Technical Overview of the Kansas Mesonet

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ABSTRACT: The Kansas Mesonet is a multipurpose network consisting of 62 automated environmental monitoring stations (as of 2019) covering the state of Kansas. Each station is equipped with research-grade instrumentation and measures precipitation, air temperature, air relative humidity, barometric pressure, wind speed and direction, solar radiation, soil temperature, and soil moisture. Observations are transferred to dedicated computer servers every 5 min via cellular modems. Data are archived and subjected to periodic quality control tests and are disseminated in near–real time through a dedicated web portal. The observations collected by the Kansas Mesonet are widely used for irrigation water management, crop modeling, pest management, wildland fire management, drought monitoring, wind energy production, environmental research, and animal management. This paper provides a technical overview of the Kansas Mesonet and includes a complete description of the instrumentation, siting criteria, instrument verification procedures, and value-added products.

KEYWORDS: Mesoscale processes; Mesoscale systems; Soil moisture; Soil temperature; Automatic weather stations; In situ atmospheric observations

1. Overview and historical outline

In the 1970s, the collection of meteorological observations for agricultural applications in the United States was dominated by direct human observation of daily minimum and maximum air temperatures and total rainfall. Meteorological observations were largely concentrated at the National Weather Service (NWS) Cooperative Observer Program (COOP) network and airport weather stations following basic guidelines of the World Meteorological Organization (WMO) (Fiebrich 2009). In the late 1970s and early 1980s, with the advent of more affordable and powerful dataloggers and the development of new electronic sensors, there was a considerable expansion of automated weather stations capable of providing subdaily observations, which in turn propelled advancements in crop phenology models (Vanderlip and Arkin 1977; Arkin et al. 1976), irrigation scheduling (Kanemasu et al. 1983; Buller et al. 1991), and insect warning systems (Harvey et al. 1982). Some of the first automated networks in the late 1970s included the Aviation Automated Weather Observing System (AV-AWOS) deployed by the Federal Aviation Administration and the Snowpack Telemetry (SNOTEL) deployed by the Natural Resource Conservation Service (Fiebrich 2009).

Concurrently with the growing demand for high temporal resolution weather data from the scientific community, the consortium of the north-central region of the High Plains Regional Climate Center led the initiative to standardize meteorological records from the growing number of automated stations in the region. The goal of this effort was to standardize measurement frequency, data quality screening, and siting standards as part of an ongoing improved regional monitoring and archival system. Following this initiative, the Kansas Mesonet was established in the Spring of 1984 by the Kansas Agricultural Experiment Station and Cooperative Extension Service (KSRE) under the leadership of D. Bark (Department of Physics) and P. Coyne (Western Kansas Agricultural Research Center in Hays, Kansas). The KSRE program is supported by county, state, federal, and private funds and is designed to generate and distribute useful knowledge for the well-being of Kansas citizens. The first station was deployed during the spring of 1984 on a grass area at the Kansas State University North Agronomy Farm in Manhattan, Kansas. By 1986, the network reached a total of 13 weather stations representing the different climatic zones of Kansas.

Historically, the evolution of the Kansas Mesonet can be divided into three phases. The first phase spans the period from 1986 to 2007, during which the network was simply known as the Weather Data Library and consisted of the 13 original automated weather stations. These 13 stations were all located at Kansas State University research stations and were typically collocated with stations of the NWS COOP network. Part of the initial goal of the network was to provide scientists with high-quality weather information near experimental research sites and to compare automated and nonautomated records to assess whether these two transitioning data collection systems were compatible. The first automated stations consisted of 2-m tripods and monitored air temperature, precipitation, solar radiation, wind speed and direction, and soil temperature at

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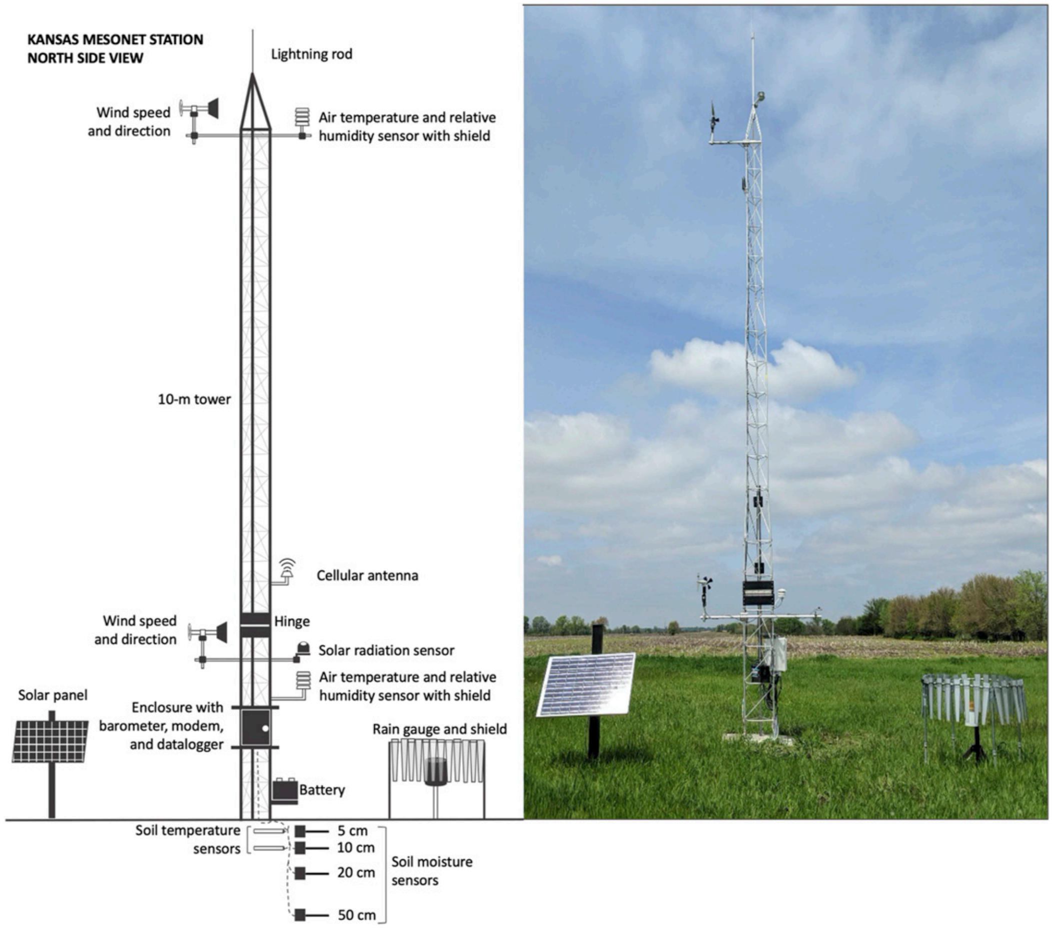

FIG. 1. (left) Schematic north side view of a 10-m tower station of the Kansas Mesonet and (right) equivalent image for the Ottawa 2SE station located at the Kansas State University East Central Research Experiment Station. The air temperature sensor in the sketch was placed slightly below 2-m depth for clarity. The drawing is not to scale.

5 and 10 cm under bare soil. Because of the limited cellular technology and the lack of a unified radio frequency across Kansas, the location of the stations was highly dependent on the presence of power and telephone lines to transmit weather data. During this phase, variables were sampled every 60 s, statistical parameters (e.g., average temperature, total daily rainfall) were computed at hourly and daily intervals, and data were retrieved from the stations only once a day. As of 2020, 11 of the initial 13 stations still remain operational.

The second phase of the Kansas Mesonet 2018 spans the period from 2007 to 2013, during which 13 new stations were added to the network and an additional 10 stations were acquired from the Kansas Water Office that were initially deployed to support irrigation and evapotranspiration research. During this phase, a new advisory board was formed with representative members of the Weather Data Library, the Kansas Water Office, and the Kansas Water Resources Research Institute. The network also adopted new siting protocols favoring the deployment of future stations over grass-covered areas and implemented similar standards as the Soil Climate Analysis Network (Schaefer et al. 2007) for soil temperature and soil moisture observations. As part of the ongoing expansion, detailed characterization of the soil profile of the new 13 stations was made by NRCS personnel and a new online platform was created for data dissemination (http://mesonet.k-state.edu).

The third phase of the network spans the period from 2013 to the present time. During this period the network underwent major organizational and infrastructure upgrades to meet the highest standards of scientific research and make observations comparable to surrounding networks such as the Oklahoma Mesonet (McPherson et al. 2007) and the Nebraska Mesonet (Shulski et al. 2018). A technical committee that includes weather and climate specialists, irrigation engineers, micrometeorologists, and soil scientists was created to provide technical guidance to the Kansas Mesonet personnel on instrumentation, site selection, sensor deployment protocols, and sensor maintenance and calibration. In relation to infrastructure, the 2-m tripods started to be replaced with 10-m high towers (Fig. 1) fixed into a concrete foundation to

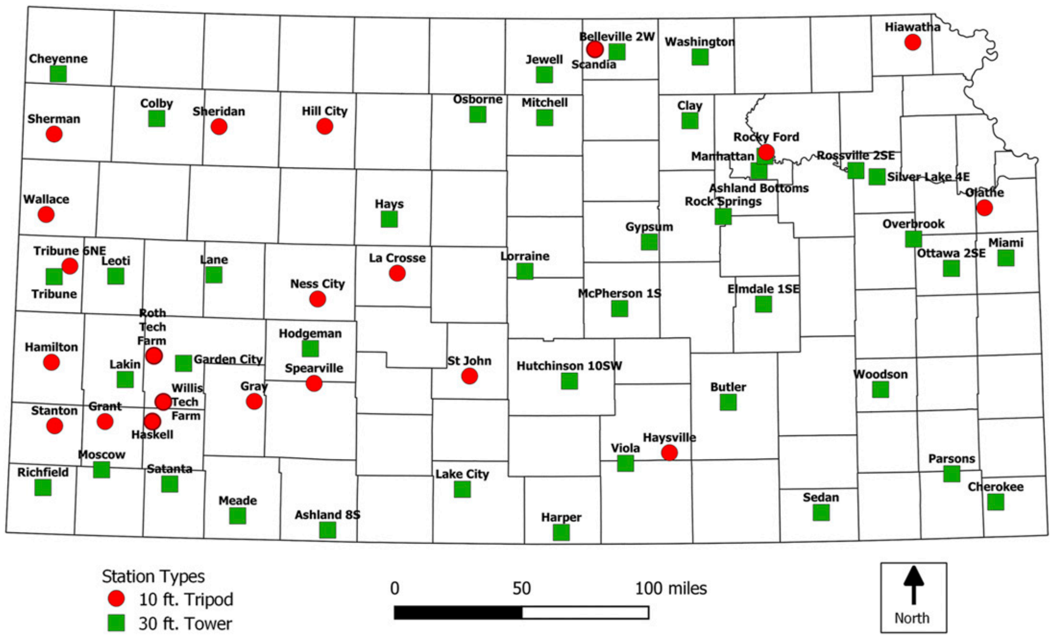

FIG. 2. Spatial configuration of the 62 stations composing the Kansas Mesonet as of October 2019.

increase long-term resistance to the elements. The 10-m towers are equipped with the same instruments as the 2-m tripods but also incorporate wind, air temperature, and relative humidity sensors at 10-m height and soil moisture and soil temperature sensors at 5, 10, 20, and 50 cm. During this phase the network was realigned as a mesoscale environmental monitoring network to better represent the growing number of observations and applications and adopted the name of Kansas Mesonet. Currently, the network consists of 62 stations (Fig. 2), 40 of them being 10-m towers and 22 remaining as 2-m tripods. Operational funds for the Kansas Mesonet are provided by Kansas State University, Kansas Research and Extension, and The National Mesonet Program. Additional financial assistance is provided through private donors, county commissions, energy industry, and stakeholder-based commodity commissions. The Kansas Mesonet Headquarters is located within the Kansas State University Department of Agronomy in Manhattan, Kansas.

This technical overview is aimed at providing end users with a detailed description of the instruments and methods used by the Kansas Mesonet and also complementing the growing documentation about research-grade mesoscale networks.

2. Network configuration and station siting

a. *Network spatial configuration*

The initial spatial configuration of the network was determined by the location of the Kansas State University Experimental Research Stations. However, the sparse and uneven distribution of stations resulted in large unmonitored areas across the state. To improve the spatial representativeness of the network, the technical committee devised a simple method to locate future stations based on the geometric arrangement of the existing stations. The current station siting method is based on a computational geometry technique that consists of identifying the largest unmonitored circle area in the network (Patrignani et al. 2020). The centroid of the largest unmonitored circle is considered as the tentative location for the next station, but the definitive location of a new station is determined by land availability and by following a multicriteria siting protocol. The devised geometric approach is simple and can be implemented recursively by the Kansas Mesonet management team to better plan the deployment of future stations. The geometric approach is unique in that the location of new monitoring stations can be assessed by coupling unmonitored network areas with georeferenced datasets of natural hazards such as droughts, wildfires, and severe thunderstorms to improve the network's ability to detect potentially hazardous events and improve public safety. For instance, using the geometric method, the technical committee identified that the largest unmonitored area of the Kansas Mesonet in 2018 was on the Flint Hills, which is a region characterized by frequent wildland and prescribed fires. This region is also characterized by silty clay loam soils that were underrepresented across the network. As a consequence, in 2018 a new station was deployed in Chase county near Elmdale, Kansas (i.e., Elmdale 1SE) to provide timely information to fire managers and increase network representativeness in silty clay loam soils (Fig. 5 and Fig. 9 in Patrignani et al. 2020).

b. *Station siting requirements*

After the tentative location for a new station is identified, the Kansas Mesonet management team searches for interested cooperators near that point. Most stations of the Kansas Mesonet are placed on private land following a signed agreement between the Kansas Mesonet and the landowner. In 2016,

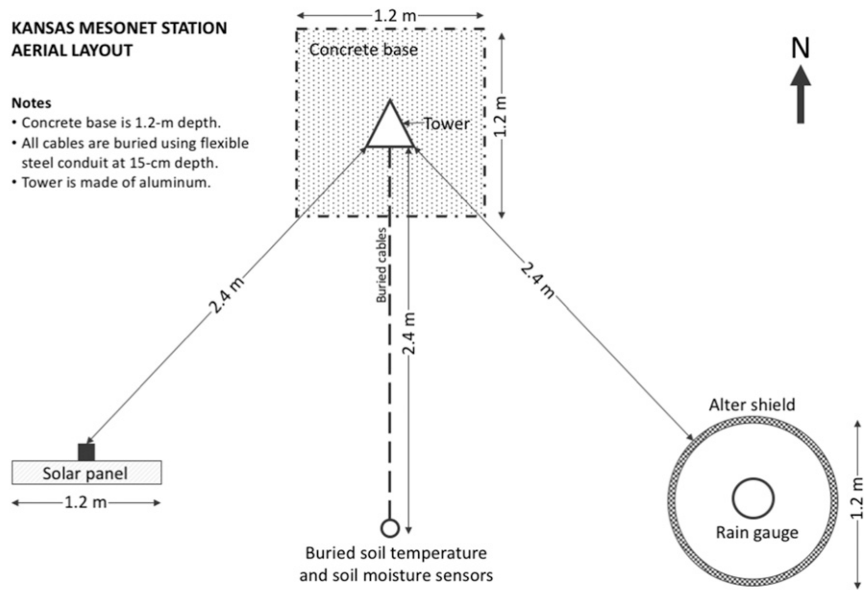

FIG. 3. Aerial layout for a 10-m station. The drawing is not to scale.

the technical committee developed a set of criteria for site selection and station deployment to increase network consistency based on the guidelines from the WMO and existing U.S. mesoscale networks (WMO 2011; McPherson et al. 2007; Schroeder et al. 2005; Shafer et al. 1993). In practice, finding an ideal site can sometimes be difficult, in which case the management team follows the guidance of the Kansas Mesonet technical committee to select the site with the fewest number of limitations. For instance, the station located in Rock Springs, Kansas, is located on shallow rocky soils that do not allow for the deployment of soil moisture sensors, yet the station was deployed to capture local weather and climate patterns that are important for end users in that region. The specifications of the current siting protocol are

- there must be long-term permanence and exposure at the selected site (>30 years) to minimize the probability of station relocation and capture long-term climate trends,
- the station must keep a distance of 10 times the height of the nearest obstruction (e.g., trees, buildings, and tall crops) to ensure optimal wind and solar radiation exposure,
- a minimum distance of 100 m away from nearest irrigated field must be maintained to minimize the localized effect of irrigated agriculture (we acknowledge that this distance may not completely eliminate the effect of nearby aspersion irrigation systems; our choice was largely dictated by two factors: (i) extensive portions of southwestern Kansas are under irrigation and (ii) a major drive for this network was the computation of reference evapotranspiration for irrigation management),
- there must be ability to fence an area of 100 m^2 to delimit the station and restrict access of animals and unauthorized people,
- the selected location should have actively growing natural vegetation,
- the site should have leveled terrain (less than 3% slope) and well-drained soils that are not prone to standing water,
- there must be availability of cellular service for data telemetry, and
- there must be year-round site access under all weather conditions using a motor vehicle.

Site specifications that are not met by a specific station are documented and added to the station metadata. End-users can always access archived pictures facing the stations from each cardinal direction through the Kansas Mesonet website.

c. *Station layout*

All weather stations use research-grade instruments which are installed following the WMO recommended guidelines within a station footprint of about 100 m^2. The typical aerial layout (Fig. 3) consists of a 10-m aluminum tower set into a concrete base with the soil temperature and moisture sensors located 2.4 m south of the concrete base. The distance of the soil sensors is dictated by cable length and by the size of the fenced area around the station. This distance of 2.4 m provides a small buffer zone that prevents any potential water runoff from the tower and concrete base to interfere with the soil moisture sensors. Soil sensors are installed to the south of the tower to minimize the effect of shadows from the tower itself on soil temperature observations. The rain gauge is located approximately 2.4 m southeast from the tower. Most stations are powered by a solar panel located 2.4 m to the southwest of the station. Tripods are staked into the ground and only have slight variations compared to the tower layout. To facilitate transport, installation, and instrument maintenance, the 10-m aluminum tower has a hinge at a about 2-m height that allows a single operator to safely lower the upper portion of the tower to a horizontal position for installation and routine maintenance of sensors at 10-m height (a photograph of the tower in the horizontal position is provided in the online supplemental material).

3. Sensors and equipment

a. Communication and power

The remote access to most weather stations is performed via wireless cellular data modems (RV50, Sierra Wireless, Carlsbad, California) installed at each weather station. Historically, the network used 2G and 3G cellular networks. However, due to the anticipated end of the 2G network, the Kansas Mesonet is currently in the process of upgrading these modems to utilize the 4G network running on a virtual private network (VPN) to prevent hacking activity. Several stations utilize wireless Internet where reliable infrastructure exists from cooperators. Most stations are powered by a solar panel ranging from 50 to 100 W that charges a 12-V 100-A-h deep-cycle marine battery capable of powering the station through the winter months. A few stations (e.g., Parsons; Fig. 2) in the proximity of existing power infrastructure are powered using alternating current with battery backup.

b. Data acquisition

All stations of the Kansas Mesonet are equipped with electronic dataloggers (CR1000; Campbell Scientific) that scan the electronic sensors and control peripheral devices. The datalogger scans all sensors at 5-s intervals and generates 1-min, 5-min, hourly, and daily data tables. The datalogger also performs real-time calculations, stores data for later retrieval, and controls practical built-in tools such as a status flag that monitors the opening and closing of the electronics enclosure door and allows for setting rain gauge test flags. All of the electronic components are housed in a 43.8-cm width × 38.7-cm length × 25.2-cm depth durable weather-resistant (i.e., NEMA 4X) enclosure made of fiberglass-reinforced polyester mounted to the tripod or tower.

c. Precipitation

Liquid precipitation is measured with a tipping-bucket rain gauge (TE525MM; Texas Electronics, Inc.) (Table 1). Two pluviometers are deployed at a WMO-recommended height of 0.76 m to the top edge of the funnel orifice and surrounded by an Alter-type single-ring wind screen (both pluviometers within the same shield, towers only) (Model 260–952; Novalynx Corp.), which consists of vertically oriented metallic galvanized planks with a radius of about 1 m around the rain gauge. Several stations have been equipped with heated siphon tipping-bucket rain gauges (TB3; Hydrological Services America) to enable year-round measurement of precipitation events. However, most snow events in the region are accompanied by gusty winds which, despite the Alter shield, often disperse snow and prevent accumulation atop the gauge to trigger an embedded proximity sensor. As a consequence, the management team determined that snowfall liquid equivalent was not being accurately reflected with these rain gauges and new preliminary tests are being performed to investigate the feasibility of using weighing rain gauges to measure precipitation.

The laboratory calibration of the tipping-bucket rain gauges is performed following the manufacturer's manual. Briefly, the laboratory calibration consists of using a container holding 473 ml with a small orifice at the bottom, so that all of the water in the container is discharged on the rain gauge in no less than 45 min. The number of tips is recorded and compared with the tolerance of 100 tips ± 3 tips recommend by the manufacturer, and any potential offsets are recorded and corrected using the adjustments screws at the bottom of the rain gauge. We also devised an alternative and practical method for checking the accuracy of pluviometers during maintenance site visits. The field test consists of slowly discharging over the pluviometers a known amount of water contained in a syringe and then comparing the recorded rainfall with the applied amount of water. This test is less accurate than the laboratory calibration but allows personnel of the Kansas Mesonet to diagnose malfunctioning pluviometers during maintenance visits. Error sources of the syringe method are associated with error counting tips by the operator, since field conditions are often noisier than laboratory conditions, and are also due to the less consistent rate of water application as compared with the slowly dripping container used for laboratory calibration. Nonetheless, trained personnel can diagnose major calibration errors in field rain gauges using this procedure. Counting errors under field conditions could be circumvented by connecting a portable computer to the serial port of the datalogger and then plotting the pluviometer signal during the syringe test using the Loggernet software (Campbell Scientific), but field conditions and the distance between the datalogger and the pluviometer sometimes make this alternative a less practical option. Prior to the pluviometer field test, a data quality flag is set by the technician to prevent the recording of an incorrect precipitation event into the Kansas Mesonet database.

d. Air temperature and relative humidity

The primary air temperature and relative humidity sensor (Vaisala HMP60; Vaisala Ltd.) (Table 1) consists of a platinum resistance thermometer and a replaceable capacitive thin-film polymer humidity sensor. The sensors are installed following the guidelines of the WMO at a height of 2 m across all stations. Stations equipped with 10-m towers also have a sensor at a height of 10 m above the ground. The air temperature and relative humidity sensor is housed in a five-plate naturally aspirated radiation shield (41303-5A; R. M. Young Company). Air temperature and relative humidity are sampled at 5-s intervals, and observations are used to calculate average, minimum, and maximum air temperature and relative humidity over 1-min, 5-min, hourly, and daily intervals.

Air temperature verification checks are performed in laboratory conditions inside a temperature-controlled chamber to test the accuracy of HMP60 sensors (Fig. 4a). Up to three HMP60 sensors (accuracy ±0.6°C) can be verified simultaneously against two factory-calibrated HMP155 sensors (accuracy ±0.2°C) that are used as reference sensors. A datalogger (CR3000; Campbell Scientific) is used to store the temperature data of each sensor. The sensor evaluation is performed at three reference air temperatures of 4.4°, 15.5°, and 32.2°C. These reference air temperatures are determined based on

TABLE 1. Variables measured and sensors installed across the Kansas Mesonet.

Variable	Height/depth	Highest processing frequency	Manufacturer	Model	Range	Accuracy
Above ground						
Precipitation	0.76 m	Each tip	Texas Electronics	TE525MM	—	±1% at rates up to 25.4 mm h^{-1}
Air temperature	2.0 m	1 min	Vaisala	HMP60	From −80° to +60°C	±0.6°C
Pressure	1.5 m	1 min	Vaisala	PTB110	500–1100 hPa	±0.3 hPa (+20°C); ±1.5 hPa (from −40° to +60°C)
Relative humidity	2.0 m	1 min	Vaisala	HMP60	0% to 100%	±3% RH (0%–90% RH at 0°–40°C); ±5% RH (90%–100% RH at 0°–40°C)
Wind vector	2.0 and 10.0 m	1 min	R. M. Young	05103	Wind direction: 0°–360°; wind speed: 0–100 m s^{-1}	Wind direction: ±3°; wind speed: ±0.3 m s^{-1} or 1% of reading
Solar radiation	2.0 m	1 min	Apogee	CS300	0–2000 W m^{-2}	±5% for daily total radiation
Below ground						
Soil temperature[a]	5 and 10 cm	5 min	Custom/Campbell Scientific	CS107	From −40° to +125°C	±0.2°C (0°–+70°C)
Soil temperature	5, 10, 20, and 50 cm	5 min	Campbell Scientific	CS655	From −50° to +70°C	±0.5°C (from −50° to +70°C)
Soil bulk electrical conductivity (EC)	5, 10, 20, and 50 cm	5 min	Campbell Scientific	CS655	0–8 dS m^{-1}	±(5% of reading + 0.05 dS m^{-1})
Soil moisture	5, 10, 20, and 50 cm	5 min	Campbell Scientific	CS655	0%–100%	±1% using custom calibration, where solution EC < 3 dS m^{-1}

[a] Thermistor (Model 100 K6A1IA from BetaTherm) of custom-made soil temperature sensor. The thermistor is housed in a copper tube filled with an epoxy resin. Range and accuracy are the same as the CS107.

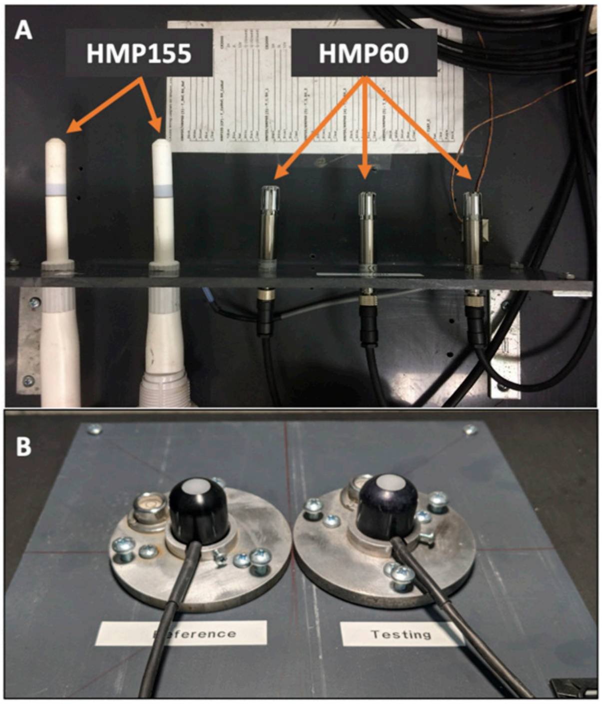

FIG. 4. (a) Verification of air temperature sensors from the field (Vaisala HMP60) against reference sensors (Vaisala HMP155) in a temperature-controlled chamber, and (b) pyranometer (Apogee CS300) verification against a reference sensor under a reference light source.

the average readings of the two reference HMP155 sensors inside the chamber. Temperature readings from the HMP60 and HMP155 sensors are recorded in the CR3000 datalogger during the test for later visual inspection by a trained operator. During the verification test, sensors must be able to maintain temperature values within 0.8°C of each reference value for at least 1 h. The threshold of 0.8°C represents the sum of the accuracies of the HMP155 sensor (Table 1) and the HMP60 sensor. If a sensor measurement deviates from one of the set temperature points it is replaced by a new sensor (chip for temperature is not available for HMP60 sensors). The temperature verification test is performed on both newly purchased sensors and field sensors that are swapped by new sensors every two years as part of routine station maintenance visits.

Relative humidity sensor verification checks are performed by inserting the sensor into custom-made polyvinyl chloride (PVC) closed chambers containing saturated aqueous saline solutions of magnesium chloride, sodium chloride, and potassium sulfate at room temperature to establish reference air relative humidity values of 33%, 75%, and 97%, respectively (Wexler and Hasegawa 1954; Greenspan 1977). Sensor humidity readings must be within 2% of the reference value; otherwise, either sensors are decommissioned or the sensing chip is replaced.

e. Solar radiation

Shortwave (i.e., solar) incoming radiation is measured using a silicon pyranometer (Apogee CS300; Apogee Instruments, Inc.) (Table 1) mounted on a leveled plate (CM225; Campbell Scientific) at 2-m height. The mounting plate is placed at about 0.3 m from the tower using a horizontal cross arm oriented to the south of the tower. Similar to temperature and relative humidity sensors, new pyranometers are tested before field deployment. The sensor verification test consists of comparing the sensor alongside a previously certified and calibrated sensor under a consistent, halogen light bulb (Fig. 4b). Any pyranometer with a discrepancy exceeding 50 W m^{-2} or exceeding 2% of the accumulated radiation will either be returned to the manufacturer or decommissioned. Deployed pyranometers are on a 2-yr rotation cycle.

f. Wind speed and direction

Wind speed is measured by a four-blade helicoid-shape propeller anemometer (R. M. Young 05103; R. M. Young Company) (Table 1) mounted to the tower by a 1.2-m aluminum cross arm. Wind direction is measured by a wind vane attached to the body of the anemometer. Wind speed and direction sensors are deployed at 2-m height and at least 0.6 m away from the mast on all stations. The 10-m-tower stations are also equipped with anemometers at 10-m height, which is comparable to observations made by the Automated Surface Observing Systems (ASOS) network and WMO standards. Observations of horizontal wind speed and direction are collected at 5-s intervals and averaged at 1-min, 5-min, hourly, and daily intervals using the *WindVector* instruction (output option: mean horizontal wind speed, unit vector mean wind direction, and standard deviation of wind direction) in CRBasic to account for the discontinuous scale (i.e., 0°–360°) of wind direction at 360°. Wind gust data are represented as the maximum 5-s wind sample recorded at either 1- or 5-min intervals.

Calibration of wind speed is done via an anemometer drive (Model 18802; R. M. Young) that rotates the anemometer shaft at a known number of revolutions per minute. The anemometer wind direction readings are verified with a vane angle bench stand (Model 18112; R. M. Young) that provides a reference direction. During maintenance visits, sensor bearings are tested in the field using a propeller torque disc (Model 18310; R. M. Young). Because of the wear, the metal bearings of the anemometers are rotated every 2 years or at shorter intervals if excessive noise is detected during maintenance visits.

g. Barometric pressure

All stations are equipped with a barometric pressure sensor (PTB110; Vaisala) (Table 1) that utilizes a silicon capacitive sensor (BAROCAP; Vaisala) and is located within the fiberglass enclosure. The barometer is sampled every 5 s and is corrected to represent sea level pressure. Both measured pressure and temperature-corrected sea level pressure averages are produced at 1-min, 5-min, hourly, and daily intervals.

h. Soil temperature

The soil temperature is measured using temperature probes (CS107; Campbell Scientific and a custom-made probe) buried at 5- and 10-cm depth under soil with natural vegetation. Soil temperature sensors are located to the south of the station, just to the east of the soil moisture sensors. The custom-made sensor has been replacing the CS107 sensor to reduce cost. The custom-made sensor consists of a thermistor (BetaTherm 100 K6A1IA purchased from Newark Co.) housed into a copper tube filled with epoxy resin (RBC #4300; RBC Industries, Inc.). Intercomparison tests conducted by the Kansas Mesonet management team indicate that both sensors have similar temperature responses and accuracy. During production of the custom-made soil temperature sensors, each sensor is tested twice to evaluate electrical circuitry and accuracy. Soil temperature sensors are tested in laboratory conditions using a controlled-temperature chamber with the same three reference temperatures employed for testing air temperature sensors.

i. *Soil moisture*

Soil moisture is measured at 5-, 10-, 20-, and 50-cm depths under naturally growing vegetation using soil water reflectometers (CS655; Campbell Scientific) (Table 1). The vertical layout of the soil profile follows the same layout adopted by the Soil Climate Analysis Network, with the only difference that the Kansas Mesonet does not monitor soil moisture at 100-cm depth. It is important to highlight that from 2007 to 2013 only 13 stations of the Kansas Mesonet were equipped with soil moisture sensors (Stevens HydraProbes; Stevens Water Monitoring Systems Inc.). The Stevens probes initially deployed across the network had rigid coaxial cables that made the installation process and backfilling of the trench difficult and prone to sensor movement. Although these sensors have been deprecated across the Kansas Mesonet, observations (i.e., soil temperature, electrical conductivity, and volumetric water content) from these sensors have been preserved in the database.

In 2016 we opted for the CS655 soil water reflectometer, which did not present the same issues with the coaxial cable as the Stevens probes, and the sensors were sold by the same vendor from which we acquire the rest of the instruments. The CS655 sensor consists of two 12-cm stainless steel rods that serve as waveguides for an electromagnetic signal and an epoxy sensor head that houses the electronics. The sensor head also contains an embedded thermistor in contact with one of the rods that provides soil temperature measurements. All output variables from the sensor are sampled every 10 s and are averaged at 5-min, hourly, and daily intervals. All raw variables reported by the sensor are saved including voltage ratio, relative permittivity, temperature, period average, electrical conductivity, and volumetric water content.

To ensure proper sensor readings, sensor rods are fully inserted into two containers located in the laboratory at room temperature with known values of relative permittivity: one filled with fine dry sand (particles < 1 mm; relative permittivity of 2.02 ± 0.05 at 25°C) and a second container filled with deionized water (relative permittivity of 78.3° at 25°C) (Malmberg and Maryott 1956). Sensors that have been previously deployed in the field and that exhibit a discrepancy larger than $\pm$ 3% of reading + 1 units of relative permittivity against the reference media are decommissioned. New soil moisture sensors that exceed this tolerance are sent back to the manufacturer for a replacement.

A new field protocol was developed in 2016 to consistently install the soil water reflectometers across the network. First, a patch with uniform vegetation and free of pronounced depressions and compaction is selected about 2.4 m to the south of the tower based on visual inspection of the area. This is just a tentative distance; occasionally small adjustments need to be made to select the best possible location. Then, a trench is manually excavated ensuring that the sod covering the ground is kept as intact as possible to facilitate regrowth after covering the soil back (Fig. 5a). During the excavation process the soil from visually distinct soil layers is kept separated on a tarp (Fig. 5b). The resulting trench opening is oval shaped, with its longest cross-sectional axis measuring about 45 cm and a depth of about 70 cm. This size allows the operator to properly install the sensors in the exposed and undisturbed trench wall that is farthest from the tower to avoid back looping the cable inside the trench. Sensors are installed at depths of 5, 10, 20, and 50 cm from a reference board at the soil surface (Fig. 5c). All installed sensors are tested to ensure proper functioning before filling back the trench. Sensor cables are looped down to the bottom of the trench to minimize preferential water flow around the cables and then the operators tightly pack the soil back into the trench following the soil layers on the tarp. Special care is taken to pack the soil around the sensor heads to prevent air gaps (Fig. 5d). The last step consists of placing back the intact patches of sod and pressing to ensure good and firm contact with the underlying soil.

4. Station scheduled maintenance

The Kansas Mesonet adopted a rolling site visit scheduling timetable in which stations that have gone the longest interval without maintenance are prioritized when scheduling future visits. This scheduling system is a departure from earlier network approaches in which technicians visited each station two times each year on a fixed schedule. The new system accounts for any emergency maintenance that has occurred through the year but sets a maximum allowable time of 6 months between maintenance visits. Emergency maintenance consists of station visits to repair core station functionality. Examples of emergency maintenance include malfunctioning or nonreporting instruments, damage by lightning strikes or wildfires, and station damage due to hail storms and strong winds. Oftentimes, general maintenance tasks are also accomplished during emergency maintenance visits, but the duration and number of tasks during emergency visits is conditioned to weather conditions, road access conditions, and the number of stations requiring emergency maintenance. In any case, activities at the station are recorded and added to the station metadata. The new system usually allows up to one extra visit per year. For instance, during 2018 alone there were a total of 221 station visits across the entire network.

Prior to each visit, the technician prints out a visit sheet specific for each station and a general maintenance overview sheet. The site-specific sheet reflects all the current metadata and is utilized to make remarks in the field. Although at times more labor intensive than digital sheets, a paper trail has been

FIG. 5. Field installation of soil moisture sensors. The four steps of the installation process of the CS655 sensors were (a) area selection and careful excavation of top soil with intact vegetation cover, (b) excavation of a small trench maintaining soil layers separately, (c) installation of sensors at accurately measured depths from a reference at the ground level, and (d) tightly repacking the soil following the order of the excavated layers.

essential in preventing data loss due to software or human errors. Photographs obtained during maintenance visits are uploaded with the paper trail. During site visits all accessible sensors, datalogger, communication devices, and power supply systems are inspected by the technician to ensure they are functioning according to Kansas Mesonet operation standards. Upon arrival to the station, the first step is to restrain the door of the enclosure open. A door control flag in the enclosure is triggered and the recorded data during the time of maintenance is flagged. The technician first inspects and tests tipping-bucket rain gauges and searches for insect nesting or spider webs, which are some of the most common issues preventing the proper function of rain gauges in this region. Each anemometer is carefully inspected for audible sound and any other malfunctioning. The solar radiation sensor is cleaned with a moist cloth and leveled if necessary. The temperature radiation shield is cleaned and inspected for insect nesting, and then the sensor is removed from the shield for visual inspection. Excessive buildup of dust, algae growth, or other particulates can alter air temperature and relative humidity values. Faulty sensors are replaced with functioning sensors, and at the end of the visit the enclosure door is closed upon departure and data are no longer flagged. Faulty sensors are tested in the laboratory and then either returned to the manufacturer for repair and recalibration or decommissioned.

The technician also checks the overall site conditions. The vegetation surrounding the station is mowed to approximately 10-cm height as necessary to standardize the vegetation cover and maintain a vegetation height approximately between 10 and 30 cm year-round, which is critical for consistent soil temperatures across the network. A short vegetation cover also prevents interference with station instruments, minimizing the intrusion of insects, spiders, debris, and other nuisances into the equipment. However, during periods of active vegetation growth (e.g., late spring and summer), the vegetation height can exceed the established upper limit of 30 cm. Taller vegetation may introduce minor biases in soil temperature and soil moisture measurements because of canopy interception of solar radiation and rainfall. Other maintenance procedures consist of filling holes created by animals, eradicating noxious weeds, and inspecting the soil condition (e.g., depressions, puddles, and cracks) in the proximity of the soil temperature and soil moisture sensors. In case of frequent soil disturbance by rodents, a thin green mesh is placed over the area of the soil sensors to prevent soil disturbance. This mesh blends with the vegetation and does not interfere with observations. The last step of the station visit consists of taking a set of four pictures from each cardinal direction of the station and its surroundings and one image of the land cover on top of the soil temperature and soil moisture sensors.

5. Quality control processes

Observations recorded by the Kansas Mesonet are under constant scrutiny by trained operators (climatologists, meteorologists, and soil scientists). A series of automatic and manual verification checks are used to ensure that observations are error-free for public use. All observations are stored in a database to preserve the raw data, but entries can be flagged or changed in a separate database before public release. Each database is backed up several times on cloud servers to ensure preservation of historical data. Quality control and assurance is performed using historical data, redundant sensors, data from nearby stations, other in situ networks, and radar- and satellite-derived gridded products.

a. Automated quality control

Raw observations are recorded by the datalogger and transferred every 3 min to a computer server. The first step of the automatic quality control takes place on the server and consists of verifying that observations fall within a physically plausible range. For instance, air temperature values that fall below the historical state record minimum (−40°C at Lebanon, Kansas, on 13 February 1905) or above the historical state record maximum (49.4°C, measured at multiple locations in July 1936) air temperature values are automatically flagged. Similarly, negative precipitation values, negative solar radiation values, relative humidity values that exceed the range 0%–100%, or wind gusts that exceed a value of 144 km h^{-1} are automatically flagged. Additional automated quality control tests include checking for daily changes in air temperature greater than 20°C for any given station (beyond the expected diurnal swing for the region) and flagging air temperature and relative humidity values between sensors at 2- and 10-m height that show a discrepancy of more than 15°C and 30% relative humidity for the same timestamp.

Any observation that exhibit values beyond the set range are assigned an ''error'' flag and are not automatically made available to the public in the database. Flagged observations require manual inspection and the interpretation of a trained operator to determine the veracity of the observation before sending the observation to the public database.

b. Manual quality control

Manual data quality control and assurance consists of visual inspection of both flagged and nonflagged raw observations by a trained operator (i.e., dedicated permanent staff member) using a combination of internal graphical and tabular tools, external in situ networks, and radar- and satellite-derived gridded products to flag observations. Maps, time series, and tables available through the Kansas Mesonet main website constitute the first layer of inspection. Trained operators visually compare observations among neighboring stations of the Kansas Mesonet and examine recent temporal and spatial changes of related variables. For instance, to analyze the potential malfunctioning of an air temperature sensor, the operator also inspects the time series of solar radiation, battery voltage, and additional air temperature sensors at the same station to determine whether a plausible or suspicious observation was caused by real weather fluctuations (e.g., approaching cold front or heat burst) or is an artifact of a potentially malfunctioning sensor. Similarly, when an operator inspects for a potentially missing rainfall event, the operator first examines the rainfall amount of neighboring stations and overlays the time series of the soil moisture sensors at 5- and 10-cm depth for the same station to inspect whether there was a detectable change in soil water storage indicative of a rainfall event. If the evidence obtained from the Kansas Mesonet is not compelling, the operator also considers additional available products, such as rainfall observations from citizen-driven networks [e.g., the Community Collaborative Rain, Hail and Snow Network (CoCoRaHS)], other in situ networks such as the FAA AWOS/ASOS sites, NWS COOP, gridded rainfall products obtained from the NWS Advanced Hydrologic Prediction Service (https://water.weather.gov/precip), and Doppler radars from the NWS Doppler radar network (http://radar.weather.gov) to confirm the missing of a rainfall event and schedule a site visit for instrument inspection and maintenance. On 19 March 2018 a missing rainfall event of about 25 mm was detected at the Lake City station caused by a clogged pluviometer. Automated quality control checks failed to detect the missing rainfall event since the rain gauge reported a plausible value of zero (i.e., no rainfall). Periodic manual quality checks detected a potential missing rainfall by observing a dramatic change in root-zone soil water storage at the Lake City station on the same date (Fig. 6a). Rainfall observations from neighboring stations on the same date (Spearville: 18.5 mm, Harper: 13.5 mm, and St. John: 8.64 mm) and further inspection of the NWS gridded precipitation product (Fig. 6b) provided additional evidence of a potential missing rainfall event at the Lake City station. The three independent pieces of evidence (i.e., time series of changes in soil water storage, neighboring stations, and the gridded precipitation product) allowed the operator to confirm the occurrence

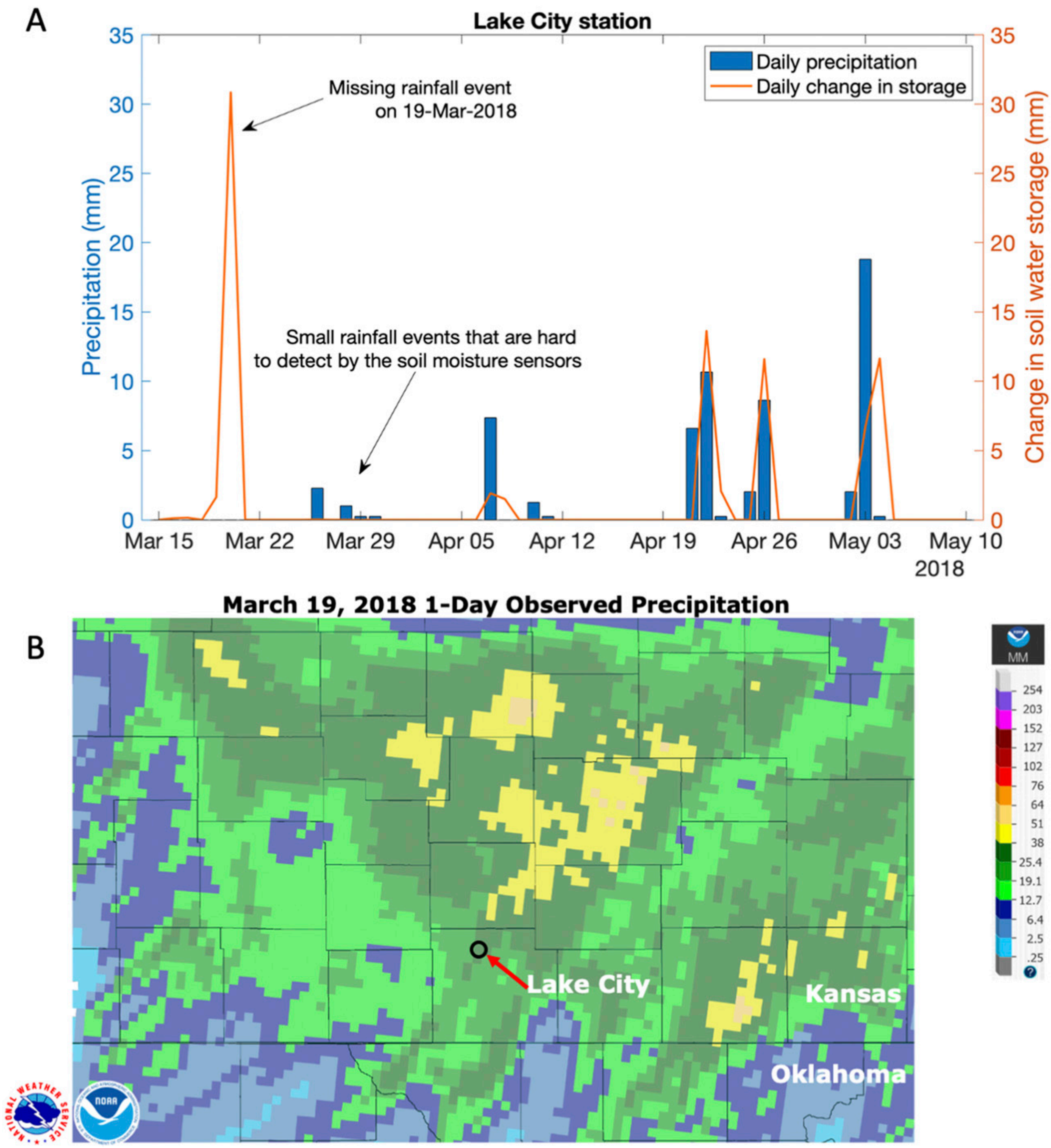

FIG. 6. Example of manual quality control for the detection of a missing rainfall event caused by a malfunctioning rain gauge on 19 Mar 2018 at the Lake City Kansas Mesonet station. Auxiliary information of (a) changes in root-zone (top 50 cm) soil water storage and (b) gridded precipitation product at 4-km spatial resolution from the U.S. National Weather Service was key to confirm the missing rainfall event. For clarity, data, station, and state labels were added to the original map obtained from the National Weather Service. The authors do not claim these labels to be part of the official government material.

of precipitation on 19 March 2018 at the Lake City station and an emergency site visit was scheduled to fix the problem. Since this event, the Kansas Mesonet has been actively researching the use of changes in soil water storage as a mechanism to detect missing rainfall events (Parker and Patrignani 2020). Unlike rainfall records from neighboring stations, changes in soil water storage are obtained for the same station, thus removing the potential spatial variability in rainfall between stations (e.g., the Harper station is about 100 km from the Lake City station). While this technique is promising, further research is required to understand the accuracy and sensitivity of this approach. This particular event also emphasized the need for redundant sensors to minimize the number of missing observations in climatological records.

c. Sensor redundancy

With stations deployed as far as 560 km away from the Kansas Mesonet's headquarters, the deployment of redundant sensors is indispensable to assist with the quality assurance process and to fill in data gaps until a technician can reach the station and inspect a given sensor. The Kansas Mesonet has adopted redundant measurements for the following variables: air temperature, relative humidity, wind speed and direction, precipitation, and soil temperature. Redundant measurements of air and soil temperature exist on all stations, while the other variables only have redundant measurements at the 10-m towers. For instance, each 10-m tower contains two collocated tipping-bucket rainfall gauges both located at the same height inside a single Alter-type shield. Wind speed and direction, air temperature, and relative humidity are monitored at 2- and 10-m height at all 10-m towers. While there are some differences between the observations at the two heights, average hourly and daily trends, as well as the time of maximum wind gusts, often exhibit similar trends. Redundant observations of soil temperature at 5- and 10-cm depth are recorded using the soil moisture sensors. Each soil water reflectometer has a thermistor embedded in the sensor head that can be used to cross check and fill in gaps in soil temperature data.

6. Applications

In addition to the monitoring of an extensive number of variables, the Kansas Mesonet also produces several value-added products (Table 2). Value-added products represent synthesized atmospheric and soil indicators that can be readily translated into actionable decisions by stakeholders and are often available in the form of maps, graphs, and tables. The most popular value-added products of the Kansas Mesonet are heat index, reference evapotranspiration, temperature inversions, growing degree-day calculator, animal comfort index, and relative soil saturation.

Soil temperature is the most visited product on the Kansas Mesonet website. Weekly averages combined with maximum, minimum, and current soil temperature values at 5- and 10-cm depths are available through the website tool and freely available to end users. Users also have access to the last 7 days of data in both charts and tabular format. Soil temperature is mostly used to inform agricultural management practices such as selecting the optimal planting date and guide pre- and in-season fertilizer application. Soil temperature data have been also used in construction to plan roads and concrete work and also to forecast frost depth.

Reference evapotranspiration is calculated using the American Society of Civil Engineers (ASCE) Penman–Monteith equation (Walter et al. 2000) and is one of the first developed and most popular value-added products offered by the Kansas Mesonet. Both grass and alfalfa reference evapotranspiration values are calculated daily and made available to the public through the historical data download portal on the main website. Reference evapotranspiration information is often used together with specific crop coefficients to guide irrigation scheduling and compute the soil water balance in crop models.

A recently developed and popular value-added product is a near-real-time monitor of temperature inversions (Fig. 7a). The phenomenon of atmospheric thermal inversion is related to near-surface atmospheric stability, where suspended droplets of volatilized pesticides can be transported over long distances and damage susceptible crops or reach populated areas. This phenomenon has gained recent attention due to the introduction of dicamba-resistant crops and the increased number of crop injury reports as a consequence of off-target herbicide drift (Bish et al. 2019; Grant and Mangan 2019). As a result, herbicide manufacturing companies have added spraying restrictions under temperature inversion conditions. The temperature inversion monitor developed by the Kansas Mesonet provides valuable information to sprayer operators and producers to assess current local inversion conditions and prevent herbicide drifts that may cause substantial losses in nearby susceptible crops (Grant and Mangan 2019). In the Kansas Mesonet, temperature inversions are defined as the positive temperature differential between the air temperature sensors at 10- and 2-m height.

Indices that integrate multiple atmospheric variables are often used to better represent the apparent temperature of the air and the thermal comfort of homeothermic organisms (e.g., humans and cattle). The Kansas Mesonet adopted an animal comfort index that accounts for a wide range of environmental conditions including air temperature, relative humidity, wind speed and solar radiation (Mader et al. 2010). Ranchers can utilize information from the web-based animal comfort index tool developed by the Kansas Mesonet to adjust cattle nutritional needs and trigger management strategies to enhance animal comfort. Data are displayed for the current and previous 7 days on the web value-added product (Fig. 7b). This information has been extensively used along with air temperature, wind chill, and precipitation data for U.S. Department of Agriculture (USDA) Farm Service Agency Livestock Indemnity Program claims.

Value-added products that track the cumulative number of heat units (also known as growing degree days) are often used to model plant phenology and pest activity. The Kansas Mesonet computes growing degree days for corn (*Zea mays* L.), grain sorghum (*Sorghum bicolor* Moench), cotton (*Gossyphium irsutum* L.), and alfalfa (*Medicago sativa* L.). The computation of growing degree days (GDD) for all crops is based on the following formula:

$$\mathrm{GDD} = [(T_{\max} + T_{\min})/2] - T_{\mathrm{base}}, \qquad (1)$$

where $T_{\max}$ and $T_{\min}$ are observed daily maximum and minimum air temperature in degrees Celsius, respectively. Before computing the average temperature term in Eq. (1), observed $T_{\max}$ and $T_{\min}$ values above- or below-crop-specific upper and lower cardinal temperatures are set equal to these crop-specific

TABLE 2. Description of value-added products generated and reported by the Kansas Mesonet.

Value-added product	Description	Obs variables[a]	Reference
Animal comfort index	Air temperature is adjusted for air relative humidity, wind speed, and incident solar radiation using the comprehensive climate index to generate an index of animal comfort	Air temperature, relative humidity, wind speed, and solar radiation	Mader et al. (2010)
Growing degrees for corn and grain sorghum	Measure of the accumulation of temperature units over a crop-specific upper and lower temperature threshold for predicting the growth and development of corn and grain sorghum	Air temperature	McMaster and Wilhelm (1997); Kansas State University (1998, 2007)
Reference evapotranspiration	Evapotranspiration from a hypothetical grass and alfalfa reference crop 12-cm height with optimal soil moisture conditions and nonnutritional or pest-related limitations	Air temperature, air relative humidity, wind speed, and incident solar radiation	ASCE Penman-Monteith equation as described in Walter et al. (2000)
Heat index	Apparent hot temperature to the human body as the result of the combined effect of high air temperature and air relative humidity	Air temperature and air relative humidity	Rothfusz (1990)
Wind chill	Apparent cold temperature to the human body as the result of the combined effect of low air temperature and wind speed	Air temperature and wind speed	Osczevski and Bluestein (2005)
Temperature inversions	Difference of the air temperature between 1.5- and 10-m height. An inversion is produced when the air temperature at 10 m is greater than the air temperature at 2-m height	Air temperature at 2- and 10-m height	Grant and Mangan (2019)
Relative saturation	Represents the fraction of volumetric water content relative to the max volumetric soil water content at saturation	Volumetric water content at 5-, 10-, 20-, and 50-cm depth	

[a] Variables represent observations by a Kansas Mesonet station.

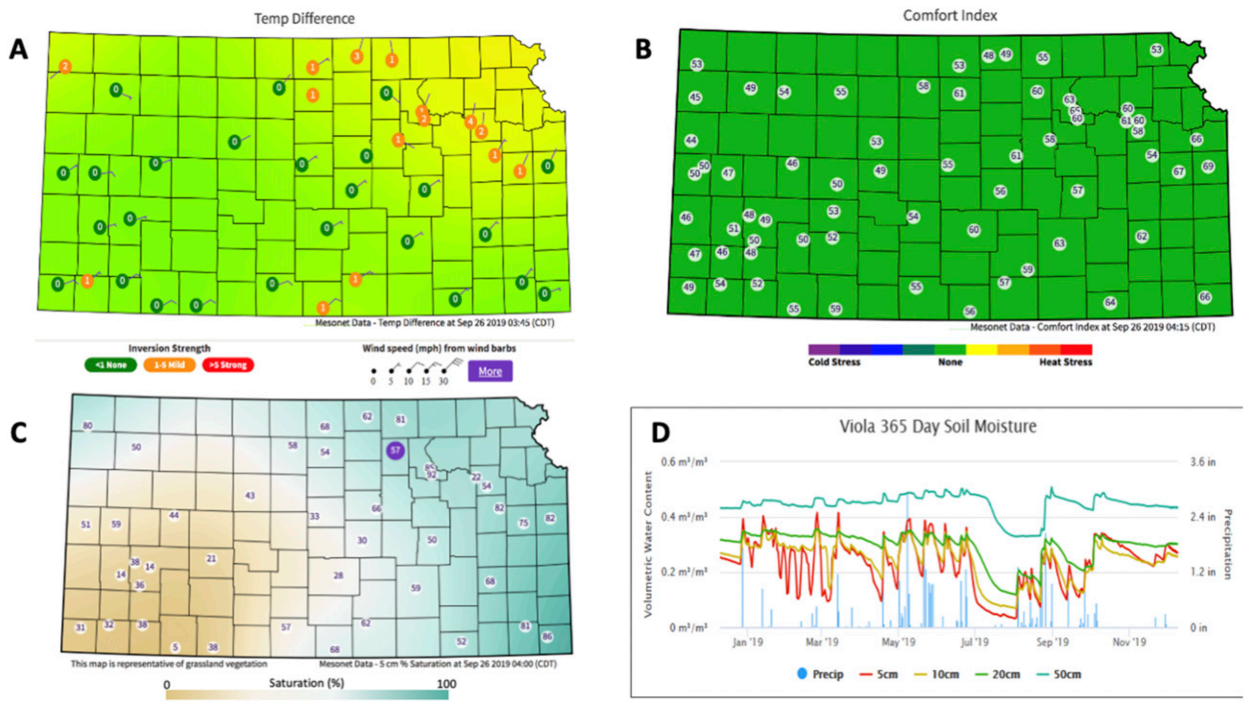

FIG. 7. Example of value-added products of (a) thermal inversions, (b) animal comfort index, (c) percent of surface soil saturation, and (d) time series of soil moisture at 5-, 10-, 20-, and 50-cm depth during 2019 for the Viola station. Value-added products in the form of interactive web ''apps'' can be accessed through the Kansas Mesonet main website (http://mesonet.k-state.edu).

thresholds (McMaster and Wilhelm 1997). The T_{base} is considered to be a plant-specific base temperature, below which plant growth is assumed null.

With the deployment of soil moisture sensors in recent years, the Kansas Mesonet has made available a new value-added product that portrays the soil relative saturation at each respective station and sensor depth. Relative soil saturation is calculated as the ratio between the current soil moisture value and the highest soil moisture value ever achieved at a given station and depth. Percent saturation is easier to interpret than volumetric water content and helps end users quickly visualize the relative level of soil water storage across the state (Fig. 7c) and for each soil layer at a particular station. Data from this tool can be used as a simple indicator of regional drought conditions. The Kansas Mesonet also publishes a 7-day change in volumetric water content for each depth (Fig. 7d) as well as an interactive graphical display to visualize time series of precipitation and soil moisture for all depths for the past 365 days.

Raw variables and value-added products generated by the Kansas Mesonet have been widely used by state agencies, researchers, and extension specialists. For example, during the statewide and exceptionally cold spring of 2019, the Kansas Mesonet documented over 70 requests for air temperature data to support livestock loss claims through Kansas county offices of the Farm Service Agency (FSA) Livestock Indemnity Program. The Kansas Mesonet was instrumental in providing reliable weather data in tabular format for each claiming county. The FSA county offices then submitted the weather records associated with each producer's claim to justify the harsh spring conditions needed to support losses due to cattle stress. As a result, over \$7.6 million dollars were paid to 1776 producers as of 4 May 2020 (D. E. Barrett, Kansas FSA Office, 2020, personal communication).

Environmental observations made by the Kansas Mesonet are also extensively used by researchers, extension specialists, and area agronomists to guide local producers with agricultural management decisions. Maps of daily average soil temperature at 5-cm depth from the Kansas Mesonet are often used to guide grazing decisions in dual-purpose (i.e., used for both grazing and grain yield) winter wheat (Lollato and Knapp 2020) and planting decisions of summer crops such as cotton and corn (Duncan 2019; Ciampitti et al. 2020). Near-surface (5–10-cm depth) soil temperatures of at least 18°C for cotton and 10°C for corn are essential to ensure uniform plant stands and prevent chilling injury during the early stages of summer crops. Maps of near-surface soil temperature encourage producers to follow soil temperature conditions instead of calendar dates to make better management decisions. A map of daily average soil temperature at 5-cm depth released by the Kansas Mesonet on 19 March 2020 (Fig. 8) clearly highlights the lag in soil temperature in the north-central and northwestern portion of the state, indicating that producers in this area should delay the timing of corn planting. Maps similar to that presented in Fig. 8 are often circulated with local producers through weekly online newsletters and regular training workshops.

Another common example of using information provided by the Kansas Mesonet includes the use of time series of root-zone

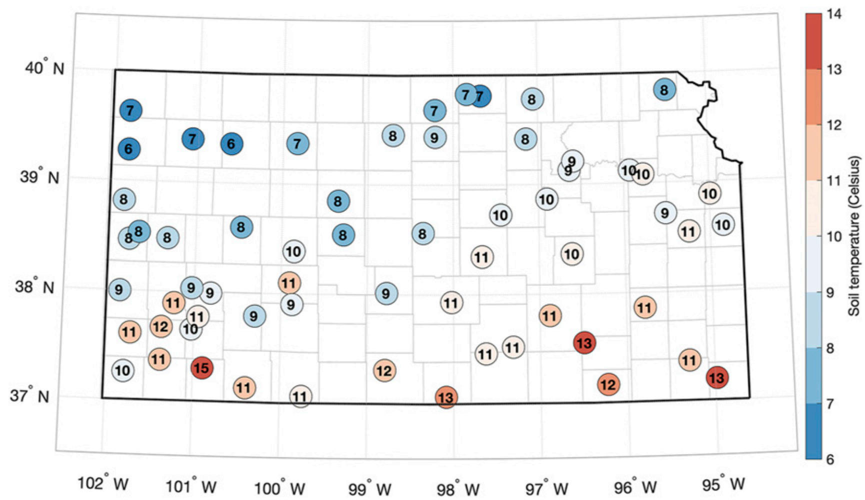

FIG. 8. Daily average soil temperature at 5-cm depth across Kansas on 19 Mar 2020. The map was generated using data from 62 stations of the Kansas Mesonet and clearly shows that the north-central and northwestern portion of the state had soil temperatures below the recommended value of 10°C for corn seeding.

soil water storage computed using data from sensors at 5-, 10-, 20-, and 50-cm depth to characterize the duration and intensity of localized drought conditions. Soil water storage data coupled with information about the soil water holding capacity can be used to approximate the amount of plant available water in the soil profile. A value of about 50% of the plant available water capacity of the soil (Allen et al. 1998) has been shown to describe the point at which most agricultural crops begin to suffer water stress. During the summer of 2017, central and north-central Kansas exhibited pronounced soil water deficits, causing the soil water storage to remain below 50% of the plant available water capacity for 86 consecutive days (Fig. 9). The presence of in situ stations provides accurate representation of local conditions that may not be accurately represented by regional or national drought monitoring systems.

Products generated by the Kansas Mesonet are also widely used in educational programs that include interactive presentations about the notion of weather and climate to fourth graders during kids' field days. Personnel of the Kansas Mesonet have also been teaching more advanced and fundamental concepts in meteorology during the Girls Research Our World (GROW) summer program organized by the Office for the Advancement of Women in Science and Engineering at Kansas State University with the goal of cultivating girls interest in science, technology, engineering, and mathematics.

7. Future of the network

Future network enhancements include (i) upgrading the remaining stations consisting of 2-m tripods to 10-m towers, (ii) equipping all stations with a secondary weighing or tipping-bucket rain gauge to minimize the number of missing rainfall records, and (iii) obtaining long-term sponsoring for future network improvement and maintenance.

Ongoing research efforts include the characterization of the soil physical properties for each station. Undisturbed soil samples are being collected at each station and sensor depth with the aim of characterizing the soil hydraulic and thermal properties. The soil physical properties will be used to better assess drought conditions using the concept of plant available water and to generate near-real-time estimates of potential groundwater recharge rates. Parallel research efforts are also focused on the calculation of winter wheat growing degree days to forecast the occurrence of first hollow stem—a crop stage that indicates the removal of cattle from dual purpose winter wheat fields. Similarly, data from the Kansas Mesonet are also being integrated into ongoing projects such as the National Fire Danger Rating System, tick research, Hessian fly

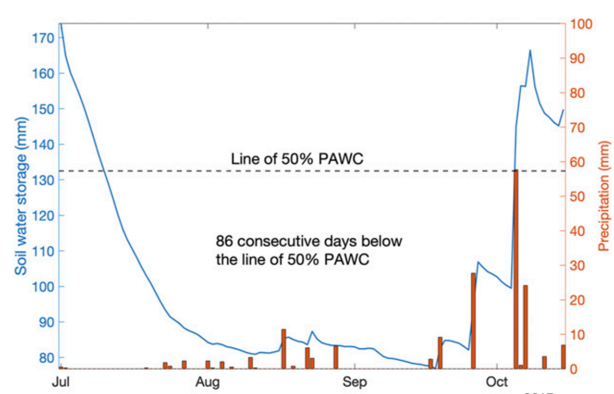

FIG. 9. Use of soil moisture information from sensors at 5-, 10-, 20-, and 50-cm depth to compute soil water storage and characterize the duration and intensity of drought conditions during the 2017 summer period at the Gypsum station located in central Kansas.

entomology, drought monitoring tracking systems, and research on precipitation trends. Stations of the Kansas Mesonet have been recently integrated with Kansas Water Technology Farms, which is a public–private partnership between the Kansas Water Office, local producers, and industry in the agricultural sector to better manage irrigation water resources.

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