BAMS Article

Snowflake Selfies

A Low-Cost, High-Impact Approach toward Student Engagement in Scientific Research (with Their Smartphones)

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ABSTRACT: An engaged scholarship project called "Snowflake Selfies" was developed and implemented in an upper-level undergraduate course at The Pennsylvania State University (Penn State). During the project, students conducted research on snow using low-cost, low-tech instrumentation that may be readily implemented broadly and scaled as needed, particularly at institutions with limited resources. During intensive observing periods (IOPs), students measured snowfall accumulations, snow-to-liquid ratios, and took microscopic photographs of snow using their smartphones. These observations were placed in meteorological context using radar observations and thermodynamic soundings, helping to reinforce concepts from atmospheric thermodynamics, cloud physics, radar, and mesoscale meteorology courses. Students also prepared a term paper and presentation using their datasets/photographs to hone communication skills. Examples from IOPs are presented. The Snowflake Selfies project was well received by undergraduate students as part of the writing-intensive course at Penn State. Responses to survey questions highlight the project's effectiveness at engaging students and increasing their enthusiasm for the semester-long project. The natural link to social media broadened engagement to the community level. Given the successes at Penn State, we encourage Snowflake Selfies or similar projects to be adapted or implemented at other institutions.

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A primary mission of university meteorology and atmospheric science departments is to train the next generation of scientists, operational forecasters, and entrepreneurs. Doing so effectively involves presenting them with the contemporary major scientific and societal challenges facing the field and incorporating into their coursework the new or emerging technologies that they will use to address these challenges. One way to do this is through *engaged scholarship*, which The Pennsylvania State University (hereinafter Penn State) defines as involving academic experiences outside the classroom that complement traditional in-course learning. Engaged scholarship is known to raise student grade point averages (GPAs), increase retention, and improve critical-thinking skills (e.g., Khu and Schneider 2008; Kilgo et al. 2015). Examples of engaged scholarship include undergraduate student involvement in research and reinforcement of material and concepts learned in core classes during out-of-classroom activities, especially those related to relevant societal issues of interest to the students. Numerous examples of engaged scholarship have been incorporated into the meteorological teaching community, including instruments such as the National Science Foundation educational deployments of the Doppler on Wheels (Richardson et al. 2008; Toth et al. 2011; Bell et al. 2015; Milrad and Herbster 2017; Clark et al. 2019).

Snowstorms, which are capable of enormous societal disruptions including hazardous roadways, delayed or cancelled air travel, widespread power outages, damage to properties, and even injuries and fatalities (Andrey et al. 2003; Picca et al. 2014; Black and Mote 2015a,b; Tobin et al. 2019), present a strong area of student interest. Further, predictions of high-impact snowstorms often captivate local officials and the public owing to the desire to anticipate the risks and mitigate losses. Unfortunately, however, quantitative snowfall forecasting is a challenging endeavor, in part complicated by the myriad of factors controlling snow-to-liquid ratios (SLRs) that are not well handled in operational numerical weather prediction (NWP) models. Accurate prediction of SLRs requires skillful forecasts of vertical air motion, thermodynamic profiles, and microphysical processes, among other factors (e.g., Roebber et al. 2003). For example, many current microphysics parameterization schemes employed in operational NWP models do not accurately treat snow growth processes, nor do they allow for the observed natural variability of ice crystal shapes (e.g., see the discussion in Harrington et al. 2013). Thus, an improved understanding of snow microphysics is one critical piece needed to improve model representations of important processes, and ultimately reduce uncertainty in forecasts of snowfall.

The long winters in central Pennsylvania afford opportunities to study the natural variability of snow and collect data useful for education and research purposes through engaged scholarship. As such, we developed a project to incorporate snow-related research experiences into undergraduate courses at Penn State to embrace the aforementioned scientific and societal challenges, natural wintertime laboratory, as well as the much-bemoaned student overuse of smartphones (Aljomaa et al. 2016; Panova and Carbonell 2018) and social media. The "Snowflake Selfies" project was thus conceived, funded through the Penn State College of Earth and Mineral Sciences Gladys Snyder Educational Grant. A subsequent adaptation of this type of project at the University of Wyoming (which has even longer winters!) also provided the opportunity to study snowfall properties under different conditions and storm types and engage a broader population of students in snow science.

The following section details the Snowflake Selfies data collection methods. Then, highlights from some of the results of the project's first implementation, including a brief analysis of two cases, is presented. This is followed by a discussion of the educational impact and lessons learned from the project, and we conclude with a summary of the main takeaways and perspectives on future improvements, outreach, and broader engagement.

Data collection methods

The primary goals of the Snowflake Selfies project were to collect useful scientific data while providing a valuable educational experience, both at extremely low cost. The low-cost design was motivated by the potential for the methods, if successful, to be more easily incorporated by the broader educational community, especially those with limited resources and underserved student populations. As such, the equipment used is rather "low tech." Each team of students was given a metal baking sheet, two identical cylindrical small glass jars, a 500-g digital kitchen scale, a ruler, and a thermometer for the duration of the project. The advantages of the baking sheet compared to the operationally used plywood "snow board" include, but are not limited to the following: no advanced preparation (cutting, painting) required; the metal has a lower specific heat capacity than wood and therefore equilibrates to the ambient temperature more rapidly (important for when students handle the equipment and/or move it from indoors); there is no potential for moisture to affect the snow accumulation or densities in unpredictable ways. Disadvantages include a smaller collection area, and some metal baking sheets have "lips" or raised edges that may affect accumulations, especially in windy environments. In such cases, the baking sheets may be turned upside down to mitigate these effects. Additionally, each student received a Beileshi clip-on currency microscope (60× magnification) adapter for smartphones, available online for <$10. The clip-on adapters are advantageous over the smartphone camera alone because of the superior magnification, affording much-improved views of riming, hollowing, and small polycrystalline structures. In the event that smartphones are inaccessible, other options include digital cameras with a "macro" mode setting, and low-cost, USB-pluggable portable microscopes. Some university libraries also provide electronic tablets for students to check out, like books; in these cases, only the clip-on microscopes would be needed. We also encourage groups to solicit technology companies or cellular service providers to donate used/recycled smartphones with functioning camera capabilities for such a project. In this way, the materials for the project may be modified as needed for cost or accessibility purposes.

The first experiment was performed from 22 January to 11 February 2018 as part of the Principles of Atmospheric Measurements course (METEO 440W) in the Department of Meteorology and Atmospheric Science at Penn State. This writing-intensive course, intended for third- and fourth-year in-major undergraduate students, seeks to familiarize them with techniques for taking, analyzing, and communicating a variety of atmospheric measurements both in laboratory and field environments, thus making the Snowflake Selfies project a natural fit. The observation period was chosen to occur during the climatological peak of observable snowfall events for State College, Pennsylvania (Fig. 1a), which typically is characterized by an average accumulated snowfall of 8 in. or 20 cm (Fig. 1b). More importantly, this period also allowed ample time for students to learn about snowfall observation and safety guidelines (NWS 2013) at the beginning of the academic semester prior to the onset of field observations. Utilizing this information, each student team was tasked with coordinating their individual intensive observing periods (IOPs) and siting (i.e., observation location) based on the snowfall outlook, team member availability, and their knowledge of snowfall observation best practices. Following the completion of the field component of the project, each student was tasked with applying their developing knowledge of technical writing from the course to write a manuscript-style term paper presenting their team results.

For the measurements, students first allowed the baking sheet and jars to equilibrate to the ambient temperature outside. The empty jars were then weighed using the scale to calibrate the mass observations. Students then placed the baking sheet and jars on a flat, level surface to begin collecting snow (Fig. 2). After a predetermined period of time to allow precipitation accumulation (typically 30–60 min), multiple measurements (minimum 5) of snow depth were made with the ruler on the baking sheet, and the average of these measurements was recorded. At least 1–2 mm of snow accumulation was needed given the resolution of the rulers distributed to the class. The multiple measurements were performed to provide an estimate of the measurement uncertainty. During this same time period, snowfall accumulated in the jars, which were subsequently weighed with the scale to obtain the snow mass that accumulated during this period. Two jars were used to provide redundant measurements, and as another means to obtain estimates of the measurement uncertainty. After measurements, the baking sheet was brushed off, and the jars emptied and dried. The mass of the empty jars was taken again after each measurement to estimate the errors associated with the digital scale and potential lingering snow in the jar. Using the estimate of snow accumulation during each period as well as the mass of snow collected in the jars, students could calculate the SLR of the freshly fallen snow at relatively high temporal resolution compared to operational measurements. During snow events, the student teams were required to set up and take measurements at least 2–3 times per event (precipitation dependent) to obtain a time series to evaluate the snowstorm's evolution. Students were dispersed across the State College area during the events (Fig. 3), allowing the spatial distribution of snowfall characteristics to be analyzed as well. The data collection may be supplemented by other measurements, including surface temperature, using the provided thermometers or nearby weather station.

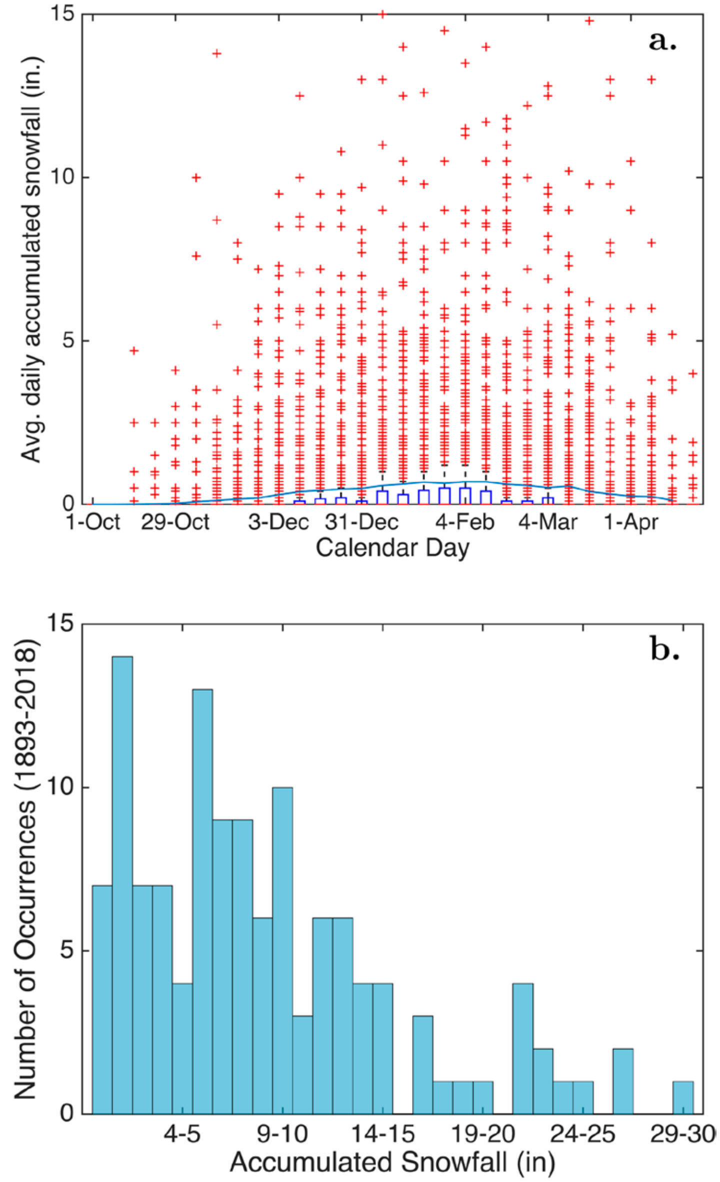


Fig. 1. Distribution of climatological (1893–2019) accumulated snowfall observed at the Pennsylvania State University cooperative observer (COOP) observation site in State College. (a) Statistical distribution of daily snowfall accumulation (binned in 7-day periods) from 1 Oct to 30 Apr [box and whisker; box edges represent 25th and 75th percentiles, red line represents the median (50th percentile), and red crosses represent outliers]. Snowfall values greater than 15 in. are not displayed for figure clarity. Overlaid is the 21-day running mean daily accumulated snowfall (blue line) for all days with measurable snowfall exceeding a trace. (b) Annual snowfall totals for 21-day period centered on the observations period (22 Jan–11 Feb), binned in 1-in. intervals. Data courtesy of Bill Syrett and the Pennsylvania State University Department of Meteorology and Atmospheric Science Weather Center.

During the period in which snow was accumulating and between accumulation measurements, students used their smartphones with microscope adapters to take photographs of snow crystals in order to characterize the crystal habits and degree of riming. Typically, students would brush clean a surface and allow a few crystals or aggregates to land before taking each picture. After each picture, the surface was again brushed clean. Examples of some of the photographs captured during the project are shown in Fig. 4. In the spring 2018 semester, students captured images of capped columns, dendrites, and needles, among other crystal habits, which they were eager (and encouraged) to share on social media.

In addition to the surface measurements, Stony Brook University's Micro Rain Radar (SBU-MRR) was operating on the roof of Walker Building on Penn State's University Park campus (Fig. 3, indicated by the red star). The SBU-MRR is a small, K-band, zenith-pointing, frequency-modulated continuous-wave Doppler radar. It operated continuously during the Snowflake Selfies project, collecting time series data at 31 vertical levels above radar location. Signal processing of data collected with this radar used Maahn and Kollias (2012), which is better suited for snowfall than the standard processing software that comes with the MRR. For several IOPs, a sounding was also released from southwest State College (Fig. 3, indicated by the flame) using a light-weight rawinsonde package (Fig. 2; Markowski et al. 2018).

Fig. 2. Photographs of data collection efforts as part of the Snowflake Selfies project. (top left) The observational set up including the metal pan and jars; (top right) Dr. Paul Markowski launching a radiosonde during a snow event; (bottom) Penn State students Kristina Salvatore and Jake Rowe from the course (left) taking microscopic photographs and (right) measuring the snow depth on the pan.

Finally, the local National Weather Service WSR-88D dual-polarization radar (KCCX), which is located 19 km northwest of State College, provided the broader view of the snow events. Dual-polarization radars have been extensively used in a variety of precipitation studies, as summarized in Zrnić and Ryzhkov (1999), Ryzhkov et al. (2005), and Kumjian (2013a,b,c, 2018). Dual-polarization observations have proven valuable to qualitatively characterize snow microphysical processes, including vapor depositional growth, aggregation, and riming (e.g., Kennedy and Rutledge 2011; Andrić et al. 2013; Schneebeli et al. 2013; Moisseev et al. 2015; Schrom et al. 2015; Schrom and Kumjian 2016). To facilitate comparison with the vertically pointing MRR, we make use of quasi-vertical profiles (QVPs) following methods outlined in Kumjian et al. (2013), Ryzhkov et al. (2016), and Kumjian and Lombardo (2017). The QVPs provide insights into the spatially averaged bulk microphysical and kinematic vertical structure of the precipitation over the region, giving context to the students' snow observations and photographs.

Each student grouping was paired by geographic proximity to each other in order to minimize travel during inclement conditions. Further, an integral part of the preexperiment planning was a lecture devoted to a discussion of safety and observation procedures. Students were reminded that no observation should come above their personal safety and to ensure that they were performing proper cold-weather safety measures. Further, the students were warned of dangers in taking measurements near roadways. Ultimately, the overall risk involved is commensurate or less than that associated with walking to class on snowy days. Observation periods were described as holding the same priority as a homework assignment, meaning that students were informed to not skip other coursework for observations, but that they were an integral part of the term project assignment. Each student group was assigned to find a safe and well-sited observation site using the National Weather Service siting standards, which resulted in a natural geographic dispersion across town that was deemed both safe and sufficient for testing the experimental objectives.

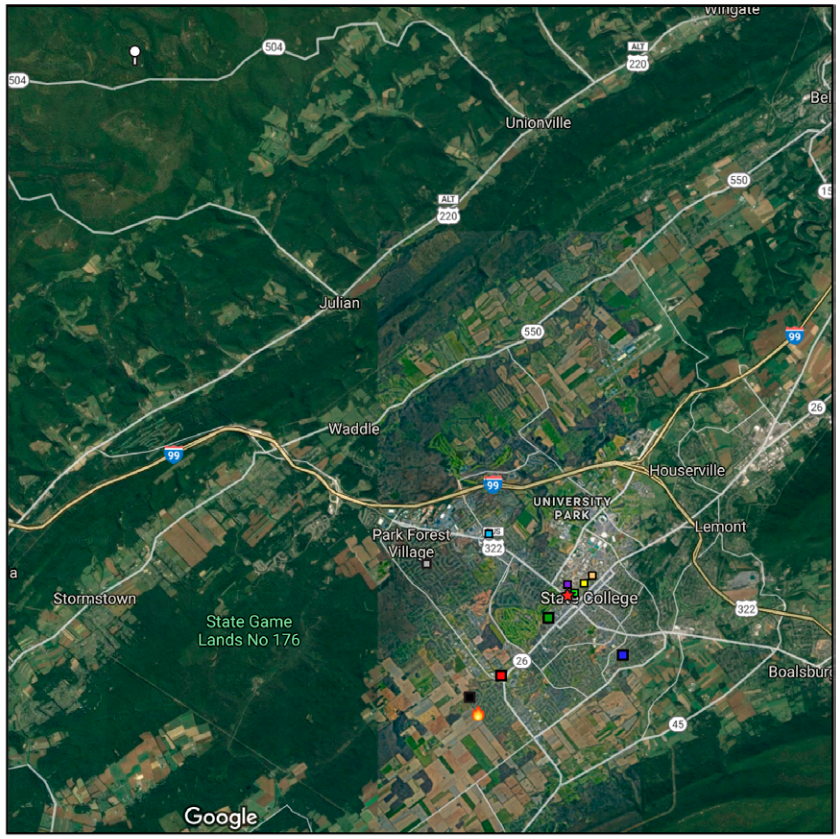


Fig. 3. Map of the project domain. Colored square markers indicate observation locations for the snowflake selfies experiment. Box colors correspond to group-observed SLR values shown in Fig. 11 with the exception of the purple and orange boxes, which did not take observations during the 4 Feb 2018 IOP. Red star marks the MRR, flame represents the sounding location, and the KCCX WSR-88D radar is denoted by the white radome symbol. Map courtesy of Google Maps.

Snowflake Selfies observations

During the experimental period, students in the course conducted four IOPs. The experiment was challenged by below-average snowfall with accumulated solid precipitation (measured daily at 1200 UTC at the Walker Building; Fig. 3, indicated by the red star) of 7.4 in. (www.meteo.psu.edu/~wjs1/wxstn/ObsCards.htm). This ranked as the seventy-first lowest 21-day period (22 January–11 February) out of the 127-yr observations database of solid precipitation for the University Park Campus (1893–2019), and directly contributed to the original project length of 14 days being extended to 21 days. Despite these challenges, the experiment nonetheless showed promise for crowdsourcing observations of snowfall accumulation and estimates of SLRs. A second event from 20 February 2019 is also shown to further demonstrate the promise that this study may provide to the meteorological community.

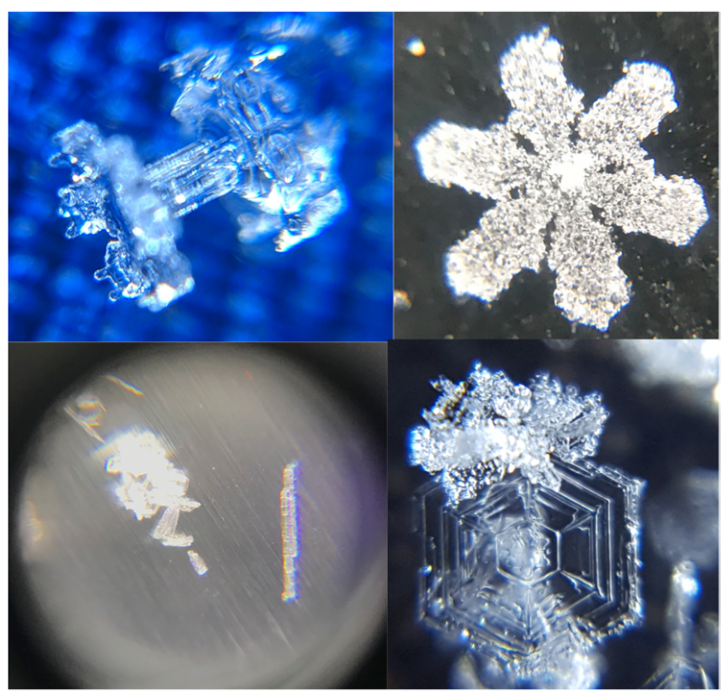


Fig. 4. Example of snow crystal photographs taken during the project.

4 February 2018. Of the four student IOPs in 2018, we present the 4 February 2018 case during which nearly every student team took measurements, despite it being Super Bowl Sunday. The students were dispersed across State College (Fig. 3) for this event. Additionally, a special sounding was released at 2042 UTC from the location of the flame in Fig. 3.

The snowfall event was associated with a broad, positively tilted upper-level trough that subjected central Pennsylvania to the equatorward entrance region of a 250-hPa jet streak as well as broad 500-hPa cyclonic vorticity advection (Figs. 5a,b and 6a,b). This widespread region of upper-level forcing for ascent resulted in an expansive region of low-level cloud coverage throughout the precipitation period (Figs. 5c, 6c). Precipitation rates increased from 1200 to 2100 UTC as the surface low pressure system deepened in response to a more favorable upper-level environment, with the heaviest precipitation rates in excess of 4 mm h^{-1} collocated with the cold front extending from Maryland to Florida (Figs. 5d, 6d). This increase in precipitation intensity from 1200 to 1800 UTC was also associated with a moistening of the surface-to-750-hPa layer near State College, with the saturation level lowering from 750 hPa at 1200 UTC to 925 hPa at 1800 UTC, and eventually resulting in a fully saturated sounding by 2100 UTC (Fig. 7). This deepening of the saturated layer is attributed both to moisture advection in the surface-to-750-hPa layer as well as ongoing precipitation falling from through the unsaturated layer (Fig. 7). Note that there is a possibility that sonde icing may have contributed to the apparently saturated troposphere in Fig. 7d. Despite warm air advection (inferred from veering geostrophic winds), temperatures remained below 0°C and clouds were present throughout, helping to reduce the rate of snowflake sublimation and prevent melting (Figs. 5c,d and 6c,d).

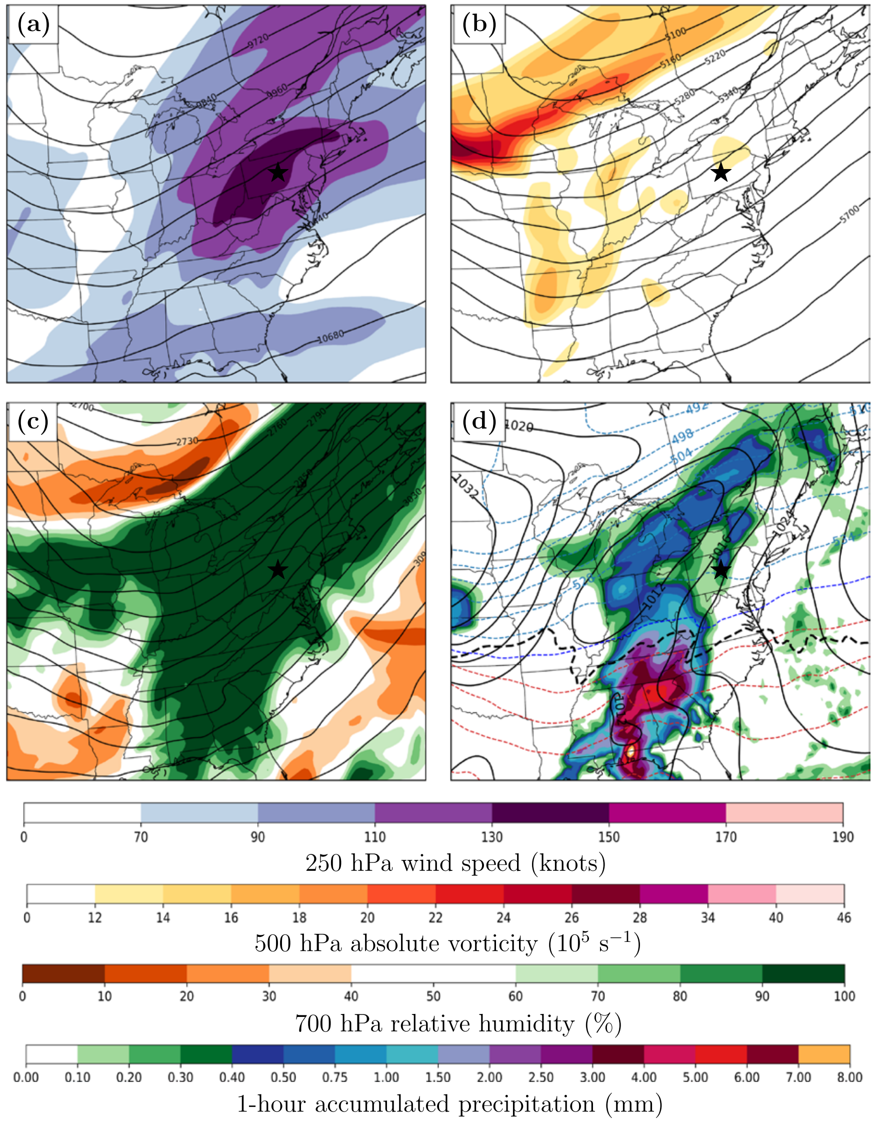


Fig. 5. ERA5 reanalysis synoptic maps for the 1200 UTC 4 Feb 2018 event. (a) 250-hPa geopotential heights (black contour, m) and wind speed [colored, knots (kt; 1 kt ≈ 0.51 m s^{-1})], (b) 500-hPa geopotential heights (black contour, m) and absolute vorticity (colored, 10^5 s^{-1}), (c) 700-hPa geopotential heights (black contour, m) and relative humidity (%), and (d) sea level pressure (black contour, hPa), 1,000–500 hPa thickness (dashed red/blue, dam), 850 hPa 0°C contour (black dashed), and 1-h precipitation (colored, mm). Black star indicates the location of State College.

Crystals photographed during this event showed a variety of polycrystalline forms, including bullet rosettes (Fig. 8). Such habits are known to form at lower temperatures (Bailey and Hallett 2009), and are less efficient aggregators than, for example, dendrites or stellars. The lack of significant secondary habits suggests lower supersaturations with respect to ice. At times, the particles also showed signs of light riming. These observations are consistent with polarimetric radar observations from the nearby WSR-88D radar KCCX (Fig. 9). The QVP of reflectivity factor at horizontal polarization (Z_H; Fig. 9a) shows several periods of heavier precipitation throughout the event, from ~0900 to 1200, 1400 to 1600, and

1700 to 2100 UTC. Aloft, there is a persistent Z_H gradient (values increasing toward the ground) around 4 km above radar level (ARL) suggestive of enhanced particle growth. The observed 2042 UTC sounding (Fig. 7d) indicates temperatures at this level were around –15°C. Rates of ice crystal growth by vapor deposition are maximized around such temperatures (e.g., Lamb and Verlinde 2011). Given sufficient supersaturations, branched planar crystals and dendrites, which are efficient aggregators, may develop and aggregate, further contributing to increased Z_H. However, the polarimetric data from this event show relatively small differential reflectivity (Z_{DR}) magnitudes throughout the depth of the precipitation (Fig. 9b). Low Z_{DR} values suggest a lack of significant particle anisotropy. The differential phase shift (Φ_{DP}) QVP (Fig. 9c) also shows only minor increases above 4 km ARL, again suggesting a lack of significant concentrations of dendrites or other branched planar crystals (e.g., Kennedy and Rutledge 2011; Schrom et al. 2015; Schrom and Kumjian 2016; Kumjian and Lombardo 2017).

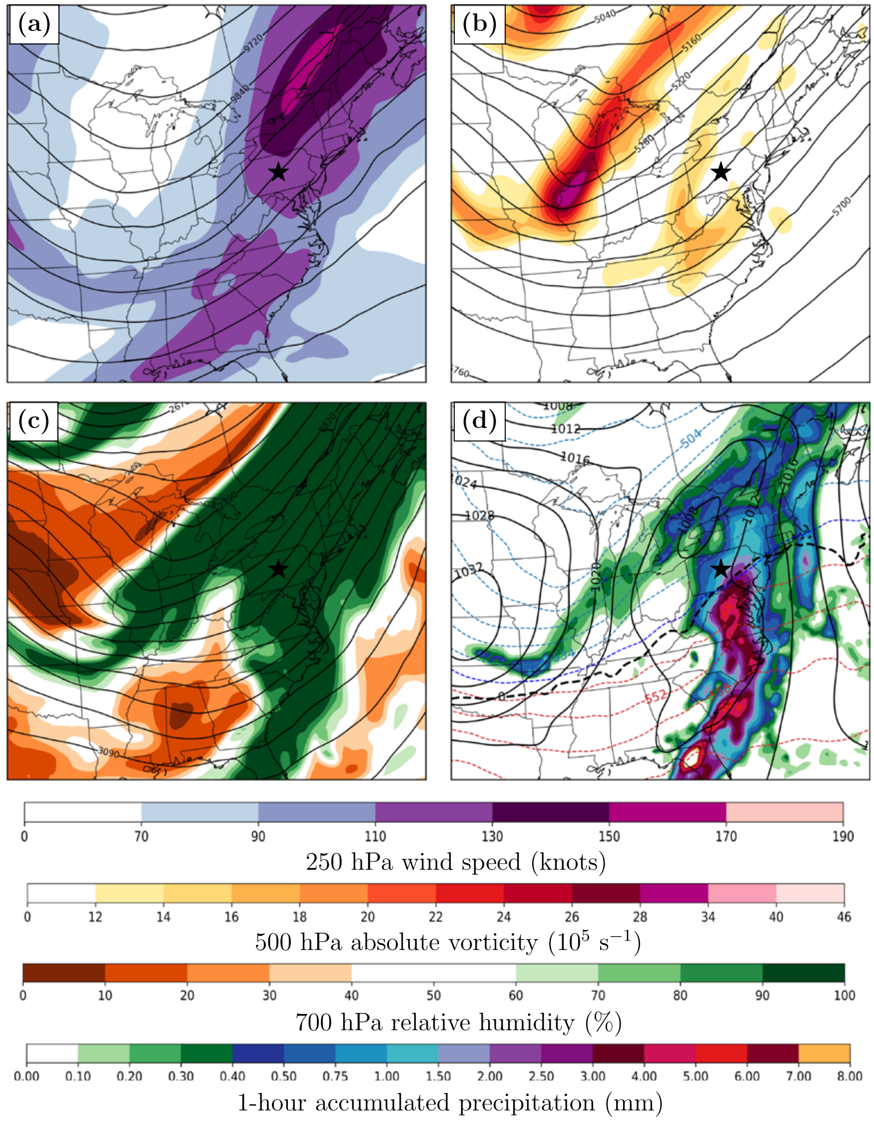


Fig. 6. As in Fig. 5, but at 2100 UTC 4 Feb 2018.

In contrast, occasional, more substantial increases in Φ_{DP} (collocated with further increases in Z_H) are found around ~2 km ARL, where observed temperatures were near –5°C. Such signatures have been attributed to the Hallett–Mossop rime-splintering process (e.g., Kumjian et al. 2016; Giangrande et al. 2016; Sinclair et al. 2016; Kumjian and Lombardo 2017). Indeed, Doppler spectra from the MRR do show an increase in particle downward motion below 2 km ARL to values exceeding what is expected for snow, which may arise from riming (Fig. 10). Needles and some riming on crystals were captured in photographs during this event (cf. Fig. 8).

The small, polycrystalline structures and/or rimed particles observed in the photographs and inferred from radar observations, paired with their intrinsic inefficiency of aggregation, would suggest lower SLRs. Data from each of the student groups, as well as from the instructor and the lead author, were compiled to determine the spread and evolution of SLRs throughout the event. The resulting time series of SLRs for the event is shown in Fig. 11. The vast majority of teams estimated SLRs smaller than 10:1, which is an oft-used rule of thumb (though this is not based on any study; see Roebber et al. 2003), in agreement with the expectations based on the snow particles observed. The average of all groups was between 5:1 and 8:1 for the

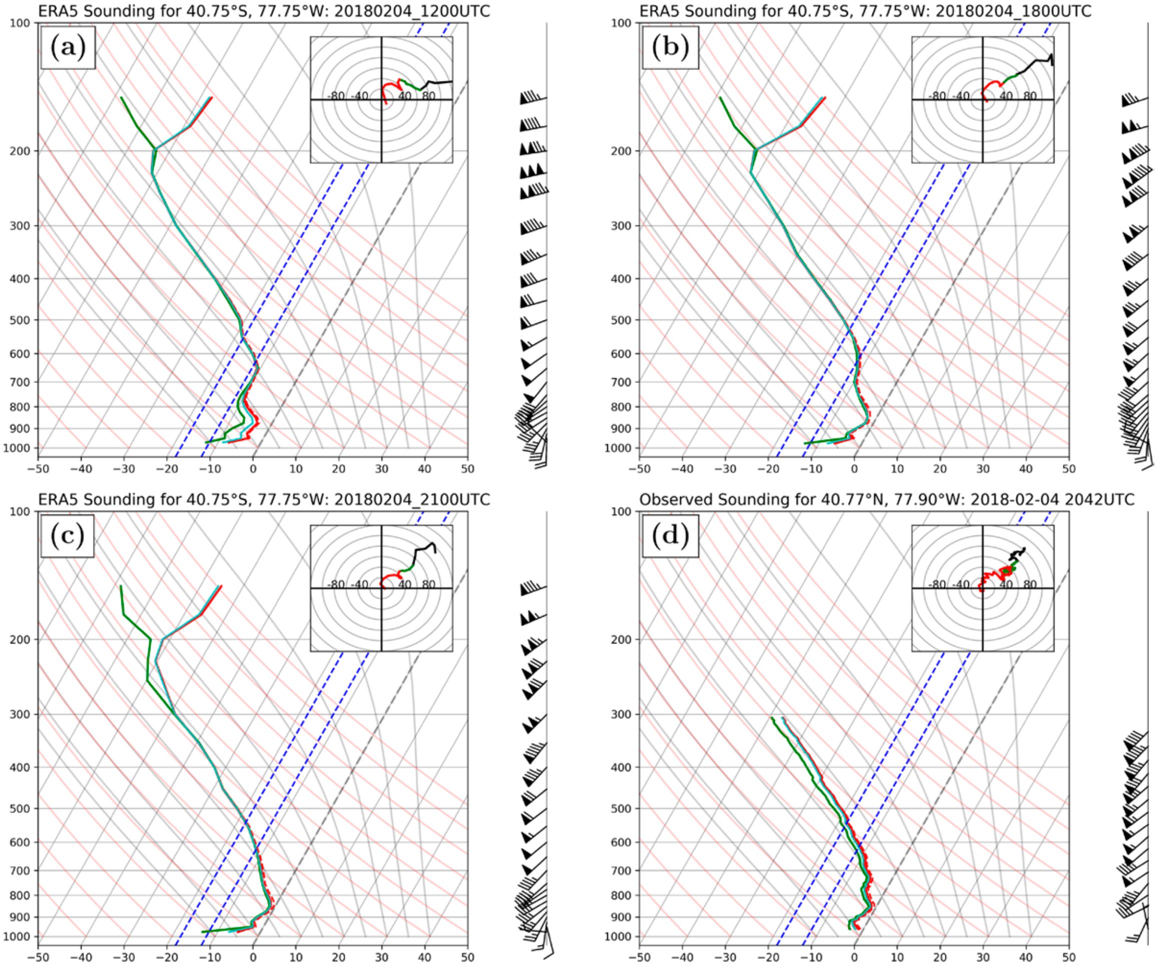


Fig. 7. ERA5 reanalysis and observed soundings for the 4 Feb 2018 event. (a)–(c) ERA5 reanalysis soundings at 40.75°N, 77.75°W for 1200, 1800, and 2100 UTC, respectively. (d) Observed special sounding from 40.77°N, 77.90°W (State College) taken at 2042 UTC. Plotted sounding variables include environmental (red), dewpoint (green), and wet bulb (blue) temperatures as well as wind speed in knots (half barbs, full barbs, and flags indicate 5, 10, and 50 knots, repsectively). Inset panels show hodographs. Wind elevations in hodograph are 0–6 km AGL (red), 6–9 km AGL (green), and 9–12 km AGL (blue). The dendritic growth zone (–18° to –12°C) and 0°C isotherms are identified with blue and gray dashed lines, respectively. Soundings were generated using SharpPy.

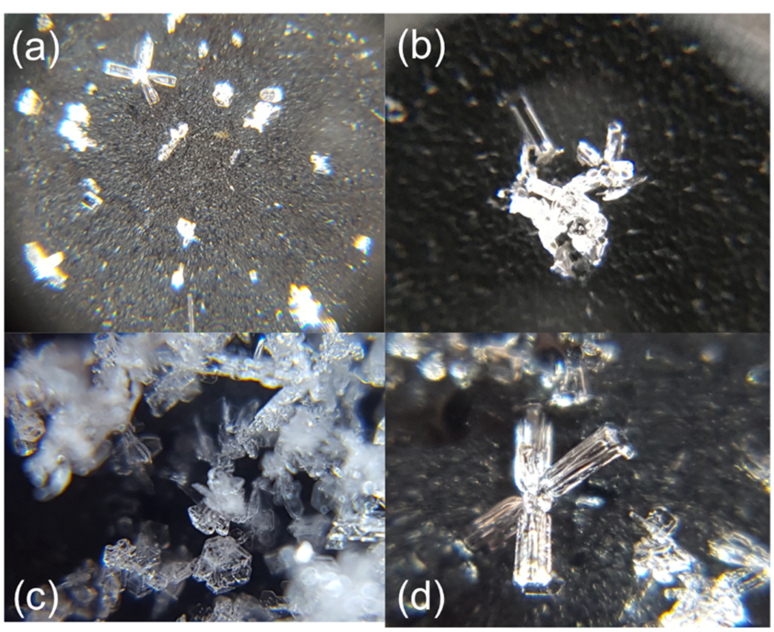


Fig. 8. Example of "snowflake selfies" taken during the 4 Feb IOP. (a) Small plates, a bullet rosette, and a needle, among other small crystals, taken at 1525 UTC; (b) a capped column and bullet rosette aggregate taken at 1904 UTC; (c) an aggregate composed of a large number of polycrystals and planar forms taken at 1904 UTC at a different location in town from (b); and (d) a bullet rosette taken at 1957 UTC.

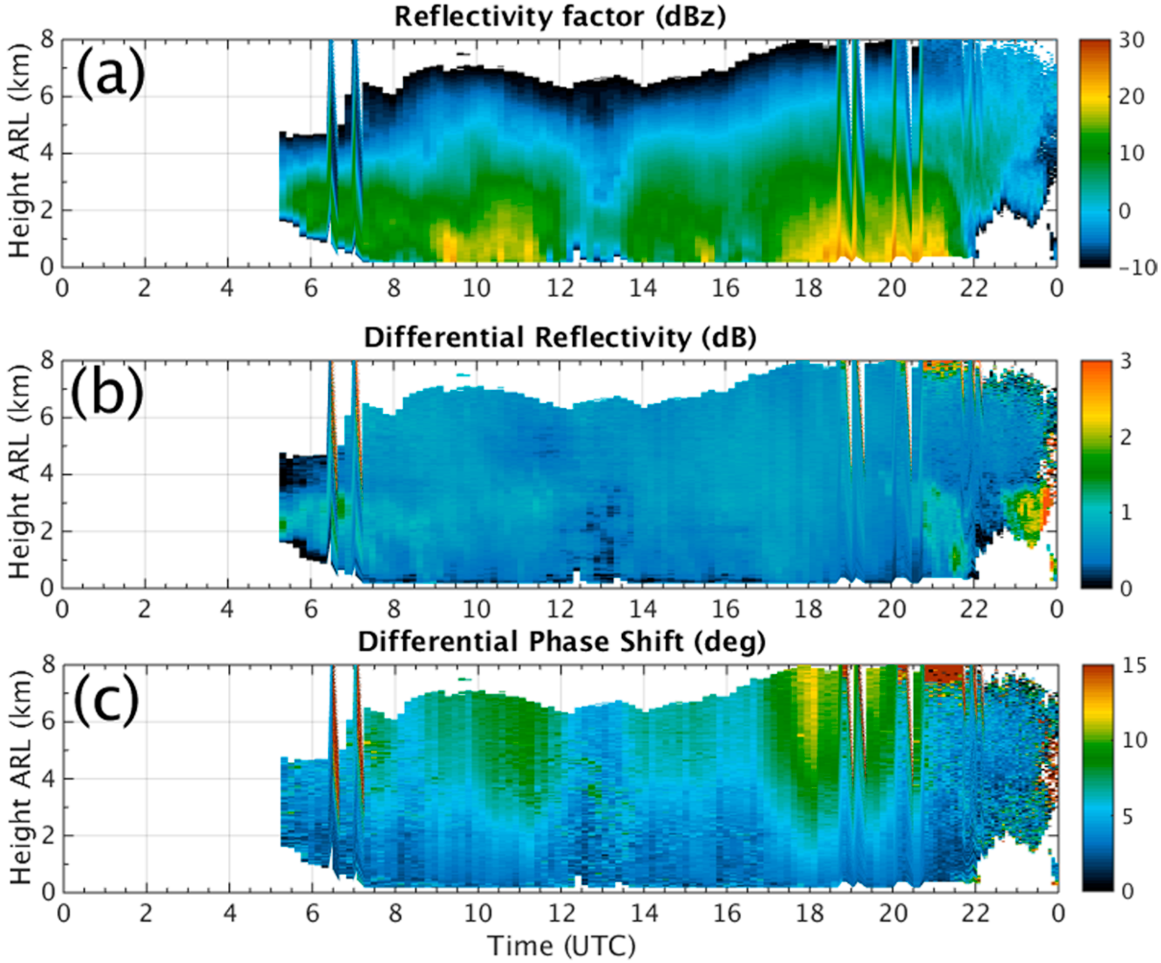


Fig. 9. Quasi-vertical profile time series of (a) reflectivity factor at horizontal polarization (Z_H, in dBz), (b) differential reflectivity (Z_{DR}, in dB), and (c) differential phase shift (Φ_{DP}, in degrees) as a function of time for 4 Feb 2018. Data from the dual-polarization WSR-88D radar near State College, KCCX. Jagged vertical lines between, for example, 0600 and 0800 UTC indicate when the operational scanning strategy was switched and the elevation angle of choice here (10°) was no longer available; the highest elevation angle available was used in these cases.

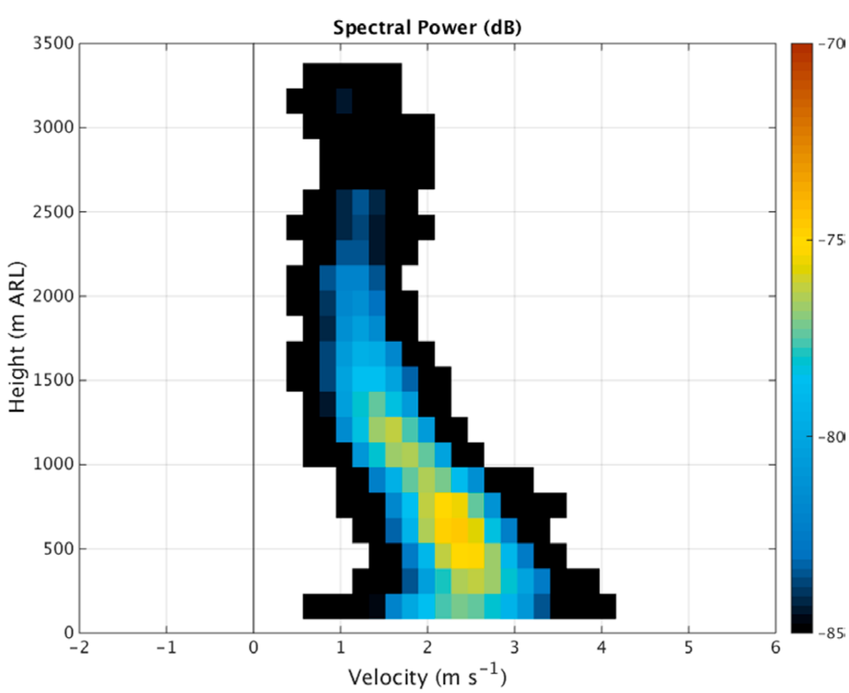


Fig. 10. Doppler spectrum power density as a function of height, from 1720 UTC 4 Feb 2019. The shading shows the amount of power (in dB) per radial velocity bin. The convention used here is positive velocities indicate downward motion.

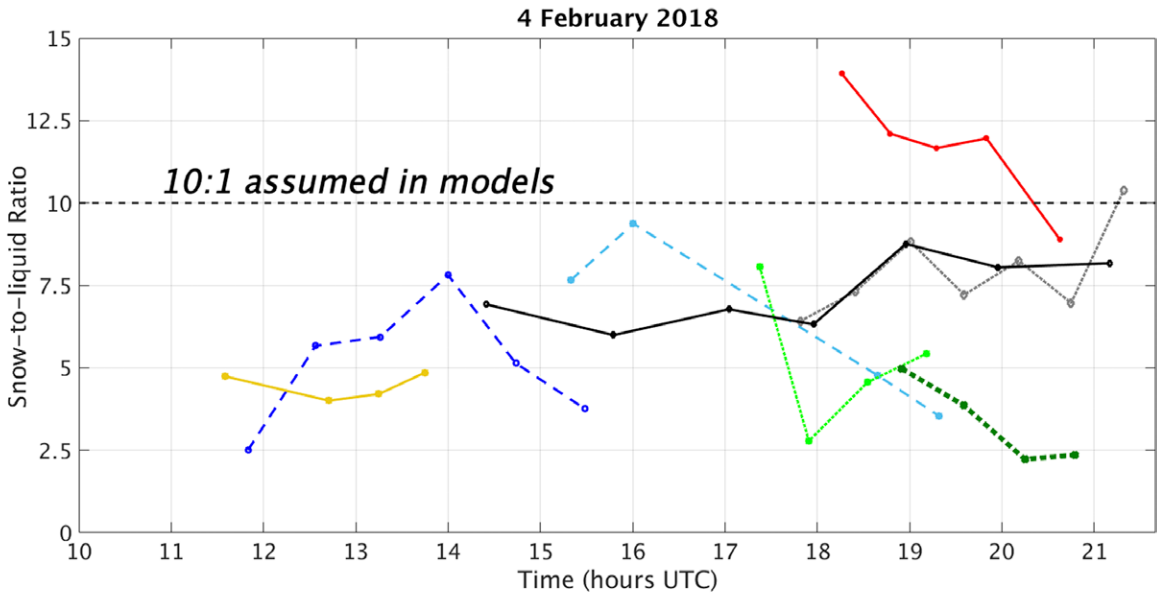


Fig. 11. Time series of snow-to-liquid ratios (SLRs) estimated from student measurements on 4 Feb 2018. The dashed line shows the 10:1 ratio typically assumed. Colors correspond to locations in Fig. 3. Line types and thicknesses varied for clarity purposes.

duration of the event, consistent with the relatively homogeneous appearance of the QVPs. Despite some spread in the resulting SLR estimates between groups, the overall uniformity between groups across the observational domain and the expectations based on the photographs is reasonable and suggests a successful data collection effort.

20 February 2019. Supplemental observations to help evaluate the technique were taken the following winter. The event was characterized by warm-air advection in the surface-to-600-hPa layer, with a saturated troposphere-deep derived sounding at 1500 UTC (Fig. 12). The 900–600-hPa layer temperatures increased throughout the event, but did not exceed 0°C in the derived soundings. This is in contradiction to the observed precipitation type in State College at the end of the event (ice pellets; Fig. 13), suggesting that the ERA5 sounding for this period is likely biased cold. Figure 13 shows the SLR time series from 20 February 2019, along with example photographs of ice crystals taken throughout the event. SLRs were computed hourly (the markers in Fig. 13 are placed on the hour, whereas the snow accumulation period was ±30 min from this time). This example is shown to demonstrate the rapid evolution of crystal habit and SLR at time scales much smaller than the operational measurements are typically taken (typically ≥6 h). Additionally, the changes in crystal habit are qualitatively consistent with expected SLR changes. Prior to 1300 UTC, branched planar crystals (efficient aggregators) resulted in SLRs > 15:1. The SLR quickly dropped to 10:1 or less as crystals took on forms such as simpler plates and capped columns over the next few hours. After a brief period of aggregates of needles after 1600 UTC, a changeover to sleet resulted in SLRs near 2. In theory, the densest packing (Gauss 1876) of solid ice spheres of the same size would result in a SLR of ~1.47, whereas solid ice would result in ~1.09 (i.e., the ratio of bulk densities of liquid to ice). In the case of real sleet, varying shapes and sizes result in nonoptimal packing, and thus higher SLRs. However, the estimated SLR approaching this limit in the observations demonstrates the accuracy of the technique. Forecasts ahead of this event called for large snow accumulations, but the lower-than-expected SLRs prevented these from materializing. SLR information was sent to the local National Weather Service via social media in real time during the event, which they found valuable and used to adjust their forecasts (M. Jurewicz 2019, personal communication).

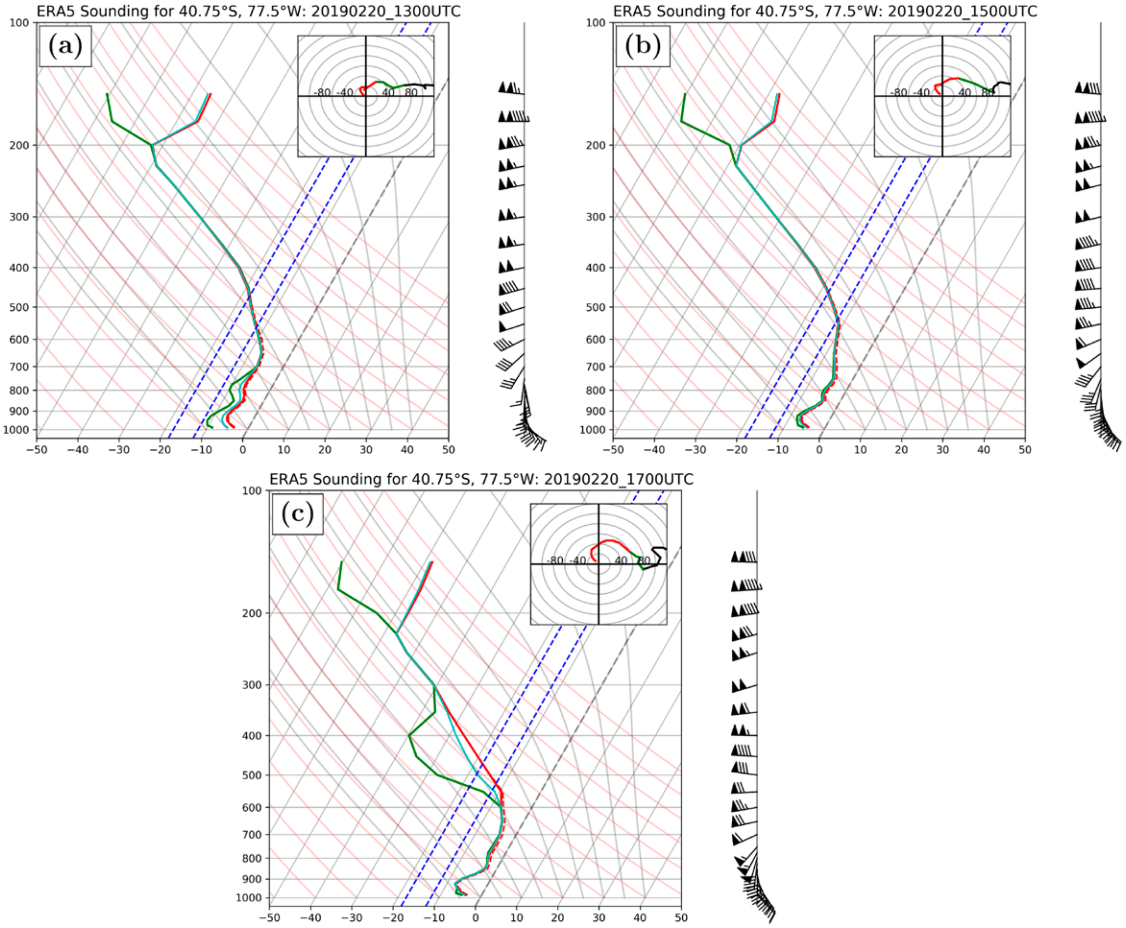


Fig. 12. ERA5 reanalysis and observed soundings for the 20 Feb 2019 event. (a)–(c) ERA5 reanalysis soundings at 40.75°N, 77.75°W for 1300, 1500, and 1700 UTC, respectively. Sounding formatting the same as Fig. 7.

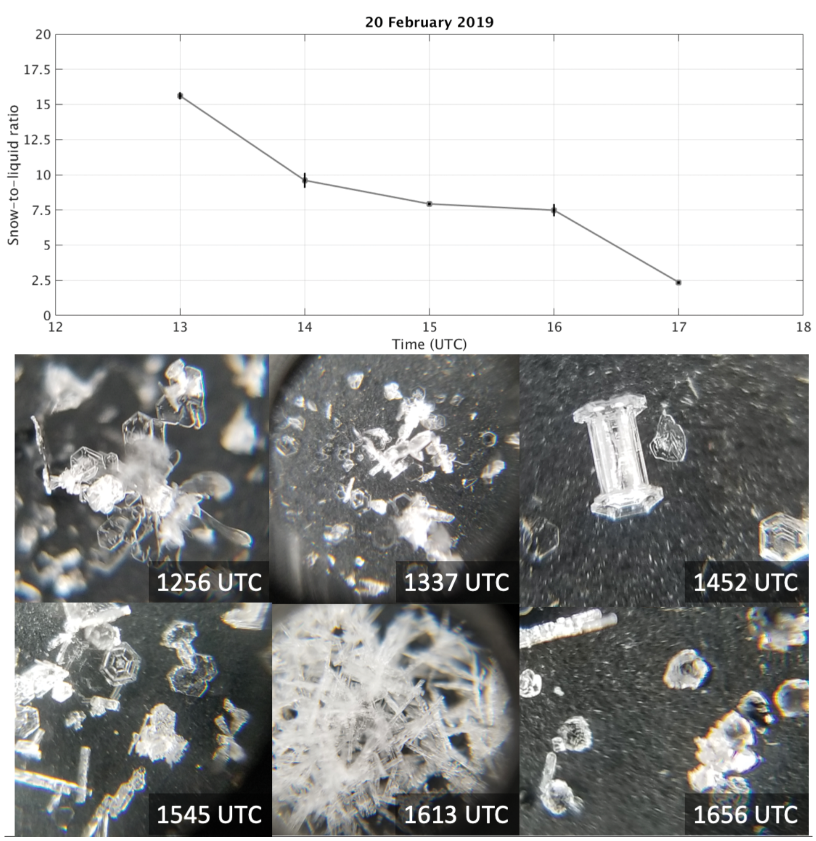


Fig. 13. Time series of snow-to-liquid ratios (SLRs) estimated using the Snowflake Selfies protocol on 20 Feb 2019, with images of snow crystals taken throughout the event.

Educational impact

The Snowflake Selfies experiment was very well received by the undergraduate students as part of this writing-intensive course. The course is typically taken by students in the latter half of their degree and is intended to meet both American Meteorological Society and federal service degree guidelines for coursework on instrumentation and communication skills through written scientific reports. The former criterion matches well to many of the skills developed and implemented during the project, including but not limited to: understanding and implementing observation techniques to increase precision, statistical analysis of observational errors, and diagnosis of systematic and random errors in results. By further coupling the experiment to a semester-long term paper, students were able to learn how to assemble and write a manuscript-based report in an iterative manner (through in-class peer review) as well as develop skills in effective communication of methods, results, and error analysis, among others. In addition, each observation team gave brief oral presentations toward the end of the semester summarizing the highlights from their measurements and showcasing their favorite Snowflake Selfie photos.

Traditionally, the METEO 440W course has included a field-based and observations-driven term project as a means to develop technical writing skills. In several previous semesters, this project was centered on the design, building, and deployment of "homemade" rain gauges for a 2–3-week period. Though this project does involve field work (daily precipitation measurements), participation is generally less active than the Snowflake Selfies project. For example, students participating in the rain gauge project have not been active with sharing their results on social media or participating in broader outreach. To compare levels of engagement with the two projects, students were surveyed on their experiences at the conclusion of the semester, the results of which are summarized in Table 1 and Fig. 14. An identical survey was also taken of students in the fall 2018 semester for the course, during which student teams completed the rain gauge project. Finally, a revamped version of the rain gauge project was introduced and surveyed in the fall 2019 semester. This change was prescribed in part by feedback from the Snowflake Selfies experiment that suggested that student engagement in the project may be increased by introducing a technology-forward aspect to the experiment. As such, rather than designing and building the gauge materials in a homemade manner (finding various materials at home and in stores), the gauges were instead designed and printed using free 3D printing technology available from Penn State. The results of this project are also presented in Table 1 and Fig. 14.

Overall, the students had a much more positive reaction to the Snowflake Selfies experiment when compared to the rain gauge experiments. Nearly all of the students strongly agreed that Snowflake Selfies helped reinforce their understanding of cloud physics and physical meteorology compared to a similar majority responding either "neutral" or "agree" regarding the rain gauge experiments. A similarly strong reaction was found for the Snowflake Selfies experiment regarding increasing students' interest in pursuing research in the atmospheric sciences (Table 1 and Fig. 14).

Positive responses for each of the experiments were generally found in response to increasing or decreasing students' interest in technical writing, with all projects eliciting a general positive to neutral response (Table 1, Fig. 14). Interestingly, more positive responses were found for the technology-forward projects (Snowflake Selfies and the 3D-printed rain gauges) in increasing or decreasing their engagement in the course. These results support the role of utilizing engaged scholarship through out-of-classroom experiences and technology-forward projects in improving the in-classroom experience of students. These experiences further manifested in student reviews of the overall course at the end of the semester. When asked "What helped you learn in this course?" students anonymously replied with responses such as "Doing a relevant science project that is actually worth doing something [for] science and society" and "Loved the term project."

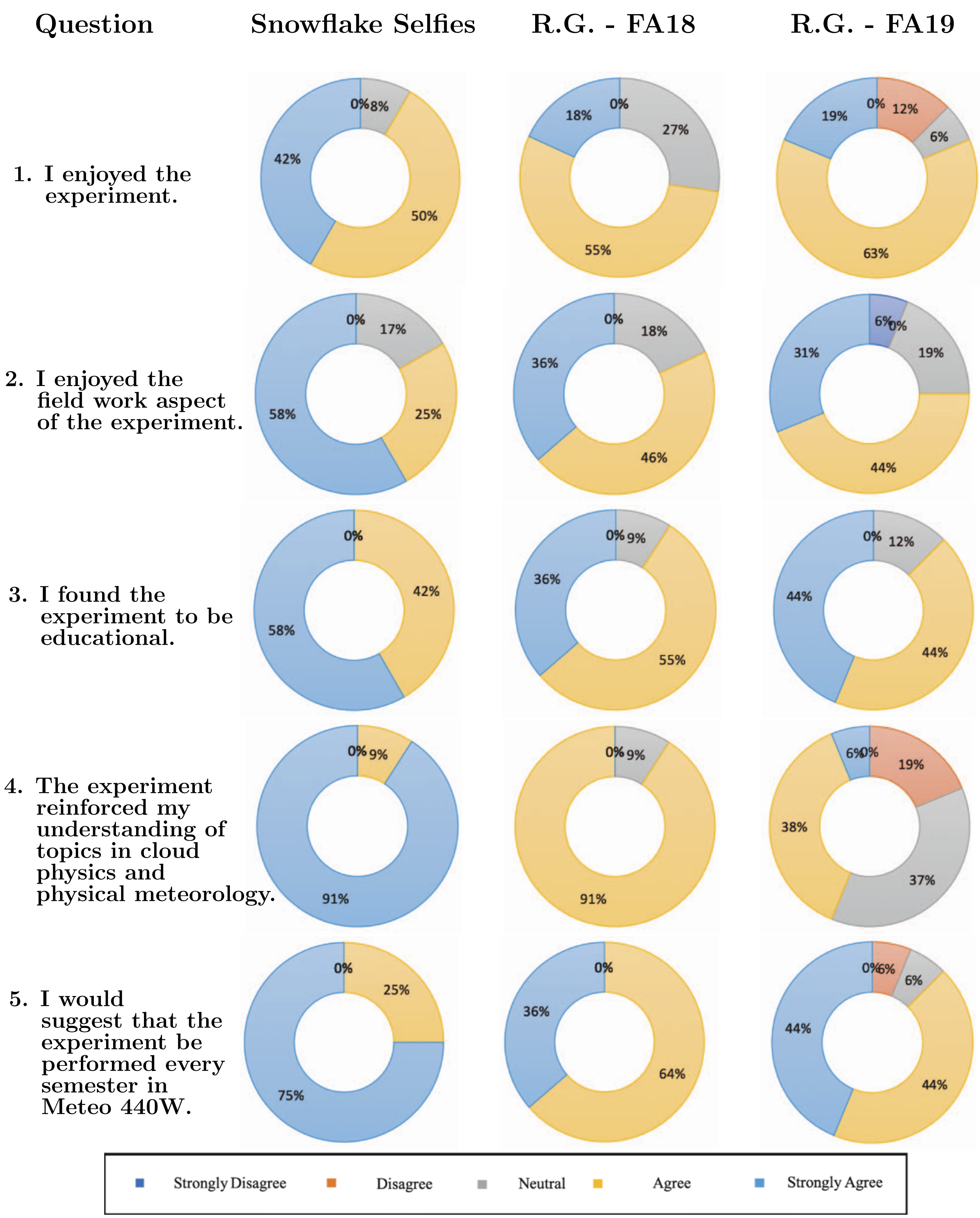
Table 1. Exit survey questions for students enrolled in METEO 440W: Principles of Atmospheric Measurements in the Department of Meteorology and Atmospheric Science at Penn State University. Students from the spring 2018 semester participated in the Snowflake Selfies experiment ("Snow"; *n* = 12 students) and students in the fall 2018 and 2019 semesters participated in the rain gauge experiment ["Rain"; (left) fall 2018, *n* = 11 students; (right) fall 2019, *n* = 16 students, separated by a semicolon].

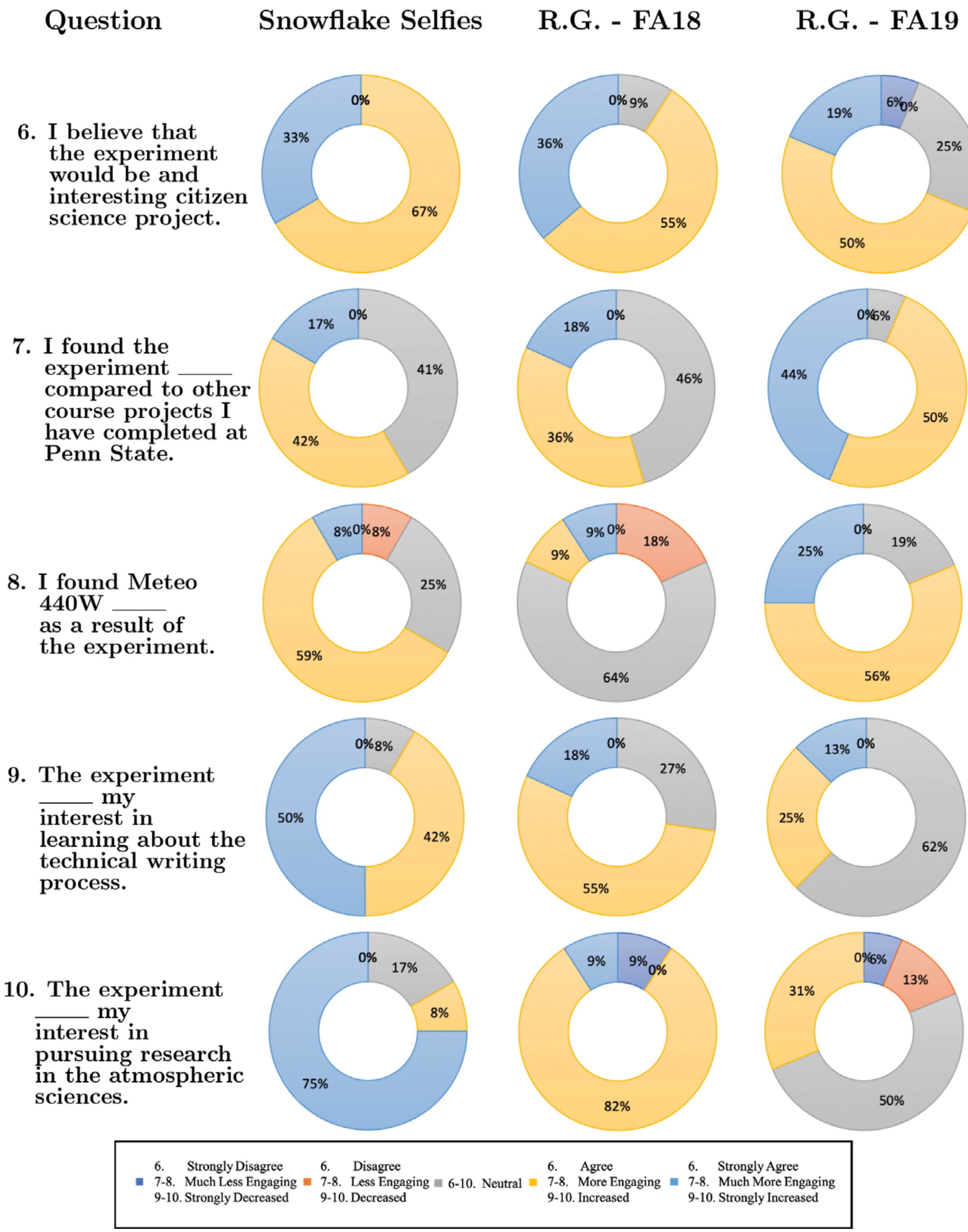
	Snow	Rain	Snow	Rain	Snow	Rain	Snow	Rain	Snow	Rain
	Strongly disagree		Disagree		Neutral		Agree		Strongly agree	
1. I enjoyed the experiment	0	0; 0	0	0; 2	1	3; 1	6	6; 10	5	2; 3
2. I enjoyed the field work aspect of the experiment	0	0; 1	0	0; 0	2	2; 2	3	5; 7	7	4; 5
3. I found the experiment to be educational	0	0; 0	0	0; 0	0	1; 2	5	6; 7	7	4; 7
4. The experiment reinforced my understanding of topics in cloud physics and physical meteorology	0	0; 0	0	0; 3	0	1; 6	1	10; 6	10	0; 1
5. I would suggest that the experiment be performed every semester in Meteo 440W	0	0; 0	0	0; 1	1	3; 1	5	6; 7	6	2; 7
6. I believe that the experiment would be an interesting citizen science project	0	1; 1	0	0; 0	2	0; 4	1	9; 8	9	1; 3
	Much less engaging		Less engaging		Neutral		More engaging		Much more engaging	
7. I found the experiment ______ compared to other course projects I have completed at Penn State University	0	0; 0	0	0; 0	0	0; 1	3	7; 8	9	4; 7
8. I found Meteo 440W (Principles of Atmospheric Measurements) ______ as a result of the experiment	0	0; 0	0	0; 0	0	1; 3	8	6; 9	4	4; 4
	Strongly decreased		Decreased		Did not change		Increased		Strongly increased	
9. The experiment ______ my interest in learning about the technical writing process	0	0; 0	0	0; 0	5	5; 10	5	4; 4	2	2; 2
10. The experiment ______ my interest in pursuing research in the atmospheric sciences	0	0; 1	1	2; 2	3	7; 8	7	1; 5	1	1; 0

The use of social media communication tools that the students were already utilizing outside the classroom also helped the class engage on the experiment. Students and instructors frequently posted their photographs and analysis of snow crystals on social media outlets, occasionally using the hashtag "#SnowflakeSelfies" (Fig. 15). This provided a pathway toward enhanced engagement with the broader meteorological community and public: several posts registered >3,000 views, and one (Fig. 15b) was reposted by an account affiliated with The Weather Channel. In addition, inclusion of social media also provided a means toward communicating important real-time observational information to local forecasters, like the State College National Weather Service office.

A term project such as the Snowflake Selfies project lends well to a measurements course this late in a student's education, as it provides a gateway toward relearning and reinforcing key concepts from previous relevant coursework. Though students in the course are expected to have a general background in atmospheric thermodynamics and cloud microphysics, students in the course are still developing further expertise in these topics and how they relate to snow microphysics. As such, bringing students up to speed on key concepts can be challenging, particularly if long time periods have elapsed between exposure to the material. To address this, we incorporated many of these key concepts into classroom discussions, forecast briefings, lectures, and student-led postevent presentations (the "Snowflake Showcase"). For example, a special lecture (using microscopic snow crystal photographs collected with the equipment) was given on snow growth microphysics, covering topics including growth of ice

Fig. 14. Results of student exit surveys conducted as part of the snowflake selfies project and rain gauge project conducted in the spring 2018, fall 2018, and fall 2019 semesters. Questions correspond to the listed questions in Table 1.





crystals from vapor (including layer nucleation, growth instabilities, and habit formation), aggregation, and riming. Such topics are presented in detail in the Atmospheric Chemistry and Cloud Physics course (METEO 437) taught in the department. Students were encouraged to relate the observed crystal habits to environmental conditions supporting such habits (Bailey and Hallett 2009) using observed or model-analyzed soundings, refreshing concepts from Atmospheric Thermodynamics (METEO 431). Further, skills developed in specialized professional electives such as Mesoscale Meteorology (METEO 414), Forecasting Practicum (METEO 415), and Advanced Forecasting (METEO 416) were frequently utilized by students

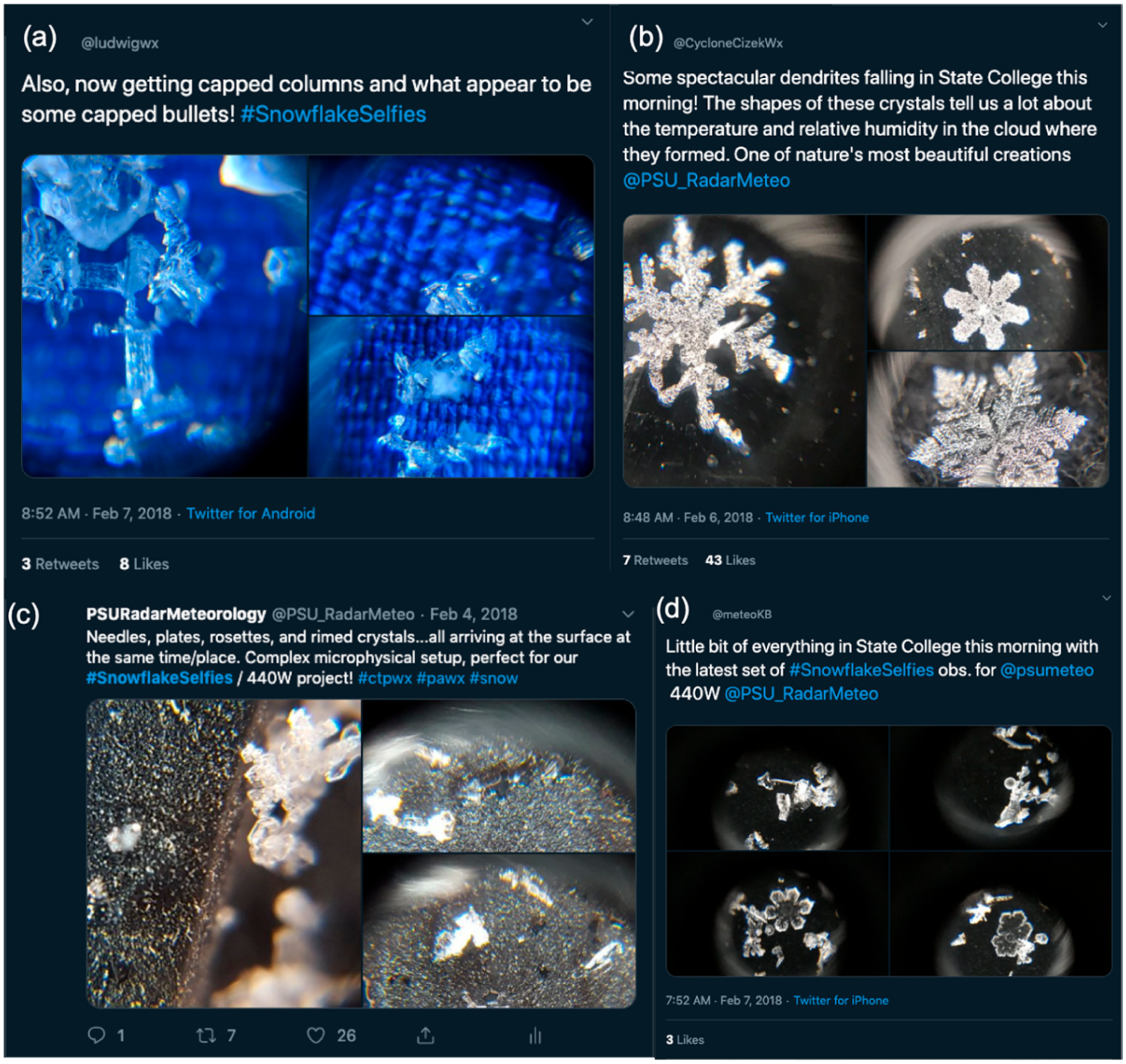


Fig. 15. Example social media posts from students and instructors during the Snowflake Selfies project. The names and photos have been removed to protect user privacy.

in the decision-making process for running IOPs, and skills and tools developed in Radar Meteorology (METEO 434) were applied in the postevent analyses.

Summary

An engaged scholarship project called "Snowflake Selfies" was developed and implemented in an upper-level undergraduate course at Penn State. Students conducted field research using extremely low-cost, low-tech instrumentation that may be readily implemented broadly and scaled as needed. During the projects, students measured snowfall accumulations, snow-to-liquid ratios, and took microscopic photographs of snow crystals. These observations were then placed in meteorological context using radar observations and thermodynamic soundings, helping to reinforce concepts from atmospheric thermodynamics, cloud physics, radar, and mesoscale meteorology courses. Students also prepared a term paper and oral presentation using their datasets and photographs to hone their communication skills.

As with any field experiment, Snowflake Selfies faced several distinct challenges. The most challenging aspect was the relative lack of snowfall events during the observational period. This was noted by several students, including multiple anonymous responses to questions about their least favorite aspect of the experiment and/or class centered on the lack of snowfall events. Another challenge was the difficulty faced by students of balancing the need to take snowfall observations at various times of the day with busy academic (or extracurricular) calendars. Though the observations were expected to be treated like any other homework assignment, this difficulty is nonetheless particularly present when incorporating this type of project into a course during an academic semester, but may be overcome with a longer observational period. Another avenue toward circumventing this issue could be encouraging the groups to collaborate by sharing their observational data with each other, an idea suggested by one student when eliciting student feedback on how to improve the project. Similar ideas could be applied if Snowflake Selfies were to be implemented as a citizen-science project, where daily schedules of observers may not allow for consistent availability for IOPs.

Despite some challenges posed by the weather and below-average snowfall season, we feel the project was a success. The student responses were overwhelmingly positive as quantified through a postcourse survey. The natural link to social media helped broaden the engagement to the community level. In addition, data were shared with the local National Weather Service office, helping to refine their quantitative precipitation forecasts. The project was implemented in the spring 2020 semester again in the METEO 440W course with the only significant change being a recommendation that students use a high-contrast surface (such as black plastic or metal) as a backdrop for imaging snowflakes and ice crystals. Further, a dedicated set of snowflake selfies equipment for a class size of 32 students has been purchased by the Penn State Department of Meteorology and Atmospheric Science for $500 (U.S. dollars) based on the experiment's successful outcome. Given these successes, we suggest that (and advocate for) the Snowflake Selfies project be expanded and broadly adopted in other departments and organizations where snowfall is typically observed. The project—particularly the remarkable photos attainable with low-cost devices—also can be an effective outreach tool for K–12 education, as well as engaging the broader community.

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