NWP and Radar Extrapolation: Comparisons and Explanation of Errors

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ABSTRACT: This paper examines nowcasts of precipitation from the High-Resolution Rapid Refresh (HRRRv2) model from the summer of 2017 along the Colorado Front Range. It was found that model nowcasts (2 h or less) of precipitation amount were less skillful than extrapolation of the KFTG WSR-88-D data at a spatial scale of 120 km. It was also found that local-scale (mesoscale) influences on rainfall intensity and amount have a much greater impact on rainfall intensity than large-scale (synoptic) influences. Thus, large-scale trends are not useful for modifying extrapolation nowcasts on the local scale. Errors in the HRRR nowcasts are attributed to an inability of the model and data assimilation to resolve convergence along outflow boundaries and other terrain-influenced mesogamma-scale flows that contribute to storm formation and evolution. While the HRRRv2 1-h nowcasts were strongly correlated with observed precipitation events, the nowcast precipitation amounts were in error by more than a factor of 2 about 50% of the time, with half of the cases being overestimates and half being underestimates. A large fraction of the HRRRv2 overestimates were associated with stratiform rain events. It is speculated that this was a result of misinterpretation of the radar bright band as more intense precipitation aloft by the data assimilation scheme. A large fraction of the HRRRv2 underestimates occurred when the data assimilation and model were unable to fully resolve the low-level convergence along small-scale, narrow boundaries that led to new storm initiation and/or storm growth.

KEYWORDS: Convective storms; Radars/Radar observations; Nowcasting; Numerical weather prediction/forecasting

1. Introduction

This paper is motivated by the desire to improve 0–2-h nowcasts of rainfall amount to support flash flood forecasting, agriculture, recreation and other sectors of the economy. There are several methods for nowcasting precipitation amounts with the two most common being extrapolation and numerical weather prediction. Extrapolation of radar reflectivity coupled with using a reflectivity–rainfall-rate relationship or polarimetric parameter–rainfall-rate relationship generally has greater accuracy than model nowcasts of rainfall amounts for nowcasts of 2 h or less. This paper quantifies the relative skill of radar extrapolation and numerical weather prediction (NWP) for nowcasting precipitation amount in the Front Range of Colorado and assesses the potential reasons why radar extrapolation forecasts trend to be more skillful than present-day operational NWP with advanced data assimilation.

Weather radar is often used to anticipate precisely where and when precipitation will occur. This might be for life-threatening situations or simply for keeping dry while running errands. The typical radar method used for anticipating where the precipitation will be in the future was originally proposed as early as 1953 (Ligda 1953). This method consists of moving radar precipitation echoes forward in time using their present intensity and recent past motion. This procedure is referred to as Lagrangian extrapolation or here simply as extrapolation. Bellon and Austin (1978) were likely the first to produce precipitation nowcasts based on this procedure. Their technique digitally matched two radar scans 1 h apart to obtain the movement. The accuracy of radar extrapolation nowcasts decreases rapidly with time particularly for smaller-scale convective precipitation. This paper does not review the long history of radar extrapolation nowcasting techniques; the interested reader can find appropriate references in Sun et al. (2014) and WMO (2017) as well as Li et al. (1995), Wilson et al. (1998), Germann and Zawadzki (2002, 2004), Bowler et al. (2006), and Mandapaka et al. (2012) for examples.

Attempts to improve extrapolation nowcasts have been largely unsuccessful. Tsonis and Austin (1981) investigated the use of time trends in echo size and intensity to improve extrapolation nowcasts of cells that already lived at least 30 min, but they found negligible improvement in skill even in elaborate nonlinear time-trending schemes. Wilson et al. (1998) also tested similar trending techniques along the Rocky Mountain Front Range region in Colorado and found similar results. Tsonis and Austin (1981) concluded that essential physical processes that dictate the change in rainfall with time are not necessarily observable in the history of a particular echo development. In the case of convective storms, these physical processes are often events occurring in the boundary layer such as wind convergence (Garstang and Cooper 1981). Nowcasting systems that include human input (expert systems) have shown improved skill over extrapolation techniques by predicting storm initiation, growth and decay based on knowing the location of boundary layer convergence lines (Mueller et al. 1993; Wilson et al. 2004; Roberts et al. 2012; Sharif et al. 2006). Satellite-based methods that incorporate model analyses of stability have also shown some promise in nowcasting convection initiation under some conditions particularly when the satellite view is unobstructed by high clouds (Iskenderian et al. 2010). Huang et al. (2012) combined multiple NWP models and observations
to improve nowcasts of temperature, relative humidity, wind speed and wind gusts.

As summarized in Sun et al. (2014) and WMO (2017), extrapolation of radar echoes tends to be more skillful than NWP in predicting precipitation intensity up to 2 h out. In most cases, NWP skill exceeds that of extrapolation after 2 or 3 h if radar data (reflectivity, radial velocities) are assimilated. Predictability is dependent on scale and forcing (Wilson et al. 1998; Germann et al. 2006; Kiel et al. 2014) with larger-scale strongly forced regions having increased rainfall predictability. NWP handles synoptic-scale forcing features, like frontal systems, better than local-scale features. On the other hand, radar is particularly effective in observing small-scale features like gust fronts, which can initiate new storms or intensify existing storms. Early nowcasting techniques to combine NWP and extrapolation consisted of applying lead-time-varying weights to the extrapolation and NWP fields. At the shorter nowcast time periods (1–2 h) full weight is given to extrapolation. That weight is then gradually decreased with time while at the same time increasing the weight given to NWP resulting in full weight to NWP by 4–8 h (Browning 1980; Doswell 1986; Austin et al. 1987; Golding 1998; Bowler et al. 2006; Pinto et al. 2010; Seed et al. 2013). More advanced techniques for combining model- and extrapolation-based forecasts have been developed that use probabilistic information from the model to blend model data with extrapolation starting as early as 1 h (Pinto et al. 2018). In addition, machine learning techniques have also been used to nowcast radar imagery (Han et al. 2017; Foresti et al. 2019; Franch et al. 2020).

As models and data assimilation techniques continue to improve, it is expected that short-term forecasts and eventually nowcasts will match or exceed that of extrapolation at all but the shortest lead times (Sun et al. 2014). These increases in skill afforded by advanced data assimilation (DA) techniques is a critical aspect of the NOAA’s Warn-on-Forecast system (Stensrud et al. 2009). A decade later, this area of intense research to assimilated submesoscale observations is still very active (Wheatly et al. 2015) but is moving toward ensemble assimilation techniques, which better captures uncertainties in the assimilation process. A full dissertation of the recent state of mesoscale data assimilation at operational and research centers around the world is given by Gustafsson et al. (2018).

Progress continues to be made in the assimilation of radar observations using variational, ensemble, and hybrid techniques (Duda et al. 2019). The assimilation of radar reflectivity either via a latent heat nudging (e.g., Benjamin et al. 2016) or directly relating reflectivity to the cloud hydrometeor properties of precipitating clouds (e.g., Dowell et al. 2011), has been shown to improve the accuracy of analyses and subsequent model nowcasts. A number of difficulties of assimilating radar data have been discussed. For example, Janjić et al. (2018) have shown that a mismatch between the scales of motion and thermodynamic variability represented in the radar observations and that which can be resolved for a given model grid can lead to significant errors. Also of particular relevance are the uncertainties associated with nonlinear moist physical processes and unbalanced flows that are characteristic of convective-scale processes (e.g., Pagé et al. 2007).

![Fig. 1. Region of the experiment. The yellow circle shows the 60-km-radius circle about the KFTG NEXRAD radar, which is the rainfall nowcast area. The red-outlined rectangle shows the area over which the model large-scale trend is obtained. The small black polygon is the East Denver Rain Gauge Network. The background is the elevation of the topography, scale on the right in thousands of feet (1000 ft = ~300 m).](image)

This paper (i) examines the skill of an operational convection-permitting NWP model with radar DA in nowcasting rainfall, (ii) assesses whether trend information available from the model can be used to improve radar-based nowcasts obtained via extrapolation, and (iii) examines error sources in 1-h nowcasts by NWP. Section 2 describes the datasets used in this study and the experimental methods. Section 3 provides a relative comparison of the model and extrapolation performance and an assessment of whether or not trends obtained from the model can be used to improve extrapolation nowcasts. Section 4 examines the processes that contribute to errors in the model 1-h nowcast of rainfall at a scale of 120 km.

2. Experiment procedure

The experiment was conducted along the Rocky Mountain Front Range for the summer (June, July, and August) of 2017. The precipitation during this time period was dominated by afternoon and evening thunderstorms that were largely initiated by mesoscale boundaries and small-scale variations in stability rather than via synoptic-scale forcing. Terrain also played a significant role on the evolution of thunderstorms that were observed; see Fig. 1 for map of the terrain. Thus, the results obtained in this study may not be transferable to other regions of the United States, and especially not to areas where synoptic-scale forcing may dominate.

a. Experimental area and time period

Figure 1 shows the Rocky Mountain Front Range. The red-outlined box defines the region (108000 km²) where the large-scale rainfall intensity trend was obtained from HRRRv2 and compared with the trend from a much smaller
area (11 304 km$^2$). This smaller area is defined by a 60-km-radius circle centered on the KFTG WSR-88-D where the HRRRv2 and radar extrapolation rainfall nowcasts were made and the radar rainfall estimates were made. The experiment covered all hours during June, July, and August of 2017. Of the possible 2208 h over the 3-month period, 2140 were used. The remaining 68 h were times for which radar data were missing.

b. Rainfall nowcast area

The 60-km-radius circle about the Denver WSR-88D (KFTG) was chosen on the basis of the desire to reduce topography influences on precipitation amount by keeping the region on the plains. At the same time, the quality of polarimetric parameters and rainfall estimation is greater at these closer radar ranges. The quality of the rainfall estimates decreases with range because of radar beam broadening and increased beam height with increasing range.

c. Rainfall estimation

Rainfall estimates were derived from KFTG shown in Fig. 1. The KFTG radar is part of the national network of WSR-88Ds, which are polarimetric S-band radars with a 1° beamwidth. These radars are considered state-of-the-art for estimating rainfall. The radar rainfall estimates were computed using the National Center for Atmospheric Research (NCAR) Environmental Operations Laboratory (EOL) “HYBRID” algorithm (Dixon et al. 2015). Using the polarimetric radar parameters, the algorithm uses a fuzzy logic hydrometeor classification technique that selects a correspondingly appropriate precipitation rate relationship for each hydrometeor type. In addition to horizontal radar reflectivity, the polarimetric radar parameters (differential reflectivity and specific differential phase) are used in estimating rainfall rate. In addition, a relationship based on specific differential phase is used in the particle identification algorithm to identify hail. The rainfall-rate algorithm also selects the best elevation angle in the case where radar beam blocking is a possibility. Figure 2 shows a radar versus rain gauge comparison of the 1-h rainfall estimates for the 3 months from the East Denver Rain Gauge Network (see Fig. 1). This group of rain gauges covers a 230-km$^2$ area. The area was chosen because it had a particularly dense uniform distribution of rain gauges. Editing of the rain gauge observations was performed to remove spurious gauge tips that were not associated with rain. The coefficient of correlation between the radar and gauge estimates is 0.89. Based on close examination of the two estimates it is not clear if one technique is more accurate than the other. At times, it was noted that the scale of the rainfall core was sufficiently small that it occurred between gauges, and thus, even with a dense network, a heavy rain area might not be detected. The 3-month total of gauge measured area-averaged rainfall over the area covered by the network of rain gauges was only 62 mm. This was far below the average Denver rainfall for the 3 months of 147 mm.

The observed rainfall exhibited a strong diurnal pattern resulting from afternoon and evening thunderstorms (Fig. 3) with a peak occurring between 1600 and 1700 LT. Figure 3 shows the diurnal cycle of total rainfall accumulation obtained with HRRRv2, extrapolation and radar observed. It is interesting to note that the model tends to overestimate the rain during the night and morning and underestimate in the afternoon, which is the most convective period. Reasons for this are advanced in section 3. Not surprisingly, radar extrapolation and radar observed agree closely except for the 1-h delay in nowcast amounts during the period of storm initiation and growth.

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1 The HRRRv2 1-h nowcast was 66 mm for the same area and time.
d. NWP model

The NWP dataset used here is from version 2 of the High Resolution Rapid Refresh (HRRRv2). As described in Benjamin et al. (2016) and C. R. Alexander et al. (2020, personal communication) “the HRRR is a NOAA real-time 3-km resolution, hourly updated, convection-allowing atmospheric model run using a horizontal grid spacing of 3 km. Radial data are assimilated into the HRRR model every 15 min over a 1-h period.” The 3-km HRRR forecasts are forced at the lateral boundaries by the 13-km Rapid Refresh (RAP) model, which is a continental-scale hourly updated assimilation/modeling system run operationally at NCEP. The HRRR model and the data assimilation system continue to be developed, with HRRRv4 becoming operational at NCEP in late 2020. It is noted that the data assimilation to be included with the HRRRv4 upgrade will be a hybrid variational ensemble scheme that will use 36 members run at convection-permitting resolution to assimilate radar reflectivity and radial winds which could help to improve initial conditions and ultimately nowcast precipitation intensity in the years to come.

e. Precipitation extrapolation

The rainfall-rate field estimated from reflectivity was extrapolated with motion vectors obtained using Thunderstorm Identification Tracking and Nowcasting (TITAN) software developed by Dixon and Wiener (1993). Note that this nowcasting system does not attempt to account for initiation, growth or dissipation of precipitation areas. The field of motion vectors was obtained in a six-step process. First, TITAN was used to identify radar reflectivity objects with reflectivities >35 dBZ. Second, TITAN determined the motion of these objects by observing their past locations. Third, zonal and meridional components \( u, v \) of the motion vector for each storm object was assigned to a 1-km grid. That is, each grid point within the storm object has the same \( u, v \) motion values. Fourth, the \( u \) and \( v \) values for each object were extended 40 km from the centroid location of each 35 dBZ precipitation object. When grid points contain more than one set of \( u, v \) values, distance weighted averaging was applied. Fifth, grid points with no values were assigned the 700-hPa wind from the HRRRv2. Sixth, temporal smoothing was applied that limits how much a vector can change in speed and direction from one time to the next. Figure 4 is an example of the above TITAN-based field of motion vectors superimposed on the rainfall-rate field.

The hourly estimated rainfall accumulation field was obtained by extrapolating in 1-min time steps the above rainfall-rate field with the TITAN-based extrapolation vectors. The individual 1-min rainfall-rate values at each 1-km grid point were then summed to obtain a field of 1-h rainfall amounts at each grid point. Then the grid points within the 60-km-radius circle were summed (11305 points) and the area-average 1-h rainfall accumulation was obtained.

3. HRRRv2: Extrapolation comparisons, blending, and errors

The rapid assimilation of radar data and the rapid cycling (15 min) by the HRRRv2 greatly reduces the model spin up period, which was often associated with low skill by NWP during the first few hours. In addition, radar data assimilation provides the HRRRv2 the distribution of precipitation at forecast time. Improved nowcasts beyond a few tens of minutes requires predicting storm initiation, growth and decay, which are dependent on small-scale wind, humidity and temperature variations in the boundary layer (e.g., Weckwerth 2000; Ge et al. 2013). Current observational networks, primarily designed for synoptic-scale forecasting, generally cannot provide the environmental conditions with the temporal and spatial resolution required for nowcasting. However, convergence lines are often evident in the radar reflectivity field (Wilson et al. 1994). These convergence lines (boundaries) often appear as thin lines in the “clear air” radar reflectivity field. However, as will be discussed later, the convergence occurs along narrow zones along these convergence lines that are often not as well observed in the Doppler velocity field and not well resolved by the 3-km grid spacing of HRRRv2. Thus, NWP data assimilation of Doppler velocity can at best only coarsely represent these boundaries. In addition, there presently is no method for assimilating the location of convergence boundaries that are indicated by radar reflectivity thin lines. The importance of boundaries with respect to HRRRv2 rainfall underestimation is examined in section 4.

In the following four subsections of section 3 the HRRRv2 hourly rainfall nowcasts for the 60-km area will be 1) compared with extrapolation, 2) investigated as a means to improve radar extrapolation nowcasts, 3) compared with radar observations, and 4) examined for skill in nowcasting the start of a precipitation event and the skill in nowcasting the hourly rainfall amounts. Section 4 examines issues that cause errors.

a. Comparison of model and extrapolation nowcasting skill

Figure 5 compares the skill of radar extrapolation and HRRRv2 as a function of nowcast time. The nowcast is for the
nowcast length. HRRRv2 (blue) and radar extrapolation (green) as a function of DECEMBER 2020 W I L S O N E T A L . 4787

in nowcasting flash floods, particularly in the first hour (Vivoni et al. 2006). These nowcasts make use of extrapolating radar intensity changes (Wilson et al. 1998). The premise being tested reflects the number of cases is relatively small.

Several studies have examined the crossover point between the skill of NWP and extrapolation. Pinto et al. (2010) and Sun et al. (2014) used the HRRR without radar data assimilation and found the cross over point near 4 h. Later studies with HRRR data from 2012 and 2013 showed increased skill with the HRRR using radar data assimilation (Pinto et al. 2015). Hwang et al. (2015) using 2013 HRRR data with radar data assimilation to forecast the maximum altitude of 18-dBZ echo top heights within a 20-km-radius circle found the crossover points between 2 and 3 h. As mentioned above the HRRRv2 data used in our study were from 2017 where radar data assimilation included both radar reflectivity and Doppler velocity and the crossover point was just over 2 h.

b. Blending HRRRv2 and extrapolation

Radar-based 0–2-h extrapolation nowcasts often have skill in nowcasting flash floods, particularly in the first hour (Vivoni et al. 2006). These nowcasts make use of extrapolating radar reflectivity and only a few techniques include nowcasting intensity changes (Wilson et al. 1998). The premise being tested here is whether predicted larger-scale trends obtained from the HRRRv2 could be used to improve 1- and 2-h radar extrapolation nowcasts on the local scale to support nowcasting flash floods and the hydrology of urban areas.

An area 300 km × 360 km (108 000 km²) was chosen for obtaining large-scale rainfall intensity changes. This area is referred to locally as the ANC (AutoNowcaster) domain and is an area for which we traditionally conduct convective storm studies. The ANC and 60-km-circle domains are shown in Fig. 1.

The procedure was to obtain the change in the area average rainfall amount from one hour to the next for 1) the model nowcast for the ANC domain and 2) the radar observed for the 60-km circle. Correlating the changes/trends for these two different size areas for all hours that any rain occurred in the ANC domain for the 3-month period resulted in a correlation coefficient of −0.003. By restricting the correlation to only occasions when the average hourly rainfall accumulation, within the 60-km-radius circle, was at least 0.5 mm (top 12% of the 412 cases) the correlation was only 0.28. From these very low correlations it is apparent that small-scale (mesoscale) influences on rainfall intensity dominate over large-scale (synoptic) influences along the Front Range of Colorado.

In addition, a similar comparison was made for the 60-km circle where the radar and model change/trend was compared for the 60-km circle. The correlation including all hours was 0.47; restricting the correlation to observed rain amounts of >0, >0.01, >0.05, >0.10, and >0.25 mm gave correlations of 0.32, 0.48, 0.50, 0.52, and 0.51, respectively. While these rainfall values seem very low, they are averages for an area of 11 304 km², where much of the area often receives no rain but amounts can be high over a small portion of the area. These low correlations together with the above results indicate that there is no scale at which model trends can be used to improve 1-h extrapolation nowcasts. This will be reinforced further in a discussion below of the HRRRv2 ability to nowcast the beginning of a rain event.

Since there is, a very large diurnal cycle in rainfall (Fig. 3) a test was made to determine if the 1-h extrapolation nowcasts could be improved by just increasing/decreasing the amount of rainfall based on trends evident in the diurnal composite of precipitation accumulation. There is a large increase in rainfall amount from 1400 to 1600 mountain standard time (MST) and subsequent decrease from 1700 to 1900 MST. Using the rates of increase from Fig. 3 the rainfall for hour 1400–1500 MST was multiplied by 2.98, 1500–1600 MST by 2.2, 1700–1800 MST by 0.58, and 1800–1900 MST by 0.76. However, this simple climatological method to modify the 1-h extrapolation nowcasts did not improve the extrapolation nowcasts (not shown). The various results all indicate that the local-scale meteorological factors contribute more to rainfall-rate changes from hour to hour than any large-scale or diurnal influences.

c. HRRRv2 compared with radar observation

Figure 6 compares the HRRRv2 1-h nowcasts of hourly rain accumulation for the 60-km circle with that observed by the radar. The diagonal lines are the factor-of-2 ratio (0.5 and 2.0) between model nowcast and radar observed. The correlation of HRRRv2 nowcasts with the radar observed—that is, all points in Fig. 6 including those with no rain—is 0.75. This correlation decreases to 0.61 for the 2-h nowcast (plot not shown). For the 1-h nowcast, excluding the hours where both techniques have no rain, the correlation is 0.70. The correlation decreases as the observed accumulation threshold is increased; for example, the correlations for thresholds of 0.01, 0.05, 0.10, and 0.25 mm are 0.67, 0.62, 0.58, and 0.53, respectively. The average ratio of HRRRv2 divided by radar observed is 1.01 for the 1-h nowcast and 1.19 for the 2-h nowcast, indicating a slight tendency to predict more precipitation than was observed.

For the entire summer, there are 1627 h with no rain from either technique of 2140 nowcast hours. Thus, 515 h remain
where at least one of the techniques is nonzero. Table 1 is a contingency table comparing all the HRRRv2 1-h nowcasts for rain with those observed by the KFTG radar. The occurrence of rain is defined as an average rainfall amount of $\geq 0.01$ mm for the 60-km-radius circle of KFTG. From Table 1 the HRRRv2 1-h nowcasts for rain/no rain were correct 91% of the time. Considering only the hours for which at least one method had rain, 62% of the nowcasts for rain were correct. The above indicates that the HRRR often nowcasts the presence of rain; however, as will be shown later, it has difficulty nowcasting the amount.

d. Nowcasting precipitation events

The question arises as to how well the HRRRv2 nowcasts the start of a precipitation event, as well as the hourly rainfall amounts during the precipitation event. A precipitation event was defined as a period at least 3 h long with at least 1 h having an area-average rain accumulation of 0.10 mm within the 60-km-radius circle. There were 41 such events observed. The start of an event was classified into three categories: translation of rain into the 60-km circle (11 events), rain initiation within the circle (25 events), and a combination of translation and rain initiation (5 events). The classification was based on examining the time series of radar reflectivity, HRRRv2 and extrapolation using the “CIDD” display ([https://ral.ucar.edu/CIDD/user_manual/cidd_users.html](https://ral.ucar.edu/CIDD/user_manual/cidd_users.html)). For the sake of simplicity, we will call rain initiating within the 60-km circle CI (convection initiation) since convective rain was always the case. There was a wide variety of skill in the HRRRv2 nowcasts of the start time of rain and the hourly rainfall amounts after the start time. For CI events the start time was correctly nowcast by the model for 7 of the 25 events, for translation events it was correct 7 of 11 times, and for a combination CI and translation it was correct for 3 of 5 events.

Figure 7 provides six examples of the performance of the HRRRv2 and radar extrapolation in the prediction of 1-h rain amounts within the 60-km circle. The figure shows, for six cases, a sequence of 1-h nowcasts by both HRRRv2 and radar extrapolation. Also shown is the verifying radar estimated 1-h rainfall amounts. Figures 7a and 7b are contrasting examples of the HRRRv2 skill in nowcasting the start time and amount of rainfall for two CI events. In Fig. 7a the model essentially misses an observed CI event with a delayed start time for nowcasts issued at 1400, 1500, and 1600 MST and greatly underestimated amounts in subsequent 1-h nowcasts. This bias in the HRRRv2 nowcasts occurred for several of the observed CI events; however, as Fig. 7b shows, just the opposite can be the case. Figure 7b shows the model significantly overpredicts the hourly amounts. In this event, the observed convective storms are moving from the northwest. Figure 7c is a particularly interesting CI case; the model, as is typical, has delayed CI and underestimates the rainfall amount until 0700 MST. Later in the morning, the HRRRv2 appears to try to “catch up” but then overestimates the rainfall amount and duration. Further investigation into this case revealed that the HRRRv2 nowcast overestimates coincided with the appearance of the radar bright band ([American Meteorological Society 2020](https://www.ametsoc.org/AMETECH/)) in the radar reflectivity data within the stratiform rain area of the convection. The linkage between nowcast overestimates and the bright band, which was apparent in several of the cases, is discussed further in section 4. While the radar bright band was linked to overforecasting in many cases, the HRRRv2 also overestimated the rainfall associated with stratiform events whether or not there was a bright band present.

Figures 7d–f are translation events. Figures 7d and 7e are examples of both over- and underestimating the rainfall. The HRRRv2 precipitation nowcasts were delayed in both of these cases. Later in the event shown in Fig. 7d, HRRRv2 nowcasts greatly overestimate the amounts. While occasionally the bright band was observed, it was not deemed to be the primary reason for the overestimation. The rain amounts associated with event shown in Fig. 7e were generally underestimated except for at the end of the event. In this case there were waves for CI events, which are unusual and likely driven by synoptic-scale features.

![Fig. 6. Comparison of HRRRv2 and radar estimates of area average rainfall for the 60-km-radius circle of KFTG. The HRRRv2 are 1-h nowcasts. The black lines represent the factor-of-2 ratio, 0.5 and 2.0, between HRRR nowcast and radar observation. The red points are the hours that are examined in detail and are the subject of the discussion in section 4. The orange point in the upper right is examined in Fig. 8, below.](https://ral.ucar.edu/CIDD/user_manual/cidd_users.html)
of intense storms moving from northwest to southeast across the domain with a squall line near the end. A bright band in the stratiform rain at the rear of the squall line coincided with the HRRRv2 overestimate of rain at hour 2100 MST. Figure 7f starts as a relative weak stratiform area with some imbedded convection, the start of which is nicely nowcast by HRRRv2. The big peak in the radar observed rain at hour 1600 MST is the result of a large area of CI associated with a convergence line. This is a nice example of the HRRRv2 not initiating storms associated with mesoscale convergence lines, which will discussed further in section 4.

In summary, the HRRRv2 had little skill in nowcasting the start of a rain event that was the result of CI within the circle; however, it had more skill when the rain translated into the circle. There was a tendency for the rain amount to be overestimated by the HRRRv2 in stratiform events and underestimated during more intense periods of convective precipitation, particularly when the storms initiated within the 60-km-radius verification circle. The presence of a radar bright band often coincided with overestimates in the 1-h HRRRv2 nowcasts of rain amount. Also, the model did not anticipate CI associated with mesoscale convergence lines. These last two items are discussed further below.

4. NWP 1-h nowcast errors

Figure 8 and the following figures provide representative examples of the performance of 1-h rainfall accumulation nowcasts obtained from HRRRv2. The case shown in Fig. 8 corresponds with the heaviest rainfall case, which is indicated
by the large orange dot in Fig. 6 (far upper right). In this case, the 1-h rain accumulation from the HRRRv2 (2.23 mm) almost perfectly matched the observed radar estimated accumulation (2.28 mm). The HRRRv2 nicely nowcasts the movement of the two most intense storms observed in Fig. 8a. It is clear that the HRRRv2 assimilation technique captures the initial spatial extent and intensity of the rainfall at analysis time and thus, produces a 1-h nowcast that captures the observed precipitation pattern within the 60-km circle. The HRRRv2 shows a third area of rainfall accumulation near the center of the 60-km-radius circle (Fig. 8c) that was not observed. This is likely the result of incorrectly initiating a new storm within the first hour of the simulation. Another notable aspect of the HRRRv2 1-h nowcast is that the rainfall fields are much more smoothly varying in space (Fig. 8c vs Fig. 8d) than observed. This is because the HRRRv2 cannot resolve the smaller-scale more intense updrafts and corresponding heavier precipitation.

Additional hours (68) examined in detail are shown in Fig. 6 as colored red dots. For 36 of the 68 being examined in detail the HRRRv2 rainfall nowcast was significantly greater than the radar observed rain amount; these cases were grouped into four categories. 1) Stratiform echo was dominant in the radar observations and the model 1-h rainfall nowcast was for intensification (19 cases). This included cases in which convective echo was embedded in the stratiform echo. Typically, the stratiform precipitation was dissipating and not intensifying. 

Fig. 8. Examination of the orange point in Fig. 6, which has the highest rainfall amount with the highest HRRR accuracy. It is the 1-h nowcast for the hour 2200–2300 UTC 10 Aug 2017. Shown are (a) radar reflectivity at 2200 UTC, (b) radar reflectivity at 2300 UTC (the echo near the tail of the orange arrow is a new storm), (c) HRRR rainfall accumulation between 2200 and 2300 UTC, and (d) the radar estimate of rainfall accumulation between 2200 and 2300 UTC. The white arrows represent the movement of the two strongest storms from 2200 to 2300 UTC, which are responsible for the heaviest rainfall tracks in (d). The short orange arrow in (a) and (b) is the movement and quick dissipation of the weak storm in (a) indicated by the small orange circle in (a) and (b). The color bar at the bottom of (a) and (b) is for radar reflectivity (dBZ). The color bar at the bottom of (c) and (d) is for hour rainfall amount (mm). The yellow circle is the 60-km radius around the KFTG radar.
2) Short-lived, small, weak storms were observed and the HRRRv2 grouped the storms into more organized, intense lines or larger areas (9 cases). 3) The HRRRv2 nowcast had considerable error in storm location and/or storm motion was too slow (5 cases). 4) The HRRRv2 significantly overforecast the rainfall or nowcast storms that did not occur (3 cases). Any single hour could have fit into more than one of these categories, but the most dominant situation was chosen when placing an hour into a category.

For 31 of the 68 1-h rainfall nowcasts, the HRRR was significantly less than the radar-estimated amount. These cases occurred during conditions in which storm initiation and/or growth was observed and are grouped into two categories: 1) storm growth and/or initiation was associated with significant increase in radar Doppler velocity convergence without dominant reflectivity thin lines (16 cases) and 2) storm growth and/or initiation was clearly associated with reflectivity thin lines (15 cases).

As mentioned above, the most dominant situations leading to HRRRv2 overnowcasting precipitation accumulation was associated with the presence of stratiform precipitation and a tendency for HRRRv2 to intensify the stratiform rain. This is
demonstrated in Fig. 9 with an example from 15 July at 1400 UTC. A likely contributing cause is the treatment of the radar bright band in the data assimilation. A radar bright band was present in nearly all the cases in the stratiform overestimation category. It is speculated that the HRRRv2 reflectivity diagnostic is interpreting the bright band as an area of more intense rainfall aloft. In this case, the top of the bright band was at about 3 km, near the freezing level. Figures 9e and 9f nicely show the radar beam intersecting the bright band at radar elevation angles of 8° at 1400 UTC and 10° at 1500 UTC, respectively. All other radar elevation angles in the figures are at 0.5°.

The second-highest number of cases in which HRRRv2 overestimates the rain is when it wrongly intensifying short-lived, small, weak, convective storms. Figure 10 is such an example from 1100 UTC 7 August. The cause for the erroneous formation of small, weak, short-lived storms in the HRRRv2 nowcast is not known and is in need of further exploration.

The two most dominant underforecasting situations were associated with the HRRRv2 missing storm initiation/growth associated with Doppler velocity-indicated convergence or reflectivity thin lines. Figure 11 is an example of significant storm intensification and initiation associated with a well-defined area of increasing radar radial velocity convergence where radar reflectivity thin lines are not dominant. This increase in convergence can be seen in the Doppler velocity in Figs. 11c and 11d as indicated by the area within the white contour. Note that most of the convergence occurs over a distance of only a few kilometers and thus would be underresolved and likely greatly smoothed by a model with 3-km grid spacing. Because of inadequate surface convergence, the model only produces modest rainfall that was more than 50% less than observed within the verification radius.
The use of radar reflectivity thin lines to detect boundary layer convergence lines and their use in nowcasting convective storms are well-documented (Wilson and Schreiber 1986; Wilson and Mueller 1993; Roberts et al. 2012). However, there is no method to ingest or assimilate thin line information into a numerical model. Figure 12 provides an example in which convergence lines (reflectivity thin line) moving rapidly south initiate new storms and enhances existing storms. Figure 13 is an example of storm initiation and intensification associated with colliding convergence lines. While radar Doppler velocities also show corresponding lines of convergence, the radial velocities are often not as reliable as reflectivity for detecting a thin line/boundary because of several factors. First the thin line is the result of a greatly increased concentration of insects that occurs within the updraft associated with the low-level convergence. This concentration of insects results in a
vertical column of enhanced reflectivity that extends above the low-level convergence (Wilson et al. 1994). Thus, the thin line is not as sensitive to the radar beam overshooting the shallow convergence. Second, much of the convergence may be below the radar beam and not available for assimilation. Third, the convergence line velocity component may be far from normal to the radar, and thus the radar may only be able to observe a small component of the total convergence. Fourth, the convergence may be horizontally narrow, greatly reducing the ability of the radar to resolve, particularly at longer ranges. In addition the HRRRv2 and other numerical models are not able to fully resolve the convergence line since the grid spacing is on a scale similar to the convergence line.

5. Summary
Local-scale influences (mesoscale) on storm evolution were far greater than large-scale (synoptic) influences. Thus using...
large-scale time trends in HRRRv2 nowcast rainfall amounts is not useful for improving radar extrapolation for 1- and 2-h rainfall amount nowcasts. Note that results presented herein are specific to the Front Range of Colorado and may not be applicable in other climatic regions across the country, particularly in areas influenced by stronger synoptic-scale forcing.

Comparison of numerical model (HRRRv2) and radar extrapolation nowcasts of rainfall amount for nowcast lead times of 1, 2, and 3 h were conducted for the 60-km-radius circle around the KFTG radar. It was found that, for this region, the HRRRv2 is more skillful at predicting rain amounts than radar extrapolation at lead times greater than 2 h for the 60-km-radius circle. This lead time, when the skill of the model exceeds that of extrapolation, is similar to that found by Hwang et al. (2015) who were using an earlier version of the HRRR (2011 version) for aviation purposes and not for nowcasting rainfall.
Comparison of the model 1-h nowcasts with the radar observed amounts for the 3-month total rainfall showed no bias (i.e., the ratio HRRRv2/radar rain amounts was 1.01 for 1-h nowcasts and 1.19 for the 2-h nowcast. The HRRRv2 nowcasts of rain/no rain over the 60-km-radius circle were correct 91% of the time. For hours when rainfall was observed (i.e., 24% of the time) the correlation coefficient was 0.70.

Comparison of individual HRRRv2 1-h nowcasts with observed 1-h rain amounts revealed that the HRRRv2 generally reproduces the broadscale observed rainfall pattern in and around the 60-km-radius verification circle, although the modeled rainfall patterns tended to be much more smoothly varying than observed rain amounts. The HRRRv2 was often delayed in nowcasting the beginning of CI events within the 60-km circle. That is, the precipitation had to be present in the observations for the HRRRv2 assimilation to produce rainfall nowcasts. There were many hours when the HRRRv2 hourly rain amounts were too large or too small by more than a factor of 2. Examination of these cases showed a variety of reasons for the errors as summarized below.

The HRRRv2 nowcasts tended to overforecast the rainfall amount in stratiform rain events. The HRRRv2 also had a tendency to intensify and not dissipate stratiform rain areas. These errors coincided with the presence of the radar bright band within the stratiform rain regions. It is believed that these areas of bright band were interpreted as areas of enhanced rainwater and thus increased latent heat release within the data assimilation system. It is speculated that further east of the Front Range this could be an even greater problem since there tends to be more stratiform rainfall associated with the presence of stronger large-scale forcing.

The HRRRv2 tended to underforecast the rainfall amount observed during convective rain events. HRRRv2 nowcasts were often delayed in both initiation and growth of convective precipitation. In particular, the model significantly underestimated rainfall in situations where there was a large increase in low-level convergence and/or boundary layer convergence lines were apparent in the radar data. It is believed that the grid spacing of the model/data assimilation of HRRRv2 was inadequate for resolving mesoscale-scale convergence features responsible for initiating storms and thus missed many cases of CI and rapid growth that were clearly associated with these low-level features. Moreover, these low-level convergence areas are often not well observed in the Doppler velocity field despite being clearly apparent in radar reflectivity field as thin lines of enhanced reflectivity that delineated areas of upward vertical motions (Wilson et al. 1994). These updrafts may extend far above the low-level convergence and thus is much more likely to be evident in radar reflectivity than in the low-level wind field. While thin lines are easy to detect in radar imagery, NWP does not have the ability to interpret them as updrafts.

Since no corrections for removing radar bright band contamination or assimilating boundary layer convergence lines have been added to the HRRR up through 2020, versions of the HRRR through 2020 will likely have the same errors that are discussed in this study. Implementing an algorithm to remove the bright band in the reflectivity field, prior to data assimilation, would be an important first step to improve the HRRR 1- and 2-h rainfall nowcasts.

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