Meteorological Sensor Array Designed for Model Validation

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One of the toughest challenges for validating high resolution atmospheric models is finding a high resolution (1-km or less), gridded-observation dataset that matches the model grid. The National Oceanic and Atmospheric Administration (NOAA)/National Centers for Environmental Prediction (NCEP) Real-Time Mesoscale Analysis (RTMA) products provide such datasets over the Continental United States at a horizontal grid spacing of 2.5 km. However, for a 1-km or less horizontal model grid spacing, use of this product requires interpolation of the model output to achieve grid matching, which can smooth wanted details in a high resolution forecast-observation comparison.

In an attempt to optimize high resolution forecast-observation comparisons, the U.S. Army Research Laboratory is constructing a gridded sensor array in New Mexico, called the Meteorological Sensor Array (MSA). Phase I of this long-term project will assemble the infrastructure and execute a Proof of Concept (PoC) Test of the MSA design. The PoC Test consists of five equally-distant towers sampling the standard meteorological parameters and insolation: three 10-m towers along a north-south axis, west of a Solar Photovoltaic (PV) Farm, and two 10-m towers along an east-west axis, situated east of a Solar PV Farm. In Phase I, the process for collecting the measurements and validating model output will be tested using a microscale model whose grid coincides with the MSA tower array. Investigative research into the environmental impacts of a large Solar PV Farm will also be pursued. In this paper, we capture the overall MSA design, the Phase I Test Plan and some of the anticipated applications for the current and future MSA.

1. BACKGROUND

One of the toughest challenges for validating high resolution atmospheric models is finding a high resolution (1-km or less), gridded-observation dataset that matches the model grid. The National Oceanic and Atmospheric Administration (NOAA) / National Centers for Environmental Prediction (NCEP) Real-Time Mesoscale Analysis (RTMA) products provide datasets over the Continental United States at a horizontal grid spacing of 2.5-km. For verifying a 1-km or less horizontal model grid spacing, use of this product requires a remapping of the 1-km model output to a 2.5-km grid spacing, to achieve a common grid with the RTMA product. This process can result in a smoothing of wanted details in the high-resolution forecast-observation comparison.

Another high resolution gridded observation data resource is the Variational Local Analysis and Prediction System (LAPS) developed by NOAA, Earth System Research Laboratory. This system is a fully integrated, data assimilation and analysis system designed to integrate all types of meteorological observations using an effective analysis scheme to harmonize high resolution temporal and spatial data onto a regular grid (Bennett et al., 2000). Through joint U.S. Army Research Laboratory (ARL) and NOAA efforts, this Variational LAPS is being modified to generate a 1-km gridded-observation output. As with the first example, however, for high-resolution data analyses, there is a potential for losing critical information during the harmonization of temporal and spatial data.

The inadequacy of mesoscale observations was recognized during the 2009 National Research Council (NRC), Board on Atmospheric Sciences and Climate (BASC) Summer Study workshop on “Progress and Priorities of U.S. Weather Research and Research-to-Operations Activities.” In this workshop, the NRC BASC identified priorities for addressing the national inadequacy as a challenge for developing accurate high-resolution mesoscale forecast models. These challenges were identified as knowledge gaps to be addressed over the next decade. The following captures some of the many NRC conclusions and recommendations (NRC, 2010):

- Observations remain inadequate to optimally run and evaluate most high-resolution models and determine forecast skills at various temporal and spatial scales.

- Assessing predictive skill is difficult, because deficiencies arise from the data and data assimilation process; errors can be found in the numerical representation; there can be intrinsic predictability limitations, and forecast verification methodology challenges. The board stated that there is a pressing need for Research and Development (R&D) leading to improved mesoscale data assimilation techniques in operational forecast systems. Further, the board states that the basis for current knowledge of assimilation techniques is weakened by the inadequate mesoscale surface observations and lack of systematic measurements of the lower troposphere profiles of water vapor, temperature, and winds.

- The board concluded that improved analyses from mesoscale models using data assimilation techniques requires better knowledge of systematic errors in observations because of the inadequacies of the current mesoscale observations.

- The board stated that it is important that mesoscale observations are a focus of test-beds designed to develop and introduce new ideas and procedures in environmental observation. They suggested the use of networks that combine observations from satellites, airborne sensors, and surface platforms. Another focus was to examine the role of mesoscale observations for new paradigms in the end-to-end forecast process important with respect to merging methods in Nowcasting with those of dynamic prediction 0–6 hour range.

- The board stated the following high priority mesoscale observing needs, based on their assessment that there is essentially no current systematic national capabilities:
    - Planetary boundary layer height;
    - High-resolution vertical profiles of humidity and temperature;
    - Improvements in the following measurements: direct and diffuse solar radiation, wind profiles, temperature profiles, surface turbulence, and near surface icing.

- The board stated that one of the principal goals of the urban test-bed is the meteorological and air quality measurement network (urban mesonet), which provide observations at high spatial and temporal resolutions from the urban core to the surrounding hinterland. The commonly accepted approach is to oversample in the test-bed and use data denial modeling techniques to identify an optimal network design (or multiple, optimum designs). Data from the urban mesonet then provide the basis for a number of important activities in the urban test-bed: development and testing of data assimilation and prediction models; model-verification metrics; and applications where the observations themselves support various applications.

- The board stated that data assimilation, as part of the forecast system, is also important for acquiring and maintaining observing systems that provide the optimal cost-benefit ratio to different user groups and their applications. Data denial experiments can selectively withhold data from one (or more) system(s) and assess the degradation in forecast skill. Data assimilation can be used to determine the optimal mix of current and future in situ and remotely sensed measurements, and also for adaptive or targeted observations. It is also beneficial to understand the impacts of observing systems on model performance and the resulting forecast accuracy.

- The board stated that observational data with high temporal and spatial resolution are crucial to the understanding of atmospheric processes, providing data for assimilation in models, and evaluating and improving those models. This requires the synergistic combination of data from diverse sources. Rawinsonde, radar, satellite, and aircraft data as well as data from other sources all play complementary roles in weather research and forecasting.

Contemporary mesonets provide atmospheric measurements and can be found around the world. However, the stations are often far apart and on irregular grids. Various atmospheric field studies have been conducted which include high resolution data sampling, but they are generally of a time-limited duration. The question remains, “Is there a long-term, high-resolution, observational data resource?” This paper will describe ARL’s response toward the lack of high resolution observational data for atmospheric model development, improvements, and calibration.

2. MSA OVERVIEW

The ARL is constructing a gridded sensor array in New Mexico, called the Meteorological Sensor Array (MSA), to improve atmospheric models (and sensor technology), by optimizing high resolution forecast-observation comparisons. A description of the MSA vision and evolving program follows.

2.1 MSA VISION

The ARL vision for the MSA Program was built, in part, on addressing the national need for high resolution observational data in developing and evaluating high resolution mesoscale forecast models. Such model development includes, but is not limited to, exploring new phenomena and analysis methods for near surface, high resolution weather forecasting. The model evaluation portion is aimed at integrating a powerful observation resource with both traditional and nontraditional validation and verification (V&V) methods. Examples of both V&V methods are given in Section 4.

The three key objectives guiding the MSA Program include (1) to provide reliable and persistent data resources that allow atmospheric modelers and sensor developers to validate and compare model and sensor performance with meteorological observations at and near the surface, in terrain of varying complexity; (2) to significantly improve high resolution atmospheric models in the boundary layer; and (3) to improve model and sensor accuracy and efficiency.

A description of the multiphased MSA Program is given in the next section.

2.2 MSA PROGRAM PHASES

The ARL MSA Program was subdivided into several phases. MSA-Phase I consists of a five-meteorological tower, “Proof of Concept” data resource. The field portion of this Phase was recently executed in southern NM. Section 3 will describe Phase I, which is currently progressing through the postfield activities.

MSA-Phase II will consist of a 36-tower array located in a New Mexico desert valley. Phase III supplements this Phase II array with another 36-tower array located climatologically upwind from the New Mexico desert valley. Projected locations for the MSA Phases II and III are shown in Figure 1. A taller than 2-km mountain range would separate the two 36-tower data resources. The Phase III configuration is also envisioned with additional sensor types, such as tethersondes, rawinsondes, and possibly unmanned aerial systems.

The plan for Phase IV shifts the focus onto mobilizing the array. A portable two-dimensional array would be created and include a triple Lidar. The Lidar would be coordinated with sodars, tethersondes, and an unmanned aerial vehicle. Phase V is slated as a remote test site capability, to be coupled with other field campaigns.

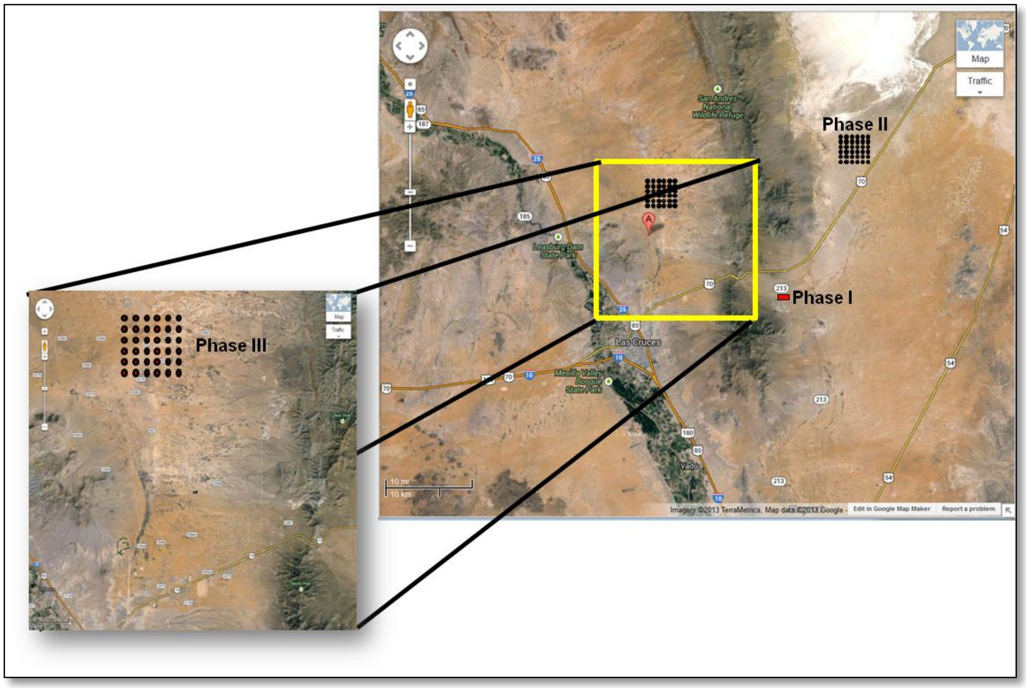

Figure 1. MSA locations: Phase I field exercise is completed. The locations for Phases II and III are projected locations.

3 MSA PHASE I

MSA-Phase I was designed as a “Proof of Concept”. The three objectives framing this task included (1) configuring the hardware and software to acquire data in an MSA subset design; (2) demonstrating the feasibility of utilizing MSA data for a V&V task; and (3) comparing the measured and modeled atmospheric impacts of a large Solar Photovoltaic (PV) Farm. The Phase I field exercise was executed from March to May of 2014, during the New Mexico ‘windy season’.

Figure 2 shows a top-down view of the Phase I field design, which consisted of five, 10-m meteorological towers, and labeled “node”. Three towers were equally spaced on a north-south axis, to the west of the Solar PV Farm. Two towers were equally spaced on an east-west axis, to the east of the Solar PV Farm. The distance separating the aligned towers was 100 m. While the grid is not “squared”, these MSA tower locations coincide with a subset of a microscale model gridded output. One of the many challenges was how to align the physical world measurements and model locations. The ‘real world’ has various hurdles such as arroyos (washes), bushes, coyote and rabbit holes, etc.

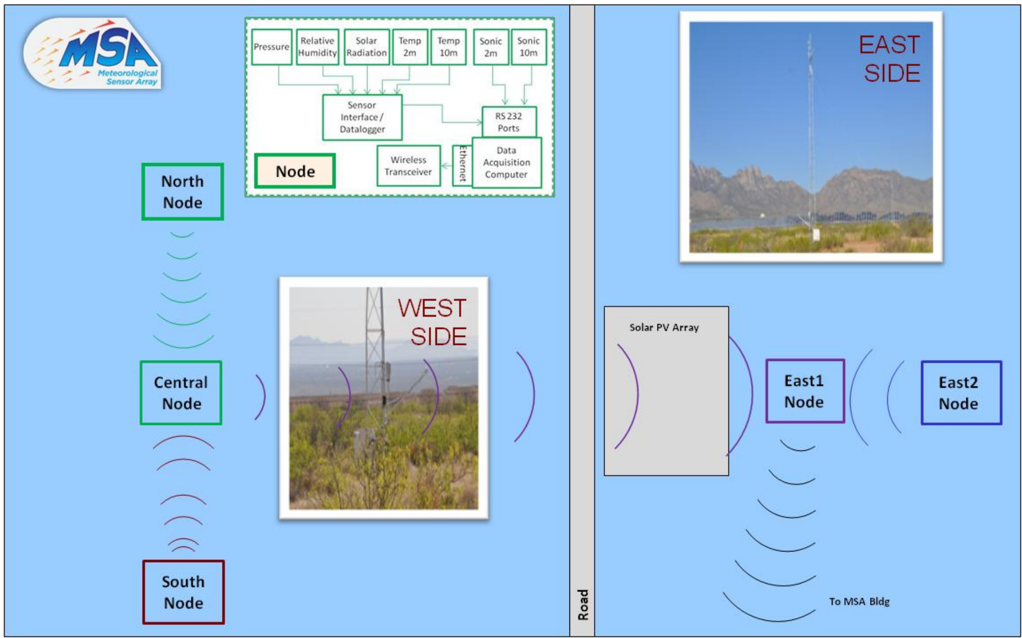

Figure 2. A top-down view of the MSA-Phase I Layout.

Each Phase I tower was instrumented with the standard meteorological sensors, as well as a Pyranometer. Figure 3 shows the sensor distribution on the 10-m towers. Table 1 captures the sensor details. Solar PV panels positioned away from the tower were used to power each tower. Data were routinely communicated to plotting routines. These data visualization tools, displayed time series which were routinely inspected for anomalies and potential atmospheric events of interest to the Phase I researchers.

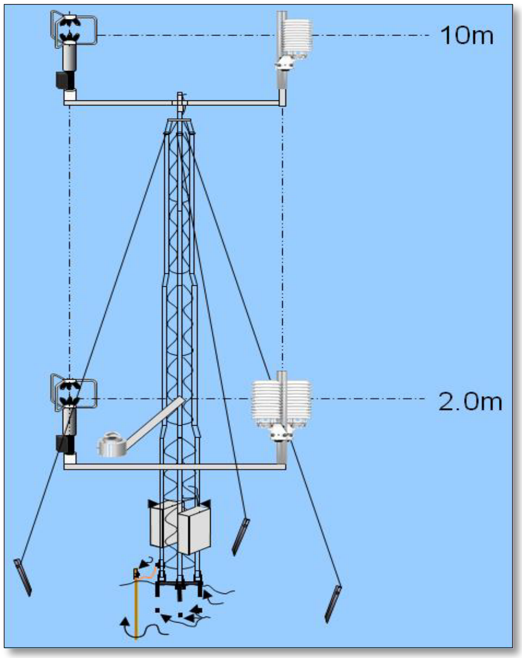

Figure 3. MSA-Phase I Meteorological sensor configuration.

Table 1. MSA Phase I sensor design.

HEIGHT (m AGL[+])	**VARIABLE**	**SENSOR**	**MANUFACTURER**	**MODEL**	**UNITS**
1	Pressure	Barometer	Vaisala	PTB-101B*	Mb
2	Temperature	Thermometer	Rotronics	HC2S3	C
2	Relative Humidity	Hygrometer	Rotronics	HC2S3	%
2	Winds	Ultrasonic Anemometer	RM Young	81000	m/s
2	Solar Radiation	Pyranometer	Kipp/Zonen	CM3 (CMP3)	W/m^2
10	Temperature	Temperature Probe	Campbell	T107	C
10	Winds	Ultrasonic Anemometer	RM Young	81000	m/s

*Campbell model number: CS106.
[+] Above Ground Level (AGL).

All sensors were subjected to a pre-exercise relative calibration, with factory-issued calibration sheets establishing sensor baselines. Arrangements were made for future phases to use a scheduled, standard calibration laboratory assessment.

4 CURRENT AND FUTURE MSA DATA APPLICATIONS

MSA Phase I "Proof of Concept" data acquisition was completed about 1 month prior to this paper's presentation at the *17th Symposium on Meteorological Observation and Instrumentation*. The task then re-focused on data applications, which were subdivided into two categories: V&V and R&D applications. Each area will be addressed, separately.

4.1 V&V APPLICATIONS

Current high resolution model assessment processes are challenged by the need for high resolution (1-km) gridded observations. To adequately show the skill of high resolution modeling, traditional, and nontraditional methods must be incorporated. Traditional approaches consist of independent gridded model output and observation comparisons (see Figure 4).

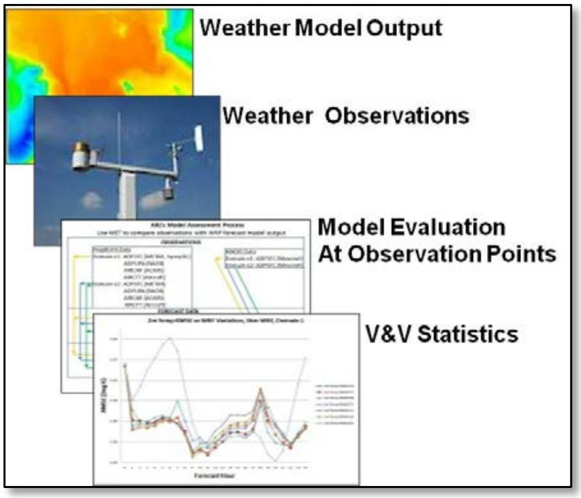

Figure 4. Traditional V&V assessment includes point-to-point comparisons of model output and observations.

Unfortunately, the model output grid and the locations of point observations often do not coincide. One solution is to calculate a representative model output at the observation point, by using a weighted mean of the gridded model output surrounding the observations. Figure 5 gives an example of the interpolation uncertainty. In this case, the black dots represent forecast model output locations and the red dot identifies the observation point location. The model-observation, point-to-point comparison can be done using the assigned weighted mean value of the surrounding model output. The result is informative, but can be misleading.

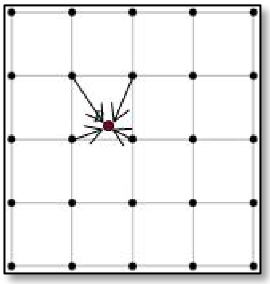

Figure 5. Interpolation uncertainty example.

The data user needs to be certain of the resource. As a generic example, Figure 6 shows four model wind data outputs (blue arrows) surrounding an observation. The length of line is proportional to the magnitude of speed. The arrow orientation shows a direct representation of the airflow (wind direction). The red arrow is the observation data point. While one would be tempted to use a weighted mean with the four surrounding data points, the diligent scientist will first check the resource before making the comparison. In this case, the data given represent two distinct vertical levels: the model output is at 2.5-m AGL, the observation is at 10-m AGL. Thus, this comparison would need additional interpolation calculations to align the vertical, before weighting the horizontal or arrange for the placement of additional wind sensors at the 2.5-m AGL level. For high resolution datasets, multiple interpolations can lead to information lost. Consequently, one needs to consider an alternate data resource (such as the MSA) to provide the needed measurements and/or nontraditional V&V methods.

Figure 6. The diagnostic model output (blue) represents winds at 2.5-m AGL. The observation wind data sample is from 10-m AGL. The yellow lines are streamlines based on analysis of the model data. The black arrow flags the model-observation data area.

An example of the nontraditional methods includes object-based diagnostic tools. While an elaboration of these tools is outside the scope of this paper, Figure 7 shows an example of one nontraditional method called, the "Method for Object-Based Diagnostic Evaluation (MODE)" tool, developed by the Developmental Testbed Center, at the National Center for Atmospheric Research (NCAR) (Davis et al., 2009; NCAR, 2013). Another innovative approach is to utilize a Geographic Information System (GIS) to geo-locate the forecast-observation pairs within a high-resolution terrain framework, then perform location-based analyses of the model errors. One type of analysis involves the animated depiction of the spatial and temporal distribution of model errors. (Foley, 2014)

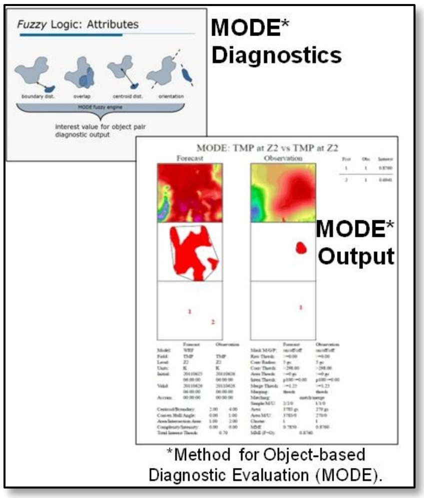

Figure 7. MODE is an example of a nontraditional V&V assessment tool. (Gilleland, 2014; Vaucher and Raby, 2014).

4.2 R&D APPLICATIONS

MSA Phase I tower array was purposefully placed around a large solar PV farm. The intended research consisted of studying the atmospheric impacts on and by the large PV farm. The data analyses for these tasks are currently underway, having been initiated just after the recent field exercise concluded. Results will be presented in future papers.

5 SUMMARY

Finding a high resolution (1-km or less), gridded-observation dataset that closely aligns or matches high resolution atmospheric models, is a significant challenge. Organizations have provided gridded-observation products at 2.5 km and may, in the not-so-distant future, provide 1-km resolutions, using an objective analysis of available point observations. However, desired details in a high resolution forecast-observation comparison have the potential of being filtered out by the objective analysis process needed to create the higher resolution gridded-observations datasets.

To improve the potential for preserving the fine-scale details of the high resolution forecast-observation comparisons, ARL is constructing a gridded sensor array in New Mexico, called the MSA. Phase I of this long-term project is a “Proof of Concept” for the MSA design. The “Proof of Concept” consists of five equally spaced towers sampling the standard meteorological parameters and insolation: three 10-m towers along a north-south axis, west of a Solar PV Farm, and two 10-m towers along an east-west axis, situated east of a Solar PV Farm. The Phase-I design, setup, and data acquisition were successfully executed this past spring. Preliminary results regarding the V&V method assessment have been promising. The ongoing MSA Phase-I continues to detail the V&V method, as well as, investigate environmental impacts on and by the large Solar PV Farm.

Future plans for the MSA Program include several developmental phases. With the lessons learned from the Phase I “Proof of Concept” experience, Phase II will include a 36-tower gridded array located in a New Mexico desert valley. Phase III will supplement the Phase II array with another 36-tower array located climatologically upwind from the New Mexico desert valley. A more than 2-km tall mountain range would separate the two 36-tower data resources. The Phase III design is envisioned to include additional sensor types, such as tethersondes, rawinsondes, and possibly unmanned aerial systems. The plan for Phase IV is focused on mobilizing a two-dimensional MSA and expanding the data resources to include a triple lidar, coordinated with sodar, tethersondes, and an unmanned aerial vehicle. Phase V is slated for a remote test site capability, which can be integrated into other field campaigns.

A long-term vision for the ARL MSA Program is to facilitate participation of government, academic and commercial research programs into the high resolution MSA data acquisition and analyses efforts.

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