How to maximize the educational benefits for students participating in a meteorological field campaign

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Early Online Release: This preliminary version has been accepted for publication in *Bulletin of the American Meteorological Society*, may be fully cited, and has been assigned DOI 10.1175/BAMS-D-24-0154.1. The final typeset copyedited article will replace the EOR at the above DOI when it is published.

ABSTRACT: Field experiments have been found to offer exceptional educational benefits by enhancing student motivation, understanding, and retention, actively involving them in the learning process and fostering deeper connections with peers and instructors, thus outperforming passive methods such as reading or attending lectures. In August 2023, the Korea Precipitation Observation Program (KPOP): international collaborative experiments for Mesoscale convective systems in the Seoul metropolitan area (MS) (KPOP-MS) engaged over 80 students from four Korean universities. The 3-week long Intensive Observation Period utilized seven rawinsonde observation sites across Seoul and Incheon, employing radiosondes alongside an extensive radar and disdrometer networks. The educational impacts of KPOP-MS were assessed using anonymous pre- and post-surveys (with 60 and 52 respondents, respectively) and an hour-long interview with each of 14 volunteering students. Our analysis reveals that KPOP-MS 2023 achieved statistically significant learning outcomes in meteorological knowledge and skillsets. Students particularly valued the hands-on experience in meteorological measurements. Moreover, the field experiment positively influenced students' perspectives on their academic careers, boosting their motivation and confidence, especially among undergraduates. The learning outcomes for graduate students were less pronounced compared to undergraduates, and based on the interviews, we attributed this difference to variations in prior experience, motivation levels, sense of obligation and peer relationships. These findings suggest that learning outcomes may plateau with repeated participation, underscoring the importance of role diversification and leadership opportunities for more experienced students. We also discuss the influence of Korean culture and possible obstacles to optimal learning outcomes in field campaigns.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-24-0154.1.

SIGNIFICANCE STATEMENT: This study explores the profound educational impact of active participation in meteorological field campaigns, specifically through the Korea Precipitation Observation Program: Mesoscale convective systems (KPOP-MS) in South Korea. Engaging over 80 students from four universities, the program significantly enhanced students' understanding of meteorology, surpassing traditional classroom-based methods. Key findings highlight the value of hands-on experience in improving meteorological skills, boosting motivation, and influencing career perspectives, particularly for undergraduates. The less pronounced benefits for graduate students suggest a need for tailored roles to maximize learning for all experience levels. This work emphasizes the potential of experiential learning to enrich atmospheric science education, providing a foundation for refining educational practices in future field campaigns.

CAPSULE: Lessons from the first multi-institutional meteorological field campaign with 80 students in South Korea

1. Introduction

The Korea Precipitation Observation Program (KPOP), sponsored by the National Institute of Meteorological Sciences (NIMS), the Korean Meteorological Administration (KMA), is a multi-year initiative conducted during the summer seasons. It aims to enhance understanding of the physical and dynamical processes and improve forecast accuracy for mesoscale convective systems (MCSs) in moisture-rich environments. KPOP's specific goals are: (1) to generate reliable observational and high-resolution analysis data for mesoscale convective systems; (2) to study dynamical and microphysical processes over diverse surfaces (ocean, tideland, farmland, urban, mountains) using multi-frequency radars and dense observations; (3) to develop high-resolution data assimilation methods incorporating advanced observation technologies like lidar, dual-polarimetric radar, wind profilers, and dense surface networks; (4) to create a feedback loop of observation, analysis, modeling, and verification to identify forecast failures and improve accuracy; and (5) to advance parameterizations of microphysics and surface processes for better modeling of mesoscale convective systems. The KPOP: international collaborative experiments for MCSs in the Seoul metropolitan area (MS) (KPOP-MS) specifically targets the considerable challenges associated with forecasting heavy rainfall from MCSs, especially the back-building MCSs over the Seoul/Incheon metropolitan

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-24-0154.1.

area. The first internationally collaborated KPOP-MS was conducted in August 2023, with plans for a more comprehensive international field campaign scheduled for 2026.

While operational meteorology has been conducted in Korea for decades, field-based atmospheric science research projects have had a comparatively shorter history. Large-scale research-focused field campaigns involving international collaboration have only recently been introduced, such as the Korea–United States Air Quality Study (KORUS-AQ) in 2016 (Crawford et al. 2021) and the International Collaborative Experiment for the PyeongChang 2018 Olympic and Paralympic Winter Games (ICE-POP) (Kim et al. 2021). Although smaller-scale field activities have previously been conducted in Korea in areas such as cloud physics or atmospheric chemistry (Kim et al. 2023; Yum et al. 2023), the Korean Precipitation Observation Program (KPOP) represents the first multi-institutional field campaign focused specifically on heavy rainfall. To our knowledge, it is also the first Korean meteorological field campaign to explicitly incorporate research on the pedagogical value of observational activities.

The scale of student involvement was also notable. Approximately 80 students from four universities participated, including not only graduate students working directly with principal investigators but also undergraduate and graduate students recruited to gain field experience. This coexistence is relatively uncommon in studies of field-based learning and provides a unique opportunity to explore how field experiences support students at different academic stages. The participating institutions—Kyungpook National University (KNU), Seoul National University (SNU), Kongju National University (KJNU), and Pukyong National University (PKNU)—together represent a substantial proportion of the seven universities in South Korea offering bachelor's programs in atmospheric science or meteorology.

Given the novelty of this field campaign and its extensive student engagement, this study aims to report on the educational benefits and unique insights gained from KPOP-MS 2023. Traditional meteorology curricula in Korea, as elsewhere, often emphasize theoretical concepts and programming skills, while underemphasizing experiential learning through active measurement and direct observation of weather systems. The COVID-19 pandemic further compounded this gap by restricting or eliminating hands-on and group activities (Kelly 2021; Kwon and Kim 2024), resulting in significant learning losses, particularly in laboratory- and practice-based STEM education (Doyle et al. 2023; Lee et al. 2023). Since the foundation of meteorology inherently lies in

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-24-0154.1.

the observation of weather, integrating field-based, hands-on experiences remains essential for a comprehensive meteorological education.

Research indicates that field-based meteorology education motivates students more effectively than passive learning methods such as reading or attending lectures (Jin et al. 2019; Fedesco et al. 2020; Rasmussen et al. 2021). Engaging students directly in the learning process deepens their understanding and retention of material (Mogk and Goodwin 2012; McNeal et al. 2019). Hands-on field experiences can foster stronger connections between students, peers, and instructors, thereby enhancing motivation and facilitating learning (McNeal et al. 2022; Bieda III et al. 2023; Nyarko and Petcovic 2022).

Field campaigns can also positively influence students' long-term career trajectories by clarifying career aspirations and providing close mentoring opportunities (Cooper et al. 2019; Trott et al. 2020). For example, the Students of Purdue Observing Tornadic Thunderstorms for Research (SPOTTR) field campaign successfully integrated career mentoring into its activities and reported positive outcomes (Tanamachi et al. 2020), while the Convective Processes Experiment – Aerosols & Winds (CPEX-AW) field campaign, despite lacking a designated career mentoring component, still observed an increased interest among students in pursuing careers in atmospheric sciences (Rios-Berrios et al. 2023).

Through detailed quantitative and qualitative analyses of surveys and interviews, this study explores the unique learning outcomes of hands-on field experience in meteorology that cannot be replicated in a traditional classroom setting and investigates how to maximize these educational benefits. We also examine how learning outcomes depend on students' demographics or prior experiences and assess any unique aspects for Korean students compared to other cultural backgrounds.

2. KPOP Field Campaign

a. Experimental Design

The KPOP-MS utilizes an extensive array of ground-based and mobile instruments, complemented by aircraft and marine platforms. The ground instrumentation includes an operational network of S-band dual-polarimetric radars, research X-band and Ka-band dual-polarimetric radars, as well as a W-band dual-polarimetric radar, Doppler lidars, wind profilers, and multiple disdrometers

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-24-0154.1.

(including 2DVD, MRR-pro, MRR, POSS, and Parsivel). The NARA aircraft, a King Air model dedicated to atmospheric research and managed by KMA/NIMS, and the KMA/NIMS Research Vessel (R/V) Gisang 1, further enhance the data collection capabilities (Fig. 1c).

The experiment was bolstered by international collaborations, featuring technological enhancements such as a Lightning Mapping Array (LMA) installed around the experimental domain in cooperation with NASA, X-band dual-polarimetric radar from Universidad de Castilla-La Mancha, Spain, a Meteorological Particle Spectrometer (MPS) deployed with Colorado State University (CSU), and a Doppler lidar provided by Environment and Climate Change Canada (ECCC).

Ground instruments operated continuously throughout the summer monsoon period from July to September 2023. However, the upper-air sounding sites were in operation during a 3-week Intensive Observation Period (IOP) from July 27 to August 17, 2023. Most research radars and microphysics suites were strategically collocated at four supersites around the Incheon area to optimize data collection (Figs. 1b and 2d). The headquarters and main meeting room for the science team were conveniently situated at a hotel near the ICA-1 supersite to facilitate the maintenance of instruments at the supersites when needed. Seven upper-air sounding sites were strategically chosen to cover the Seoul metropolitan area and its western upstream regions (Fig. 1a). The seven upper-air sounding sites employed storm trackers, designed by Hwang et al. (2020) as the main radiosonde instrument, with Vaisala and GRAW sondes used concurrently for select cases for cross-validation. Using storm trackers, which are more affordable than traditional radiosonde instruments, enabled us to observe upper-air soundings more frequently over seven different locations throughout the IOP.

b. Daily operation and Students activity

Science team leaders, including the lead-PI (Gyuwon Lee) and a lead scientist, primarily operated from the headquarters, while most students were stationed at the upper-air sounding sites (Fig. 1a). The headquarters typically hosted six to eight team members during the IOP, including a weather forecaster and two or three instrument managers. A rotating post-doctoral fellow (Kwonil Kim, Yoonjin Lee, or Chelsea Nam) served as the lead scientist, managing student activities, data logging, and educational efforts. Senior PhD students from KNU rotated weekly to deliver twice-daily weather briefings, providing undergraduates with models of how to synthesize and communicate evolving meteorological conditions.

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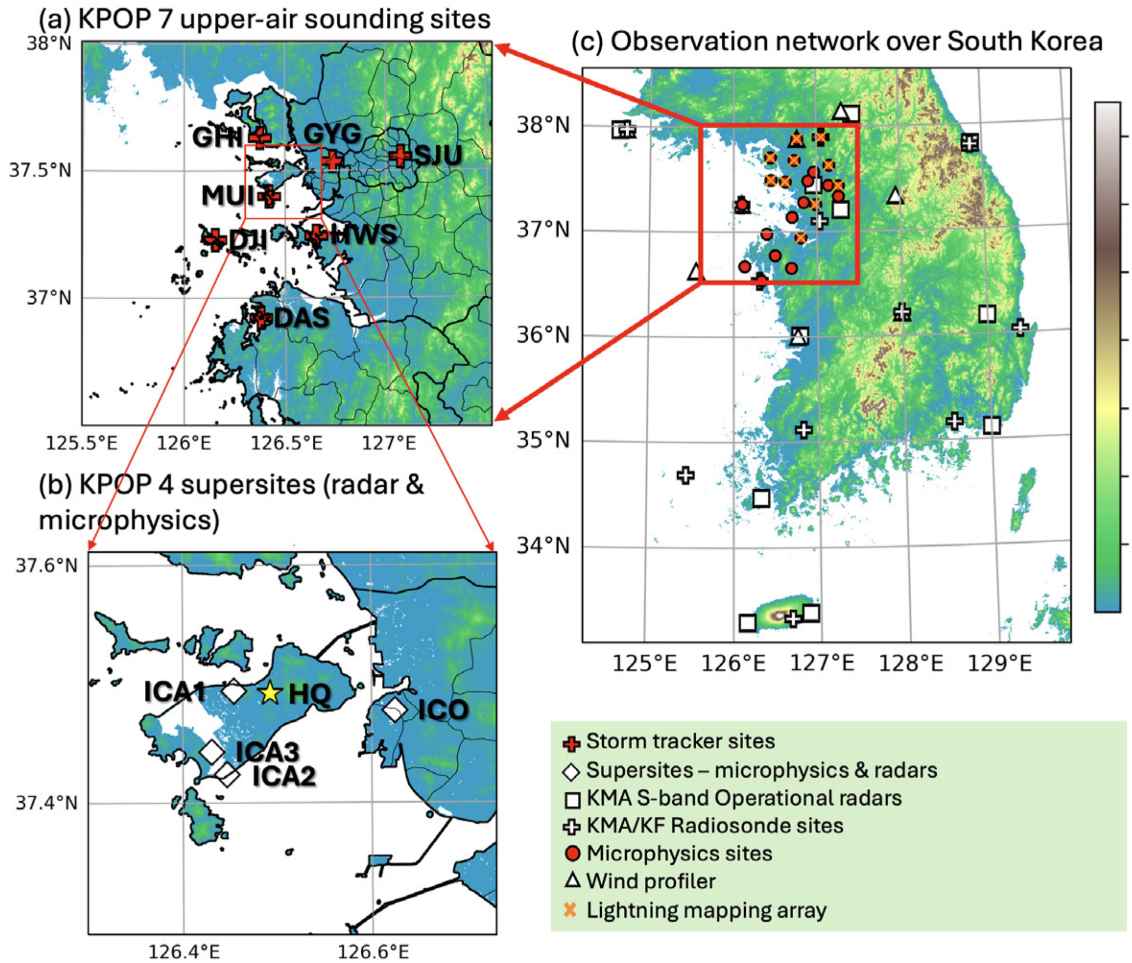

Fig. 1. Map of the meteorological observational network indicating (a) the seven KPOP upper-air sounding sites (GHI, GYG, SJU, MUI, DJI, HWS, and DAS), (b) four supersites equipped with microphysical instruments and research radars (ICA-1, ICA-2, ICA-3, and ICO), and (c) the comprehensive South Korea domain including operational instruments.

Two virtual meetings were conducted daily at 9:30 AM and 5:30 PM, led by the lead scientist. Each meeting started with a status check from each radiosonde site, followed by a weather briefing. The science team leaders and the forecaster participated in the KMA operational weather brief at the Aviation Meteorological Office at Incheon International Airport, which facilitated real-time weather discussion for our operation. Radiosonde launches were scheduled every three hours by default but increased to every two hours when warranted by weather forecasts, allowing students to follow the

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FIG. 2. KPOP activity photos (a) Gyuwon Lee demonstrating how radiosonde measurement works to students at MUI site, (b) balloon launch captured by a drone at SJU site, (c) balloon launch site set up at GYG site, (d) X-band radar at ICA-1 supersite (photos courtesy of Chelsea Nam, Juseob Kim, Subin Lee and Hongmok Park).

headquarters' decision-making process and understand the forecast-based reasoning. Educational seminars lasting 15-20 minutes followed the weather briefings, covering topics pertinent to the field campaign (Supplementary Table 1). The lead scientist organized the seminars, while the seminar was also given by the lead-PI or invited external lecturers. Sometimes, students were required to multitask with ongoing balloon launches or data monitoring to participate in the meetings (Fig. 2c).

Headquarters operated primarily during daytime (8 AM to 8 PM), except for emergencies or instrument issues at night. Radiosonde sites, managed by four to five students each, operated continuously, rotating shifts to maintain 24-hour operations. The seven upper-air sounding sites (Fig. 1) were each staffed by students from the participating universities: KNU (MUI, DJI, DAS), SNU (HWS, SJU), KJNU (GYG), and PKNU (GHI). Site managers—either graduate or senior undergraduate students—coordinated launch schedules, ensured data quality, and prepared daily site logs, experiences that built leadership, decision-making, and technical writing skills. Communications outside of the daily meetings were facilitated through mobile group chat and

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Google Drive, where students collaboratively maintained data logs and shared daily summaries, reinforcing concise scientific reporting. Each site was responsible for balloon launches, data uploads, logs, and daily data sharing with KMA. Because students participated for different lengths of time—from short, 3–4 day segments to full 1–3 week shifts—the composition of personnel at the sounding sites was not constant over the course of the IOP.

3. Surveys and Interview

The educational impacts of the KPOP-MS were assessed both quantitatively and qualitatively through anonymous surveys conducted immediately before and after the field campaign. Both surveys were administered using Google Forms. Students were asked to complete the pre-survey on their first day of participation, which varied by individual schedules, and the post-survey was distributed on August 15, a day before the last day of the field campaign.

Undergraduate students were recruited through class announcements, department bulletin boards, and postings on the department website, and participation was voluntary. Graduate student participation was encouraged by faculty whose research groups were involved in the field campaign. Student participants received monetary compensation for their contributions. All participating students were invited to complete the surveys, with survey links distributed multiple times and reminders provided during Zoom meetings.

Out of approximately 80 participants, the response rates were commendable, with 60 students (75%) responding to the pre-survey and 52 students (65%) to the post-survey. The demographic breakdown for the pre-survey included 56.7% undergraduate students, 21.7% master's students, 15% PhD students, and 6.7% other (i.e., post-doctoral and post-master's researchers). The post-survey saw a similar distribution: 61.5% undergraduates, 19.2% master's students, 17.3% PhD students, and 1.9% other. Although gender was not included in the surveys, the overall field campaign population consisted of 27% male and 73% female undergraduates, 67% male and 33% female graduate students, and 41% male and 59% female participants overall.

The surveys were designed to gauge participants' self-evaluated skills and background knowledge relevant to the field campaign, as well as their motivation and career perspectives. We drew inspiration for some of our questions from those used by Tanamachi et al. (2020), but the final items and scales were tailored to the KPOP-MS context and were not formally validated through

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psychometric testing. A comprehensive list of survey questions is available in the Supplementary Materials.

While the surveys included paragraph and long-answer questions, the simplicity of the responses prompted us to conduct in-depth interviews for more nuanced insights. To ensure the quality and richness of the data, purposive and criterion sampling strategies were implemented to recruit interview candidates (Creswell 2007). Recruitment targeted six interviewees from KNU, and three interviewees from each of the other three institutes in proportion to the participating students' numbers. Due to a last-minute cancellation, we had a total of 14 interviewees. Also, using the multiple stakeholder view by Takeuchi (2010), we recruited seven undergraduates, six master's students, and one doctoral student. Demographically, the interviewees included 10 males and 4 females. Most (8 out of 14) participated in the campaign for one week, five for two weeks, and one for the entire three weeks.

The interviews were semi-structured (Merriam 2009) with a set list of interview questions but allowing spontaneous follow-up questions (see the Supplementary Materials). Each interview was conducted in Korean via Zoom and lasted approximately one hour. The interviews were conducted in January 2024, five months post-campaign. All interviews were recorded with interviewees' agreements. Then, the recorded interviews were transcribed. Triangulation was implemented to enhance the credibility and reliability of the findings by sending individual emails to each interviewee with the summarized interview note, and they were asked to notify the researcher if there was any inaccurate information (Anderson 2017).

Data analysis began with open coding, which involves breaking down, examining, and categorizing the transcribed interviews to identify meaningful units or codes (Creswell 2007; Yin 2014). The coded items were then subjected to inductive axial coding (Merriam 2009) using a card-sorting technique. In this technique, coded items were written on cards, then organized into distinct categories based on sameness, similarity, or congruent meanings of the data (Bowker and Star 1999; Chai et al. 2016). The coding process was conducted in Korean. For English quotes used in this paper, accuracy was ensured through forward-backward translation. This method involves translating text from Korean to English and then back to Korean by another translator, comparing the original and back-translated versions to resolve discrepancies (Pan and de La Puente 2005).

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4. Student Learning Outcomes

a. The value of hands-on experience

We aimed to evaluate the extent of unique learning experiences gained from participating in a field campaign. Throughout both the pre- and post-surveys, as well as the interviews, students consistently expressed a high regard for the opportunity to gain hands-on experience with meteorological measurements. Figure 3 illustrates students' expectations and evaluations concerning the value of this hands-on experience. Initially, the pre-survey revealed that hands-on experience was the aspect students were most excited about, with over 80% selecting it as one of their top three choices out of five possible options (Fig. 3a). This enthusiasm persisted in the post-survey results, where 61.5% of participants reported that engaging directly with meteorological instruments and conducting observations was the most enjoyable part of the field campaign, followed by networking and acquiring new knowledge (Fig. 3b).

In-depth interviews further underscored the value of these experiences. All 14 interviewees shared that their hands-on experiences were significantly beneficial. When comparing learning during the field campaign to their classroom experiences, one student noted, "While the classroom focuses on general atmospheric science knowledge, field campaigns also provide technical and practical learning, like operating instruments, which sets them apart from traditional learning." Another student remarked on the enduring impact of experiential learning, stating, "Although I learn a lot of important information from general courses, the hands-on experience during fieldwork tends to stick with us longer."

We also observed empowerment among students through problem-solving experiences, a core component of experiential, hands-on learning. One student shared a reflective insight: "In the field campaign, I encountered challenges I wouldn't have tackled on my own, which pushed me to take the initiative—something very different from the classroom." Echoing this sentiment, another student noted, "The biggest difference between learning in a classroom and the hands-on experience is that you must understand both what you are doing and what you need to do next. This awareness makes me feel responsible for my learning and helps me understand my role in achieving the broader goals of the field campaign."

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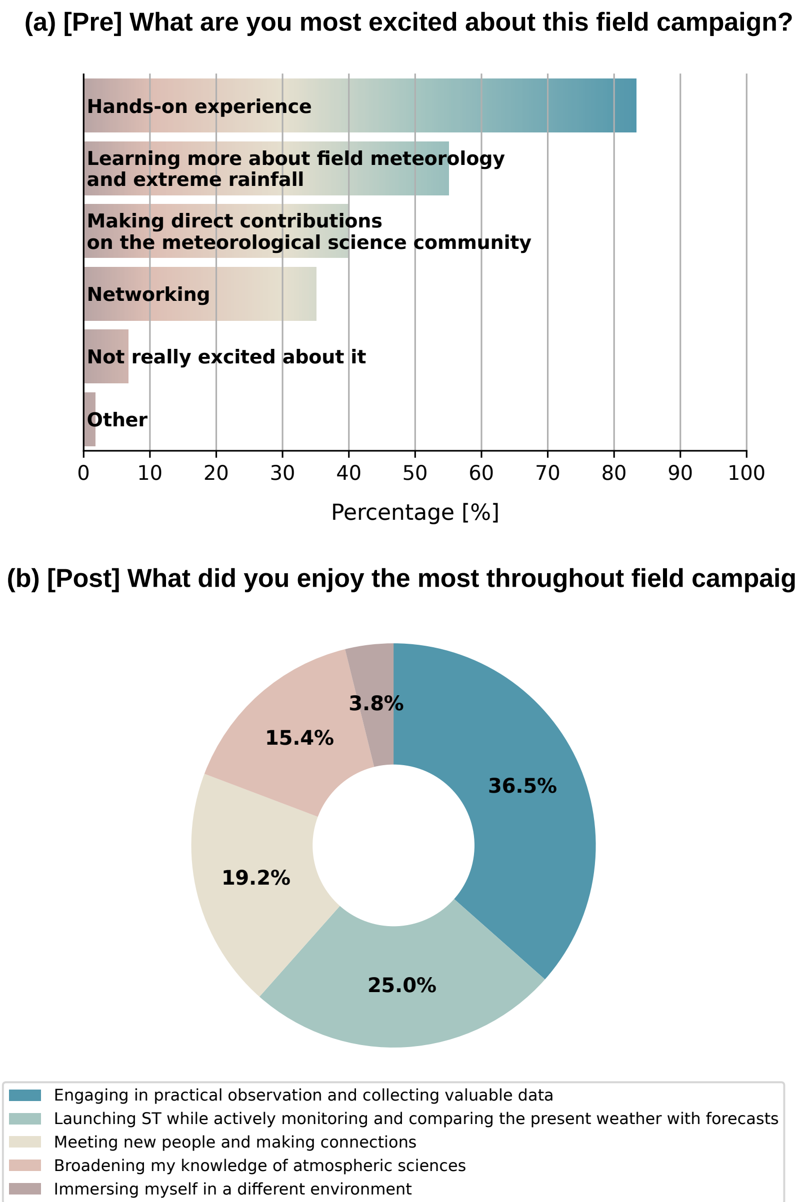

FIG. 3. Responses to survey questions showing (a) the percent of respondents selecting each option for excitement about the field campaign from the pre-survey (participants could select up to three), and (b) enjoyment of the field campaign from the post-survey (single choice).

For many participants, the KPOP-MS field campaign was their first experience in conducting actual meteorological observations, despite their majors in atmospheric science or meteorology. This gap was attributed to a lack of laboratory classes due to COVID-19 and a curriculum focused

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on theoretical training. As a result, students expressed a strong desire for more field-based opportunities. One student concluded his statement on the value of hands-on experience during the field campaign, “The skills learned from the field campaign can be directly applied in the future if I get a job in operational meteorology, which makes it incredibly valuable. I hope there were more opportunities like this for me and future students.”

b. Knowledge and Skills

To evaluate the progress of students’ meteorological knowledge and specific skills associated with the field campaign, identical sets of questions were included in both the pre- and post-surveys. This approach enabled a direct comparison of changes in students’ self-assessments before and after the campaign. The surveys were designed to target specific areas of knowledge and skills deemed relevant to the field campaign. A general question followed these specific inquiries, asking students to rate their overall confidence in the knowledge and skills related to the field campaign (refer to Questions 3-7 in Supplementary Materials 1.1).

Figure 4 presents density histograms that contrast the confidence levels reported by students in their knowledge and skills before and after the campaign. Statistical analysis using a Student’s t-test on the mean differences demonstrated that post-survey responses exhibited a statistically significant increase in students’ self-efficacy at the 99.9% confidence level for both knowledge and skills.

Notably, no post-survey responses rated their confidence on knowledge or skills as 1 or 2 out of 10, whereas approximately 10% of pre-survey responses fell within this low range. The most significant positive shifts (> 20%) in specific skills were observed in communication-related tasks such as interpreting observation data, decision-making, and writing scientific reports. Among specific knowledge areas, the largest improvements were seen in upper air sounding measurements, where over 40% of students reported increased confidence—this reflects their primary responsibilities during the campaign, which included balloon launches and logging skew-T diagrams. Substantial gains were also observed in radar, satellite, and ground-based measurements (> 20%), which is generally consistent with the topics of the series of seminars provided during the campaign (Supplementary Table 1). However, less progress was noted in the areas of mesoscale and synoptic meteorology.

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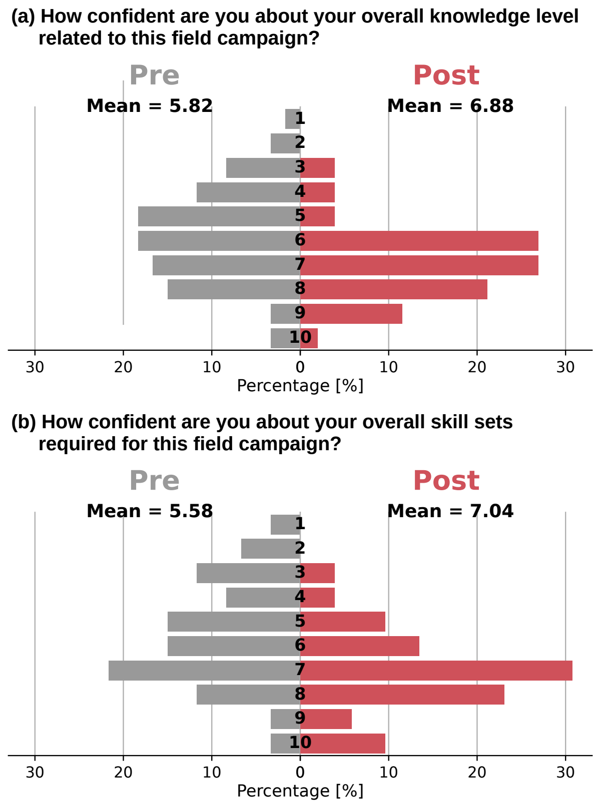

FIG. 4. Histograms contrasting students' confidence levels regarding their (a) knowledge and (b) skills related to the field campaigns, comparing responses from the pre-survey (n=60) to the post-survey (n=52).

Separate t-tests for undergraduate and graduate groups showed distinct patterns. Undergraduates reported a statistically significant increase in both knowledge and skills, with self-efficacy rising at the 95% confidence level. For graduate students, the increase in skillset self-efficacy was statistically significant at the 99% confidence level, but the increase in knowledge confidence did not reach statistical significance at the 95% confidence level. Differences between undergraduate and graduate responses will be explored in more depth in Section d.

c. Career Perspectives

We explored how the KPOP-MS experience influenced our participating students' perspectives on their careers in atmospheric science and research. From the interviews, 71% of participants (10

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out of 14) reported that the field campaign had a significant influence on their career perspectives, while the remainder felt that the impact was minimal.

The campaign provided opportunities for students to reflect more deeply on their career paths. One student noted, "I had already decided to pursue a master's degree in meteorology before participating in KPOP-MS. The field experience not only reinforced my interest but also led me to consider a doctoral degree seriously." Interaction with mentors, including professors, post-doctoral fellows, and senior students, was frequently mentioned as influential. An undergraduate student remarked, "During the field campaign, I had several discussions about meteorology careers with senior and master's students, which helped me understand the various career paths available in the field." Another undergraduate echoed this sentiment, "The field campaign enabled me to engage with professors, which was a rare opportunity outside of this setting."

Some graduate students noted that their research interests were refined during the campaign. "Through the field experiences, I found observational experiments particularly enjoyable, which influenced my current research focus. Since then, most of my research topics have been based on observational data, and I believe this shift was shaped by the field experience." shared a graduate student.

Figure 5 shows the changes in students' responses to career-related survey questions before and after the KPOP-MS field campaign. For undergraduates (Fig. 5a), positive responses increased by about 40% across all five questions, indicating that the field campaign strengthened both their motivation and their confidence in pursuing a research career, particularly in observational meteorology. It was particularly encouraging to see that there was a 30% increase in undergraduates confidently stating they possessed the motivation and persistence required for a research-oriented career in the post-survey compared to the pre-survey.

Surprisingly, this positive shift in career perspective was not as pronounced among graduate students (Fig. 5b). While there was a slight increase in responses positive toward field campaign careers, responses to general questions about leadership and graduate research careers showed a 10% decrease. The following section will further discuss the contrasting responses between graduates and undergraduates.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-24-0154.1.

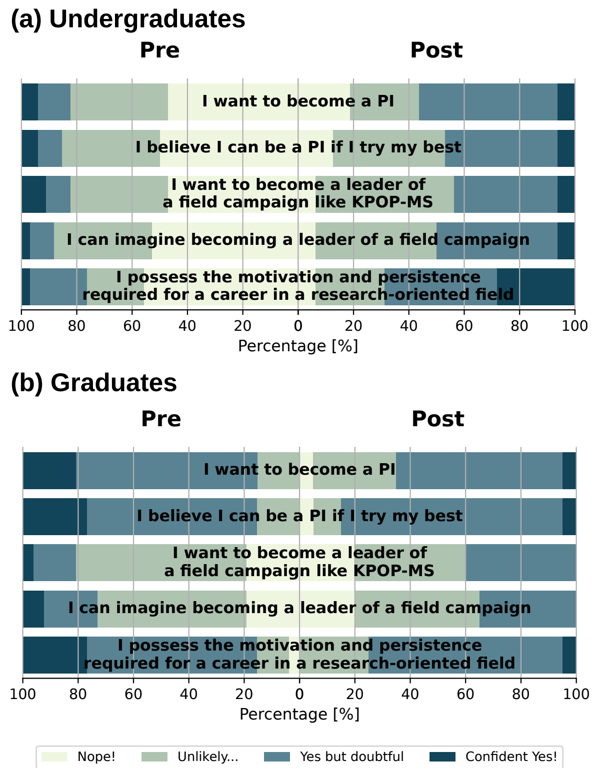

FIG. 5. Proportion of responses to survey questions about future career goal from (a) undergraduate group (n=34 for pre, n=32 for post), (b) graduate group (n=26 for pre, n=20 for post).

d. Dependency on career stage

In previous sections, we highlighted notable differences between undergraduate and graduate responses. While undergraduates displayed substantial increases in meteorological knowledge, skills, career motivation, and confidence, graduates exhibited notable gains only in skills, with less pronounced increases in knowledge and even decreases in career confidence and motivation.

To further investigate the reasons behind the limited learning outcomes for graduates, we analyzed responses to additional survey questions. When asked about their enjoyment during the field campaign, 90.6% of undergraduates responded positively, 9.4% was uncertain, and there were no negative responses. In contrast, only 50% of graduates responded positively, 35% were uncertain, and 15% expressed negative experiences (Fig. 6a-b). A potential explanation for these differences could be rooted in students' perspectives on the field campaign. Interviews revealed that undergraduates generally viewed the experience as enjoyable and social, appreciating the opportunity to

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-24-0154.1.

stay with peers in a remote area while also being compensated. Conversely, some graduate students perceived the campaign as an additional duty beyond their research, which could explain their less positive experience.

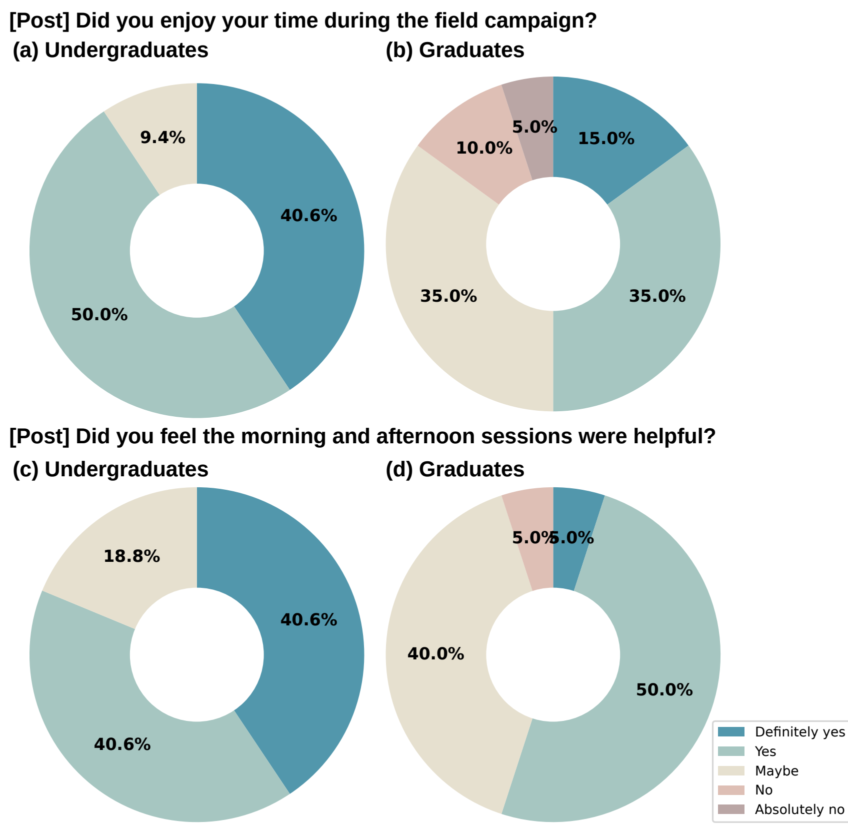

FIG. 6. Proportion of responses to the post-survey questions asking if they enjoyed the field campaign from (a) undergraduates (n=32), (b) graduates (n=20), and if they found the virtual meetings and seminars helpful from (c) undergraduates (n=32), (d) graduates (n=20).

This less enjoyable experience for graduates likely contributed to the field campaign not positively influencing their career perspectives, despite the skills they gained. Additionally, a substantially lower percentage of graduate students (55%) found the morning and afternoon Zoom sessions on weather forecasting and seminars helpful, compared to 91.2% of undergraduates (Fig. 6c-d). This discrepancy may account for why learning outcomes in meteorological knowledge were less significant for graduates. The seminar was designed at an undergraduate level, as the majority of participants were undergraduate students, and consequently, graduate students might have found

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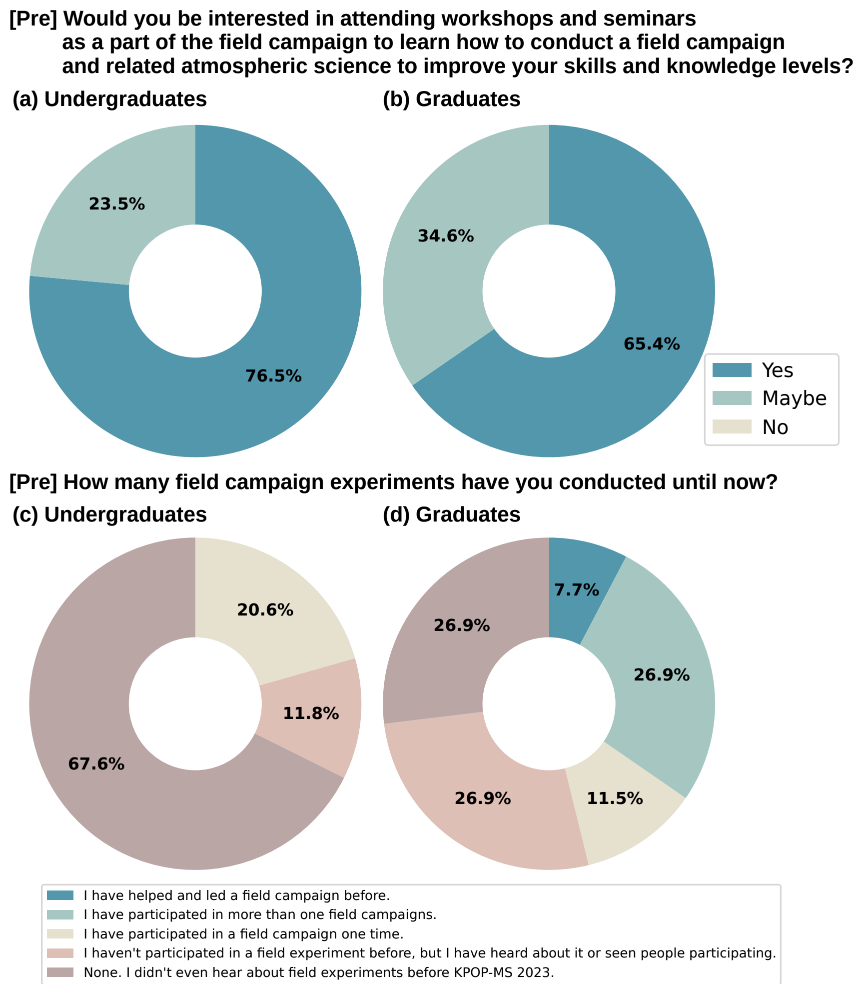

Fig. 7. Proportion of responses to the pre-survey questions asking their interest in workshops and seminars from (a) undergraduates (n=34), (b) graduates (n=26), and their previous field experiences from (c) undergraduates (n=34), (d) graduates (n=26).

it less engaging. However, it appears at least partially attributable to lower motivation levels of the graduate students. From the pre-survey, 76.5% of undergraduates versus 65.4% of graduates expressed interest in attending related seminars (Fig. 7a-b).

In addition, for the question asking for their excitement in the pre-survey (see Fig. 3a), more than 90% of undergraduates were excited about the hands-on experience, compared to less than 70% of graduate students. A higher proportion of graduate students (3 out of 26) were "not really excited"

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-24-0154.1.

about the field campaign compared to undergraduates (1 out of 34). Some graduates mentioned that their participation was primarily driven by advisor rather than voluntary interest.

Differences in motivation and excitement for the field campaign and learning opportunities therein may stem from varying prior experiences. For about 80% of undergraduate students, the KPOP-MS field campaign was their first ever field experiment (Fig. 7c). However, 46.2% of graduate students had previous field campaign experience, with a third having led or participated in multiple campaigns (Fig. 7d).

Our findings indicate that the learning outcomes from field campaigns may diminish with repeated experiences as knowledge and skills accumulate, leaving less room for progress and reducing enthusiasm and motivation for further learning. To address this observed saturation of the learning curve, we suggest diversifying the experience by providing different roles and leadership opportunities. For instance, the increase in communication skills among graduates can be attributed to their roles as site leaders, responsible for coordinating with the headquarters and managing operations. However, excessive responsibility may burden students and hinder optimal learning, suggesting a need for balanced roles that challenge yet do not overwhelm students.

We note that the undergraduate group had a substantially higher proportion of female students (73%) than the graduate group (33%), which could be another factor contributing to the contrasts in survey responses between undergraduates and graduates. Prior research shows that women, particularly in Confucian-influenced East Asian cultures, are often subject to stronger social expectations of agreeableness and positive self-presentation, which can foster more favorable or acquiescent survey responses (Carli 2001; Harzing 2006; Hamamura et al. 2008; Kim and Kim 2016; Liu 2017). Consequently, the more positive self-reported learning outcomes among undergraduates may partly reflect gender-related response styles as well as genuine differences in experience. We cannot, however, directly test the influence of gender in this study because gender information was not collected in the surveys.

e. Obstacles against optimal learning

We gathered students' feedback on unsatisfactory aspects of the field campaign through post-survey questions and in-depth interviews, aiming to identify areas for improvement and to enhance future learning outcomes. In the post-survey, students were prompted to discuss "What made

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-24-0154.1.

you most uncomfortable during the field campaign?" Additionally, during interviews, we explored various facets of the campaign to comprehensively understand what might have hindered students' learning experiences (see Supplementary Materials). This section discusses the two most significant obstacles identified.

1) Physical and logistical challenges

A common issue raised by the students was the demanding workload. Out of 52 responses, 18 mentioned the rigorous physical demands, and six cited under-staffing as a key concern. The schedule of weather balloon launching at two or three hour intervals was particularly taxing for students on the night shift. One interviewee expressed, "Physically, it was tough to fully concentrate on the lectures. We were frequently interrupted by the need to monitor ongoing work or prepare for the next observation." Another noted, "Attending seminars for students on the night shift felt less beneficial than resting. Seminars early in the morning were ineffective as day-shift students were still waking up."

Furthermore, the living conditions at the observation sites were frequently criticized. Fourteen students described the lodging as unsatisfactory, and nine disapproved of the sites' remote, rural locations. One participant stated, "The isolation, coupled with a lack of nearby amenities and all the insects, made it mentally exhausting and significantly impacted my learning ability."

2) Cultural barriers to communication

Despite efforts by the science team to foster active participation during daily meetings, student interaction was minimal. Interviews revealed that students felt hesitant to openly voice their concerns. "I had never interacted with professors or PhD students before, which made it challenging to ask questions and engage fully in observations," one student shared. Another reflected, "We were understaffed, making scheduling a challenge. Yet, it was difficult to bring up these concerns during meetings."

The cultural context likely played a role in this reticence. East Asian Confucian values, which emphasize interpersonal harmony and respect for hierarchy, may have stifled open communication, particularly towards individuals in senior positions (Chen and Chung 1994; Zhang et al. 2005). This cultural influence underscores the need for thoughtful strategies to foster an environment that encourages lively discussions, which are vital for active learning (Linton et al. 2014), especially

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-24-0154.1.

for Korean students who may experience more cultural barriers compared to their peers educated in Western cultures.

5. Conclusions and Recommendations

This paper has introduced the KPOP-MS field campaign, marking a significant milestone as the first multi-institutional field campaign of its scale in South Korea, with a particular focus on the educational impacts on students' learning outcomes. Grounded in both quantitative and qualitative analyses from surveys and interviews, this study offers insights to guide future campaigns toward maximizing educational outcomes with an emphasis on awareness of cultural nuances.

The immersive learning environment provided by the field experiments significantly enhanced students' scientific communication and analysis skills. Students reported that the skills and knowledge acquired during the campaign were more impactful and enduring than those gained in traditional classroom settings. Additionally, virtual lectures and weather briefings effectively augmented their understanding of meteorological concepts, especially among undergraduate participants. Furthermore, the campaign facilitated self-directed learning and empowered students through problem-solving experiences. Informal interactions with mentors and peers proved to be beneficial (Watkins and Marsick 2021), influencing their career perspectives and enhancing their motivation and confidence towards pursuing research careers in meteorology (Han and Chai 2024).

However, the campaign also unveiled challenges that could hinder optimal learning. A notable discrepancy in learning outcomes between graduate and undergraduate students was observed, likely due to differences in prior experience, motivation, and perceived obligations. Physical and logistical challenges, along with cultural and psychological barriers, further complicated active learning. In addition, the graduate and undergraduate groups differed markedly in gender composition, but we could not assess its impact because the surveys did not collect gender information at the individual-response level. Future research should investigate how gender and related cultural norms may influence learning outcomes in meteorological field campaigns.

To enhance the efficacy of future field campaigns, we recommend the following targeted strategies:

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-24-0154.1.

(i) Improving Living Conditions and Scheduling Providing comfortable living conditions and well-organized work schedules is crucial to reduce physical and mental fatigue, enabling students to engage more effectively in learning activities (Jolley 2024).

(ii) Inclusive Recruitment and Role Diversification Actively recruiting students without prior field experience, particularly from underrepresented groups (Jensen et al. 2021; Núñez et al. 2019), can enrich the learning environment and achieve greater learning outcomes. Providing diverse roles for experienced students—such as leadership, mentoring or teaching, and data-analysis positions—can help differentiate the experience from previous ones, introducing new motivations and aid in their professional development.

(iii) Pre-Campaign Workshop Hosting a workshop before the campaign can equip students with essential background knowledge, communicate expectations clearly, and discuss potential challenges and strategies for addressing them (Lonergan and Andresen 1988). For field campaigns that involve multiple sites and rely heavily on virtual communication, such as KPOP-MS, an in-person workshop beforehand would also have helped to build rapport. Stokes and Boyle (2009) found that extracurricular social and cultural activities in undergraduate geoscience fieldwork enhanced learning by linking emotion and cognition. Establishing rapport—through intentional team-building activities such as ice-breaker discussions or informal social gatherings—is particularly important for overcoming hierarchical cultural barriers, a notable factor in societies influenced by Confucian values such as Korea. Additionally, this setting provides an excellent opportunity for targeted career mentoring (Rasmussen et al. 2021).

(iv) Seminar Topics Relevant to the Field Campaign The seminars conducted during the campaign were most impactful on students' learning when the topics were directly related to the field observations (Mogk and Goodwin 2012). We recommend covering fundamental meteorological topics in pre-campaign workshops to better utilize time during the field campaign for focused measurement and case analysis.

(v) Structured Discussion Opportunities Implementing structured discussions can foster greater student engagement and help overcome cultural barriers. For example, during Typhoon Khanun's approach, proactive encouragement from lead scientists, organizing a separate discussion session

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-24-0154.1.

on Typhoon preparedness, led to more active and open discussions among students, highlighting the benefits of structured and inclusive discussion formats (Lonergan and Andresen 1988).

(vi) Post-Campaing Workshop Reflection is a critical element in the experiential learning theory, playing a mediating role between experience and learning (Kolb and Kolb 2017; Kuk and Holst 2018; McDonald 2019). Interviews revealed that students who discussed their field experiences with peers after the field campaign developed more organized thoughts and felt a deeper impact on their career perspectives and research orientation. Facilitating structured reflection sessions, encouraging students to articulate their experiences and insights can deepen their understanding and potentially influence career trajectories more profoundly and even help solidifying their scientific identity (Trott et al. 2020; Kortz et al. 2019). The workshop can also present the overall mission results, allowing students to recognize the success of the campaign and to share in the sense of achievement from their contributions.

By integrating these strategies, we believe future atmospheric science field campaigns can not only replicate but also significantly enhance the successes of the KPOP-MS field campaign, fostering robust learning outcomes and contributing to the advancement of meteorology education.

Acknowledgments. We thank the editor, Dr. Wendilyn Flynn, and the three reviewers for their constructive and insightful comments. This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (RS-2023-00210507) and the Korea Meteorological Administration (KMA) R&D Program “Observing Severe Weather in Seoul Metropolitan Area and Developing Its Application Technology for Forecasts” (KMA2018-00125).Institutional Review Board approval for this study was obtained from Texas A&M University (Protocol STUDY2023-0039; Exempt determination).

Data availability statement. Due to privacy and ethical concerns, and in accordance with the Institutional Review Board policy on human subject data, the raw survey and interview responses from this study cannot be made available. To ensure reproducibility, a complete list of the survey and interview questions used during the study is provided in the Supplementary Materials. For additional information, please contact the corresponding author.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-24-0154.1.

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