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Ice Cryo-Encapsulation Balloon (Project ICEBall) Field Campaign Report

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ARM

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Acronyms and Abbreviations

ARM	Atmospheric Radiation Measurement
FAA	Federal Aviation Administration
GPS	Global Positioning System
ICEBall	Ice Cryo-Encapsulation Balloon
KASACR	Ka-band Scanning ARM Cloud Radar
KAZR	Ka-band ARM Zenith-pointing Radar
SEM	scanning electron microscope
SGP	Southern Great Plains

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1.0 Summary

The Ice Cryo-Encapsulation Balloon (ICEBall) field campaign was designed to sample the ice crystals that compose high-altitude cirrus with a passive device. The campaign made use of a new instrument, ICEBall, which is a balloon-borne ice crystal sampling system. The ice crystal sounding system is capable of measuring ice crystal concentration, temperature, atmospheric pressure, ice crystal habit, aerosol particle morphology, and residual composition. The 3-kg instrument is carried upwards at 5 m s^{-1} by a high-altitude balloon. The instrument can be cut down from the balloon at any altitude up to 20 km, and the apparatus returns to the surface by parachute. Basic measurements such as temperature and pressure are recorded onboard, and high-frequency Global Positioning System (GPS) records altitude and latitude/longitude. Ice crystal concentrations are measured through the use of a high-resolution video camera mounted on the device. Ice crystals are collected through an open aperture leading to insulated collection chambers cooled with dry ice. Upon exiting the top of the cloud system, the chamber aperture is closed, and the ~1 mm^3 sample cell is magnetically sealed and isolated at -78 °C, ensuring that ice particles do not sublimate or grow after collection. Once the crystals are returned to the surface, they are double-sealed and immersed at liquid nitrogen temperature in “dry-cryo shippers” before being transported back to the laboratory. Dr. Magee’s laboratory at The College of New Jersey contains a cryo-stage scanning electron microscope (SEM), which was used to interrogate the crystals and aerosol particles. The main purpose of this pilot field campaign was to provide an unprecedented level of detail on the crystal habits and ice surface complexity in mid-latitude cirrus, which may help resolve issues associated with habit identification and classification in cirrus.

The ICEBall campaign was originally scheduled to run from March 28 to April 18 of 2021 at the U.S. Department of Energy Atmospheric Radiation Measurement (ARM) Southern Great Plains observatory. The COVID-19 pandemic intervened and caused us to shift the dates of the experiment to October 16-November 6 of 2021. This period is also climatologically favorable for cirrus. The approximately six-month gap between our original field campaign dates and the actual dates afforded us the opportunity to build two new ICEBall payload instruments (see Figure 1).

Figure 1. ICEBall payload (left) and in flight (right).

These instruments were tested during an August 2021 trip to The College of New Jersey. During this field testing phase, we decided to launch the ICEBall payload upstream from the ARM SGP site with the goal of landing in the vicinity of the site. Our goal was to sample the ice crystals before the cirrus were advected over the remote-sensing instruments at the SGP site. The team assembled for the field campaign consisted of the Principle Investigator (PI) and Co-Principle Investigator (Co-PI) (Drs. Harrington and Magee), The Pennsylvania State University research scientist Dr. Alfred Moyle, and two graduate students (Ms. Marley Majetic and Gwenore Pokrifka). The team operated out of a house rented in Enid, Oklahoma (see Figure 2).

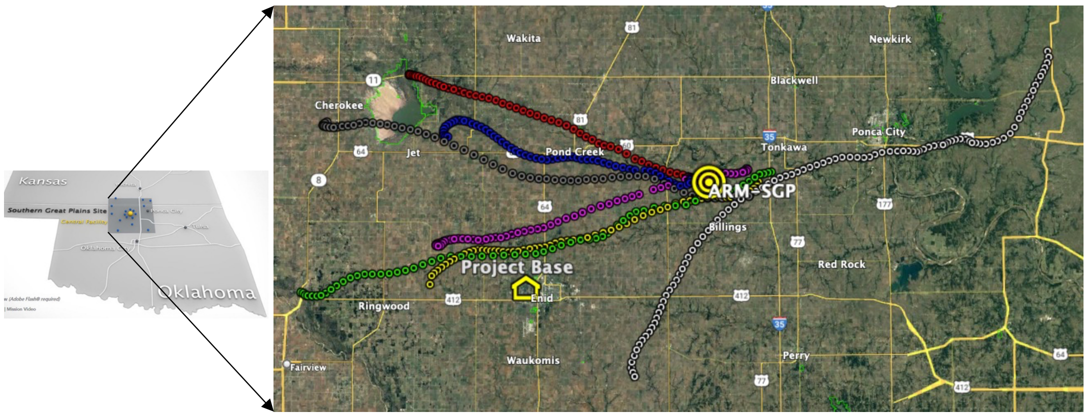

Figure 2. Schematic of ICEBall field campaign area (left) and balloon trajectories for the seven successful flights (right). Location of our project base and the ARM SGP site are shown.

We successfully sampled seven cirrus cloud systems during the three-week field campaign (October 21, 23-26, 31, and November 1). This was a much higher success rate than either of the PIs anticipated (our goal was closer to sampling three or four cases). The balloon was typically launched from oil pads or farm fields northwest of Enid and the payload was typically retrieved somewhat north of the SGP site. We never landed directly at the SGP site, and so did not need regular access to the SGP facilities. Our greatest concern going into the field campaign was the longer-term storage of crystals in the -196°C cryo dry-shipper dewars and the subsequent transport across the country. We had tested storage and transport prior to the field campaign, but we had never stored crystals for a few weeks nor had we transported the dewars over long distances. To our great relief, the storage and transport worked flawlessly and we were able to image a large number of crystals from six of the seven cases (see Section 2).

Working with the staff at the ARM SGP office was excellent. They not only helped us find the sources we needed for helium, liquid nitrogen, and other materials, but also helped with contacts within the Federal Aviation Administration (FAA) and Vance Air Force Base.

One goal of our field project was to tie the in situ measurements of ice crystal habits to the radar signatures derived from the Ka-band ARM Zenith-pointing Radar (KAZR). Unfortunately KAZR was down for the duration of our experiment. However, the Ka-band Scanning ARM Cloud Radar (KASACR) was put into vertically pointing mode during the ICEBall campaign and those data, along with Doppler lidar measurements, have proved very useful.

2.0 Results

Our group is the process of analyzing the crystal data taken during the ICEBall field campaign in conjunction with the KASACR radar data, ARM soundings, and numerical modeling. The field experiment produced a large quantity of ice crystal images taken from cirrus with temperatures between -40 and -55C. While the general habit forms are consistent with prior in situ observations, there were a number of surprising features of the observed crystal habits. About 40% of the observed habits were some form of a rosette crystal; however, the classical hexagonal bullet arm was nearly always absent (see Figure 3).

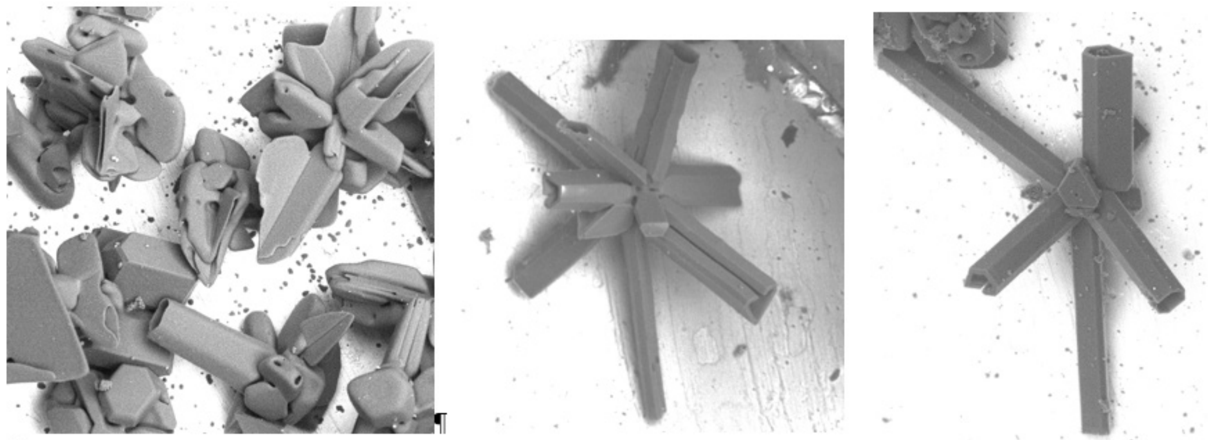

Figure 3. "Star" shaped rosettes with rounded edges, likely sublimated (left image); rosettes with either scroll or sheath arms (middle and right images). Most rosettes showed extremely hollowed arms and few were classical bullets.

We often found that the edges of the rosettes were rounded, indicating that these crystals were sampled during sublimation. Many of the rosettes had either scroll arms, where the ends of the arms turn inward like a medieval scroll, or sheaths. In each case, the arms were extremely hollowed, indicating growth at a relatively high supersaturation.

About 10% of the sampled crystals were "interfused" polycrystals, meaning that multiple crystals emerge at various angles (Figure 4, right image) and another 10% of the observed crystals were planar polycrystals (middle image). Only a small percentage (5%) were classical single crystals (left image).

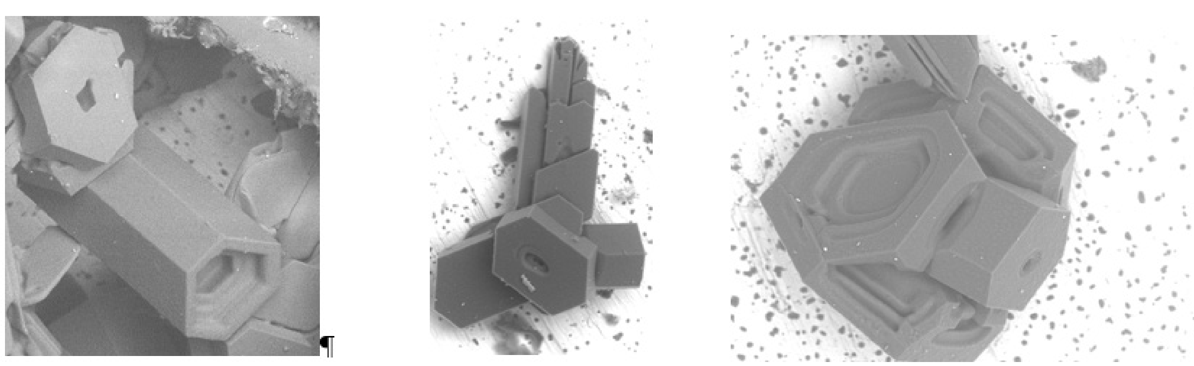

Figure 4. Classical single crystals (hexagonal plate and column, left image), planar polycrystal (middle image), and interfused polycrystals (right image).

Hollowing is a general feature of many of the observed crystals, and this hollowing was even evident on the smallest crystals (Figure 5, left image). This result is surprising because some theories suggest that hollowing only occurs once crystals reach some threshold size (i.e., Mason 1993), whereas other theories suggest that hollowing depends primarily on supersaturation (i.e., Wood et al. 2001, Bacon et al. 2003). It is difficult to observe the details of hollowing and crystal complexity for small crystals, though some prior observations suggest substantial degrees of complexity for small ice (Järvenin et al. 2018). Scrolled features on columnar ice and rosette arms were commonly observed (Figure 5, middle image) as were some new habit forms (Figure 5, "clover crystal"). None of the crystals shown in Figure 5 are especially large: The scroll column is about 100 micrometers long, whereas the distance across the hollowed end of the clover crystal is about 200 micrometers.

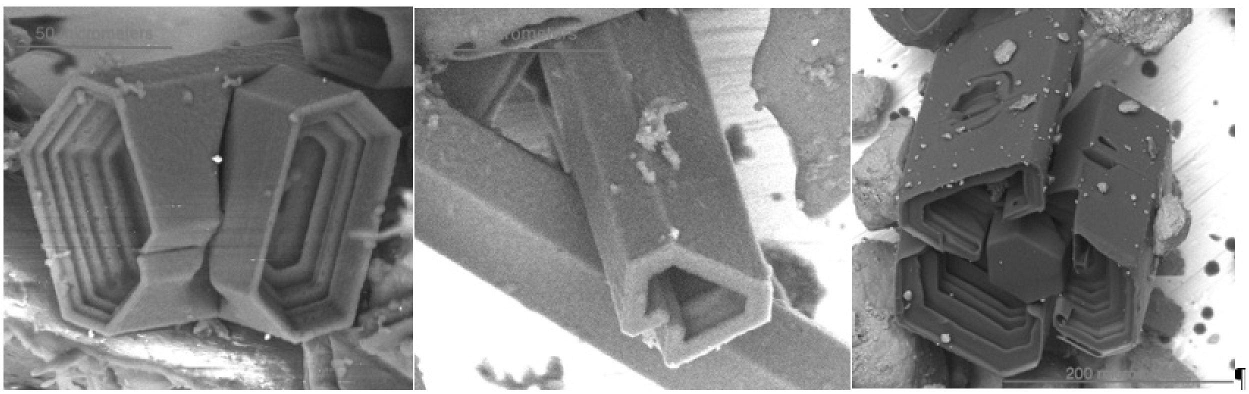

Figure 5. Substantial hollowing on a small (50-micrometer) twinned column (left image), close-up of the scrolled end of a column (middle image), and a "clover" crystal composed of a central solid hexagonal crystal and three hollowed scroll columns along the prism planes (right image).

The degree of hollowing shown in the images is fairly common, and this indicates that the mass of cirrus crystals could be severely over-estimated if this is not considered. This degree of hollowing matches, in a qualitative sense, laboratory-measured crystal growth rates at cirrus temperatures (Pokrifka et al. 2023): The measured growth rates can only be made to match theory if substantial reductions in density (through hollowing and branching arms) occurs once the supersaturation rises above a threshold level.

We are currently trying to connect the measured crystal habits to the mesoscale forcing that drove the cirrus for each case. The cases are also being interpreted with both one-dimensional and three-dimensional cloud models. The ARM KASACR data are being used to help constrain the model simulations, and to provide additional information on the smaller-scale dynamic motions that forced the cirrus.

The success of the ICEBall field campaign was encouraging, especially given the high quality of the crystal data that we were able to obtain. Since ICEBall was a two-year pilot study designed to test the feasibility of this sampling methodology, we hope to run a more extensive field campaign in the future with an improved sampling system.

3.0 Publications and References

3.1 Publications

We are currently working on two publications based on the data collected during the field experiment:

Magee, N, J Harrington, I Silber, M Majetic, G Pokrifka, and A Moyle. 2023. "Observed Habit Complexity during the Ice Cryo-Encapsulation Balloon Field Campaign." To be submitted to *The Bulletin of the American Meteorological Society*.

Chandrakar, K, H Morrison, and JY Harrington. 2023. "The Influence of Ice Crystal Diversity on Cirriform Cloud Microphysics and Dynamics." To be submitted to the *Journal of the Atmospheric Sciences*.

3.2 Invited Talks

Harrington, JY, and G Pokrifka. 2022. "Using Laboratory Measurements and In Situ Observations to Develop Microphysical Models of Warm and Cold Cirrus." PIRE Cirrus Discussion Group.

3.3 Conferences

Harrington, JY, AM Moyle, G Pokrifka, NB Magee, and H Morrison. 2022. "The Influence of Laboratory-Determined Growth Rates on The Early Growth of Ice in Cirrus." Conference on Cloud Physics, American Meteorological Society. Madison, Wisconsin.

Magee, NB, JY Harrington, M Kumjian, M Majetic, AM Moyle, G Pokrifka, and I Silber. 2022. "Morphology of Midlatitude Cirrus Ice Crystals from Balloon-Borne Measurements." Conference on Cloud Physics, American Meteorological Society. Madison, Wisconsin.

Magee NB, JY Harrington, M Majetic, A Moyle, I Silber, G Pokrifka, and M Kumjian. 2022. "Balloon-Borne Measurements of Midlatitude Cirrus Ice Crystals: Morphology and Cirrus Simulations." U.S. Department of Energy, Atmospheric Systems Research Science Team Meeting. Rockville, Maryland.

Marley, M, I Silber, NB Magee, JY Harrington, G Pokrifka, and M Kumjian. 2022. "Unique Ice Crystal Observations from the ICE-Ball Field Campaign Combined with Model Simulations Elucidate Cirrus Development." Conference on Cloud Physics, American Meteorological Society. Madison, Wisconsin.

3.4 References

Bacon, NJ, MB Baker, and BD Swanson. 2003. "Initial Stages in the Morphological Evolution of Vapour-Grown Ice Crystals: A Laboratory Investigation." *Quarterly Journal of the Royal Meteorological Society* 129(591): 1903–1927, https://doi.org/10.1256/qj.02.04

Järvenin, E, H Wernli, and M Schnaiter. 2018. "Investigations of the Mesoscopic Complexity of Small Ice Crystals in Midlatitude Cirrus." *Geophysical Research Letters* 45(20): 11465−11472, https://doi.org/10.1029/2018GL079079

Mason, BJ. 1993. "Growth Habits and Growth Rates of Snow Crystals." *Proceedings of the Royal Society of London A* 441(1911): 3−16, https://doi.org/10.1098/rspa.1993.0045

Pokrifka, G, A Moyle, and J Harrington. 2023. "Effective Density Derived from Laboratory Measurements of the Vapor Growth Rates of Small Ice Crystals at -65 to -40C." *Journal of the Atmospheric Sciences* 80(2): 501−517, https://doi.org/10.1175/JAS-D-22-0077.1

Wood, SE, MB Baker, and D Calhoun. 2001. "New Model for the Vapor Growth of Hexagonal Ice Crystals in the Atmosphere." *Journal of Geophysical Research – Atmospheres* 106: 4845−4870, https://doi.org/10.1029/2000JD900338

4.0 Lessons Learned

With regard to lessons learned from our fall, 2021 field campaign, we were very happy with the overall field planning, collaboration with ARM SGP, field protocol, and execution. Nevertheless, regarding a possible future ARM campaign using the ICEBall instrument, we would take the following lessons into account:

- Launching a large balloon during Oklahoma surface winds above about 20 knots proved very challenging. We adapted by launching out of the back of a rented U-Haul truck in high winds. This worked reasonably well, but further advance planning could perhaps include alternate wind-protection schemes.
- In the high winds, blowing surface dust and bio-aerosol contaminated some sample cells, reducing our capacity to analyze composition of interstitial and particle-scavenged aerosols. In any future campaign, we will make more careful efforts to protect sample cells from surface contamination.
- The KASACR and Doppler lidar at ARM SGP provided a unique, valuable, remoted-sensing/in situ microphysics synchronous observation. Nevertheless, we would be interested to collect in coordination or conjunction with KAZR, and potentially alongside other in situ sampling schemes.
- The design of the cm-scale cryo sample cells and cryo-dry shippers did an excellent job preserving the sampled crystals, including allowing for imaging up to ~4 months post-capture. However, to allow for quantitative analysis of scavenged and nucleating aerosol particles, the geometry of the sample cells should be optimized to allow for better x-ray signal path in the SEM.
- The ICEBall instrument itself performed more effectively than expected overall, but several improvements would be high priorities: a) attachment of a radiosonde package directly to the ICEBall payload, b) upgraded capture mechanism to allow collection of around eight altitude-separated ice particle samples, and c) upgraded optics and lighting to improve real-time particle vision contrast, to allow automated particle concentration analysis.

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