Title: Training the next generation of researchers in exploring cloud dynamics and microphysics using millimeter-wavelength radars

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Summer School in MM-Wavelength Radar Observations of Cloud and Precipitation
What: Twenty-five undergraduate and graduate students learnt about the physical principles of millimeter-wavelength radars and ancillary instruments and their applications to observe and investigate cloud and precipitation microphysics and dynamics.
When: 4 – 9 June 2023
Where: Stony Brook University, Stony Brook, New York, USA

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Millimeter-wavelength radars, with their ability to collect observations and high spatiotemporal resolution, have become cornerstone instruments for investigating cloud and precipitation microphysics and dynamics in the last two decades. Since the1990s the US Department of Energy Atmospheric Radiation Measurement (ARM) program has invested in mm-wavelength radar technology progressively adding scanning capability, additional frequencies and polarimetric capability (Kollias et al. 2020a). In addition, atmospheric observatories including those technologies have been operated overseas (e.g., Löhnert et al., 2015). Those technologies have enhanced our understanding of cloud and precipitation processes. Only a few universities operate those instruments and use them for educational purposes. The central role of mm-wavelength radars and their role will be further highlighted in the next decade. NASA and other international space agencies are planning to launch millimeter-wavelength (i.e., Ku, Ka, W, G-bands) Doppler radar in space to improve our understanding of cloud and precipitation formation, evolution and their impacts on global climate.

The National Science Foundation (NSF) supports the Stony Brook University millimeter-wavelength cloud radar and ancillary instruments operated by Stony Brook University (SBU) in collaboration with Brookhaven National Laboratory (SBU-BNL Radar Observatories, SBRO; http://radarscience.weebly.com/observatories.html; Kollias et al. 2020a; Oue et al. 2021; 2024) as one of the NSF Community Instruments and Facilities (CIF, https://www.nsf.gov/geo/ags/programs/fare/) to expand the usage of the facility to a broader community for research and education. The flagship radar is a sensitive, sophisticated, and well-calibrated Ka-band (35-GHz) scanning fully-polarimetric radar (KASPR), complemented by two profiling radar systems operating at W-band (94-GHz) and K-band (24-GHz) as well as ground-based in-situ measurements including disdrometers and precipitation gauge and remote sensing measurements by a lidar and a microwave radiometer. Under the NSF support, SBU - BNL Radar Science Group organized the Summer School in MM-Wavelength Radar Observations of Cloud and Precipitation at Stony Brook University, Stony Brook, NY, during June 4 - 9, 2023.

Overview

The summer school was advertised through social media and by distributing a call for applications to a large list of US national and international universities from November 2022 to

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the mid February 2023. The application package was expected to have a one-page motivation letter, one recommendation letter, and a résumé. Thirty-four students from around the world responded to the call for applications. The organizing committee of the summer school carefully reviewed the application packages to choose the attendees, considering their research interests, learning levels, and diversity. Several members of the organizing committee of this summer school had also organized or attended the second ARM Summer Training and Science Applications Event (Ghate et al. 2018). The present summer school was held three and half weeks after the end of the federal COVID-19 Public Health Emergency (PHE) Declaration (May 11, 2023).

The summer school was a one-full-week in-person event attended by twenty-five students including 21 undergraduate and graduate students from US universities and 4 international graduate students. Daily activities started from keynote lectures in the morning. A total of ten lectures were given by five early- to mid-career scientists and three senior scientists throughout that week. In the afternoon, students were divided into five research groups, each with 5 students assigned with one or two instructors focusing on one research topic. The summer school also included ice-breaker activities on Day1 (Sunday) where each participant (students and instructors) gave a 5-min self-introduction, a field trip on Day 4, and a social gathering on Day 4 where the participants enjoyed dinner and bowling. A student of SBU was hired for coordinating and organizing the entire event, including attendees' accommodation, scheduling, and daily meals.

This was a unique summer school event including several respects from the lecture topics to the organized activities:

1) The event focused on high-resolution millimeter-wavelength cloud radar observations to capture fine-scale cloud microphysics and dynamics.
2) Most of the lecturers (five) were early-career to mid-career scientists and three lecturers were senior scientists who were working on the cutting edge of their research area.
3) Daily activities included not only lectures, but also hands-on experiences in conducting research using real observation data.

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4) The final competition was held on the last day, each group presented their research project which was reviewed by a group of experts in the community,
5) A diverse background of the attendees including the 21 domestic students and 4 international students.

Goals

The main goals of this event are (1) to expose a new generation of scientists to mm-wavelength radar and lidar observation techniques in the atmospheric science field and (2) to grow the use of the mm-wavelength radar and lidar data for the research of atmospheric science. To achieve those goals, the main objective of this event is to give the trainees an opportunity (i) to learn how to use the mm-wavelength radar and lidar measurements for atmospheric science and (ii) how to use multi-sensor, multi-wavelength radar measurements and data to study cloud microphysics and dynamics, in order to educate next-generation young atmospheric scientists and researchers particularly for the mm-wavelength radar and lidar measurements. Secondary aims include forging a close relationship among the students and young-to-senior scientists for the remote-sensing and atmospheric science community and teaching the students learning group work and presentation skills of the research results.

Lectures

The keynote lectures, 90 min each, comprise the following nine topics (nine in-person and one online lectures):

- Basics of atmospheric radiation
- Ground-based radars for atmospheric measurements
- Space-borne radars for cloud and precipitation measurements
- Basics of Radar Doppler spectra
- Applications of radar Doppler spectra measurements
- Basics of polarimetric radars
- Applications of polarimetric radars combined with multi-wavelength and Doppler spectra measurements

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- Lidar technologies and measurements
- Forward simulators for radar and lidar measurements
- Optimal estimation techniques

Those lectures focused on the basics of remote sensing measurements including technology and theory used in the measurements and the basics of atmospheric dynamics and microphysics that can be observed by the remote sensing. The lectures also included applications of the remote sensing techniques for detailed cloud dynamics and microphysics at high-spatiotemporal resolutions, including multi-sensoring techniques, machine learning, inverse optimization, forward operators based on lecturer's cutting-edge expertise. Some lecturers also gave hand-on exercises at the end of their lectures. In Q&A time at each lecture, students asked questions, some of which could also provide the instructors inspirations for new ideas for future studies.

Research projects

An important aspect in training the next-generation atmospheric scientists is to provide them hands-on experience through conducting research on a particular scientific topic and offer them a team work environment to collaborate with other peer students and instructors. Based on the participant's scientific interest expressed in the motivation letter, each attendee was assigned to one of the five research groups (Table 1). Every afternoon from Day 2 (Monday) to Day 5 (Thursday) was the group research time. On day 6 each group gave a presentation of their research and was reviewed by a group of experts in the community. The group with the research topic of warm cloud microphysics won the competition.

Table 1: List of groups for research projects.

Group No.	Research Focus Area	Project Title	Project Objective
1	Warm cloud microphysics	Investigation of drizzle initiation and spatial variability using cloud radar and in-situ measurements	Combining the remote sensing and in-situ measurements to understand the mechanisms of drizzle formation and the distribution characteristics of drizzle particles in stratocumulus clouds.
2	Snow Microphysics	Multi-frequency, multi-parameter radar analysis of a	Analyzing multi-wavelength, multi-parameter radar measurements to

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		New York snow squall event	understand snow particle formation processes in a snowstorm
3	Mixed-Phase Clouds	Utilizing radar observations to explore signatures of microphysical processes in Arctic mixed-phase clouds	Analyzing radar Doppler spectra in mixed-phase cloud to understand the interaction between liquid and solid hydrometeors
4	Shallow Convection	A focus on continental cumulus mass flux	Investigating characteristics of mass flux in shallow cumulus clouds using multi-year cloud radar datasets.
5	Deep Convection	Deep convection studies using multi-frequency spaceborne Doppler radars	Examining behavior of multi-wavelength satellite radars in observing deep convective clouds using observations and model simulations

The group research activity was specifically designed to strongly leverage observational data from a wide spectrum millimeter-wavelength radar measurements including ground-based and spaceborne measurements in conjunction with multi-frequency, Doppler spectra, polarimetric, and in-situ measurements and simulation data. Each group consists of one or two instructors and five students. Described in brief below are the five group projects and their outcomes as reported during the presentations.

1. Warm cloud microphysics

The aim of this research group is to understand the initiation mechanism and the distribution characteristics of drizzle particles in warm clouds. To achieve this objective, nine months of cloud radar observation were analyzed using Ka-band Doppler spectra and in-situ data from the Eastern North Atlantic (ENA) observational site operated by the ARM program. The students applied radar Doppler skewness to characterize drizzle particles in marine stratiform clouds. Results show that drizzle embryos tend to form near cloud top and grow to larger sizes as cloud thickness increases. This phenomenon is consistent with the previous research (Kollias et al., 2011; Luke et al., 2013; Zhu et al., 2022). Additionally, results show that cloud-top radar reflectivity is larger in thicker clouds, indicating larger drizzle embryos being generated. This finding is also validated by the in-situ measurements collected during the Aerosol and Cloud

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Experiments in the Eastern North Atlantic (ACE-ENA) field campaign (Wang et al. 2022). Supported by the observational evidence, a hypothesis was proposed: thick clouds favor drizzle formation due to the longer residence time and higher liquid water content.

2. Snow Microphysics

The aims of this project included (1) to familiarize themselves with the multi-frequency, multi-parameter radar data and the analysis techniques and (2) to understand mesoscale and microphysical characteristics and snow precipitation processes in the US northeast coast region. The students worked on a case study analysis focusing on a snow squall event that passed through Stony Brook, NY on January 30, 2019, using multi-frequency, multi-parameter radar data combined with the ancillary measurement data including ceilometer, microwave radiometer, and Parsivel disdrometer collected at SBRO. The students addressed the work by utilizing a variety of datasets including the mesoscale reanalysis data, polarimetric variables and dual-wavelength ratio (DWR) from the SBRO Ka-band and W-band radars, time series of cloud base heights, liquid water path, and surface particle size distributions. They revealed that the mesoscale updrafts did not appear to be important to hydrometeor production/growth and suggested a presence of smaller scale updrafts to facilitate the hydrometeor production/growth. Their radar polarimetric and DWR analysis combined with the ancillary measurements revealed rapid changes in snow particle growth processes from aggregation to riming associated with liquid water in a shallow cloud depth (2 km), which occurred within 15 minutes.

3. Mixed-Phase Clouds

The students in this group analyzed polarimetric Ka-band radar Doppler spectra data to identify microphysical properties of Arctic mixed-phase clouds collected at the North Slope of Alaska (NSA) ARM observatory. They chose a case from November 19, 2018 with a persistent, precipitating low-level boundary layer cloud that merged with a much deeper cloud for part of the time, creating a seeder-feeder scenario. The group started by learning the nuts and bolts of Doppler spectra processing by developing code to estimate noise floors, to compute moments (reflectivity, mean Doppler velocity, spectrum width, and skewness), and to compute spectral linear depolarization ratio (LDR). They also learned the tradeoffs of short-pulse versus pulse compressed spectra applied to a complicated case such as this. Analyses then revealed complex

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snow particle formation processes in each cloud, plus pockets of supercooled liquid embedded in the deep cloud. Enhanced vertical gradients of radar reflectivity were found beneath these pockets, suggesting that riming was facilitating ice particle growth. In the boundary layer, a persistent supercooled liquid cloud layer, with an abundance of supercooled drizzle beneath it was discovered, accompanied by turbulent air. These were thought to be the source of dendritic particles with aggregation and light riming found at the surface using Multi-Angle Snowflake Camera (MASC) data. The group was keen to find secondary ice, and in the seeder-feeder cloud, a few patches of Doppler spectra exhibiting multiple peaks did suggest evidence of ice multiplication processes.

4. Shallow Convection

The students conducted literature review to (1) improve their understanding of the importance of shallow convection to the global climate system and (2) familiarize themselves with existing measurements techniques to study shallow convection. The students were given a 10-month dataset of continental shallow cumulus comprising data collected by the ARM program Ka-band Zenith Radar and Doppler lidar. They applied techniques described in Lamer et al. (2015) to estimate bulk mass flux for ensembles of continental shallow cumulus clouds. The students' analysis suggests that mass flux peaks ~100 m above cloud base in this cloud regime. Subsequently, the students investigated the internal structure of individual clouds. Their analysis suggests that, like marine clouds, continental shallow cumulus present the strongest updrafts near cloud top.

5. Deep Convection

This group investigated the information contained in the spaceborne multi-frequency radar and Doppler velocity measurements on cloud microphysics and dynamics, aiming to understand the strength and limitations of each frequency as well as the benefits of synergy. Highly realistic W-, Ka- and Ku-band doppler radar observables were simulated using WRF and RAMS model outputs, with the impact of multiple scattering and non-uniform beam filling taken into account. The group examined two cases - a squall line event over Oklahoma, and oceanic convections at various life stages over the Marshall islands. The students (1) demonstrated that lower-frequency radar is capable of penetrating deeper in the convective cores, while subject to an

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underestimation of the updraft intensity and overestimation of its width; (2) evaluated the use of differential radar reflectivity and Doppler velocity for hydrometeor size retrievals; (3) examined the differing sensitivities of path integrated attenuation observations at different frequencies to the total water path.

Field trip

The students were given a tour of the SBRO radar facility at the SBU South P. Lot. on Day 4 to learn about the operation of the instruments. They visited the KASPR control room at the site and learned about the components of the radar system and how the radar is operated and maintained. The instructors performed a demonstration of KASPR scans and explained the Multisensor Agile Adaptive Sampling technique (MAAS, Kollias et al. 2020b) which has been used to optimize KASPR scan strategies using the SBU X-band phased array radar (SKYLER-I, Kollias et al. 2022) and real-time satellite data. This gave an opportunity to see the millimeter-wavelength cloud radar's size, typical scan speed, and its components. The students were also exposed to the SBU mobile radar truck and shown inside the second SBU X-band phased array radar (SKYLER-II, Kollias et al. 2022), optical disdrometer, and mobile sounding system, which comprise part of its payload (Fig. 1).

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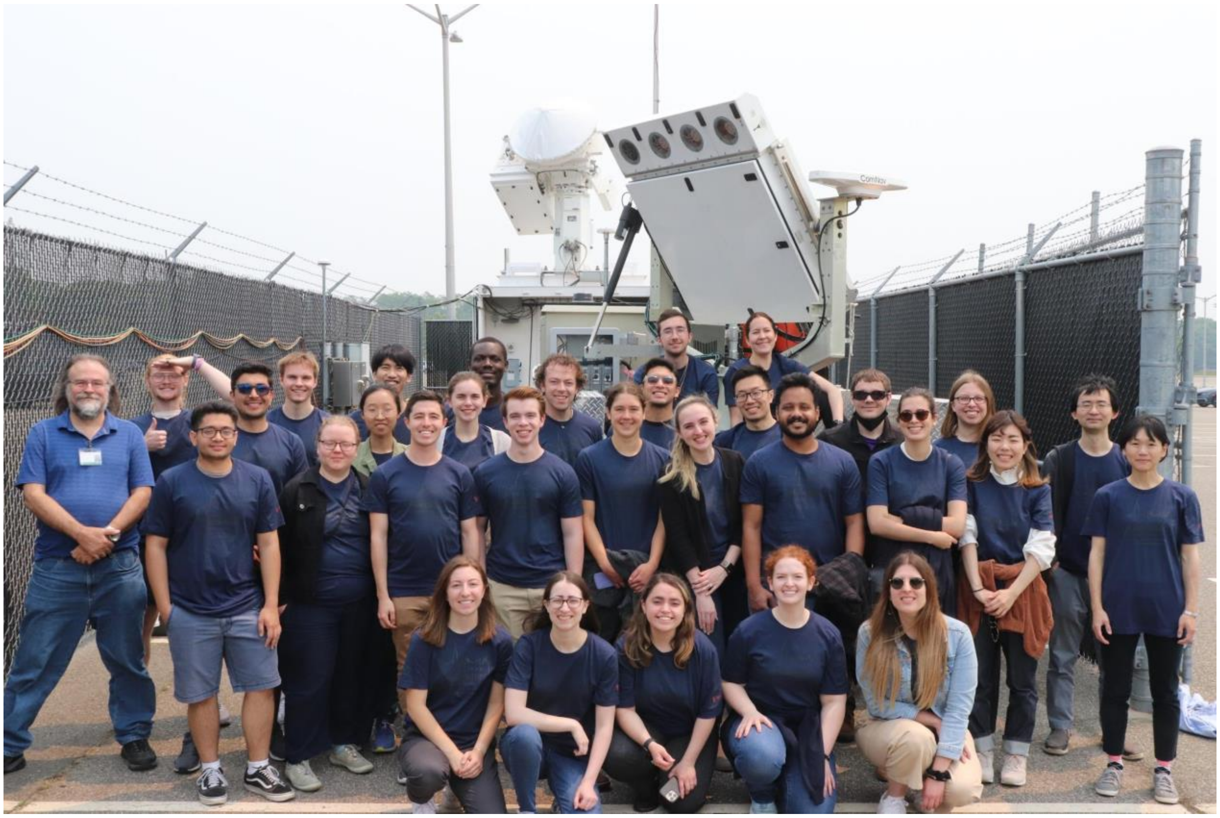

Fig. 1: A group photo of the students and instructors at the SBRO site.

Outcomes

With the growing use of mm-wavelength radars and lidars for high-spatiotemporal resolution atmospheric measurements from both space and ground in the world, the community has required the well-educated, fruitful-skilled atmospheric scientists particularly specialized for remote-sensing measurements and analyses. This event gave opportunities to be exposed to the real mm-wavelength radars and data, which are possessed by only a few universities, and to work together with the front-line young to senior scientists for this research field, leading to the next-generation atmospheric scientists and researchers for atmospheric remote-sensing measurements. The instructors also got inspiration and ideas for their future research and analyses from student's activities. This synergy could further motivate both students and instructors to boost up their own research. The relationship created during this event can never break up, expecting future collaborative research and projects producing scientists for future generations.

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While the scale of this event (25 participants and eight lecturers) was proper to provide hospitality and generous assistance for research and learning opportunities, it was also suggested that this kind of event should be extended to a wider community and continued in future every year. In particular, although this event targeted undergraduate to graduate students, we should also hold summer schools or short courses targeting postdocs and younger researchers around the world and utilize international conferences and multi-institutional field campaigns to give associated short courses.

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