7.1 SUOMINET EFFORTS IN THE U.S. SOUTHERN GREAT PLAINS

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1. INTRODUCTION

SuomiNet (Ware et al. 2000) is a university-based, real-time, national network of Global Positioning System (GPS) installations established in 2000 for geosciences research and education, with funding from the National Science Foundation and cost sharing from collaborating universities. The network exploits the ability of ground-based GPS receivers to make atmospheric measurements, including integrated water vapor. The University of Oklahoma (OU), in partnership with the U.S. DOE Atmospheric Radiation Measurement (ARM) Program, is establishing geodetic quality SuomiNet receivers over the next year at 15 ARM Southern Great Plains (SGP) extended facilities (EFs) located throughout Oklahoma and Kansas and at one Oklahoma Mesonet (Brock et al. 1995) weather station in central Oklahoma.

The establishment and scientific applicability of the SuomiNet sites within Oklahoma and Kansas will have several unique aspects. SuomiNet water vapor data will augment ARM's suite of water vapor measurements, which includes a GPS micronet centered on the site's central facility in northern Oklahoma, a number of microwave radiometers, a microwave profiler, a Raman lidar, an atmospheric emitted radiance interferometer, radiosondes, and various standard relative humidity devices located at ground level and on a 60-m tower. The ability to perform water vapor measurement intercomparison studies, conduct instrument development, and operate enhanced, short-term water vapor experiments over the region will be greatly enhanced by SuomiNet's dual-frequency GPS receivers. These high quality receivers, along with co-located surface meteorological data, will allow direct measurement of wet delay and, therefore, total slant-path water vapor. The average station spacing is 50-60 km, thus providing a meso-beta scale horizontal distribution of integrated precipitable water.

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Other unique aspects of the SGP deployment will be the use of ruggedized laptop computers to collect the GPS data and push them to SuomiNet computers using local Internet Service Providers (ISPs). The OU's School of Meteorology and Center for the Analysis and Prediction of Storms (CAPS) will evaluate the potential of using the suite of water vapor measurements to improve the skill of numerical weather forecast models. OU scientists in the School of Geology and Geophysics will use the data to conduct plate tectonics studies.

2. SITE DEPLOYMENT AND INSTALLATION

The SuomiNet GPS receivers are anticipated to be deployed at 15 extended facility sites within the SGP Cloud and Radiation Testbed (CART) domain. Figure 1 shows the SGP CART, which include 23 EFs, 4 boundary facilities (BF), and a central facility (CF), all located in Oklahoma and Kansas. The 15 sites to be instrumented with SuomiNet receivers include Larned, LeRoy, Plevna, Halstead, Towanda, Elk Falls, Coldwater, and Ashton, Kansas; and Byron, Pawhuska, Lamont, Ringwood, Meeker, Cyril, and Seminole, Oklahoma. The Oklahoma Mesonet site to be instrumented is located in Norman (Cleveland County). The EFs are continuously operating and are instrumented to measure typical meteorological parameters (wind speed and direction, temperature, pressure, relative humidity, and precipitation), as well as upwelling and downwelling longwave and shortwave radiometers and surface layer heat exchanges by either the energy balance Bowen ratio or eddy correlation methods. An EF also typically includes a multi-filter rotating shadowband radiometer (MFRSR).

These sites were chosen due to their relatively uniform spatial distribution and because they have the necessary surface meteorological measurement systems already in place. Because there is no existing structure at these sites suitable for mounting the GPS antenna, a high-stability monument will be installed at each location. These will follow the Continuously Operating Reference Station (CORS) monument design developed by Murray (2000) for the NOAA National Geodetic Survey. These monuments are comprised of

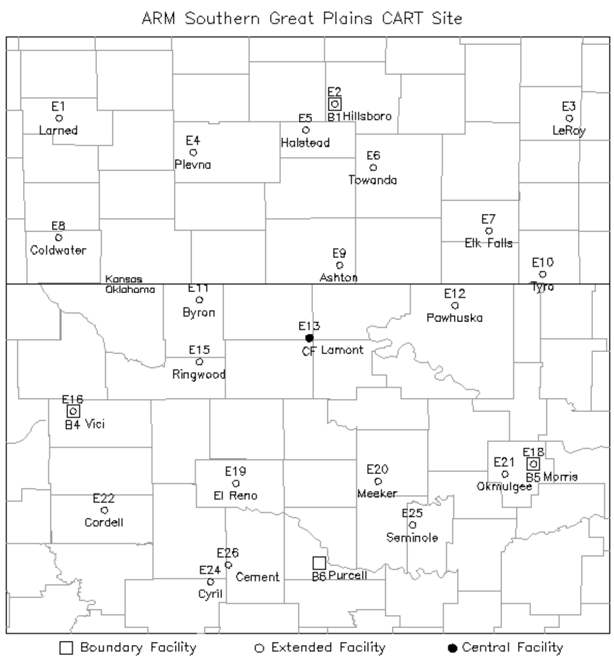

Fig. 1. ARM Southern Great Plains Cloud and Radiation Testbed. Extended facilities are labeled as "E"; central facility is "CF". Norman Mesonet site (not shown) is located just north of Purcell.

a reinforced concrete pillar extending 3 to 4 meters below ground, or until rock is encountered. They are designed to be of geodetic quality; that is, they will be sufficiently stable to permit geologic analyses of the GPS data in addition to the atmospheric analyses needed by OU meteorologists and the ARM Program.

The sites will be installed in a phased approach. The first deployment, scheduled for October 2000, will be at the SGP central facility. Subsequent installations will be carried out as resources permit, to maximize the spatial distribution of the array over the SGP CART domain.

3. NEW SITE DATA COLLECTION SYSTEM

3.1 Background

Each EF instrument reports its measurements to a data logger. Each EF is currently equipped with one phone line that is connected to a U.S. Robotics V.everything modem and a Black Box SW540A Code Operated Switch (COS). The data system at the CF periodically calls each EF, causes the COS to connect to an instrument data logger and acquires the measurement data from that instrument. Programmatic requirements necessitate recovering data from each EF multiple times per day.

This communication architecture requires a large number of phone calls from the CF, most of which incur costly long distance fees. While this architecture was a reasonable implementation when the EFs were installed in 1992, technologies are available today that allow the ARM Program to build a much more cost-effective communications architecture.

OU and ARM, as part of the SuomiNet project, are now in the process of upgrading this system by developing and testing new Linux based laptop systems to replace the COS at each of the EFs. The current operation, in addition to incurring high communications costs, also often results in less than optimal data recovery rates. The new Linux systems will acquire the data from the instruments, archive and compress them on-site, and periodically ship them to CF data system computers via a local call to an ISP. This is expected to greatly reduce communications costs while increasing data recovery rates.

3.2 Hardware Configuration

OU and ARM have been testing a laptop-based Linux system at the Pawhuska EF since March 2000. The data communications equipment and instrumentation at the EF are supported by AC power line regulation, surge suppression, and a UPS. The Linux laptop and associated data modem are installed in a non-insulated, white-painted steel, NEMA 4, sealed electrical enclosure attached to posts on a concrete pad, with the largest surfaces facing the south and north. An internal circulation fan runs continuously to aid the dissipation of heat from the enclosure. A thermostatically controlled, 100 watt heater maintains the internal temperature to greater than 5° C in the winter. Figure 2 illustrates a typical EF enclosure installation.

Fig. 2. Typical ARM SGP extended facility enclosure installation.

The operating temperature inside the NEMA 4 enclosure is critical to the proper operation and longevity of the laptop and modem located within the enclosure. The field testing of this system included monitoring temperatures within and external to the enclosure over a period of several months, spanning early spring and summer 2000. While there were no ambient temperatures below 0° C during the test period, the internal heater and electronic equipment maintained an internal operating temperature consistently above 5° C thoughout the test period. Summer ambient temperatures exceeded 45° C several times throughout the test period. However, the operating temperature within the enclosure was consistently held below 48° C.

It is worth noting that the heat dissipated by the equipment within the enclosure keeps the internal temperature approximately 4° C above the ambient environment. This minimizes the occurrence of condensation within the enclosure.

The new EF data collection system consists of the following components:

- Itronix XC6250 ruggedized notebook PC Pentium 266 MHz, Color SVGA, 128 MB RAM, 6.2 GB disk, PCMCIA floppy drive, internal modem;
- Edgeport Universal Serial Bus with 8 RS-232 ports;
- 3Com Ethernet PC card for network connection for the field technicians' portable computer; and
- Telephone line surge protection.

The Itronix XC6250 is factory tested to operate reliably in an environment exceeding 60° C. The laptop PC provides a compact package with low heat dissipation while providing a keyboard and screen for an operator interface.

Communication between the laptop PC and the instruments at the EF is implemented with fiber optic cable and bit drivers. This architecture provides electrical isolation between the laptop and the instruments. It also supports very long (up to 2000 meter) cable lengths between the laptop and the instruments. The fiber cable infrastructure of the EFs has performed virtually without problem for over 8 years. The original optical bit drivers, which required an external power source, are in the process of being replaced by a version that derives power from the RS-232 interface, reducing the required number of hardware components.

3.3 Description of Operation

The Linux operating system was selected for use on the EF PCs because it has a demonstrated history of reliability, can be configured for high security, and includes, by default, an open user interface and all of the necessary protocols for communications with instrumentation and the CF data system. In addition, porting the existing ARM instrument collection software from the Sun Microsystems, Inc. Solaris-based CF data system was easily accomplished.

The EF instruments log data to a Campbell Instruments CR10 series data logger. Data collections are currently scheduled to occur hourly using the operating system's cron utility. Time synchronization is performed, if necessary, at each collection. Instrument logger time adjustments and any problems associated with data collection are logged, time-stamped and identified by instrument platform.

Periodically (currently hourly), the cron utility runs ARM applications software that transfers data and logs between the EF and the CF data system. This process:

- Initiates a dial-up Point-to-Point (PPP) communication link with the local ISP;
- Initiates an ftp transfer of data and log files in a compressed tar format to the CF data system;
- Logs transfer problems, if any;
- Marks files as transferred as appropriate;
- Keeps the PPP connection alive for a few minutes in the event CF operators need to login to perform maintenance; and
- Closes the PPP connection and terminates the phone call.

Phone line quality in rural locations is often less than optimal. The data modems typically connect at 19,200 to 28,800 bits per second. If there were problems establishing communications with the ISP or the CF, or there were problems transferring files, the communications application will make another attempt at the next scheduled transfer time. The system is currently configured to buffer up to 60 days worth of data.

3.4 OU/ARM/SuomiNet Software

SuomiNet GPS receivers will be installed by OU/ARM at the 15 selected ARM EFs. OU/ARM is working with SuomiNet project technicians to integrate SuomiNet GPS and data transfer software into the EF PCs. It is expected that this integration and testing will be complete and deployable by October 2000.

All but one (Pawhuska) of the ARM EFs selected as SuomiNet installations include existing meteorological instrumentation, so SuomiNet MetPacks will not be necessary. Thus, OU/ARM is developing the software necessary to emulate the SuomiNet MetPack data using its existing ARM EF instrumentation. A MetPack will be necessary for the Pawhuska site.

3.5 Performance to Date

The prototype EF Linux laptop system at Pawhuska has been operating since March 2000. From installation through 15 September 2000, 100% of the available data have been recovered from all instrumentation at the site. Data gaps do exist for those periods of time during which the operations staff perform bi-weekly maintenance.

One non-maintenance related data loss was due to a failure of the MFRSR instrument. However, the xtty collection software (Schlemmer 1998), as designed, identified that the instrument stopped and reset it, thus restoring data collection without manual intervention. On another occasion, the local ISP went down for a period of approximately seven days. Upon resumption of ISP service, all data accumulated over the outage period were successfully transferred to the CF data system without manual intervention.

4. SCIENTIFIC IMPORTANCE TO ARM PROGRAM

The chief near-term contribution of SuomiNet to the ARM Program will be to characterize the spatial (horizontal) distribution of precipitable water vapor (PWV) over the SGP CART domain. ARM currently measures PWV only at its CF in the center of the CART box and at its four BFs on the edges of the box (which are located approximately 150-175 km from the CF) with two-frequency microwave radiometers. Although ARM has deployed broadband radiometers at each of its EFs in order to measure the spatial distribution of solar and infrared radiation fluxes over the SGP CART domain, ARM has no capability to measure PWV at any of these facilities. Locating SuomiNet GPS receivers at 15 of the EFs would significantly improve ARM's ability to understand the spatial variations in the (clear sky) radiation field.

In addition, one of the most important and sensitive inputs to Single Column Models (i.e. a single column from a General Circulation Model) is the time rate of change or "advective tendency" of moisture at each face of the model domain. At present these are derived solely from balloon-borne soundings launched from the central and boundary facilities at 3-hour intervals during Intensive Operating Periods (IOPs). The addition of 15 spatially distributed measurements of PWV at hourly or half-hourly intervals will substantially improve the accuracy of the derived moisture tendencies.

In the longer term, the SuomiNet GPS measurements will permit the three-dimensional spatial distribution of water vapor over the SGP CART domain to be determined from measurements of Slant Water Vapor (SWV) along the line-of-sight to each of the ~8 GPS satellites typically in view. MacDonald et al. (2000) have demonstrated the feasibility of such a scheme with an Observing System Simulation Experiment (OSSE) for a simulated GPS network with 40-km spacing. Braun et al. (1999) have deployed an array of 20 inexpensive single-frequency GPS receivers in a 10x10 km area centered on the SGP CF for the purpose of measuring SWV and using tomographic reconstruction methods to determine the three-dimensional distribution of water vapor. However, because these receivers have only a single frequency, they cannot account for ionospheric contributions to the signal delay and must rely on models to estimate this. The dual-frequency SuomiNet receivers will permit the ionospheric contribution to be precisely determined over the entire SGP CART domain, and will thus improve the accuracy of the single-frequency measurements and permit the low-cost single-frequency array to be expanded if desired.

5. IMPORTANCE TO MESOSCALE NWP

Moisture fields are often inadequately defined in mesoscale modeling research studies as well as in operational numerical weather prediction (NWP) models. Timely, accurate, and high-resolution moisture data are necessary for advancing research on the requirements and use of such data (e.g., McPherson et al. 1997) and to improve short-term forecasts (Emanuel et al. 1995).

The mesoscale modeling and forecasting group at CAPS produces real-time mesoscale (10-100 km) and storm-scale (1-10 km) forecasts (Xue et al. 1996; Carpenter et al. 1998) using its ARPS (Advanced Regional Prediction System) model (Xue et al. 1995). Real-time WSR-88D radar data are used to improve its prediction of severe storms (Droegemeier et al. 1999). It is anticipated that assimilation of high-resolution moisture field data derived from SuomiNet GPS in combination with other moisture data sources will allow the modeling of convection before it is detected by radar reflection from hydrometeors (K. Droegemeier, personal communication).

Additionally, improved vertical structure of water vapor and short-term precipitation forecasts can be obtained by assimilating surface humidity and precipitable water data into mesoscale models (Kuo et al. 1996). Park and Droegemeier (1996) showed that simulations of thunderstorms can be quite sensitive to the distribution of water vapor in the near environment. Crook (1996) found that while thunderstorm initiation is most sensitive to the temperature profile, thunderstorm strength is most sensitive to water vapor content. Thus, better measurements of the entire water vapor burden, as would be provided by SuomiNet, are likely to yield better thunderstorm forecasts. OU scientists at CAPS plan to take full advantage of the SuomiNet data suite to achieve these modeling improvements.

6. IMPORTANCE TO PLATE TECTONICS STUDIES

In order to upgrade the existing ARM EFs and the Norman Oklahoma Mesonet weather station to geodetic-quality GPS ground stations, specially designed, reinforced concrete piers must be constructed down to and into bedrock. This is required for the long-term (at least five to ten years) stability of the sites. OU/ARM plans to establish the Mesonet site, and the ARM CF site, as geodetic quality first, and then over time will upgrade the remaining 14 EFs to such quality.

With the geodetic option, we will be able to determine the absolute position of the piers within about 1-mm horizontal and 2-mm vertical precision. Obtaining this accuracy requires averaging data over a several month period, but the positioning information would be available on a continuous basis over several years. When compared with absolute positions from precision GPS stations on other continents, plate tectonics motions, which are on the order of tens of millimeters per year, will be apparent.

What will make the data from these mid-continent SuomiNet stations uniquely valuable is the possibility of detecting small strains within this region, an area that has largely been ignored in favor of more tectonically active regions in the U.S., primarily west of the Rocky Mountains. Although not as active as California, the mid-continent does have substantial seismicity, with a significant chance of damaging ground accelerations, for example, over the next 50 years (Figure 3). Besides

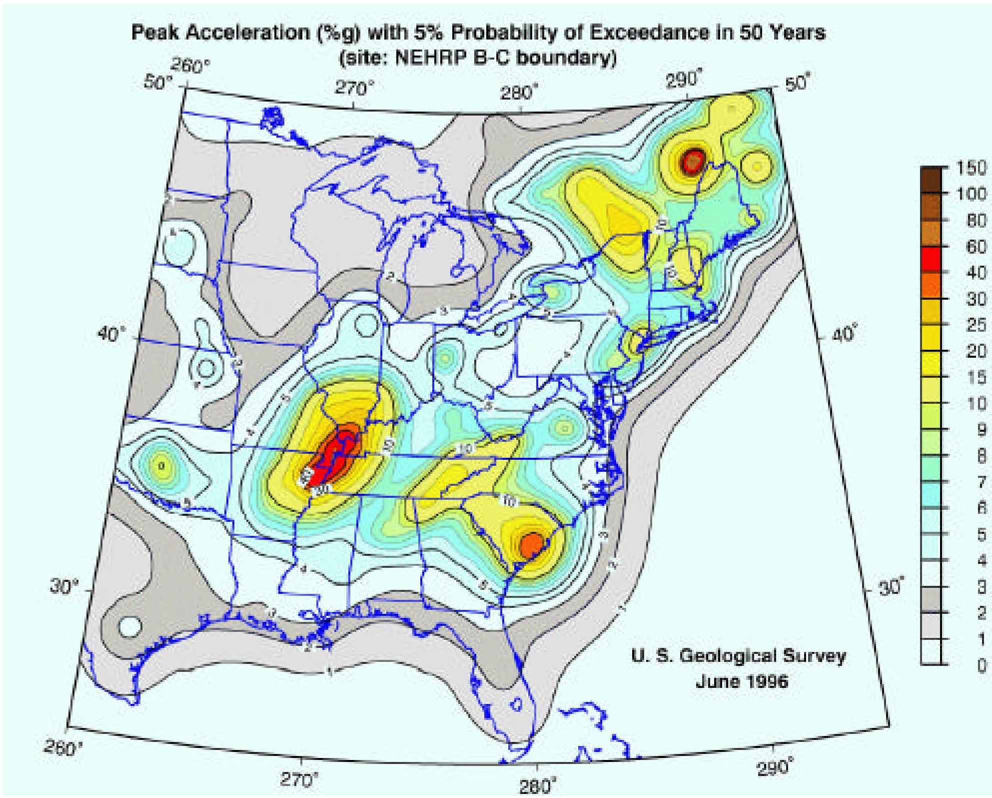

Fig. 3. Seismically active regions in the mid-continent and eastern parts of the U. S. The cause of seismicity in central Oklahoma, which has included the 1952 magnitude 5 El Reno earthquake, is poorly understood. A network of precise GPS stations in this region, combined with an existing seismograph network, may help provide some answers.

Fig. 4. The Meers Scarp in southwestern Oklahoma. It is the only visible fault scarp east of the Rocky Mountains. The scarp can be seen in this low-sun-angle air photo running from the upper left corner of the image to the lower right corner. In some places the scarp exhibits several meters of vertical offset. (Photograph by D. B. Slemmons)

the New Madrid region in Missouri, Illinois, Arkansas and Tennessee, there is a seismically active region centered in Oklahoma that extends northward into Kansas. Oklahoma, for example, averages about 100 recorded locatable earthquakes per year, with about 1 or 2 felt (usually greater than magnitude 2) earthquakes per year. Furthermore, the only visible fault scarp east of the Rocky Mountains (Meers Scarp) runs through southwestern Oklahoma and was the site of an estimated magnitude 7 earthquake within the last two or three thousand years (Figure 4). The geodetic control provided by the SuomiNet stations may allow us to detect strains responsible for some of this seismicity.

When combined with data from other stations in the mid-continent region (for example, geodetic-quality stations were proposed for Nebraska; Indiana; Dallas, San Antonio, and El Paso, Texas; and Little Rock, Arkansas), we hope to be able to detect crustal strains due to micro-plate motions, fault movement, fluid withdrawal and other causes.

Another benefit of geodetic-quality stations is their use as part of real-time kinetic differential GPS (DGPS) positioning with mobile equipment, allowing for precision surveying for geological and geophysical fieldwork. The DGPS positioning capability will also aid storm intercept activities in Oklahoma and Kansas during severe weather season.

7. SUMMARY

SuomiNet provides great promise for advancing research at the University of Oklahoma in numerical weather prediction and plate tectonics studies, and will further help the U.S. DOE ARM Program better specify the measurement of water vapor over the Southern Great Plains. The SuomiNet program is also allowing ARM to upgrade its data collection infrastructure to provide more reliable and near real-time observations not only to SuomiNet but also to other researchers.

Acknowledgments. The authors would like to thank Dr. Kelvin Droegemeier of CAPS and the OU School of Meteorology, a co-author of Ware et al. (2000), for his contributions both there and here on numerical weather prediction.

8. REFERENCES

Braun, J., C. Rocken, C. Meertens, and R. Ware, 1999: Development of a water vapor tomography system using low-cost L1 GPS receivers. *Proc., Ninth Annual ARM Science Team Meeting*, San Antonio, Texas, U.S. Department of Energy. [Available online at http://www.arm.gov/docs/documents/technical/conf_9903/braun-99.pdf.]

Brock, F. V., K. C. Crawford, R. L. Elliot, G. W. Cuperus, S. J. Stadler, H. L. Johnson, and M. D. Eilts, 1995: The Oklahoma Mesonet, a technical review. *J. Atmos. Oceanic Technol.*, **12**, 5-19.

Carpenter, R., Jr., and Coauthors, 1998: Storm-scale NWP for commercial aviation: Results from real-time operational tests in 1996-1997. Preprints, *12th Conf. On Numerical Weather Prediction*, Phoenix, AZ, Amer. Meteor. Soc., 213-216.

Crook, N., 1996: Sensitivity of moist convection forced by boundary layer processes to low-level thermodynamic fields. *Mon. Wea. Rev.*, **124**, 1767-1785.

Droegemeier, K., J. Zong, K. Brewster, T. Crum, H. Edmon, D. Fulker, L. Miller, R. Rew, and J. Martin, 1999: 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. Preprints, *15th Int. Conf. On Interactive Information and Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology*, Dallas, TX, Amer. Meteor. Soc., 295-299.

Emanuel, K., and Coauthors, 1995: Report of the First Prospectus Development Team of the U.S. Weather Research Program to NOAA and the NSF. *Bull. Amer. Meteor. Soc.*, **76**, 1194-1208.

Kuo, Y.-H., X. Zou, and Y.-R. Guo, 1996: Variational assimilation of precipitable water using a nonhydrostatic mesoscale adjoint model. *Mon. Wea. Rev.*, **124**, 122-147.

MacDonald, A. E., Y. Xie, and R. Ware, 2000: Diagnosis of three-dimensional water vapor using slant observations from a GPS network. *Wea. Forecasting,* in review.

McPherson, R., E. Kalnay, and S. Lord, 1997: The potential role of GPS/MET observations in operational numerical weather prediction. The Global Positioning System for the Geosciences. NRC Rep. 9254, National Academy Press, 111-113. [Available online at http://www.nap.edu/catalog/ 9254.html.]

Murray, O., 2000: Guidelines for Setting a CORS monument. Appendix B in *National Continuously Operating Reference Station (National CORS) Site Monumentation - Final Report.* NOAA National Geodetic Survey.

Park, S., and K. Droegemeier, 1996: Sensitivity of 3-D convective storm evolution to water vapor and implications for variational data assimilation. Preprints, *11th Conf. On Numerical Weather Prediction*, Norfolk, VA, Amer. Meteor. Soc., 137-139.

Schlemmer, J., 1998: xtty version 1.5.5, http://hog.asrc.cestm.albany.edu/~rsr/bits/softdocs/xtty/xtty.html, May 8, 1998.

Ware, R. H., and Coauthors, 2000: SuomiNet: A real-time national GPS network for atmospheric research and education. *Bull. Amer. Meteor. Soc.*, **81**, 677-694.

Xue, M., K. K. Droegemeier, V. Wong, A. Shapiro, and K. Brewster, 1995: *ARPS Version 4.0 User' s Guide*, 380pp. [Available from the CAPS, 100 East Boyd Street, Norman, OK, 73019.]

Xue, M., and Coauthors, 1996: The 1996 CAPS spring operational forecasting period: Real-time storm-scale NWP, Part II: Operational summary and sample cases. Preprints, *11th Conf. On Numerical Weather Prediction*, Norfolk, VA, Amer. Meteor. Soc., 297-300.