11.5 GEMS: AN AIRBORNE SYSTEM FOR URBAN ENVIRONMENTAL MONITORING

Randolph J. Evans[1], John Manobianco, Jonathan L. Case, and Joseph Dreher
ENSCO, Inc., Melbourne, FL

1. INTRODUCTION

Three-dimensional meteorological and air quality data collected over an urban environment are valuable for air pollution and homeland defense applications. Collecting the three-dimensional data, especially above the ground, can require extensive resources and sampling networks that may not be feasible for certain urban areas. Field studies such as Urban 2000 (Allwine et al. 2002) demonstrate the complexities of collecting meteorological and pollutant concentration data at and above ground level. These field studies also show how important the data are for input into atmospheric dispersion models (Warner et al. 2004). In discussing the need for improved capabilities to estimate uncertainty and predictability in air quality modeling on urban scales, Dabberdt et al (2004) state that "more extensive measurements of meteorological parameters and chemical composition are needed to support data assimilation, air quality forecasting and air quality forecast model evaluation. Data on winds and turbulence, air temperature, and concentration would be the most valuable."

This paper describes a revolutionary, new observing system designed for environmental monitoring that will integrate MicroElectroMechanicalSystems (MEMS) and nanoscale technologies. MEMS combine electrical functions with sensors and other mechanical devices embedded in semiconductor chips.

The concept, known as Global Environmental Micro Sensors (GEMS), features an integrated system of airborne probes that will remain suspended in the atmosphere and take measurements of pressure, temperature, humidity, and wind velocity as they are carried by atmospheric currents. The u- and v-wind components will be measured by displacements in probe position. In addition to gathering meteorological data, the probes could be used for monitoring and predicting the dispersion of particulate emissions, organic and inorganic pollutants, ozone, carbon dioxide, and chemical, biological, or nuclear contaminants.

This paper provides background on GEMS including a concept description in section 2 and a summary of the proposed global system in Section 3. Section 4 provides details of the application of GEMS for urban scales and presents preliminary results of a modeling study conducted at the intermediate to spatial urban scales as defined by Dabberdt et al. 2004.

2. CONCEPT DESCRIPTION

GEMS is envisioned as a global system for environmental monitoring. However, the system could easily be adapted to small-scale field tests in an urban setting. Preliminary work on GEMS in a phase I project funded by the NASA Institute for Advanced Concepts (NIAC) focused on validating the viability of the concept, defining the major feasibility issues, and determining the primary enabling technologies required for future design and development of the system (Manobianco 2002; Manobianco et al. 2003). A brief summary of the key issues and enabling technologies identified in phase I is given in Table 1 and highlighted in the following paragraphs of this subsection.

Each probe will be self-contained with a power source consisting of batteries, fuel cells, and/or solar power to provide sensing, data processing/computation, location/navigation, and communication functions. Fuel cells are a very promising long-term solution for autonomous system power generation because their energy densities are dramatically higher than that of batteries. The colder temperatures of the upper atmosphere present a challenge for both battery series resistance and fuel cell operation.

In order to regulate power consumption, active power management may be necessary using adaptive measurement strategies whereby the temporal (and therefore spatial) frequency of sensing and communicating is linked with vertical and horizontal changes in atmospheric parameters.

[1] *Corresponding author address*: Randolph Evans, ENSCO, Inc., 4849 N. Wickham Rd., Melbourne, FL 32940. e-mail: evans.randy@ensco.com

Based on specific applications, the probes will integrate micro and nanoscale technologies to make them lightweight enough so that they pose virtually no danger upon contact with people or property. The size, mass, aspect ratio, component geometry, buoyancy control, and aerodynamic design will all determine how long probes remain airborne. Materials science will play a key role to limit probe mass and potentially make them biodegradable or at least bioinert, thereby minimizing risks to the environment as probes settle out of the atmosphere.

Buoyancy control and aerodynamic design will probably be the most effective way to reduce the terminal velocity of probes and keep them suspended for much longer periods of time. There are many examples of such design in nature including dandelion seeds, threads of balloon spiders, and auto-rotating maple seeds (Walker 1981).

Table 1. Key issues and enabling technologies affecting GEMS design and development

Major Feasibility Issues	Primary Enabling Technologies
Probe design	Materials science, nanotechnology, biomimetics
Power	Batteries, micro fuel cells, solar energy
Communication	MEMS-based Radio Frequency and/or free-space optical systems
Navigation	Global Positioning System, MEMS-based accelerometers/ gyroscopes
Networking	Artificial intelligence (autonomous self-healing networks)
Measurement	MEMS-based pressure, temperature, humidity sensors
Deployment/dispersion/scavenging	Numerical weather prediction and Lagrangian particle models
Data impact	Observing system simulation experiments
Data collection/management	Artificial intelligence, data mining
Cost	MEMS mass production and packaging, deployment strategies, networking and data collection infrastructure
Environmental	Biodegradable and/or bioinert materials

The probes will communicate with other probes, remote receiving platforms, and data collectors using Radio Frequency (RF) transmissions to form a wireless, mobile, in situ network. As part of a wireless network, the probes will not require recovery to collect data and therefore will be disposable.

A critical challenge for GEMS is to define a viable networking solution given available power and probe separation. The separation distance, power constraints, and communication range will determine whether each probe can transmit to a remote receiving platform or if mobile networking via multihop routing is an option. Global Positioning System (GPS)-aided inertial navigation and network localization will both be viable long-term options for probe navigation. With network localization, only a fraction of the probes have knowledge of their absolute locations, and the remaining probes estimate their relative positions from RF signals (Savvides et al. 2001).

While GEMS will likely complement current and even next-generation in situ sensors and ground/space-based remote sensing platforms, the system has the capability to provide a 100-fold increase in the horizontal resolution of current in situ synoptic observations in the PBL, upper troposphere, and lower stratosphere. GEMS would be ideal for targeted or adaptive observational campaigns as part of research (e.g. field experiments) and operational (e.g. hurricane reconnaissance) missions, especially in data sparse regions where it is cost effective and practical to obtain high-resolution spatial and temporal resolution measurements only over limited domains. As envisioned, GEMS could provide observing capabilities spanning an extremely broad range of time and space scales from the detailed life cycle of individual clouds through planetary-scale weather (Figure 1).

Figure 1. Conceptualization of GEMS illustrating both global and local distribution of probes with communication and networking between probes and data collectors.

3. GLOBAL SYSTEM PROJECT

For the current phase II NIAC effort, the feasibility issues are being studied in detail to examine the potential performance and cost benefits of a global sensor system, and to develop a technology roadmap that will help NASA to integrate the concept into future missions and programs. Assessment of the optimum probe design and deployment strategy requires an interdisciplinary collaboration to examine complex trade-off issues such as the number of probes required in the network, development and manufacturing costs, and the impact of probe observations on forecast accuracy.

The nature of atmospheric flow patterns is sufficiently variable that probes could remain near their release point or be rapidly swept away by the wind. Simulated measurements of atmospheric temperature, pressure, humidity, and wind velocity taken by these probes can be used to evaluate the impact of observations on meteorological analyses and forecasts for different weather regimes. Measurements from the probe network must be of sufficient accuracy and spatial coverage to improve the diagnosis and forecasting of weather patterns, above and beyond the skill attainable with conventional weather observations.

3.1. Simulation System

The Advanced Regional Prediction System (ARPS; Xue et al. 2000; Xue et al. 2001) coupled with a Lagrangian particle model (LPM) is used to simulate dispersion of and observations collected by an ensemble of probes.

3.2. Probe Dispersion

Probe dispersion is simulated using the LPM embedded within ARPS. The probes are assumed to be passive tracers moving independent of one another and transported by the wind. The LPM tracks the location of each probe based on three-dimensional wind components, and updates probe position using the resolvable-scale components of wind velocity directly from the ARPS model, as well as turbulent velocity fluctuations. The turbulent velocity fluctuations are estimated from a subgrid scale (SGS) turbulence parameterization (Mellor and Yamada 1980) similar to the SGS scheme of Deardorff (1980) used in the ARPS model. A vertical slip velocity for gravitational settling is included to estimate how rapidly probes fall in the atmosphere based on their diameter and density, and air density. A parameterization scheme for wet deposition or precipitation scavenging is included in the LPM to simulate the impact of frozen and liquid precipitation on probe trajectory and possible washout (Seinfield and Pandis 1998).

3.3. Simulated Observations

To simulate measurements obtained from probes and conventional observational networks, interpolation is used to extract values of temperature, humidity, pressure, cloud water, and other model variables at locations throughout the model integration. Assuming the probes are passive tracers, temporal changes in their absolute or relative position are used to estimate wind velocities. A random component representing measurement error is added to the simulated observations in order to address questions regarding instrument accuracy.

3.4. Deployment

A number of potential deployment strategies are being studied including probe release from high-altitude balloons (Girz et al. 2002; Pankine et al. 2002), surface stations assuming positive buoyancy, unmanned aerial vehicles for targeted observation strategies (Holland et al. 2001), and vertical profiles similar to rawinsonde measurements. Each of these deployment strategies will be simulated using the ARPS/LPM on a 50-km hemispheric grid to determine long-range probe dispersion patterns. Since data impact studies will be focused on much finer scales, two one-way nested grids will be implemented with grid spacings of 10 km and 2 km covering synoptic- and regional-scale domains, respectively (Figure 2).

3.5. Regional Data Impact Studies

Observing system simulation experiments (OSSEs) will be used to assess the impact of probe measurements on weather analyses and forecasts following Atlas (1997) and Lord (1997). OSSEs have been conducted for decades in meteorology to evaluate the potential impact of proposed remote and in situ observing systems, determine trade-offs in instrument design, and evaluate the most effective data assimilation methodologies to incorporate the new observations into regional and global NWP models (Arnold and Dey 1986; Rohaly and Krishnamurti 1993; Atlas 1997; De Pondeca and Zou 2001).

Figure 2. Domain for 50-km hemispheric ARPS simulations with sample locations and coverage of 10-km (blue-shaded) and 2-km (yellow shaded) grids to be used for mesoscale observing system simulation experiments.

3.6. Global System Results

The simulated dispersion of probes deployed from a hypothetical configuration of stratospheric balloons over the Northern hemisphere is shown in Figure 3. Details of this experiment performed during the phase I project are given in Manobianco (2002). Details and results of regional OSSEs using only the ARPS model over the Florida peninsula for short range (< 24 h), limited, data impact studies are also given in Manobianco (2002).

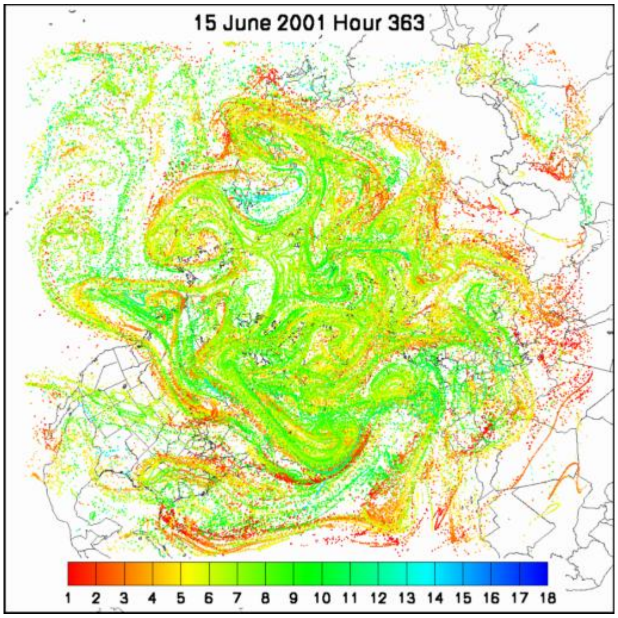

Figure 3. Probe positions at 0300 UTC 15 June 2001, 15.125 days after the model initialization time. Probe altitude (km) is denoted by the color bar showing altitude range from 1-18 km above ground level.

4. URBAN-SCALE GEMS

The original GEMS concept focused on its application as a global observing system. The current study described in this section shows how GEMS could be used for taking fine-scale measurements in an urban or battlefield environment. Dabberdt et al (2004) describe four regimes of urban distance scales as summarized in Table 2. While the study described in this paper focuses on the intermediate to spatial scales, GEMS is envisioned to be a useful system for monitoring at the block or neighborhood scale as well.

Table 2. Distance scales for urban dispersion regimes (Dabberdt et al. 2004).

Scale name	**Range**	**Encompassing limits**
Small	< 100 m	Street canyons
Block or neighborhood	100-1000 m	Several buildings
Intermediate	1-10 km	Several blocks
Spatial	10-100 km	City, suburbs, and rural surroundings

The modeling study described in the following subsections was patterned after the hemispheric simulations described in section 3 where one model provided the "truth" and was used as a comparison for simulated measurements extracted from a different modeling scenario. This study used two different mesoscale models along with a dispersion model and graphical gridding routine to assess the impact of releasing airborne probes to measure pollutant concentrations.

4.1. Probe deployment

Probes were deployed using the inline LPM described in Section 3. ARPS was run with a nested 2-km grid spacing configuration shown in Figure 2. While the ARPS/LPM has the capability of numerous possible deployment scenarios, the one chosen for this simulation is presented in Table 3. This scenario represented a boundary layer release that might occur from an elevated tall tower with mechanisms that would eject sensors at designated time intervals at fixed height intervals. The prevailing model winds carried the probes toward their sampling destination. Maps showing the probe locations at four different times during the 12-h release are shown in Figure 4.

Table 3. Probe deployment scenario.

Location	200 km SW of Salt Lake City, UT (38.82^{o}N, 113.17^{o}W)
Height above ground	100-199 m at 3 m intervals
Frequency/Duration	6 sec / 12 hours
Time	0600 UTC 6 Sep 1999
Total probes released	244,800
Total probes remaining	116,968
Settling velocity	[1]Average 0.005 m s^{-1}

[1]Settling velocity is density dependent (see Manobianco et al. 2004)

During the 12-h simulation, approximately half of the released probes settled to the ground and were no longer tracked within the LPM. The dispersion patterns (Figure 4) show how the probes moved relative to the mountains and valleys in western Utah. The probes were deployed upwind of the pollutant release location such that they would drift over the pollutant plume and measure concentrations.

4.2. Pollutant release

The pollutant release was modeled by first generating meteorological data using the Regional Atmospheric Modeling System

(RAMS) (Pielke et al. 1992). RAMS was run at 3-km grid spacing for the 24-hour period beginning 0000 UTC 6 September 1999. Data were output hourly for use by the dispersion model.

The dispersion model used for these analyses was the CALMET/CALPUFF system (Scire et al. 2000). RAMS data were converted to CALMET format where the data were gridded to 2-km horizontal resolution and 11 vertical layers from the surface to 3000 m. CALPUFF was run using the CALMET data on the same 2-km grid. Data on the pollutant release are presented in Table 4.

Table 4. Pollutant release scenario.

Location	65 km north of probe release point (39.40^{o}N, 113.21^{o}W)
Pollutant sample	SO_2
Base elevation	1640 m msl
Release height	150 m
Exit temperature	300 K
Exit velocity	1 m s^{-1}
Emission rate	10 g s^{-1}
Release Time Start	0700 UTC 6 Sep 1999
Output	Hourly to 1900 UTC

CALPUFF concentration output was used to provide a three-dimensional concentration field that was the truth for the probes to sample. The technique allows for numerous modeling simulations with the truth generated from one set of models: RAMS, CALMET/CALPUFF; and the sampling measurements obtained using another set of models: ARPS/LPM.

To compare the CALPUFF truth concentrations with the simulated measured concentrations, two different simulations were made. The truth simulation computed concentrations on the 2-km grid so that the precise location of the plume along with the concentration gradients was known. The “measured” concentrations were computed using the exact same release configuration as the truth but with receptors located at the probe positions rather than at grid points. The measured concentrations from the 116,968 probes at a single time were then run through a gridding program in the mapping software Surfer 8 using the Triangulation with Linear Interpolation method (Golden Software 2002).

4.3. Sensitivity Tests

Sensitivity tests were conducted to determine if fewer than 116,968 probe measurements could be used to map the plume. The motivation for such a test was to plan for a field deployment of the system. Fewer probes will be less costly and easier to manage in an actual field test. For the sensitivity tests, the total number of probes was reduced to 50%, 25%, 10%, 1%, 0.05%, and 0.01% of the original number of non-settling probes and the resulting measurements were used to regrid and remap the plume.

4.4. Results

Comparisons of the truth with the measured plume locations are presented in Figure 5. The location and shape of the measured plume closely matched that of the truth plume over the plume centerline and over the areas of highest concentrations. On the western edge of the plume, where concentrations fell below 0.01 µg m^{-3} and there were no probes to adequately sample the plume, the gridding software extended the lower concentrations of the plume approximately 50 km to the northwest over areas where the concentrations were actually zero. However, both simulations located the peak concentration at the same location with the truth at 2.29 µg m^{-3} and the measured at 5.09 µg m^{-3} for the peak concentrations.

The sensitivity test with 1% of the number of probes is shown in Figure 6. Derived using approximately 1200 probes, the 1% plume showed similarities to the 100% plume, with the 1% plume extending the lower concentrations (< 0.01 µg m^{-3}) to the north and east of the 100% plume (Figure 5b) and the truth plume (Figure 5a). The sensitivity tests with 50%, 25% and 10% of the probes showed only slight variation in plume location and concentration from the run with 100% of the probes.

These results indicate that the entire set of probes used in the simulations was not required to accurately measure the plume concentrations and movement. In these simulations, 244,800 probes were deployed, 116,968 remained airborne after probe settling occurred, and 1169 probes were able to locate the plume in the sensitivity test.

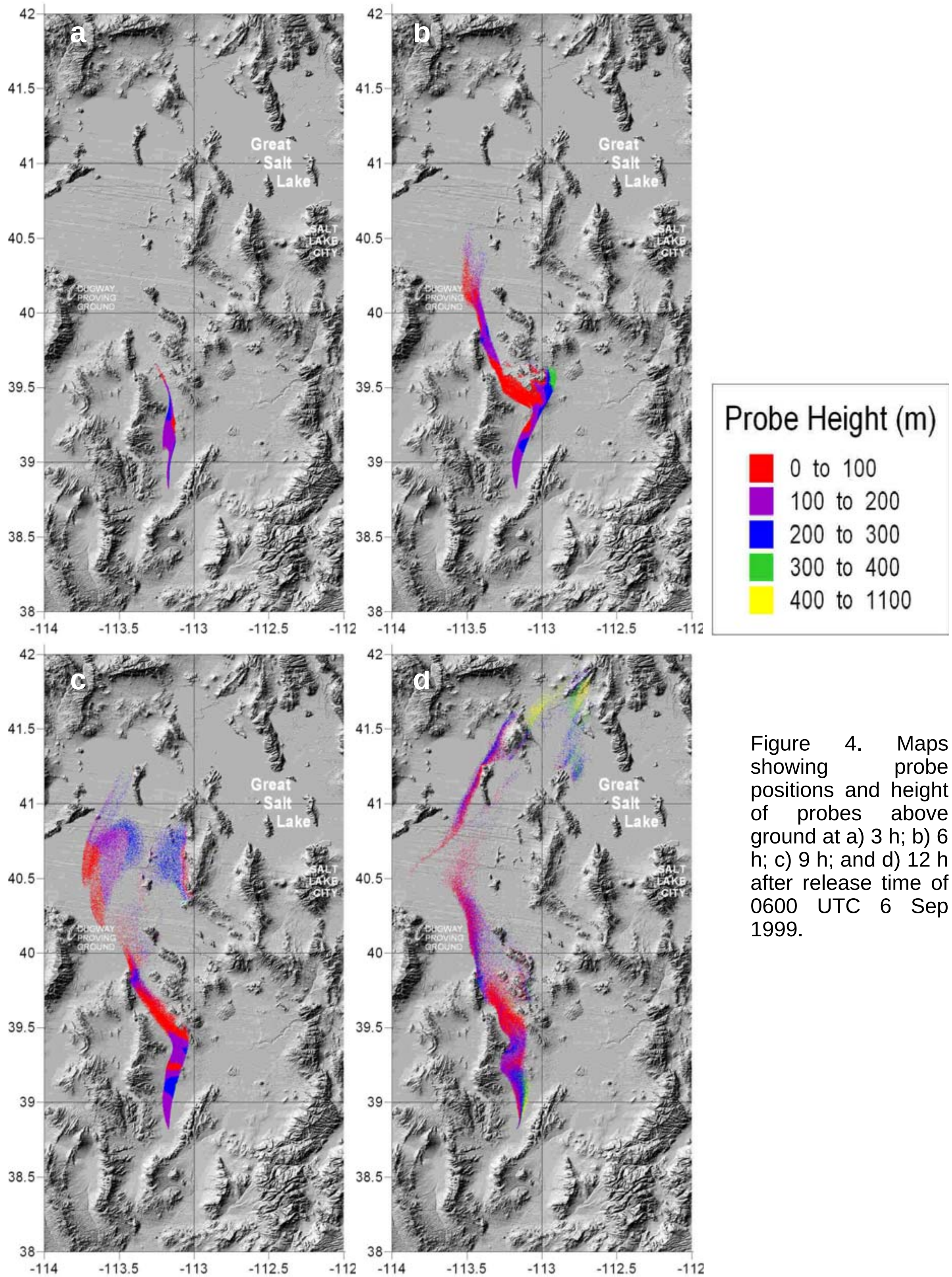

Figure 4. Maps showing probe positions and height of probes above ground at a) 3 h; b) 6 h; c) 9 h; and d) 12 h after release time of 0600 UTC 6 Sep 1999.

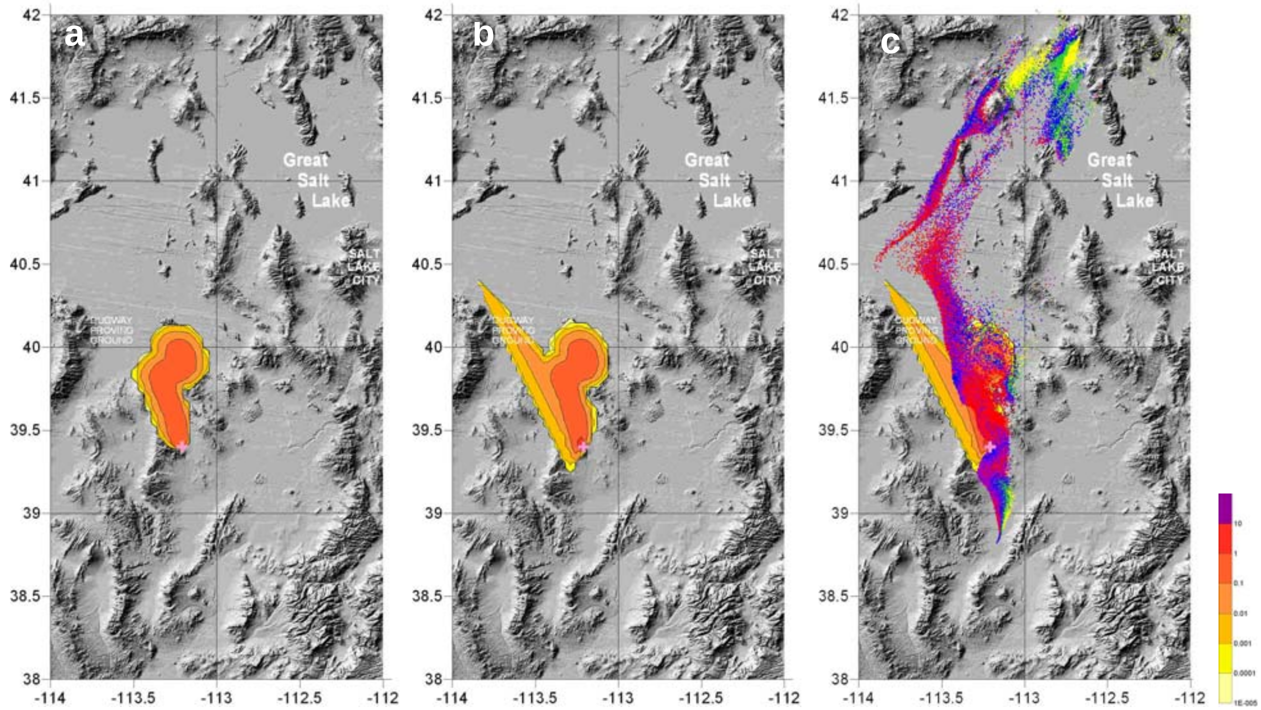

Figure 5. Maps showing comparison of a) CALPUFF truth concentrations and b) CALPUFF simulated measured concentrations and c) the simulated measured concentrations overlaid with 100 percent of the probes at 12 h after deployment. The concentration scale (µg m^{-3}) is shown at right and the legend for the probe heights is shown in Figure 4.

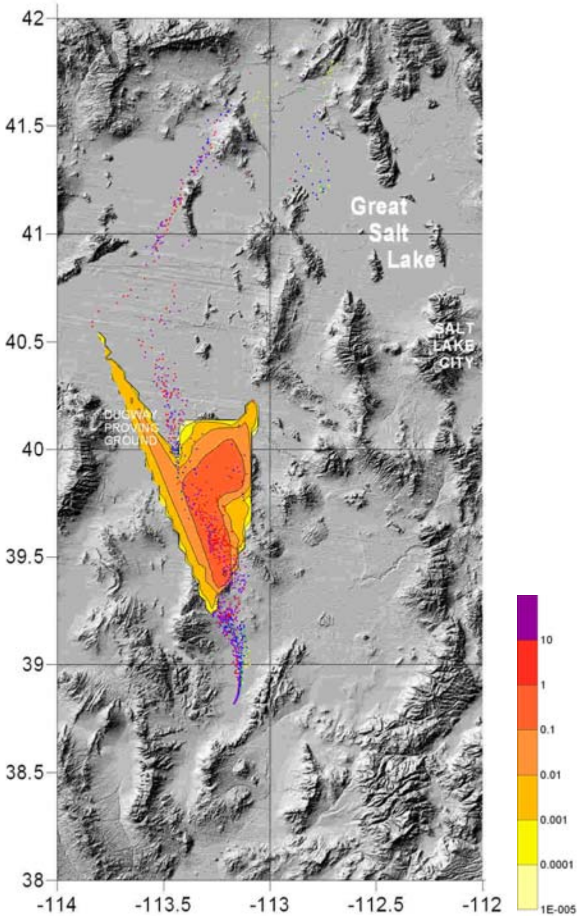

Figure 6. Map showing probe locations for 1% of original probes shown in Figure 5c at 12 h after deployment, overlaid on the CALPUFF plume generated from those probes. The concentration scale (µg m^{-3}) is shown at right and the legend for the probe heights is shown in Figure 4.

5. CONCLUSIONS

This paper described an application of the GEMS system for urban-scale environmental monitoring. Simulated air quality measurements were taken by deploying probes within the ARPS model and allowing them to drift over a CALPUFF-modeled plume of SO_2.

The results showed that:

- GEMS is capable of locating and characterizing the ambient air and peak concentrations resulting from a pollutant release for simulations covering a range of 100 km.
- Locations where the simulated measured plume differed from the truth plume were areas where the probes had not been transported.
- The probes do not have to sample completely the entire plume to map the gradients and boundaries.
- Sensitivity tests showed that using as few as 1% of the original number of probes deployed in a baseline simulation (~245,000) may provide adequate data needed to locate and characterize pollutant plumes.

This work is in progress and preliminary results show the feasibility of using such a system at the intermediate and spatial urban scale. While these initial simulations are not yet at the block or neighborhood scale to model an actual urban landscape, it is a favorable step in that direction.

Additional work is needed to model other deployment strategies including different release locations and heights to provide more coverage with the probes as they take both pollutant and meteorological measurements. Future goals are to reduce the grid spacing of the mesoscale model below 1 km, include high-resolution terrain and building profile data in future simulations, and deploy actual probes in a real-time field experiment simulating a possible chemical, biological, or nuclear release.

6. ACKNOWLEDGEMENTS

The work on GEMS described in Sections 2 and 3 is being supported by the Universities Space Research Association's NASA Institute for Advanced Concepts.

7. REFERENCES

Allwine, K. J., J. H. Shinn, G. E. Streit, K. L. Clawson, and M. Brown, 2002: Overview of URBAN 2000—A multiscale field study of dispersion through an urban environment. *Bull. Amer. Meteor. Soc*., **83**, 521-536.

Arnold, C. P. Jr., and C. H. Dey, 1986: Observing system simulation experiments: Past, present, and future. Bull. Amer. Meteor. Soc., 67, 687-695.

Atlas, R., 1997: Atmospheric observations and experiments to assess their usefulness in data assimilation. *J. Royal Meteor. Soc. Japan*, **75**, 111-130.

Dabberdt, W. F., and Coauthors, 2004: Meteorological research needs for improved air quality forecasting. *Bull. Amer. Meteor. Soc*., **85**, 563-586.

De Pondeca, M. S. F. V., and X. Zou, 2001: Moisture retrievals from simulated zenith delay "observations" and their impact on short-range precipitation forecasts. *Tellus,* **33A**, 192-214.

Deardorff, J. W., 1980: Stratocumulus-capped mixed layers derived from a three-dimensional model. *Bound.-Layer Meteor*., **7**, 199-226.

Girz, C. M. I. R, and Coauthors, 2002: Results of the demonstration flight of the GAINS prototype III balloon. Preprints, *6th Symp. On Integrated Observing Systems*, Amer. Meteor. Soc., Orlando, FL, 248-253.

Golden Software, 2002: *Surfer 8 User's Guide*. Golden Software, Inc., 135-137.

Holland, G. J., and Coauthors, 2001: The aerosonde robotic aircraft: A new paradigm for environmental observations. *Bull. Amer. Meteor. Soc*., **82**, 889-901.

Lord, S. J., E. Kalnay, R. Daley, G. D. Emmitt, and R. Atlas, 1997: Using OSSEs in the design of the future generation of integrated observing systems. Preprints, *First Symposium on Integrated Observing Systems*, Amer. Meteor. Soc., Long Beach, CA, 45-47.

Manobianco, J., 2002: Global Environmental MEMS Sensors (GEMS): A Revolutionary Observing System for the 21st Century, Phase I Final Report. [Available online at http://www.niac. usra.edu/studies/].

Manobianco, J., J. L. Case, R. J. Evans, D. A. Short, and K. S. J. Pister, 2003: Global Environmental MEMS Sensors (GEMS): A revolutionary observing system for the 21st century. Preprints, 7*th Symposium on Integrated Observing Systems*, Long Beach, CA, Amer. Meteor. Soc.

Manobianco, J., R. J. Evans, J. L. Case, and J. Dreher, 2004: GEMS: A revolutionary observing system to support the next 50 years of numerical weather prediction. Preprints, *Symposium on the 50th Anniversary of Operational Numerical Weather Prediction*, Adelphi, MD, Amer. Meteor. Soc.

Mellor, G. L., and T. Yamada, 1982: Development of a turbulence closure model for geophysical fluid problems. *Rev. Geophys. Space Phys*., **20**, 851-875.

Pankine, A. A., E. Weinstock, M. K. Heun, and K. T. Nock, 2002: In-situ science from global networks of stratospheric satellites. Preprints, *6th Symp. On Integrated Observing Systems*, Amer. Meteor. Soc., Orlando, FL, 260-266.

Pielke, R. A., W. R. Cotton, R. L. Walko, C. J. Tremback, W. A. Lyons, L. Grasso, M. E. Nicholls, M. D. Moran, D. A. Wesley, T. J. Lee, and J. H. Copeland, 1992: A comprehensive meteorological modeling system – RAMS. *Meteor. and Atmos. Physics*, **49**, 69-91.

Rohaly, G. D., and T. N. Krishnamurti, 1993: An observing system simulation experiment for the Laser Atmospheric Wind Sounder (LAWS). *J. Applied Meteor*., **32**, 1453-1471.

Savvides, A., C. Han, and M. Srivastava, 2001: Dynamic fine-grained localization in ad-hoc networks of sensors. Proceedings, *ACM MobiCom 2001*, Rome, Italy, 166-179.

Scire, J. S., Strimaitis, D. G., and R. J. Yamartino, 2000: *A User's Guide for the CALPUFF Dispersion Model (Version 5.0)*. [Available online at: http://www.src.com/calpuff/calpuff1.htm.]

Seinfeld, J. H., and S. N. Pandis, 1998: *Atmospheric Chemistry and Physics – From Air Pollution to Climate Change*, John Wiley and Sons Inc., New York, 1326 pp.

Walker, J., 1981: The aerodynamics of samara: winged seed of the maple, the ash, and other trees. *Sci. American*, **Oct.**, 226-237.

Warner, S., N. Platt, and J. F. Heagy, 2004: Comparisons of transport and dispersion model predictions of the URBAN 2000 field experiment. *J. Appl. Meteor*., **43**, 829-846.

Xue, M., K. K. Droegemeier, and V. Wong, 2000: The Advanced Regional Prediction System (ARPS) — A multi-scale nonhydrostatic atmospheric simulation and prediction model. Part I: Model dynamics and verification. *Meteor. Atmos. Phys.*, **75**, 161-193.

______, and Coauthors, 2001: The Advanced Regional Prediction System (ARPS) — A multiscale nonhydrostatic atmospheric simulation and prediction tool. Part II: Model physics and applications. *Meteor. Atmos. Phys*., **76**, 143-165.