Advancing Radar Data Assimilation in the HRRR/RRFS Model

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What is this work really about?

Two sides of the same coin: we need to get better at
(1) inserting thunderstorms that are missing from the initial conditions of a weather model forecast, and
(2) eliminating falsely predicted storms in the model background

We do this by using a more mathematically rigorous algorithm to process weather radar – the best tool for measuring thunderstorms – and inserting that information into the model in a more balanced way.

Background

Numerical Weather Prediction (NWP) using high resolution models

At its most fundamental nature, numerical weather forecasting is an initial and boundary value problem. The non-linear partial differential equations that govern atmospheric flow are discretized and solved using numerical approximations to the partial derivatives. A successful NWP forecast requires accurate initial (IC) and lateral boundary (LBC) conditions. In this project I am concerned with IC accuracy. In particular, I am examining how the accuracy of ICs for a convection-allowing model (CAM) such as the High-Resolution Rapid Refresh (HRRR; soon to transition into the Rapid Refresh Forecast System, RRFS) impacts subsequent forecasts.

Initializing an NWP model

NWP models get their ICs from one of two sources: (1) an objective analysis created using an algorithm based on current meteorological observations; (2) the atmospheric state from some other NWP model that is large enough to completely cover the domain of the NWP in question. Source #2 represents approximately 100% of routinely conducted NWP model forecasts.

Problem – the driving model does not contain the necessary meteorological entities to provide adequate ICs!

The HRRR/RRFS run on a 3-km grid, and thus are able to explicitly contain small scale features such as thunderstorms. But the models from which they obtain ICs are typically run on grids of 12 km or coarser and are not able to represent these features. Therefore,

the HRRR/RRFS are handed a model state that is completely missing the features it is trying to predict!

The good news is there is a solution to this problem – **data assimilation**.

What is data assimilation (DA) in NWP?

Data assimilation involves combining sources #1 and #2 above to create a better set of ICs to drive an NWP model forecast. In essence, another model's forecast grid (usually on a coarser grid and obtained from a forecast initialization time in the past) is used as a *background* or *first-guess* state which is subsequently modified by incorporating meteorological observations to create an *analysis* following a (potentially complex) mathematical operation.

So where does radar fit into DA?

Weather radar provides an invaluable source of meteorological observations for NWP models. It is among the only tools available that can sample thunderstorms with sufficient specificity and detail for meteorologists to understand not only that a storm exists and its motion vector, but the internal structure of the storm (e.g., how tall is the storm? How heavy is the rain? Is there hail? If so, where in the storm is it?). In essence,

weather radar provides the solution to the problem of the HRRR/RRFS being handed a model state that is missing thunderstorms.

Narrowing the focus

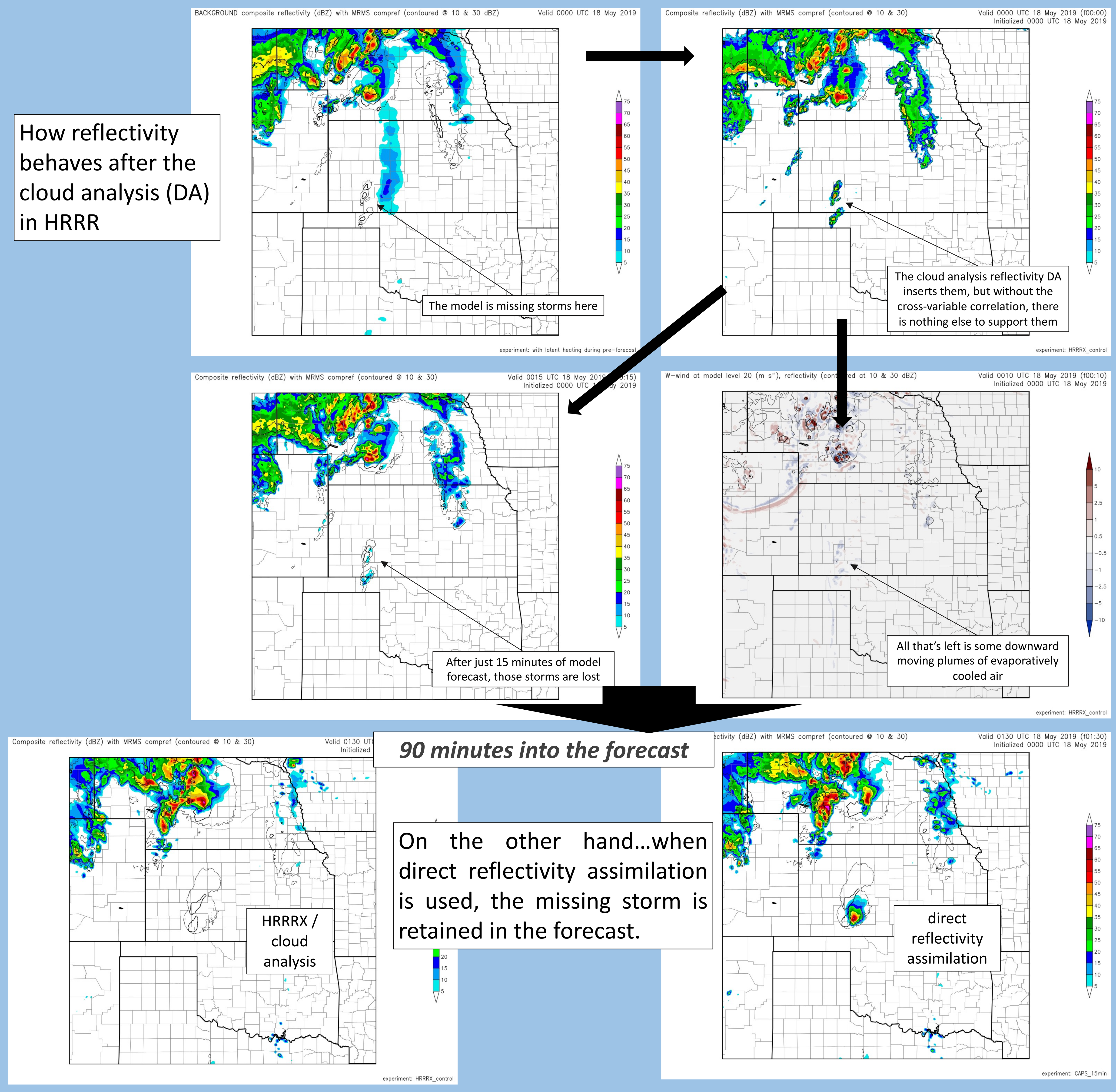
Now that we have established the problem and have a solution, the issue comes down to implementation and optimization. Existing HRRR forecasts have used a mathematically unsophisticated and somewhat ad-hoc type of DA for inserting missing storms into a model (as well as eliminating storms from the background that should not be there because they were falsely predicted). This method (the cloud analysis with forced latent heating) has been acceptable for the time being, but it is far from perfect, and recent attempts to improve upon this method have proven successful and tractable (mathematically and computationally).

The new method is called direct reflectivity assimilation. Reflectivity is a radar product that you are probably already familiar with if you have watched your local TV meteorologist give the regular evening weather report when rain, storms, or snow was occurring. The product represents the location and intensity (spatial density) of condensed water particles (hydrometeors). With this new method, radar reflectivity is mathematically more rigorously and accurately assimilated into the model grid. Not only does it improve this aspect over that in the HRRR, but this new method also uses cross-variable correlations to update other atmospheric fields (e.g., temperature, humidity, wind) that are impacted by the presence of thunderstorms and results in a model grid that is "dynamically balanced," meaning the model's atmospheric state doesn't contain any weird abnormalities that would cause ripple effects throughout the model grid and interfere with making a quality forecast (and in some cases, can be significant enough to be catastrophic and cause the model to crash!)

Test name	Reflectivity DA	Latent heating?	Radar DA frequency	Cycled?
HRRRX_control	cloud analysis	yes	60 min	no
CAPS_control	direct	no	60 min	no
HRRRX_cycled	cloud analysis	yes	60 min	yes
CAPS_cycled	direct	no	60 min	yes
CAPS_15min	direct	no	15 min	no
CAPS_15min_cycled	direct	no	15 min	yes

Definitions and acknowledgments

- CAPS – the Center for Analysis and Prediction of Storms at the University of Oklahoma developed the direct reflectivity assimilation code and handed it off to Jeff Duda at CIRES/GSL for testing in a HRRR-like forecasting environment
- "cycled" – whether or not a short NWP forecast from a given DA analysis was used as the background for a subsequent DA analysis. The length of the forecast is identical to that in the "radar DA frequency" column in the table above



Summary

Q: Is this result consistent over many forecasts?
A: Probably, but uncertainty remains.

Large-sample tests (see verification at right) have revealed an improvement in the forecast that extends several hours into the forecast, although the jury remains out on whether these results are statistically significant when applied to a large sample of severe storm forecasts common in the spring and early summer.

The ~140 cases verified occurred in the late summer of 2020 during a quiet period for thunderstorms. Therefore, the degree of impact on the forecast from the direct reflectivity assimilation remains uncertain. More testing and samples are needed.