

## THE EXPLICIT NUMERICAL PREDICTION OF AN INTENSE HAILSTORM USING WSR-88D OBSERVATIONS: THE NEED FOR REAL TIME ACCESS TO LEVEL II DATA AND PLANS FOR A PROTOTYPE ACQUISITION SYSTEM

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### 1. INTRODUCTION

The US National Weather Service recently completed the installation of 164 WSR-88D Doppler weather radars in a national network (e.g., Alberty *et al.*, 1991) as part of its \$4.5 B Modernization and Restructuring Development Plan. This unique observing system provides nearly continuous single-Doppler radar coverage across the continental United States which, when coupled with the radar's superb sensitivity, sophisticated processing algorithms, and advanced user training, has led to a substantial improvement in the identification and short-term warning of intense local storms.

The WSR-88D or NEXRAD network was conceived first and foremost as a real time surveillance system, and no provision was made to either archive the data for later use or to transmit in real time to researchers or operational elements the complete set of Doppler moments (so-called Level II, wide band or base data, which includes the radial velocity, spectrum width, and reflectivity). The former was eventually accomplished via a retrofit of all radars with a robotic tape cartridge recording system (Crum *et al.*, 1993), and data are now archived routinely at the National Climatic Data Center. The latter issue was addressed in a provisional manner via the Radar Interface and Data Distribution System (RIDDS) (Jain and Rhue, 1995), though only for selected radars and for limited periods of time.

During the past several years, an increasing appreciation of the utility of the WSR-88D network, coupled with continued rapid advances in computational power and wide area networking, have led the research and operational communities to consider using WSR-88D data to initialize numerical forecast models (Lilly, 1990; Droegemeier, 1990, 1997). Indeed, the Center for Analysis and Prediction of Storms (CAPS) at the University of Oklahoma was established in 1989 to demonstrate the practicability of using such models -- at resolutions down to 1-2 km -- to predict explicitly the short-term (out to 6 hours) morphology of intense small-scale weather with the WSR-88D radar as the primary data source. However, because a single Doppler radar provides only the radial component of the wind (with all three components being required for initializing a forecast model), and because the coverage patterns of the WSR-88D radars overlap only over small areas at rather large ranges, CAPS spent considerable effort developing techniques to retrieve the unobserved wind components from a time series of single Doppler velocity volume scans (e.g., Sun *et al.*, 1991; Xu and Qui, 1994a,b,c; Qui and Xu, 1992, 1996; Shapiro *et al.*, 1995; Zhang and Gal-Chen, 1996). These methods, and extensions of them developed by others (e.g., Sun and Crook, 1994, 1997), have been used with some success both in case study testing and in real time operational tests of storm-scale numerical weather prediction (e.g., Janish *et al.*, 1995; Droegemeier *et al.*, 1996a,b; Xue *et al.*, 1996a,b).

Unfortunately, real time forecast tests, which have been performed in close collaboration with National Weather Service Forecast Offices, the Storm Prediction Center, and other entities of the Federal and private sector, have generally been limited to the use of digital NIDS (NEXRAD Information Dissemination Service)

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data (Carpenter et al., 1997, 1998) which, although available in real time for every WSR-88D radar, are generally of limited value for NWP by virtue of their reduced volume coverage, degraded spatial resolution, and value quantization. In those real time operational tests coordinated by CAPS which did in fact use the full Level II data stream (e.g., Droegemeier et al., 1996b; Xue et al., 1996b), the model domains were notably small because the data were available only from the Oklahoma City radar (KTLX). To fully test the concept of small-scale NWP, real time access to Level II data is needed from multiple radars over a large region -- and for sufficiently long periods of time -- to capture both weakly- and strongly-forced events in all seasons.

Based partly on results from the real time tests described above, The National Centers for Environmental Prediction (NCEP) has established a set of operational requirements for WSR-88D data in the context of numerical analysis and prediction (NCEP, 1998). In light of the compelling needs for real time Level II data, as demonstrated further in the next section, this document describes an effort to establish a prototype real time Level II acquisition test bed for 8 radars in the southern Great Plains.

## 2. A CASE STUDY OF LEVEL II DATA IN STORM-SCALE NWP: THE LAHOMA, OKLAHOMA HAILSTORM

### a. Overview of the Lahoma Storm

To demonstrate the need for WSR-88D Level II data in storm-scale numerical prediction, we present here several forecasts of an intense, long-lived supercell hailstorm (the so-called Lahoma storm of 17 August 1994; Conway et al., 1996; MacGorman et al., 1996; Morris and Janish, 1996; Morris and Shafer, 1996; Lemon and Parker, 1996; Janish et al., 1996; Zong et al., 1998) that was observed by up to four WSR-88D radars. (The term "storm-scale" refers here to the initialization and explicit prediction of individual convective elements using grid resolutions of 1-3 km.) The forecasts differ only in the data used to define the initial state, and as noted below, include experiments using either NIDS or Level II data, the latter with single Doppler velocity retrieval.

As shown in Figure 2, the Lahoma storm, which formed in relatively benign synoptic conditions (Janish et al., 1996), began in central Kansas as a disorganized multicell. Moving southward, it encountered higher CAPE and storm-relative environmental helicity, becoming a supercell upon crossing the border into Oklahoma. The storm produced significant hail that partially destroyed an Oklahoma Mesonet site near Lahoma, OK, and continued to move southward where it underwent a further transition to a bow echo. The reader is referred to the references cited previously for further details.

### b. Experiment Design

We use the Advanced Regional Prediction System (ARPS) (Xue et al., 1995) to simulate the Lahoma

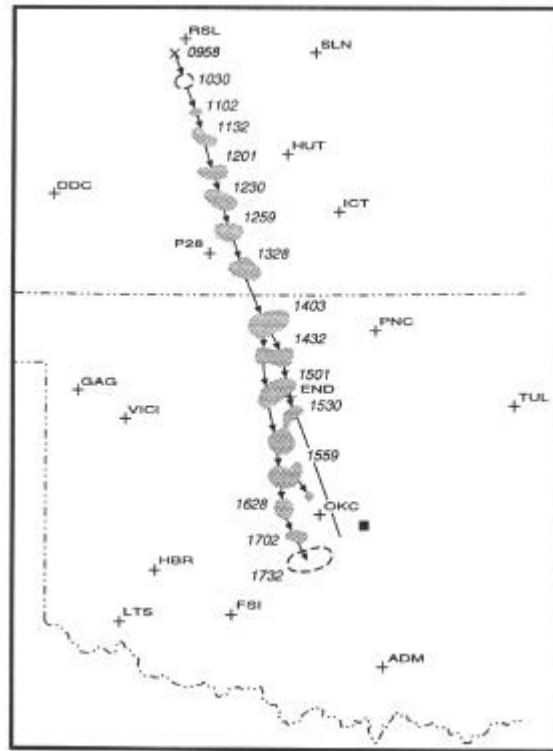


Figure 2. Track of Lahoma storm echoes exceeding 50 dBz. Times are CDT, and the transformation to a bow echo begins between 1530 and 1559 CDT. From Conway et al. (1996).

storm with a variety of real-data initial conditions. As shown in Figure 3, the model is configured with an outer grid of 18 km resolution, nested within which is a storm-resolving grid of 2 km resolution. Only one-way nesting is used in these experiments. We utilize all physics options in the ARPS, including short wave and long wave radiation, terrain, and full surface physics

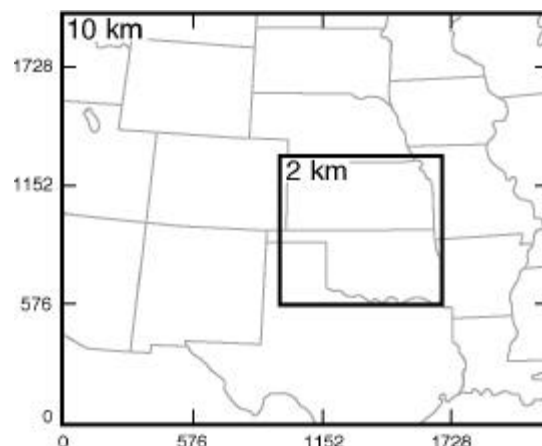


Figure 3. One-way nested grid configuration used in the Lahoma forecast experiments.

and physiography (including a two-layer soil model). The outer domain uses both the Kain-Fritsch cumulus

parameterization as well as the Lin-Tao explicit 6-category microphysics scheme (which includes water vapor, cloud water, rain water, cloud ice, snow, and graupel/hail); the inner domain uses only the latter.

The background fields of the model initial state for *all experiments* are provided by the 12 UTC RUC analysis on 17 August 1994. The lateral boundaries of the outer domain are interpolated from 3-hourly RUC analyses, and the inner lateral boundaries are interpolated every 30 min from the outer solution provided by the ARPS. While most groups running mesoscale models in real time use only an operational analysis or forecast, suitably interpolated to higher resolution, to define the initial state, i.e., without adding high-resolution data, *the unique basis of our work is to move beyond this strategy and use Doppler radar observations, and quantities retrieved therefrom, to provide the model with data of spatial resolution comparable to the scales being predicted.*

Therefore, using the ARPS Data Analysis System (ADAS; Brewster, 1996), we add to the background RUC analysis at 12 UTC surface observations from the Oklahoma and Kansas Mesonets, the ARM Project, and standard NWS sites. In addition, we incorporate upper-air observations as well as wind data from 31 Wind Profiler Demonstration Network systems. This initial condition is used for the 10 km resolution outer grid experiment, and the ARPS is integrated for 6 hours, i.e., from 12 UTC to 18 UTC. At 18 UTC, intermittent data assimilation -- using the 6 hour ARPS forecast as a background -- is applied to incorporate those wind profiler and surface data available at that time. The model integration is then continued to 00 UTC.

The fine grid is initialized at 1841 UTC (1341 CDT) -- when the Lahoma storm is just north of the Oklahoma-Kansas border (Fig. 2) -- by direct interpolation from the coarse grid solution. Both the coarse and fine grid experiments just described define our reference or control experiment in which no radar data are used:

- **Experiment #1 - No Radar Data:** Initial state based on RUC analysis + OK/KS Mesonet + ARM + SAO + Upper Air + Wind Profiler

To demonstrate the relative merits of using either NIDS (Level III) or wide band (Level II) data in predicting the evolution of the Lahoma storm, we conduct two additional experiments:

- **Experiment #2** - Same as experiment #1, but with NIDS reflectivity data added to the fine grid at 1841 UTC from the following WSR-88D systems: Oklahoma City (KTLX), Dodge City (KDDC), and Wichita (KICT). The rainwater mixing ratio is estimated using a Z-R relationship (values above 50 dBz are set to 50 dBz), and the water vapor field is adjusted to saturation, with appropriate changes in temperature to maintain constant buoyancy, in regions where the rainwater exceeds 1 g/kg. Finally, the rainwater mixing ratio is set to 70% of its observed value to reduce the impact of water loading in the updraft. (A procedure for retrieving the motion field from a time series of NIDS

reflectivity volume scans has now been developed at CAPS but is not used here.)

- **Experiment #3** - Same as experiment #1, but with the full 3-D storm-scale wind, thermodynamic, and moisture fields retrieved using Level II radial velocity and reflectivity data. Specifically, we first use the two-scalar single-Doppler velocity retrieval scheme of Shapiro et al. (1995) to retrieve the azimuthal and polar wind components at 1836, 1841 and 1847 UTC using Level II data from KICT. Following Weygandt et al. (1985), we then retrieve the thermodynamic fields (i.e., perturbation potential temperature and pressure) using a Gal-Chen type scheme. During this step, the water vapor mixing ratio is adjusted to saturation in updrafts and to 80% of saturation in downdrafts when the reflectivity exceeds 20 dBz. The rainwater mixing ratio is specified to be 70% of the value calculated from the Z-R relationship.

### c. Results

Figure 4 presents a comparison of observed and predicted composite radar reflectivity at approximately 30 min intervals for the Lahoma storm. Note that, in experiment #1 (no radar data), the Lahoma storm is absent at the initial time and never develops during the 2 hour and 19 min forecast. (Note that two spurious storms do in fact develop in south central Kansas around 2030 UTC.) This result clearly demonstrates the limitations associated with running high-resolution models using only coarse-resolution NCEP analyses or forecasts as the starting point (in the present case, the RUC analysis was augmented with other information, e.g., from the Oklahoma Mesonet -- and the result was still a useless forecast). Of course, in cases where the forcing is strong (e.g., fronts, significant terrain, lake effect events), sufficient information may be present in the mesoscale and synoptic scale fields to generate the appropriate small-scale structures, though probably not a particular observed storm.

In experiment #2, the NIDS data provide useful information concerning the structure and location of the Lahoma storm at  $t = 0$ . Unfortunately, the storm quickly dissipates due to the absence of storm-scale velocity information (principally updraft), and only two spurious storms form in south-central Kansas, as in experiment #1.

In experiment #3, which uses full Level II data along with SDVR and thermodynamic retrieval, the predicted Lahoma storm moves in approximately the correct direction for the first hour. However, instead of maintaining an intense reflectivity core on the southwest side, it shows a clear decline in intensity. During the next hour (1940 to 2040 UTC), the predicted storm weakens further and tends to drift to the southeast rather than moving south as observed.

While these results are not definitive (we believe they can be improved by a better representation of the cold pool and other modifications), they do provide compelling evidence -- as do other experiments at CAPS (e.g., Weygandt, 1998), -- for real time access to Level II data.

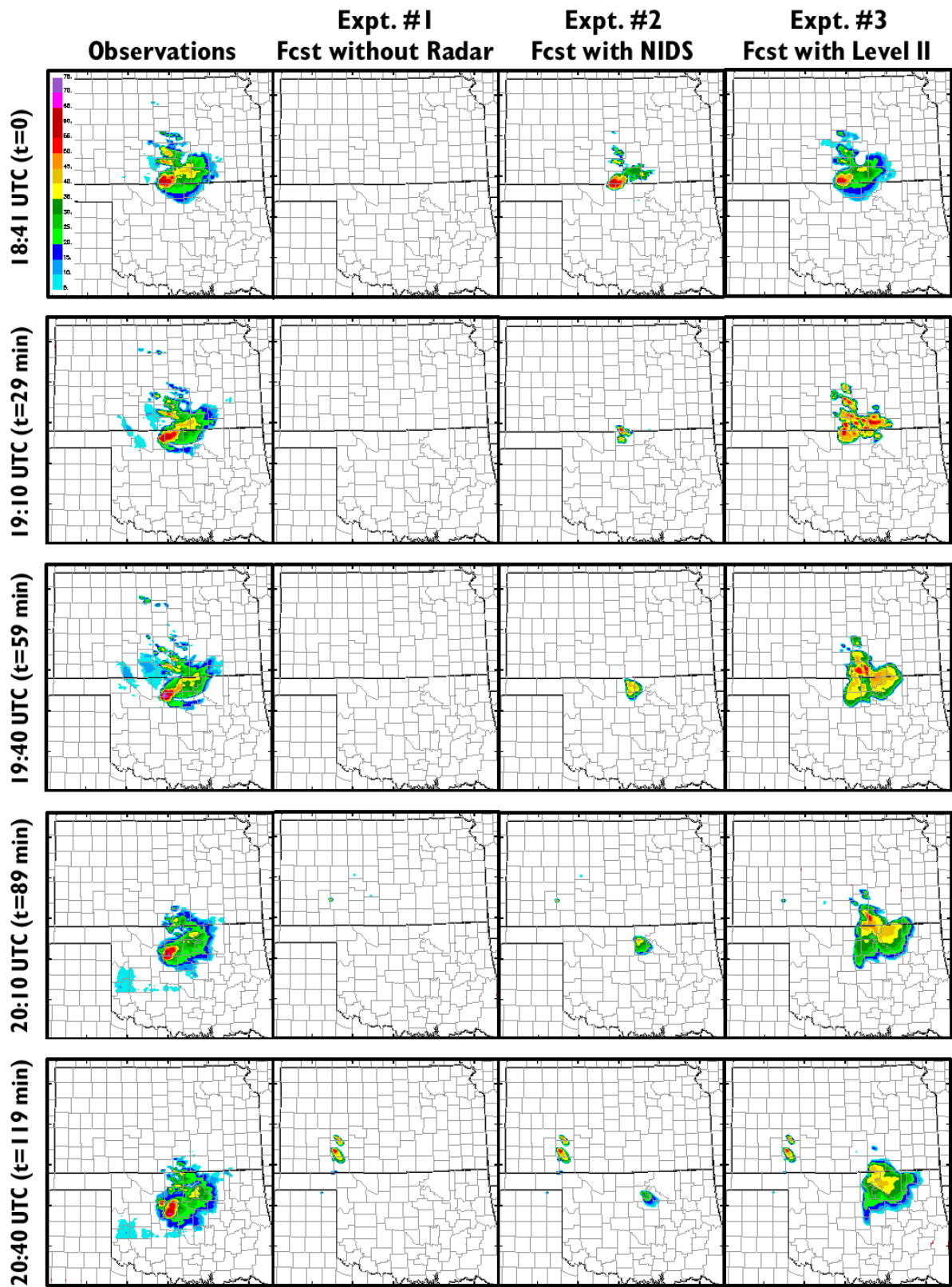


Figure 4. Observed and predicted composite radar reflectivity at approximately 30 min intervals for the Lahoma storm. See the text for further details.

In the next section we describe a prototype system that is being implemented to provide such data for use in real time testing of high resolution forecast models over the southern Great Plains.

### 3. THE COLLABORATIVE RADAR ACQUISITION AND FIELD TEST (CRAFT)

The Center for Analysis and Prediction of Storms, the Universities of Oklahoma of Washington, the UCAR Unidata Program, the Oklahoma State Regents for Higher Education, and the NOAA WSR-88D Operational Support Facility have joined forces on a collaborative project to establish a prototype system for ingesting WSR-88D Level II data in real time from 8 radars in the southern Great Plains: *Oklahoma City, Tulsa, Fort Smith, Wichita, Dodge City, Amarillo, Lubbock, and Fort Worth*. Known as the Collaborative Radar Acquisition and Field Test (CRAFT), this project will serve as a mechanism for testing various aspects of data compression, ingest, and quality control, as well as the use of Level II data in creating high resolution analyses and forecasts for real time operational evaluation. It is hoped that CRAFT will serve as the starting point for a national Level II ingest and redistribution capability for education, research, and operations. Because of space limitations, we provide here only a brief sketch of the strategy. Readers are encouraged to visit the CRAFT home page (see section 5) for further information and status reports.

The Unidata Local Data Manager (LDM) software will be used by CRAFT to compress and transmit Level II data. Because each LDM node can both transmit its own data onto the network and pass data through from other nodes, it affords greater flexibility and redundancy than a star configuration in which each radar is linked independently to a central ingest site. Although CRAFT will use the present RIDDS-based ingest system, as described below, it will be fully compatible with the new "open systems" standard to be introduced in the next 2 years.

Currently, Level II data are sent from the WSR-88D radar product generator (RPG) over a high speed serial line to a Sun SparcStation 5 running the RIDDS software. The Sun workstation ingests the data and outputs it in TCP/IP UDP packets to an 8 port Ethernet hub. (In the future, the RPG is will be replaced by an "Open RPG", which will eliminate the need for the Sun SparcStation.)

CRAFT is considering two options for transmitting Level II data from the Ethernet hub. In the first, an additional SparcStation running RIDDS would be used to read the data from the hub and place it in a circular buffer. This method is useful if the SparcStation is also used to locally display the radar data (e.g., with the NSSL Warning Decision Support System, or WDSS). In the second strategy, a PC running Linux would be connected to the hub to read the data directly. Both options require the placement of an additional computer at the local NWS office which operates the RIDDS SparcStation.

Several versions of the Unidata LDM ingestor can run on either of the above systems (Fig. 5). In all cases, the data may be compressed and sent out on another

Ethernet interface via the Internet to a remote LDM system that can then ingest the data and/or send it to other users. The raw data rate for a single radar volume scan (9.8 Mbytes) at 6 minutes per volume is 218 Kbits per second. However, the data can be compressed down to 10-20% of its original size. In a 10-day experiment with the Seattle WSR-88D radar, the maximum data rate for compressed data was 46 Kbits per second. Thus, if the data can be read off of the Ethernet hub and hardware compressed at the NWS office, they can easily be transmitted over a BRI ISDN line (128 Kbits per second) or an ADSL line -- thereby eliminating the need for the second computer at the NWS office.

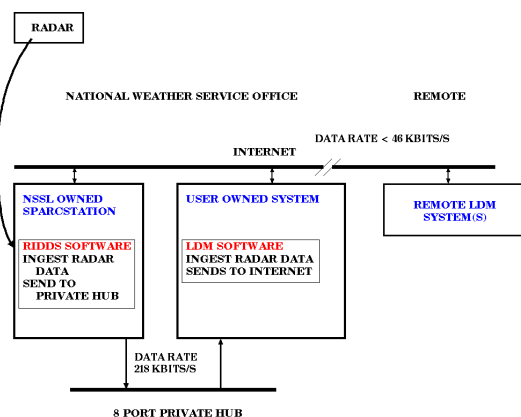


Figure 5. Possible LDM configuration for CRAFT.

On 10-11 September 1998, the authors of this paper, building upon the LDM-based Level II access system at the University of Washington, conducted the first test on the Oklahoma City WSR-88D. Data have now been exchanged in test mode between the Washington and Oklahoma City systems, and it is hoped that the other 7 radars in the southern Great Plains will be using the LDM system by early 1999. At the present time, sufficient funding is in place to maintain the 8 connections for approximately 2 years, with the central ingest facility located at the Oklahoma State Regents for Higher Education in Oklahoma City. CAPS hopes to be using these data in its real time forecasts by spring 1999, and the NSSL will likewise be using the data in their WDSS.

### 4. ACKNOWLEDGEMENTS

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