BAMS Article

Camera Network for Use in Weather Operations, Research, and Education

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ABSTRACT: Camera technology has evolved rapidly over the last decade; photo quality continues to improve while cameras are getting smaller, more rugged, and cheaper. One outcome of this technological progress is that cameras can now be deployed remotely at low cost wherever solar power and wireless communication are available. While numerous camera networks are deployed nationwide to survey traffic conditions and monitor local security, the adoption of cameras as a weather observing tool is relatively new. The New York State Mesonet (NYSM) is a network of 126 weather stations deployed across the state of New York, collecting, archiving, and disseminating a suite of atmospheric and soil variables every 5 min. One unique feature of the NYSM is that every station is equipped with a camera. Still images are collected every 5 min coincident with the standard environmental data during daylight hours, and hourly during the overnight hours. Since installation of the first station in 2015, the camera network has proven to be an essential element of information gathering, a critical data source for the forecast and emergency management communities, and a unique teaching resource of pictorial and visualized learning for kindergarten through high school (K–12) education. More specifically, the camera network supports 1) weather operations, 2) commercial applications, 3) data quality control, 4) site metadata, 5) site security, and 6) research and 7) educational opportunities. This article will review the many benefits, some challenges, and the future functional applications of cameras as part of an observation network. A strong case is made for making cameras an essential component of every weather station.

KEYWORDS: Automatic weather stations; Data quality control; Instrumentation/sensors; Surface observations; Decision support; Education

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Photography is an understated wonder of nineteenth-century technological progress. The ability to record visual images for posterity was unprecedented at the time, and its impact on society no less profound. Photography got its start in the mid-1820s (the oldest photograph still in existence is from 1826) and by midcentury had become far more advanced and widespread. The first photos of the moon (1840), the sun (1845), lightning (1882), and tornado (1884) affirmed their value to the natural sciences.

The camera was, and continues to be, an essential instrument in meteorology. The first reference to photography in *Monthly Weather Review* was in 1878 for use in documenting cloud development and upper airflow (Editors 1878). By 1900, photography had become a central tool of meteorologists and remained so through the years despite the advances made in other technologies. Pictures provided proofs of new phenomena and verification of theory. As examples, photography was important for the study of clouds (Crowson 1949), aerosols (e.g., Cannon 1970), rainfall processes (Jones 1959; Magarvey and Geldart 1962; Gokhale and Lewinter 1971), snow and ice crystals (Zikmunda and Vali 1972; Blanchard 1998; Newman et al. 2009; Kleinkort et al. 2017), wind shear (Woodbridge 1959), horizontal diffusion (Eckman and Mikkelsen 1991), tornadoes (e.g., Snow 1984; Golden and Purcell 1978; Wakimoto et al. 2018), waterspouts (Golden and Bluestein 1994), and dust devils (Lorenz et al. 2010). Extending beyond the visible spectrum, infrared imagery is now used to compute cloud-base height (Allmen and Kegelmeyer 1996), cloud cover, and brightness temperature of clouds (Smith and Toumi 2008). Fisheye (whole-sky) imaging cameras are used for routine monitoring of cloud cover, type, and height (Lund and Shanklin 1972; McGuffie and Henderson-Sellers 1989). Stereophotogrammetry, utilizing multiple cameras, has been adopted to explore clouds (Kassander and Sims 1957; Romps and Öktem 2018) and tornadoes (Rasmussen et al. 2003). Cameras also play an important role in phenology research; for example, the PhenoCam Network has been operating since 2008 (Richardson et al. 2018; https://phenocam.sr.unh.edu/webcam/) for monitoring vegetation phenology across a variety of ecosystems worldwide.

Cameras are now an integrated component in some atmospheric sensing equipment. Camera systems are being converted into radiation sensors to measure and validate cloud and radiation properties (e.g., Dev et al. 2019). Video disdrometers use imagery to monitor the sizes of droplet particles and estimate precipitation amount (e.g., Nešpor et al. 2000). Visible imagery has been an essential element in satellite development and operations. High-speed charge-coupled device (CCD) imagers are used in lightning detection.

Despite this long history of successful applications, government sponsored weather observing platforms [e.g., the Automated Surface Observing Systems (ASOS) program] have yet to include photography as a standard component. But current power and communication technology has progressed to feasibly allow for cameras to be deployed as basic weather station equipment, and artificial intelligence (AI) is being developed to extract more qualitative and quantitative information from images than ever before (e.g., using camera images for autodetection of visibility). Furthermore, social science research continues to show the value of images for motivating action during high-impact situations (Rickard et al. 2017).

This article explores the requirements, challenges, and many applications made possible with the addition of cameras as an essential instrument for standard weather station networks. The New York State Mesonet (NYSM; Brotzge et al. 2020; http://nysmesonet.org) is a network of 126 weather stations deployed across the state of New York. Each station comprises a 10-m tower centered within a 100-m^2 fenced area that hosts over a dozen meteorological sensors. In addition, a digital camera is deployed on each tower (Fig. 1). To the best of our knowledge, the NYSM is the first statewide mesonet in the United States to include cameras as a standard component. The first NYSM site was installed in August 2015, and so 5 years or more of archives are now available from most sites. This article reviews the challenges and benefits brought by the addition of cameras to a weather station network and how cameras can be exploited for use in operations, commercialization, research, and education.

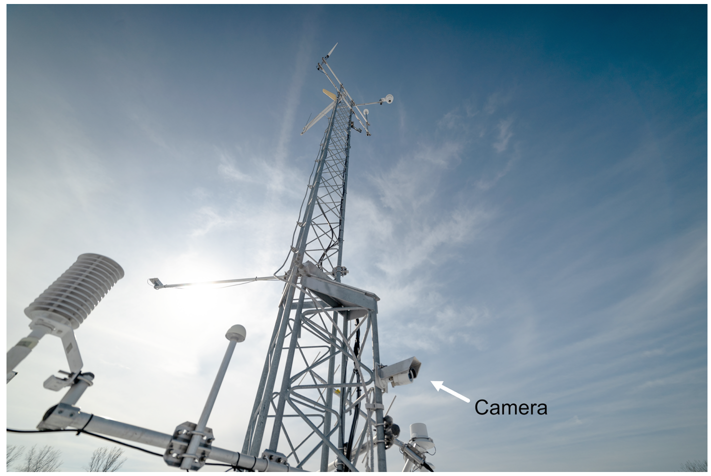

Fig. 1. The NYSM station near Clifton Springs. The camera is mounted at 3 m AGL, facing north to reduce glare. Photo courtesy of Samuel Cherubin.

Network deployment

The NYSM first deployed the DS-2CD2032-I security network camera manufactured by Hikvision. The Hikvision camera weighs about 500 g, requires a maximum of 5 W, and operates between –30° and 60°C. An infrared capability enables image collection at night, and the camera permits livestreaming. Due to federal security concerns, however, the Hikvision is no longer being purchased; alternative cameras with similar specifications are being tested. At the time of this writing, the cameras are among the most economical sensors deployed across the NYSM. Once installed and leveled, the camera is low maintenance; the most common problem is water getting into the camera or cabling, but this can be minimized with proper sealant.

Each camera is oriented such that the horizon is centered in the photo, with the ground encompassing the lower half of the image and the sky the upper half (e.g., Fig. 2). This allows for regular monitoring of snow and vegetation heights as well as sky conditions. Each camera is mounted level on the station tower at a height of 3 m. Small roofs have been built over each camera to protect them from snow and ice falling from the tower above.

Most cameras face north toward the station gate. This provides some level of security for the site, as well as minimizing direct solar glare on to the camera lens. Cameras at 25 sites (20% of the network) face a direction other than 0° (north). In some cases, site hosts requested that the camera be pointed in a different direction for privacy concerns (e.g., away from the family pond). In other cases, other angle directions provided a much longer-range vista, yielding greater applications of the camera when the view to the north was blocked by nearby trees or other obstructions. At a few sites, a particularly picturesque view in some other direction was more desirable. Once the camera was installed, adjustments would be kept to a minimum for preserving continuity in the long-term record.

Fig. 2. An example photo collected at 1515 LT 27 Jun 2017 at the Penn Yan NYSM station.

Camera still images are collected every 5 min from each site during daylight hours. To reduce bandwidth use and storage, images are collected generally only once per hour during the night. [Occasionally at the request of the National Weather Service (NWS), night images are collected every 5 min during high-impact weather situations.] This switch to night data collection is made 30 min prior to sunrise and 30 min after sunset via commands sent to the camera remotely from NYSM servers, which also download the images to the central archive. A 2 MP (1,920 × 1,080 resolution) image is taken, but the photo is downgraded such that a 0.9-MP (1,280 × 720) image is downloaded from the site, and this can reduce the bandwidth requirements by over 50%. Infrared capability allows for nighttime images to be captured (in black and white). Cameras automatically switch to infrared mode once light levels drop below a given threshold. Real-time video is an option but is rarely used in order to limit bandwidth.

Approximately 20,000 photos are collected daily from across the network. The latest photos from each site are displayed in real time on the NYSM's website and on display walls in the NYSM operations center, where they are used for real-time monitoring of network status and ambient weather conditions. All photos are archived; the storage requirements for the photos are estimated at about 750 GB yr^{-1}. Collected since initial deployment of the network in 2015, over 30 million photographs are now available for download. Photos are available to the public at cost upon request via the online NYSM Request Data form (www.nysmesonet.org/weather/requestdata). Photographs are archived by site, date, and time; no other metadata are recorded at this time. Animation software was developed in-house to allow for easy access and review of archived images and time series.

Applications

The original purpose for deploying cameras was to monitor the weather and sky conditions as well as variation of the surrounding station environment such as the seasonal change of vegetation conditions (green up/brown down). A 4-ft scale (Fig. 2) was added to aid in tracking snow depth and grass height. Having additional visual information to accompany numerical weather data were (correctly) assumed to aid understanding of the weather situation being monitored. But the applications for using Mesonet photos have expanded far beyond those originally anticipated.

Weather operations. Camera imagery is becoming gradually more integrated into operational weather monitoring (e.g., Longmore et al. 2015). Few governmental automatic weather station (AWS) networks have yet to fully adopt photographs or video into regular operations. However, one notable exception is the Hong Kong Observatory, which operates a territory-wide AWS network currently installed with 28 cameras (www.hko.gov.hk/en/wxinfo/ts/index_webcam.htm). The Hong Kong Observatory also developed the Community Weather Observing Scheme (CWOS) to collect weather photos from trusted CWOS members (www.facebook.com/groups/icwos/). Nevertheless, the use of photographs and video is novel to most weather operations. To better understand the strengths and weaknesses of cameras for use in weather operations, the NYSM collaborated with its NWS partners to fully evaluate how camera photos can best be used operationally.

A 2-yr evaluation was carried out to track all references to the NYSM as recorded in forecast discussions and updates issued from the five regional NWS Weather Forecast Offices (WFOs) covering New York State (ALY, BGM, BTV, BUF, OKX). During the study period from 1 November 2019 to 31 October 2021, the NWS referenced the NYSM 725 times; of those, 123 (17%) referenced the camera network. Photos were used to confirm the presence of light precipitation, snow, snow cover, precipitation type, icing conditions, cloud cover, solar radiation, and fog. Cameras were especially helpful during the winter months (DJF) when the camera images comprised 27.8% of the NYSM references (57 times out of 205 total references). Photos aided confirmation of the occurrence of light precipitation (flurries, light snow) and during precipitation type transitions (e.g., identifying the location of the rain–snow transition line). In contrast, cameras were mentioned only once out of 118 total NYSM references during the summer months (JJA; 0.8%). Thus, cameras are most helpful in areas where wintry and/or foggy conditions are frequently observed (e.g., Splitt et al. 2021).

Cameras were often used to confirm surface weather conditions, especially when these conditions contrasted with inferred conditions from satellite or radar imageries/data. A few example references include the following:

NWS Albany, NY 119 p.m. EST Mon 18 November 2019

NEAR TERM/UNTIL 6 p.m. THIS EVENING/ ...

Adjusted temperatures with observational and blend with latest guidance. **NYS Mesonet stations have been extremely helpful identifying where very light precipitation has been occurring and p-type thanks to temperatures and web cams.**

NWS Albany, NY 1250 p.m. EST Thu 5 December 2019

NEAR TERM/UNTIL 6 p.m. THIS EVENING/ ...

As of 1:30 p.m. ... Snow showers are progressing eastward into the Mohawk and Schoharie Valley early this afternoon as cold air in the wake of our cold frontal passage continues advecting over the warm Lake Ontario waters. **While bands are still disorganized compared to what the high-res NAM was showing this morning, the NYS mesonet cameras show visibility dropping considerably under these bands**. Thus, we have issued a Special Weather Statement to alert motorists of potential rapidly changing visibilities this afternoon...

NWS Binghamton, NY 407 a.m. EST Thu 12 December 2019

NEAR TERM/THROUGH TONIGHT/ ...

Latest GOES-16 satellite imagery shows a lake-effect cloud band extended eastward from Lake Ontario into our far northern zones of C NY (north of the NY Thruway). **Despite poor radar coverage with KTYX radar down and other nearby radars overshooting the low-topped convection embedded within the LES band, New York State Mesonet (NYSM) webcams show light snow continuing to fall overnight across western and northern Oneida Co. (likely extending a bit southward into far northern Onondaga and Madison Counties**...

To take full advantage of the camera network, some NWS offices routinely display NYSM camera images/data within their operations (e.g., Fig. 3). A similar display is used

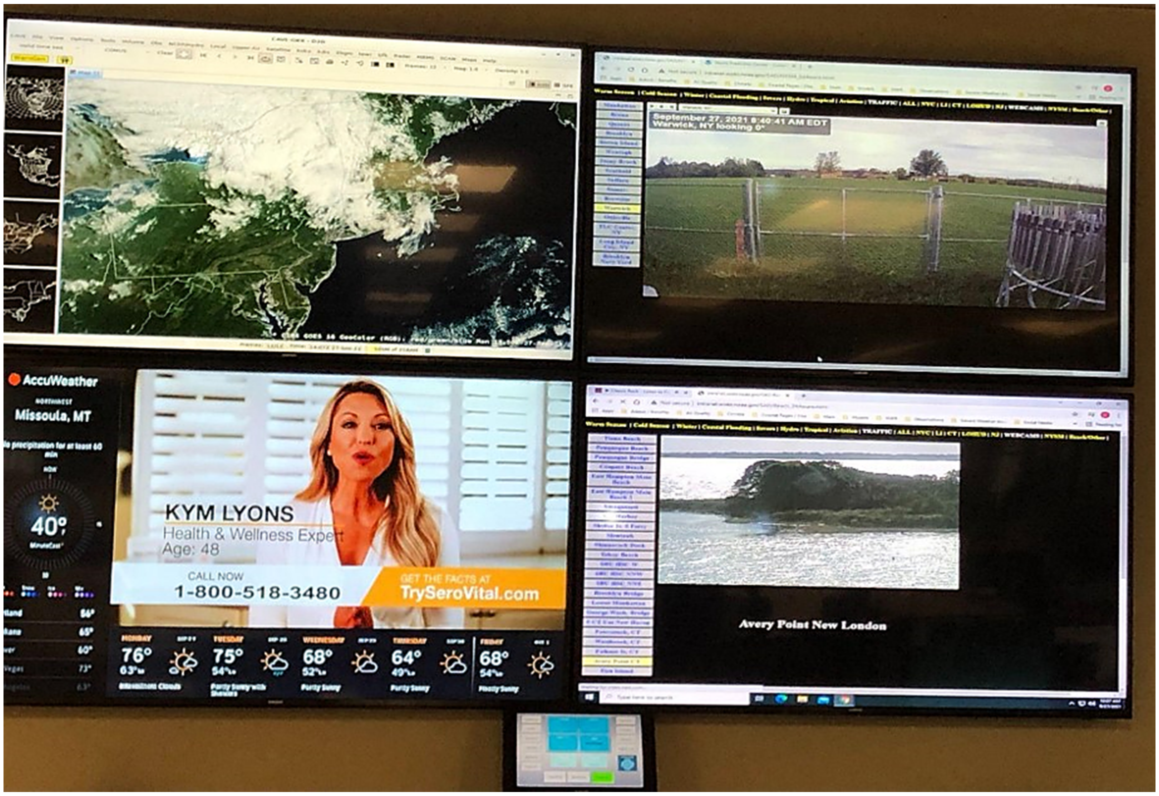

Fig. 3. NWS wall monitors located at the OKX WFO. Note the NYSM station camera display in the upper right. Figure courtesy of Dr. David Radell, NWS.

within the New York State Department of Homeland Security and Emergency Services (DHSES).

Real-time photos can confirm the presence and development of rare, high-impact events. For example, two waterspouts have been observed by NYSM cameras, despite the stations being up to 5 km from the water. One waterspout was seen on 8 August 2019 from the Oswego site, located within a kilometer of Lake Ontario (Fig. 4a). A second waterspout was spotted on 4 August 2020 from the Fredonia site, located 5 km from Lake Erie (Fig. 4b).

More generally, local cameras are an excellent aid to confirm the presence of severe and hazardous situations, confirm public storm reports, and verify NWS warnings. For example, on 15 May 2018 the Beacon NYSM station recorded a severe wind event with a

Fig. 4. (a) Waterspout observed over Lake Ontario looking north from the Oswego site on 8 Aug 2019. (b) Waterspout observed from the Fredonia site over Lake Erie on 4 Aug 2020.

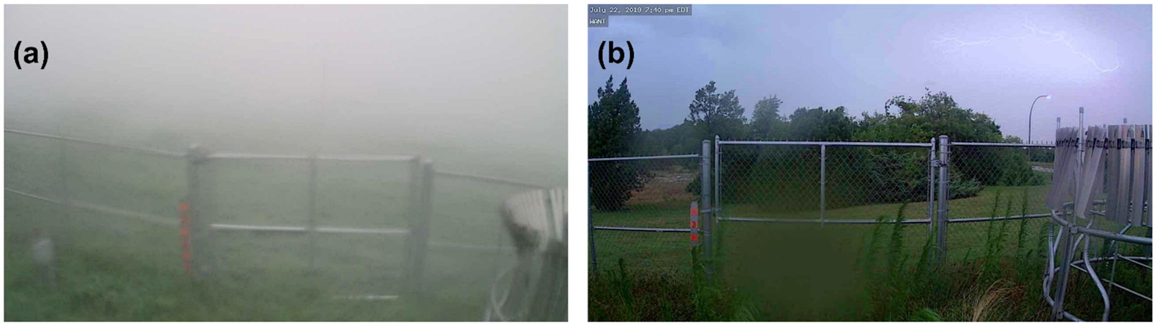

Fig. 5. (a) A severe windstorm at the Beacon site on 15 May 2018. (b) Cloud-to-cloud lightning observed at the Wantagh site on 22 Jul 2019. Lightning images are rare; only two lightning photos have been recorded in the network.

wind gust of 34.6 m s^{-1} measured by the station anemometer, which was well reflected in its corresponding photo (Fig. 5a). Photos also help convey the ground ("public") view of an event (Fig. 5b). While weather radar provides much of our wind and precipitation information during rapidly developing convective events, surface photos can confirm whether these radar-observed features aloft are impacting the surface. Understanding the connection between radar imagery and actual sky and surface conditions is helpful for situational awareness, and a network of cameras can be used to monitor storm development across an entire line. For example, cameras ahead of a linear convective event on 8 August 2019 provided real-time situational awareness on the ground as the system moved eastward (Fig. 6).

Even during more tranquil weather, cameras are essential for filling gaps in an otherwise comprehensive observational network. Statewide aviation organizations monitor NYSM cameras for changes in low-level cloud cover and fog across remote areas of the state (e.g., Figs. 7a,b); these clouds and fog inhibit flight landings which are often not observed as clearly by satellite due to their low altitude. During winter, cameras are used to confirm precipitation type, verify snow depth, track the rain–snow line, and observe light drizzle or flurries often missed by standard gauges (e.g., Figs. 7c,d).

Snow squalls are among the more difficult high-impact events to track and warn across New York. Snow squalls are severe yet highly localized; local visibilities can drop to near zero with little warning. An example with a snow squall passing the New York City Manhattan site is shown in Fig. 8. Conditions deteriorated from partly sunny to near-zero visibility in just 10 min. The entire storm passage lasted less than 45 min. The New York State Thruway authority partnered with the NYSM to deploy an additional dozen weather stations equipped with

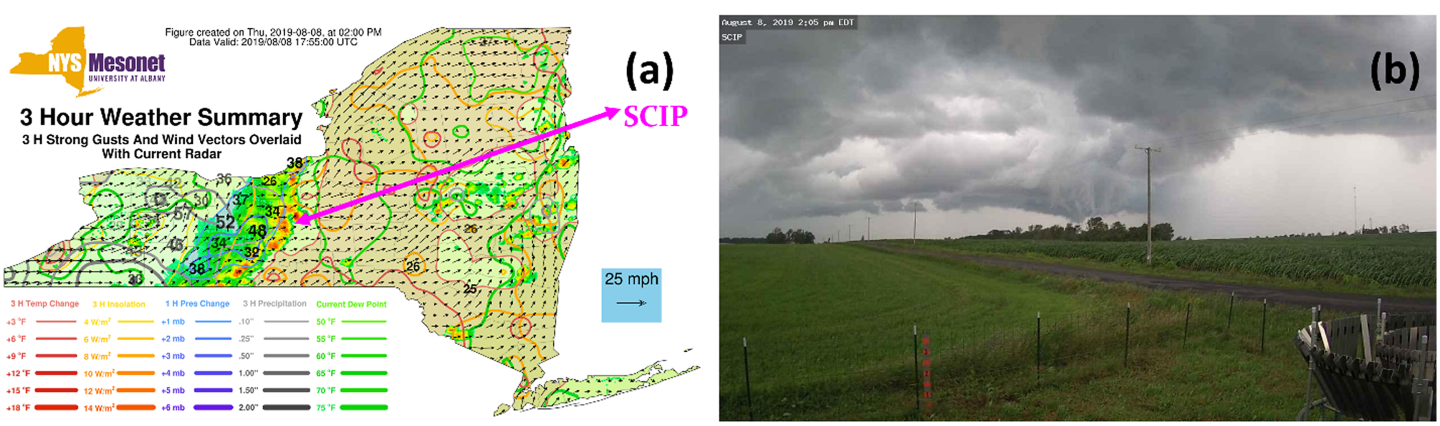

Fig. 6. (a) Statewide radar composite overlaid with NYSM data and gridded output on 8 Aug 2019. (Figure courtesy of Dr. Nick Bassill.) (b) A coincident photo taken from Scipio Center (SCIP).

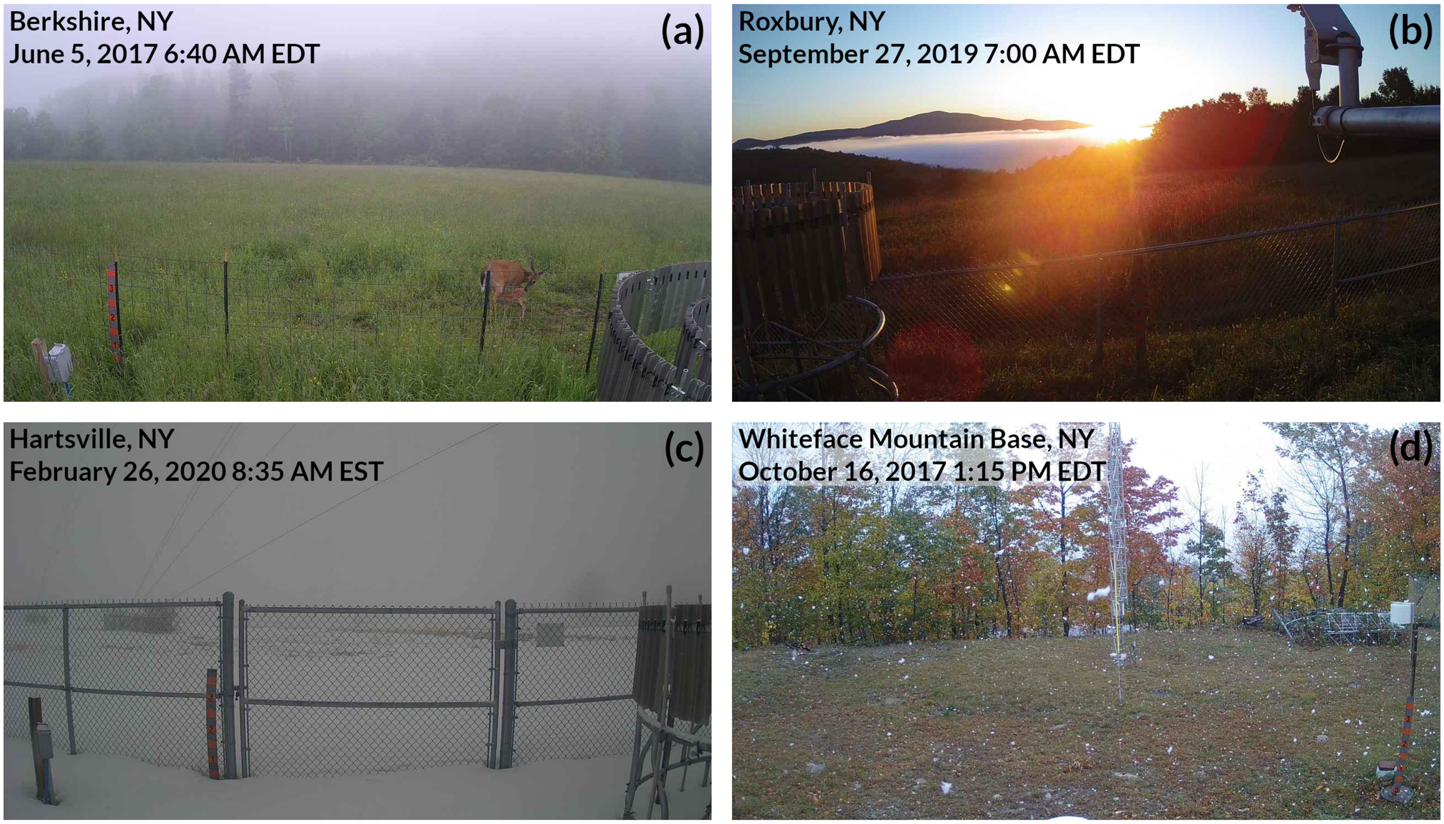

Fig. 7. (a) Fog observed on 5 Jun 2017 at the Berkshire site. (b) Valley fog as seen from the Roxbury site on 27 Sep 2019. (c) Snow cover and fog observed at Hartsville on 26 Feb 2020. (d) The start of flurries at the Whiteface Mountain Base (WFMB) site on 16 Oct 2017.

cameras along Interstate 90 across western New York in part to more carefully monitor for rapid fluctuations in visibility from snow squalls (see http://nysmesonet.org/applications/transportation).

Commercial use. As with the public sector, private firms have found cameras to be a valuable complement to their weather operations. Indeed, the commercial sector has a long history of collecting photos with weather observations. Some weather companies include cameras as

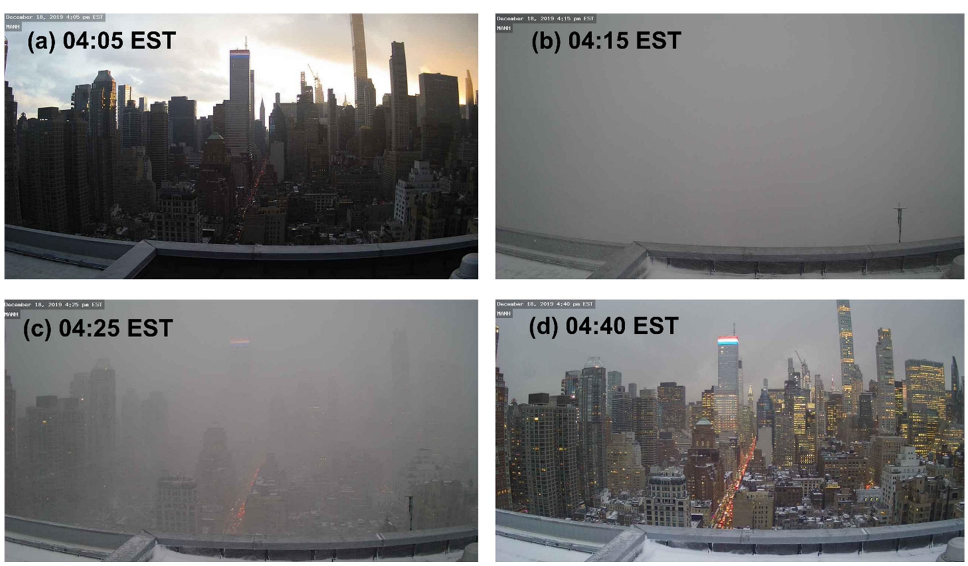

Fig. 8. A fast-moving snow squall moving across Manhattan on 18 Dec 2019. Images are shown at (a) 1605, (b) 1615, (c) 1625, and (d) 1640 eastern standard time (EST).

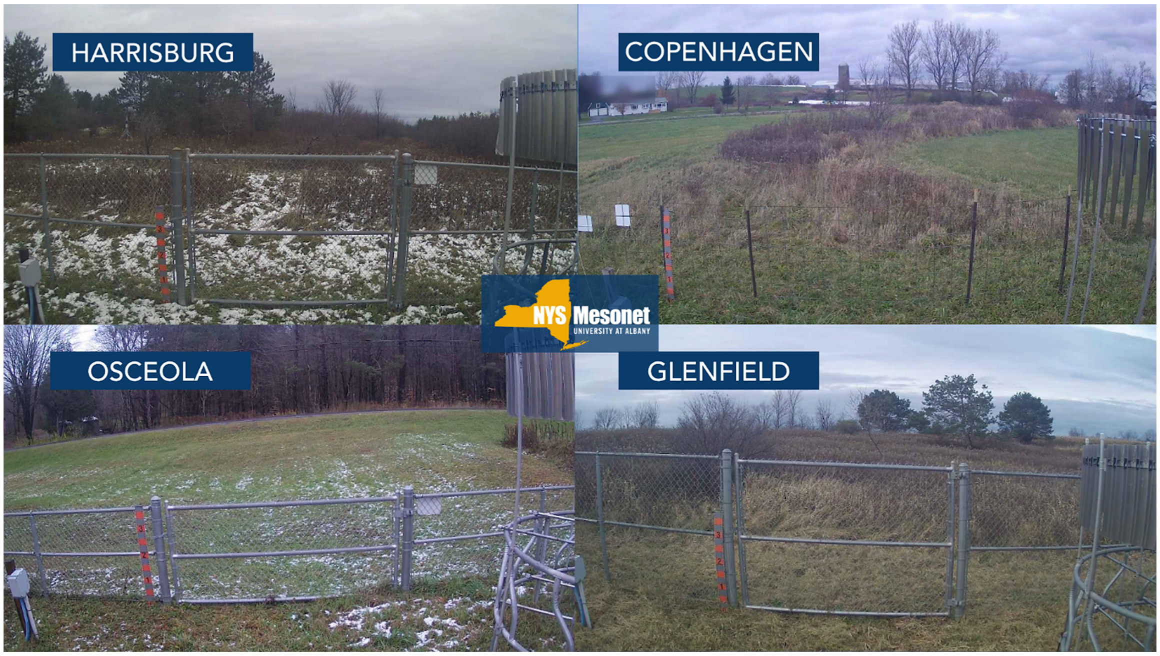

Fig. 9. This example from WWNY in Watertown, New York, demonstrates how photos are displayed on-air. Photo courtesy of Kris Hudson.

part of their regular weather station suite (e.g., EarthNetworks; www.earthnetworks.com/product/data-analytical-model-delivery/live-camera-feed/) and have done so for some time. Some companies (e.g., ALFA Insurance; www.alfainsurance.com/claims/catastrophe-center/weather-camera-network) sponsor camera networks used by local television news stations. Other companies (e.g., WeatherBug, www.weatherbug.com/weather-camera/albany-ny-12203; weatherUSA, www.weatherusa.net/skycamnet; The Weather Network, https://s.theweathernetwork.com/maps/traffic-cameras) include publicly available cameras such as traffic cams to provide national coverage. The Helios program operated by L3Harris (www.l3harrisgeospatial.com/Software-Technology/Helios) applies AI to publicly available cameras to extract weather analytic information.

A common application of camera networks is by local television weather media. Many television stations have a local network of cameras spread across their viewing areas, an excellent tool for showing time lapse and live video of weather across the region. Across New York, local stations are tapping into the NYSM and showing camera views on air (e.g., Fig. 9). New York State is relatively mountainous, and during the transitional seasons camera networks are especially helpful for highlighting precipitation type and how it varies with elevation across the local area.

Data quality control. Like most weather networks, NYSM data are quality controlled using a series of automated and manual checking procedures. However, the reasons behind why a sensor or station fails is often not readily apparent. Understanding why sensors fail can expedite the restoration of that equipment. Onsite camera photos have contributed to a significant improvement in the data quality control process.

Camera images are most commonly used to confirm whether or not sensors are behaving properly. For example, photos can confirm the presence of very light precipitation, such as drizzle, light snow, or even dew. Such light precipitation data can otherwise be discarded by automated QC routines that are relying on weather radar or neighboring stations for confirmation. The NYSM uses camera images for validation of precipitation gauge, snow depth, and pyranometer data, and some derived products, such as precipitation type (e.g., Fig. 10) and freezing rain (Wang et al. 2021). Photos also help to confirm extreme events, such as high to severe winds as recorded by station anemometers.

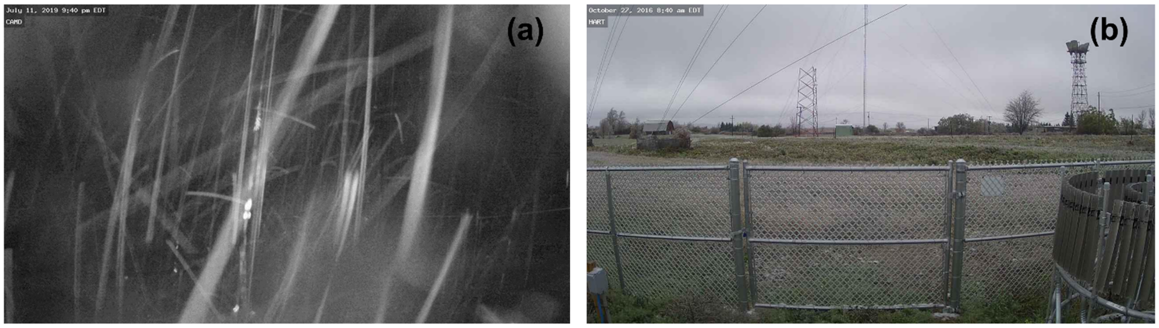

Fig. 10. Photos are used to validate in situ measurements. (a) Rainfall as seen in the nighttime infrared imagery on 11 Jul 2019 at the Camden station. (b) Ice as observed on the fence and ground following a freezing rain event on 27 Oct 2016 at the Hartsville site.

In some rare circumstances, photographs can provide direct evidence of an issue. For example, on 26 July 2017, several sensors at the Clifton Springs site mysteriously began to fail. A careful review of the sensor data failed to reveal the source of the problem. However, a quick look at the camera image clearly showed that cows had broken the site gate lock and entered the station (Fig. 11a).

To facilitate network quality control and operations, camera images from 126 Standard Network, 12 NYS Thruway Network, and 17 New York City Micronet stations are displayed within the NYSM Operations Center (Fig. 11b). Images are displayed in a matrix, with multiple sites displayed per screen. Multiple screens are mounted about the room, with each screen representing a different region of the state. Stations are arranged geographically on each screen, and the screens are arranged geographically (west to east) in a clockwise direction around the room. A 2-h loop is continually updated and looped, allowing Operation Center staff to monitor each site and quickly identify any significant changes in time. This display also allows for significant, high-impact events to be easily tracked across the state in real time.

As part of routine data quality control, camera images are used in several additional ways. During winter, snow depth estimates, as read visually from the snow scale in the photos, are used to calibrate the SR50A snow depth sensor (e.g., Fig. 12). During summer, vegetation heights are estimated from the snow scale, recorded in an Excel file, and visualized on a map (e.g., Fig. 13). The map is used to issue trouble tickets (TTs) to cut the grass at sites where grass heights exceed 0.6 m (2 ft). Camera images also are used to identify clear-sky days, which are used for pyranometer validation by comparing against calculated clear-sky solar irradiance.

Station metadata. In addition to quality control, photographs can help with interpretation of data. Climatological trends can reveal changes that are not readily understood. However, regular systematic images from a site can help identify (or rule out) local anthropogenic

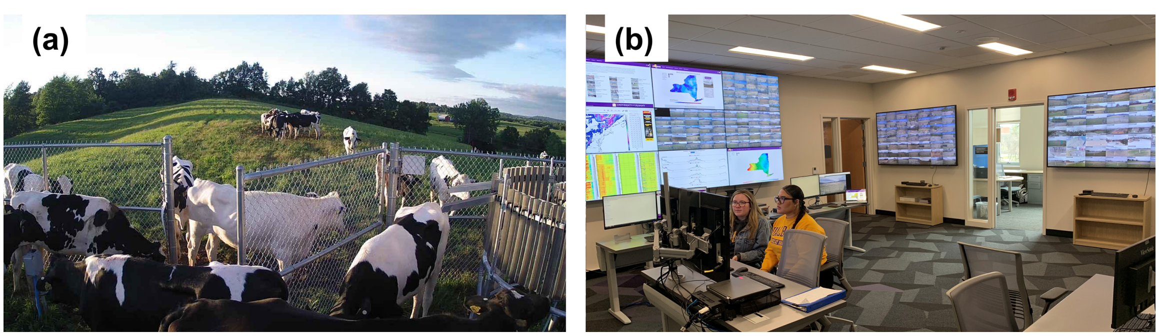

Fig. 11. (a) Cows causing damage in the NYSM station near Clifton Springs on 26 Jul 2017. (b) Cameras are displayed in real time within the NYSM Operations Center.

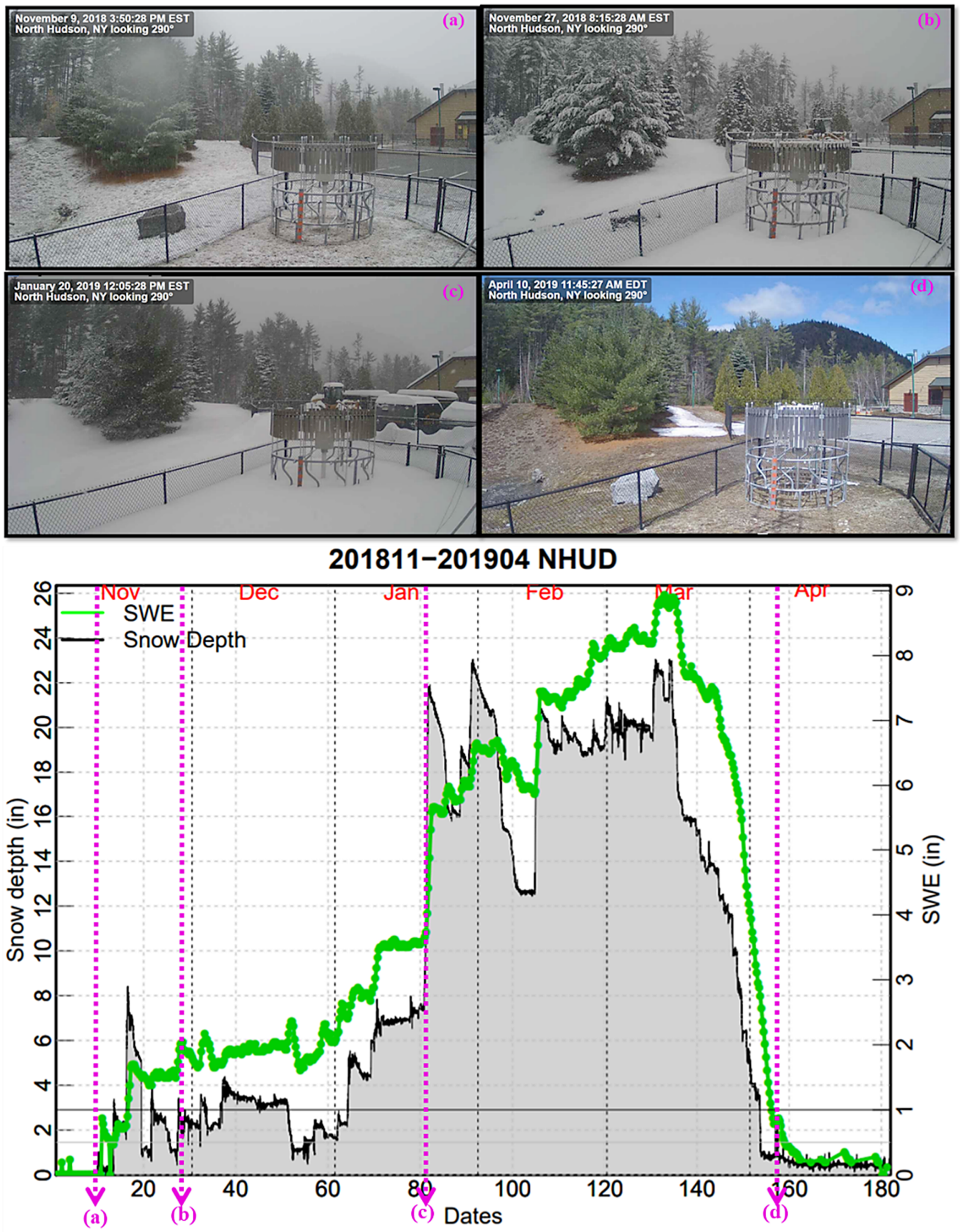

Fig. 12. (top) (a) Photos taken by the North Hudson (NHUD) camera on 3 Nov 2018. (b) The first snow/sleet storm (27 Nov 2018); (c) a heavy and wet snowstorm, the largest snowstorm in the 2018/19 winter (20 Jan 2019); and (d) almost-completely melted snow (20 Apr 2019). See the time-lapse video from 1 Nov 2018 to 30 Apr 2019 on https://operations.nysmesonet.org/public/references/2022_Brotzge_Cameras/nhud-2018-2019-snow.mp4. (bottom) Time series of snow depth (gray shaded area) and snow water equivalent (SWE; green lines) during the 4 months. The vertical magenta dotted lines in the bottom panel denote the 4 days shown by the photos in the top panel.

changes that could be biasing the weather station record. For example, during the operation of the NYSM network from 2015 to 2018, several stations have had solar farms and buildings constructed within several hundred meters of the NYSM stations; camera imagery can help identify the time and date when these changes occurred.

Photographs also help to monitor seasonal changes in the environment. For example, about one-third of NYSM sites are located on farms, and a regular photo archive can help document the dates when fields around the sites are planted and harvested, changes to the ground cover that could impact the long-term climatology of the weather station. Photos also document changes in snow cover (Fig. 12) as well as the annual "green-up" and "brown-down" of plant foliage (e.g., Fig. 14). For example, a 1-yr time series of images from noon local time

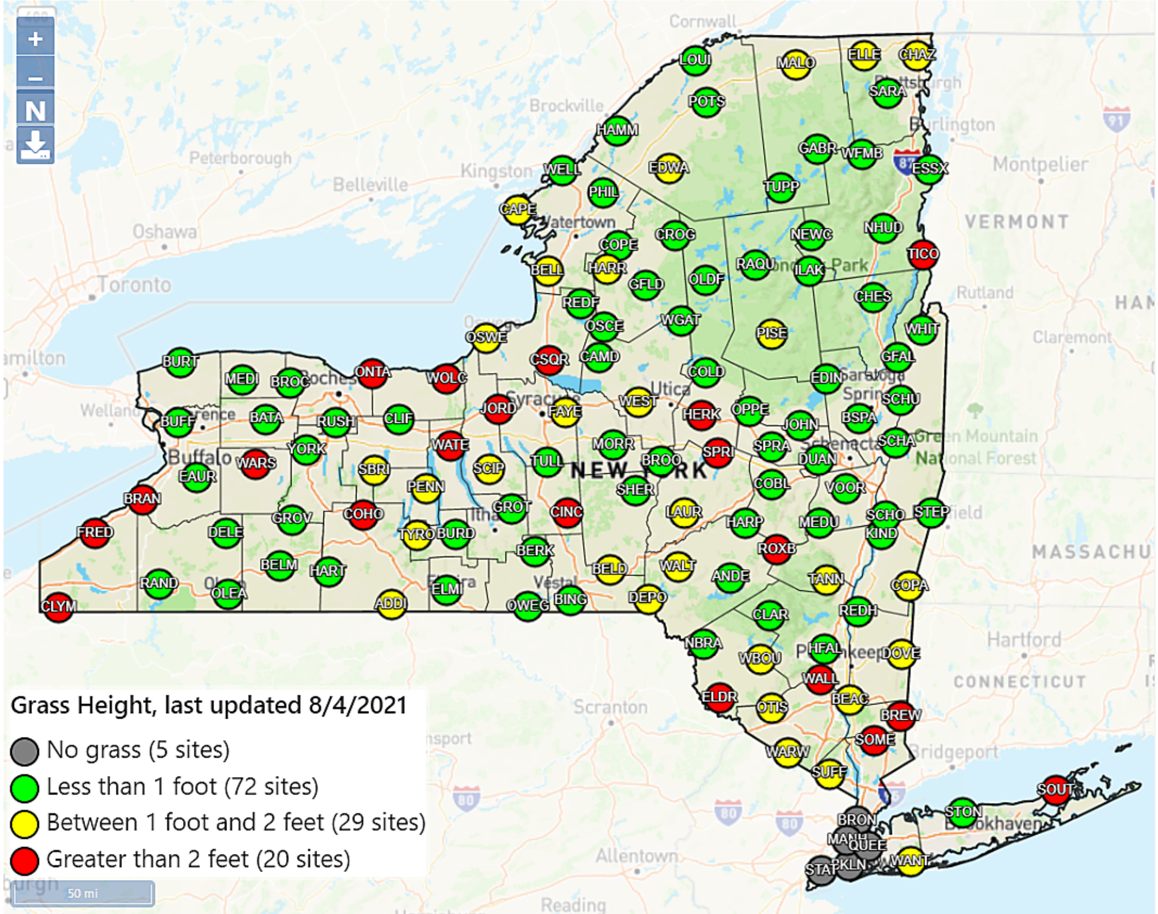

Fig. 13. Daily grass height maps are created by hand from manual reviews of the camera photos.

from the NYSM station near Morrisville during 2019 shows seasonal and agricultural cycles that are likely impacting station data to varying degrees (https://operations.nysmesonet.org/public/references/2022_Brotzge_Cameras/morr_2019.mp4). Recording these visual changes can provide important metadata for station climatological records.

Site security. Cameras at the NYSM sites provide a small measure of security. In general, the presence of a camera helps deter theft and vandalism. Although some may not notice or disregard the camera; in one case, NYSM photos captured a clear image of a thief stealing a Mesonet snow stick in midafternoon. In another example, cameras captured someone stealing a fake lizard a site host had placed on station fencing; the photo was used to identify the vehicle and perpetrator, and the site host was able to retrieve the lizard from the thief.

In a couple of cases, cameras captured more serious crimes. In one example, a car was driven deliberately across a school's athletic fields causing considerable damage (Fig. 15). NYSM photos captured images of the vehicle, and the images were turned over to campus police. In another example, NYSM photos were provided to police investigating a felony case.

Research. Beyond operations, the NYSM camera network promises several avenues of research, especially when used in conjunction with in situ station data. A number of researchers are now extracting quantitative weather information from photos (e.g., Hallowell et al. 2005; Ozcan et al. 2020; Splitt et al. 2021) through the use of AI and machine learning (ML) technologies. In collaboration with the NSF AI Institute for Research on Trustworthy AI in Weather, Climate and Coastal Oceanography (AI2ES; http://ai2es.org), a team of scientists are working to build upon this previous work to extract weather information and products directly from the NYSM camera images. AI will be applied to camera photos to extract products such as visibility and

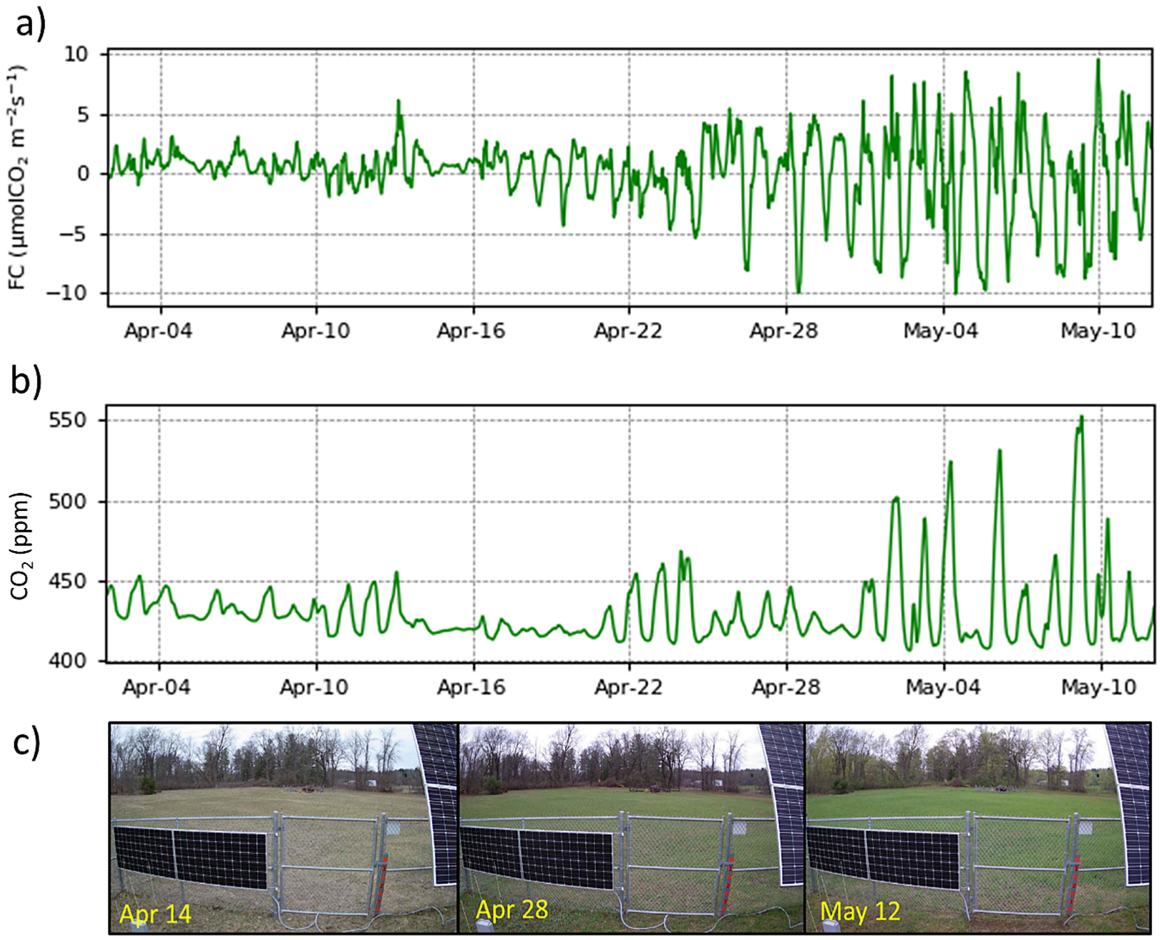

Fig. 14. The 3-h running mean of (a) CO_2 flux and (b) CO_2 mixing ratio at the Schuylerville (SCHU) station. (c) Photos taken SCHU on 14, 28 Apr, and 12 May show the corresponding spring "green-up" as indicated by the CO_2 measurements (reprinted from Covert 2019).

precipitation type, which have direct application for transportation, aviation, and emergency management. Furthermore, relationships can be derived and trained from this network and then applied to stand-alone camera networks not associated with weather networks, such as highway camera systems.

Fig. 15. This photo captured a car driving across a school's athletic fields, which caused considerable damage. The photo was turned over to campus police.

Additional research has explored the use of camera data for extracting vegetation phenology, such as tracking leaf color (e.g., the annual green-up and brown-down). However, the ability to do this is closely tied to the camera color sensitivity. It was found that the NYSM cameras were not sensitive enough to extract foliage color accurately enough to extract quantitative information, but this avenue could be explored further with more sensitive camera systems.

The ability to extract quantitative data from camera imagery allows for an expansion in the usage of the photos. Automated routines utilizing machine learning software could greatly enhance the products, metadata, and searchability of the photo archive.

Nevertheless, because the NYSM is relatively new (just over 5 years old), research using the camera photos has been limited thus far. However, as the network matures we anticipate a growing body of research to take advantage of this unique resource.

Education. For kindergarten through high school (K–12), meteorology is often a key entry into STEM, and photographs provide a unique tool for hands-on, visual learning that many students find engaging. Having access to a statewide network of cameras with coincident weather data presents a wide range of pedagogical opportunities. One of the coauthors (Ms. Perno) is a middle school teacher in New York who has adopted NYSM data for use in her science courses. While working to satisfy the New York State Science Learning Standards, the coauthor has developed several lessons using NYSM data. As one example, students learned how the solar angle changes with latitude and time of day by comparing tower shadows in the camera images with time of day and across different sites (Fig. 16).

The camera data have been especially helpful in teaching difficult concepts in weather, geography, and astronomy. Many students have not traveled much beyond their local jurisdiction, and the camera photos allow students to visually explore the geography and climate across the state, areas of the state they may never have the opportunity to visit personally. Seeing how a single storm impacts regions differently helps broaden understanding of weather patterns and impacts.

Camera data can also contribute to adult education. For example, a rare blowing snow phenomena known as sastrugi was observed on 21 January 2019 at the Penn Yan station (Figs. 17a,b). A video of the event was posted on YouTube, which garnered nearly 100,000 views (https://twitter.com/nysmesonet/status/1087438261084217345). This was also spread by news outlets around the world (e.g., Nam 2019). Other phenomena such as rainbows are commonly observed (Fig. 17c). A rare biological event was seen on 11 May 2016 at the Berkshire site (Fig. 17d). A thick swarm of insects filled the image; upon closer investigation, the team

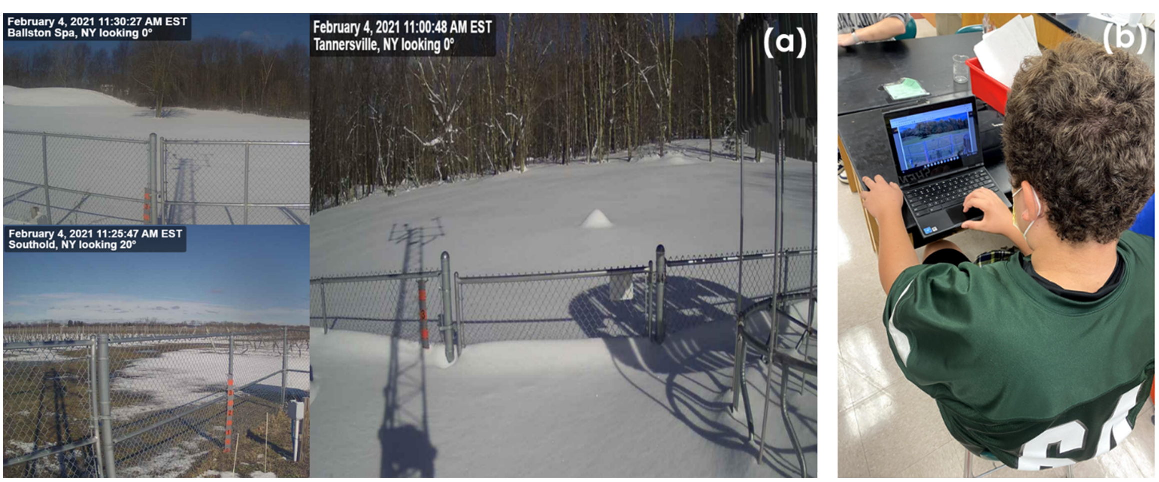

Fig. 16. (a) Students use tower shadows at different sites to learn how the solar angle changes with latitude and time of day. (b) A student using the camera data in the classroom.

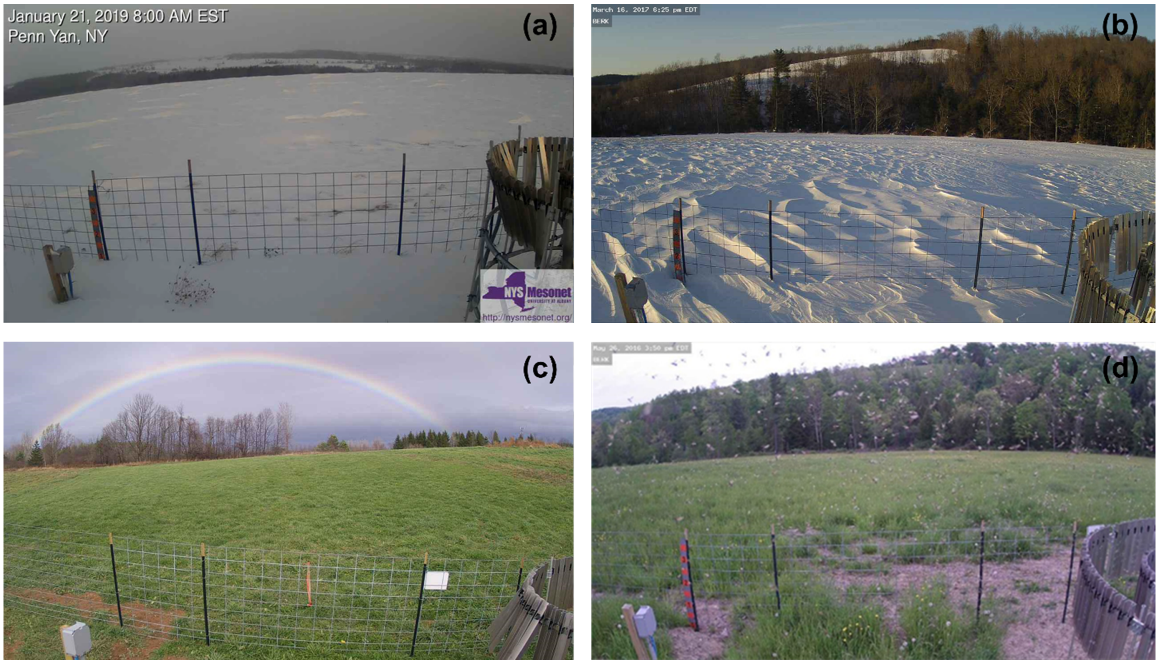

Fig. 17. (a) Sastrugi observed at the Penn Yan station on 21 Jan 2019. (b) Sastrugi as seen from the Berkshire site on 16 Mar 2017. (c) Rainbow observed at the Westmoreland site on 19 Nov 2015, one day after installation. (d) A swarm of cicadas observed at the Berkshire site on 11 May 2016.

discovered that it was the 17-yr cicada. The cicada hatch in the spring once soil temperatures reach 17°C (Climate Central 2021). NYSM measurements confirmed that the soil temperatures reached 17°C immediately prior to the cicada being observed on camera.

While not necessarily educational, a popular pastime of users is spotting wildlife (Fig. 18). Since photos are collected continuously at all sites with many in very remote areas, a wide range

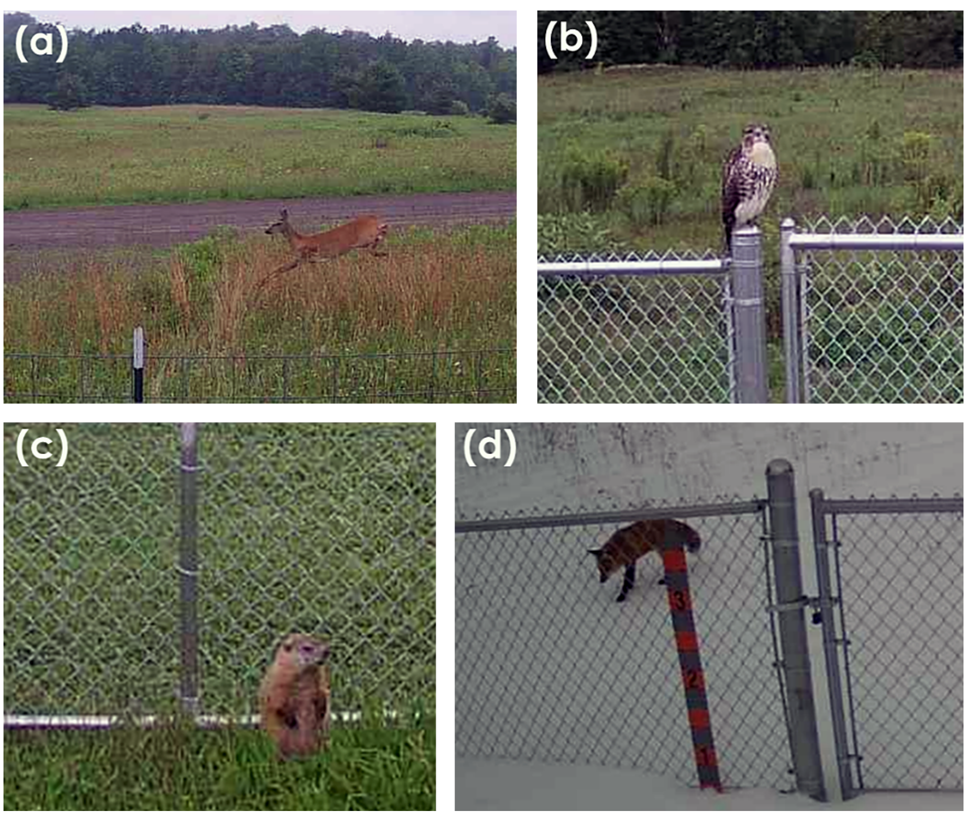

Fig. 18. Wildlife is commonly seen in the photos. The following (a) deer, (b) hawk, (c) groundhog, and (d) fox are frequent visitors.

of birds and mammals are regularly seen. Deer, turkeys, hawks, vultures, foxes, and groundhogs are commonly observed. In one instance, a camera captured a doe giving birth to twins.

Challenges

While there are many benefits to cameras, making network photos publicly available in real time also poses some challenges. These challenges include privacy concerns and grandstanding. About half of all sites are on private land, so the NYSM remains sensitive to any privacy concerns expressed by the site host. So far, all site hosts have been supportive of the cameras, though a few have requested pointing the cameras in a slightly different direction from the north due to privacy concerns. A much greater problem has been "grandstanding." For example, on rare occasions someone will post a sign wishing someone a special birthday greeting. But these instances have been rare, and only a few have had to be removed by field staff. A few site hosts have personalized their sites; for example, one site has had a sturdy cutout of Bigfoot tied to the site fence. But these are on private land, and the NYSM encourages site hosts to take ownership of their sites.

Future applications

"A picture is worth a thousand words," and while cliché, that phrase has often proved true in meteorology. The atmospheric sciences have a long and illustrious history with photography and related imaging technologies. Photos help us to understand the atmosphere, monitor real-time weather conditions, and motivate emergency management response. Yet only recently have cameras been adopted into the "standard" weather station suite of sensors. The inclusion of cameras within the NYSM have greatly expanded the value of its in situ data, allowing for a greater understanding of the quantitative information collected, improved quality control, and more comprehensive metadata. For weather operations, the camera images have been invaluable, providing real-time "eyes on the ground" in every county across the state. Cameras have been used by the NWS for monitoring precipitation type and intensity, visibility, and snow depth. In addition, cameras have likely discouraged vandalism, spurred commercial activities, enabled research, and broadened educational opportunities. Looking ahead, sky-imaging (fisheye) cameras would provide full 180° sky views, capturing more coherent cloud development. Multiple cameras added per site would yield full 360° viewing, thereby providing even greater site security and environmental monitoring. More frequent sampling (1 min or more) could enable cloud tracking capabilities. Finally, very localized multicamera networks could also permit cloud height estimation. In summary, camera networks are opening a new era in long-term environmental monitoring.

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Data availability statement. NYSM data are available publicly at cost in accordance with the NYSM data policy: www.nysmesonet.org/about/data. Real-time and archived data may be requested via online Data Request page: www.nysmesonet.org/weather/requestdata.

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