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The Backyard Weather Science Curriculum: Using a Weather-Observing Network to Support Data-Intensive Issue-Based Atmospheric Inquiry in Middle and High School

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Abstract
This theoretical article proposes using statewide weather-observing networks (Mesonets) to support data-intensive, issue-based teaching of atmospheric topics in middle and high school science. It is argued that the incorporation of this new technology and its affordances into the school curriculum can drastically change the ways that atmospheric topics are taught and learned in classroom settings, from dull lectures to engaging explorations of weather phenomena with potential not only to spark in-the-moment curiosity but also long-term interest in STEM. However, this educational revolution is contingent upon the availability of instructional materials that are pedagogically sound and developmentally appropriate. School-aged students require strategic instructional design and supportive pedagogic scaffolding to pursue their curiosity feelings and develop a motivational profile that is conducive to interest in STEM (self-efficacy, outcome expectation, etc.) as well as situational awareness. In addition to articulating the theoretical underpinnings of this proposition, an account is provided of ongoing efforts to turn this cutting-edge scientific technology into a curriculum space for students to explore weather phenomena, conduct map-based inquiries, and engage in data-based deliberation in the context of real-world issues. Centered on the provision of investigative cases that are locally situated and relevant to students' lifeworld (place), the Backyard Weather Curriculum is presented to illustrate how this can be accomplished through the adoption of a place-based approach wherein relevance serves as an essential design principle for curricular development and enactment. Such curriculum, it is argued, can help promote student development from curious explorers to inquirers with a deep epistemic interest in STEM.

Keywords Weather-observing networks · Atmospheric science instruction · Data-intensive teaching · Case-based earth science · Student curiosity · Interest in STEM

Evidence abounds of the pedagogical potential of issue-based teaching approaches whereby school-aged students learn by participating in classroom activities that are contextualized in real-word issues (e.g., environmental cases). Characterized by high levels of authenticity and personal relevance, issue-based learning tasks allow for active and firsthand exploration of complex natural phenomena like the weather. However, contextualizing science instruction in real-word issues requires access to "big data." This is particularly true for issues in the field of atmospheric sciences, which has recently witnessed the advent of what has come to be known as the fourth science paradigm (Hey et al., 2009), that is, scientific discovery based on massive datasets and intensive computing. Data-intensive science relies on large-scale networks of densely deployed sensors capable of real-time, remote monitoring of complex environmental systems. Enormous quantities of data flowing in real-time from distributed locations are stored as massive databases that can be accessed online. Being able to access and analyze this big data is essential for classroom deliberation and student negotiation of complex atmospheric issues. The wide-scale deployment of dense weather-observing networks has made this possible.

Taking advantage of such possibility, the present article examines how a statewide weather-observing network called Mesonet can be productively used to support data-intensive, issue-based teaching of atmospheric topics. More specifically, an analytical account is provided of our efforts to turn this innovative computational resource into a curriculum

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space for students to explore weather phenomena, conduct map-based inquiries (Cravey et al., 2000), and engage in data-based deliberation in the context of real-world issues. Additionally, attention is given to currently available online platforms (e.g., Desmos, Google Sheets, JASP, R, and CODAP) and dashboards with data visualization capabilities, such as interactive meteograms, data display of local weather events in real-time, and time-lapse photography sequences synchronized with dynamic graphical information that allow students to see what the sky conditions look like as they analyze and interpret the graphical information for weather events.

The above educational efforts and tools are considered in light of recent scholarship (theoretical and empirical) on issue-based science instruction, teaching and learning of atmospheric science content, data visualization, and modeling (Finzer, 2013; Konold et al., 2017). More specifically, we review research on student development of analytic and modeling skills such as analyzing "messy" data sets and developing quantitative models (Rosenberg et al., 2020) as well as student development of visualization abilities; for example, we will explore the ability of students to visualize actual meteorological conditions behind symbolic representations on a weather map or *situational awareness* (Wilson, 2020). Our ultimate goal is to articulate a theory-based, research-informed perspective on the pedagogical potential of the Mesonet to promote data-intensive, issue-based instruction of atmospheric science at the school level. Additionally, exemplars of curricula are provided to illustrate our theoretical arguments. Lastly, implications for future research and pedagogical practice are discussed.

Mesonet

Mesonet is a type of weather-observing network with stations spaced close enough to adequately sample "mesoscale" weather. Mesoscale refers to weather phenomena that range in size (from several miles to hundreds of miles) and duration (from minutes to hours) such as thunderstorms, heat bursts, and tornadoes. Across the USA, there are more than 20 statewide Mesonets varying in goals, number of stations, instruments, and operating agencies (Mahmood et al., 2017; McPherson et al., 2007).

Our efforts have centered specifically on the newly established state-of-the-art New York State Mesonet (NYSM), which consists of 126 weather stations deployed across the state with an average station spacing of 17 miles (Brotzge et al., 2020). All stations make 5-min measurements of standard meteorological variables (pressure, temperature, humidity, wind speed and direction, precipitation), plus total solar radiation, soil moisture, soil temperature, and snow depth. Additionally, each station has cameras that capture still images every 5 min, 24 h a day, and 7 days a week (Fig. 1). All data are processed in real-time, feeding weather prediction models and decision-support tools for emergency management, transportation, energy, education, agriculture, etc. (Brotzge et al., 2020). This data is available through the website http://nysmesonet.org.

Another important feature of the NYSM network is its physical proximity to schools. Nearly every NYS school is within 10 miles of a weather station, with 12 of them being located directly in the "backyards" of schools. As a result, NYSM provides access to large amounts of meteorological and environmental data (numerical and visual) from students' "backyard" that are relevant to their daily life, from what to wear, how we drive, to where we choose to live. It can also be used to examine how the weather and climate impact students' daily life. As such, NYSM holds promise as an innovative technological tool that can support issue-based school science through access to big data and visual exploration of weather phenomena.

As part of ongoing educational efforts, we have sought to capitalize on the NYSM's open, data-intensive, networked infrastructure as a means to promote authentic scientific practices advocated by the Next Generation Science Standards such as computational thinking (NGSS Leads State, 2013). In particular, our educational use of this weather network has been aligned with the disciplinary core idea *ESS2D: Weather and Climate* within the discipline of *Earth and Space Sciences* (Table 1). Students can take advantage of NYSM instruments and data to build knowledge and skills in the subject of earth science, which includes a unit on weather and climate. Such a unit is typically taught didactically due

Fig. 1 (Left panel) Map of 126 NYSM sites (green) with sites in K-12 schools (red). (Center panel) NYSM site at Red Hook High School. (Right panel) Configuration of a typical NYSM site

to the unavailability of the costly equipment necessary to collect and analyze atmospheric data at most schools. As a result, students experience atmospheric science passively, as a collection of sterile facts to be memorized. NYSM can help change this and enrich earth science curriculum through the availability of exciting visuals and increased amounts of data for conducting atmospheric inquiries. The present article provides a research-based account of how the Mesonet database can be used by science educators to shift from the traditional "show and tell" to a data-intensive, issue-based type of weather instruction that is more engaging, relevant, and authentic. It is a first step in our efforts to turn a statewide Mesonet into a curriculum space for students to make real scientific discoveries as they develop computational thinking in line with the essential practices of science and engineering outlined in the NGSS.

Teaching Atmospheric Science in Schools

Atmospheric science constitutes an important part of national educational policy and current school science curriculum. As Table 1 shows, this is particularly true for the middle and high school levels where science instructors are called upon to promote student learning about a variety of atmospheric science concepts (e.g., weather conditions, energy) and practices (posing questions, modeling, arguing from evidence, etc.). School educators are also called upon to foster student development of *climate literacy* (U.S. Global Change Research Program (USGCRP), 2009), that is, a solid and systematic conceptual understanding of the Earth' physical climate system as well as solid grasp of the complex interactions between climate and human society and activity on multiple scales of time and space.

In response to this call for action, schoolteachers have increasingly relied on investigative learning tasks wherein students learn through inquiry/discovery, that is, by positing scientific questions, collecting, and analyzing data to answer them, and by using evidence to evaluate claims and explain phenomena. This educational trend has been driven by research showing that students taught through inquiry tend to demonstrate higher levels of engagement and motivation (Lynch et al., 2005; Oliveira, 2010), improved achievement (Banilower et al., 2010; Geier et al., 2008; Wilson et al., 2010), and more positive attitudes toward science (Gibson & Chase, 2002) than pupils who receive traditional textbook-based instruction. Inquiry-based learning has also been used to promote middle school students' computational thinking in the context of weather and weather prediction (Marcum-Dietrich et al., 2019).

Effectiveness of inquiry-based instruction is contingent upon the relevance of the material to the lives of students (Baker & Leary, 2003; Shapiro & Sax, 2011; Subotnik et al.,

Table 1 BWS alignment with Next Generation Science Standards for middle and high school (New York State Education Department, 2016)

Performance expectations		
Students who demonstrate understanding can:		
• MS-ESS2-5. Collect data to provide evidence for how the motions and complex interactions of air masses result in changes in weather conditions		
• MS-ESS2-6. Develop and use a model to describe how unequal heating and rotation of the Earth cause patterns of atmospheric and oceanic circulation that determine regional climates		
• MS-ESS3-2. Analyze and interpret data on natural hazards to forecast future catastrophic events and inform the development of technologies to mitigate their effects		
• HS-ESS2-2. Analyze geoscience data to make the claim that one change to Earth's surface can create feedbacks that cause changes to other Earth systems		
• HS-ESS2-4. Use a model to describe how variations in the flow of energy into and out of Earth's systems result in changes in climate		
• HS-ESS3-1. Construct an explanation based on evidence for how the availability of natural resources, occurrence of natural hazards, and changes in climate have influenced human activity		
• HS-ESS3-6. Use a computational representation to illustrate the relationships among Earth systems and how those relationships are being modified due to human activity		
Science and engineering practices	Disciplinary core ideas	Crosscutting concepts
• Asking questions and defining problems	• ESS1.B: Earth and the Solar System	• Stability and change
• Planning and carrying out investigations	• ESS2.A: Earth Materials and Systems	• Cause and effect
• Analyzing and interpreting data	• ESS2.D: Weather and Climate	• Systems and system models
• Developing and using models	• ESS3.A: Natural Resources	• Influence of engineering, technology, and science on society and the natural world
• Constructing explanations and designing solutions	• ESS3.B: Natural Hazards	• Scale, proportion, and quantity
• Using mathematics and computational thinking	• ESS3.D: Global Climate Change	• Stability and change
• Obtaining, evaluating, and communicating information		• Energy and matter
• Engaging in argument from evidence		

2010). To serve as a source of transformative experiences, inquiry-based learning requires not only a realistic context but also access to personally meaningful data (collected locally by the students themselves). However, when it comes to atmospheric science, such instructional approach is typically absent from school science due to logistical challenges such as the need for advanced and costly scientific equipment more commonly found at the undergraduate level, such as rotating weather tanks (Mackin et al., 2012), high-altitude weather balloons (Coleman & Mitchell, 2014), geographic information systems (GIS) (Jant et al., 2020), micronets (Shapiro et al., 2009), and meteorological instruments (e.g., thermometers, barometers, hygrometers, anemometers, mobile radar, radiosondes, and disdrometers) (Shellito, 2020; Tanamachi, et al., 2020). As a result, students do not often experience atmospheric phenomena in their classroom.

Given the sheer size and complexity of Earth's atmosphere, school-aged students are usually precluded from conducting hands-on activities or experimental labs on atmospheric phenomena. Instead, to deal with the above obstacles, science teachers have traditionally resorted to a "canned and decontextualized approach" wherein students are provided with preexisting sets of atmospheric data with little (if any) direct connection to their local reality or daily live (Bhattacharya et al., 2020; Marcum-Dietrich et al., 2019; Pertzborn & Limaye, 2000). Despite having pedagogical merits such as allowing students to experience data analysis from the positionality of atmospheric scientists and provision of developmentally appropriate datasets less likely to lead to cognitive overload, this approach usually has important limitations such as reduced authenticity (e.g., students cannot experience data collection) and reduced student agency and ownership over the data (e.g., datasets are pre-assembled for the students, without their input).

Such an approach is inconsistent with research showing how to foster student development of *data literacy* — the ability to use different forms of data (Donovan, 2008; Gibson & Mourad, 2018; Marx, 2013). To become data literate, students must first understand the purpose behind collecting a certain data set, how the data is collected, and how this evidence might, hopefully, provide evidence to address the question or problem they are investigating. Since visualized representation of weather is directly linked to quantitative measurements in atmospheric science, it is critical for learners to be afforded the opportunity to develop as analytical thinkers who are capable of visualizing connections to the real world and translating abstract graphic information into concrete real-life application (Kozhevnikov et al., 2007; Maltese et al., 2015).

Another important drawback of the above data-based approach is the fact that students cannot see what the sky conditions look like at the time of data collection. Faced with the impossibility of direct visual observation, learners are left with the cognitively demanding challenge of having to "imagine" (i.e., create mental pictures of their own) as they analyze largely removed atmospheric measurements. However, leaving to students' imagination can be problematic since the Earth's atmosphere is a highly complex and dynamic global system whose phenomena often involve distal and indirect causality. Rather than having a single, direct, and proximal cause (Choi et al., 2003), anthropogenic global warming is the result of distal and indirect chains of cause and effects within a complex system. Put differently, climate processes involve sophisticated sequences of ripple effects, which Maddux and Yuki (2006) define as "downstream effects of actions and events, particularly those effects that are relatively indirect and distally related to the focal event… [wherein] attention is directed toward the broader context and toward the interrelationships among individuals and events" (p. 671). McGee and Pea (1994) describe the atmospheric system as follows:

> Small changes in one part of the system can eventually affect other parts of the system that are thousands of miles away. Atmospheric scientists must take into account many interrelated variables in order to understand some of the basic processes. Forecasters who are interested in predicting the weather for a specific city, must take into account the weather trends that are taking shape in other parts of the world. (p. 24)

Yet, as research shows, school-aged students tend to hold oversimplified interpretations of complex systems, commonly overlooking long-term and indirect consequences of ecological actions and decisions (Hogan, 2002) and often lacking the complex system thinking skills needed to infer nonlinear and indirect forms of causality (cyclic, domino, mutual, probabilistic, emergent, etc.) within ecosystems (Grotzer & Baska, 2003). As such, difficulty in understanding climate change and the anthropogenic contribution to global warming can be attributed to people's reductive biases (Feltovich et al., 1993) such as their tendency to overlook processes with multiple, decentralized, non-obvious, and cumulative causes that involve temporal delays, spatial gaps, and no intentional agency (Grotzer & Lincoln, 2007). As emphasized by Grotzer and Perkins (2000), oversimplified interpretations of complex systems not only foster misconceptions but "can also distort the scientific information to the point where parts of the causal story are lost or misconstrued" (p.3). This often leads to difficulty in understanding atmospheric phenomena such as anthropogenic causation of global warming.

To deal with the above challenges and support of data modeling approaches to atmospheric science teaching in K-12 schools, some have resorted to the use of Internet-accessed, real-time weather data to teach meteorological topics (Mulvany et al., 2008), whereas others have opted for technological tools such as spreadsheets, graphing display, statistical tests, and data structuring (Finzer, 2013;

Konold et al., 2017). However, these tools have relatively limited data visualization capabilities, mostly in the form of graphic displays of quantitative data (line-graph generation). Likewise, currently available online platforms (e.g., Desmos, Google Sheets, JASP, R, and CODAP) are esthetically unappealing, artistically lacking, and highly abstract. A good example is the traditional meteograms, which typically display abstract representations of the values of the different weather parameters (numbers, lines, etc.) (see Fig. 2). Although these platforms are laudable for their potential to help students develop data analytic and modeling skills (e.g., analyze "messy" data sets, develop quantitative models) (Rosenberg et al., 2020), their highly abstract nature can pose interpretive challenges to younger students who often are concrete thinkers (Leppink et al., 2013; Mayer, 2005) and may be unable to visualize the actual meteorological conditions behind the symbolic representations on the meteogram. As research shows, computer-based graphs are not always "transparent" to students as commonly assumed (Ainley, 2000; Aydın-Güç et al., 2022). A graph may be considered transparent only when it is visible to inspection for extracting information and at the same time invisible by allowing the user access to meanings and significance which lie beyond the artifact itself. Analogous to a window, students need to be able to see the graph itself as well as through it. Such visual ability can be developed in learning situations where students can manipulate the graph; change its appearance (i.e., engage with interactive graphs); and use the graph to solve a problem in a familiar or meaningful context (i.e., engage in a purposeful task). In these learning situations, students have a chance to develop *professional vision* (Goodwin, 1994), that is, the ability to see or notice weather phenomena like expert atmospheric scientists while looking at graphs.

Another technological tool commonly used by a growing number of educators is webcams. Outdoor cameras allow viewers to see the sky, ground, and surrounding conditions and can be used to observe weather phenomena (e.g., storms, tornados) in real time. Webcams also provide school educators with a means to overcome the financial and logistical constraints of the fieldwork often required for the effective teaching of important environmental concepts of spatial and temporal change and atmospheric movement (Sawyer et al., 2010). However, pedagogical approaches have been mostly limited to isolated webcams which do not allow students to see large-scale weather phenomena. Visually monitoring mesoscale phenomena like thunderstorms requires systems of networked cameras to that span larger areas.

In an effort to help teachers deal with the above challenges, we have begun to develop an inquiry-based curriculum called the *Backyard Weather Science* (BWS). Built around the existing NYSM network, BWS is a school science curriculum being collaboratively designed by scientists and science educators to enable students to embark on "analytical journeys" and navigate the Mesonet's "ocean of data" in a manner that is personally and locally relevant, scientifically authentic, and visually rich without experiencing the cognitive overload often associated with exposure to large datasets. This curriculum is described and illustrated next.

The Backyard Weather Science (BWS) Curriculum

As an inquiry-based atmospheric science curriculum, BWS is being designed specifically to encourage students to authentically and purposefully explore the massive Mesonet dataset (like real scientists) as they conduct atmospheric inquiries. The BWS curriculum takes advantage of the Mesonet weather station cameras which continuously capture still images of meteorological and environmental conditions. These cameras provide an oblique view of the landscape, capturing unprecedented events, hazardous weather storms, rare weather phenomena (sastrugi, waterspouts), and animal activities (Fig. 3). For example, from a series of images of cicadas, student can explore how these organisms hatch when the soil temperature reaches around 64°F. Students can analyze NYSM soil temperature data and visually investigate the camera images.

Although other educational programs have been built around Mesonets (e.g., the Earthstorm education program at the Oklahoma Mesonet, https://www.mesonet.org/index.php/earthstorm), they do not take advantage of the possibility of engaging students in online exploration of real-time data collected right in their backyard. In addition, NYSM is the first Mesonet with a camera at each site to provide the unprecedented visual depictions of weather outside (Brotzge et al., 2022). The NYSM's power to enrich earth science curriculum and instruction by means of authentic and relatable classroom inquiries wherein students can use a weather-observing network to see across an entire state is yet to be attempted. Additionally, we go beyond isolated webcams and utilize a statewide system of networked cameras to allow students to see large-scale weather phenomena that span an entire state. A preliminary sample activity developed for the BWS curriculum is provided next.

Sample BWS Activity

Ms. Perno (Author 3) has played a pioneering role in the development and field testing of BWS curriculum. A middle school science teacher with 15 years of teaching experience, Ms. Perno has a BS in Geology and an MS in Atmospheric Sciences and Education. Her first attempt to develop BWS materials took place during the 2020–2021 school year when she set out to use the NYSM website to have

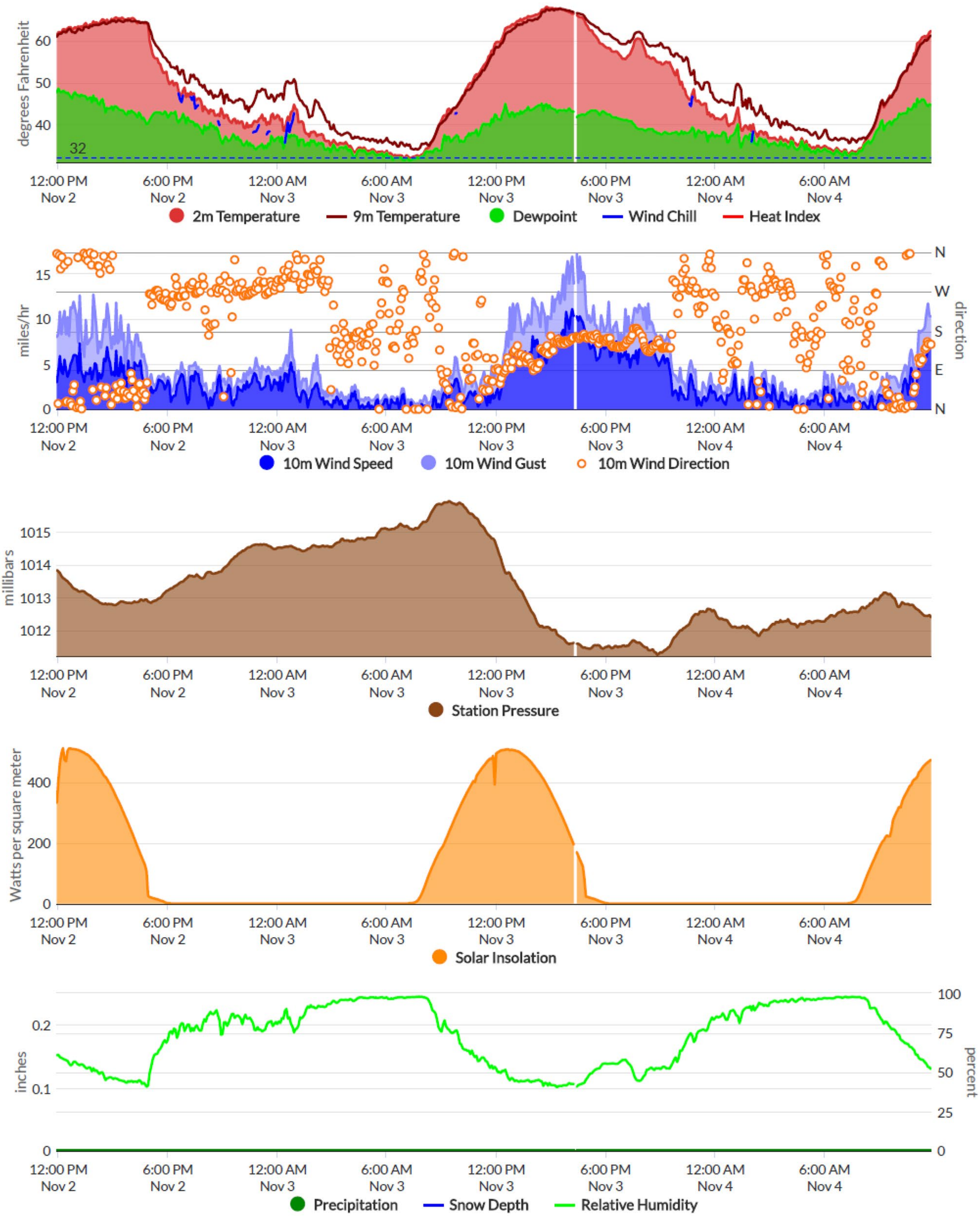


Fig. 2 Sample meteogram showing 2-day variations in temperature (top), wind speed and direction, surface pressure, solar insolation, and relative humidity at the weather station in Voorheesville, NY

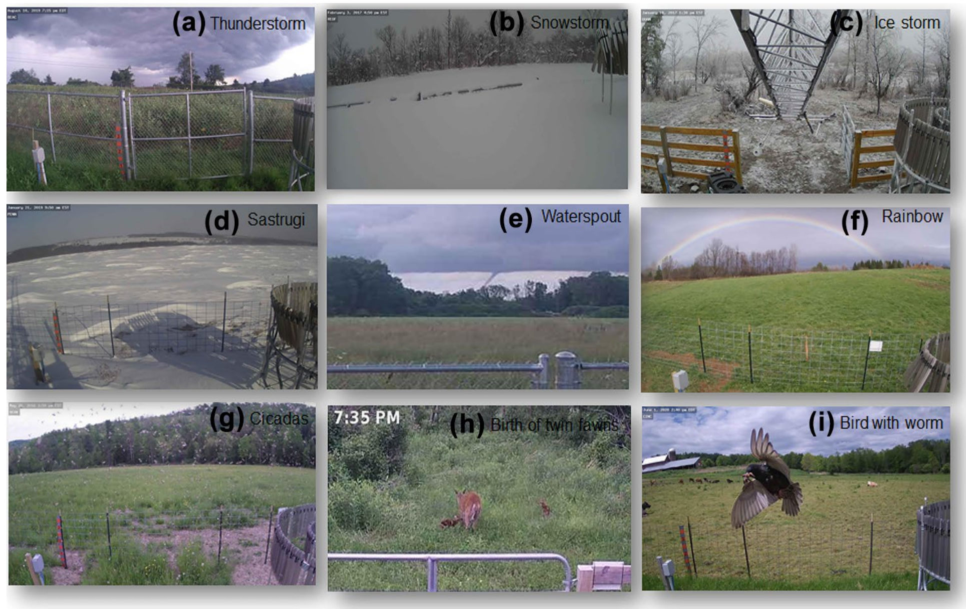


Fig. 3 Nine NYSM camera images showing storms ((**a**)–(**c**) top row), rare weather phenomena ((**d**)–(**f**) middle row), and animal activities ((**g**)–(**i**) bottom row)

students actively and collaboratively explore weather variables using locally collected data. Prior to that, her students had only had access to data from the Weather Channel app, the National Weather Service, and the National Center for Atmospheric Research (NCAR) websites. However, most of these data was collected from weather stations far from the students' locations, was updated every 3 h, and did not offer a visual image of those sites. Students would look outside to see the observable conditions at the time of learning but had to rely on satellite and radar data to infer what the weather was like in different areas of NYS (largely removed from the local context).

To make her atmospheric science instruction more effective, Ms. Perno developed an instructional unit in which students are introduced to weather instruments from the Mesonet network, learn to interpret weather maps, and then engage in various multivariable weather activities. Using the multitude of maps available on the Mesonet website, students learn about the scope of the network and its products and are then asked to make weather forecast for different locations of NYS. To this end, they are provided with weather data and real-time camera imagery from the NYSM website, including temperature, pressure, wind speed and direction, dewpoint/humidity, precipitation, solar radiation, snow depth, and soil temperature and moisture. Lastly, students are presented with locally relevant, investigative cases. A good example is "1–2-3 Strikes You're out! On our way to Cooperstown" (Appendix), an investigative case wherein students use Mesonet data to help the little league coordinators make a decision about a baseball game using the NYS Mesonet data. Unlike the more traditional, data-based atmospheric science activities, this case is uniquely situated in these particular students' lifeworld (not meant to be used statewide or nationwide), students can authentically experience atmospheric data collection as well as data analysis, and students help select the dataset (the data is not simply selected for them). Additional investigative cases similar to this one are currently under development as part of our efforts to expand the BWS curriculum.

In "1–2-3 Strikes You're out! On our way to Cooperstown," teachers and students assemble and analyze a set of images (graphs, pictures, etc.) of local weather conditions. It is important to note that this case is not meant to be used as just another canned activity whereby a fixed dataset is prepared in advance for the students and simply handed to them. Instead, our vision is that of an instructional approach whereby students play an active role in the selection of the appropriate data needed for answering their atmospheric inquiries through participation in brainstorming sessions and teacher-led discussions about important parameters such as day, time, geographical location, and type of atmospheric measurement. The provided images and numbers are simply examples of the type of data that students can decide to include in their analysis.

After being introduced to known patterns of planetary winds and learning about the direction storms usually move across the USA, students locate several local cities on a map of New York State and decide on the data that needs to be obtained from the Mesonet database. Then, working on computers, student groups use this data to systematically make observations of weather conditions as a storm moves across various local cities. With guidance from the teacher, student groups make connections between the local weather observed on the inspected Mesonet images/numbers and larger atmospheric patterns, thus being able to make weather predictions for Cooperstown.

Our use of investigative cases is informed by research showing that instructional cases constitute powerful pedagogical tools for contextualize science instruction, promote inquiry, and teaching skills such as scientific argumentation (Eastwood et al., 2012; Herreid, 2005; Oliveira et al., 2012; Sadler et al., 2007). Taking the form of short narratives wherein students are provided with problematic scenarios (real or hypothetical) whose resolution requires investigation (data collection and analysis), these cases have been shown to be highly effective as a means to increase student motivation and interest in learning science. Such power stems from pedagogical features such as relevance, authenticity, and purposefulness. Informed by this research, cases involving local atmospheric issues have been created and added to the BWS curriculum. Reflecting our commitment to data-intensive issue-based science instruction, these cases are designed to serve as springboards for student engagement with atmospheric data from NYSM.

An important characteristic of the BWS curriculum is the pervasive use of mapping activities, which have been shown to have many benefits to learners. Map-based inquiries evoke curiosity and engagement by allowing students to use their personal experiences, explore ideas on how they see the world they live in, and gain awareness of one's surroundings on Earth as they gain exposure to STEM professional practices and career awareness (Anthamatten et al., 2018; Claesgens et al., 2013; Nolan et al., 2019). Maps can also provide viewers with a lens for critically examining/interrogating their place in the world (physical, cultural, political), and as such, they have potential to foster critical thinking and empowerment (Cravey et al., 2000).

Theoretical Underpinnings of BWS Curriculum

Student Interest Development

Underlying the BWS curriculum is an epigenetic perspective (Weaver, 2019) on student development of interest in STEM careers. From this theoretical perspective, interest development constitutes a long-term developmental process involving complex, long-term interactions between internal factors (e.g., feelings of curiosity and self-efficacy) and external factors (e.g., visual stimuli, teacher support, social interactions). Like other epigenetic phenomena (intelligence, talent), we consider student interest to be socio-ecologically emergent rather than simply determined by one's biological or psychological traits (e.g., genes, IQ, personality). Learning experiences and the sociocultural environment interact with internal/mental factors as part of a developmental process that over time produces individuals with a (pre) disposition to engage in science activity and with an interest in pursuing science careers. Interest in STEM careers is not a personality trait that one is simply born with but rather a behavioral predisposition that can instructionally nurtured and cultivated.

Our development of the BWS curriculum is based on the premise that student engagement in computer-based atmospheric inquiries can lead to increased individual interest in STEM. Such a premise is informed by previous research linking increased interest in STEM fields to technology-enhanced learning activities (Berkeihiser & Ray, 2013; Hayden et al., 2011; Plant et al., 2009). Instructional technologies like computers provide learners with novel perceptual stimuli that draw their attention to certain events or objects (e.g., natural phenomena), effectively fostering feelings of curiosity and inviting exploration (Arnone et al., 2011; Kidd & Hayden, 2015). Learner experience of these *in-the-moment feelings of curiosity* (Ainley, 2019) in the context of technology-rich environments is well documented, constituting a critical first step in student development of deeper and more enduring interest in a domain of activity (Arnone et al., 2011; Hidi & Renninger, 2006). Students' interest deepens over time as they recurrently pose and pursue *curiosity questions* (Johnson et al., 2004; Renninger, 2000). Enduring interest emerges out of student pursuit of their curiosity feelings. As Engel (2011) writes, "curiosity, the engine of intellectual development, is possibly the most valuable asset a child brings to her education" (p. 633).

While creating the BWS activities, we envision a developmental process that begins with the arousal of *situational interest* (Hidi et al., 2004; Schiefele, 2009) — a temporary emotional state aroused by specific features of a situation or task (e.g., relatability of a problem, vividness of a data visualization tool, novelty, etc.). Characterized by an epistemic desire to know, this fleeting state involves focused attention, increased cognitive functioning, persistence, enjoyment or affective involvement, and curiosity (Hidi et al., 2004; Renninger, 2000; Silvia, 2006). Once students' situational interest (curiosity) has been triggered by novel and puzzling stimuli, subsequent cognitive activity feels relatively effortless. A particularly effective source of curiosity-arousing stimuli is computerized presentation of problems. Previous studies have shown that using computers to present learning problems to students is a strong trigger of situational interest (Bernacki & Walkington, 2018; Høgheim & Reber, 2015). This research-informed our decision to design BWS as a computer-based curriculum centered on brightly colored and vivid photography. Such a visually rich, computerized learning environment was designed to provide learners with the sensorial stimuli previously shown to trigger the attention processes that underpin student experience of curiosity feelings/episodes within the domain of science.

However, active pursuit of curiosity feelings is contingent upon the students' self-efficacy and outcome expectations (Bandura et al., 1986). *Self-efficacy* refers to students' beliefs in their ability to complete tasks ("Can I do this?"), whereas *outcome expectations* refer to what students anticipate as consequences of task completion ("If I do this, what will happen?" "What will I gain/lose?"), including rewards, approval, and self-satisfaction. Students continuously evaluate their own ability to complete tasks and expectations of positive outcomes, making adjustments based on each new exposure. Over time, (re)engagement in activities in which students perform well, on which they receive positive feedback, and that provide them with memorable/meaningful experiences leads to the development of an enduring interest in a domain. Likewise, active pursuit of curiosity questions depends on whether students believe that they have the ability/capacity to find answers and whether they expect a positive outcome (success, satisfaction, etc.). In the absence of these motivational conditions, students may instead choose to simply dismiss their curiosity feelings (as opposed to actively pursuing answers to their curiosity questions). Put differently, the basis for curiosity- and interest-driven action is self-perception and self-knowledge of previous performances, feelings, etc. Therefore, it can be argued that self-efficacy and outcome expectations constitute a vital part of individual interest development. This argument is corroborated by Renninger (2010) who theorizes the link between interest and self-efficacy as follows:

> Like interest, self-efficacy is characterized by the feelings and valuing that accompany competence… unlike self-efficacy, interest is not a belief; although learners may hold beliefs about content that is of interest to them. (p.118)

Like us, Renninger (2010) considers learners to have *motivational profiles* (developmental levels characterized by unique sets of interrelated motivational variables). Interest, self-efficacy, and outcome expectations are distinct but complementary motivational variables and as such need to be considered together in analytical accounts of human development. In a similar vein, exposure to BWS activities, which were designed to give rise to situational interest (Fig. 4), is also expected to promote improved self-efficacy and outcome expectations (Bandura et al., 1986). This is the motivational profile that we expect students to develop as a result of their engagement with the BWS activities.

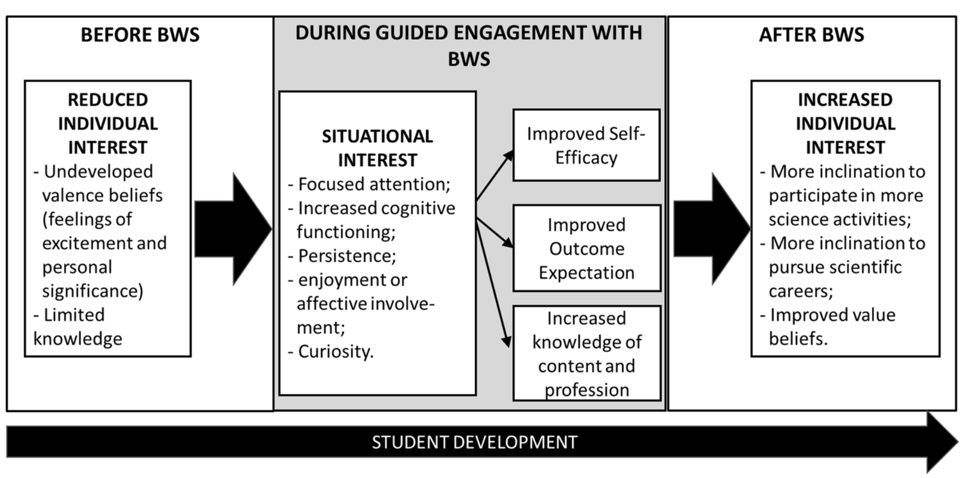
Studies show that self-efficacy and outcome expectations are good predictors of student interest and future career choices (Byars-Winston et al., 2010; Gainor & Lent, 1998; Waller, 2006; Wang, 2013). This literature also shows that classroom exposure to science and mathematics activities can help enhance high school students' self-efficacy and outcome expectations. As such, it lends empirical support to our contention that, to boost students' STEM career interest, self-efficacy, outcome expectation, and interest in the scientific domain should all be simultaneously cultivated given their interrelated nature.

Central to the emergence of student interest is the availability of social support. In previous scholarship, student development of curiosity and interest is consistently linked to the presence of social stimuli such as support from teachers (Alexander et al., 2012; Chak, 2010). This is emphasized in the work of Dewey (1933) himself, who once wrote:

> Curiosity rises above the organic and social level and becomes intellectual in the degree in which it is transformed into interest in finding out for oneself the answer to questions that are aroused by contact with persons and things. (p.144)

In practice, this means that exploratory activity should be accompanied by supportive social interactions such as teacher modeling and encouragement of exploration and

Fig. 4 Theoretical underpinning of the BWS curriculum



questioning and expression of positive feelings (Engel, 2011). This is precisely how we envision classroom implementation of the BWS activities. More specifically, we foresee a highly collaborative and supportive social environment wherein intellectual curiosity is encouraged, valued, and enacted. In addition to being conducive to the emergence of an interest predisposition, these social conditions are also likely to have a positive impact on students' self-agency. As emphasized by Bandura et al. (1986), one's self-efficacy is positively influenced by social means such as verbal persuasion (e.g., a teacher telling a student "you can do this") and vicarious experiences (e.g., a student seeing teacher posing curiosity questions). These stimuli from the students' social surroundings provide them with feedback that can positively shape students' self-perception and self-knowledge. However, rather than being part of the BWS curriculum design itself, these social conditions need to pedagogically co-crafted by teachers and students during classroom enactment. Such a need indicates that our curriculum development efforts may have to be accompanied by professional development that can ensure teacher pedagogical expertise.

Backyard Weather

Theoretical consideration must also be given to the BWS curriculum's focus on *backyard weather* (atmospheric phenomena that occurs in places that are familiar and in close physical proximity to students). This curricular focal point is consistent with recent calls for placed-based approaches to science education. Science instruction that is removed from students' reality (place) tends to alienate them, leading to disinterest and disengagement. To avoid this problem, students need to be offered science instruction that is locally grounded and that is situated in the context of students' place in the world (Aikenhead et al., 2006; Semken, 2005). Such an alternative approach leads to learning experiences characterized by increased authenticity and personal relevance.

Our emphasis on backyard weather is further supported by psychological research revealing that place constitutes an important source of stimuli for epistemic curiosity. Like objects that invite tinkering, places can spark curiosity feelings in students, generating a motivational drive to acquire new knowledge and the desire to learn more about it through exploration (Engel, 2011). Despite their reduced degree of novelty, familiar places provide stimulus based on personal importance (Boscolo et al., 2011), being characterized by intermediate or moderate levels of complexity that are less likely to overwhelm students (compared to the completely unknown whose highly complex stimulus can lead to cognitive overload) (Kidd et al., 2014). This motivated our decision to focus on students' place of livid experience (their backyard). Such a focus is meant to appeal to students' *sense of place* (Stedman, 2002), being strategically designed to foster emotional connection with atmospheric phenomena under exploration and promote a sense of personal investment.

Future Plans

Moving forward, we plan to develop an educational web-based dashboard that can support online, pictorial, and visualized learning of real-time, "backyard" weather and climate for middle and secondary students in earth science. This dashboard will accompany the BWS investigative cases. To be developed in JavaScript and Python, this new computer-based pedagogical tool will be an interactive, dynamic, and developmentally appropriate interface capable of synchronized presentation of graphical information and time-lapse photography so that students can see what the sky conditions look like as they analyze graphical information for local weather events (Fig. 5). This ambition comes in light of the present unavailability (to the best of our knowledge) of computational tools capable of real-time, pictorial–graphical data display of local weather events (atmospheric conditions in students' backyards) that can support school implementation of data-intensive issue-based atmospheric science curricula such as those presented in this article. Additionally, we plan to develop new classroom activities that examine climate-related data on the Mesonet website, namely, humidity readings in the area, temperature patterns for coastal versus inland locations, and temperature variations with elevation, latitude, time of the day, and season. This curriculum and software will be designed in a way that they be easily adopted by similar networks across the country.

Our curriculum development efforts will be paralleled by an extensive research agenda. More specifically, we plan to conduct a series of studies to systematically examine students' emergent abilities to interpret messy data in light of prior understanding of Earth systems' spatial and temporal scales, possible pedagogical strategies to scaffold student data science thinking, effectiveness of using predetermined/closed datasets versus more open datasets of variable sizes, and student experience of curiosity episodes as well as their emerging interest and situational awareness. Attention will also be given to the cognitive load associated with the pairing of data (images and numerical information), how placed-based reasoning emerges, and how reasoning with complex data is best approached, for whom, and under what conditions. Lastly, we will seek to answer important questions that remain such as how much training does a teacher need? How much prior knowledge is required? How much access to raw data should there

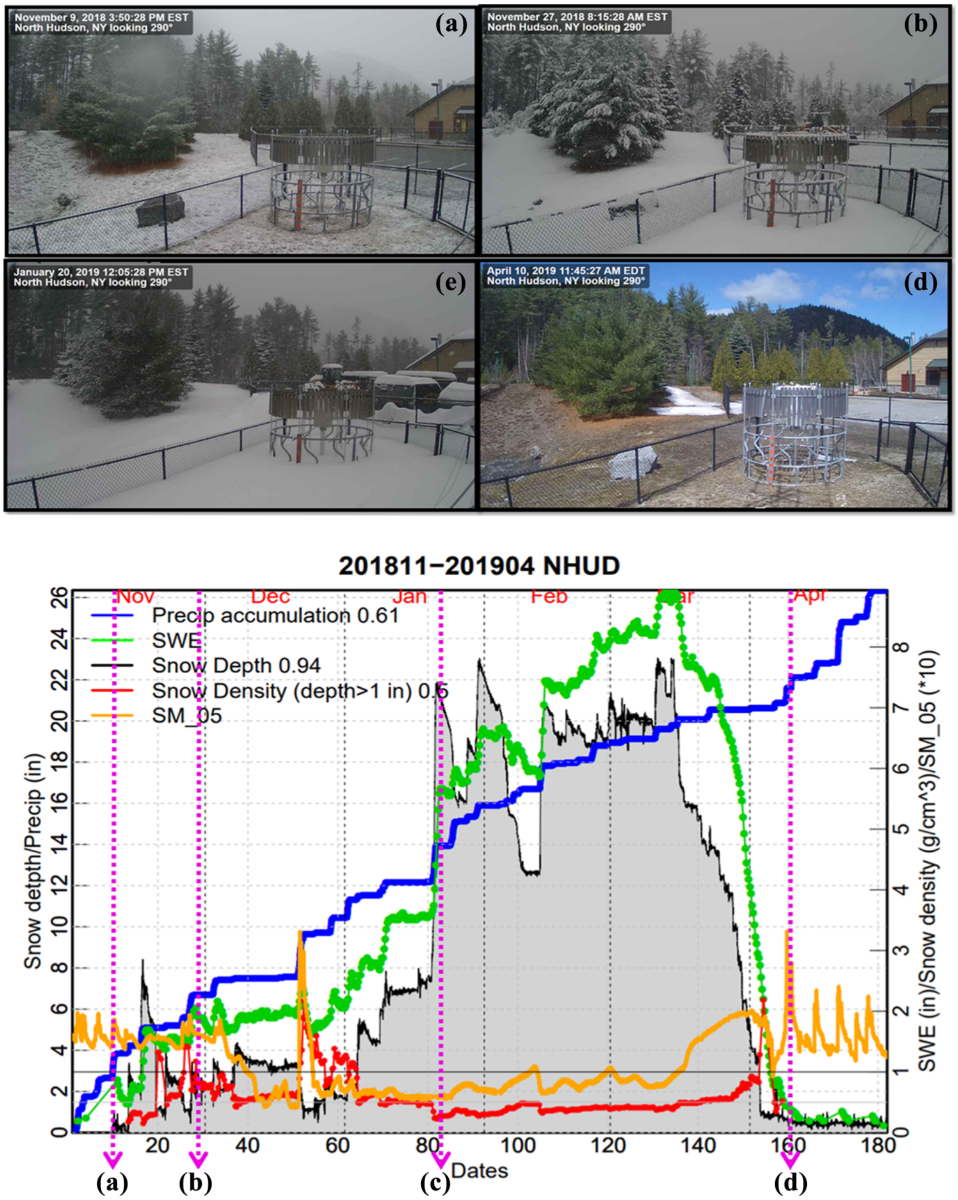


Fig. 5 (Top panel) Photos taken by the North Hudson (NHUD) camera on November 3, 2018 (the first snow/sleet storm); November 27, 2018 (a heavy and wet snowstorm); January 20, 2019 (the largest snowstorm in the 2018–2019 winter); and April 20, 2019 (almost completely melted snow). See the time-lapse video from November 1, 2018, to April 30, 2019 on https://operations.nysmesonet.org/public/references/2022_Oliveira/NHUD.mp4. (Lower panel) Time series of snow depth (gray shaded area) and other variables during the four months

be? How is reasoning developed over the course of the BWS activities?

Conclusion

Innovative technologies can radically transform issue-based science education in ways that can foster student curiosity and interest in STEM. The advent of weather-observing networks like Mesonet has made authentic engagement of school-aged students in data-intensive fields of inquiry such as atmospheric science a real possibility. Rather than having to picture distant atmospheric phenomena in their heads, students can now collect data and directly observe local weather events such as thunderstorms in real-time. Incorporation of this new technology and its affordances into the school curriculum can drastically change the ways that atmospheric topics are taught and learned in classroom settings, from dull lectures to engaging explorations of weather phenomena with potential not only to spark in-the-moment curiosity but also long-term interest in STEM. However, this educational revolution is contingent upon the availability of instructional materials that are pedagogically sound and developmentally appropriate. School-aged students require strategic instructional design and supportive pedagogic scaffolding to pursue their curiosity feelings and develop a motivational profile that is conducive to interest in STEM (self-efficacy, outcome expectation, etc.) as well as situational awareness. As illustrated by our efforts, this can be accomplished through the adoption of an issue-based approach centered on the provision of investigative cases that are place-based and hence highly relevant to students' lifeworlds. As such, we align ourselves with a longstanding tradition of educators (e.g., Dewey and Freire) for whom relevance constitutes an essential design principle for curricular development and enactment. Such an approach requires, among other things, reflective consideration of questions such as "relevant to whom?", "relevant to what?", "relevant how?", and "relevant when?" (Doherty, 2015). Keeping such critical questions in mind while designing data-intensive, issue-based science curriculum can increase the chances that science educators might succeed in their efforts to promote student development from curious explorers to inquirers with a deep epistemic interest in STEM.

Appendix

BWS Sample Case: 1–2-3 Strikes You're out! On our way to Cooperstown 

Grade Level

8–10

Driving Question

What causes the different weather and the movement of storms in the area?

Learning Goal

Students will use weather data to predict if the weather will affect their area.

Crosscutting Concepts/Science and Engineering Practices Addressed

Developing and using models

Analyzing and interpreting data

Obtaining, evaluating, and communicating information

Patterns

Cause and effect

Stability and change

NYS Learning Standards

HS-ESS-2–8: Evaluate data and communicate information to explain how the movement and interactions of air masses result in changes in weather conditions.

Scenario

Cooperstown is home to the baseball hall of fame museum and little league baseball. Baseball players from all over the state come to play summer tournaments in Cooperstown. This is the pinnacle of a little leaguers' career. Many teams fundraise for many months to be able to participate in such an event. Teams are given a specific week in the summer to compete in Cooperstown, ending the week with a championship game. Cooperstown is located approximately 60 miles southwest of Albany, 67 miles southeast of Syracuse, and 145 miles northwest of NYC. See the maps below. The closest Mesonet Station is Springfield NY.

A little league team has been staying in Cooperstown the week of June 27, 2022, and is scheduled to play their championship game on July 1 at 6:30 pm. There is a storm that is forecasted to pass over during the championship game. Hotels are booked months before the event, and there is no time to reschedule the game. It is 5 pm on July 1, and the organizers of Cooperstown have asked you to see if the championship game could be played safely. You are asked to use the NYS Mesonet database to determine if the game will be playable. The decision must be made at 6:10 pm. The clock is ticking (Fig. 6)!

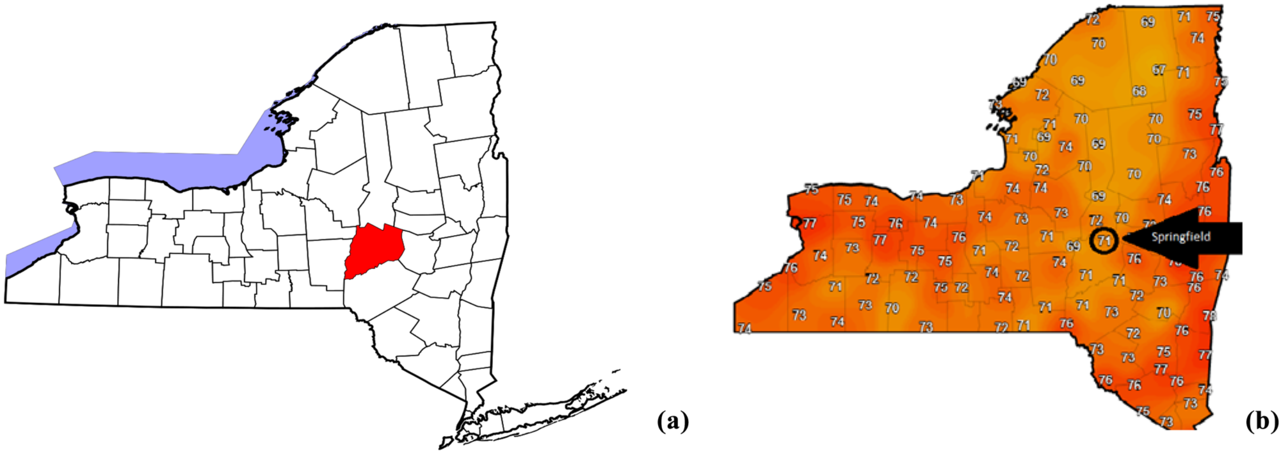


Fig. 6 Maps of New State showing (**a**) the central location of the Otsego County (in red) where Cooperstown is located and (**b**) an example of the NYS Mesonet dashboard temperature map, including in Springfield. **Teacher notes:** Through visual inspection of these maps, students will be able to see where the Mesonet Springfield station is located in NYS. Many students may not be familiar with the location of Springfield and Cooperstown. Teacher might want to have a blown-up section of Otsego County and have students locate where Cooperstown and Springfield are. Students are using the Springfield station as this station is the closest one to Cooperstown

Cooperstown Baseball Regulations

- The fields are made of clay and can only take on a certain amount of precipitation. This clay field can take 0.3 inches per hour of rain if the soil is dry. If there was precipitation in the past day, the field can take 0.2 inches per hour of rain.
- Games during this tournament have a maximum time limit of 2 h. There are also no lights on the fields. For safety reasons, games will be called 30 min after sunset.
- If lightning is seen, the game is delayed 30 min from the last strike of lightning.

Your Task

Your mission is to help the Cooperstown little league directors and make an educated decision to see if the forecasted storm will impact the championship game. You will be using radar imagery and the NYS Mesonet data.

Phase 1: Explore

This initial phase of the lesson is aimed at setting the stage for learning by peaking students' interest and inspiring a "need to know." To this end, students watch a video of an approaching storm, are given the background of the Cooperstown tournament, and are introduced to the task (the scenario above). Working in small groups, students then brainstorm questions, possible questions that they need to research to help the Little League Director. These may include:

1. What time is the storm coming?
2. Will the storm hit Cooperstown?
3. Which direction is the storm coming from?
4. How fast is the storm moving?
5. How much precipitation will occur?
6. Will there be thunderstorms?
7. What is the weather like west of Cooperstown?
8. When does the sun rise and set on Jul 1st, 2022?

Teacher Notes Students need to decide on the specific data (numerical/images) they will need to examine in order to complete their task. The teacher facilitates a discussion about important parameters (day, time, geographical location, types of measurements), helping them recognize the need to explore a location west of Cooperstown during the day/time leading up to the game.

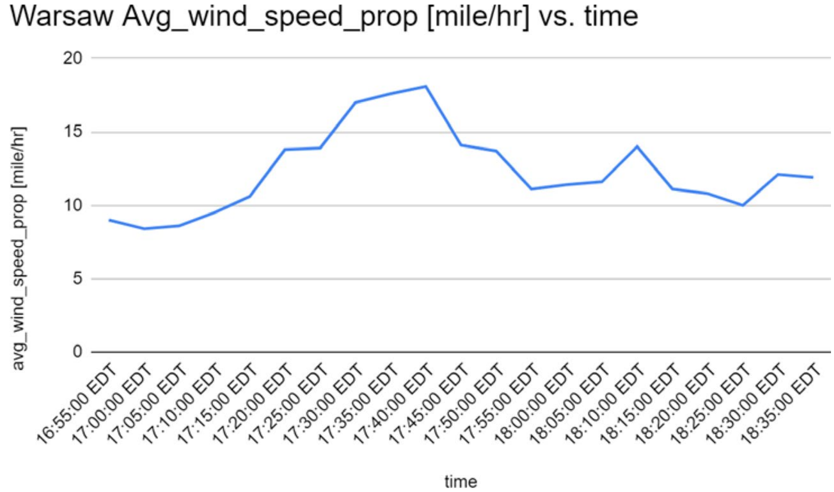
Phase 2: Explore

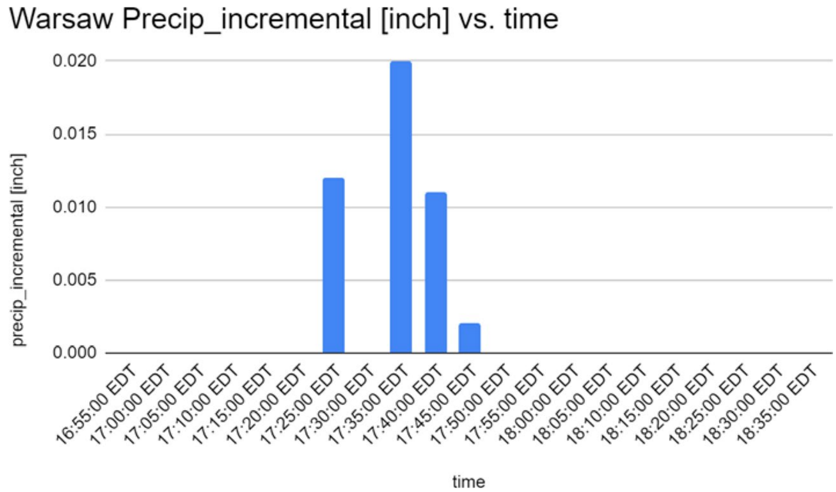
After obtaining the decided weather data from NYS Mesonet, students now explore radar images and analyze measurements (examples are provided below). With the teacher's guidance, students construct tentative ideas or explanations (Figs. 7, 8, 9, 10, 11, 12, 13 and 14).

Phase 3: Explain

In this phase of the lesson, the teacher provides "direct instruction" (or "review") of skills/concepts/terms (fronts, air masses, atmospheric variables). Students are taught

- Warsaw Weather Data:





specific skills/concepts, misconceptions are addressed, and an essential vocabulary is taught, such as radar, satellite, dewpoint, relative humidity, planetary winds, air mass, fronts, and atmosphere.

Phase 4: Elaborate

This phase is designed to allow students to practice/apply the "new" or "reviewed" skills/concepts. To this end, students are prompted to go back to the previously explored forecast, radar imagery, Mesonet camera images, and data charts and determine what weather can be expected for Cooperstown during the evening of July 1 2022 (6–9 pm) by applying the concepts learned in the Explain phase. Students are also prompted to answer questions such as:

1. How fast is the storm moving and which direction? Explain how you derived your answer?
2. When does the sun rise and set on July 1, 2022?
3. Should the championship game start at 6:30 pm?
4. What are multiple pieces of evidence that can support your claim?
5. What is your scientific reasoning?

Phase 5: Evaluate

In this final phase, student understanding and mastery are assessed. To this end, students are provided with the following prompt:

> "The next day, you are asked to meet with the little league coordinators to debrief on your decision. You are asked to look at the weather data from the storm (below) that passed over Cooperstown on July 1, 2022 and to indicate whether your decision about the baseball gale was correct or not, and to explain why. The purpose of this meeting is to educate the directors and help predict the weather for future games."

- 3-hour weather summary created at 6:00 pm on July 1st (30 minutes prior to the game).

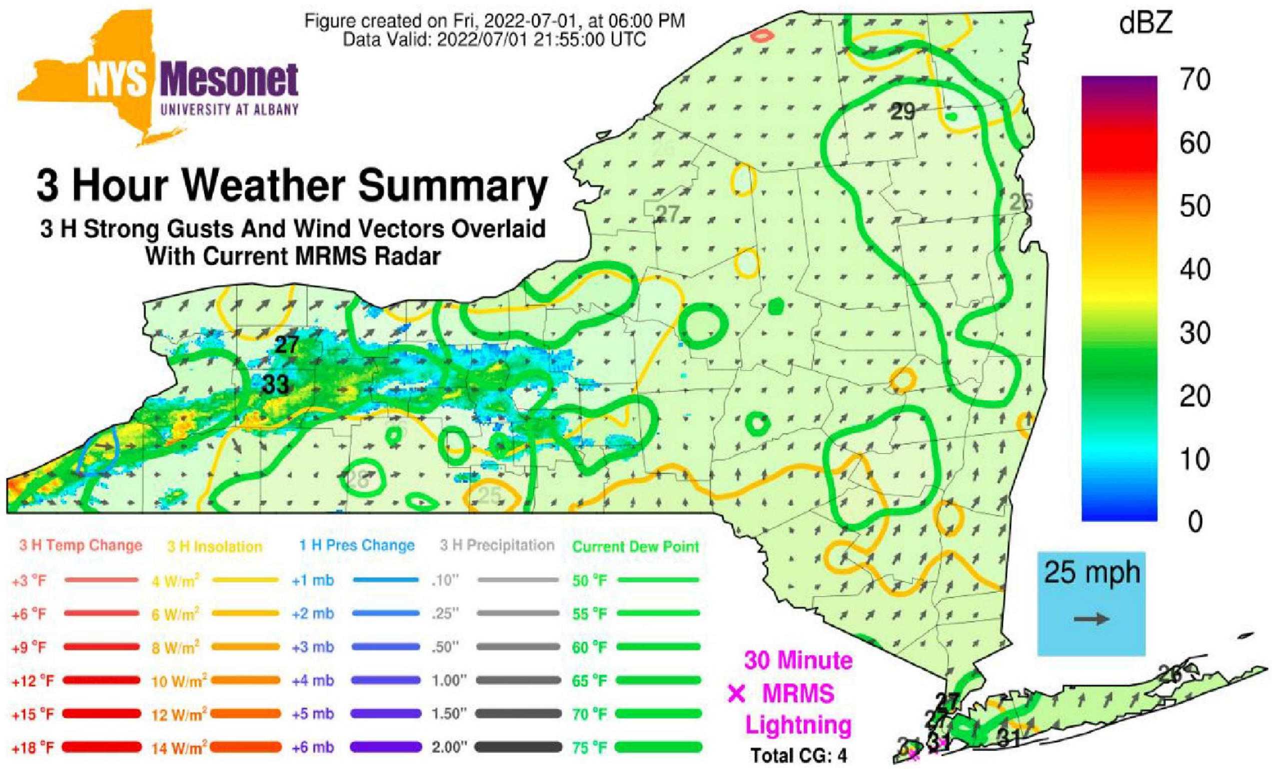
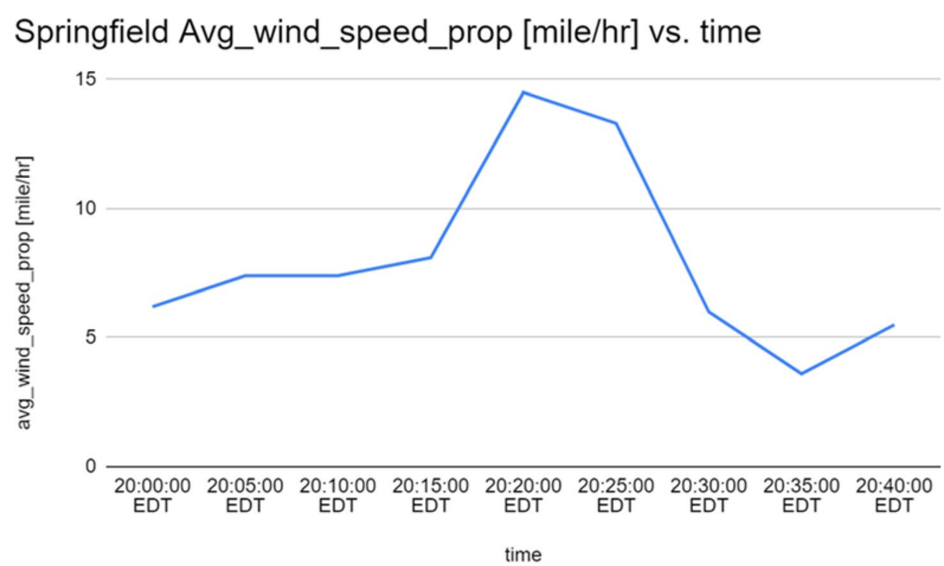


Fig. 7 Map of New State showing 3-h weather summary. **Teacher notes:** Through visual inspection, students should be able to see the arrows showing the direction of the wind. Students will be able to see the radar data and current dewpoint temperatures 30 min prior to the game. Teachers should help students by asking them to recall planetary winds and where the storm will move next due to the planetary winds. Teacher should also help students realize a high dewpoint, meaning there is a lot of water vapor in the air. Teacher should ask students where they think the storm will move next and what evidence from the map do they have to support this claim

- Data from During the Storm:



[**Teacher Notes:** Students should be able to see that the winds were strongest around 8:15-8:25pm]

- Zoomed out map of NYS taken at 6:03pm:

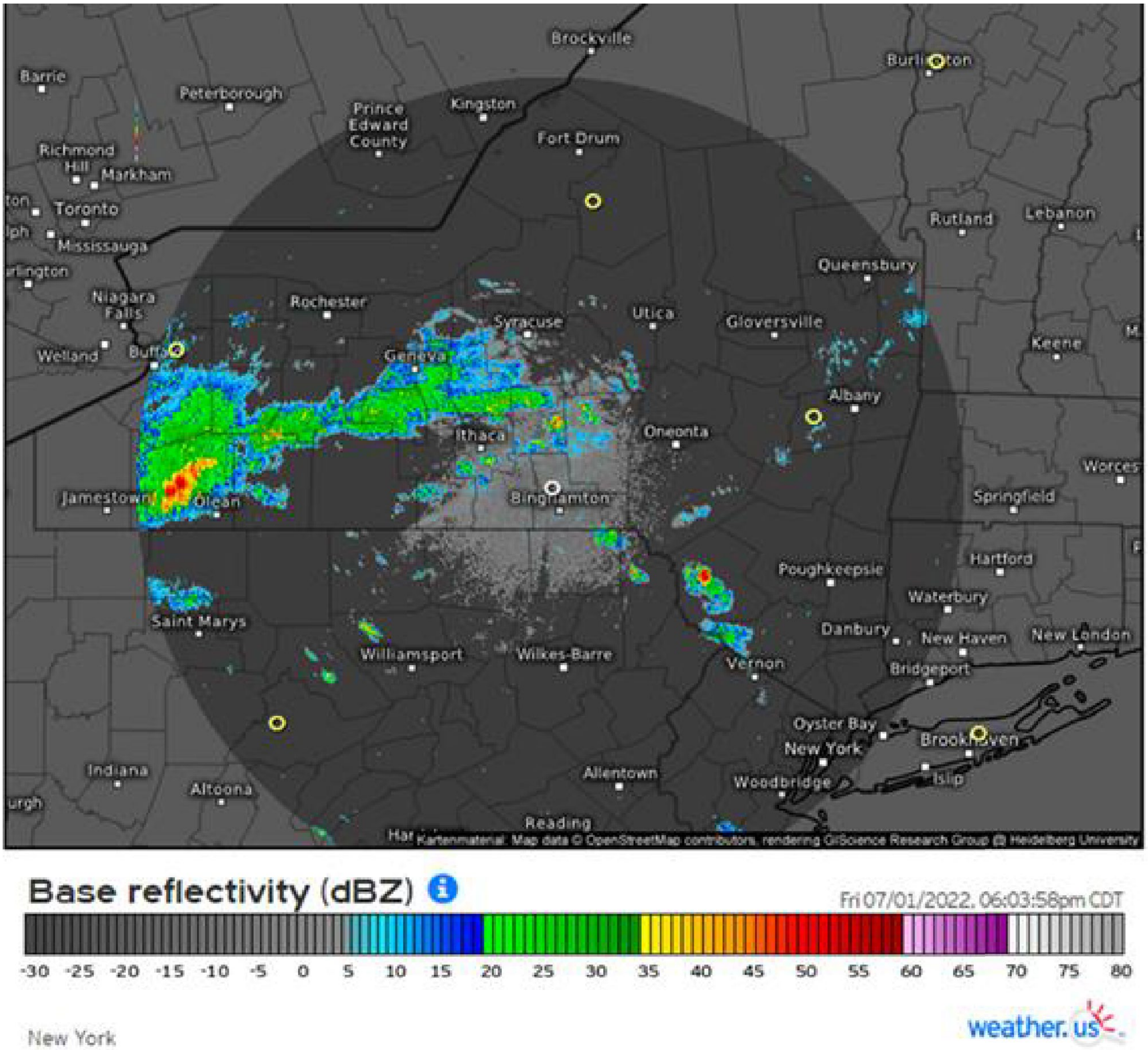


Fig. 8 Map of New State taken at 6:03 pm showing the radar report. **Teacher notes:** Through visual inspection, students should be able to see on the radar imagery that a big storm is occurring west of Cooperstown. Teachers should help students by asking where the storm will move next. Students should understand that the darker red colors mean an intense storm

- Zoomed in map of Chenango at 6:03 pm:

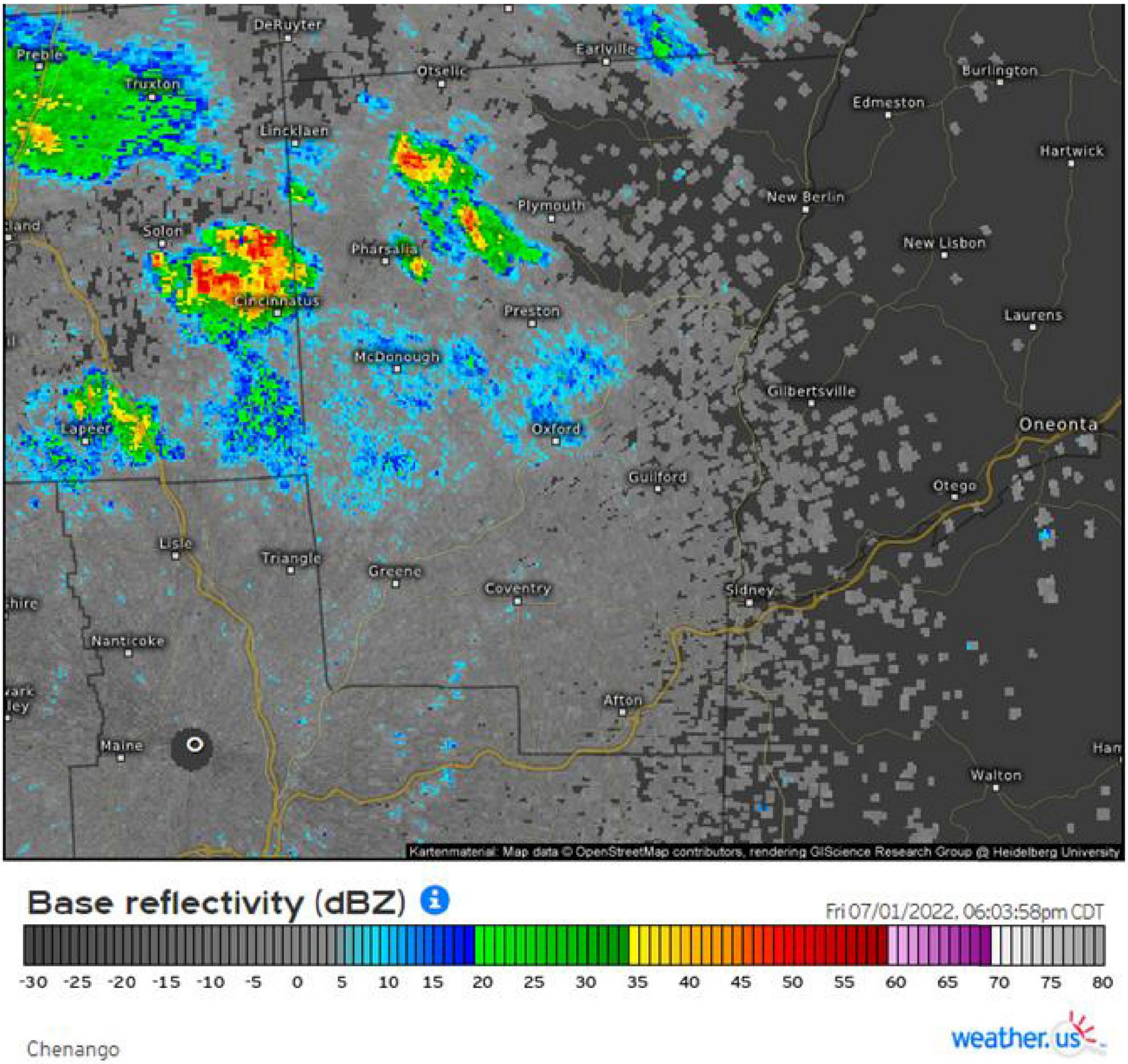


Fig. 9 Zoomed in portion of the NYS map that shows the students where the intense part of the storm is. **Teacher notes:** Through visual inspection, students should be able to see where the strongest part of the storm is. Teacher should help students by asking students what they think the difference in colors of the radar map represents. Teacher should make sure the students know the red and orange zones are areas of intense rain

- Zoomed in map of Courtland at 6:03 pm:

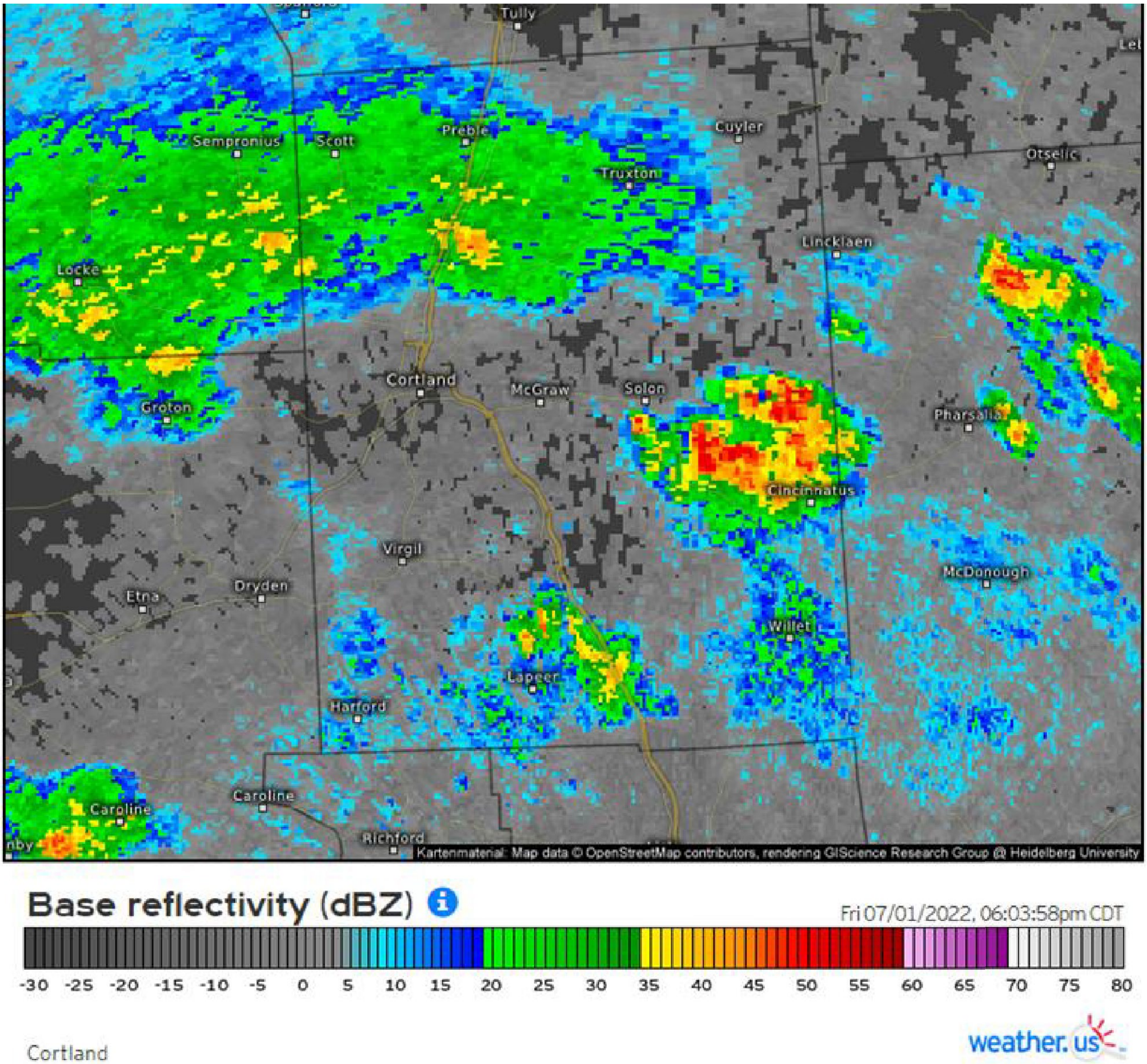


Fig. 10 Map of New State zoomed in showing the storm near Courtland NY at 6:03 pm. **Teacher notes:** Through visual inspection, students should be able to see that the storm is more intense around Courtland. Teacher should ask students to compare the maps of Courtland and Chenango. Teachers should help students see that Chenango is west of Courtland and has not received the intense rain. Teacher should ask students what time they think the storm will hit Chenango

- Radar imagery of Courtland taken at 6:12pm (students can calculate how fast the storm is moving by comparing it to previous image)

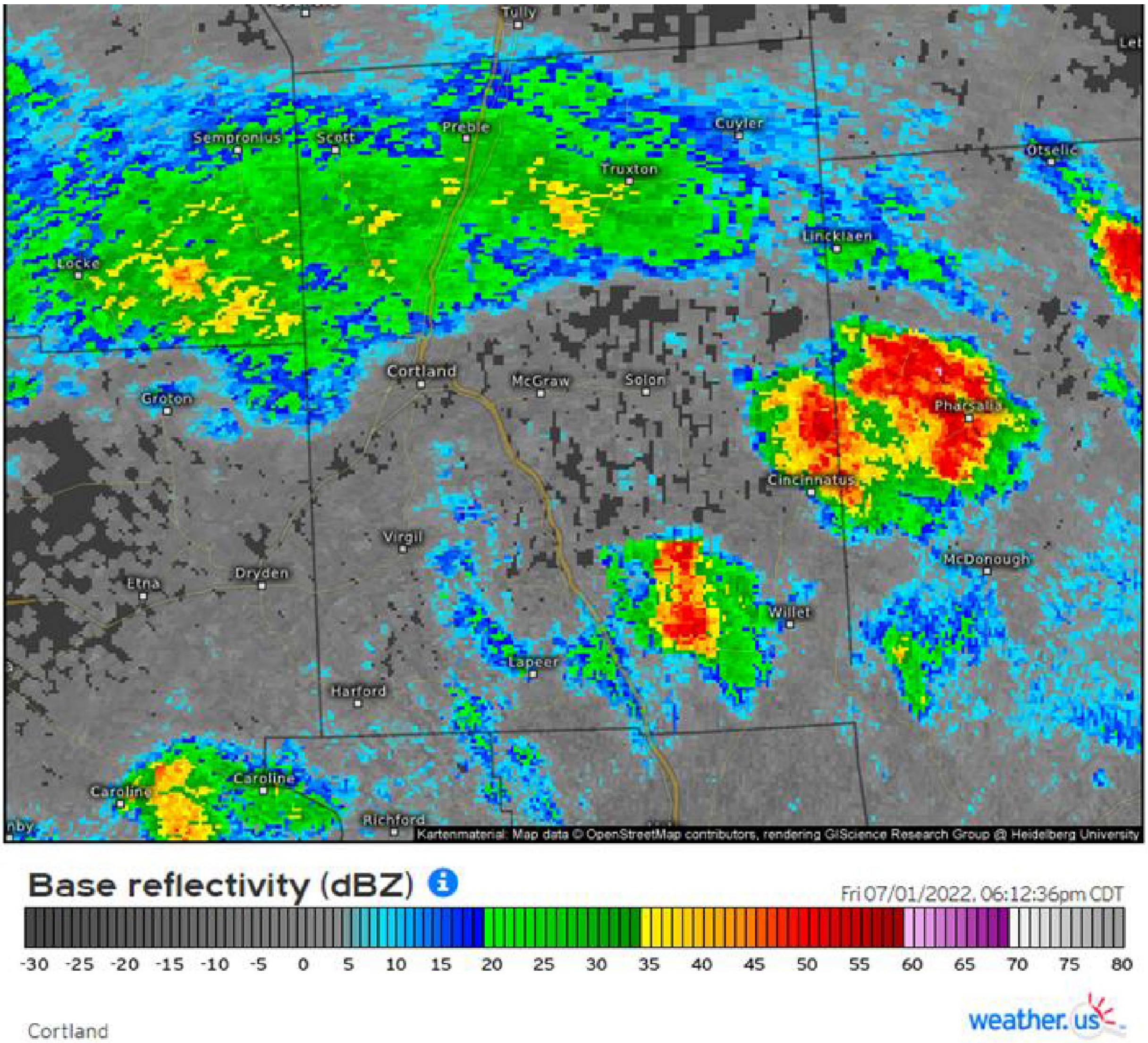


Fig. 11 Map of New State showing the radar of Courtland at 6:12 pm. **Teacher notes:** Through visual inspection, students should be able to see that 9 min later, the storm has moved west. Teachers should help students locate the most intense part of the storm; from 6:03 map, it was centered around Cincinnatus, and on the 6:12 map, the most intense part of the storm was centered around Phoenicia. Teacher should have students measure the distance between these two cities and then calculate the rate of movement of the storm

- Mesonet Cameras of the Springfield Station:

Left image taken at 5:45pm Right image taken at 6:00pm

Fig. 12 Sky pictures showing atmospheric conditions at the NYS Mesonet station of Springfield. **Teacher notes:** Through visual inspection, students should be able to see that there is a storm in the upper left-hand corner of the 6:00 pm image. Teachers should help students by pointing out the cloud formation in the upper left-hand corner

- Location of Warsaw on NYS map (left) and on the Mesonet station map (right):

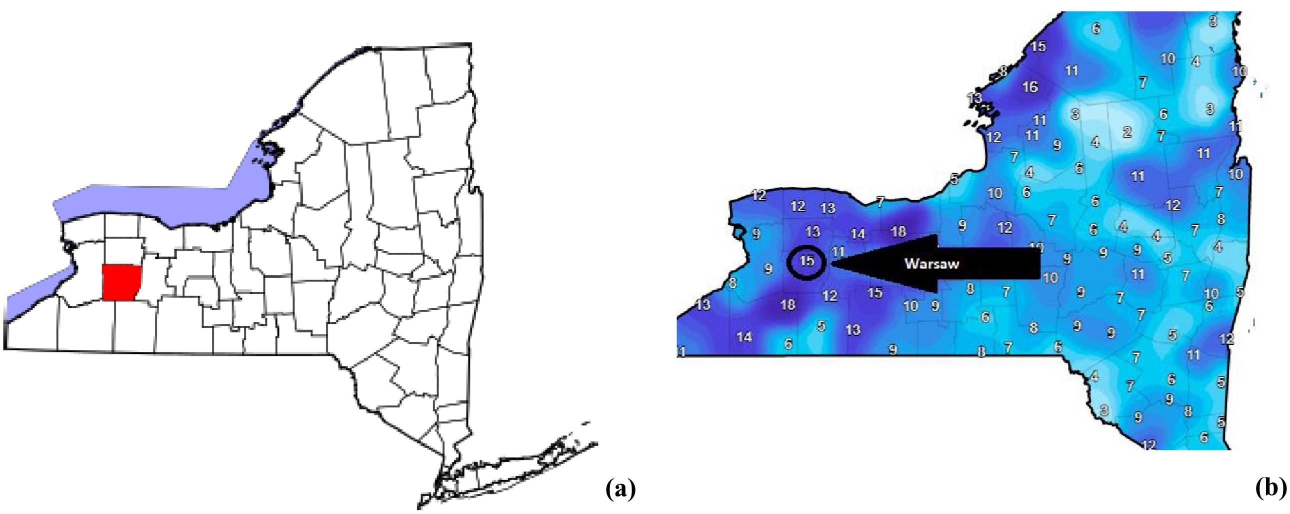
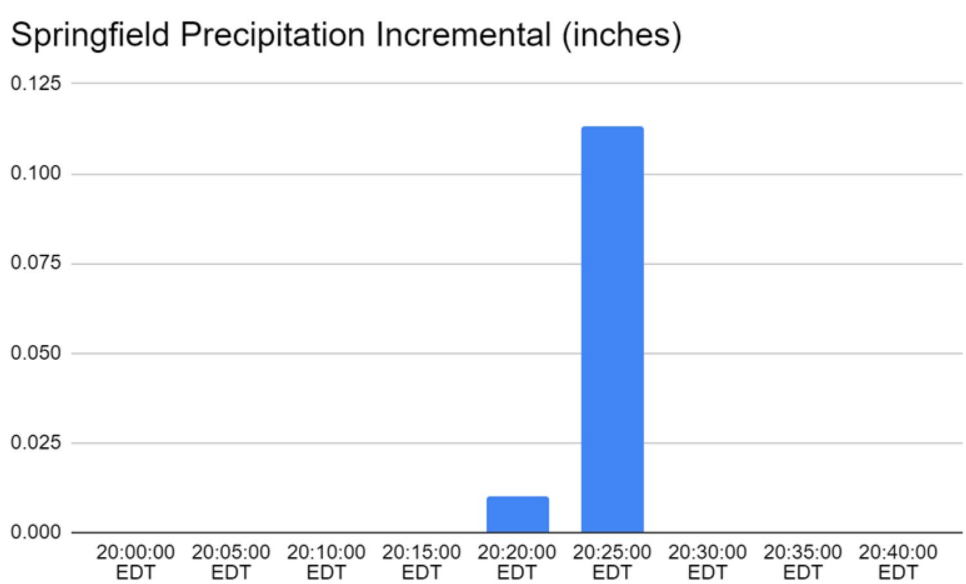


Fig. 13 Maps of New State showing **a** the location of Warsaw (in red) a nearby town where another Mesonet station is located and **b** the Mesonet station of Warsaw circled

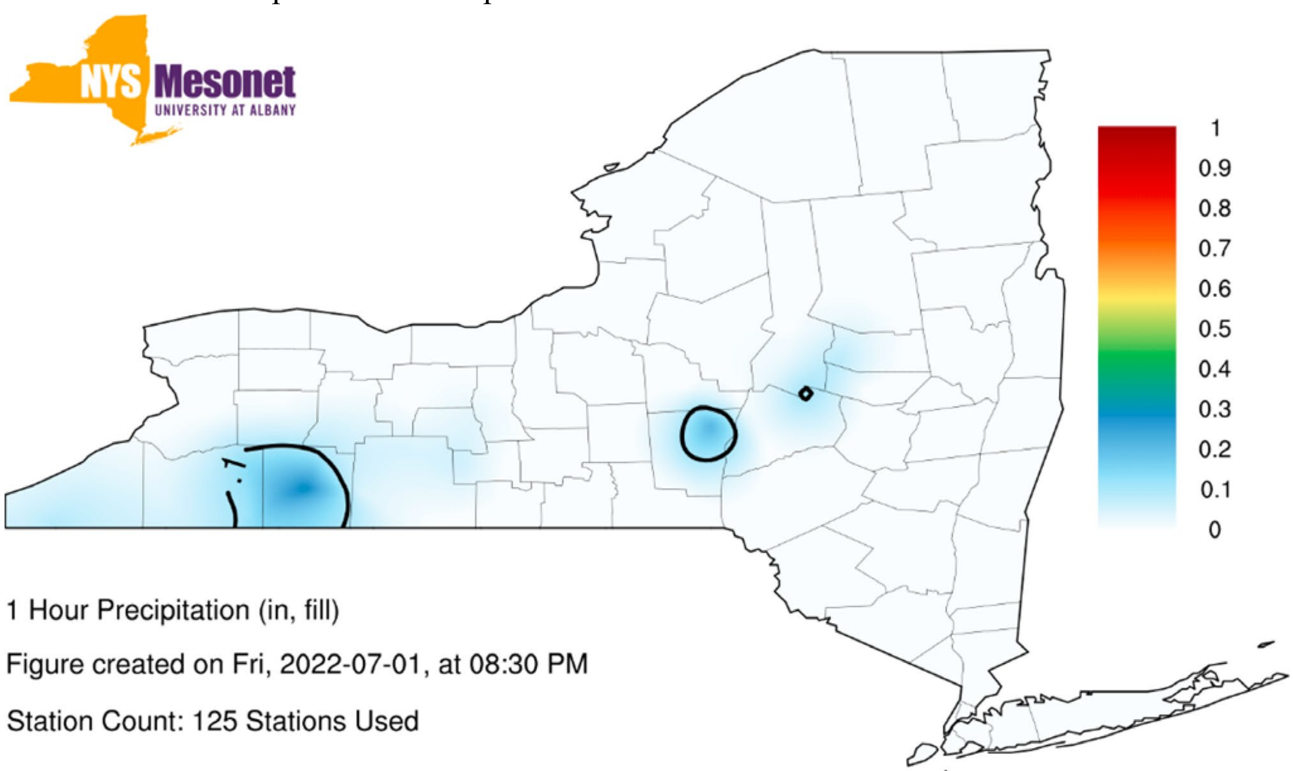
Fig. 14 Sky pictures showing atmospheric conditions at Warsaw. **Teacher notes:** Through visual inspection of these images, students should be able to see that the wind has picked up by the moving rectangles of the precipitation gauge. This is only to get a visual understanding of the storm that occurred an hour before the storm that will hit Cooperstown. Teacher notes: Through visual inspection, students should be able to see that the wind picks up between 5:20 pm and 5:35 pm with maximum wind gusts at 5:40 pm. The precipitation from the storm occurs between 5:25 and 5:45 pm. Teachers should help students by asking them to note the change in wind speed and how much rain fall occurred



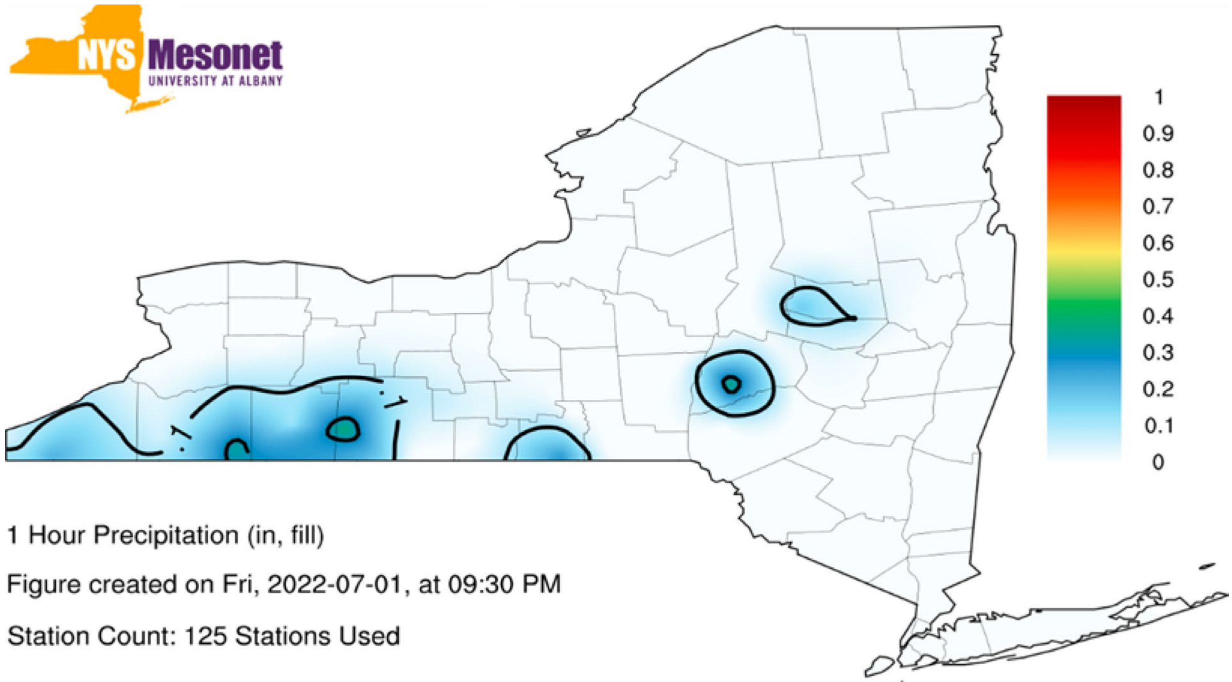
- Springfield Wind Direction:

Time	Wind Direction
20:00:00 EDT	208
20:05:00 EDT	207
20:10:00 EDT	213
20:15:00 EDT	217
20:20:00 EDT	217
20:25:00 EDT	217
20:30:00 EDT	225
20:35:00 EDT	233
20:40:00 EDT	205

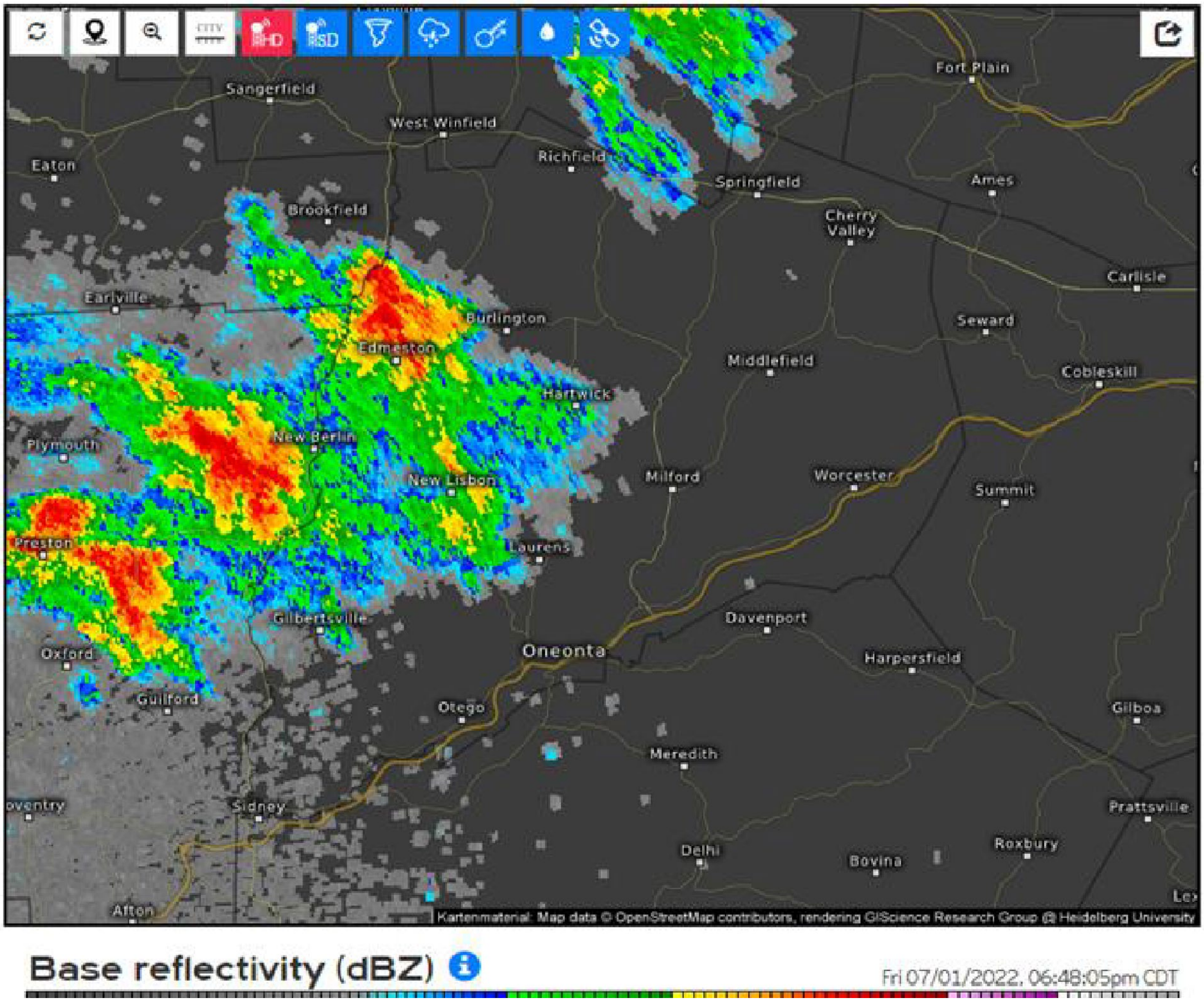
- One-Hour Precipitation at 8:30 pm:



- One-Hour Precipitation at 9:30 pm:

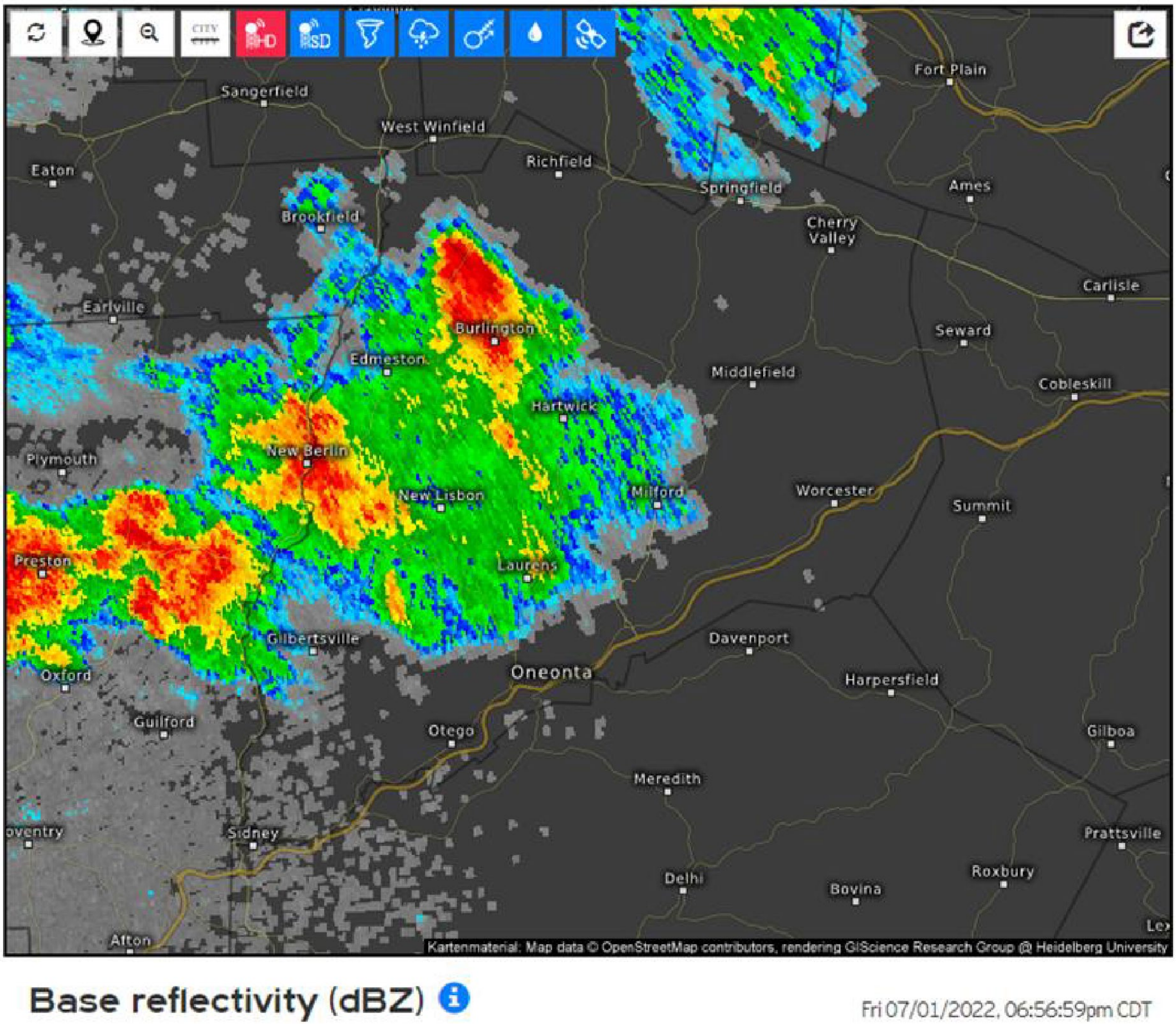


- Radar imagery of Springfield taken at 6:48 pm:



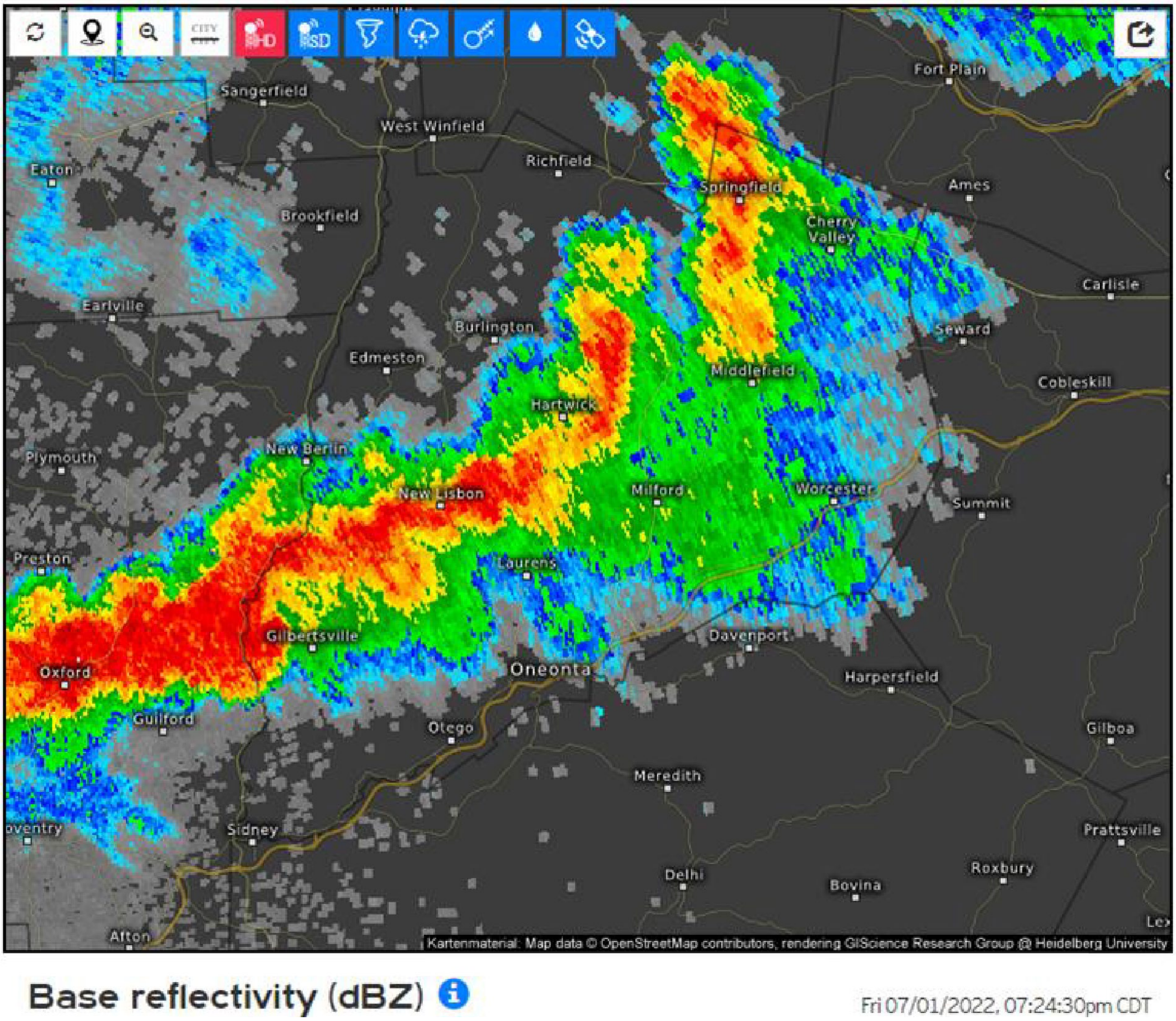
[**Teacher Notes:** Students should be able to see that the storm is Southwest of Springfield.]

- Radar Image Springfield 6:56 pm:



[**Teacher Notes:** Students should be able to see that the storm has not reached Springfield yet. Teacher should ask students to observe where the current storm is and relate how planetary winds will move this storm Northeast.]

- Radar Image Springfield 7:24 pm:



[**Teacher Notes:** Students should be able to see the storm intensified from the pictures west of Springfield. Teachers should ask students to give evidence on how they know the storm intensified. Students should be able to explain that the darker red and orange colors represent heavy rain. Students should note that Springfield is in the red color meaning that at 7:24 pm when this picture was taken Springfield was getting hit with an intense storm.]

- Mesonet Camera Images- Springfield at 7:35pm (left) and 7:45pm (right)

[**Teacher Notes**: Students should be able to see that dark clouds represent the approaching storm and also observe the moving rectangular pieces from the rain gauge. Teacher should ask student to note the time they think the storm impacted the Springfield station.]

[**Teacher Notes:** Students should be able be able to review the data and support with evidence from the storm if their decision was correct. Students' answers may vary with supporting evidence]

Data Availability Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

Conflict of Interest The authors declare no competing interests.

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