A Technical Overview of the North Carolina ECONet

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ABSTRACT

Regional weather networks–also referred to as mesonets–are imperative for filling in the spatial and temporal data gaps between nationally supported weather stations. The North Carolina Environment and Climate Observing Network (ECONet) fills this regional role; it is a mesoscale network of 44 (as of 2022) high-frequency, automated weather stations across North Carolina. This paper provides a technical overview of ECONet, including a description of the siting criteria, station maintenance procedures, data quality control procedures, and data availability. We also summarize unique aspects of ECONet data collection as well as innovative research and applications that rely on ECONet data. Each ECONet station consists of research-grade sensors measuring 15 environment and weather variables every minute. Measured variables include air temperature, precipitation, relative humidity, barometric pressure, wind speed, wind direction, total solar radiation, photosynthetically active radiation, soil temperature, soil moisture, leaf wetness index, and black globe temperature. All data undergo quality control procedures and are made freely available to the public via data portals hosted by the State Climate Office of North Carolina at North Carolina State University. ECONet data are used by many sectors including, but not limited to, emergency management, natural resources management, public health, agriculture, forestry, science education, outdoor recreation, and research. ECONet data and data-powered applications offer valuable insights to local, regional, and federal partners yet opportunities to expand ECONet research and applications remain.

SIGNIFICANCE STATEMENT

We wrote this paper to explain the ongoing and emerging impacts of a state-wide weather station network called the North Carolina Environment and Climate Observing Network (ECONet). ECONet is made up of 44 (as of 2022) high-frequency, automated weather stations located across North Carolina. Each station collects 15 environment and weather variables every minute. ECONet data and data-powered applications offer valuable insights to local, regional, and federal partners. There are many opportunities to expand ECONet-based research and applications.

1. Introduction and Historical Context

The State Climate Office of North Carolina (SCO) at North Carolina State University (NCSU) operates and maintains 44 (as of 2022) high frequency, automated weather and environmental sensing stations across North Carolina (Fig. 1). Specifically, observations are recorded at one minute intervals and sent to SCO computer servers every five minutes via cellular communication where they are stored for downstream use. The mission of this mesonet, called the North Carolina Environment and Climate Observing Network (ECONet), is to serve the data, research, and application needs of North Carolinians for a wide range of sectors; including but not limited to, agriculture, forestry, public health, emergency management, natural resource management, outdoor recreation, science education, and research. Additionally, the SCO works with regional partners to advise the maintenance of three (as of 2022) ECONet Extended (ECOExt) stations (Fig. 1). These stations do not have all the sensors and equipment of a standard ECONet station but complement ECONet. Most importantly, ECOExt stations provide publicly accessible data to regional partners and North Carolina communities. The goal of this technical overview is to provide researchers as well as other local, regional, and federal partners a detailed description of ECONet, including: standard siting criteria and station layout, station maintenance procedures, data quality control procedures, data availability, and a discussion of existing and emerging ECONet data-driven applications. Furthermore, this work summarizes unique aspects of data collection, processing, and applications that set ECONet apart from other regional mesonets and also contributes to a growing number of publications demonstrating the important impact of state-lead mesonets on weather and environmental monitoring, research, and applications (Brock et al. 1995; McPherson et al. 2007; Brotzge et al. 2020; Patrignani et al. 2020).

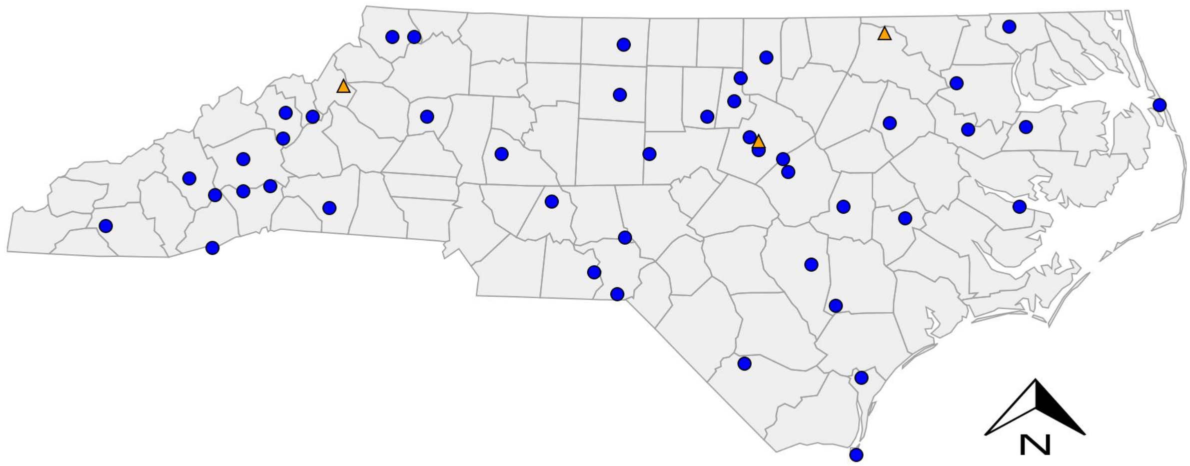

Fig. 1. Map of North Carolina Environment and Climate Observing Network (ECONet) stations. Standard ECONet stations are shown as blue circles and non-standard ECONet Extended (ECOExt) stations are shown as orange triangles.

The development of the ECONet spans three major periods: (1) an initial focus on agricultural research and applications in the late 1970s to late 1990s, (2) a new chapter in ECONet research and applications in the late 1990s to mid 2010s that included agriculture but began to expand to other important sectors, and (3) the mid 2010s to present day period that focuses on providing high-resolution, high quality, publicly accessible weather and environmental data for a wide range of research, applications, and users. The first ECONet station was established in 1978 at the Central Crops Research Station in Clayton, North Carolina. This station along with 13 others established on state and university research farms from 1978-1987 were supported by the North Carolina Department of Agriculture and Consumer Services (NCDA&CS) and NCSU). In these early days, the network was known as the Agricultural Network (AgNet) and its user base consisted mainly of scientists conducting basic and applied agricultural research such as developing cucumber harvest date models (Perry and Wehner 1990). From 1991 to 1996, the NCSU Department of Horticultural Sciences managed and maintained AgNet with support from the NCSU Department of Horticultural Sciences' North Carolina Agricultural Weather Program and NCDA&CS.

In 1997, the supervision of AgNet was transferred to the SCO and the network mission grew beyond its initial focus on agriculture. Specifically, the SCO collaborated with state and local agencies between 1997 and 2000 to establish weather stations that were relevant to emergency management and air quality management; these weather stations were designated as members of the Emergency Management Network (EMNet) and Department of Air Quality Network (DAQNet), respectively. By 2000, all 20 weather stations under the SCO's purview were updated from 3 m tripods to 10 m towers to meet World Meteorological Organization standards (WMO 2011). In 2001, the various distinct networks (i.e., AgNet, EMNet, DAQNet) were merged into the modern-day ECONet. Throughout the 2000s and 2010s, the number of ECONet stations increased steadily with several stations being established at K-12 grade schools and for fire weather management applications.

By 2007, ECONet stations had a standard set of sensors (see Sections 2 and 3), relied on a common data standard for data storage and reporting, and collected measurements at 1-min intervals. In 2012, the SCO was awarded a National Mesonet Program contract to support ECONet station maintenance and data delivery moving forward. To date, all ECONet data are freely available to the public through the SCO Cardinal data portal (https://products.climate.ncsu.edu/cardinal/) and CLimate Office Unified Data System (CLOUDS) application programming interface (https://api.climate.ncsu.edu/). ECONet data are also available to the National Weather Service (NWS) and other federal agencies through the Meteorological Observational Database and Data Delivery System (MADIS; https://madis.noaa.gov/) and on the Weather Information Management System (WIMS) maintained by the National Wildfire Coordinating Group. While ECONet stations were originally established for and supported by the agricultural sector, ECONet data currently supports research and applications in a wide range of sectors across North Carolina from agriculture, to weather forecasting, forestry and forest fire management, emergency management, air quality, science education, public health, and much more.

2. Network Spatial Configuration, Station Siting, and Station Layout

2.1. Network Spatial Configuration

ECONet spatial configuration strategies have shifted over time as local, state, and federal partners' needs and the mission of the network have changed. While non-uniform, the initial distribution of ECONet stations emphasized agricultural centers of the state, which are mainly located in central and the eastern North Carolina. As the SCO began to partner with a wider range of sectors (e.g., air quality management, emergency management, K-12 schools), the distribution of ECONet stations prioritized the needs of the partner as well as areas that lacked established automated weather stations. Starting in the 2000s, the SCO set an internal standard that required new station locations to be at least 20 km away for another nearby automated weather station, where applicable (Fujita 1962). This initially prioritized ECONet to expand into and represent heterogeneous land use areas of central and western North Carolina and balances the representation of diverse land uses and data applications with station coverage across the state. Currently, SCO uses geographic information systems to determine potential areas of interest that are 20 km or more from a current automated weather station. These potential areas are then ranked by distance and targeted as tentative areas for new ECONet stations. However, ECONet staff (henceforth, we) determine the final location of these stations based on stakeholder interest and engagement, funding availability, and whether there is a location that maximizes standard siting criteria as discussed in Section 2.2.

2.2. Station Siting Requirements

Upon selection of a general area for the placement of a new station, we follow World Meteorological Organization (WMO 2011, 2018), United States Environmental Protection Agency (USEPA 1987, 2000), American Association of State Climatologists (AASC; Bingham et al. 1985), and American Society for Civil Engineers (ASCE, Ley 1993; Brown 1993) guidelines combined with manufacture guidelines (e.g., Campbell Scientific 2022) as closely as possible to ensure data accuracy and proper representation of the surrounding area (Section 2.4). In the event that a proposed station location does not meet all WMO guidelines, we work directly with station partner(s) to locate the most suitable location with the fewest limitations. There are three key factors that we consider when determining the location for a new station. The first factor is the distance from existing ECONet stations. To fill gaps in the network, new stations are ideally placed 20 km or more away from existing stations. The second factor is distance from obstructions (i.e., trees, buildings). Ideally, stations are located away from any obstructions at a distance of 10 times the height of the obstruction (WMO 2011). The third factor is landscape slope. Siting a station in an area with minimal slope ensures the station accurately represents the surrounding area and can be more easily lowered into a horizontal position for maintenance.

2.3. Station Layout

The standard layout of an ECONet station is depicted in Fig. 2. Each ECONet station is located on a plot of land roughly 10 m by 7 m following the WMO preferred guidelines (WMO 2011). Every station consists of a 10 m aluminum tower (9-30, Universal Towers) set in a 1.2 m length by 1.2 m width by 1.2 m depth concrete base. In locations that experience high wind gusts, the size and depth of the concrete base is larger and the tower is further stabilized by three galvanized steel guy wires extending 6 m out from each of the three legs of the tower. Each station also includes a 45.7 cm long by 40.6 cm wide by 22.9 cm deep weather-resistant, fiberglass-reinforced, polyester enclosure box (ENC16/18, Campbell Scientific), which houses the datalogger and other sensitive components. Additionally, each station includes a communications antenna, a power supply (Section 3.1), and a suite of environmental sensors that are both surrounding and attached to the tower.

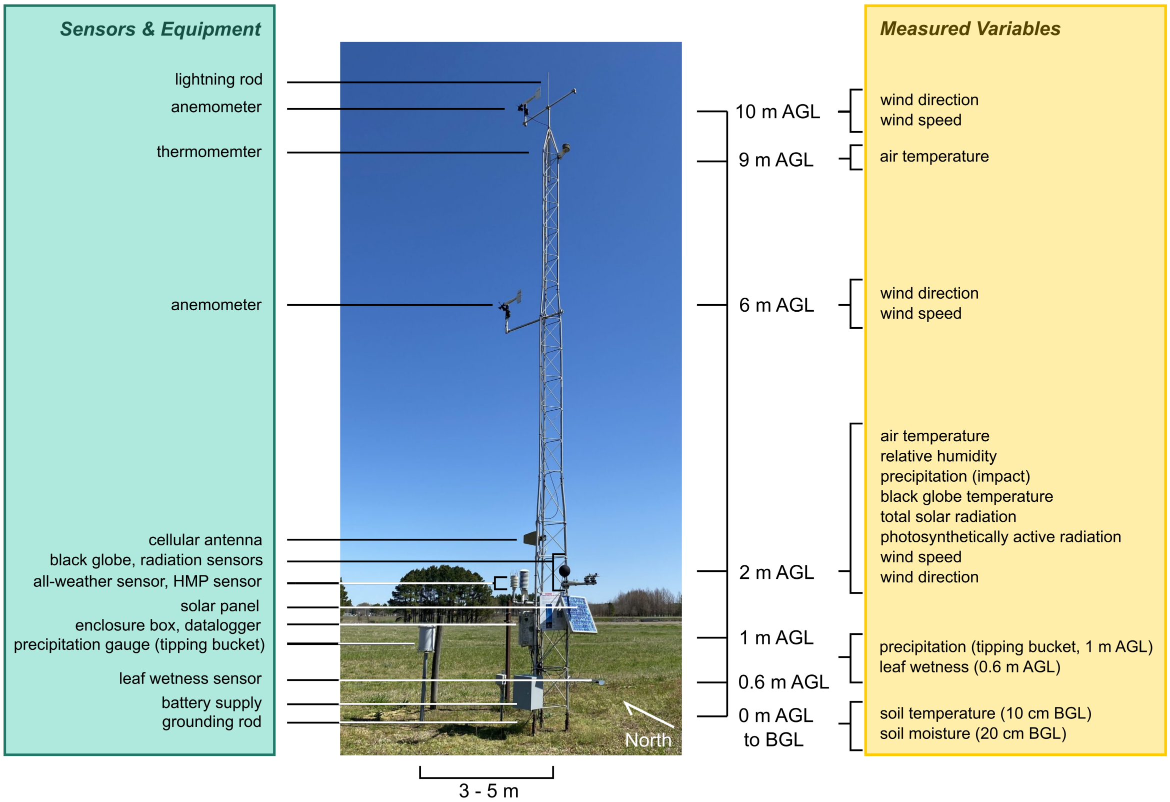

Fig. 2. Image displaying the standard layout of an ECONet station, including: sensors, equipment, and measured variables. The tower pictured is the Goldsboro, North Carolina (GOLD) ECONet station in March 2022.

The suite of environmental sensors located on the tower are as follows. We mount a leaf wetness sensor to one end of a 1 m long section of aluminum corner trim and attach it horizontally to the tower at a height of 0.6 m above ground level with the sensor facing due north. The 90^{o} angle property of the aluminum corner trim boom facilitates the mounting of the leaf wetness sensor at a 45^{o} angle. At a height of 2 m above ground level, we mount a variety of sensors on booms extending roughly 0.6 m from the tower. These include an all-weather sensor, an air temperature and relative humidity sensor housed in a radiation shield, and a pair of radiation sensors measuring solar radiation and photosynthetically active radiation. The all-weather sensor measures air temperature, relative humidity, precipitation (i.e., impact sensor), barometric pressure, wind speed and wind direction. Therefore, all ECONet stations have some redundancy in temperature, precipitation, and relative humidity observations at 2 m above ground level. We measure black globe temperature, which can be used to measure heat risk and danger, at 2 m above ground level by mounting it on a 0.3 m boom that is perpendicular to one of the 0.6 m booms. We position the black globe thermometer so it is not shadowed by or does not cast a shadow on other sensors; shadows will interfere with measurements. We mount propeller-based anemometers at the end of 0.9 m long booms to measure wind speed and direction at 6 m and 10 m. In addition to measuring air temperature at 2 m above ground level, each ECONet station has a radiation shield that we mount just off the tower at a height of 9 m. This radiation shield houses a sensor to measure air temperature higher up in the tower profile. To limit damage to the tower and the many sensitive components in the event of a lightning strike, a lightning rod sits atop the tower connected to a grounding rod that we bury underground. See Section 3.3 for a full description of sensors on the tower.

Surrounding the tower, we measure soil temperature and soil moisture below natural vegetation at depths of 10 cm and 20 cm, respectively, and at a distance of 2 to 3 m away from the tower with cables that are buried along a 10 cm deep trench. We place soil moisture and temperature sensors near, but not directly under, the tipping bucket precipitation gauge to best account for the response of these measurements to precipitation. We install the primary precipitation measurement, an unheated tipping bucket rain gauge, at a distance of 3 to 5 m from the tower at a height where the rim of the funnel orifice is 1 m above ground level. See Section 3.3 for a full description of sensors surrounding the tower.

3. Sensors, Equipment, and Data

The foundation of ECONet station data collection starts with each individual sensor measuring a particular weather or environmental variable (e.g., wind speed, Fig. S1a). Once these observations are collected by the sensor, these data are aggregated and saved on the tower datalogger (Fig. S1b) before being transmitted offsite (Fig. S1c). Once transmitted offsite, ECONet data are received and managed by SCO and NCSU Office of Information Technologies staff via a combination of Windows and Linux computer servers (Fig. S1d), and ultimately, made publicly available through several SCO data portals (Fig. S1e). In Sections 3.1 to 3.4, we discuss key sensing and equipment components for standard ECONet stations, including: sensors

(Section 3.1), data acquisition, sampling, and power (Section 3.2), communications (Section 3.3), and data storage and sharing (Section 3.4).

3.1. Sensors

Each ECONet station has 12 categories of sensors (Table 1). Several of these categories use multiple approaches to measure particular variables (e.g., tipping bucket versus impact sensor precipitation observations) and are located at various elevations along the tower profile (Fig. 2). As a result, there are a total of 18 uniquely measured variables per ECONet station and each measured variable (Fig. S1a). We install and maintain all sensors according to manufacturer sensor specifications (Table 1), this includes but is not limited to the measurement elevation, installation preparations, and the sensor replacement frequency. For example, we replace soil temperature sensors every two years according to the manufacturer recommendations (Table 1). All measured variables undergo quality control checks, which we describe generally in Table 1 and in full detail in Section 5. As of 2022, ECONet is the only regional mesonet to be fully-instrumented with black globe thermometers at 2 m. These data power an innovative current conditions wet bulb globe temperature tool that visualizes hourly heat risk across the state (Section 6.1.2).

Table 1. Summary of standard ECONet sensors, corresponding manufacturer information, quality control checks performed, and replacement and calibration frequency. See Section 5 for specific quality control (QC) checks performed for each sensor. Abbreviations: above ground level (AGL), below ground level (BGL), pressure, temperature and humidity (PTU), air temperature (Ta), relative humidity (RH), range check (R), buddy check (B), intersensor check (I), trend check (Z).

Measured Variable	Height	Sensor Manufacturer and Code	Sensor Range	Sensor Accuracy	QC Checks Performed	Manufacturer Reference	Replacement/Calibration Frequency
Air temperature	2 m, 9 m AGL	Vaisala WXT-536 at 2 m	-52 C to +60 C	±0.3 C at +20 C	R, B, Z	Vaisala WXT, 2022	PTU module replaced every 2 years
		Vaisala HMP155 at 2 m	-80 C to +60 C	±(0.226 - 0.0028 * Ta) C from -80 o to +20 C; ±(0.055 + 0.0057 * Ta) C from +20 to +60 C	R, B, Z	Vaisala HMP, 2021	Replaced with either a factory recalibrated or new sensor every 2 years
		Campbell Scientific (CS) 109 Temperature Probe at 9 m	-50 C to +70 C	±0.1 C from 0 C to +70 C increasing to ±0.5 C at -50 C	R, B, Z	Campbell Scientific 109, 2022	Replaced every 2 years
Barometric pressure	2 m AGL	Vaisala WXT-536	500-1100 hPa	±0.5 hPa from 0 C to +30 C; ±1 hPa from -52 C to +60 C	R, B, Z	Vaisala WXT, 2022	PTU module replaced every 2 years
Black globe temperature	2 m AGL	Campbell Scientific BlackGlobe-L	-5 C to +95 C	< ±0.2 C from 0 C to +70 C, and ±0.3 at +95 C	R, Z	Campbell Scientific BG 2022	Replaced every 5 years
Leaf wetness index	0.6 m AGL	METER Group PHYTOS 31	250 -1,250 mV	+/- 10 mV	R	METER PHYTOS, 2022	Replaced every 2 years
Photosynthetically active radiation	2 m AGL	Apogee Instruments SQ-100X-SS	0-2500 µmol m^{-2} s^{-1}	±5%	R, I, Z	Apogee SQ, 2022	Replaced with either a factory recalibrated or new sensor every 2 years)

Precipitation (tipping bucket, liquid)	1 m AGL	HyQuest Solutions TB3	0-700 mm h^{-1}	±2% from 0-250 mm h^{-1} and ±3% from 250-500 mm h^{-1}	R, I, Z	HyQuest TB3, 2022	Calibration checked once per year, Recalibrated as needed
Precipitation (impact, liquid)	2 m AGL	Vaisala WXT-536	0-200 mm h^{-1}	±5% for daily accumulation (weather dependent)	R, I, Z	Vaisala WXT, 2022	Replace the whole unit as needed
Relative humidity	2 m AGL	Vaisala WXT-536	0-100%	±3% RH from 0 to 90% RH and ±5% from 90 to 100% RH	R, B, Z	Vaisala WXT, 2022	PTU module replaced every 2 years,
		Vaisala HMP155	0-100%	±(1.2 + 0.012 * reading)% RH from -40 C to -20 C; ±(1.0 + 0.008 * reading)% RH from -20 C to +40 C; ±(1.2 + 0.012 * reading)% RH from +40 C to +60 C	R, B, Z	Vaisala HMP, 2021	Replaced with either a factory recalibrated or new sensor every 2 years
Soil moisture	20 cm BGL	Delta-T ML3	0-1.0 m^3m^{-3}	±0.01 m^3m^{-3} from 0 to 0.5 m^3m^{-3} range with soil specific calibration	R, B, Z	Delta-T ML3, 2022	Replaced every 5 years
Soil temperature	10 cm BGL	Campbell Scientific 109 Temperature Probe	-50 C to +70 C	±0.1 C from 0 C to +70 C and increasing to ±0.5 C at -50 C	R, B, Z	Campbell Scientific 109, 2022	Replaced every 2 years
Total solar radiation	2 m AGL	Apogee Instruments SP-510-SS	0 - 2000 Wm^{-2}	±5% for daily total irradiance	R, I, Z	Apogee SP, 2022	Replaced with either a factory recalibrated or new sensor every 2 years)
Wind direction	2 m, 6 m, 10 m AGL	R.M. Young 05103	0^o-360^o	±3^o	R	R.M. Young 2022	Whole unit replaced every 10 years
Wind speed	2 m, 6 m, 10 m AGL	R.M. Young 05103	0-100 ms^{-1}	±0.3 ms^{-1} or 1% of reading	R, B, I, Z	R.M. Young 2022	Propeller shaft bearings replaced every 2 years, Whole unit replaced every 10 years

3.2. Data Acquisition, Sampling, and Power

Each ECONet station is equipped with an electronic datalogger (Fig. S1b), typically a Campbell Scientific CR1000, or in some rare cases, a Campbell Scientific CR1000X or CR3000. The datalogger is placed within a weather resistant enclosure box and serves to collect and store all observations from all sensors on an ECONet tower before these data are transmitted off-site via various data communication methods (see Section 3.3). Observations are stored locally on the datalogger as a data table within the device's dedicated random-access memory. In terms of the frequency of recorded observations for a given sensor–often referred to as data sampling–we set the datalogger to record wind speed, wind direction, and precipitation at 5-second intervals. We average wind speed and wind direction over a 1-minute period. We record wind gusts as the maximum 5-second wind speed value sampled over a 1-minute period and record precipitation as the total sum of precipitation observed over a 1-minute period. We record all other measured variables once per minute (i.e., instantaneously).

Of the 44 ECONet stations (as of 2022), 31 are powered via solar power, and the remaining 13 are powered via alternating current (AC) power. For solar powered stations, a 20 W solar panel provides power to the datalogger and charges a 12 V deep cycle marine battery via a charging regulator (CH150, Campbell Scientific). Overnight, the station runs off battery power from the 12 V deep cycle marine battery. For AC powered stations, electricity is provided via an underground power line running to a power box near the ECONet tower. The power box typically contains a surge protector and an AC-DC converter. The electricity is then run via another underground cable from the nearby power box to the charging regulator within the station enclosure box attached to the tower. The charging regulator funnels electricity to the datalogger and a 12 V 7 Ah backup battery, the latter of, which can power the station for a limited amount of time in the event of an AC power outage.

3.3. Communications

ECONet stations communicate data back to the SCO every five minutes using various communication methods (Fig. S1c). The most common method of data communication method that we use is a cellular modem connection. As of 2022, 36 stations communicate via Sierra Wireless RV50 cellular modems, and three stations communicate via Campbell Scientific

CELL210 cellular modems. Alternative methods of communication include RF Radio and IP (two stations), WiFi (two stations), and landline telephone (one station). We rely on using these alternative communication methods when the cellular communications signal is weak or the alternative method is more economical than cellular communications.

3.4. Data Storage and Sharing

As described in Sections 3.2 and 3.3, all ECONet observations are stored locally as a data table within the random-access memory of the datalogger until they can be transmitted back to the SCO at five minutes intervals. Specifically, ECONet observations are initially stored in data tables using Loggernet software (Campbell Scientific) installed on one of two Windows machines (Fig. 3d). One of the Windows machines is a desktop computer located in the SCO, which receives communications from landline-based ECONet stations. The other Windows machine is a virtual machine hosted by the NCSU Office of Information Technologies, which receives communications from the remaining ECONet stations. Once stored in Loggernet software-formatted data tables using standard manufacturer methods (Campbell Scientific 2020), we have a custom, timed shell script that moves ECONet data from Loggernet into a series of SCO-managed, Linux-based databases every five minutes (Fig. S1d). The multiple database structure minimizes data access latency issues and provides redundancy by backing up data. In addition to custom, timed shell scripts that run every five minutes, we have a series of ECONet data ingest scripts that are scheduled to run in the early morning each day for the purpose completing automatic quality control checks of ECONet data (Section 5.1) and generating summary quality control score emails (Section 5.2). See Section 5 for a full description of data quality control processes.

Once ingested into the Linux-database and quality controlled, ECONet data are freely available to the public (Fig. 3e) via the SCO Cardinal data portal and Station Scout tool (https://products.climate.ncsu.edu/cardinal/), CLimate Office Unified Data System (CLOUDS) application program interface (API, https://api.climate.ncsu.edu/), and Station Scout allows users to explore ECONet data availability as well as the availability of a number of other publicly accessible weather station network data for North Carolina. Once a user has a handle on which stations, measured variables, data frequency, and data duration that they would like to obtain, they can create a free SCO data access account and use Cardinal to build and submit a data request. For users who are more familiar with programmatically requesting data using a computer programming language, they can create a free SCO data access account and use the CLOUDS API to build and submit a data request. Notably, ECONet data are one of several local, state, and national weather networks included in the SCO Cardinal data portal, Station Scout tool, and CLOUDS API; therefore, users of these tools benefit from the aggregation of these weather data. ECONet data are also available to the National Weather Service (NWS) and other federal agencies through the Meteorological Observational Database and Data Delivery System (MADIS; https://madis.noaa.gov/) and on the Weather Information Management System (WIMS) maintained by the National Wildfire Coordinating Group.

4. Station Maintenance

We perform routine and emergency maintenance periodically throughout the calendar year to ensure ECONet stations are functioning as expected. Routine maintenance occurs three times a year while emergency maintenance is done all year round provided there is safe access to the station of concern. Specifically, a number of ECONet stations are located along the southern extent of the Appalachian Mountains; therefore, these high elevation stations are subject to heavy ice and snowfall. Oftentimes during the winter months, roads are inaccessible or closed completely making emergency maintenance difficult, if not impossible.

Routine maintenance takes places during three seasons: spring, summer and fall. Spring maintenance runs are often the busiest and consist of either replacing or rotating in newly calibrated leaf wetness sensors, radiation sensors, HMP-155 sensors which measure both temperature and relative humidity, and the barometric pressure, temperature, and relative humidity (PTU) modules in the Vaisala WXT-536. Summer maintenance runs consist of calibrating the rain gauges using a field calibration device (FCD-314 or FCD-653, HyQuest Solutions) and checking the integrity of or replacing the soil moisture and temperature sensors. During fall maintenance runs, we lower towers into a horizontal position via a hinge mechanism at the base. This allows us to access and replace propeller shaft bearings in the anemometers at 6 m and 10 m as well as the 9 m air temperature sensor.

Emergency maintenance consists of restoring a station to its fully-functioning state, or in rare cases, restoring as much functionality as possible until a longer-term solution can be implemented. Typical emergency maintenance station visits include replacing dead or failing batteries, replacing damaged or malfunctioning sensors, and investigating power or communication issues. While rarer, emergency maintenance may also involve repairing or replacing equipment after it has been vandalized. To help save time and resources, we may complete routine maintenance during an emergency maintenance visit when the timing coincides closely with regularly scheduled maintenance.

Before heading out into the field for routine or emergency maintenance, we create an itinerary outlining the tasks to be completed along with a generalized time schedule. We will bring this itinerary along with the station notebook to each station visit. Every ECONet station has a dedicated field notebook, which contains a detailed log of past visits and metadata along with station-specific wiring diagrams and other relevant station notes and directions. Upon arrival at a station, we perform a quick visual and audible inspection of the site, examining for any signs of potential damage. During the inspection, audible clues give us insights into the overall operations of the tower. For example, absence of a faint chirping noise, particularly from the Vaisala WXT-536, indicates either a loss of power to the station or the sensor itself. Dull grinding noises from above likely means the bearings in the anemometers need to be replaced. After identifying any potential problems, we will fix any issues and make note of these repairs in the station notebook. We then conduct routine or emergency maintenance according to SCO standard operating procedures as well as checking and performing other maintenance tasks as needed during each visit. These include: (1) clearing vegetation that is obstructing sensor operation (i.e., weeding, mowing the grass), (2) wiping off equipment and sensors such as the solar panel, black globe thermometer, and other sensors that have built up dust, grime, and pollen, (3) removing pests including ant hills and wasps nests, and (4) removing any debris clogging or inhibiting proper tipping bucket precipitation gauge operation.

Before leaving an ECONet station site, we will verify data quality and ensure data communications are flowing uninterrupted back to the SCO computer servers. We will also take metadata photos of the station surroundings in all eight cardinal and intercardinal directions as well as a profile photo of the full station. Upon returning to the office, we upload these photos to the ECONet website, which enables us to keep a visual, spatial and temporal record of station surroundings.

5. Data Quality Control

ECONet observations are continuously monitored using automated (Section 5.1) and manual (Section 5.2) quality control checks to ensure these publicly available data are high quality. All observations from ECONet are stored in a database with an associated flag column that includes the automated and manual quality control flags for a given observation. While we may append additional labels to manual quality control flags denoting instances of erroneous data, we never change ECONet observations. Therefore, users must take care to view and use the quality control flags that are available along with ECONet observations obtained from the Cardinal and Scout data portals and the CLOUDS API (Section 3.4). A custom, internal software interface (see Section 5.2) helps SCO staff determine the quality of ECONet observations and assign manual quality control flags, as needed.

5.1. Automated Quality Control

Raw (i.e., pre-quality controlled) ECONet observations are stored in a database every five minutes (Section 3.4) and timed scripts run a series of four automated quality control checks run every 30 minutes to ensure ECONet data is high quality. These four quality control checks include: (1) range check, (2) buddy check, (3) intersensor check, and (4) trend check. We describe each of these automated quality control checks in further detail below.

The first automated quality control check is a range check, which runs in two phases: static and dynamic. Every ECONet observation undergoes the static phase range check and the purpose of this check is to determine whether an observation value is within the physical bounds of the sensor. For example, any temperature observation reported from the Vaisala WXT-536 that is below -52 °C or above 60 °C (Table 1) will automatically fail the static phase range check and not undergo any additional quality control checks. Similar to air temperature values, relative humidity values below 0% or above 100%, wind speed values greater than 100 ms^{-1}, negative precipitation values, and negative radiation values will all fail the static phase range check and not undergo any additional quality control processing. If observations pass the static phase range check, then the dynamic phase range check. The purpose of the dynamic phase range check is to determine whether observation values fall within the North Carolina climatological range for the given time of year. Observation values that fall outside either the static or dynamic range checks are given a quality control flag associated with the level of failure ranging from R0 (pass) to R4 (highest level of failure).

Following the range check, the second automated quality control check is the buddy check. The purpose of the buddy check is to ensure spatial consistency between data points. Not all measured variables are subjected to the buddy check; see Table 1 for a complete list of measured variables that undergo a buddy check. First, an interpolated value is assigned to the observation using inverse distance weighting of nearest neighbors. The number of stations is limited to either 15 stations or all stations within a 50 km radius, whichever is fewer. If the interpolated value and observed value are within a margin of error, the observation value passes the buddy check. We assign a quality control flag to an observation based on how close the observed value is to the interpolated value. Buddy check quality control flags range from B0 (pass) to B5 (highest level of failure).

The third automated quality control check is the intersensor check, which applies to redundant measured variables (e.g., air temperature at 2 m above ground level is measured by two different sensors at each ECONet site, see Table 1). The purpose of the intersensor check is to ensure that the redundant sensor measurements are reporting similar values. Based on the difference between the redundant sensors, we assign an observation value an intersensor flag, which has three possible values: I0 (pass), I2 (suspect), or I4 (failure).

The fourth automated quality control check is the trend check. Not all measured variables are subjected to a trend check; see Table 1 for a complete list of measured variables that undergo a trend check. The purpose of the trend check is to look for short-term asymmetries (e.g., spikes) in ECONet observations over time. The trend check compares values from the previous hour for a given observation and determines whether the observation is expected given values from the previous hour. The trend check also identifies data that remains constant, or flatlines, for a prolonged period of time. Identifying flatlining observations is useful when, for example, the anemometer propeller freezes over during winter storms. Another example of when it is beneficial to identify flatlining observations is when soil moisture sensors approach either field capacity or wilting point. Trend check flags include either Z0 (pass), Z2 (suspect), or Z4 (failure).

All automated check flags are combined into one flag serial code (e.g., R0B0I0Z0; Table S2) and saved in a column of the database. We then use this combined flag serial code to calculate an automated quality control score. The quality control score ranges from -1 (i.e., value not quality controlled) to 3 (i.e., value fails quality control). A quality control score of 0 indicates the observation passed all automated quality control checks. We received an email summary of all quality control scores at the start of each day to inform manual quality control processes (Section 5.2, Fig. 3). For a list of all quality control score definitions and quality control flag combinations, see Tables S1 and S2, respectively.

5.2. Manual Quality Control

We do manual quality control each morning to first verify when one or more automated quality control routines failed the day before and then append manual quality control labels to automatic quality control flags. Specifically, we receive an email that details the quality control score percentages for each ECONet station (Fig. 3). This allows us to quickly pinpoint ECONet stations that have a potential sensor malfunction. Each station ID in the email is a URL hyperlink. When we click on this URL hyperlink, we are directed to an internal quality control software program called the ECONet Quality Control Data Viewer (QCDV; Fig. 4). The daily email alert and corresponding QCDV were custom developed and implemented in PHP and Javascript code by a member of our team (John McGuire) to: (1) simplify manual quality control processes, (2) visualize temporal and spatial patterns in automated quality control checks, and (3) minimize human-induced quality control errors. Within the QCDV, we can select an ECONet station, measured variable, and time frame. Most importantly, we can visualize and append a manual flag to the automatic quality control flags. QCDV will append a U0 (passed by human check) or a U4 (failed by human check) to the front of all human-updated versions of the automated quality control flags. Manual quality control is important to override automated quality control checks for correct observations occurring during extreme weather conditions or denoting incorrect observations made during routine maintenance (e.g., cleaning or calibration of the rain gauge).

QC Status of all ECONet Stations:
From 2022-06-30 05:05:00 EST To 2022-07-01 05:05:00 EST

Station	Var	Count %	QC-1 ?	QC0 ✔	QC1 ✔?	QC2 ×?	QC3 ×	Last Ob
ROCK	ob	97	1.4%	96.2%	9#	92#	2.1%	2022-07-01 05:24:00
SPRU	ob	97	1.4%	97%	30#	62#	1.3%	2022-07-01 05:24:00
REID	ob	97	1.4%	97.8%	27#	106#	135#	2022-07-01 05:24:00
MITC	ob	96.7	1.4%	95.7%	2%	220#	92#	2022-07-01 05:20:00
NCAT	ob	97	1.4%	97.9%	10#	120#	89#	2022-07-01 05:24:00
BUCK	ob	97	1.4%	98%	59#	69#	80#	2022-07-01 05:24:00
SALI	ob	97	1.4%	98.2%	3#	62#	75#	2022-07-01 05:24:00
LILE	ob	97	1.4%	98.2%	8#	52#	61#	2022-07-01 05:24:00
OXFO	ob	97.1	1.5%	98.1%	7#	89#	60#	2022-07-01 05:25:00
DURH	ob	97	1.3%	98.1%	19#	86#	60#	2022-07-01 05:24:00
JEFF	ob	97	1.4%	97.2%	26#	1.2%	59#	2022-07-01 05:24:00
WAYN	ob	97	1.4%	96.6%	1.6%	63#	59#	2022-07-01 05:24:00
AURO	ob	97	1.4%	98.3%	2#	48#	54#	2022-07-01 05:24:00
BALD	ob	97	1.4%	98.1%	15#	67#	54#	2022-07-01 05:24:00
CLAY	ob	97	1.4%	98.1%	10#	101#	50#	2022-07-01 05:24:00

Fig. 3. Example of a daily quality control score table email from June 30, 2022 at 5:05 am EST. The table shows the automated quality control scores by station to guide subsequent manual quality control and potential station maintenance. Stations are ordered by their unique four-digit identifier in descending order based on the percentage of all sensor observations (ob) receiving a quality control score of three (QC3), which indicates a poor quality control score. A number followed by a "#" symbol indicates the number of total observations, when less than 1% of all observations failed automated quality control checks (Section 5.1).

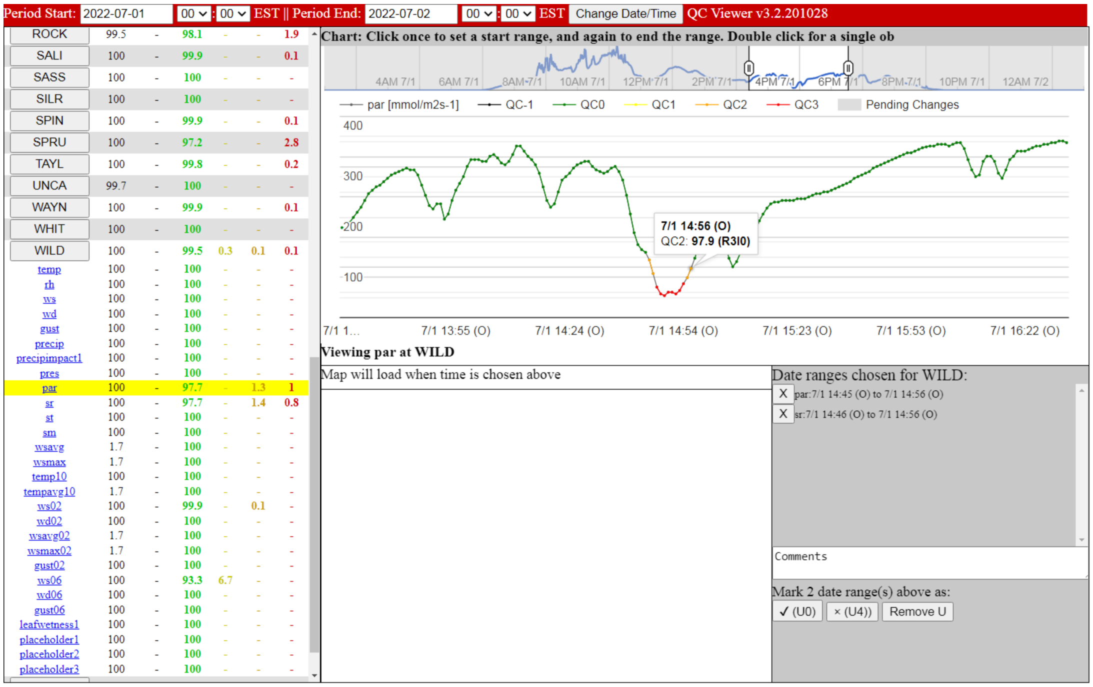

Fig. 4. ECONet Quality Control Data Viewer (QCDV) graphical user interface window showing photosynthetic active radiation (PAR) observations at the Williamsdale Field Lab ECONet station (WILD) in Wallace, North Carolina on July 1, 2022. Left panel shows results for all stations and each individual sensor and the right top panel shows the time series plot for the selected sensor measurement variable (e.g., PAR) with observations colored by quality control score. Right bottom panel shows a map, any manual quality control notes, and user flag indicator selection. User notes and user flags provide more context in manual quality control processing (Section 5.2). Orange or red points in the time series indicate observations that have a quality control (QC) score of two or three, respectively, and need further investigation.

6. Applications, Outreach, & Research

6.1. Applications

In addition to the extensive monitoring of real-time data, the SCO and its collaborators create applications that use ECONet data to help local, state, and federal partners make quick and data-driven decisions. Many of these applications are typically in a map, graph, or tabular form and are presented as a web page or web application. A list of popular applications that use ECONet data can be found in Table 2 and three specific applications are highlighted below in Sections 6.1.1 and 6.1.2. In Section 6.1.3, we discuss the unique benefits of ECONet data for two North

Carolina agencies (i.e., North Carolina Department of Air Quality and North Carolina Emergency Management).

Table 2. Description of applications using ECONet data (as of 2022). All ECONet measured variable elevations are given in above ground level units.

Number	Application Name	Description	ECONet Measured Variables	Application URL
1	Peanut Disease Monitoring & Alerts	Daily alert during growing season to alert growers whether spraying is needed due to the number of hours of high relative humidity values.	2 m air temperature, 2 m relative humidity, 2 m leaf wetness	http://ncsupeanut.blogspot.com/
2	Inversion Monitoring	Map displaying the current conditions rating for herbicide spraying.	2 m and 9 m air temperature, 6 m wind speed	https://econet.climate.ncsu.edu/inversion
3	Wet Bulb Globe Temperature	Map displaying current and recent conditions of wet bulb globe temperature	2 m air temperature, 2 m relative humidity, 2 m wind speed, 2 m black globe temperature	https://econet.climate.ncsu.edu/wbgt
4	Growing Degree Days	Time series displaying the cumulative number of growing degree days over the course of a year	2 m air temperature	https://products.climate.ncsu.edu/cardinal/scout
5	Wind Rose	Rose chart showing the frequency of winds from different directions, at different speeds, over a period of time	10 m wind speed and wind direction	https://airquality.climate.ncsu.edu/wind/
6	Ambient Information Reporter	Map displaying current weather and air quality conditions	2 m air temperature, 2 m wind speed, 2 m wind direction, 2 m relative humidity, 2 m black globe temperature, 2 m total solar radiation, 1 m precipitation	https://airquality.climate.ncsu.edu/air/
7	Fire Weather Intelligence Portal	Map displaying past, current, and future fire risk conditions.	2 m air temperature, 6 m wind speed, 6 m wind direction, 1 m precipitation, 2 m relative humidity, 2 m solar radiation, soil moisture, soil temperature	https://products.climate.ncsu.edu/fwip/

6.1.1. Crop Monitoring Tools

Crop disease monitoring represents an original and ongoing use case of ECONet data. In 2005, SCO researchers collaborated with researchers in the NCSU Department of Crop and Soil Sciences to develop a peanut disease monitoring and alert tool to alert users when current weather conditions favor peanut plan fungal disease outbreaks (Table 2). Early leaf spot and late leaf spot fungal disease outbreaks are favorable in peanut crops when air temperatures are between 16 and 20 °C with high (> 93%) relative humidity (Shew et al. 1988). This application relies on air temperature, relative humidity, and leaf wetness observations at ECONet stations located in areas of high peanut production. Users located within a warning region receive a daily alert email explaining the potential for early leaf spot and late leaf spot disease outbreak as the number of favorable hours for disease formation ("favorable hours" in Fig. 5). The peanut disease monitoring and alert tool notifies peanut producers of potential fungal outbreaks in real-time and can reduce the number of fungicide North Carolina peanut producers apply during the growing season.

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July 3, 2019 PEANUT LEAF SPOT ADVISORY FOR WHIT
Border Belt Tobacco Res Stn (Whiteville, NC)
setDate = 2019-06-24 07:00:00
lethal conditions = false
favorable hours = 38
LESD = 2019-06-13
WHIT Advisory: do not spray today
Growing degree days (base 56) since LESD = 483.7
Growing degree days (base 56) since May 1 = 1322.7
Records count: 216 out of 217
Most recent db ob to 8am EDT: 2019-07-03 08:00:00

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Fig. 5. Portion of a daily email alert sent to peanut disease advisory tool users that proves recommended spraying practices based on past weather conditions based on the Whiteville, North Carolina ECONet station (WHIT).

With the addition of 9 m air temperature sensors in 2019, SCO staff collaborated with researchers in the NCSU Department of Crop and Soil Sciences to develop the inversion monitoring tool (Table 2). This application detects temperature inversions–when 9 m air temperatures are higher than 2 m air temperatures–and determines the current viability of spraying herbicide. Herbicides, such as dicamba, are volatile and more likely to drift off-site during temperature inversions (Bish and Bradley 2017; Egan and Mortensen 2012). By using 2 m and 9 m air temperature data and 6 m wind speed data from ECONet stations, this tool summarizes inversion conditions for the local area around the station and visualizes the favorability of current weather conditions so growers can optimize herbicide application (Fig. 6).

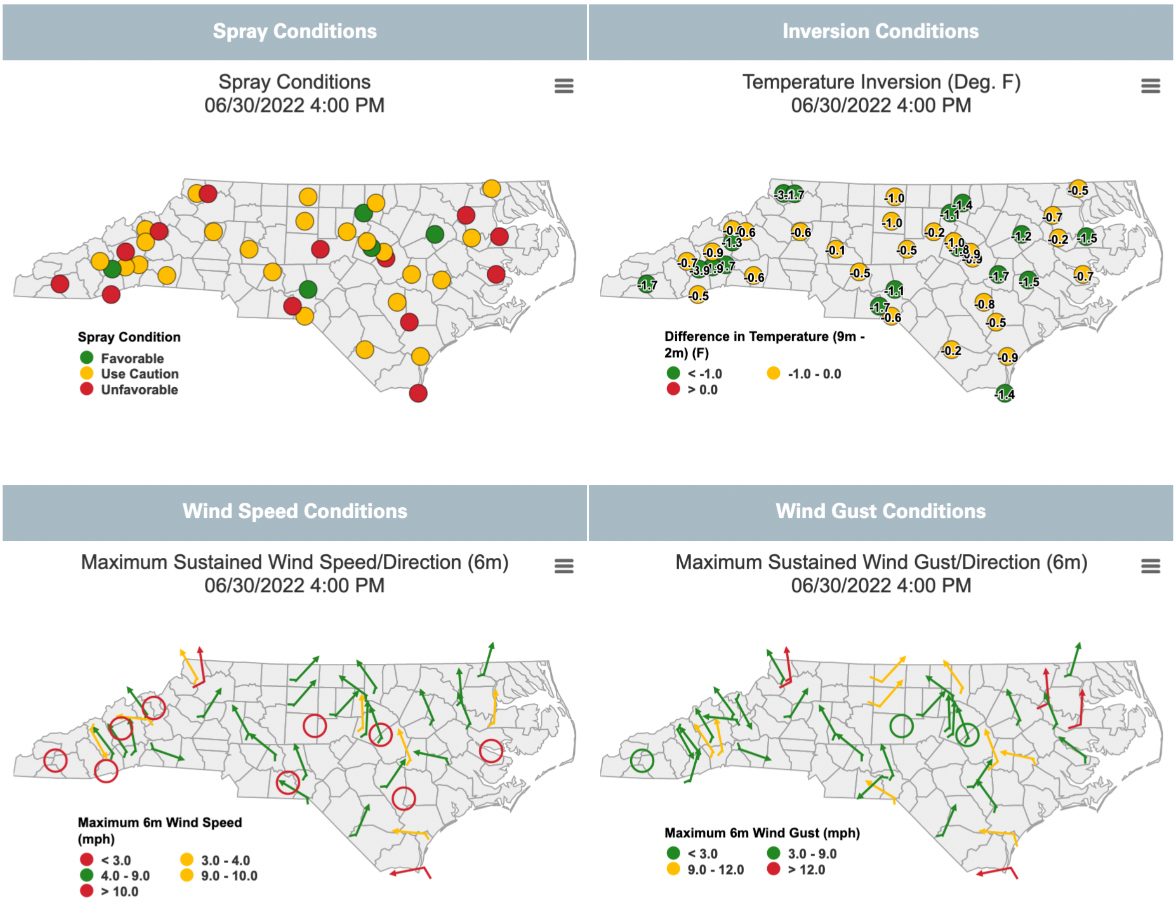

Fig. 6. ECONet Inversion Monitoring tool screenshot from June 30, 2022 at 4pm EST showing current favorability classifications for pesticide spray conditions (top left), current temperature inversion conditions (top right), current maximum sustained wind speed (bottom left), and current maximum wind gust (bottom right).

6.1.2 Wet Bulb Globe Temperature Tool

Human and animal heat health is a prevalent topic in North Carolina due to the humid temperate climate of the region. First used to combat heat stress illnesses within the United States military, wet bulb globe temperature (WBGT) values are used to determine the potential impact of heat stress on the human body (Budd 2008). The United States Occupational Health and Safety Administration (OSHA), the American Center of Governmental Industrial Hygienists (ACGIH), and the NWS offer categorical guidelines based on WBGT values (OSHA 2017; ACGIH 2017; NWS 2022; Dimiceli et al. 2011). These guidelines explain how long a person needs to rest out of direct sunlight to avoid heat stress. For example, under WBGT “elevated” conditions OSHA recommends that people take a 15 minute break out of direct sunlight for every hour they are working or exercising in direct sunlight. WBGT is a function of air temperature, relative humidity, wind speed, and total solar radiation. Under a solar load (i.e., daylight hours), we calculate WBGT as follows (Hunter and Minyard 1999):

$$WBGT = 0.7T_w + 0.2T_g + 0.1T_a$$

Without a solar load (i.e., nighttime hours), we calculate WBGT as:

$$WBGT = 0.7T_w + 0.3T_g$$

where T_w represents natural wet bulb temperature in degrees Celsius, T_g represents globe temperature in degrees Celsius, and T_a represents air temperature in degrees Celsius. We convert the final WBGT value to degrees Fahrenheit for easy interpretation by United States stakeholders, including but not limited to military personnel, agricultural workers, athletic associations, and local weather forecast staff, who regularly work outdoors during hot, humid summers in North Carolina.

As of 2022, ECONet is the only regional mesonet to directly measure air temperature and black globe temperature at all sites. Therefore, we only need to estimate natural wet bulb temperature to determine WBGT. We estimate T_w using methods from Bernard and Pourmoghani (1999), Stull (2011), Dimiceli et al. (2011), and a revised Dimiceli et al. (2011) method implemented by the NWS for the National Digital Forecast Database (Boyer 2022). The Bernard and Pourmoghani (1999) method estimates T_w as a function of air temperature, relative humidity, wind speed, and black globe temperature while the Stull (2011) and Dimiceli et al. (2011) methods are a function of air temperature and relative humidity. The Boyer (2022) method is a function of air temperature, relative humidity, wet bulb depression, wind speed, and solar radiation. We combine estimates for T_w with air temperature and black globe temperature observations from each ECONet station to determine WBGT (Table 2). We then show these ECONet WBGT values on a map that we color-code (Fig. 7) according to NWS WBGT heat stress categories (NWS 2022). WBGT tool users can select a date, time, and ECONet station location of interest to view associated WBGT data over time. We provide this interactive WBGT tool to stakeholders so they can make informed decisions about outdoor activity. At this time (as of 2022), WBGT calculations on our website use the Boyer (2022) method to estimate natural wet bulb temperature and we are collaborating with our local NWS weather forecast office to standardize our visualizations with methods used by other regional and national NWS offices.

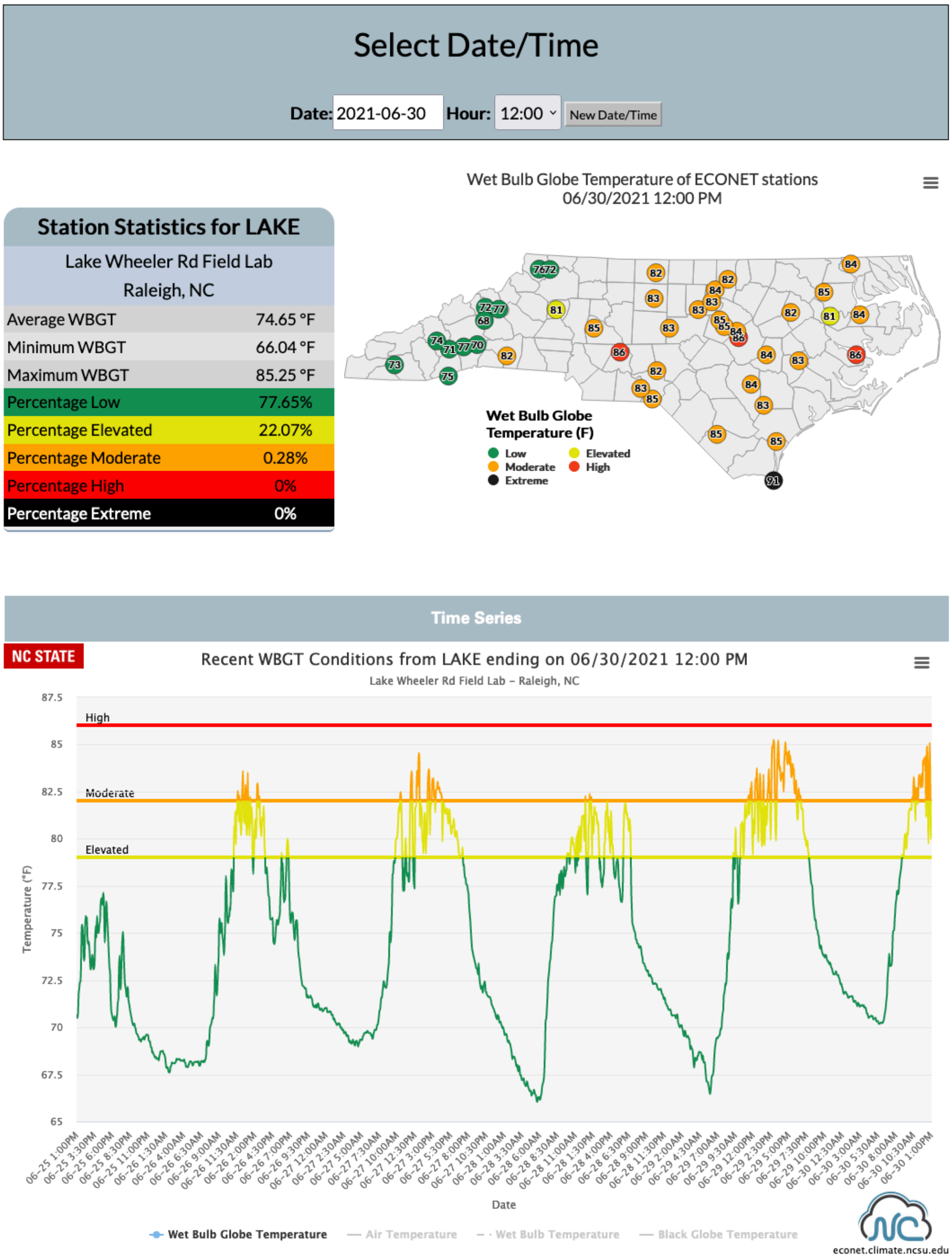

Fig. 7. Wet bulb globe temperature (WBGT) tool screenshot with a map of ECONet WBGT values from June 30, 2022 at 12pm EST (top) and time series of WBGT for the Lake Wheeler ECONet station (LAKE) in Raleigh, North Carolina (bottom). ECONet station locations are color-coded according to National Weather Service WBGT heat stress categories. Results presented here use the Boyer (2022) method to estimate natural wet bulb temperature. This tool is available online at https://econet.climate.ncsu.edu/wbgt/.

6.1.3 State Agency Applications

Many individuals and organizations in North Carolina leverage ECONet data in novel ways to make important decisions over the period of hours to years and across the various state ecological regions (i.e., the Mountains, Piedmont, and Coastal Plain). Here, we highlight the benefits of ECONet data to three state agencies: North Carolina Department of Air Quality, North Carolina Emergency Management, and North Carolina Forest Service. North Carolina Department of Air Quality forecasters benefit from high-elevation ECONet sites because these stations, in tandem with their own monitors, can provide an indication of large-scale westerly wind patterns that may spread pollution or create poor air quality across North Carolina (see the Wind Rose and Ambient Information Reporter tools in Table 2). North Carolina Department of Air Quality forecasters also use ECONet air temperature and wind speed data during heat events to track potential ozone formation, which is most likely to occur during hot temperatures and stagnant winds.

North Carolina Emergency Management staff use ECONet data for (1) state-wide impact summaries for hurricane maximum wind gusts and total rain and snow accumulations, (2) location-specific meteorological data summaries after natural disasters, and (3) communications relevant to winter weather outlooks and weather extremes. For example, during Hurricane Florence in September 2018, North Carolina Emergency Management staff included total rainfall and maximum wind gust maps, which included ECONet data, in weather announcements to senior agency leadership and to communications that reached hundreds of organizations across the state working to support individuals and communities impacted by the event.

North Carolina Forest Service supported the addition of 6 m wind speed and wind direction sensors to all ECONet towers in 2011 and since then shares ECONet data with the Weather Information Management System (WIMS) maintained by the National Wildfire Coordinating Group. Data submitted to WIMS are used to calculate National Fire Danger Rating System parameters, which can be visualize in the Fire Weather Intelligence Portal (Table 2). More specifically, this application leverages ECONet data and several other weather station networks to provide a high density of weather information and fire risk estimates across North Carolina and 12 other states. Lastly, North Carolina Forest Service staff use data from some ECONet stations to set district-level readiness plans (e.g., https://www.ncforestservice.gov/fire_control/fc_rpmap.asp) based on their calculated fire danger.

6.2 Outreach

ECONet data and stations provide many opportunities for the SCO to engage with the public; especially in areas where weather data is difficult to access. As part of their standard school curriculum, K-12 grade students often meet with us at a local ECONet station to learn more about the role of weather stations, how each sensor measures a particular atmospheric and environmental variable. K-12 school students and teachers can access ECONet data on SCO data portals (Section 3.4) and use ECONet data for science experiments and science and mathematics lessons. K-12 educators can also access pre-developed lesson plans such as the "Measuring Weather and Climate" lessons that use ECONet data (https://climate.ncsu.edu/learn/how-do-we-measure-the-weather-and-climate/). These lessons are available on the SCO education website (https://climate.ncsu.edu/learn/about-our-climate/). For larger public events, we set up a small-scale ECONet station, record real-time conditions on site, and share ECONet tools and visualizations to discuss ECONet stations and the mission of the SCO. These outreach events provide an opportunity to directly interact with North Carolina communities and data users. Additionally, these interactions can often catalyze discussions regarding the installation of new ECONet stations and ECONet data applications.

6.3 Research

ECONet data are used in a wide range of research conducted in the fields of agricultural sciences, atmospheric sciences, environmental sciences, health sciences, and more. For example, ECONet data have been used to explore the mechanisms behind regional weather patterns (e.g., Sims and Raman 2016), the application of ECONet data to pressing weather and climate issues (e.g., Rennie et al. 2021), the development of crop models (e.g., Perry and Wehner 1990), among others. A summary of peer-reviewed studies using ECONet data (as of 2022) are shown in Table 3.

Table 3. Description of peer-reviewed studies using ECONet data (as of 2022).

Study Number	Reference	Description
1	Perry and Wehner, 1990	Development and evaluation of a cucumber harvest date model
2	Perry et al., 1993	Development and evaluation of a pepper harvest date model
3	Perry, 1994	Discussion of current and future agricultural weather observation needs for cooperative extension services
4	Perry, 1998	Discussion of weather monitoring needs for frost and freeze protection of horticultural crops
5	Sims, 2001	Validation of a numerical mesoscale precipitation model for North Carolina
6	Boyles, 2006	Analysis of radar-based, mesoscale precipitation processes in North Carolina and South Carolina
7	Holder et al., 2006	Comparison of automated ECONet data and manual National Weather Service's Cooperative Observer Program data (COOP)
8	Pan et al., 2012	Classification of ECONet station soil types
9	Xia et al., 2015	Evaluation of automated quality control procedures for North American Soil Moisture Database (NASMD) products
10	Coopersmith et al., 2016	Validation of machine learning model-derived near surface soil moisture estimates
11	Doran and Golden, 2016	Analysis of temporal trends in urban heat islands for Raleigh-Durham, North Carolina
12	Quiring et al., 2016	Development and applications of the North American Soil Moisture Database (NASMD)
13	Sims and Raman, 2016	Analysis of summer mesoscale circulation patterns along the East Coast of the United State
14	Rennie et al., 2021	Validation of heat stress indices for the United States Climate Reference Network (USCRN)
15	Ahn et al., 2022	Validation of experimental wet bulb globe temperature hindcast across the United States
16	Shea et al., 2022	Evaluation of random forest models for liquid manure application identification in eastern North Carolina satellite images

7. Future of the North Carolina ECONet

Overall, the mission of the North Carolina ECONet is to serve the data, research, and application needs of North Carolinians for a wide range of sectors; including but not limited to, agriculture, forestry, public health, emergency management, natural resources management, and outdoor recreation. Despite the numerous ECONet-driven tools, outreach, and research outlined here, many opportunities remain to apply ECONet data to a wide range of cutting-edge research questions and applications. In the short-term, ECONet will continue to provide high frequency, quality-controlled data for various research projects and applications pertinent to North Carolina stakeholders. In the long-term, we will establish collaborations, conduct high quality research, and build out new value-added applications, including web tools and data visualizations geared towards summarizing and improving the accessibility of ECONet data for practical use cases. Given the regional focus and placement of ECONet stations, we recognize there are opportunities to support and enable cutting-edge research that would have otherwise been difficult due to limited data availability on private lands (e.g., Shea et al., 2022). Additionally, several stations have over 30 years of data on record; therefore, there are research opportunities for long-term trend analyses. We will work to build new partnerships and establish ECONet and ECOExt stations that fill in data coverage gaps while providing publicly available data access to North Carolina communities. When combined, these short- and long-term goals mark a new phase of the ECONet—one that focuses on leveraging past, present, and future ECONet data to support user-driven weather and climate research and applications.

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CRedIT Statement (https://casrai.org/credit/): SMS, SPH, MDN, WL, and JAM formulated the manuscript concept, wrote the original draft, and reviewed revised versions. KDD reviewed revised versions. SMS and SPH prepared the visualizations. SMS administered the project and supervised work on the manuscript. KDD supervised work on the manuscript.

Data Availability Statement

There is no code or data associated with this paper. Additional tables and figures are included in the separate supplemental information document.

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Supplemental Material for

A Technical Overview of the North Carolina ECONet

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File Continents:

This file contains Table S1, Table S2, and Figure S1 as referenced in the main text of the article.

Number of Pages: 3

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This document includes the supporting tables for this study as referred to in the main text of the article. The associated manuscript is also available as a preprint on the EarthArXiv (INSERT_LINK_HERE).

Table S1. Quality control (QC) scores and their associated descriptions.

QC Score	Description
QC -1	Data has not been quality controlled.
QC 0	Data has passed all QC tests.
QC 1	Data has failed 1 QC test, but is more likely good than not.
QC 2	Data has failed more than 1 QC test and is more likely bad than not.
QC 3	Data has failed all QC tests or has been determined erroneous by human QC.

Table S2. Quality control (QC) scores arranged according to QC flag combinations. Abbreviations: manual State Climate Office of North Carolina staff/user check (U), range check (R), buddy check (B), intersensor check (I), trend check (Z). Numeric values following each letter (e.g., 0 in U0) in the QC flag indicate a range of QC outcomes from pass (0) to fail (4). See Section 5.1 of the main text for a detailed description of these numeric flag values.

QC 0		QC 1		QC 2		QC 3	
U0	R0Z0	R0Z2	R0I0Z2	R0Z4	R0I2	U4	R0I2Z4
R0	R0I0Z0	R0I0Z4	R0B2Z0	R0I2Z0	R0I4	R0I0Z4	R0B1Z4
R0I0	R0I1Z0	R0B3Z0	R1	R0I4Z0	R0B0Z4	R014Z4	R0B4Z0
R0I1	R0B0I0Z0	R1B0Z4	R1B1	R0B2	R0B2Z4	R0B3Z4	R0B5Z0
R0B0	R1Z0	R1B2Z0	R2Z0	R0B3	R1Z4	R0B4Z4	R4
R0B1Z0	R1B0Z0	R2B0	R2B2Z0	R1B1Z4	R1B2	R0B5Z4	R1B3Z4
R1B0	R2B0Z0	R3B0Z0	R3B1Z0	R1B2Z4	R1B3Z0	R1B3	R1B4Z4
R1B1Z0	I0	I1	B0Z4	R2	R2Z4	R1B4Z0	R1B5Z4
Z0	B0Z0	B1	B2Z0	R2B0Z4	R2B2	R1B5Z0	R2B3Z4
B0	B1Z0			R2B3Z0	R3	R2B2Z4	R2B4Z4

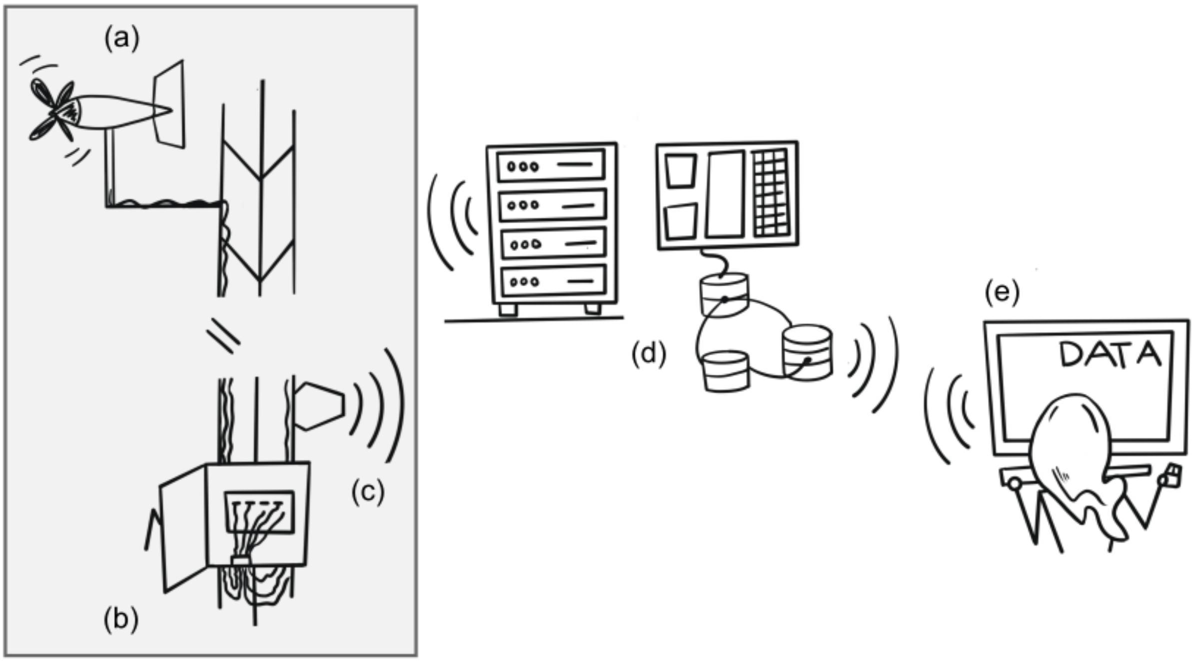

Fig. S1. Diagram showing the flow of ECONet data from the (a) individual sensor, (b) to the station datalogger, and then (c) transmitting the data off-site using various communication methods, (d) to being stored on databases at computer servers located at the State Climate Office of North Carolina and North Carolina State University and (e) shared on public data portals. The grey shaded box around (a), (b), and (c) indicates processes taking place on-site (i.e., at the ECONet station location). This is separate from off-site processes like those in (d) and (e), which happen away from the ECONet station location.