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 2023) automated stations collecting 12 environmental variables every minute across North Carolina. Measured variables include air temperature, precipitation, relative humidity, barometric pressure, wind speed, wind direction, total solar radiation, photosynthetically active solar 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. 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. 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 consists of 44 (as of 2023) automated stations located across the state. Each station collects 12 environmental 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.

Keywords: atmosphere, mesoscale processes, automated weather stations, instrumentation/sensors, decision support

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 2023) automated environmental sensing stations across North Carolina (Fig. 1, blue circles). 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. 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 research and 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 environmental monitoring, research, and applications (Brock et al. 1995, Shafer et al. 2000, Schroeder et al. 2005, McPherson et al. 2007, Mahmood et al. 2019, Brotzge et al. 2020, Fiebrich and Crawford 2001, Fiebrich et al. 2006, 2010, 2020, Patrignani et al. 2020a; 2020b).

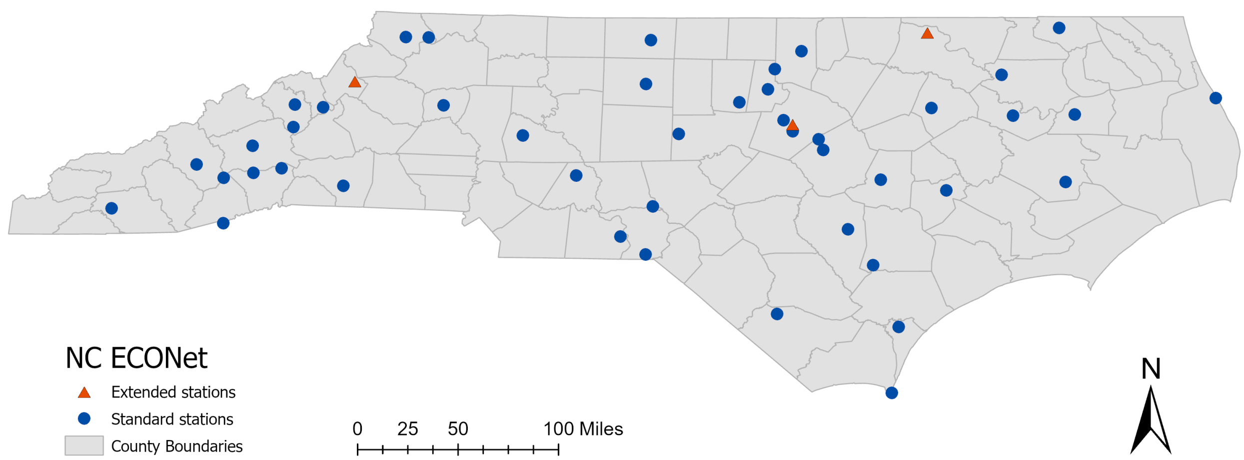


Fig. 1. Map of North Carolina Environment and Climate Observing Network (ECONet) stations. Standard ECONet stations are shown as blue circles and non-standard ECONet Extended (ECOExt) stations are shown as orange triangles.

The development of 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 (i.e., 1-minute intervals), quality controlled (i.e., standardized automated and manual processes) environmental data for an even wider 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-funded agricultural research stations and university field laboratories 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 and crop condition monitoring (Perry 1994) such as developing cucumber harvest date models (Perry and Wehner 1990) and providing information about frost and freeze conditions (Perry 1998). 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 because of the broader role of the SCO, which is a public service center that supports the weather and climate research, education, Extension, and monitoring needs of North Carolina. Between 1997 and 2000, the SCO collaborated with state and local agencies 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 Division of Air Quality Network (DAQNet), respectively. By 2000, all 20 weather stations under the SCO's purview were updated from 3 meter tripods to 10 meter towers to meet World Meteorological Organization standards (WMO 2021). In 2001, the various distinct networks (i.e., AgNet, EMNet, DAQNet) were merged into the present-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 transitioned from collecting measurements from every hour to every minute. In 2012, the SCO was awarded a National Oceanic and Atmospheric Administration (NOAA) National Mesonet Program contract to support ECONet station maintenance and facilitate the delivery of ECONet data into federal weather data repositories (e.g., Meteorological Observational Database and Data Delivery System). The goal of NOAA's National Mesonet Program is to support smaller weather station networks capable of "[delivering] critical information required for improved weather prediction and warnings across the United States" (NMP 2022).

To date, ECONet data are freely available to the public through SCO data portals and various U.S. federal agency-led portals (Section 3.4). Furthermore, SCO staff are exploring new ways to meet the research and application needs of stakeholders in North Carolina; whether that be expanding the footprint of ECONet stations, installing new sensors, designing and implementing new web tools, or conducting new analyses of historic ECONet data.

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 partnered 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 these new partners as well as diverse land use types, data applications, and locations that lacked established automated weather stations. In the 2000s, the SCO first envisioned hosting one ECONet station in each of the 100 counties that make up North Carolina. The SCO currently collects data at ECONet stations located across 37 counties. At present, the majority of ECONet stations (64%) are located on land covers defined by the National Land Cover Dataset (NLCD) as cropland/pasture (Anderson et al. 1976, MRLC 2019, Dewitz and USGS 2021). To represent the diverse ecology and topography of North Carolina, stations are also located in open areas on land classified by the NLCD as deciduous and evergreen forest (7%), shrub and herbaceous (9%), barren (2%), and urban/built-up (18%; Anderson et al. 1976, MRLC 2019, Dewitz and USGS 2021). These land cover categories provide a broad description of land cover surrounding ECONet stations. ECONet staff (henceforth, we) manage the direct footprint of ECONet stations (Fig. S1) so they match the natural vegetation of the surrounding area (e.g., Fig. 2); the soil is not intentionally left bare.

2.2. Station Siting Requirements

We follow World Meteorological Organization (WMO 2018, 2021), United States Environmental Protection Agency (USEPA 1987, 2000), American Association of State Climatologists (AASC; Bingham et al. 1985), American Society for Civil Engineers (ASCE; Ley 1993, Brown 1993), and mesonet community (Fiebrich et al. 2020) guidelines combined with manufacturer guidelines (e.g., Campbell Scientific 2022) as closely as possible to ensure data accuracy and proper representation of the surrounding area. In the event that a proposed station location does not meet all standard guidelines, we work directly with station partner(s) to find the most suitable location with the fewest limitations.

There are five key factors that we consider when determining the location for a new station (Table S1). The first factor is the distance from existing ECONet stations as well as other existing national, state, and local automated weather stations (e.g., Automated Surface Observing Systems network). Ideally, ECONet stations are placed an average distance of 30 km away from one another to prioritize filling existing environmental data gaps and optimizing mesonet-scale measurements (Fiebrich et al. 2020). We recognize established methods to formally optimize station placement (e.g., Vose and Menne 2004, Leeper et al. 2019, Patrignani et al. 2020b) and are working to incorporate these into existing site establishment practices. 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 2018). The third factor is landscape slope. We aim to site ECONet stations in areas with minimal slope. Minimal slope is defined by the AASC (2019) as “flat to gently rolling” land and further specified in the U.S. Department of Agriculture’s Soil Survey Manual as slope classes having a “nearly level” (0-3%) to “undulating” (1-8%) to “rolling” (4-16%) slope (USDA 2018). Ideally, the immediate area around an ECONet station footprint is “nearly level” (0-3%) to ensure the station can be easily and safely lowered into the horizontal position for maintenance. The overall landscape slope surrounding ECONet stations varies across the state to accurately represent the region. The average and standard deviation of landscape slopes surrounding ECONet stations in the Mountains (western NC) is 13.7% +/- 6.62%, in the Piedmont (central NC) is 3.63% +/- 2.51%, and in the Coastal Plain (eastern NC) is 2.38% +/- 1.65% (Newcomb et al. 2013, NCSU 2013). The fourth factor is accessibility, which refers to both year-round accessibility by road as well as communication accessibility via strong cellular service or another communication method (e.g., landline). The fifth factor is that the new ECONet station will benefit one, if not multiple stakeholders while also representing a unique geographic, ecological, or social aspect of North Carolina that is either not yet represented or underrepresented by current mesonet-scale monitoring.

Currently, we use geographic information systems to spatially rank potential new station locations based on a combination of distance from existing automated weather stations, accessibility by road, land cover type, percent slope, and distance from state-owned land. This spatial ranking provides us with a starting point to discussion potential ECONet sites with stakeholders, However, we ultimately determine the final ECONet station site based on stakeholder interest and engagement, whether we can identify a location that maximizes the standard siting criteria discussed above, as well as the availability of funding to support station installation and long-term maintenance.

2.3. Station Layout

The layout of a standard ECONet station is depicted in Figs. 2 and S1. Each ECONet station is located on a plot of land roughly 10 m by 7 m following the WMO preferred guidelines (WMO 2018, 2021). Every station consists of a 10 m aluminum tower (9-30, Universal Towers) set in a 1.2 m long by 1.2 m wide by 1.2 m deep 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 (Fig. S1). 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. Each standard ECONet station includes a suite of environmental sensors that are both surrounding and attached to the tower (Section 3.1), a power supply (Section 3.2), and communications antenna (Section 3.3).

Sensor-specific maintenance, manufacturing, and quality control details are included in Section 3.1, Section 5, and Table 1; however, the overall layout of these sensors at a standard ECONet station is as follows (Figs. 2 and S1). 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 (i.e., Vaisala WXT-536 in Table 1), an air temperature and relative humidity sensor housed in a solar radiation shield (i.e., Vaisala HMP-155 in Table 1), a total solar radiation sensor and a photosynthetically active solar radiation sensor. The all-weather sensor measures air temperature, relative humidity, precipitation (impact sensor-based), barometric pressure, wind speed and wind direction. All standard ECONet stations have redundancy in temperature, precipitation, and relative humidity observations at 2 m above ground level. We align the small arrow on the underside of the all-weather sensor so it faces true north to ensure correct wind direction readings from the ultrasonic anemometer. We install the solar radiation sensors on a boom that points 180 degrees from true north (i.e., south) to allow full exposure to the sky and sun's transit without any shadows cast by the tower or any instruments. We measure black globe temperature at 2 m above ground level by mounting it on a 0.3 m boom that is perpendicular to the boom holding the solar radiation sensors. We align the black globe temperature sensor facing 180 degrees from true north. 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. We align the junction box on the anemometers vertical shaft to face 180 degrees from true north. This ensures correct wind direction readings. In addition to measuring air temperature at 2 m above ground level, each ECONet station has a solar radiation shield that we mount just off the tower at a height of 9 m. This solar radiation shield houses a sensor to measure air temperature higher up in the tower profile. We mount a leaf wetness sensor at a 45^{o} angle 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 true north. This minimizes exposure to solar radiation and prolongs wetness or dew exposure, which would otherwise be lost due to solar radiation. We take care to position sensors so they are not interfering with one another. For example, we make sure the black globe sensors it is not shadowed by or does not cast a shadow on other sensors such as the solar radiation sensors.

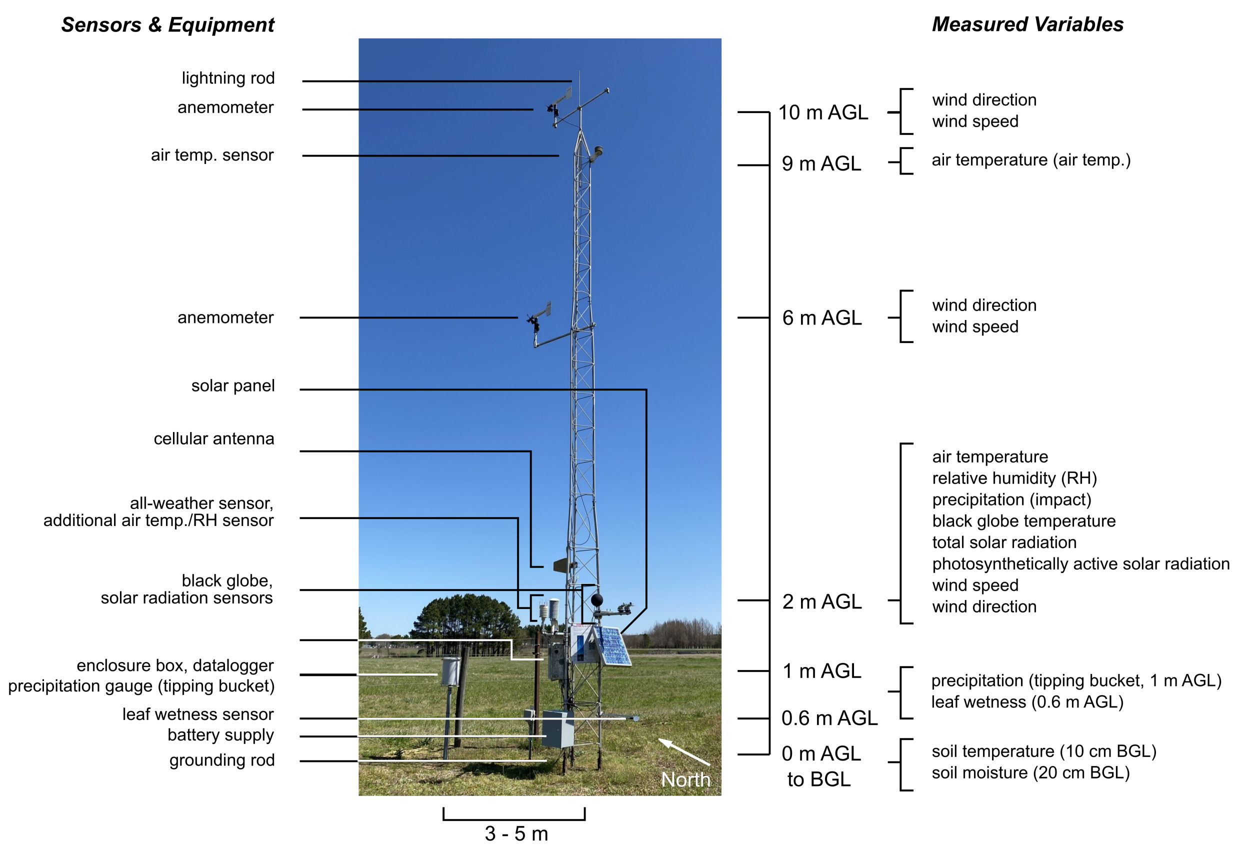


Fig. 2. Image displaying the layout of a standard ECONet station. The tower pictured is the Goldsboro, North Carolina (GOLD) ECONet station in March 2022. Abbreviations: above ground level (AGL), below ground level (BGL). See Fig. S1 for a top view.

Surrounding the tower, the layout of a standard ECONet station is as follows (Figs. 2 and S1). We install soil temperature and soil moisture sensors at a distance of 2 to 3 m away from the tower and burry their cables along a 10 cm deep trench. We install the soil temperature sensor at 10 cm below natural vegetation and the soil moisture sensors at 20 cm below natural vegetation according to manufacturing installation guidelines. Since our network was originally designed as an agricultural weather network, these depths are used to monitor soil temperature and moisture changes in the soil surface for irrigation and tillage management (Evans et al. 1996). We install soil temperature and moisture 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. 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.

3. Sensors, Equipment, and Data

The foundation of ECONet station data collection starts with each individual sensor measuring a particular environmental variable (e.g., wind speed, Fig. S2a). Once observations are collected by the sensor, these data are aggregated by and saved on the tower datalogger (Fig. S2b) before being transmitted offsite (Fig. S2c). 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. S2d), and ultimately, made publicly available through several SCO data portals (Fig. S2e). 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 standard ECONet station records 12 different variables at multiple heights (e.g., 2 and 10 m wind speed) and using various sensing approaches (e.g., tipping bucket versus impact sensor precipitation observations) for a total of 18 unique measurements (Table 1; Figs. 2 and S1). We install and maintain all sensors according to manufacturer sensor specifications (Table 1). This includes, but is not limited to the measurement height, installation preparations, and the sensor calibration and replacement frequency. For example, we replace soil temperature sensors every five years according to the manufacturer recommendations (Table 1). All measured variables undergo quality control checks, which we describe in Table 1 and Section 5.

Table 1. Summary of standard ECONet sensors, corresponding manufacturer information, quality control checks performed, and replacement and calibration frequency. All sensors are mounted at 90^{o} (i.e., vertical) unless specified in the main text. See Section 5 for more on quality control (QC) checks. 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 (Angle)**	**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 HMP-155 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 solar 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 HMP-155	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 5 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, 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 (Figs. 2 and S2b) and serves to collect and store all observations from all sensors on an ECONet tower before these data are transmitted off-site. 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.

Of the 44 ECONet stations (as of 2023), 31 use solar power while the remaining 13 use alternating current (AC) power. For solar powered stations, a 20 W solar panel supplies 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 cable running to a power box near the ECONet tower, which contains a surge protector and an AC-DC converter. A second underground cable supplies electricity from a power box to a charging regulator within the enclosure box attached to the tower. The charging regulator funnels electricity to the datalogger and a 12 V 7 Ah backup battery, the latter which can support 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. S2c). The most common data communication method that we use is a cellular modem connection. As of 2023, 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

All ECONet observations are stored locally (i.e., in the field) as a binary data table within the random-access memory of the datalogger until they can be transmitted back to the SCO where they are then stored in Loggernet software-formatted data tables (Campbell Scientific) installed on one of two Microsoft Windows (operating system) machines (Fig. S2d). 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 Technology, which receives communications from the remaining cellular-based ECONet stations. Once stored in ASCII 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 databases every five minutes (Fig. S2d). The multiple database structure minimizes data access latency issues and provides redundancy by backing up data. In addition, we have a series of ECONet scripts that are scheduled to (1) complete automatic quality control checks of ECONet data twice per hour (Section 5.1) and (2) generate summary quality control score emails once per day (Section 5.2).

Once ingested into the Linux database and quality controlled, ECONet data are freely available to the public (Fig. S2e) via the SCO Cardinal data portal and Station Scout tool (NCSCO 2023a) and the CLimate Office Unified Data System (CLOUDS) application program interface (API; NCSCO 2023b). The Station Scout tool also 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 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 multiple weather data networks all in one place. In addition to SCO-hosted portals, ECONet data are available to the National Weather Service (NWS) and other federal agencies through the Meteorological Observational Database and Data Delivery System (MADIS; NWS 2018) 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 (Fiebrich et al. 2006, 2020). Routine maintenance occurs once each season in the spring, summer, and fall. Spring maintenance runs are often the busiest and consist of replacing or rotating in newly calibrated leaf wetness sensors, solar radiation sensors, HMP-155 sensors (i.e., 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 rain gauges using a field calibration device (FCD-314 or FCD-653, HyQuest Solutions), checking the integrity of soil moisture and temperature sensor cables, which can get damaged by vegetation maintenance, and replacing soil moisture and temperature sensors that have reached the end of their lifespan or are not functioning as expected. During fall maintenance runs, we lower towers into a horizontal position via a hinge mechanism at the base. This allows us access to replace propeller shaft bearings in the anemometers at 6 m and 10 m as well as check the integrity of and clean the 9 m air temperature sensor and its solar radiation shield. Spring, summer, and fall routine maintenance runs all consistently include the following routine maintenance tasks: (1) trimming vegetation that is obstructing sensor operation (i.e., weeding, mowing the grass) to a height that is consistent with the surrounding landscape, (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.

Emergency maintenance is done on an as-needed basis all year round, provided there is safe access to the station of concern. For emergency maintenance visits, we restore a station to its fully-functioning state, or in rare cases, restore 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 involve repairing or replacing equipment after it has been destroyed due to extreme weather events or 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 tasks to be completed along with a generalized schedule. We 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 station metadata such as station-specific wiring diagrams and other relevant station notes and directions. In addition to creating an itinerary, we check the weather and road conditions for the period of field work to avoid challenges that may hinder safe routine and emergency maintenance. For our region, these conditions may include extreme rainfall, wind, heat, dense fog, and icy road conditions. Upon arriving at a station, we perform a quick visual and audible inspection of the site, examining the station 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 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. Before leaving an ECONet station, we verify data quality and ensure data communications are flowing uninterrupted back to the SCO computer servers and take metadata photos of the station surroundings in all eight cardinal and intercardinal directions as well as a profile photo of the full station. We upload and share these photos via public-facing ECONet station webpages because they provide data users context of potential obstructions that were difficult for us to avoid while siting the station. Additionally, we backup past photos to keep a visual, spatial, and temporal record of station surroundings. Upon returning to the office, we transfer written metadata records from the station notebook into a digital database, including: dates/times of the visit, staff member conducting the maintenance, new equipment serial numbers, and short descriptions of any station maintenance performed. This database allows us to easily catalog metadata as well as prioritize and plan future maintenance.

5. Data Quality Control

ECONet observations are continuously monitored using automated (Section 5.1) and manual (Section 5.2) quality control checks to ensure they are of high quality when they are released publicly (Shafer et al. 2000, Fiebrich et al. 2010, 2020). All ECONet observations stored in the previously mentioned Linux database (Section 3.4) have an associated flag column that encodes 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, when obtaining data from SCO-hosted data portals, users must take care to view and use associated quality control flags.

5.1. Automated Quality Control

We conduct automated quality control of ECONet data by programmatically scheduling a series of quality control scripts to analyze data that was most recently added to the Linux database. As mentioned in Section 3.4, these scripts run twice an hour and include four quality control checks: (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. 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). The physical bounds of the sensor are determined by the manufacturer. 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 solar 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 they undergo a 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.

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. Buddy check flags vary from B0 (pass) to B5 (highest level of failure). Using the Barnes objective analysis (Barnes 1964; Shafer et al. 2000; Schroder et al. 2005; Fiebrich et al. 2010), an interpolated value is assigned to the observation using inverse distance weighting of nearest neighbors. The number of stations included in this analysis is limited to either 15 stations or all stations within a 50 km radius of the station, whichever is fewer. Similar to Feibrich and Crawford (2001) and Fiebrich et al. (2010), the observation passes the buddy check if the interpolated and observed values are within the threshold determined dynamically for a particular variable. The severity of the buddy check flag is determined by the magnitude of the difference between the interpolated and observed values. To account for the variable specific thresholds, static factors of 1, 1.6, 3.5, and 5.1 are assigned to determine the failure severity. For example, if the air temperature threshold value is 4.1 C, a B0 flag is assigned when the difference between an observation and interpolated value is less than 4.1 C. A B1 flag is assigned when the difference between an observation and interpolated value is greater than 4.1 C but less than 6.6 C. A B5 flag—the highest level of failure—is assigned when the difference between the observed and interpolated value is greater than 20.9 C (4.1 multiplied by a static factor of 5.1). We determined these static factors after an extensive long-term analysis of ECONet data across multiple variables.

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; Table 1), and thus, is dependent on the variable being tested. The purpose of the intersensor check is to ensure that the redundant sensor measurements are reporting similar values. Intesensor flags have three possible values: I0 (pass), I2 (suspect), or I4 (failure). If multiple sensors measure the same variable, we use the sum of the sensor accuracy for each sensor (i.e, +/- 0.2 C, +/- 2%) to compare differences. For example, the air temperature intersensor check determines the difference between the two sensors. If the difference exceeds the sum of the accuracy between the two sensors, it is assigned an I2 flag. If the difference exceeds twice the sum of the accuracy, it is assigned an I4 flag. In some cases, we perform an intersensor check between sensors that do not measure the same variable. For these cases, we use a comparison ratio determined from published literature. For example, when comparing the total solar radiation and photosynthetic active solar radiation sensors, we use an empirical ratio determined by Rao (1984) and Akitsu et al (2022). If the ratio calculated from ECONet observations is outside the empirical ratio +/- 10%, the observations are assigned an I2 flag. If the ratio calculated from ECONet observations exceeds the empirical ratio +/- 20%, the observation is flagged I4.

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. Trend check flags include either Z0 (pass), Z2 (suspect), or Z4 (failure). 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 or when soil moisture sensors approach site-specific field capacity or wilting point values (Pan 2010, Pan et al. 2012).

All automated check flags are combined into one flag serial code (e.g., R0B0I0Z0) for each observation and saved in a column of the Linux database. We then use this flag serial code to calculate an automated quality control score. The quality control score ranges from -1 (i.e., value not quality controlled; Q-1 in Fig. 3) to 3 (i.e., value fails quality control; Q3 in Fig. 3). A quality control score of 0 indicates the observation passed all automated quality control checks (Q0 in Fig. 3). For a list of all quality control score definitions and quality control flag combinations, see Tables S2 and S3, respectively.

5.2. Manual Quality Control

Following automated quality control, we carry out 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 every day before 6:30am Eastern Time that details the quality control score percentages for each ECONet station (Fig. 3). This email 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 left panel of the QCDV shows results for all stations and individual sensors. The right top panel shows the time series plot for the selected sensor measurement variable with observations colored by quality control score. The right bottom panel of the QCDV 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. 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. The daily email alert and corresponding QCDV were custom developed and implemented in PHP and Javascript code by SCO staff 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 quality control flag to the automatic quality control flags. Namely, 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 showing automated quality control scores by station. Stations are ordered 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 "#" symbol indicates the number of total observations, when less than 1%, that failed automated quality control checks (Section 5.1). QC-1 to QC3 refer to QC scores of -1 to 3 (Section 5.1).

Fig. 4. ECONet Quality Control Data Viewer (QCDV) graphical user interface window showing photosynthetic active solar radiation (PAR) observations at the Williamsdale Field Lab ECONet station (WILD) in Wallace, North Carolina on July 1, 2022.

6. Applications, Outreach, & Research

6.1. Applications

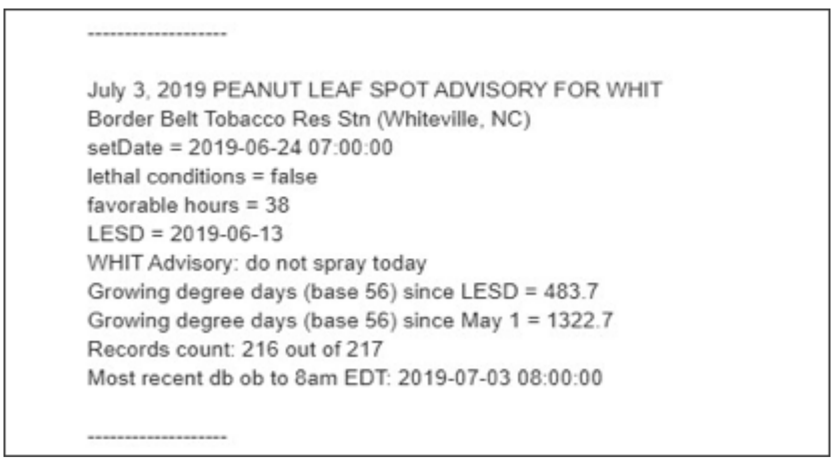
In addition to the extensive monitoring of real-time data, the SCO and its collaborators create applications that use ECONet data to help local, state, and federal partners make quick and data-driven decisions. Many of these applications are typically in a map, graph, or tabular form and are presented 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 Division of Air Quality and North Carolina Emergency Management).

Table 2. Description of applications using ECONet data (as of 2023). All ECONet measured variable heights are given in above ground level units. To view these applications, visit the ECONet website (ECONet 2023).

Number	Application Name	Description	ECONet Measured Variables
1	Peanut Disease Monitoring & Alerts	Daily alert during growing season to notify 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
2	Inversion Monitoring	Map displaying the current conditions rating for herbicide spraying.	2 m and 9 m air temperature, 6 m wind speed
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
4	Growing Degree Days	Time series displaying the cumulative number of growing degree days over the course of a year	2 m air temperature
5	Wind Rose	Rose chart showing the frequency of winds from different directions, at different speeds, over a given period of time	10 m wind speed and wind direction
6	Ambient Information Reporter	Map displaying past, current, and forecasted 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
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 total solar radiation, soil moisture, soil temperature

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 notify 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.



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

Fig. 5. Portion of a daily email alert sent to peanut disease advisory tool users that provides 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, Fig. 6). 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.

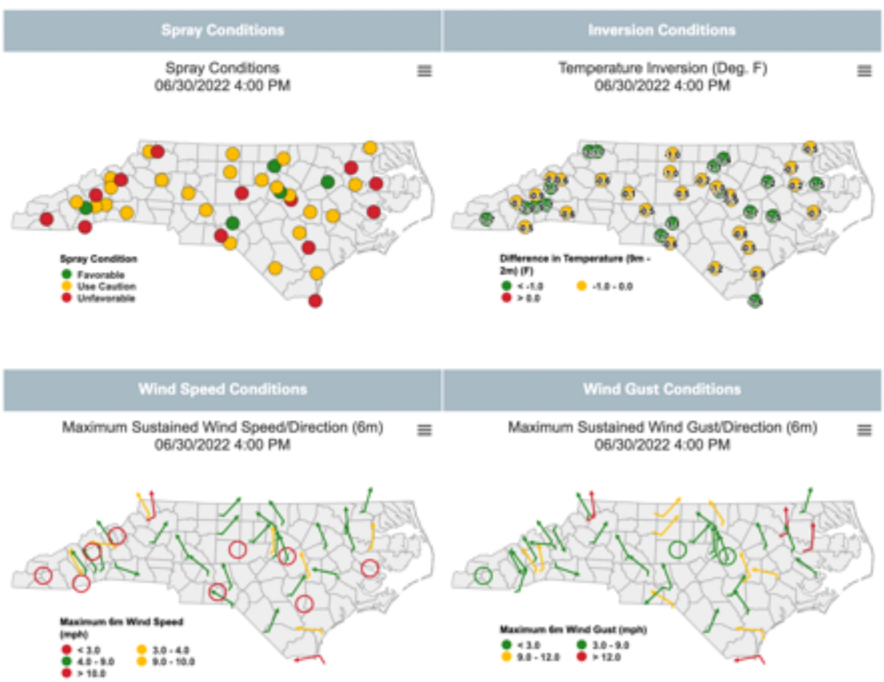


Fig. 6. ECONet Inversion Monitoring tool screenshot from June 30, 2022 at 4pm EST showing current favorability classifications for pesticide spray conditions (top left), current temperature inversion conditions (top right), current maximum sustained wind speed (bottom left), and current maximum wind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

6.1.2 Wet Bulb Globe Temperature Tool

Human heat risk is a prevalent topic in North Carolina due to its humid temperate climate. Wet bulb globe temperature (WBGT) is an emerging heat risk metric derived from multiple environmental variables that influence how humans feel heat stress (e.g., temperature, humidity, wind speed, and solar radiation; Budd 2008). The United States Occupational Safety and Health 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; Rennie et al. 2021):

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

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 2023, ECONet is the only regional mesonet to directly measure air temperature and black globe temperature at all sites. Therefore, we only need to estimate T_w to determine WBGT. We can 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, dew point temperature, wet bulb depression, wind speed, atmospheric pressure, solar radiation, and sky cover. We combine estimates for T_w with air temperature and black globe temperature observations from each ECONet station to determine WBGT. We then show these ECONet

WBGT values on a map (Fig. 7, Table 2) colored by NWS WBGT heat risk category (NWS 2022). WBGT tool users can select a date, time, and ECONet station location of interest. We provide this interactive WBGT tool to stakeholders so they can make informed decisions about outdoor activities. At this time, WBGT calculations on our website use the Boyer (2022) method to estimate wet bulb temperature and we are collaborating with our local NWS weather forecast office to standardize ECONet visualizations with methods used by regional and national NWS offices. The tool shown in Fig. 7 is available online at https://econet.climate.ncsu.edu/wbgt/.

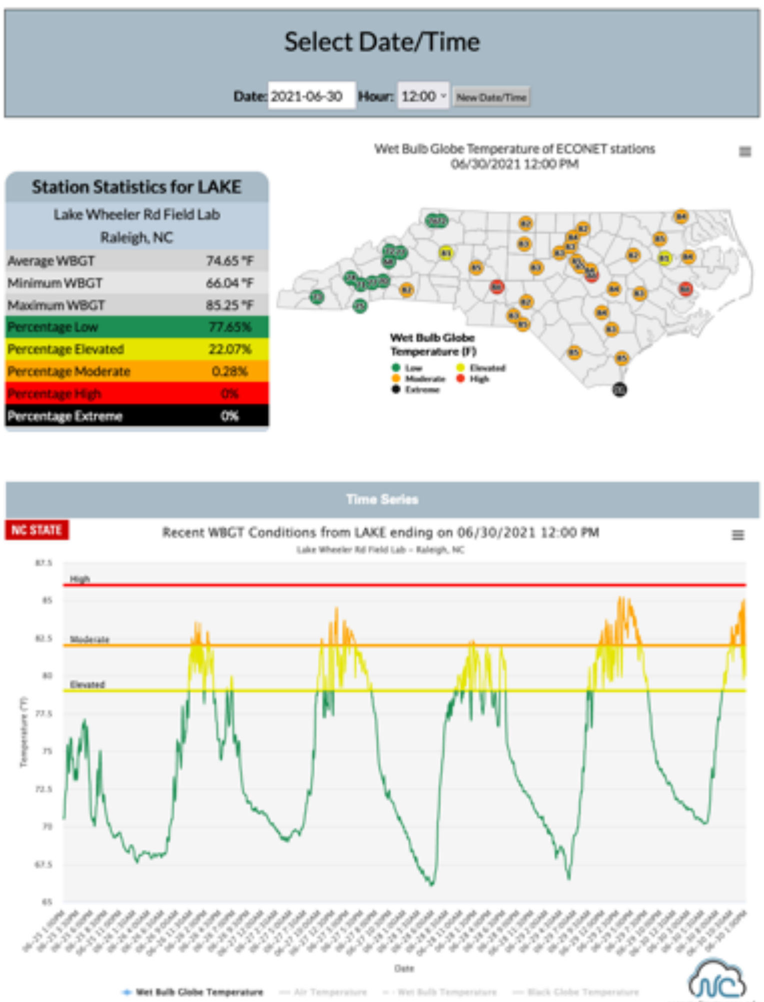


Fig. 7. Wet bulb globe temperature (WBGT) tool screenshot with a map of ECONet WBGT values from June 30, 2021 at 12pm EST (top) and time series of WBGT for the Lake Wheeler ECONet station (LAKE) in Raleigh, North Carolina (bottom).

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). We highlight the benefits of ECONet data to three state agencies: North Carolina Division of Air Quality, North Carolina Emergency Management, and North Carolina Forest Service. North Carolina Division 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 Division 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 visualized 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 (NCSCO 2023c). These lessons are available on the SCO education website (NCSCO 2023d). 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.

In instances where there is an engaged stakeholder yet funding for a full 10 m tower is limited or an existing station already exists, SCO will work with the stakeholder to establish what is known as an ECONet Extended (ECOExt) station (Fig. 1, orange triangles). ECOExt stations do not have all the sensors and equipment of a standard ECONet station (Sections 2 - 3 and Table 1), but they complement standard ECONet by providing technical support and publicly accessible data to regional partners and North Carolina communities.

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 (Sims 2001; Boyles 2006; Sims and Raman 2016), the application of ECONet data to pressing weather, climate, and environmental issues (Doran and Golden 2016; Rennie et al. 2021; Ahn et al. 2022; Shea et al. 2022), the development of crop models (Perry and Wehner 1990; Perry et al. 1993), the validation of soil measurements (Holder et al. 2006; Pan et al. 2012; Xia et al. 2015; Coopersmith et al. 2016; Quiring et al. 2016), among others. A summary of peer-reviewed studies using ECONet data (as of 2023) are shown in Table 3.

Table 3. Description of peer-reviewed studies using ECONet data (as of 2023).

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

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 standard ECONet and non-standard 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, SPH, and MDN 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:

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Table S1. Key factors considered when siting a new ECONet station.

Factor	Description	Reference
1	Distance from an existing automated weather station (ECONet or other). We aim for an average spacing of 30 km between stations.	Fiebrich et al. (2020)
2	Distance from obstructions. We aim for a site that is located 10 times the distance away from the height of nearby obstruction.	WMO (2018)
3	Landscape slope. We aim for a site that has a minimal slope; 0-3 percent is ideal, in our experience.	AASC (2019), USDA (2017)
4	Vehicle and communications access. We aim for sites that can be easily accessed by road year-round and have strong cellular service or another alternative communication method available (e.g., landline).	--
5	Stakeholder engagement and benefits. We aim for locations that represent one, if not multiple, engaged stakeholder groups interested in environmental monitoring for unique research and applications.	--

Table S2. 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 S3. 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

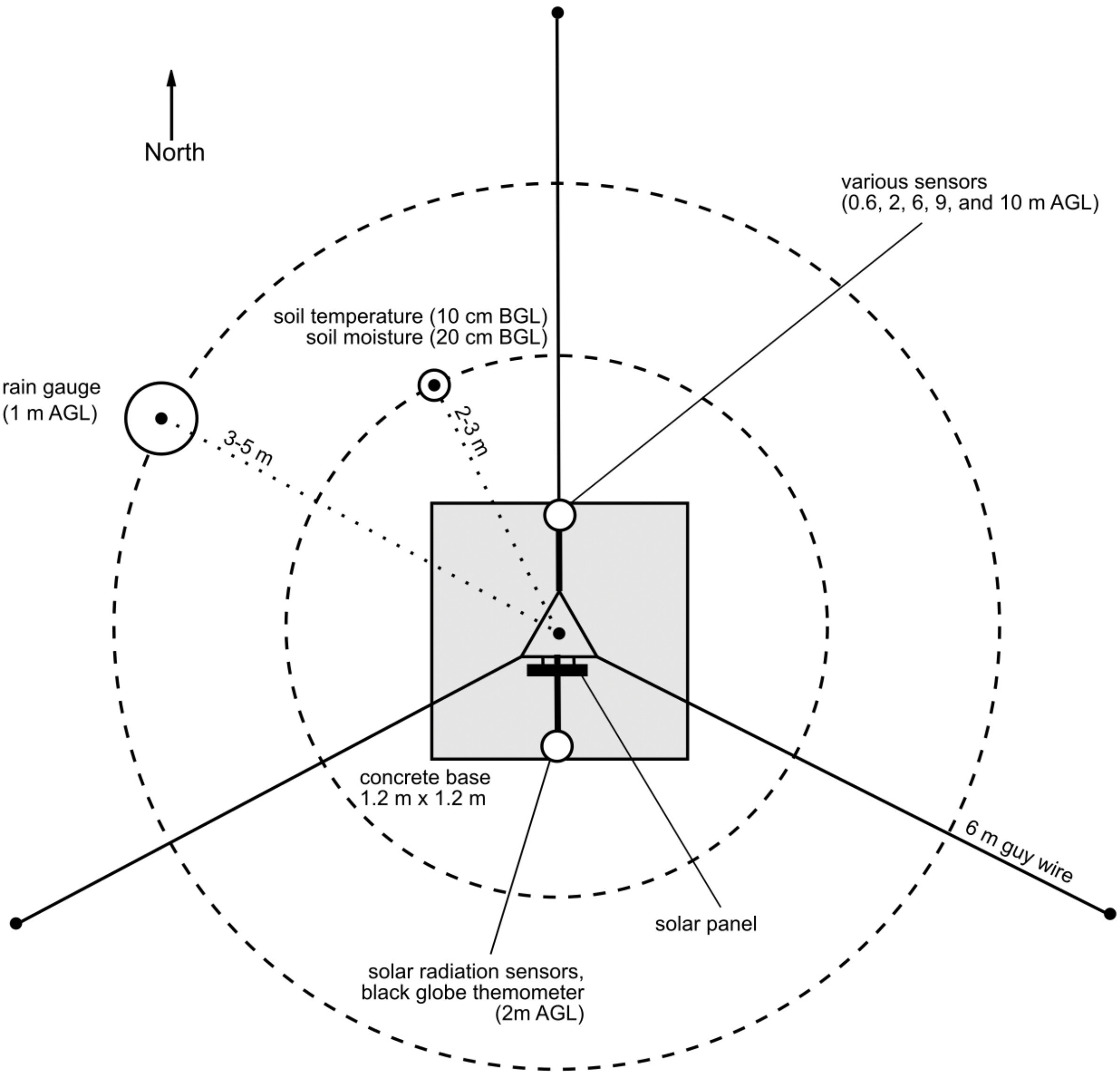

Fig. S1. Top view drawing of an ECONet tower. Abbreviations: above ground level (AGL), below ground level (BGL).

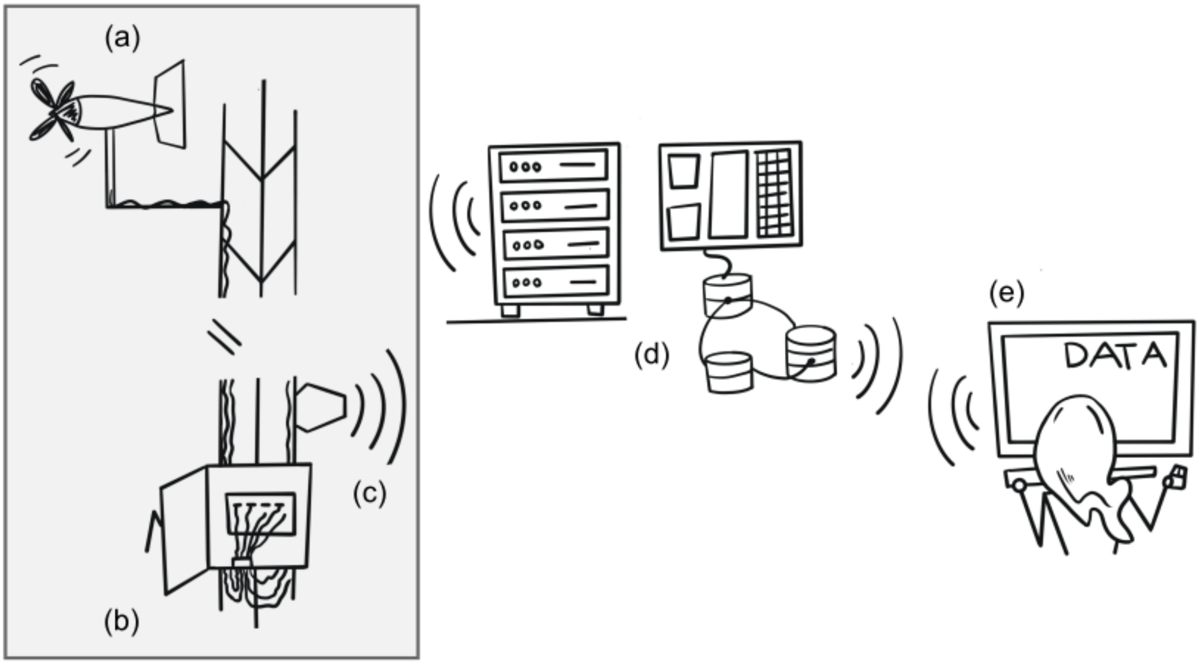

Fig. S2. Diagram showing the flow of ECONet data from the (a) individual sensor, (b) to the station datalogger, and then (c) transmitting the data off-site using various communication methods, (d) to being stored on databases at computer servers located at the State Climate Office of North Carolina and 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.