Statewide Monitoring of the Mesoscale Environment: A Technical Update on the Oklahoma Mesonet

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ABSTRACT

Established as a multipurpose network, the Oklahoma Mesonet operates more than 110 surface observing stations that send data every 5 min to an operations center for data quality assurance, product generation, and dissemination. Quality-assured data are available within 5 min of the observation time. Since 1994, the Oklahoma Mesonet has collected 3.5 billion weather and soil observations and produced millions of decision-making products for its customers.

1. Introduction

The University of Oklahoma (OU) and Oklahoma State University (OSU) operate more than 110 surface observing stations comprising the Oklahoma Mesonet (Brock et al. 1995). Remote stations send data every 5 min to an operations center, located at the Oklahoma Climatological Survey (OCS), for data quality assurance, product generation, and dissemination. The Oklahoma Mesonet (see online at http://www.mesonet.org) was established as a multipurpose network to provide research-quality data in real time. The mission of its personnel is to operate a world-class environmental monitoring network; to deliver high-quality observations and timely value-added products to Oklahoma citizens; to support state decision makers; to enhance public safety and education; and to stimulate advances in resource management, agriculture, industry, and research. Since 1994, the Oklahoma Mesonet has collected 3.5 billion weather and soil observations and produced millions of decision-making products for its customers.

2. Overview of the Oklahoma Mesonet

Scientists and engineers at OSU and OU planted the seeds of the Oklahoma Mesonet during the early to mid-1980s and joined forces in 1987, beginning the partnership to design, implement, maintain, and fund the Oklahoma Mesonet. In late 1990, with the endorsement of Oklahoma’s governor, the U.S. Department of Energy (DOE) awarded $2.0 million in oil-overcharge funds to support the design and implementation of the network. OSU and OU provided an additional $0.7 million.

All governing powers of the Oklahoma Mesonet are vested in and exercised by a six-person steering committee. Each university controls interest in three seats on the committee. The committee is responsible for 1) general supervision of the affairs, funds, and property of the Oklahoma Mesonet; 2) establishment of organizational policies; and 3) consultation whenever an activity creates significant obligations on network staff time or funds. As a result, the steering committee also guides strategic planning, develops fundraising strategies, verifies compliance with state and federal statutes,
monitors long-term risks, and assesses requests for substantial changes in operational and service activities.

In early 1991, under the direction of the steering committee, more than 50 experts, representing a variety of organizations and potential data uses, served on 11 mission-oriented subcommittees to study specific planning issues (e.g., data communications, station siting, variables to be measured, equipment specifications, etc.) and provide recommendations to the steering committee. The first operational stations were installed in December 1991, and the last of the original 107 stations was installed in July 1993. After testing and troubleshooting, networkwide data collection and dissemination began on 1 January 1994.

Support for network operations during the mid-1990s resulted from contributions by eight state cabinet agencies, a growing base of user fees, and a series of research grants designed to enhance network operations. In 2000, an external review panel from the American Association for the Advancement of Science recommended that the steering committee seek permanent state funding to sustain core network operations and maintenance. Permanent state dollars of ~$1.6 million per year, administered by the Oklahoma State Regents for Higher Education (OSRHE), were made available in July 2001.

3. Remote stations and sensors

a. Station siting

In 1991, experts evaluated technical standards for station siting (Shafer et al. 2000). Their main objective was to increase data usefulness by ensuring that the physical characteristics of a site be as representative of as large an area as possible. Because National Weather Service (NWS) stations already monitored urban areas, a secondary objective was to establish a rural network. Using guidance from the World Meteorological Organization (WMO; WMO 1983), the site standards committee provided the following recommendations to the steering committee:

1) Minimize influences of urban landscapes, irrigation, forests, and large bodies of water;
2) Minimize obstructions that impede ventilation of the site;
3) Minimize the slope of the site and neighboring landscape;
4) Select locations accessible by light truck or van during all seasons; and
5) Minimize extremes of both bare soil and fast-growing vegetation coverage by selecting sites with uniform, low-growing vegetation.

The experts also recommended collocation of several sites with those of other networks, such as the NWS’s Automated Surface Observing System and stations in the National Oceanic and Atmospheric Administration (NOAA) Cooperative Observer Network.

Another committee applied these recommendations and suggested private and public landowners who would support the network with a no-charge lease of the land required. Oklahoma Mesonet personnel scouted possible locations and selected appropriate sites.

After 12 yr of operation, only one site was moved by request of the landowner. Two sites were relocated to improve marginal exposures, one was moved to improve all-season access, two were repositioned to become extensive research stations, and one was moved because of repeated vandalism. The renamed, alternate sites were located within a few kilometers of the original sites to minimize impacts on scientific research.

b. Station layout

An Oklahoma Mesonet station occupies a 100-m² plot of land and comprises a datalogger, solar panel, radio transceiver, lightning rod, and environmental sensors located on or surrounding a 10-m tower (Fig. 1; Elliott et al. 1994). Remote stations measure more than 20 environmental variables (Table 1). Installed at the top of the tower, a lightning rod connects to a ground rod buried to 2.5 m. On average, lightning strikes eight stations each year.

The wind speed and direction sensor is mounted on the top of the tower (Fig. 1). Below, air temperature (at 1.5 and 9 m), humidity (at 1.5 m), and wind (at 2 m) sensors mount from booms projecting ~1 m from the tower. Near the base of the station, a metal enclosure contains the datalogger, radio transceiver and modem, barometer, and battery for the station. Heavy-duty, welded-wire fencing encloses most stations to protect the tower from livestock and the groundcover from undocumented vegetation maintenance by landowners.

Soil temperature is measured at depths of 5 and 10 cm below both a bare plot and a native vegetation cover. Where bedrock does not prohibit sensor installation, soil temperature is also monitored at 30 cm under native vegetation. Soil moisture sensors are installed to the west of the tower at depths of 5, 25, 60, and 75 cm, if possible. During station installation, soil samples were extracted from the locations of the belowground sensors for soil textural analysis.

Northwest of the tower, a 121-cm-diameter Alter shield (Alter 1937) surrounds the aboveground rain gauge. The height of the shield does not exceed that of
the orifice of the gauge, and the screen is beveled to minimize wind flow across the orifice.

c. Datalogger

In 1999, the Oklahoma Mesonet upgraded from the Campbell Scientific, Inc. (CSI) CR10T to CR10X-TD and CR23X-TD dataloggers because of enhanced sensor measurement, sensor control, and on-site data processing. Approximately three-quarters of the stations have more than 25 sensors, requiring the increased sensor-interface capacity of the CR23X-TD (i.e., up to 24 analog voltage signals). Most stations are equipped with a CSI AM416 relay multiplexer, allowing 32 additional analog measurements. Four pulse-counting channels measure wind speed, and eight digital input/output ports are available to communicate with digital sensors, switch power to the relative humidity sensor, and detect reed-switch closure for the unheated tipping-bucket rain gauge. Several stations use the CR23X-TD and CR10X in tandem, with the latter operating as a supplemental processor for computing flux variables and performing high-frequency measurements with a three-dimensional ultrasonic anemometer.

d. Station sensors

The sensor suite of the Oklahoma Mesonet includes primary sensors that are located at every site and secondary sensors at ~100 stations. In 2000, a National Science Foundation (NSF)-funded project permitted the installation of experimental sensors at 10 sites that represented different climate regimes. As of 2006, two sites remain operational. Table 1 lists the primary, secondary, and experimental sensors installed across the Oklahoma Mesonet.

Prior to sensor deployment, personnel in the calibra-
tion laboratory verify that the equipment meets the “Mesonet lab accuracy specifications,” the accuracy designated by Oklahoma Mesonet management as attainable using available calibration equipment. Table 2 catalogs the manufacturer’s specified accuracy, the Mesonet’s laboratory accuracy specifications, and the expected field accuracy.

1) **Barometer**

Prior to 2001, the Oklahoma Mesonet recorded atmospheric pressure with the Vaisala PTB202 barometer. Production of the PTB202 ceased in 1993. Since then, technicians have upgraded some stations to the PTB220 model. The two models have nearly identical specifications except that the PTB220 has a slightly lower measurement range. A short length of tubing extends from the barometer’s pressure port to outside of the datalogger enclosure to expose the sensor to the free atmosphere. The manufacturer’s specified accuracy of the barometer is ±0.2 hPa across the range of 700–1100 hPa.

2) **Relative Humidity Sensor**

The Oklahoma Mesonet upgraded its measurement of relative humidity from Vaisala’s HMP35C sensor to its HMP45C in 2005, when the vendor stopped producing the former sensor. The manufacturer’s specified accuracy for both sensors is ±2% between values of 0% and 90%, and ±3% between 90% and 100%. Because of the sorption sensor’s inherent inaccuracy at saturation (S. Alpert 2004, personal communication), the Mesonet processing system restricts all readings greater than 100% to an upper bound of 100%.

3) **Air Temperature Sensors**

Prior to 2004, air temperature at 1.5 m was measured by the combination thermistor–sorption HMP35C probe (Brock et al. 1995). The HMP35C probe utilized a Fenwal Electronics UUT51J1 thermistor, added to a Vaisala sorption sensor by CSI. Temperature data prior to March 1997 exhibited a varying bias (−0.5° to 1.0°C) caused by sampling the relative humidity (RH) prior to the air temperature (Fredrickson et al. 1998; Shafer et al. 2000).

On 1 January 2004, the network transitioned to a faster-responding, bare-bead thermistor assembly for 1.5-m air temperature measurements (Table 2). This sensor uses a Thermometrics Unitherm Interchangeable Thermistor (UIM) DC95 mounted in a stainless
steel housing that couples the thermistor with the atmosphere. The Oklahoma Mesonet used this thermistor for its 9-m measurements since 1994. The Thermometrics sensor has an operating range of \(-30°C\) to \(50°C\).

R. M. Young multiplate radiation shields house both air temperature sensors. Power constraints at the station required a nonaspirated shield; hence, field inaccuracy can be as high as \(1°C\) in light winds and strong radiation (Hubbard et al. 2004; Tanner et al. 1996). Fortunately, these conditions are relatively infrequent across Oklahoma.

4) RAIN GAUGE

Since inception, the Oklahoma Mesonet has used a 30.5-cm-diameter MetOne tipping-bucket rain gauge. During the mid-1990s, network personnel modified the gauge substantially to reduce unscheduled technician visits to fix problems (Shafer et al. 2000). Changes included raising the height of the funnel rim, using a more robust tipping-bucket bearing, and changing to a magnetic switch. The gauge has a resolution of 0.25 mm. Station power constraints prohibit the use of any heating device that would allow for measurement of frozen precipitation. As a result, snow and ice are measured as liquid equivalent after melting occurs.

5) PYRANOMETER

The Oklahoma Mesonet uses LI-COR’s LI-200 silicon photodiode-type pyranometer to measure down-
welling, global solar radiation. Sensor-specific calibration coefficients are applied to the data. The pyranometer originally was mounted on a separate tripod south of the tower (Brock et al. 1995); in 1999, however, the sensor was moved to a boom extending southward from the tower to minimize lightning damage.

Measurements during morning and evening are sensitive to obstructions to the east and west of the station. (This sensitivity may be examined using panoramic site photos available online at http://www.mesonet.org/sites.)

6) Wind sensors

WMO-standard wind observations are measured at 10 m with the R. M. Young 5103 wind monitor, a combination propeller and vane anemometer. The starting-threshold wind speed is 1.0 m s\(^{-1}\) for the propeller and 1.1 m s\(^{-1}\) for the vane. The sensor can record speeds between 1.0 and 60.0 m s\(^{-1}\) with a specified accuracy of \(\pm 0.3\) m s\(^{-1}\). The wind direction accuracy is \(\pm 3^\circ\). From this sensor, the datalogger computes a 5-min-average scalar wind speed, 5-min-average vector wind speed and direction, 5-min standard deviations of wind speed and direction, and maximum 3-s wind speed during the 5-min period.

The R. M. Young 3101 cup anemometer measures wind speed observations at 2 and 4 m (Brock et al. 1995) with a manufacturer’s specified accuracy of \(\pm 0.5\) m s\(^{-1}\). The datalogger only reports a 5-min average wind speed for this sensor.

7) Soil temperature sensor

Fenwal Electronics, Inc., manufactured the original soil temperature sensor installed by the Oklahoma Mesonet. The Fenwal sensor used a chip thermistor, housed in a sealed stainless steel tube, and had a specified accuracy of \(\pm 0.4^\circ\)C. Because of a supply problem that the manufacturer could not overcome, the Oklahoma Mesonet switched to a BetaTHERM model in 1997. The BetaTHERM is similar to the previous sensor except that electronics potting material, rather than air, fills the gap between the thermistor and the tubular housing.

Because soil temperature gradients can be substantial through the top 10 cm of soil, field technicians attend to maintenance of accurate sensor depth, especially after heaving occurs during the winter (Fiebrich et al. 2006). From late spring to early fall, direct sunlight on the tower casts afternoon shadows upon the soil temperature plots for up to 30 min. In extreme instances, this shading results in an artificial, 1\(^\circ\)C–2\(^\circ\)C decrease in 5-cm soil temperature.

8) Soil moisture sensor

In 1996, the Oklahoma Mesonet installed CSI’s 229-L soil moisture sensors at approximately half of its sites (Basara and Crawford 2000, 2002). Since then, additional sites have received soil moisture sensors.

The 229-L is a heat dissipation sensor that utilizes a thermocouple as a temperature sensor and a resistor as a heating element, both housed within a hypodermic needle embedded within a porous ceramic matrix. During operation, the thermocouple measures the ambient temperature immediately before and after a 21-s heating of the sensor by an electric current. The difference between the two measurements is large (small) in dry (wet) soil. This difference measures heat dissipation, related directly to the soil-water potential (Reece 1996; Starks 1999; Basara and Crawford 2000). Volumetric water content of the soil is calculated via an empirical relationship that uses soil-water potential and the soil characteristics (Arya and Paris 1981).

9) Experimental sensors

The Oklahoma Mesonet has deployed many experimental sensors. For example, from 1994 to 1999, leaf wetness was measured using printed circuit boards (Fisher et al. 1992). In 1999, 89 stations were augmented with instruments to measure components of the surface energy and radiation budgets. Sensors included a net radiometer (Kipp and Zonen NR LITE; Brotzge and Duchon 2000), ground heat flux plates (REBS HF 3.1), 0–5-cm integrated soil temperatures (REBS STP), and infrared temperature sensors (Apogee Instruments, Inc.) measuring surface skin temperature (Fiebrich et al. 2003).

At 10 of these upgraded stations, a sonic anemometer (CSI’s CSAT3) and krypton hygrometer (CSI’s KH20) were added to compute sensible and latent heat fluxes (Brotzge 2000). Furthermore, a four-component net radiometer (Kipp and Zonen CNR 1) at these sites provided observations of both upwelling and downwelling shortwave and longwave radiation. The krypton hygrometers were not designed for continuous, long-term use and were removed from the network in 2004. Other sensors were removed in 2006 (see Table 1).

e. Sampling and averaging

Stations report data in 5-, 15-, or 30-min records, depending on the variable measured. The 5-min record contains averages for all aboveground sensors, heat flux, battery voltage, and station maintenance status. The sampling rate for aboveground sensors is 3 s, with the exception of the barometer (12 s) and rain gauge (event driven). The record also reports the maximum
wind speed (i.e., the highest 3-s sample during the 5-min period). Liquid precipitation is recorded as the number of bucket tips since 0000 UTC.

The 15-min record contains averages for soil temperatures using a sample rate of 30 s. Soil moisture, based on a single sample per depth measured, composes the 30-min record. On management’s request, stations can report 1-min averages of most above-ground sensors in a separate data record. Two stations also send three additional 5-min data records for sensors sampling at 1 Hz (four-component radiation) and 8 Hz (three-dimensional wind speed).

f. Power requirements

Solar energy powers all Oklahoma Mesonet stations. Power requirements range from 1.3–4 W, depending on the communications and sensor configuration. In 2004, a networkwide communications system upgrade required an increase in the capacity of the power system. Currently, the system includes a 30-W photovoltaic module, charging regulator, and 75-AH sealed lead-acid battery. Two of the stations require an additional 100-AH battery and 30-W photovoltaic module to power experimental sensors (Table 1). All stations have a minimum power reserve of 18 days.

4. Communications, operations, and monitoring

a. Communications

The Oklahoma Law Enforcement Telecommunications System (OLETS) forms the backbone of the Oklahoma Mesonet communications infrastructure at no additional cost to state taxpayers. OLETs supports a high-speed digital communications network connected to 250 city, county, state, federal, and military law enforcement and criminal justice agencies across Oklahoma.

The Oklahoma Mesonet system polls each observation station every 5 min. Data are sent from the station to a nearby OLETs connection via VHF radio (at 4800 bps) using one of two NOAA hydrologic frequencies (Fig. 2). At each OLETs-connected agency, the data are streamed via TCP/IP on a secure, encrypted Wide Area Network to the OLETs Network Switching Center and finally to OCS for ingest into the Mesonet processing system (Fig. 3). The minimum speed for OLETs’s connections to its agencies is 56 Kbps, sufficient for transmission of Oklahoma Mesonet data (at its daily average bandwidth of 60 bps).

The Oklahoma Mesonet also employs two small networks of 900-MHz spread-spectrum communications (Fig. 2). One network collects data in a region where the Oklahoma Mesonet has experienced transmission difficulties. These data also arrive in Norman, Oklahoma, via OLETs linkages. The other network supports data transfer directly to the operations center from stations in line of sight to a 15-story building on the OU campus.

All communications pathways from the station to the Oklahoma Mesonet’s central computers are two way, enabling operators at OCS to set clocks, download
datalogger programs, and request missed or corrupted observations to be resent. In the event of communications failure, 100 stations store data for more than 40 days and the remaining stations store data for 13 days.

b. Computer ingest, processing, and dissemination system

Oklahoma Mesonet data are collected using multiple, redundant network connections to CSI’s LoggerNet software. The LoggerNet system uses four inexpensive x86 servers running Windows XP Professional. Observation records are sent, via TCP/IP sockets, from LoggerNet to multiple instances of ingest and archival software running on four x86 Linux servers, where they are stored as both ASCII and NetCDF files. Real-time and historical data ingest, processing, quality assurance (QA), and product generation are distributed across the four Linux machines. Because generic computers are used, any computer outage can be resolved by replacing the broken unit with an off-the-shelf spare. XServe RAIDs archive data utilizing RAID-5 sets and hot spare disks for redundancy and availability.

Data arrive at the central computing facility 3–3.5 min after the variables are measured. Within 2 min, data are quality assured and products are disseminated from three load-balanced Web and FTP servers. Users downloaded more than 525 GB of Oklahoma Mesonet data files and an additional terabyte of related data and products (e.g., agricultural model output, radar data) during 2004.

c. Database

To manage both data and metadata, the Oklahoma Mesonet uses a MySQL relational database. The database has four interrelated components: 1) a user module, 2) a network site module, 3) an equipment module, and 4) a quality assurance module. The database integrates network data ingest, processing, and quality assurance.

The database’s user module stores and retrieves information about each internal user type, including system administrators, laboratory and field personnel, and quality assurance meteorologists. The module manages permissions to check instruments to or from the inventory, to insert or edit calibration coefficients, or to view metadata. The network site module stores information regarding the overall network (e.g., commissioning date), details about each site (e.g., latitude, distance to nearest city), and both the variables measured and their attributes (e.g., units of measurement).

![Diagram of the Communications System of the Oklahoma Mesonet](image-url)
Information about individual sensors and other equipment is managed by the database’s equipment module. This module maintains the date received, serial number, cost, manufacturer, dates commissioned and retired, calibration history (e.g., date, resultant coefficients), installation date and location, and problem history of each item, as appropriate. When anyone handles equipment, the location and handler are recorded in the database.

The value of the previous modules increases significantly when they integrate with the QA module. As detailed in sections 5c and 5d, should a data problem be detected, a meteorologist makes the final decision regarding how to “flag” the data. The meteorologist issues a “trouble ticket” that records the problem, the required deadline for repair, and the quality flag assigned to associated observations until the problem’s resolution. The trouble ticket is sent automatically to the field technicians. Repair details include the date and time fixed, what error source was diagnosed, and how the issue was resolved (e.g., sensor cleaning, equipment replaced). The information submitted by the technician becomes available to the QA meteorologist for inclusion in the database.

d. Real-time operations and monitoring

The Oklahoma Mesonet supports an operations and monitoring center that combines both automated and manual oversight of real-time data ingest, processing, and dissemination. Operators monitor data ingest, support technicians in the field, check every product daily, collect any data that missed their scheduled collection time, provide customer support, serve on-call in case of emergencies, and issue network status reports. Web pages display information from database modules, allowing these student operators to aid remote field technicians efficiently.

Automated monitoring programs issue pages if a system fails, communications are disrupted, or products are not created. These programs decrease the administrative pressure to staff the operations center continuously. The operator on call can access necessary software utilities via the Internet or modem connections within minutes of an automated system page, or staff can arrive at the operations center within 15 min if network connections have been disrupted.

5. Data QA

The primary focus of network operations and maintenance is to obtain research-quality observations in real time. From the receipt of a sensor from a vendor to the dissemination of real-time and archived products, the Oklahoma Mesonet follows a systematic, rigorous, and continually maturing protocol to verify the quality of all measurements (Fig. 4).

a. Sensor calibration

Oklahoma Mesonet personnel test or calibrate every new sensor before it is deployed to the field (i.e., pre-field calibration) and every previously installed sensor after its return from the field for repair or rotation (i.e., postfield calibration). The postfield calibration occurs prior to sensor cleaning and adjustment, thus documenting the sensor’s performance at the time of removal from the remote station. If the sensor can be cleaned, repaired (if needed), and rotated back into the field, then it is calibrated again, prior to redeployment.

Experience gained through Oklahoma Mesonet operations since 1994 has led to preferred rotation intervals for some sensor types (Table 3; Fiebrich et al. 2006). A technician replaces a station’s sensor if it has resided in the field beyond the residence time designated for its sensor type, even if no problems with the sensor’s data are evident.

1) Barometer

Laboratory personnel calibrate barometers using a two-reservoir pressure system and a commercial temperature chamber. A technician connects each barometer to the pressure system via tubing, and then places a set of barometers into the chamber. The system uses a Paroscientific barometer, certified by the National Institute of Standards and Technology (NIST), as a reference. It also uses a Vaisala PTB220 as a “lab standard” (i.e., a barometer from the Mesonet’s general sensor inventory that is designated to remain in the calibration system during every run to ensure the stability and continuity of all tests).

Because the accuracy of the silicon-capacitive absolute-pressure sensor used in the digital barometers is dependent on temperature, the barometers are calibrated across ranges of pressure (650–1100 hPa) and temperature (−25° to +50°C). As the calibration progresses, electronic valves precisely release air from the high to the low pressure reservoir, resulting in a series of pressure steps. Meanwhile, the temperature chamber sinusoidally varies the environmental air temperature. Upon completion of the run, customized LabVIEW software computes and downloads a set of eight coefficients to bring the error of each barometer within the laboratory accuracy of ±0.4 hPa.
2) Relative Humidity Sensor

The Oklahoma Mesonet uses a Thunder Scientific Model 2500 Benchtop Humidity Generator, a NIST-certified reference instrument, to calibrate its relative humidity sensors. Two different models of humidity sensors remain in the chamber for every calibration run and serve as laboratory-standard instruments. The Thunder Scientific chamber uses a two-pressure method to produce known humidity values. The calibration system checks the accuracy of humidity measurements at 10% intervals from 10% to 98%. If a sensor fails field drip test.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Variable measured</th>
<th>Rotation interval (months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Campbell Scientific HMP45C</td>
<td>Relative humidity</td>
<td>24</td>
</tr>
<tr>
<td>LI-COR LI-200</td>
<td>Solar radiation</td>
<td>36</td>
</tr>
<tr>
<td>MetOne 380C</td>
<td>Rainfall</td>
<td>Upon failing field drip test</td>
</tr>
<tr>
<td>R. M. Young 5103</td>
<td>Wind direction at 10 m</td>
<td>60</td>
</tr>
<tr>
<td>R. M. Young 5103</td>
<td>Wind speed at 10 m</td>
<td>48</td>
</tr>
<tr>
<td>R. M. Young 3101</td>
<td>Wind speed at 2 and 4 m</td>
<td>24</td>
</tr>
<tr>
<td>Thermometrics UIM DC95</td>
<td>Air temperature at 1.5 and 9 m</td>
<td>60</td>
</tr>
<tr>
<td>Vaisala PTB202/220 barometer</td>
<td>Pressure</td>
<td>48</td>
</tr>
</tbody>
</table>
3) AIR TEMPERATURE SENSORS

Technicians calibrate air temperature sensors using a Tenney temperature chamber and two NIST-certified reference temperature probes by Hart Scientific. To ensure that probes are in equilibrium, a technician places the reference and test probes in an aspirated inner chamber within the main temperature chamber. The sensors are tested across the range from −30° to +50°C using 10°C steps. Because correction coefficients are not applied to temperature probes, every sensor must meet the ±0.35°C error specification or it is not deployed.

4) RAIN GAUGE

Rain gauges are calibrated with a two-step process. First, a laboratory technician performs a static calibration to ensure that the tipping-bucket mechanism results in a tip when 18.53 mL of water enters a bucket. The bucket mechanism is adjusted so that a tip occurs within ±2% of the proper water volume.

Upon successful completion of the static calibration, the technician performs a dynamic calibration similar to that described in Brock et al. (1995). A digital scale weighs water as it drains from a 5-L cylindrical reservoir into the rain gauge. Simulated rain rates are output from measurements taken by both the scale and the gauge. Software computes correction coefficients based on rain rate, and the resultant calibration record describes the gauge performance at various rates. This calibration accounts for the mechanics of the gauge that prevent the buckets from tipping instantaneously (Duchon and Essenberg 2001). A higher rain rate results in a larger underestimation of rainfall.

5) PYRANOMETER

Prior to 2005, the Oklahoma Mesonet tested its silicon-cell pyranometers against a calibrated Eppley PSP. These sensors were mounted side by side outdoors, and data were collected for 1–2 weeks during days with relatively high solar-elevation angles (e.g., May–September). This method required a technician to decide subjectively which observations should be used to generate calibration coefficients (e.g., all observations or those only during clear days).

In late 2004, the Oklahoma Mesonet purchased a Kipp and Zonen Calibration Facility for indoor calibration. This system exposes both reference and test pyranometers to a stable metal-halide lamp that radiates at 450 W m⁻². The reference sensor, a LI-COR silicon-cell pyranometer, has been calibrated by the Solar Radiation Research Laboratory at the National Renewable Energy Laboratory. Based on observed readings from the two sensors, LabVIEW software calculates a calibration coefficient. This method takes only minutes to perform, provides an objective calculation of calibration coefficients, and allows for calibrations at any time of the year.

6) WIND SENSORS

The Oklahoma Mesonet uses an outdoor facility to check its propeller- and cup-type wind sensors. Technicians install sensors on 3-m steel posts in a 9-m² grid for 7–14 days, after which they compare wind speeds from the test sensors and a NIST-certified propeller-vane reference sensor. Test sensors must have a mean error of ±0.2 m s⁻¹ to pass. Mesonet personnel manually check and adjust the direction portion of the propeller-vane sensor using a vane-angle bench stand to align the vane through the range of 0°–359° within a ±3° error specification.

7) SOIL TEMPERATURE SENSOR

Laboratory technicians use a bath of 50% water and 50% antifreeze to calibrate soil temperature sensors. The probes are placed in a 4-L beaker with both a NIST-certified Hart Scientific reference thermometer and a laboratory standard sensor. A sensor mount holds the probes at the same depth in the bath. A freezer cools the beaker to −25°C. The beaker is placed on a stirring hot plate and its temperature is increased slowly until the liquid reaches 60°C. Every sensor must meet a ±0.5°C error specification before it can be deployed to a station.

8) SOIL MOISTURE SENSOR

Soil moisture sensors receive both laboratory and field calibrations. The laboratory calibration is a two-point test that uses the driest and wettest observations that can be attained in the laboratory environment. To obtain the dry point, probes are sealed in a plastic bag with desiccant; for the wet point, probes are immersed in distilled water. A datalogger records the sensor readings in each environment for 5 days, and calibration coefficients are generated via linear regression. After the sensors are deployed in the field, their individual coefficients are updated if the soil creates drier or wetter situations than observed in the laboratory.
b. Site passes and field intercomparison

During each of three, scheduled annual maintenance passes, Oklahoma Mesonet technicians perform standardized tasks, including cleaning and inspecting sensors, verifying depth of subsurface sensors, cutting and removing vegetation, taking photographs, and conducting on-site sensor calibrations (Fiebrich et al. 2006). In addition, technicians may upgrade equipment, rotate sensors, and perform communications testing and maintenance. The technician opens the datalogger enclosure door upon arrival and closes it on departure, signaling the automated QA system to mark all data as erroneous (Shafer et al. 2000). Digital photographs (available online at http://www.mesonet.org/sitepass) are taken of the 100-m² site; net radiometer footprint; vegetation height (both upon arrival and departure); and plots where soil temperature, soil moisture, and soil heat flux are measured.

In 1999, Oklahoma Mesonet management required that vegetation height be cut to match the height of surrounding vegetation, to a maximum height of 45 cm. To protect equipment from wildfire, the technician also cuts a firebreak (maximum height of 5 cm) in a swath that extends from the tower base to the rain gauge (Fig. 5).

To examine sensor accuracy in the field, an instrumentation meteorologist designed and manufactured a portable system to compare field observations of air temperature, relative humidity, solar radiation, and barometric pressure to calibrated reference sensors (Table 4; Fiebrich et al. 2006). This portable system aspirates both the reference and station air temperature and relative humidity sensors. A personal data assistant interfaces with the system to collect comparison observations, to display data for on-site evaluation by the technician, and to generate a detailed report for analysis by QA meteorologists.

c. Automated QA software

The automated QA software of the Oklahoma Mesonet is designed to detect significant errors in the real-time data stream and to incorporate manual QA flags that capture subtle errors in the archived dataset. Observations are never altered; each datum is flagged as “good,” “suspect,” “warning,” or “failure.” Automated flags are set using a three-step process: 1) QA filter, 2) QA independent algorithms, and 3) QA decision maker. The QA filter immediately flags data coincident with a technician visit, those failing the variable’s range test, and those known to be bad (as determined by a QA meteorologist). The QA independent algorithms differ according to the variable observed, but include step, persistence, and spatial tests. In addition, like-instrument and variable-specific tests are applied when appropriate. The QA decision maker compiles the results of the independent tests and uses logic to determine the final automated QA flag assigned to the observation. Only good and suspect data are delivered in real time to users.

Written in C++, the automated QA software uses a single program for real-time, daily, and historical use through XML-based configuration files. For real-time data, up to eight QA tests are run per observation, operating on the past 6 h of data. Once per day, up to 13 QA tests are run on each variable, operating on the past 30 days of data. As a result, more than 111 million calculations are completed daily. Currently, real-time QA completes within approximately 1 min.

d. Manual QA

Human intervention can override any automated QA flag. The QA meteorologist determines whether automated flags mark real events (e.g., heatburst, gust front; Fiebrich and Crawford 2001) by analyzing the results of a Web-based, daily QA report. The report lists stations with suspected data problems, what variable the automated QA software has flagged, and the number of observations flagged by the individual tests (Martínez et al. 2004; Shafer et al. 2000; Fiebrich and Crawford 2001). The meteorologist can obtain detailed output from the automated tests, a graph of the variable from the site in question and neighboring sites, a graph of both the variable in question and other relevant variables at the station, and a tabular output of the original observations. Should data be deemed erroneous, the start date/time of the problem is analyzed and observa-
tions are flagged manually in the QA database. The QA meteorologist then issues a trouble ticket to the appropriate field technician. All sensor problems are documented with a trouble ticket.

To detect subtle problems in the rainfall dataset, a meteorologist compares a station’s accumulated rainfall to that of nearby sites using double mass analysis (Martinez et al. 2004). To aid in the analysis, the QA meteorologist uses complementary datasets, including soil moisture observations, rain gauge data from the U.S. Geological Survey, NWS surface observations, radar data, and terrain maps. For example, OCS software calculates storm-total rainfall from Oklahoma Mesonet data for the time interval corresponding to the NWS storm-total precipitation product. A resultant map is generated (Fig. 6), and the QA meteorologist compares the values to find any malfunctioning gauges.

Examination of monthly data supplements daily and event-driven manual QA to detect slight biases or drift in sensors. Monthly statistics for each variable (e.g., averages, differences, accumulations) are computed, plotted, and analyzed both spatially and temporally (Martinez et al. 2004). Data from similar instruments at different heights or depths allow the diagnosis of sensor biases, small-amplitude noise in the data, and anemometer starting-threshold problems. After analyses are complete, the meteorologist prepares a monthly QA report that documents any problems as well as repairs and activities performed by field technicians that may have affected data quality during the previous month.

As a result of continual development of automated and manual techniques, the QA process of the Oklahoma Mesonet continues to improve. As improvements are implemented, all data in the period of record are reprocessed through the QA system to obtain the most consistent, highest-quality dataset for climate analysis and scientific research.

6. Applications of data

The Oklahoma Mesonet provides its data and value-added products to citizens, businesses, state agencies, growers, educators, first responders, and other Oklahoma decision makers. High-quality datasets have supported a host of scientific investigations and attracted multidisciplinary research projects to the state. Instructional programs help nonmeteorologists apply Oklahoma Mesonet data and products properly to their daily activities. Specific audiences targeted by these outreach programs include education (both K–12 and collegiate), public safety, and agriculture. These customers, in turn, provide grassroots support via vocal and positive feedback to the state legislature and OSRHE, the sources of network funding. More importantly, local decision makers have used the data to mitigate negative societal impacts from weather events and natural or man-made disasters (e.g., Morris et al. 2002).

a. Outreach programs

From 1992, the Oklahoma Mesonet made educational outreach a priority. The motivation was twofold: 1) to foster multipurpose uses of its data, and 2) to advance political support statewide. Two years prior to network commissioning, OCS launched a K–12 program known as EarthStorm with intensive workshops for teachers (McPherson and Crawford 1996). Materials evolved from hard copy lessons and a dial-up bulletin board system to a comprehensive Web site (see online at http://earthstorm.ocs.ou.edu). Teacher workshops focused on authentic learning modules (Killion 1999), core scientific knowledge, and development of curricula and science fair projects. Between 1993 and 2005, scientists, engineers, and mathematicians judged 885 Oklahoma Mesonet-related projects, representing 1215 K–12 students, in statewide science fairs.

Based upon EarthStorm experiences, OCS began a program for emergency management, fire service, and law enforcement agencies in 1996. Called OK-First, this initiative provides access to real-time weather data via a Web-based decision-support system for multiple hazards (see online at http://okfirst.ocs.ou.edu), a mandatory instructional regimen, and customer support (Morris et al. 2001). Consequently, OK-First participants proactively have evacuated citizens, closed roads and bridges before flooding, notified fire crews of impending wind shifts, provided weather support for local civic and athletic events, and improved responses to natural disasters.

EarthStorm and OK-First pioneered the dissemination of Oklahoma Mesonet products, radar data,

<table>
<thead>
<tr>
<th>Variable measured</th>
<th>Station sensor</th>
<th>Reference sensors (calibrated accuracy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow-response air temperature</td>
<td>Vaisala HMP45C</td>
<td>Rotronics Pt100 RTD (±0.1°C); Thermometrics UIM DC95 (±0.2°C)</td>
</tr>
<tr>
<td>Fast-response air temperature</td>
<td>Thermometrics UIM DC95</td>
<td>Rotronics Pt100 RTD (±0.1°C); Thermometrics UIM DC95 (±0.2°C)</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>Vaisala HMP45C</td>
<td>Rotronics MP 100H (±1% RH); Vaisala HMP35C (±3% RH)</td>
</tr>
<tr>
<td>Barometric pressure</td>
<td>Vaisala PTB202/220</td>
<td>Vaisala PTB220 (±0.1 hPa)</td>
</tr>
<tr>
<td>Solar radiation</td>
<td>LI-COR LI-200</td>
<td>Kipp and Zonen SP LITE (±5%)</td>
</tr>
</tbody>
</table>
and instructional materials to rural users. In 1996, OSU initiated outreach efforts for the agricultural and natural resource communities by creating an AgWeather Web site (see online at http://agweather.mesonet.org). AgWeather implements a variety of weather-based agricultural models and decision-support tools that integrate Oklahoma Mesonet data and value-added products with market summaries from the U.S. Department of Agriculture (USDA), programs and publications of the Oklahoma Cooperative Extension Service, and information from grower associations.

b. Products using real-time data

The Oklahoma Mesonet Web site (see online at http://www.mesonet.org) is the primary conduit for both information about the network and observations from the network. Real-time products range from single- and multiple-variable plots, contour maps, and meteograms for all customers to models and forecasts generated for specific user communities. The suite of static images and interactive displays (Table 5) refresh every 5 min, allowing NWS forecasters and ~180 Oklahoma public safety officials to maintain situational awareness 24 h day$^{-1}$.

A popular product for Oklahoma’s broadcast media is the “Mesonet Top-10” (Fig. 7), a current summary of temperature, precipitation, and solar radiation extremes since midnight local time. The media, public safety, and water resources communities use maps of rainfall accumulation for periods ranging from 1 to 72 h.

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**Fig. 6.** An example of tools used by a meteorologist to ensure the quality of Oklahoma Mesonet data. In this case, a malfunctioning rain gauge at the Tahlequah (TAHL) site was diagnosed by overlaying storm-total precipitation from the Fort Smith, AR, radar (at 1933 UTC 5 Jun 2005) with (top right) Oklahoma Mesonet rainfall observations (in.), (bottom left) radar-estimated rainfall (in.), and (bottom right) the difference between the gauge observations and radar estimates (in.). The TAHL gauge recorded no rain during the event from 2307 UTC 4 Jun 2005 to 1933 UTC 5 Jun 2005. Nearby Oklahoma Mesonet gauges, however, received up to 25 mm (1.0 in. on map) of rain. The quality assurance meteorologist confirmed that the gauge at TAHL had malfunctioned, issued a trouble ticket, and manually flagged the rainfall data as erroneous.
In addition, a decision-support tool compares current rainfall accumulations with corresponding county-by-county values of flash flood guidance from the NWS (Fig. 8). To help officials document significant wind events, the Oklahoma Mesonet produces maps and tables of the current and previous day’s maximum wind gusts. First responders also receive pages automatically when gusts exceed severe criteria (25.7 m s⁻¹).

To serve fire managers, the Oklahoma Mesonet created the Oklahoma Fire Danger Model (Carlson et al. 2002), adapting the National Fire Danger Rating System to incorporate real-time county-scale data. This model generates tables and 1-km-resolution maps of fire danger parameters, including burning index, spread component, ignition component, and the Keetch–Byram Drought Index.

Tools designed to support agricultural operations include a dispersion model; evapotranspiration models (for more than a dozen specific crops); degree-day calculators for Oklahoma crops; and pest-management models for alfalfa weevils, peanut leafspot, pecan scab, watermelon anthracnose, pecan casebearer, and spinach white rust. Pest models feature interactive site-specific spraying recommendation forms (Fig. 9). Initially developed to mitigate odors downstream from livestock operations, the Oklahoma Dispersion Model also has applications for smoke management, pesticide application, and hazardous material spills.

c. Products using archived data

Climatological, agricultural, and hydrological products are generated from archived Oklahoma Mesonet data to assist Oklahoma decision makers. Statewide and county-scale climatologies of temperature, precipitation, and heating/cooling degree-days have applications to energy, agriculture, and water resources management.

Some agricultural tools blend Mesonet archives with daily data. For example, OSU’s Spinach White Rust Model incorporates 10-yr averages of specific variables and compares them graphically to the current year’s values and projected values of white rust infection hours.

Climate-division and county-level precipitation sta-

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**Table 5. Suite of products produced by the Oklahoma Mesonet that update every observation period on its Web site (see online at http://www.mesonet.org).**

<table>
<thead>
<tr>
<th>Meteorological station model plot</th>
<th>Fire-weather station model plot</th>
<th>Heat index or wind chill</th>
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</thead>
<tbody>
<tr>
<td>High and low temperatures*</td>
<td>Wind chill</td>
<td></td>
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<tr>
<td>Max wind gusts*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rainfall accumulations for 1, 3, 6, 12, 24, 48, and 72 h since midnight local time*</td>
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</tr>
<tr>
<td>3- and 24-h change in temperature and dewpoint</td>
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<tr>
<td>3-h pressure change</td>
<td></td>
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</tr>
<tr>
<td>Meteograms (24-h time series of air temperature, dewpoint, wind speed and direction, pressure, rainfall, and solar radiation)</td>
<td></td>
<td></td>
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<tr>
<td>Flash flood guidance product</td>
<td></td>
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<tr>
<td>Dispersion conditions</td>
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<tr>
<td>Inversion conditions</td>
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<tr>
<td>Contour and vector (gridded) plots of standard meteorological variables</td>
<td></td>
<td></td>
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<tr>
<td>Graphs of individual (or grouped) variables for past 6, 12, 24, 36, and 48 h</td>
<td></td>
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<tr>
<td>Graphs of soil moisture for past 7, 15, 30, 60, or 90 days</td>
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<tr>
<td>Maps of average soil temperature for past 1, 3, and 7 days</td>
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<tr>
<td>Maps of fractional water index, moisture category, and matric potential</td>
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* This product includes values for both current and previous days.

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**Fig. 7. Oklahoma Mesonet “top-10” product developed for the broadcast media. The product denotes daily extreme values observed across the network.**
tistics, such as total rainfall, departure from and percent of normal rainfall, driest and wettest periods, and statistical rankings for various time periods (e.g., year, season, water year), help water managers determine current water supplies and demands. Soil moisture observations at four different depths (Fig. 10) are used to derive the fractional water index, representing the relative dryness of the soil (Schneider et al. 2003). These products and other historical data compose the Oklahoma Drought Monitor (see online at http://climate.ocs.ou.edu/drought/), designed for the Oklahoma Water Resources Board and other hydrologic agencies.

d. **Visualization software**

To aid customers in viewing weather information, software engineers of the Oklahoma Mesonet have developed easy-to-use visualization software. The most recent display and analysis tool, called WeatherScope (see online at http://sdg.ocs.ou.edu), is based on C++ and OpenGL and displays weather and geographical information from sources both within and outside Oklahoma (Fig. 11). WeatherScope is a stand-alone, HTTP-based tool that operates on Microsoft Windows 2000/XP and Apple Macintosh OS X. It displays maps and animations as data plots, wind vectors, color contours, or line contours. Radar and other geospatial data can be displayed on the same map with Oklahoma Mesonet observations.

The software downloads quality-assured data to the user’s computer and generates images via a customizable XML file. The XML file contains information about the data (e.g., source, date, and time), geographic overlays, map projection, font type and size, line or symbol size, translucency of the map layer, and refresh rate.

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**Fig. 8.** Comparison product between Oklahoma Mesonet rainfall accumulation and corresponding values of flash flood guidance (FFG) issued by the NWS River Forecast Center. Counties are colored according to the ratio of rainfall accumulation (point value) and FFG (countwide value). For example, counties highlighted in yellow indicate that current rainfall accumulation is 50%–75% of FFG. Maps display 1-, 3-, and 6-h values as well as the “worst case,” incorporating the highest ratio for a given county.
Fig. 9. Example output from the Site-Specific Spraying Recommendation for the Peanut Leafspot model on the Oklahoma Ag-Weather Web site (see online at http://agweather.mesonet.org). In this case, the grower specified a station (Hinton, OK), the planting date (15 May 2005), and the date of the most recent fungicide application (1 Aug 2005).

Fig. 10. An example of a soil moisture product from the Oklahoma Mesonet. The Fractional Water Index is plotted for 5 (red), 25 (orange), 60 (green), and 75 cm (blue) over a 60-day period at the Perkins station.
Because of the quality, quantity, and types of observations collected, the Oklahoma Mesonet has provided scientists with data to study sensor deployment, data quality assurance, mesoscale processes and phenomena, improvements in forecast models, and validation of remote sensing technologies. In addition, the network aids field experiments in Oklahoma through provision of real-time and archived data, collaborations with its research team, dissemination of daily weather forecasts, and community support via appropriate public relations activities.

Studies have used the observations to gain knowledge of physical processes that occur across various spatial and temporal scales. For example, McPherson et al. (2004), McPherson and Stensrud (2005), and Haugland and Crawford (2005) studied the impact of Oklahoma’s winter wheat belt on the overlying atmosphere. Illston et al. (2004) quantified soil moisture...
variability across Oklahoma at a variety of temporal scales, and Brotzge and Richardson (2003) investigated the temporal correlation of atmospheric and soil variables. Basara and Crawford (2002) used Oklahoma Mesonet data to quantify the relationship between soil moisture and atmospheric variables throughout the planetary boundary layer, and Brotzge (2004) studied the differences in the energy and water budgets of sites across Oklahoma. In addition, Illston and Basara (2003) examined the relationship between short-term droughts and soil moisture conditions in Oklahoma.

The unique suite of observations collected by the Oklahoma Mesonet has been applied to develop or enhance new technologies and products. These data have helped validate and improve land surface models used in numerical weather prediction (e.g., Sridhar et al. 2002; Marshall et al. 2003; Robock et al. 2003; Nemunaitis et al. 2004), satellite technologies and products (e.g., Czajkowski et al. 2000; Anderson et al. 2004; Sun et al. 2004), and radar-derived products (e.g., Lu et al. 1996; Pereira Fo. et al. 1998; Young et al. 2000). In addition, studies conducted with Oklahoma Mesonet data have improved fire prediction capabilities (Carlson and Burgan 2003) and the characterization of downwelling longwave radiation (Sridhar and Elliott 2002).

Oklahoma Mesonet data provide a consistent, long-term dataset to enhance field experiments. Limited-term experiments have included the Fall Water Vapor Intensive Observation Period, sponsored by the DOE (Richardson et al. 2000); the Southern Great Plains (SGP) experiments of 1997 and 1999, sponsored by the National Aeronautics and Space Administration (NASA: Jackson et al. 1999); the International H2O Project, sponsored by the NSF (Weckwerth et al. 2004); the Soil Moisture Experiment of 2003, sponsored by NASA (Cosh et al. 2003); and the Joint Urban 2003, sponsored by the Departments of Defense and Homeland Security (Allwine et al. 2004). The entire archive of Oklahoma Mesonet data serves research programs of the DOE and USDA.

7. Future of the Oklahoma Mesonet

The vision of the Oklahoma Mesonet is to pioneer state-of-the-science collection, dissemination, and application of surface weather observations to provide extraordinary dividends for Oklahomans and to be a prototype for future monitoring networks and applications. Because the Oklahoma Mesonet was established as a multipurpose network that focused on research-quality data available in real time, enhancements to its suite of sensors and data services are limited only by personnel time for research and development while maintaining a 24/7 operational environment. Current targets for enhancement to and development of the Oklahoma Mesonet include an upgrade to the network’s wind and pressure sensors, integration with road weather monitoring needs of the Oklahoma Department of Transportation, environmental monitoring within urban areas, and decision-support tools for transportation engineers, economic development agencies, and urban gardeners.

Acknowledgments. This manuscript is dedicated to the Oklahoma Mesonet employees who have devoted countless hours to ensure excellence in network operations and outreach. Oklahoma’s taxpayers fund the Oklahoma Mesonet through the Oklahoma State Regents for Higher Education. Soil moisture observations resulted from funding by NSF and NOAA.

We appreciate the continued support of the OU and OSU administrations in embracing the Oklahoma Mesonet partnership. Dr. Fred Brock, Timothy Hughes, Dr. Scott Richardson, and Christopher Fiebrich have served as managers of the network. Siddrovia Blackburn, John Humphrey, and Ryan Davis designed graphics for this manuscript.

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