventional+Satellite+Vr

(Vr+Z) – Conventional+Satellite+Vr+Z

Test with Single Shipboard Doppler Radar Data

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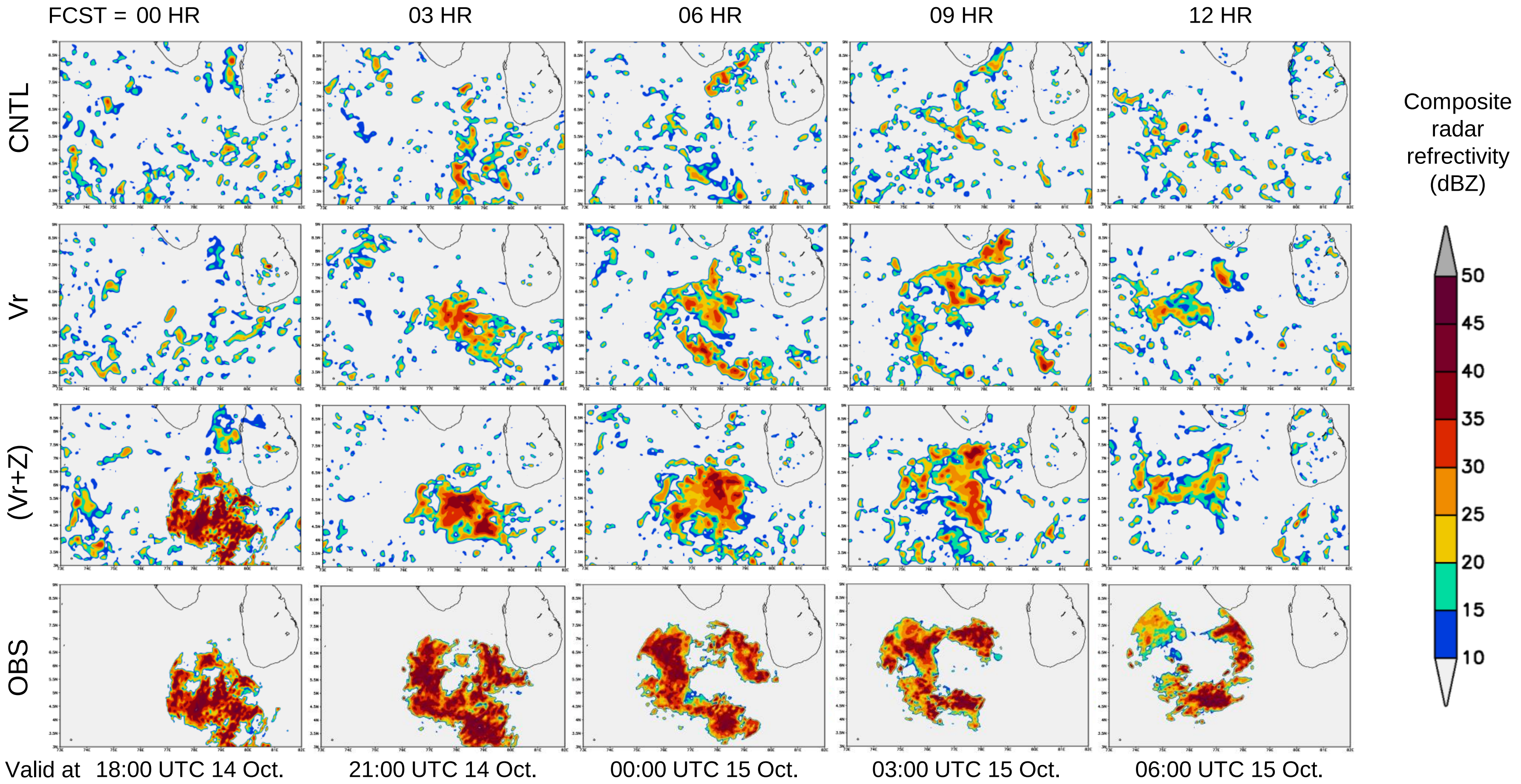

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Test with Single Shipboard Doppler Radar Data

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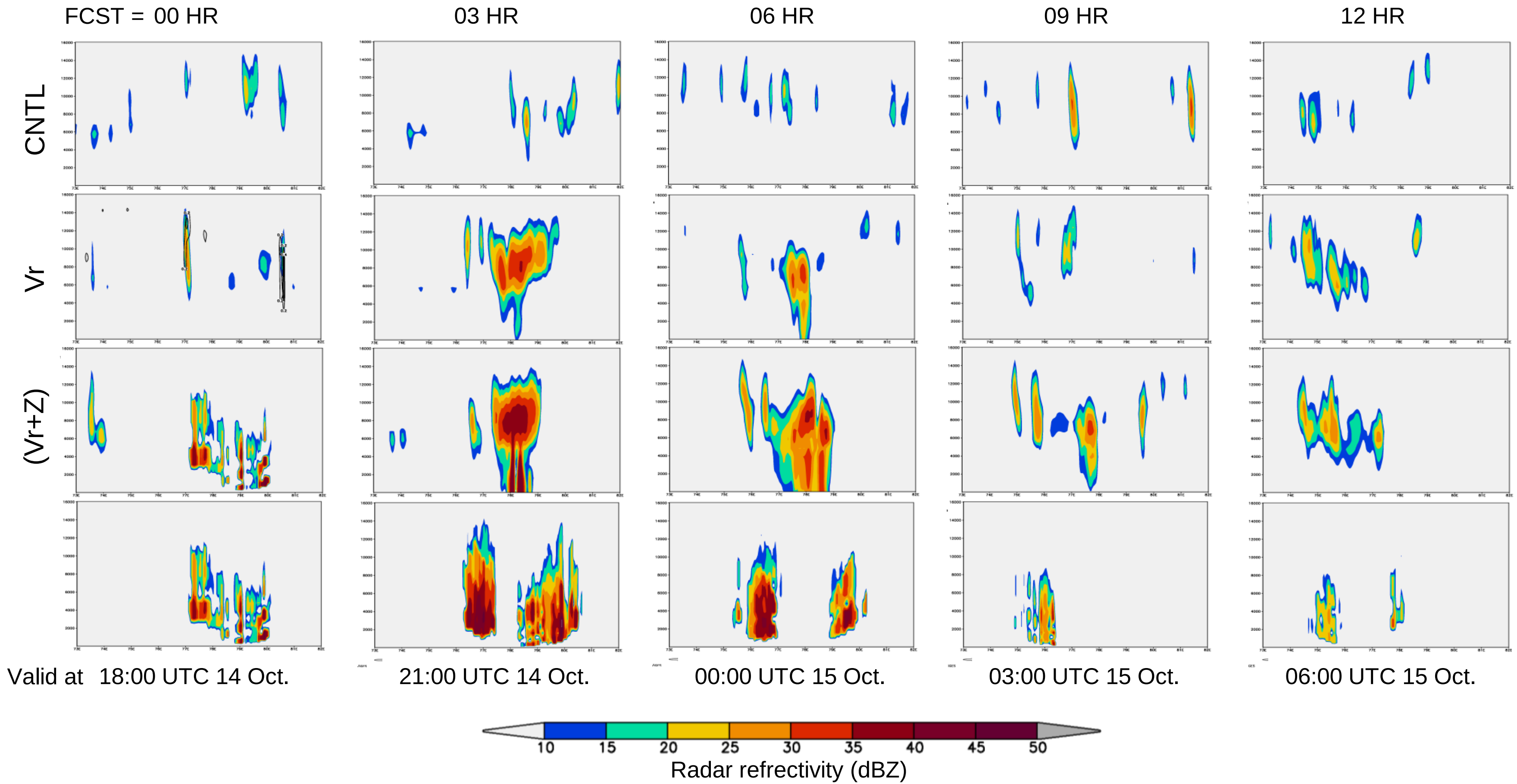

Test with Single Shipboard Doppler Radar Data

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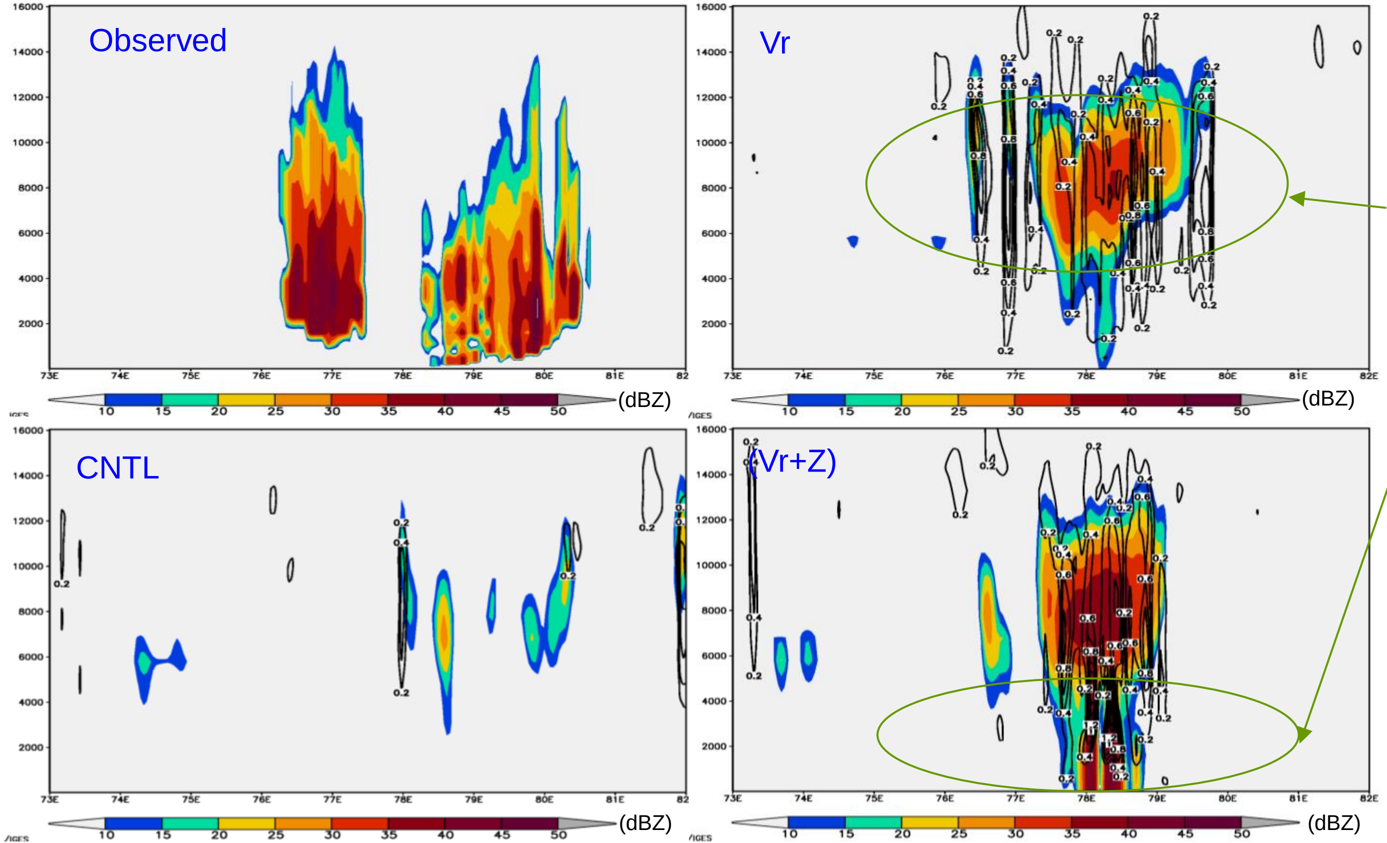
Upward Motion (contours, ms^{-1}) at FCST=3H



- The control forecast basically missed the storms because it missed the upward motion in the storm areas.
- V_r DA increases the upward motion at middle and upper levels (above ~4km) in storm areas, with max upward velocity of ~0.8 ms^{-1} at ~7km. This is more conducive dynamics for intensification.
- The combined (V_r+Z) DA improves upward motion at all vertical levels inside the storms with the max upward velocity of ~1.2 ms^{-1} near the storm base; again conducive for providing sufficient moisture and energy for storm development.

Test with Single Shipboard Doppler Radar Data

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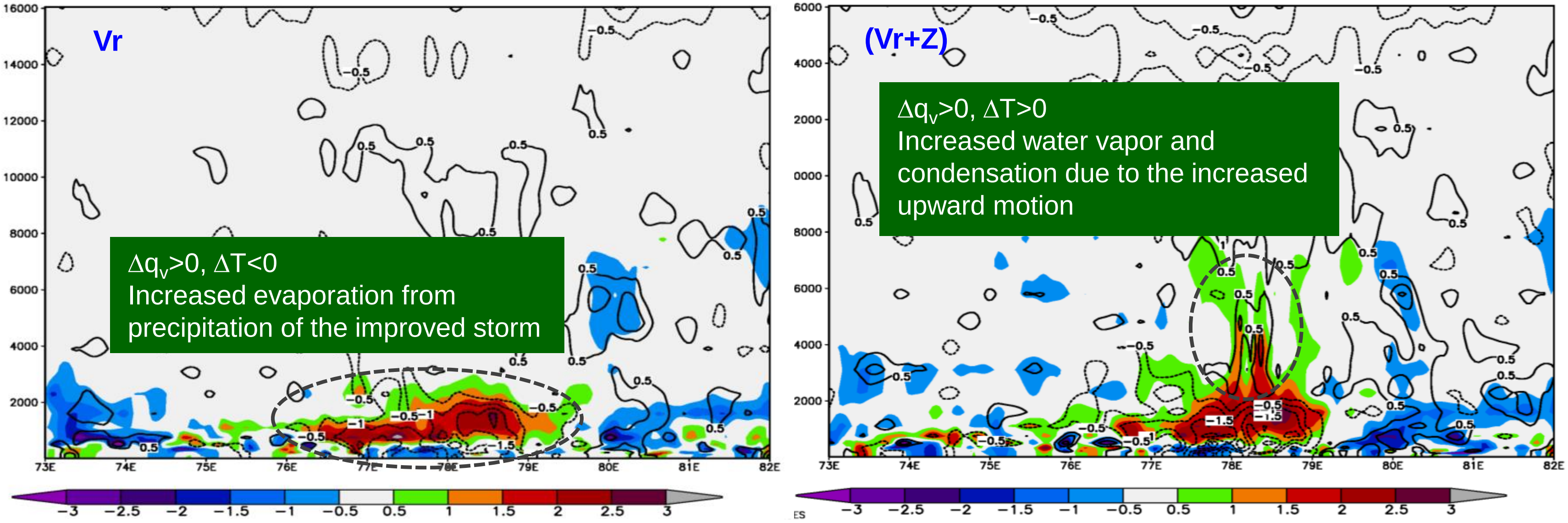
Increments (EXP-CNTL) of q_v (colored areas, g kg^{-1}) and T (contours, K) at FCST=3H



- V_r DA increases moisture below the storm base (~2km). This could be from the increased evaporation of precipitation from the improved storm above. The negative temperature change in that area shows the cooling effect of the precipitation evaporation.
- The combined (V_r+Z) DA increases the moisture both below and above the storm base for the improved storm. The positive temperature change above ~2km shows the increased condensation due to the increased moisture that aids the storm development.

Test with Single Shipboard Doppler Radar Data

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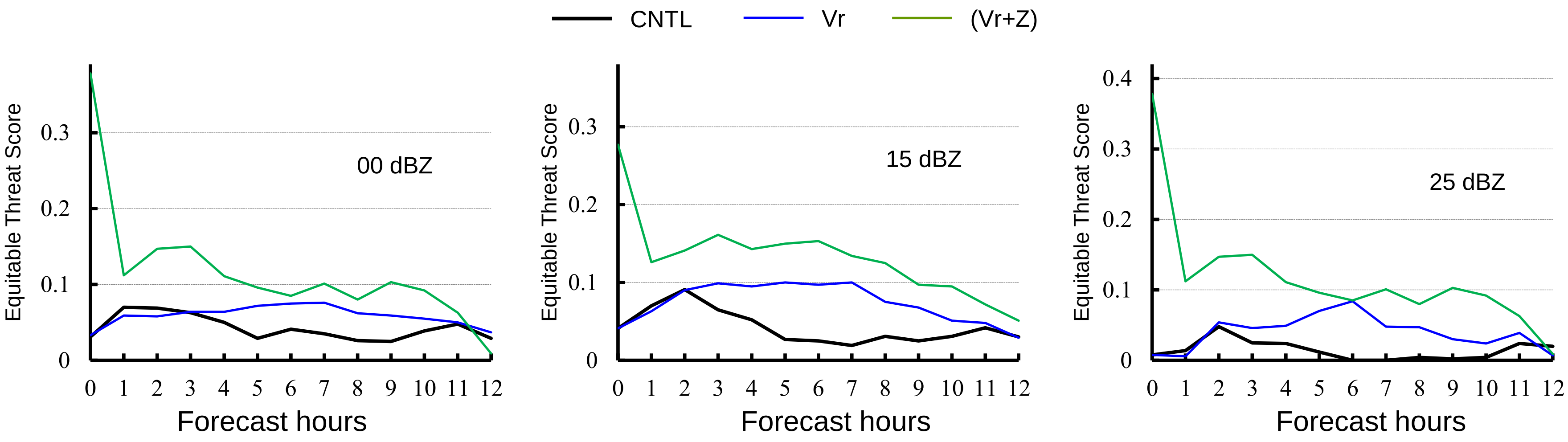
Equitable Threat Scores of Storm Forecasts (measured by radar reflectivity) from CNTL, Vr, and (Vr+Z)



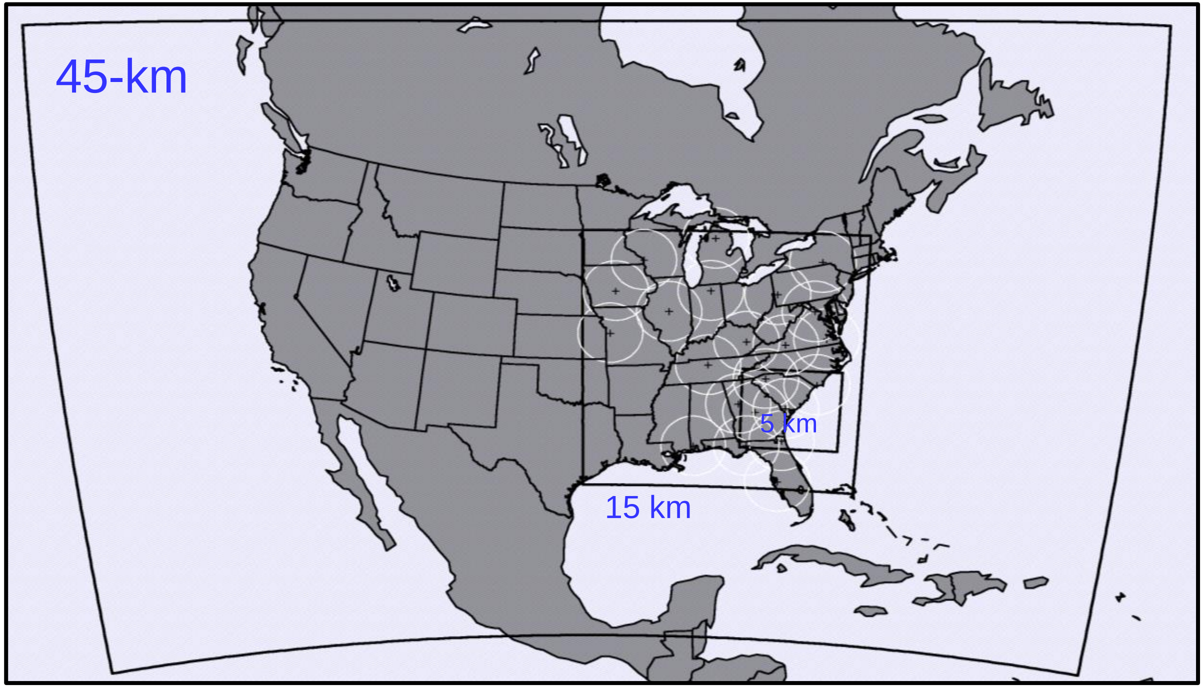
- HWDDC data assimilation improved both storm location and intensity forecasts

Test with WSR-88D Radar Data

1-hr window for radar data

6-hr window for conventional & satellite data

12Z 22 June	00Z 23 June	12Z 23 June	00Z 24 June	12Z 24 June	00Z 25 June	12Z 25 June	00Z 26 June	12Z 26 June	00Z 27 June	12Z 27 June



- Level-II Vr and Z data from 22 WSR-88D radars were collected and assimilated to all model grids (5-km, 15-km, 45-km) every 12 hours along with conventional and satellite data over the 6-day period
- Model forecasts from the three experiments were verified against sounding profiles over the model domains

Three experiments:

CNTL – Conventional+Satellite

Vr – Conventional+Satellite+Vr

(Vr+Z) – Conventional+Satellite+Vr+Z

Test with WSR-88D Radar Data

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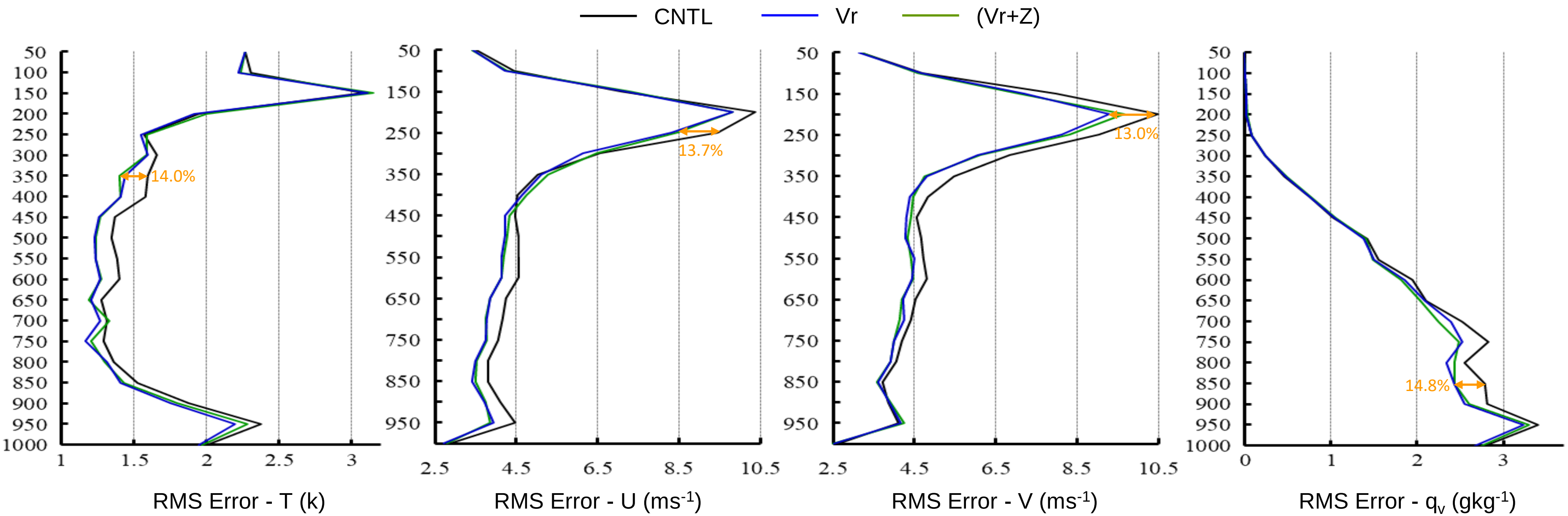
6-day (23-27 June) Average RMS Errors of 48h-Forecasts Verified Against Sounding OBS (15km grid)



- Both Vr and (Vr+Z) data assimilations reduced the forecast errors of model state variables at most vertical levels. The reductions in model forecast errors mainly improve the large-scale environment for storm development.
- The improvement was basically attributed to Vr DA impact. Radar reflectivity (Z) DA did not add additional value to the large-scale environment forecast.

Test with WSR-88D Radar Data

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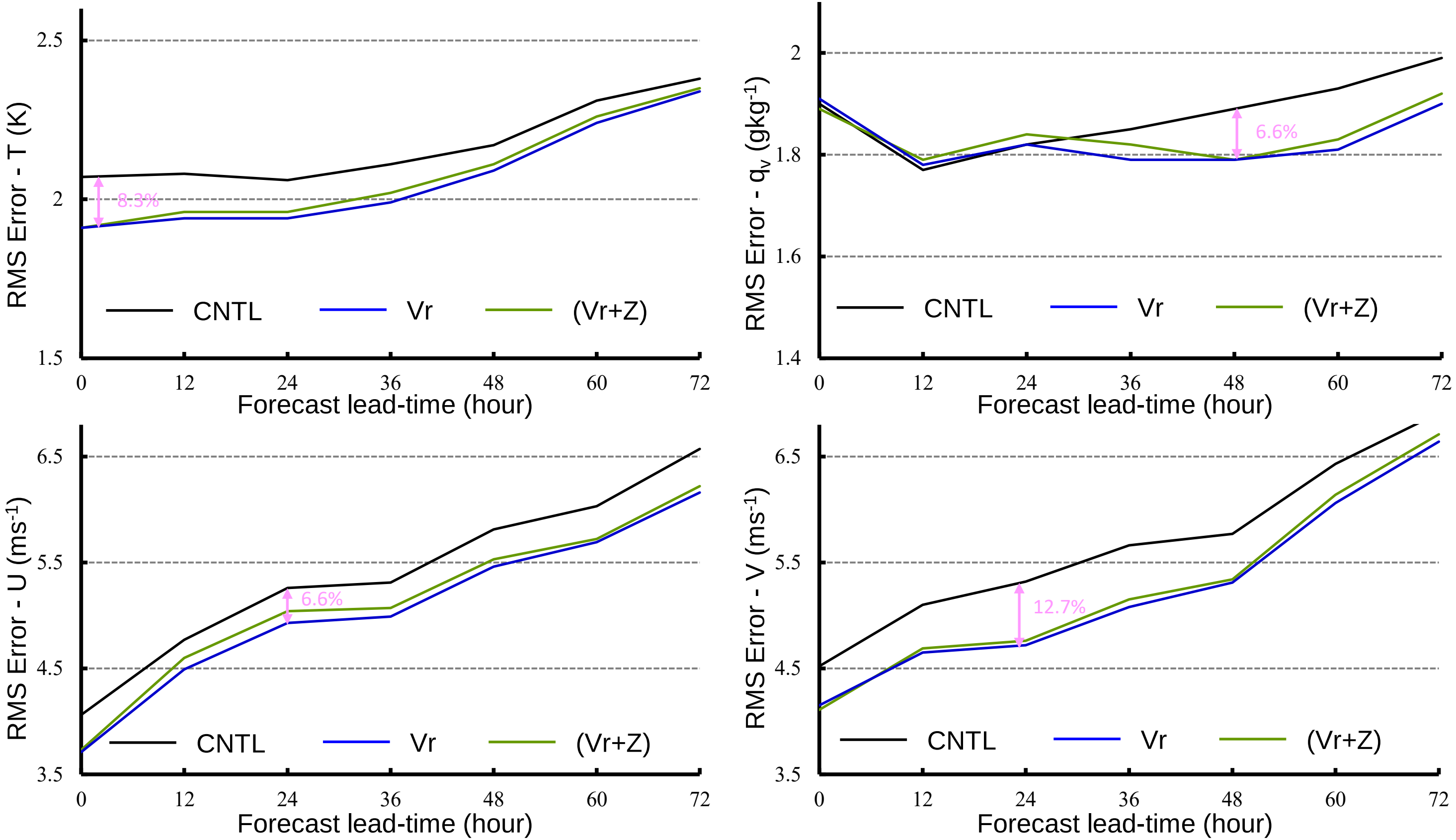
6-day (23-27 June) Average RMS Errors (15km grid, averaged over the 3D domain)



- Radar data assimilation impact lasted for more than 72 hours for most state variables.

Conclusions

- Radar data assimilation improves storm forecasts for both locations and intensity
- Single shipboard Doppler radar data showed notable impact on improving storm prediction for more than 12 hours
  - In regions where conventional meteorological data are limited, radar observations of storms are critical in storm forecast
  - Vr data showed improved storm structures mainly at middle and upper levels, while Z data showed impact at lower levels

- While both Vr and Z improve storm structures, Vr data assimilation also enhance the mesoscale and large-scale environment for storm development
- Enlarged radar data coverage and cycled data assimilation are the key factors in extending the data assimilation impact from hours to days

Thank you