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P.69 INCREMENTAL ANALYSIS UPDATING WITH VARIABLE-DEPENDENT TIMING APPLIED TO A REAL-TIME HIGH RESOLUTION FORECAST SYSTEM

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1. MOTIVATION

For the past several years the Center for Analysis and Prediction of Storms (CAPS) at the University of Oklahoma has been running a real-time high resolution analysis system (400-m grid spacing) and an efficient assimilation and Numerical Weather Prediction (NWP) system with 1-km grid spacing producing 0-to-2 hour forecasts with low latency over a portion of the Southern Plains. Initially set-up for the Collaborative-Adaptive Sensing of the Atmosphere (CASA, McLaughlin et al. 2009) Integrated Project-1 (IP1) in southwestern Oklahoma (Brewster et al., 2007, Brewster et al., 2008, Brewster et al., 2010), the system has since been moved with the CASA radars to the Dallas-Ft Worth (DFW) metro area (Brewster et al., 2014) and established as part of the DFW Urban Testbed (Figure 1).

Very low latency on modest computing resources for the NWP system is achieved by utilitizing a 3DVAR analysis with complex cloud analysis (Gao et al., 2004, Brewster et al., 2005, Hu et al., 2006, Brewster, 2015). The analysis increments are assimilated into the ARPS (Xue et al, 2001, Xue et al., 2003) model using Incremental Analysis Updating (IAU, Bloom et al., 1996). This allows production of the complete 2-hour thunderstorm resolving forecast in about 20 minutes of wall-clock time on fewer than 200 cores.

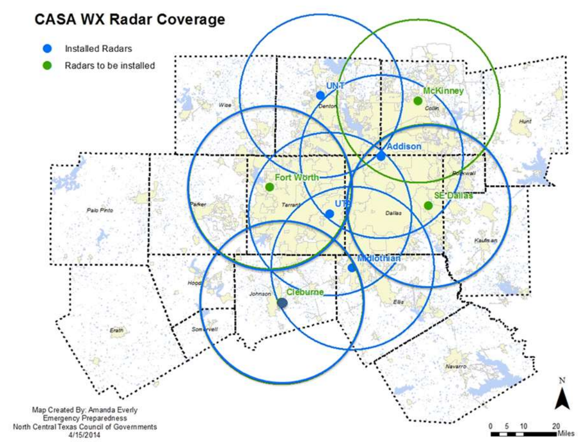

Figure 1 Map of the DFW Urban Testbed showing current status of CASA X-band Radar Network. Blue circles indicate 40-km range rings for radars deployed as of November, 2016. Green circles are for planned radar sites. Background map shows county boundaries of the North Central Texas Council of Governments.

In the course of running the model some cases were noted in which the forecast sometimes could not maintain initial very heavy rain and hail cores during the assimilation period into the early part of the forecast. This would sometimes cause the premature collapse of the initialized heavy thunderstorms. Observing this behavior lead to the idea of allowing the insertion of the hydrometeors to lag the insertion of wind and latent heat increments; with this approach the hydrometeors might be better retained once the storm updraft is fully established, thus improving

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the fidelity of the assimilated storms and the subsequent NWP forecasts.

To accomplish this, the Incremental Analysis Updating with Variable-Dependent Timing (IAU-VDT) assimilation method was developed. The IAU-VDT allows the timing of the introduction of analysis increments to vary for each variable.

In this paper the IAU-VDT technique is described and tested in a hail storm case from March 2015. IAU-VDT has since been implemented in the operational DFW Testbed forecast system, so real-time forecast results from the 26 Dec 2015 tornado outbreak in the D/FW metro area are presented along with recent tests of IAU-VDT with a double-moment microphysics scheme.

2. IAU WITH VARIABLE-DEPENDENT TIMING

In the incremental analysis updating scheme (IAU, Bloom et al., 1996) observations are assimilated in the forecast system through the following process: 1) increments to a background forecast are calculated using an analysis scheme such as 3DVAR, 2) the analysis increments are applied to the NWP model over an assimilation time window appropriate to the scale being modeled. The IAU allows the forecast model to smoothly accept the increments by allowing the unobserved variables to gradually adjust to the new observation information without creating excessive numerical noise.

Traditionally the IAU assimilation is applied with a triangular distribution of the fractional increments in time such that the largest fraction of the increment is applied in the middle of the time window, ramping up from zero at the beginning and then ramping down to zero fractional increment being applied by the end of the window. The increments to all model variables are applied using the same fractional distribution in time.

In the CAPS real-time system (detailed further in Section 4) observations are applied in a cycled IAU. Each cycle has a 10-minute assimilation window during which increments to all variables,

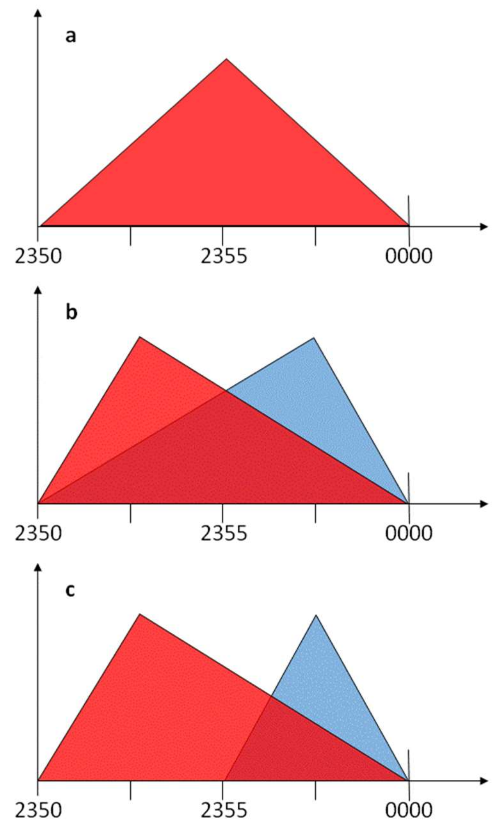

Figure 2 Three IAU-VDT time weighting shape pairs: a) Uniform triangular weighting "A", b) early mass-wind bias (red) with late hydrometeor bias (blue), "B", c) early mass-wind bias (red) with delayed-start hydrometeor insertion (blue), "C".

including a latent heating estimate and hydrometeors, are applied with triangular time distribution.

As mentioned, examining the vertical cross sections in some cases of very heavy rain and/or hail in the analyses revealed the model had some difficulties in establishing and maintaining an updraft in a strong convective storm from a larger-scale background without such a storm.

It is hypothesized that supporting the weight of the hail, graupel and heavy rain would be improved by first adjusting the model wind and mass fields to allow the updraft velocities to become established without the burden of significant rain and hail loading and/or updraft-decelerating cooling due to melting of hail and/or graupel. This can be accomplished by adjusting the increment distribution in time so that a larger fraction of the latent heat and wind increments are applied early in the IAU window, and also introducing the hydrometeors using a different fractional distribution in time, one that applies a greater fraction of those increments toward the end of the IAU window. Thus the IAU with Variable-Dependent Timing (IAU-VDT) was developed.

The ARPS IAU code was modified to allow user specification of the IAU increment distribution in time by specifying one or more shapes for the increment fraction and then assigning a shape to each variable. To test the IAU-VDT, three shape couples are defined

Shape A: the centered triangular shape uniformly applied to all variables as is commonly used in IAU systems (Fig 2a),

Shape B: a triangular weighting that is skewed toward the beginning of the assimilation window to be used for temperature, water vapor and wind fields with a triangular weighting skewed toward the end of the assimilation window to be applied to hydrometeor increments (Fig. 2b), and

Shape C: a weighting for temperature, water vapor and wind as in Shape B, but with the start of hydrometeor insertion delayed until the middle of the assimilation window (Fig. 2c).

The IAU-VDT is tested using data from 24 April 2015, a day featuring a strong squall line passing through the CASA DFW Testbed with wind high winds and hail observed (Fig 3). We will examine east-west vertical cross-sections along y=40.5 km as indicated by horizontal line in Fig 3.

Figure 4 shows the hydrometeor estimates from the cloud analysis using the Milbrant and Yau single-moment microphysics (MYSM, Milbrant and Yau, 2005a, 2005b). A hail and graupel core is analyzed with maxima as indicated in the first column of Table 1. .Figure 5 shows the result of the 10-minute forecast/assimilation with the analysis increments applied using the three IAU-VDT time weighting schema previously described. The maxima after the assimilation are recorded in columns 3-5 of Table 1. Comparing the three panels in Fig. 5 it is apparent that there is

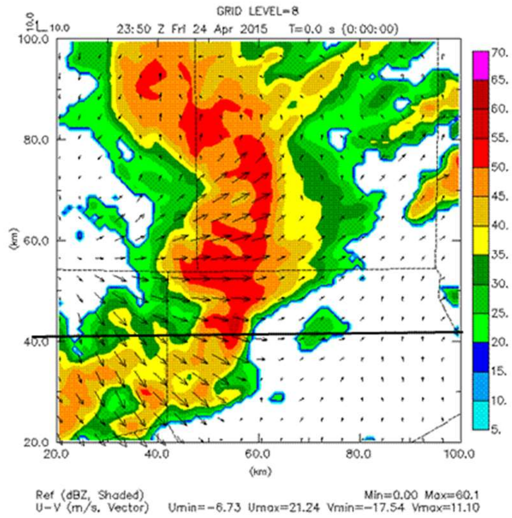

Figure 3 Initial reflectivity (dBZ, colors) and wind at grid level 8 at 2350 UTC (using mosaicked data from 2350-UTC) that is used to generate analysis increments for IAU in the 2350-0000 assimilation window. Cross-sections along y=40.5 km as indicated by horizontal line.

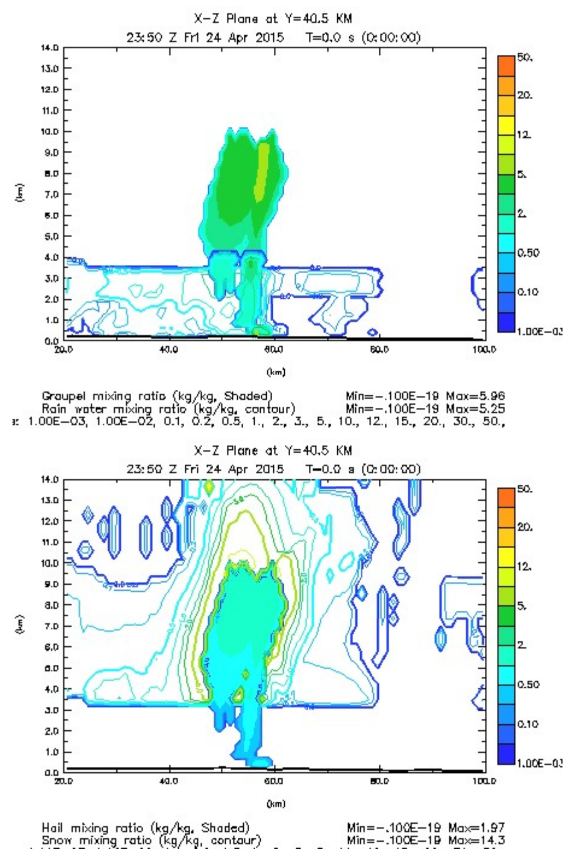

Figure 4 East-west cross-section at y=40.5 km. Estimated hydrometeor fields from the complex cloud analysis at 2350 UT. Top panel: graupel (color) and rain (colored contour lines). Bottom panel: hail (color shading) and snow (color contours).

Table 1 Maxima of Selected Variables at end of IAU time window (2350-0000 UTC)

Variable	Analysis	IAU-Orig	IAU-B	IAU-C
Rain	5.3 g/kg	2.4	2.7	3.3
Snow	14.3 g/kg	4.0	5.3	10.0
Graupel	6.0 g/kg	2.1	2.1	2.0
Hail	2.0 g/kg	0.3	0.3	0.6
W	8.4 m/s	6.2	7.5	7.9

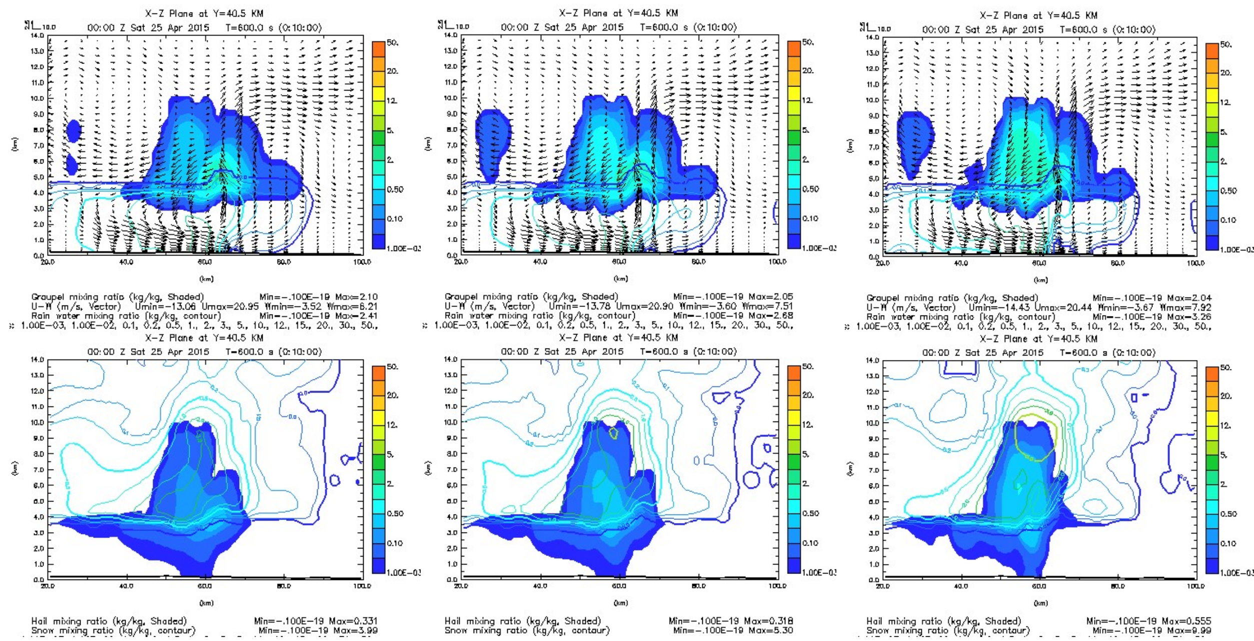

Figure 3. Cross-section at y=40.5 km after 10-min IAU assimilation window. Variables as in Fig 2. Left IAU-VDT time weighting scheme A, Center: IAU-VDT scheme B, Right: IAU-VDT scheme C.

improvement in retention of updraft vertical velocity, hail and graupel using Scheme B over the traditional equally-weighted triangular Scheme A, particularly in the hail core between 3 and 6 km. There is additional improvement when delaying the start of hydrometeor assimilation as shown in the results for Scheme C, again in the hail core aloft as well as in the maximum values of graupel and hail. It is also evident that there is an improvement in the structure of the hail core, being less spread out horizontally in the lowest 3 km, after applying Scheme C compared to the other IAU time weighting shapes.

3. APPLICATION OF IAU-VDT TO THE CAPS REAL-TIME FORECAST SYSTEM

3.1 CASA Dallas-Fort Worth Testbed

The Dallas/Ft. Worth Urban Testbed (D/FW Testbed) has been established as a site for evaluating real-time observing systems, data analysis and short-term forecasting over an urban area. A number of high-density observing networks are being tested in the region, including X-band Doppler radars, citizen weather observations, mobile sensors, and ground based profilers. These systems, along with the Federal surface and radar networks, comprise the diverse data that the CAPS is utilizing in our real-time analysis, nowcasting and short-term NWP efforts.

Besides providing real-time information for local governments and the National Weather Service (NWS) Forecast Office in Fort Worth, the system can be used as a basis for the testing of observation system impacts, including Networks of Networks (NRC, 2009) that are being integrated into the National Mesonet Program. Some of that work is described in Carr et al, 2016.

Beginning in 2012 some of the CASA IP-1 X-band radars were moved to North Texas from Oklahoma to be the cornerstone of the newly-established D/FW Urban Testbed with the support of the North Central Texas Council of Governments (NCTCOG), the NWS and other public and private sector partners.

As of December, 2016 seven of eight planned X-band radars had been deployed in the CASA D/FW Testbed (Fig 1), two relocated from the original CASA IP1 Network in southwestern Oklahoma, and one each from Ridgeline Instruments, EWR, Furuno, and Enterprise Electronics (EEC).

These radars are in addition to the three Federal radars in the metro area, namely the NEXRAD (WSR-88D) at Fort Worth (KFWS) and Federal Aviation Administration (FAA) Terminal Doppler Weather Radar (TDWR) serving Dallas Love Field (TDAL) and the TDWR serving the Dallas/Ft Worth Airport (TDFW). The analysis and forecast system also utilize other, more distant, NEXRAD radars that cover portions of their domains.

The combined Doppler radar network has good to excellent dual-Doppler crossing angles (Fig 2) and low-level coverage over the NCTCOG region and especially over the densely populated Dallas and Tarrant Counties.

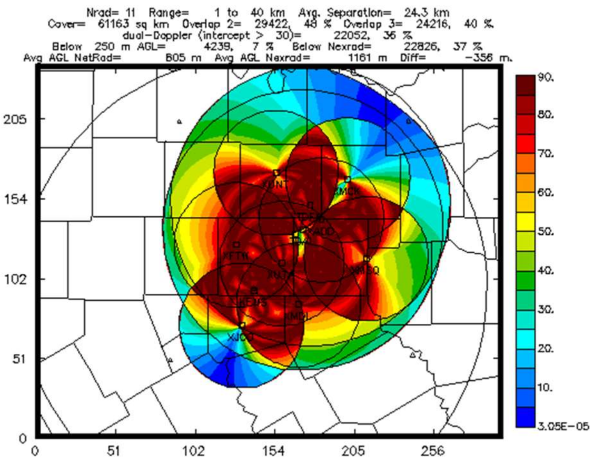

Figure 4. Maximum dual-Doppler crossing angles (color, degrees, scale at right) for combined CASA X-band (40 km range rings), TDWR and NEXRAD radar network.

In addition to the radars and conventional surface observation systems, a number of additional non-conventional instruments are in the region, or will soon be brought into the testbed.

1. REAL-TIME ANALYSIS & FORECAST DESIGN

CAPS designed a 400-m grid resolution real-time analysis and 1-km real-time data assimilation, nowcasting and NWP system using the Advanced Regional Prediction System (ARPS, Xue et al., 2001; Xue et al., 2003), and the ARPS 3D-Variational (3DVAR) with cloud analysis (Gao et al., 2004; Brewster et al., 2005; Hu et al. 2006a,b, Brewster et al., 2015) and ran the system in a domain covering central and southwest Oklahoma (Brewster et al., 2007 and 2010). The system, as repositioned for the D/FW Testbed, is described below with summary details for the forecast system detailed in Table 3, below.

Data assimilation and short-term forecasting are run on a 350 x 320 km domain with 1-km grid spacing. 53 vertical grid levels are used with domain top at 20 km and enhanced vertical resolution near the ground (20 m minimum vertical grid spacing).

Table 2 Features of Real-Time NWP Forecasts

Model	ARPS
Assimilation	2 cycles IAU
Processors	192 Cores MPI
Interval	15-30 minutes
Forecast Time	0-2 hours
Typical Run Time	20-25 minutes
Grid Spacing	1 km
Vertical Grid Spacing	400 m mean 20 m minimum
Grid Dimensions	363 x 323 x 53

For the short-term forecast there is no cumulus parameterization, clouds and precipitation are modeled using the Lin 3-Ice scheme (Lin et al., 1983). The model uses NASA Goddard atmospheric radiation transfer parameterization. Surface fluxes are calculated from stability-dependent surface drag coefficients using predicted surface temperature and volumetric water content. The model employs 1.5-order TKE closure based on Sun and Chang (1986), and a simple two-layer force-store soil model based on Noilhan and Planton (1989).

The NWP model is run when there is significant precipitation in the D/FW Testbed area or when precipitation is expected and the X-band radars are running. In December 2015 the data assimilation ran on 192 Intel Xeon Sandy Bridge cores of Boomer at the OU Supercomputing Center for Research and Education (OSCER), every 15-30 minutes. The model, including image post-processing and web posting, takes about 20-25 minutes to run so two sets of cores are used.

Interested readers can find the real-time analysis and forecast products on the Web during our operational periods via the links at http://forecast.caps.ou.edu .

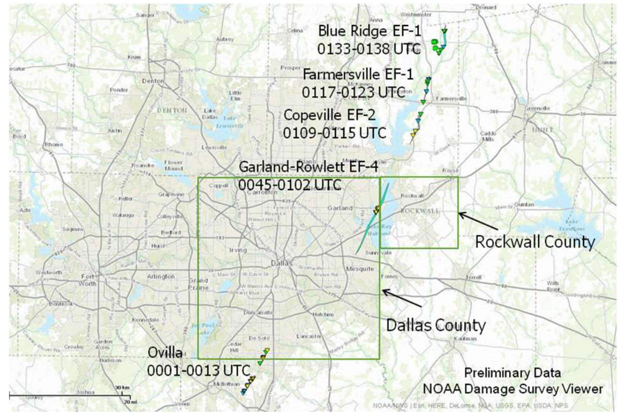

Figure 5. Tornado tracks near Dallas on 26-Dec-2015 (UTC Times 27-Dec-2015). Dallas and Rockwall Co. are highlighted to aid reader orientation with model output figures. From NOAA Damage Survey Viewer.

4. GARLAND-ROWLETT, TX TORNADO CASE

Example products from the newly-updated assimilation and forecast system are presented from a recent significant event in the Dallas-Ft. Worth region.

In the late afternoon and early evening of 26 December 2015 supercell thunderstorms moved generally north-northeast across the Dallas Metroplex. A total of 13 tornadoes were observed and damage tallied at more than $40 M (SPC, 2016, Marshall et al., 2016). Among the tornadoes in the Dallas area were an EF3 tornado near Ovilla around 00 UTC 27 Dec and 45 minutes later a large long-track tornado (approximately 20 km long, 500 m wide) with EF4 damage rating that touched down just south of Interstate-30 in Sunnyvale and passed through the portions of Garland and Rowlett in the northeast part of the metro area (Fig. 5). Following that, there were additional tornadoes to the north-northeast of Rowlett as the parent storm continued tracking in that direction.

The real-time NWP system had been updated with the new IAU-VDT assimilation scheme, and used as indicated in Fig 6. Two analysis and assimilation cycles are performed.

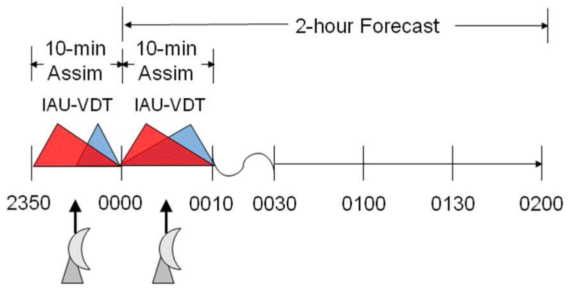

Figure 6. Data assimilation and forecast diagram for a forecast with nominal start time of 0000 UTC.

In the first cycle, Scheme C in Fig. 2 is utilized. For the second cycle, the assumption is the updraft will have been mostly established so the more moderate timing offset of Scheme B in Fig. 2 is applied.

The forecast system on this day was being run at 30 minute intervals. As of December 2015 five of the X-band radars in the DFW Testbed were installed, the radars at Ft. Worth and Mesquite were added since that time.

The forecasts were very successful in maintaining the storms and producing very strong rotation as indicated in the 1-6 km updraft helicity (UH) plots. Figure 6 shows four successive real-time forecasts (initialized 2300 to 0030) at the valid time for each where the forecast was indicating a strong UH field near the starting point of the Garland-Rowlett tornado. The tornado damage survey points are show as the triangles in the plot, the contours are reflectivity in 10 dBZ intervals with the UH indicated in color contours, non-linear scale at right. The timing of the rotation center was a bit fast in each, with successive forecasts asymptotically approaching the 0045 actual estimated time of touchdown. Given that the latency for the 2-hour output is about 20-25 minutes these forecasts had nearly one hour actual lead time on the observed 0045 UTC touch down time

The forecast initialized at 2330 UTC was the strongest at the time of touchdown and also through most of the track, peaking at 3000 m^2s^{-2}. Based on this and other cases there seems to be about a 15-20 minute spin-up time for the model to develop full strength of circulations and updrafts.

The left column of Figures 8 & 9 shows a sequence of forecast images from the forecast initialized at 0000 UTC in to be compared to the observed radial velocity in the right hand column. The sequence shows forecasts out 45 min to 1:15 (Fig. 8) and 1:30-1:45 (Fig. 9) into the forecast. The forecasts were quite accurate on the location of the maximum UH which were nearly coincident with the actual track.

Overall the real time forecasts performed remarkably well for this grid scale and showed good run-to-run consistency in the development and locations of the strongest rotation

The second column is a re-run of the forecast using the IAU-VDT applied to the Milbrant and Yau single-moment microphysics (MYSM), which is being considered for upgrading the real-time forecast system. With the MYSM microphysics, the forecast has a similar track to the real-time run but a somewhat stronger magnitude to the updraft helicity, especially in the 0115-0130 UTC time frame. The Milbrant and Yau double moment scheme (MYDM) produced similar results (not shown) although the MYDM was a bit weaker than the MYDM in the Rowlett storm while maintaining stronger rotation longer in the remnant of the Ovilla cell to its west.

5. SUMMARY AND FUTURE WORK

A unique enhancement to the IAU assimilation scheme has been developed and tested, IAU with Variable-Dependent Timing (IAU-VDT). This method, as demonstrated with the 26-Dec-2015 case, has been implemented in our real-time workflow and is producing quality short-term forecasts.

As mentioned we are evaluating the MYDM for upgrade of the operational forecast system for the spring of 2017.

Formal quantitative evaluation is planned for precipitation forecasts using Equitable Threat Scores and object-based methods for tornadoes, following recent work of Stratman and Brewster (2015).

Separately, training of forecasters and emergency managers in the use of these and other CASA tools will also be done in the coming year, with subjective evaluation by other stakeholders to follow, based on results.

6. ACKNOWLEDGMENTS

Brenda Philips and Apoorva Bajaj of the University of Massachusetts lead the CASA DFW Urban Testbed activities. Thanks to Karen Cooper of NSSL for access to the real-time Level-II FAA TDWR data for the D/FW Testbed. Thanks to all private partners who provided real-time radar and other data.

Oklahoma Mesonet data provided by the Oklahoma Climatological Survey. West Texas Mesonet data provided by Texas Tech University.

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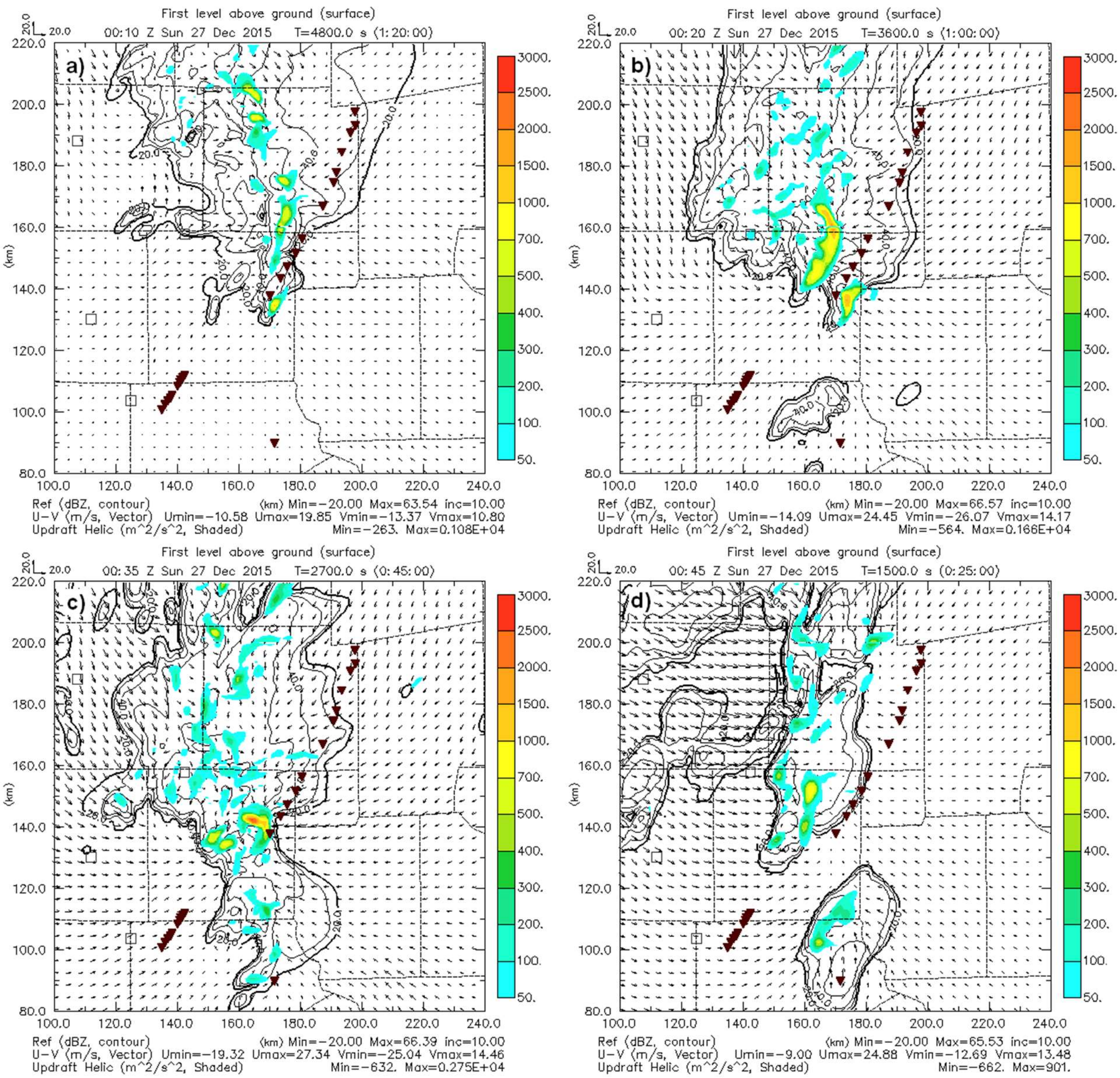


Figure 7. Four sequential real-time 1-km grid forecasts showing nearest forecast to the beginning of the 26 Dec 2015 Garland-Rowlett tornado track. Near surface perturbation winds and reflectivity (contours 1-6 km integrated updraft helicity (color shading, m^2 s^{-2}). Forecast initialized a) 2300 UTC, b) 2330 UTC, c) 0000 UTC, d) 0030 UTC.

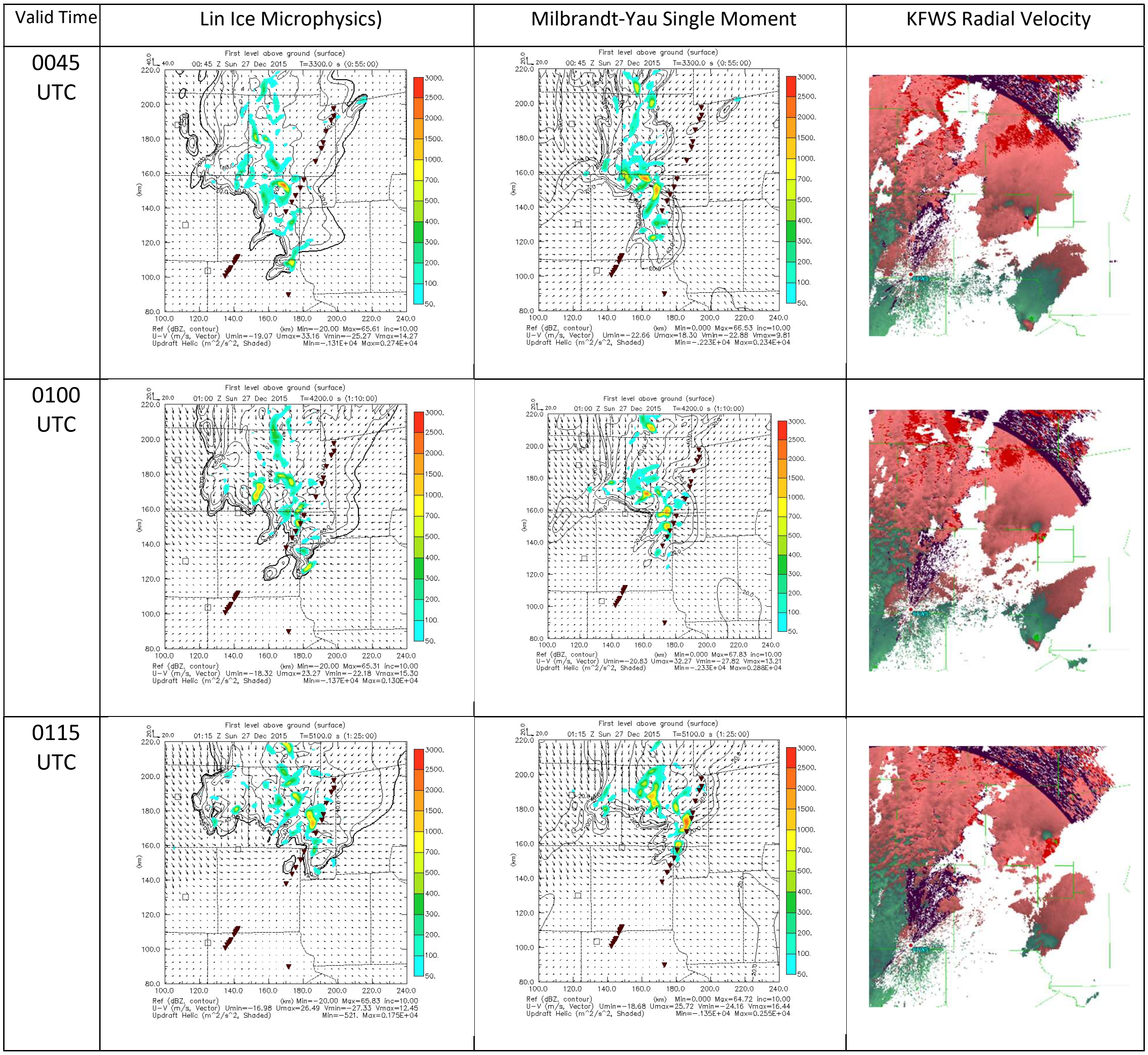


Figure 8. Forecasts of updraft helicity (color fill) and radar reflectivity (contours) and low-level wind vectors for 1-km forecasts initialized at 0000 UTC 27 Dec 2016. Real-time forecast using Lin microphysics (left colomn), forecast using MYSM microphysics (middle column), and KFWS radar radial velocity. For 27-Dec-2015 0045-0130.

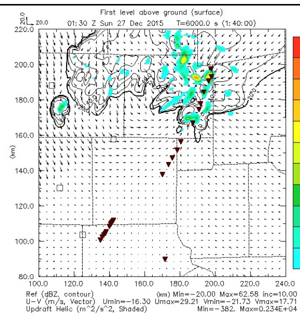
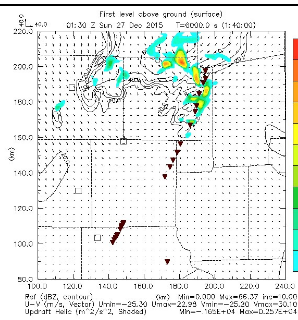
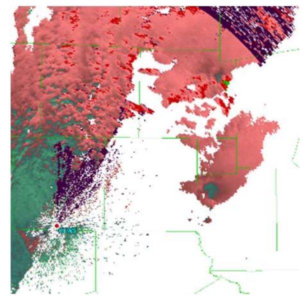
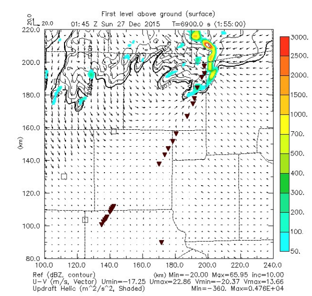
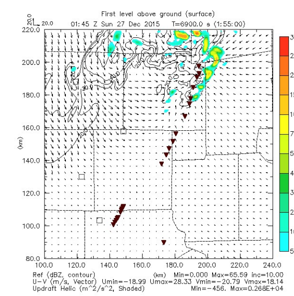
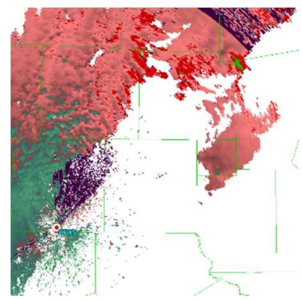
Valid Time	Lin Ice Microphysics)	Milbrandt-Yau Single Moment	KFWS Radial Velocity
0130 UTC			
0145 UTC			

Figure 9. As in Fig 8, 0000 UTC forecasts and KFWS radar continued for 0130-0145 UTC.