AMERICAN
METEOROLOGICAL
SOCIETY

Bulletin of the American Meteorological Society

The DOI for this manuscript is doi: 10.1175/BAMS-D-15-00258.1

Mahmood, R., R. Boyles, K. Brinson, C. Fiebrich, S. Foster, K. Hubbard, D. Robinson, J. Andresen, and D. Leathers, 2016: Mesonets: Meso-Scale Weather and Climate Observations for the U.S. Bull. Amer. Meteor. Soc. doi:10.1175/BAMS-D-15-00258.1, in press.

Mesonets: Meso-Scale Weather and Climate Observations for the U.S.

(Submitted to: *Bulletin of the American Meteorological Society*)

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Abstract

Meso-scale in-situ meteorological observations are essential for better understanding and forecasting the weather and climate and to aid in decision-making by a myriad of stakeholder communities. They include, for example, state environmental and emergency management agencies, the commercial sector, media, agriculture, and the general public. Over the last three decades, a number of meso-scale weather and climate observation networks have become operational. These networks are known as mesonets. Most are operated by universities and receive different levels of funding. It is important to communicate the current status and critical roles the mesonets play.

Most mesonets collect standard meteorological data and in many cases ancillary near surface data within both soil and water bodies. Observations are made by a relatively spatially dense array of stations, mostly at sub-hourly time-scales. Data are relayed via various means of communication to mesonet offices, with derived products typically distributed in tabular, graph and map formats in near real time via the World Wide Web. Observed data and detailed metadata are also carefully archived.

To ensure the highest quality data, mesonets conduct regular testing and calibration of instruments and field technicians make site visits based on "maintenance tickets" and pre-scheduled frequencies. Most mesonets have developed close partnerships with a variety of local, state, and, federal level entities. The overall goals are to continue to maintain these networks for high quality meteorological and climatological data collection, distribution, and decision-support tool development for the public good, education, and research.

Capsule Summary: Mesonets play a critical role in near surface weather and climate observations. It is essential that we continue to maintain, operate, and expand these networks.

Meso-scale in-situ meteorological observations, roughly spanning 30 km (~20 mi) radius or grid-box around a given location, are essential to better foster weather and climate forecasting, and decision-making by a myriad of stakeholder communities. The latter include, for example, state environmental and emergency management agencies, water managers, farmers, energy producers and distributors, the transportation sector, the commercial sector, media, and the general public. To meet these needs, the past three decades have seen a growth in the number of meso-scale weather and climate observation networks over various regions of the United States (U.S). These networks are known as mesonets (short for meso-scale network) and are largely a result of efforts at the state level (Figure 1). In addition, these mesonets are playing a key role in fulfilling the objectives of the weather and climate observation community as identified by two recent National Research Council (NRC) reports (NRC 2009, 2012).

Most of these networks are operated by universities, reflecting a commitment to research, service and outreach, and focus on observation quality and integrity. Levels of funding to support mesonets vary widely, reflecting a range of institutional and state priorities. As technological advances and societal needs for weather and climate information grow, mesonets continue to undergo an evolution from the formative age of mesonet development to a period of growth and integration. Hence, it is important to communicate the significant development and current status of these valuable means of environmental monitoring.

In this paper, we will discuss a brief history and context that provided the impetus to develop these networks, types of data mesonets collect, data collection frequency and dissemination approaches, site selection, station exposure, instrumentation, station maintenance, meta-data, research applications, decision-support tools based on the mesonet data, funding issues, and future challenges and opportunities.

Brief history

Surface weather observations in the U.S. began on the East Coast in the late 17th Century (Fiebrich 2009). Weather observations remained sparse and sometimes sporadic until agencies including the Surgeon General, Army, and General Land Office began requesting regular observations at widespread locations. The Smithsonian Institution was responsible for organizing the first large "network" of volunteer weather observers across the nation. These observers became the foundation for today's National Weather Service Cooperative Observing Program (COOP). In the 1970s, improvements in electronics (miniaturization) and increased dependability of storage devices led to improved sensors and to multiple function data processors at remote sites. This made it possible to automate weather data collection (Hubbard et al. 1983). Applications of weather data continued to grow and users sought the data for near real-time decisions. This led to the development and growth of automated weather networks in the latter part of the 20th century through present. An important aspect of this growth was the development of spatially dense networks with sub-hourly (with resolution up to 5 minutes) observations in the 1980s and 1990s. Two examples of networks that led the way are the Nebraska Mesonet (Hubbard et al. 1983; Hubbard 2001) and Oklahoma Mesonet (McPherson et al. 2007). Since these networks were developed with high spatial density (e.g., up to every 32 km), the term mesonet was coined to describe the new observation networks. The Oklahoma Mesonet was built with an injection of state funding, while the Nebraska Mesonet was built more "bottom-up" with local funding sources. These two mesonets represent alternative models for funding and development, and this is an important point to the evolution of mesonets elsewhere. Further information on the development of weather observations in the U.S. can be found in Fiebrich (2009).

Table 1 contains a list of statewide networks. The two networks from Alabama and the networks from West Texas and Louisiana are not truly statewide mesonet because they focus on particular regions of their respective states. On the other hand, networks from Illinois, Iowa, Minnesota, and New Mexico are quite sparsely distributed. There are many smaller public networks, but these do not have the following qualities: a) non-federal, b) statewide coverage, and c) weather and climate focused. The third item is important because it helps to distinguish many mesonets from, for example, transportation networks [i.e., Road Weather Information Systems (RWIS)], which many states operates. Many mesonets (not all) are maintained not only for real-time use, but are also managed or strive to maintain "climate" standards. Most of these networks are operated by universities and are co-located with State Climate Offices.

Instrumentation and variables observed

Many mesonets across the U.S. utilize research grade instrumentation to measure a number of important environmental parameters, as maintaining a highly reliable network with accurate data is central to the mission of every mesonet. The typical instrumentation suite used by mesonets today was highly influenced by earlier mesonets, which were commonly based around, at least in part, agriculture-climate-related applications (Hubbard et al. 1983; Brock et al. 1995). The suite of meteorological instrumentation incorporated in these early networks had a focus on providing a better understanding of the water balance through the estimation of reference evapotranspiration and automated, remote measurements of precipitation. Table 2 shows a list of typical instruments used in current mesonets across the U.S.

In the context of limited funding for the mesonets, these types of instruments have the advantage of being quite accurate, robust and somewhat affordable to acquire and maintain.

Depending on the local stakeholder needs and availability of funding, mesonet operators provide data from networks with as few as a dozen stations, for example, South Alabama Mesonet, to well over a hundred stations, like the Oklahoma Mesonet. Instrument acquisition and maintenance costs are critical to the long-term viability of all mesonets, since fiscal support is typically limited and may be highly variable from year-to-year. Differences in instrumentation among networks are driven by a combination of local stakeholder needs, science goals of the network, and the availability of funding to support the network. For instance, since 2007 the Delaware Environmental Observing System (DEOS) has added 26 sonic snow depth sensors to its network to serve the Delaware Department of Transportation's snow removal reimbursement program.

Some networks differ based on their deployment strategies. The Kentucky Mesonet and Oklahoma Mesonet utilize aspirators on their air temperature sensors to improve the quality of their air temperature data. Some mesonets use heating elements on their tipping bucket rain gauges, while others use weighing rain gauges winterized with antifreeze to melt frozen precipitation and obtain liquid equivalent precipitation. Meanwhile, some mesonets do not attempt to measure frozen precipitation at all. Soil sensors are another common feature of mesonets across the U.S. Most networks measure volumetric water content (VWC) and soil temperature at one or all of the World Meteorological Organization's (WMO) soil sensor depth specifications (5, 10, 20, 50, and 100 cm). This is typically done using soil water reflectometers for VWC and encapsulated thermistors for soil temperature. Meanwhile, other networks measure soil water matric potential using a thermocouple encased in a porous ceramic block (Illston et al., 2008).

Most networks' meteorological stations take multiple samples (3 to 5 second sampling is the most common) from sensors every observation period, depending on sensor response coefficients, station power consumption constraints, and the intrinsic variability of the parameter being measured. Hence, the sampling and observation interval varies from network to network. However, as indicated above, nearly all mesonets have sub-hourly observation intervals, commonly at a 5-minute increment. Given highly reliable and robust measurement systems, U.S. mesonets are thus able to provide quality, high temporal and spatial resolution data to many stakeholders for real-time weather and climate applications.

Station exposure and site selection

The majority of mesonet stations consist of sensors wired directly into central data logging and microprocessing units. Sensors, data logger, power, and communications sub-systems are mounted onto tripods or towers with small horizontal footprints of between 1 and 3 meters. With all sensors effectively co-located, sensor exposure is chosen based on a number of siting criteria and operational requirements. While each sensor performs best under different exposures, stations are often placed in locations that best achieve the following objectives (AASC 1985; EPA 1987; WMO 1983; WMO 2008; LeRoy 2010):

1. Maximize airflow for naturally aspirated temperature, humidity, and pressure sensors.
2. Minimize nearby obstructions to ensure accurate radiation measurements.
3. Minimized wind flow around the precipitation gauge.
4. Ensure soils are representative of the surrounding region.
5. Maximize distance from tall obstructions (e.g., buildings and trees) to ensure accurate wind measurements that are often recorded at 2, 3, 5 and/or 10 m above ground. One rule

of thumb is that the minimum desired distance between a tall object and a station is about 10 times the height of the object.

6. Maximize long-term stability of surrounding land cover.
7. Maximize site host's ability to support the station over the long-term.

Radiation, temperature, humidity, wind and pressure sensors typically require open exposure, with no obstruction to incoming radiation or airflow.

Station siting requirements also must consider needs for power and communications. Some mesonet stations require access to AC power, particularly to meet the power demands of aspirated temperature shields and sensors with heating elements. However, many mesonet stations use only solar panels to power sensors (including aspirated shields), data logger, and communication subsystems. In either case, mesonet stations typically use power sources interfaced with trickle-charge batteries, providing stored energy capacity. Also, as wireless cellular communications networks become more pervasive and cost-effective, many mesonets make siting decisions based on access to these networks.

An example of a mesonet station is shown in Figures 2 and 3. With constrained energy storage capacity, many mesonet stations with solar panels use a naturally aspirated temperature shield, often a Gill radiation shield. Figure 4 shows (a) an aspirated radiation shield and (b) a non-aspirated Gill radiation shield. In the latter case, sensors inside the Gill radiation shields perform best when the background wind consistently moves ambient air across the sensors. However, as noted above, other mesonets use aspirated temperature shields throughout their network.

Figure 5a-b shows differences in temperature for non-aspirated and aspirated shields from Christian County site in western Kentucky where temperatures measured by non-aspirated (naturally ventilated) is typically higher for all months for both maximum and minimum temperatures. However, it is also apparent that these biases are higher during the summer months for maximum temperatures when solar radiation loadings are higher and wind speeds are lower. Figure 6a-c shows noticeably higher temperature in the early morning hours when wind speeds and solar angle are low. As wind speed increases in the afternoon, these differences declined. Detailed analysis of influence of wind speed and solar radiation on temperature measurement can also be found in Hubbard et al. (2004 and 2005).

In contrast, precipitation sensors perform best under calm wind conditions ((Rodda 1973; Sevruk 1983; Yang 1989; Duchon and Essenberg 2001). Wind can create turbulence around the rim of accumulation-based precipitation gauges, causing under catchment of both liquid and, especially, frozen precipitation. While many mesonets deploy wind screens to reduce wind near the rim of the gauge, this undercatch cannot be completely eliminated in locations with steady or high winds. A majority of the mesonets use tipping bucket rain gauges, while weighing bucket gauges are also used by the mesonets that receive substantial frozen precipitation. Weighing bucket gauges reduce the magnitude of undercatch during intense rain storms (Duchon and Biddle 2010). However, the costs of purchase and maintenance are also significantly higher compared to tipping buckets.

In the eastern U.S., where forested landscapes are relatively common, stations are often selected to ensure adequate exposure and fetch for the wind sensors, which are typically located at 2, 3, 5, or 10 m above ground level. While achieving this objective can be relatively easy in more arid regions of the central and western U.S., in the east this is often the most challenging siting requirement to meet. The WMO and EPA standard is to ensure that the horizontal distance between the sensor and any substantial obstruction is at least 10 times the height of the obstruction. For a station with nearby trees of 20 m (~60 ft), this means the wind sensor should ideally be at least 200 m (~600 ft) away from those trees. For many locations in the eastern US, this becomes quite challenging or impossible (Figure 7). Only large pastures, cropland, and grassland often meet this requirement.

Another factor that often drives station site selection is the ability of the site host to support the station for years to come. Often, this means that the host (public or private) must agree to the location of the station. The sensors cannot interfere with other activities at the location, such as crop management (planting, irrigation, harvest protocols and equipment), airport flight operations, or water treatment. Occasionally, mesonet stations must also meet aesthetic requirements of the host, as not all potential site hosts find these stations visually pleasing.

Regardless of instrumentation, the quality and utility of observations collected by a mesonet station depend upon the quality of the site. Siting criteria typically favor stations located in flat, open, grassy areas, far removed from the influences of sources of anthropogenic forcing. More importantly, stations are located to ensure the data recorded is reliable and representative of the weather and climate of the area, not just recording the microclimate of the small footprint of the base. In practice, however, station siting is one of the greatest challenges that mesonets face. Site hosts often want a tripod mounted or tower installed near a building, on a rooftop, or along the edge of property lines – locations generally thought to be “out of view”. This creates a conflict with the scientific objectives for sensor exposure that demand the siting of sensors in open areas away from buildings, trees, and roof lines. Mesonet managers sometimes work with potential hosts for months or even years to find locations that adequately satisfy these conflicting objectives. Since data from the mesonet sensors are used for a variety of purposes, including long-term climate monitoring, mesonet managers try to select locations that will not be exposed to land use and land cover change for decades to come. Each potential station move to accommodate changes in host's needs introduces a discontinuity in the climatic data record, and limits the ability for scientists to use the data record for long-term studies. Occasionally, exposure for some sensors is compromised because no other suitable site is available in the area (Figure 5).

Availability of wireless communication also plays an important role in the final selection of sites. As noted previously, many mesonets provide data for near real-time emergency management and other time-sensitive decision-making. Hence, wireless infrastructure to enable reliable communication and data transmission from a mesonet site is critical. Situations are sometimes encountered where a site meets all the scientific criteria and has a willing land-owner host, but lacks reliable communication infrastructure nearby. As the reach of wireless infrastructure expands, more high-quality sites for weather and climate monitoring become available.

As noted above, it is desirable that mesonet stations are located approximately every 30 km. However, in many cases it is difficult to achieve this objective. Several factors influence the ability of a mesonet to achieve spatial uniformity. These include, among others, the ability to secure local funding commitments to cover station installation and operating costs. Hence, stations are more likely to be placed on public lands where host agencies have a specific requirement for weather and climate data, or in municipalities that desire to have weather information for a myriad of uses.

Transmission of data from remote stations to a central ingest and processing facility

The majority of stations in various mesonets rely on wireless transmission of data and these data get relayed in near real-time to computer servers located at the home institution. Most of the mesonets apply near real-time automated quality assurance (QA) and quality control (QC) procedures (further discussion is provided in the following section) before disseminating data to specific users or to the general public. QA/QC procedures are developed based on known science related to physical behavior of the near-surface atmosphere. While commonalities exist, mesonets have typically developed their own automated QA/QC procedures. Some of the more established mesonets have developed robust QA/QC procedures, while others have developed more rudimentary ones, again often a function of available funding. In either case, the goal is to identify and flag problematic data. These data can then be further investigated by a QA/QC operator and, if warranted, a maintenance ticket may be issued and a technician sent to the site to further investigate and resolve the issues. Additional details regarding QA/QC are provided in the next section.

Data transmission and distribution can be challenging. Disruptions of service sometime occur when commercial wireless providers perform maintenance on their communication networks or when station communication devices in the field fail or become unstable. In some cases, these disruptions may simultaneously impact multiple mesonet stations. Normally, data from mesonet stations are not lost, as they are temporarily stored in the data logger, often for at least a month. When communication with the station is re-established, data are retrieved from storage. While mesonets increasingly benefit from outsourcing their communications to wireless providers, they have no influence over the operation of those private networks beyond access to available technical support services. Further, in order to maintain seamless data transmission, mesonets must plan appropriately in order to be prepared to upgrade modems and related communications protocols when communication providers introduce next-generation technologies.

Data QA/QC and site maintenance

Quality control of data is necessary to maintain credibility of data sets. Mesoscale meteorological data can become inaccurate for a variety of reasons (Fiebrich et al. 2010). For measurements, the first line of defense against erroneous observations is the calibration of sensors against primary or secondary standards. When a sensor to be deployed in a mesonet is evaluated alongside a standard sensor, the resulting signal from the mesonet sensor can be calibrated against the standard (e.g., Aceves-Navarro,et al. 1988). Employing statistics for the calibration can estimate the error associated with the mesonet sensor (e.g., the standard error of estimate). Sensors should be calibrated on a frequency appropriate for the stability of the sensor as determined by testing the change in calibrations over time. This may be as frequent as every 18-36 months for sensors such as hygrometers and pyranometers or as long as 48 to 60 months for more stable sensors such as thermistors and anemometers (Fiebrich et al. 2006). In any case, the calibration leads to an estimate of the systematic error to be expected from the sensors.

A multitude of automated and manual quality control tests have been developed for mesoscale meteorological data. The techniques range from general sensor and climatological range tests to more sophisticated temporal, spatial, and sensor-specific ones. Fiebrich et al. (2010) provided a detailed review of the various techniques commonly used for QA/QC. Daily evaluation of the flagged data will provide early identification of sensors that may be drifting or malfunctioning and thus lead to an overall improvement in the data quality.

Routine site maintenance plays an important role in ensuring quality data from a mesonet (Fiebrich et al. 2006). The frequency of site maintenance varies from every month (at least for part of the year) to seasonal to annual, depending on environmental factors (e.g., vegetation growth), sensor performance, and availability of resources (e. g., funding). Vegetation conditions can have a significant effect on measurements of soil temperature and moisture, as well as a notable effect on air temperature, humidity, and wind speeds. In general, the goal of vegetation maintenance is to minimize the microscale influences of the station location. Routine site visits also permit technicians to periodically inspect, level, clean, test, and rotate the sensors at a station. Each site visit is also an opportunity to collect valuable metadata (e.g., periodic station photographs and sensor inventories). Note that most mesonets have detailed databases where they archive detailed metadata regarding status of the site (e. g., photographs, technician-notes during their site visits), sensor make and model, sensor calibration information, and timing of sensor deployment, among others. These metadata are extremely valuable during analysis of data for a variety of meteorological and climatological studies.

Decision-support tools for users

An important aspect of development and usage of mesonet data is their wide variety of applications in emergency management to near real-time to day-to-day to longer time-scale decision-making. The “local scale” of mesonet observations intrinsically allows forecasters to pinpoint the locations of fronts and other boundaries for convective initiation and wind shifts.

The mesonet observations also provide precise identification of the freezing line at the surface for predicting winter precipitation type. Most mesonets have developed additional decision-support tools for farmers, agriculture concerns, emergency managers, foresters, water managers, weather forecasters, K-12 educators, and many others. In most cases, these tools are available free of charge through the World Wide Web. Recently, mesonets have begun to develop smart phone-based applications that are available for free or for a small fee. Specific examples include decision tools for irrigation scheduling, evapotranspiration calculation, pest management, planting date determination, severe weather warnings, forest fire forecasts, and drought monitoring, to name a few. Decision tool development, sophistication, and availability to users generally depends on funding availability. Overall, the practical and economic impacts of such information can be significant. For example, Michigan State University's Enviro-weather Project provides information to support agricultural and natural resource-related decision-making in Michigan, based on the input data from an 83-site mesonet. In a recent survey of cherry and apple growers across the state, mesonet data users reported significant reductions in their use of pesticides (relative to non-users), increases in both crop yield and quality, and an estimated collective yearly economic beneficial impact of more than $1.7 million dollars associated with the use of web-based information (Andresen et al. 2012).

Partnerships

A distinguishing aspect of mesonets represented in this paper is that they operate as not-for-profit entities, and most involve strong grassroots efforts. Thus, mesonets have developed strong collaborative partnerships with their users. These partners include individual citizens (e.g., a site host who provided access to their land for a station tower), state and local government entities (e.g., emergency management, county fiscal court, local school board, etc.), and private industry and local businesses (sponsoring a station by making pre-determined annual contribution for station maintenance). In some cases, these local-level entities also bear the cost of the station purchase and installation, and contribute toward recurring annual costs of communication and maintenance. Success in building and sustaining local-level partnerships requires a substantial engagement and persistence on the part of mesonet operators. But these local-level partnerships constitute an invaluable foundation of support, as they facilitate exchange of information and ideas that help mesonet operators better meet the needs of diverse user communities. Through time, state and local partners develop a greater appreciation of the value of locally accurate and timely weather and climate data from perspectives including public safety and economic benefit. In addition, through these long-term partnerships, local and state entities come to value the local expertise available at institutions that operate these mesonets.

State and federal partnerships are also key elements of mesonets. In many cases, mesonets receive funding from state agencies in return for defined deliverables, normally relating to public safety and emergency response. Regionally, some mesonets share data with Regional Climate Centers funded by the National Oceanic and Atmospheric Administration. A number of mesonets have been providing data for various federal entities over many years, most often these exchanges are free of charge. However, there are cases where a federal partner provides limited funding for the data. Increasingly, mesonets are contributing near real-time data and metadata through the federally-supported National Mesonet Program (Dahlia 2013). These data support a variety of National Weather Service (NWS) activities tied to weather forecasting. Independent of this effort, many mesonets make data available directly to local NWS offices for their forecasting and alerting activities as a public service to local residents. Indeed, many local NWS offices are among the strongest partners of the mesonets.

Funding challenges

Public availability of weather and climate data helps to enhance public health and safety, promote economic development, and further environmental awareness and education. Recognition of these societal benefits creates an expectation that observing networks should be publicly funded and that data should be freely available. However, public funding is scarce and within this context, mesonet operators face ongoing challenges to secure financial resources necessary to develop, operate, and maintain networks that collect and ensure data that support research and high-value decision-making.

Various funding models have been implemented, as each mesonet has developed from a unique set of circumstances. Some have a strong top-down structure, relying heavily on start-up and recurring annual operating funding from a single or small number of sources at the level of state government. The target markets for data and information provided by mesonets are often dictated by the funding sources. Mesonets that are funded by and serve agricultural interests can be found at some land-grant universities. Other mesonets emphasize public safety and emergency management, with funding channeled through corresponding state agencies. Still, when funding is provided through a single or small number of entities, mesonets can be vulnerable to sizeable budget cuts during economic downturns or when administrative priorities change.

On the other hand, in an effort to develop agility and resilience, mesonets may also strive to build a bottom-up funding model based on funding at the local level tied to development and operation of individual monitoring stations. Agility enables a mesonet to identify and pursue opportunities to expand network coverage on a station-by-station basis. Bottom-up funding also creates resilience by diversifying funding streams. However, some downsides to a bottom-up approach include high administrative overhead and investment of significant staff time to acquire and maintain funding. Additionally, individual mesonets may pursue opportunities to leverage their networks through research and development projects, including public-private partnerships. Ultimately, the sustainability and growth of mesonets are enhanced through successful efforts to develop funding streams through partnership building at the local, state, and federal levels, while providing value to partners at each level.

Future direction

In-situ weather and climate observations collected by mesonets provide ‘ground truth’ of near-surface atmospheric and surface conditions. They are increasingly used to advance understanding of land surface-atmosphere interactions and the evolution of meteorological events, to initialize and validate forecast models, and to improve weather forecasting. On a longer time scale they enable insights into climate variability and climate change. Near real-time availability of data also make them valuable in emergency management and response situations. Data from mesonets are used in applications associated with agriculture (irrigation, crop planting, fertilizer and pesticide applications, freeze protection, insurance), water management, drought, public health, air quality, renewable energy generation, and transportation. Through various applications, they inform societally relevant policy and decision-making.

We hold that these mesonets are vital assets contributing to their states and to society at large. Based at and operated by universities, those operating these networks share a commitment to develop, operate, and maintain environmental monitoring that provides research-grade information. Though some mesonets are well established and have been in operation for decades, we note that the collective development of mesonets is still in the formative stage. This is evident in the diversity of operational and funding models. While this represents a strength resulting from the diverse range of experiential and expert knowledge collectively provided by these mesonets, we envision a future stage of development that will lead to greater commonality in the structure of mesonets, though each will remain unique.

Therein, we make the following recommendations:

1) *Network operation, maintenance and expansion:* In-situ observation networks should continue to be operated and maintained. Reliable streams of operating funding should be provided to support and more fully leverage the value of these networks. Funding mechanisms need to be developed to facilitate the expansion of networks such that greater geographic coverage, at times at a high density, be provided in areas where needed observations are unavailable.
2) *New observation capabilities*: We recognize that advances in technology and improved budgetary conditions are likely to enable mesonets to expand the array of environmental measurements that they record. This could include adding temperature and wind measurements at different levels, flux measurements for land-atmosphere interactions, incorporation of atmospheric profilers or unmanned aerial vehicles (UAVs) to better monitor the boundary layer, expanding soil monitoring, adding cameras to capture images and video, and otherwise developing more intelligent monitoring networks. These and other advances are likely to result through expanding partnerships, both in the public and private sectors.

3) *Network upgrade:* The authors appreciate that availability of funding for maintaining and upgrading existing observational infrastructure is limited. However, we hope we have illustrated that the societal value, including direct social and economic benefit of these networks far outweighs (by many fold) the investment. Funding should also be directed in such a way that a currently operating network can continue to upgrade their instrumentation and exposure so that they can further meet scientific requirements for data quality. For instance, a network could switch from 3 m to 10 m towers for better wind monitoring and possible relocation of stations for better exposure. In addition, funding can go to add any missing but critical observations (hence, instrumentation) for any particular network.

These recommendations are not all encompassing. We suggest that they offer a foundational basis for the mesonets to play an important role in the weather and climate observation and continue to provide valuable scientific and societally relevant information.

Acknowledgements: The authors would like to thank Dolly Na-Yemeh for preparation of Figure 1. Thanks also go to two anonymous reviewers for their valuable comments and suggestions.

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Table 1. State-wide mesonets.

State	**Network**	**Total number of real-time stations**
Alabama	North Alabama Climate Network	22
Alabama	University of South Alabama Mesonet (CHILI)	25
Arizona	Arizona Meteorological Network	21
Arkansas	Arkansas State Plant Board Weather Network	50
California	California Irrigation Management Information System	152
Colorado	Colorado Agricultural Meteorological Network	75
Delaware	Delaware Environmental Observing System	57
Florida	Florida Automated Weather Network	42
Georgia	Georgia Automated Weather Network	82
Illinois	Illinois Climate Network	19
Iowa	Iowa Environmental Mesonet	17
Kansas	Kansas Mesonet	51
Kentucky	Kentucky Mesonet	66
Louisiana	Lousiana Agroclimatic Information System	9
Michigan	Enviro-weather	82
Minnesota	Minnesota Mesonet	8
Missouri	Missouri Mesonet	24
Nebraska	Nebraska Mesonet	68
New Jersey	New Jersey Weather and Climate Network	61
New Mexico	New Mexico Climate Network	6
New York	New York Mesonet	101
North Carolina	North Carolina ECONet	40
North Dakota	North Dakota Agricultural Weather Network	
Oklahoma	Oklahoma Mesonet	120
South Dakota	South Dakota Mesonet	25
Texas	West Texas Mesonet	98
Utah	Utah Agricultural Weather Network	32
Washington	Washington AgWeatherNet	176
	Total	**1610**

Table 2. Typical set of instruments used on U.S. mesonet meteorological stations.

Instrument	**Parameter Measured**
Platinum Resistance Thermometers	Air Temperature
Capacitive Hygrometer	Relative Humidity
Propeller Anemometer	Wind Speed
Potentiometer Wind Vane	Wind Direction
Silicon Photovoltaic Pyranometer	Solar Radiation
Tipping Bucket Rain Gauge	Rainfall/Precipitation
Capacitive Barometer	Barometric Pressure
Soil moisture sensors (widely varies)	Soil moisture

Figure Captions:

Figure 1a-d. Example of mesonets in the U.S.: a) a map of conterminous U.S. with four states with mesonets (filled in black color), b) Kentucky Mesonet, c) Delware and New Jersey mesonets, and d) Oklahoma mesonet.

Figure 2. Instrumentation and lay out of a mesonet station. Intrumentations are: A.wind monitor, B. relative humidity Sensor, C. datalogger enclosure, D. temperature sensors, E. pyranometer, F. wetness sensor, G. single alter shield, H. precipitation gauge, I. battery enclosure, and J. solar panel. Soil moisture and temperature sensors and guy wires not shown and drawing not to scale.

Figure 3. A mesonet station in Kentucky with good exposure.

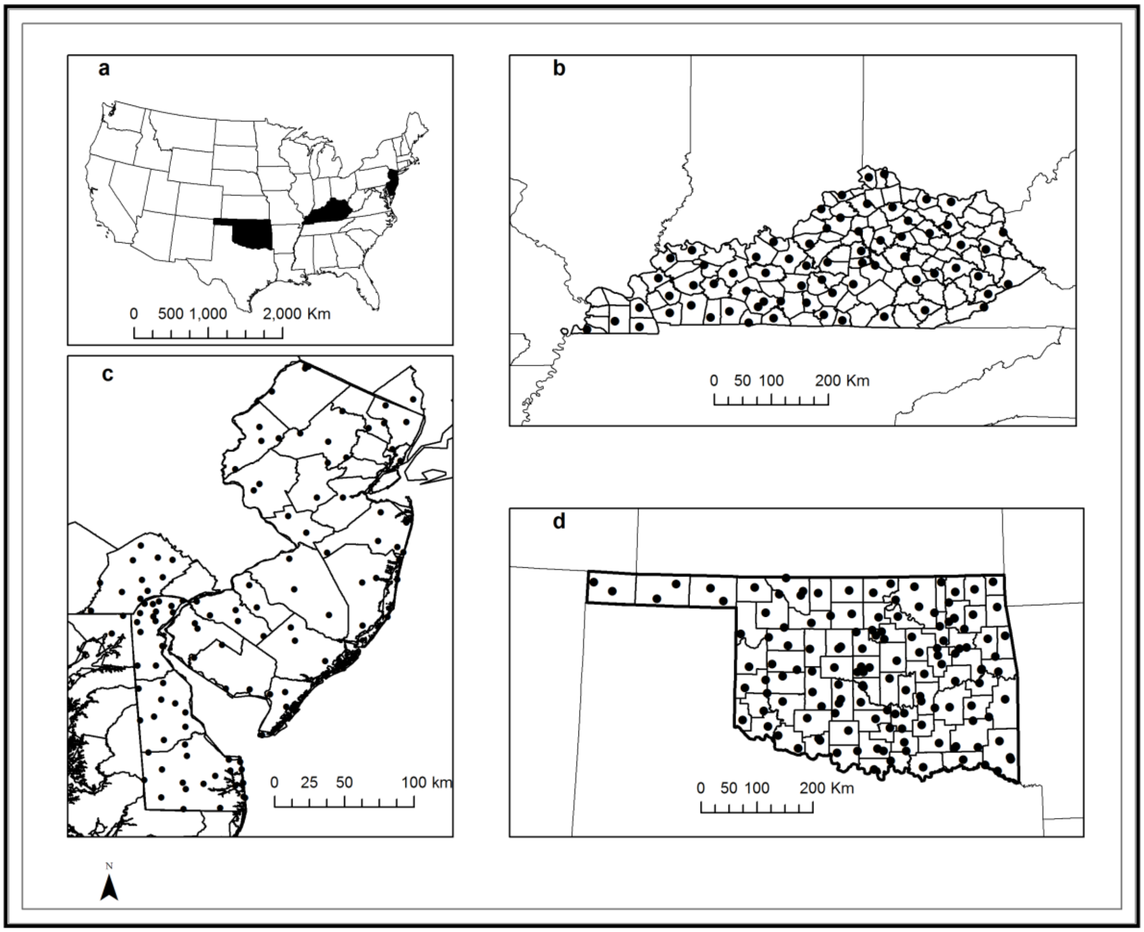
Figure 4a-b. a) Aspirated radiation shield, and b) Gill radiation shield (naturally ventilated).

Figure 5a-b. Differences of temperatures between non-aspirated and aspirated radiation shield: a) mean monthly maximum temperature, and b) mean monthly minimum temperature. Positive differences suggest warmer temperature under non-aspirated shield. Data are from Christian County station of Kentucky Mesonet and from December 2012 through November 2013.

Figure 6a-c. a) Time series plot of the air temperature at Norman, Oklahoma on 12-13 February 2008. The blue line shows measurements made by an aspirated temperature sensor, while the black line shows measurements made by a non-aspirated (naturally ventilated) temperature sensor; b) Wind speed; c) difference between the temperature observations made by the non-aspirated (naturally ventilated) temperature sensor and the aspirated temperature sensor. Differences were greatest in the late morning hours when both sun angle and wind speed was low (1 ms^{-1}).

Figure 7. A mesonet station in North Carolina with nearby obstructions (trees).

Figure 1



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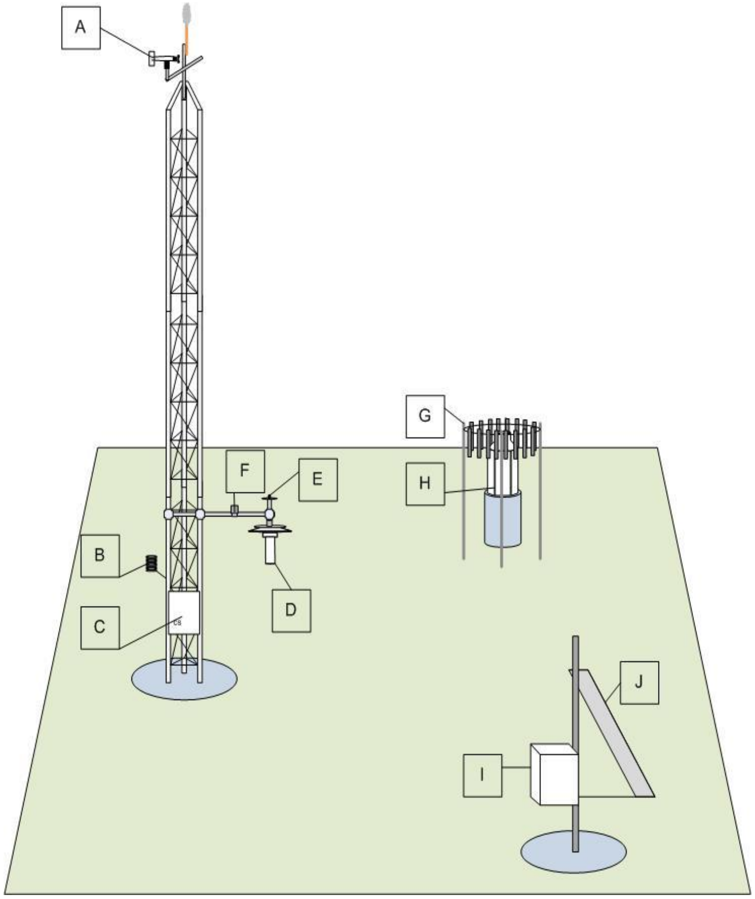

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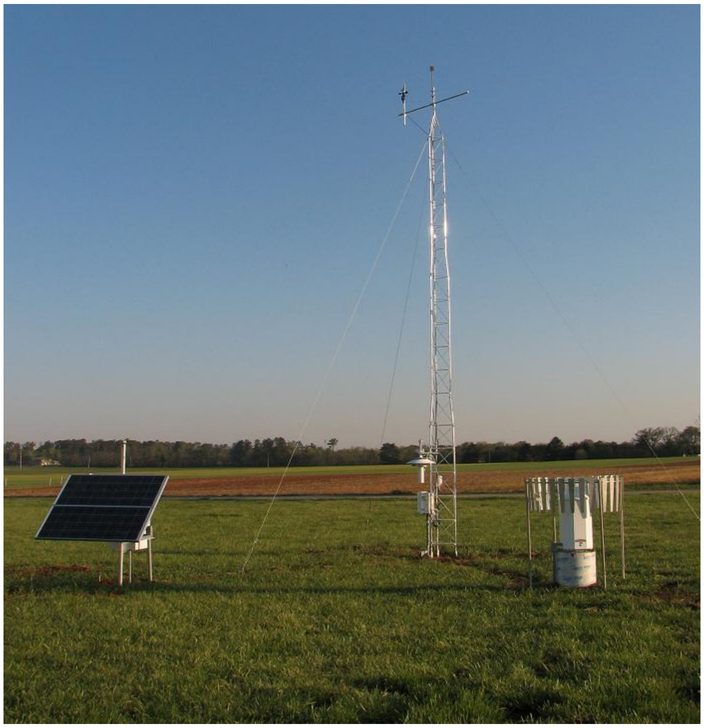

Figure 3. A mesonet station in Kentucky with good exposure.

a.

b.

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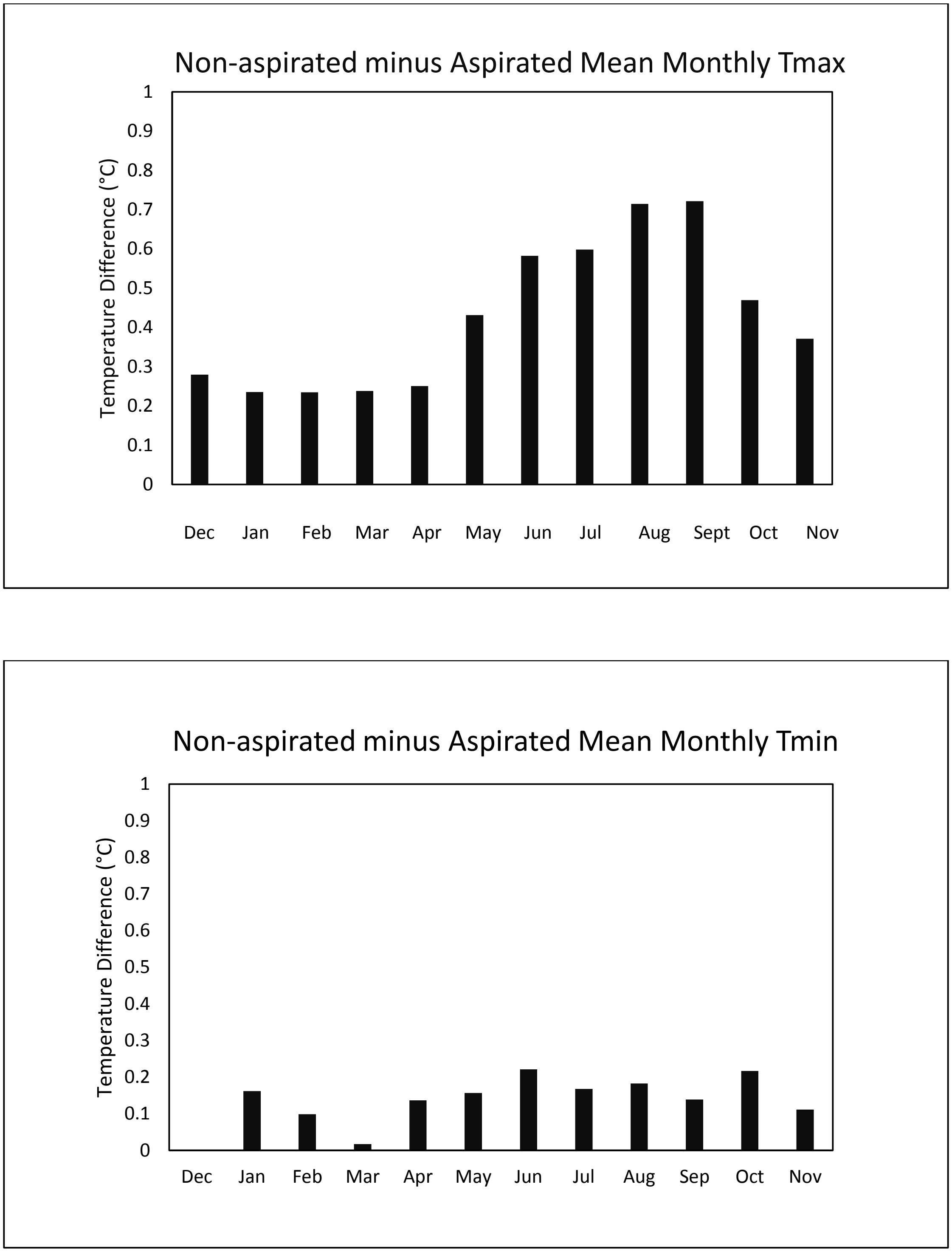
a.



b.

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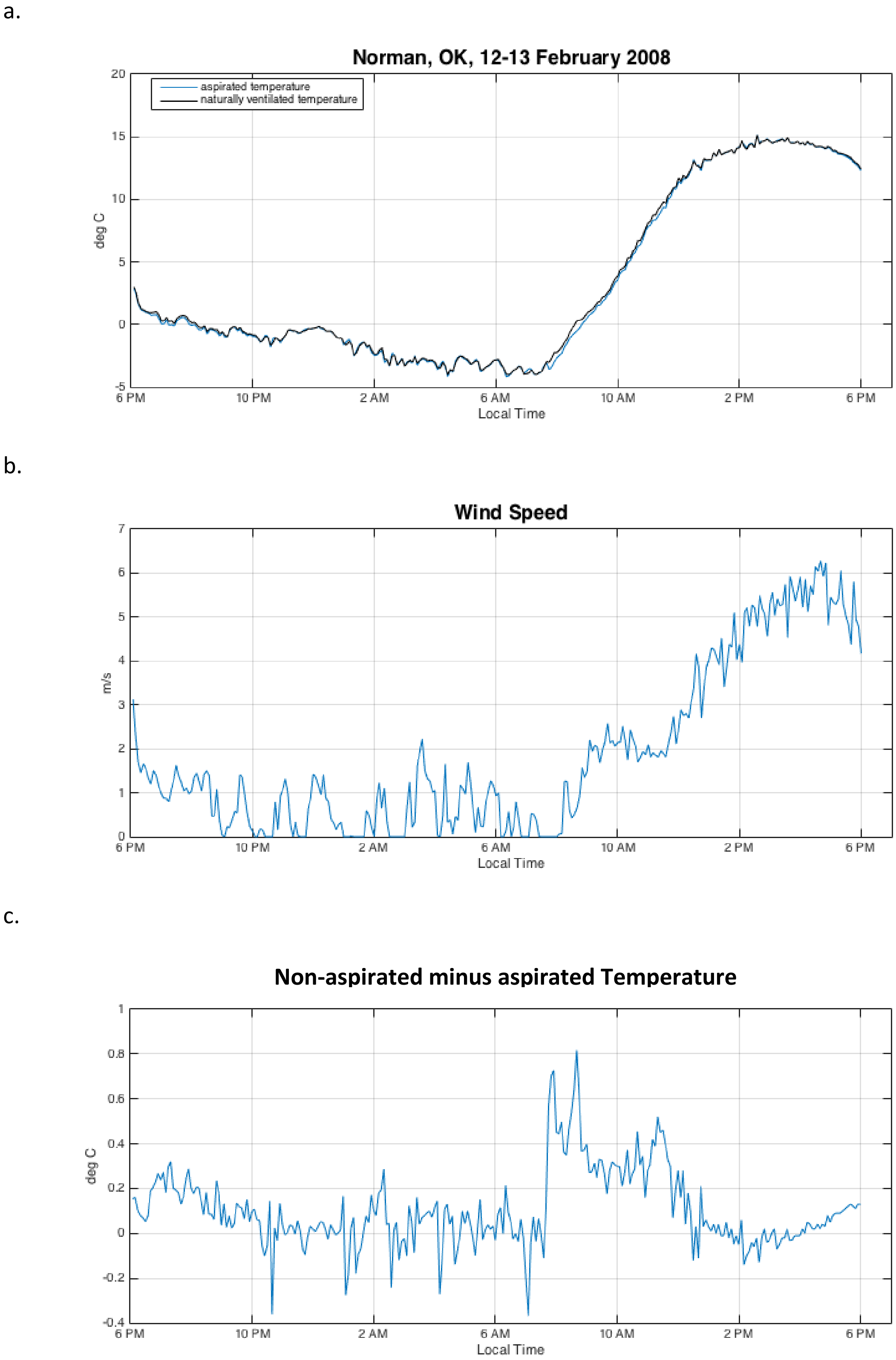
Figure 6



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