U.S. DEPARTMENT OF ENERGY | Office of Science

DOE/SC-ARM-21-011

Ice Fog Field Experiment at Oliktok Point Campaign Report

HJ Fernando I Gultepe

June 2021

ARM

DISCLAIMER

DOE/SC-ARM-21-011

Ice Fog Field Experiment at Oliktok Point Campaign Report

HJ Fernando, University of Notre Dame
Principal Investigator

I Gultepe, University of Toronto Institute of Technology
Co-Investigator

June 2021

Work supported by the U.S. Department of Energy,
Office of Science, Office of Biological and Environmental Research

Acronyms and Abbreviations

3D	three-dimensional
ABL	atmospheric boundary layer
AMF3	third ARM Mobile Facility
ARM	Atmospheric Radiation Measurement
ASR	Atmospheric System Research
BCP	backscatter cloud probe
CCN	cloud condensation nuclei
CDMS	Cloud Droplet Measurement System
CDP	control/display panel
DOE	U.S. Department of Energy
FRAM-IF	Fog Remote Sensing and Modeling–Ice Fog
HYSPLIT	Hybrid Single-Particle Lagrangian Integrated Trajectory
IF	ice fog
IFFExO	Ice Fog Field Experiment at Oliktok Point
IN	ice nuclei
IOP	intensive operational period
LPM	laser precipitation monitor
LSN	light snow
LWC	liquid water content
MWR	microwave radiometer
NSA	North Slope of Alaska
NWP	numerical weather prediction
NWS	National Weather Service
ONR	Office of Naval Research
OPC	optical particle counter
PI	principal investigator
POPS	portable optical particle spectrometer
STAC	size and time-resolved aerosol collector
TBI	tethered balloon system impactor
TBS	tethered balloon system
UAV	unmanned aerial vehicle
UOIT	University of Ontario Institute of Technology
VIPS	Video Ice Particle Sampler
WRF	Weather Research and Forecasting model
WRF-ARW	Weather Research and Forecasting for Advanced Research
WRF-Chem	Weather Research and Forecasting coupled with Chemistry
WRF-LES	Weather Research and Forecasting Large-Eddy Simulation

Contents

Figures

Tables

1.0 Summary

The Ice Fog Field Experiment at Oliktok Point (IFFExO) on the North Slope of Alaska was sponsored by the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) user facility and took place during November, 2020.

1.1 Introduction

The purpose of this field project was to better understand and predict the formation, evolution, and decay of arctic ice fog, which is typically defined as frigid conditions with suspended ice crystals (size < 200 μm) in the lower atmosphere where the atmospheric visibility (Vis) is below 1 km. Ice fog (IF) usually occurs at subfreezing temperatures T (< -10ºC), by direct deposition of vapor from the environment onto ice nuclei or freezing of supercooled small droplets in the atmospheric boundary layer (ABL) (Gultepe et al. 2014, 2020, Kim et al. 2014). IF may also originate at low-level (0.5-1 km) mixed-phase stratiform clouds associated with inversion layers, where mixed-phase clouds constitute supercooled droplets and ice crystals. The microphysics of IF in this case are related to those in mixed-phase clouds, and thus studies of the microphysics of one shed light on the other, specifically related to ice nuclei (IN) processes.

1.2 Campaign Objectives

The principal investigators (PIs) were granted a two-week intensive field campaign on IF (IFFExO) at the Oliktok Point ARM site where the third ARM Mobile Facility (AMF3) is located (https://www.arm.gov/research/campaigns/amf2020iffexo). It was scheduled for 22 March to 5 April, 2020, postponed due to COVID restrictions, but was successfully conducted during 9-21 November, 2020 thanks to openhanded support of the ARM personnel. ARM's write-up of the project can be viewed at: https://arm.gov/news/facility/post/68301. The IFFExO campaign included: (1,2) Wind and large-scale turbulence measurements using Doppler lidar (Fernando et al. 2021); (3) and integrated water vapor path measurements from a Radiometrics microwave radiometer (MWR); (4) Vertical profiling by in situ sensors mounted on a tethered balloon system (TBS) supported by the AMF3, augmented by a number of guest user-provided instruments for aerosol microphysics; and (5) Instruments for surface energy budget, meteorology, and turbulence. The novelty of IFFExO was the simultaneous measurement of dynamic, thermodynamic, microphysical, and physicochemical properties and their spectral characteristics akin to IF, allowing the reckoning of possible natural and anthropogenic aerosol contributions. IFFExO had two major objectives to evaluate ice fog conditions, as summarized below.

1)Short-term objectives: 1) improve monitoring of ice fog environments, (2) validate the Advanced Research version of the Weather Research and Forecasting model (WRF), WRF-ARW (Dimitrova et al. 2021), (3) delineate environmental and process-level information from IFFExO data, supported by high-resolution WRF-ARW and WRF coupled with Chemistry (WRF-Chem) and, resources permitting, WRF-Large-Eddy Simulation (WRF-LES) simulations, and (4) develop/refine IF microphysical parameterizations to assist future IF and climate change modeling. A proposal has been submitted to DOE's Atmospheric System Research (ASR) program for comprehensive data analysis, interpretation, and modeling pertinent to IFFExO.

2)Long-term objectives: (1) improve TBS-based IF measurements that can lead to future unmanned aerial vehicle (UAV)-based fog research, (2) classify and characterize IF and light snow (LSN) particle spectral measurements vis-à-vis those of mixed-phase conditions, and understand their nexus, (3) help develop physics-based algorithms for Vis and N_i (that affect autoconversion of cloud ice to snow or IF) for different fall velocities and autoconversion processes to be included in numerical weather prediction (NWP) models, and (4) Support the vitality of the ARM IF database.

2.0 Results

2.1 IFFExO Field Campaign and TBS Flights

IFFExO provided data for four IF cases and two low-level mixed-phase clouds. While the campaign (10-21 November,11 days) was shorter than the PIs originally requested, propitiously, IF events occurred for ~ 30% of the time (Figures 1-3), each lasting ~ 2-5 hrs. This was higher than the ~ 20% IF occurrences during the Fog Remote Sensing and Modeling–Ice Fog (FRAM-IF) campaign reported by Gultepe et al. (2014).

Figure 1. Gondola and CDMS in fog with iced ropes at 04:44 during Flight 2 of IFFExO on Nov. 13.

Figure 2. Light snow before the IF event on Nov. 17 (shown in Figure 3).

Figure 3. Gondola laser in IF during Flight 2 with instruments along the tetherline on Nov.17.

The extensive suite of leading-edge instruments deployed in IFFExO are listed in Appendix A. The flight operational periods with all instruments deployed were defined as Intensive Operational Periods (IOPs). The instrument ensemble consisted of three groups: (1) AMF3 surface in situ instruments; (2) TBS-based platforms, including guest platforms such as Gondola, Video Ice Particle Sampler (VIPS), and Cloud Droplet Measurement System (CDMS) (Figures 1 and 4); and (3) AMF3 remote sensors. Standard satellite products also provided IOP guidance.

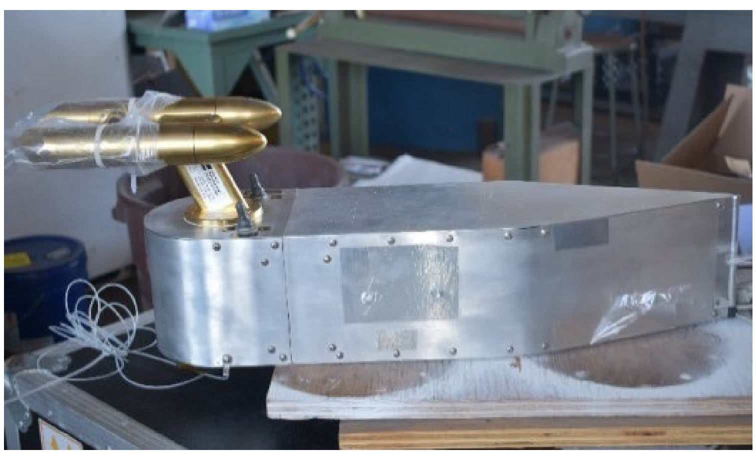

Figure 4. The Gondola platform of the University of Ontario Institute of Technology (UOIT).

The instrument-laden TBS operated in profiling and loitering (tower) modes. In the former, continuous upward traverses to ~ 1-km altitude took ~ 60 min (Figures 3 and 5).

Figure 5. Deployment during IFFExO on Nov. 18, 2020. (Photos 2-5 by Dr. Darielle Dexheimer, Sandia National Laboratories.)

Tests with constant altitude (loitering) flight legs took ~ 2 hrs with 3-20 min loitering at each altitude depending on the weather and flight objectives; 10 altitudes from 10 m up to 1 km with ~100-200-m intervals were used. The data transmission and internal data storage in Gondola were all successful. Flights were suspended during blowing snow and winds > 15 m s^{-1} that posed danger. Table 1 summarizes campaign conditions (with acronyms) and flights. Careful flight planning enabled us to obtain time-height cross-sections of meteorological and microphysical variables. Using the measurements of surface-based instruments and remote-sensing platforms, it is possible to calculate the surface turbulent heat and moisture fluxes, nucleation parameterizations, vertical profiles of 3D air velocity and turbulence, temperature T, (specific) humidity, droplet and ice-crystal physical and optical properties, and cloud physical and optical heights.

2.2 TBS Flight Summaries

Major data from microphysical observations that include both control/display panel (CDP) and backscatter cloud probe (BCP) sensors on Gondola cover IF crystal size range 1-75 μm. Alongside these sensors were a VIPS and an icing sensor that provided particle phase and size spectra up to 1 mm (Dexheimer et al. 2019). Using measurements of aerosol spectra at 16 channels (0.3-10 μm; portable optical particle spectrometer [POPS]), aerosol composition and spectra (0.1-0.5 µm at 1Hz; size and time-resolved aerosol collector [STAC]; also see below) and cloud condensation nuclei (CCN) concentration (<1 μm down to 20 nm; optical particle counter [OPC]) and tethered balloon system impactor (TBI; aerosol composition), it will be possible to obtain IN composition and N_i and N_d spectra that can be used to evaluate IF and LSN microphysical characteristics (de Boer et al. 2016, Gultepe et al. 2019, Dexheimer et al. 2019). The vertical structure of microphysical properties measured via TBS profiling as well as surface measurements yielded a unique data set on IF and low clouds as well as surface heat and moisture budgets.

Table 1. Observed and predicted conditions during IFFExO. Some days were dedicated for instrument testing and intercomparison. Reduced visibility days/conditions are highlighted. IF - ice fog; FFG - freezing fog; FG - fog; LSN - light snow, BSN - blowing snow; HPS - high-pressure system; LPS - low-pressure system; ICG - icing; HICG: high icing; MICG - moderate icing; LICG - low icing; CLR - clear weather.

IOPs	Airmass origin via HYSPLIT model back-trajectories	IFFExO In-situ Obs.	NWS Obs.	National Weather Service (NWS) Forecast	# of Flights
Nov 10	Arctic Ocean, N	FG & IF	HPS 1031 mb	-16°C; FG & mist	1 flight
Nov 11	Pacific Ocean, SW	No fog	LPS 965 mb	-12°C; FFG & CLR	No flights
Nov 12	Arctic Ocean, NW	No fog	HPS, 1005 mb	-13°C; FFG & LSN	1 flight/2 profiles
Nov 13	Arctic Ocean, N	FFG, IF, FFG &HICG	HPS, 1004 mb	-19°C; FG, mist & LSN	2 flights
Nov 14	Arctic Ocean, NW	No fog	HPS, 1010 mb	-11°C; LSN & FG	Testing/Calibration
Nov 15	Arctic Ocean, NW	LSN-IF	HPS, 1025 mb	-09°C; FFG & LSN	2 flights
Nov 16	Arctic Ocean, SW	LSN	HPS, 1030 mb	-13°C; SN	No flights
Nov 17	Arctic Ocean, NW	*Low Vis*	HPS, 1029 mb	-06°C; FG	Testing (LSN, IF)
Nov 18	Arctic Ocean, N	*Cloudy*	HPS, 1012 mb	-11°C; FFG & cloudy	2 flights
Nov 19	Continental, SW	IF&ICG	HPS, 1008 mb	-14°C; CLR & cloudy	3 flights
Nov 20	Arctic Ocean, E	IF&MICG	HPS, 1012 mb	-15°C; FFG	1 flight, testing
Nov 21	Arctic Ocean, NE	BSN	HPS_1010 mb	-18°C; FFG	End of campaign

The VIPS sensor (Schmitt and Heymsfield 2009) measured particle sizes and shapes recorded on a chemical-coated belt in the 10-1000-μm size range. TBS observations at 10 m (~ surface) provided IF particle spectra, resulting in N_i, effective diameter R_{eff}, and IWC and LSN characteristics (for precipitation < 0.5 mm hr^{-1}). Beyond 100-μm size range, LPM provided spectral information on LSN and precipitating aggregates up to 1-cm size range. The ice crystal and snow spectra from CDP, BCP, VIPS (Schmitt and Heymsfield 2009), CDMS, and LPM cover the IF and LSN physical characteristics over extended size range of 1 µm to 1 cm. The Doppler lidar provides the backscattering, extinction (Vis), flow velocities, and turbulence parameters in the vertical (Figure 6).

The broadband radiative flux measurements from the radiometers (AMC) provide both long- and shortwave fluxes. The 3D ultrasonic anemometer at 10-m height recorded air velocity (at 32 Hz), and provided information on surface turbulence, turbulent heat/momentum fluxes, and meteorological parameters (e.g., Figure 7).

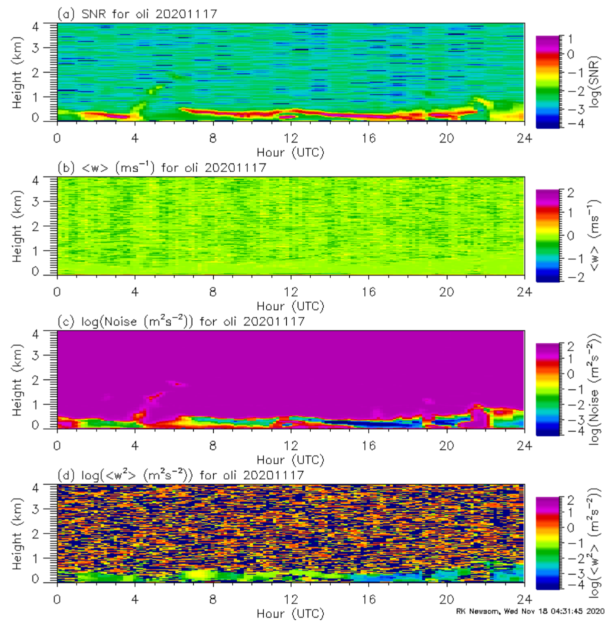

Figure 6. Doppler lidar time-height cross-sections of (a) Signal-to-noise ratio, (b) 1Hz vertical velocity, (c) 10-min vertical velocity error variance (noise), (d) 10-min vertical velocity variance (without noise correction) on 10 Nov. 2020 at AMF3. Courtesy: Dr. Rob Newsom and Dr. Raghu Krishnamurthy (Pacific Northwest National Laboratory lidar mentors).

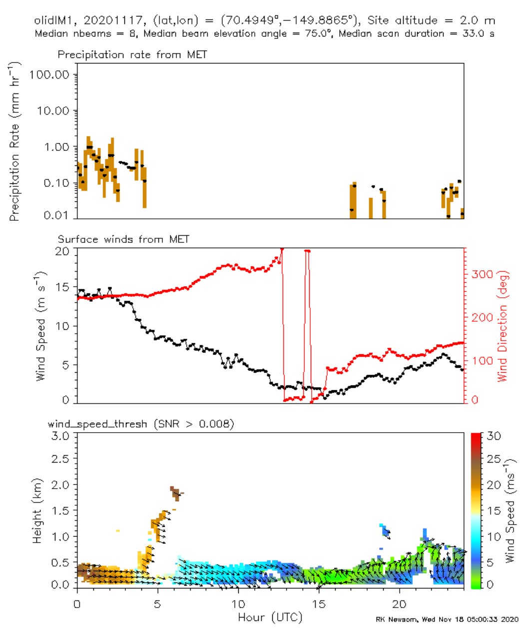

Figure 7. Time series of 10-min averaged (a) precipitation rate, (b) surface wind speed and direction, (c) Doppler lidar profiles of wind speed and direction on 17 Nov. 2020 at AMF3.

The Pacific Northwest National Laboratory's aerosol impactor system (TBI) mounted on TBS together with OPC and POPS measured aerosols (0.25 nm-10 μm) critical for CCN and IN. These and STAC data (see below) will be particularly helpful given the presence of operational oil wells in the proximity of AMF3, aerosol plumes from which may influence IF formation.

Another highlight of IFFExO was the deployment of STAC (Appendix A), a one-of-a-kind aerosol instrument developed at DOE's Environmental Molecular Sciences Laboratory, which was lofted on the TBS for aerosol vertical profiling. The data from STAC will be analyzed using multi-modal micro-spectroscopy methods to derive physical properties and size-resolved chemical composition of particles─for example, if particles are rich in salt or organics, or coated with organics. Different tracer compounds will inform about aging of particles (Ireland 2020). Data analysis of STAC will be valuable for the aerosol community and promote new technology far beyond this project.

2.3 Future Research Opportunities

We expect to design a future field study at the North Slope of Alaska (NSA) ARM site at Utqiaġvik (formerly Barrow), and submit a proposal to the ARM Infrastructure Management Board. Its conduct as well as data analysis fall outside the purview of this project. We have already apprised the Office of Naval Research of our interest in developing a joint ONR-ARM project. The IFFExO aims to record natural, and if any, anthropogenic, nucleation effects on IF at AMF3, given its proximity to oil rigs. The NSA project will study natural aerosol composition impact on the IF life cycle. Several studies with divergent results exist on ice nucleation on soot aerosols (Hoose and Mohler 2012, Fornea et al. 2009), and the bulk of them show no impact of soot on ice nucleation in the temperature regime -20 to -40 ºC (i.e., IF formation temperatures). A future experiment at NSA will help address this issue. Our design will assume that TBS operations are available at least to a lower altitude with instruments suspended (including Gondola) to quantify aerosols and their relation to IF microphysical parameters and dynamical conditions. DOE-ARM TBS mentors are quite keen on the idea of an NSA campaign.

3.0 Publications and References

The field campaign was completed in 2020 November, so most journal publications are in preparation.

3.1 Publications

Fernando, HJ, et al. 2021. "IFFExO Arctic field project." *Bulletin of the American Meteorological Society*, in preparation.

Gultepe, I, HJ Fernando, M Shaw, D Dexheimer, G de Boer, R Krishnamurthy, S China, R Newsom, S Wagh, A Vakhtin, and C Schmitt, 2021. IFFExO Arctic Ice Fog Microphysics Study: Impact on Local weather and Climate. ICCP (Inter Commission on Cloud and Precipitation) Conference, August 2-6, Pune, India. Accepted oral presentation.

Gultepe, I, HJ Fernando, E Pardyjak, CE Dorman, Q Wang, and AJ Heymsfield. 2021. Warm and cold fog microphysics: EDR-Vis parameterization. AOGS2021 Virtual, 18th Annual Meeting, 1-6 August AS43-A004, invited talk.

Gultepe, I, et al. 2021. "IFFExO Arctic field project focusing ice fog microphysics". *Quarterly Journal of the Royal Meteorological Society*, in preparation.

3.2 References

de Boer, G, S Palo B Argrow, G LoDolce, J Mack, R-S Gao, H Telg, C Trussel, J Fromm, CN, Long, G Bland, J Maslanik, B Schmid, and T Hock. 2016. "The Pilatus unmanned aircraft system for lower atmospheric research." *Atmospheric Measurement Techniques* 9(4): 1845–1857, https://doi.org/10.5194/amt-9-1845-2016

Dexheimer, D, M Airey, E Roesler, C Longbottom, K Nicoll, S Kneifel, F Mei, RG Harrison, G Marlton, and PD Williams. 2019. "Evaluation of ARM tethered-balloon system instrumentation for supercooled liquid water and distributed temperature sensing in mixed-phase Arctic clouds." *Atmospheric Measurement Techniques* 12(12): 6845–6864, https://doi.org/10.5194/amt-12-6845-2019

Dimitrova, D, A Sharma, HJ Fernando, I Gultepe, V Danchovski, S Wagh, S Bardoel, and S Wang, 2021. "WRF model simulations for coastal fog prediction." *Boundary Layer Meteorology* (in press).

Fernando, HJ, I Gultepe, C Dorman, E Pardyjak, Q Wang, S Hoch, D Richter, E Creegan, S Gabersek, T Bullock, C Hocut, R Chang, D Alappattu, R Dimitrova, D Flagg, A Grachev, R Krishnamurthy, DK Singh, I Lozovatsky, B Nagare, A Sharma, S Wagh, C Wainwright, M Wroblewski, R Yamaguchi, S Bardoel, RS Coppersmith, N chisholm, E Gonzalez, N Gunawardena, O Hyde, T Morrison, A Olson, A Perelet, W Perrie, S Wang, and B Wauer. 2021. "C-FOG: Life of Coastal Fog." *Bulletin of the American Meteorological Society* 102(2): E244−E272, https://doi.org/10.1175/BAMS-D-19-0070.1

Fornea, AP, SD Brooks, JB Dooley, and A Saha. 2009. "Heterogeneous freezing of ice on atmospheric aerosols containing ash, soot, and soil." *Journal of Geophysical Research − Atmospheres* 114(D13): D13201, https://doi.org/10.1029/2009JD011958

Gultepe, I, T Kuhn, M Pavolonis, C Calvert, J Gurka, AJ Heymsfield, PSK Liu, B Zhou, R Ware, B Ferrier, J Milbrandt, andB Bernstein. 2014. "Ice fog in Arctic during FRAM–Ice Fog Project: Aviation and nowcasting applications." *Bulletin of the American Meteorological Society* 95(2): 211−226, https://doi.org/10.1175/BAMS-D-11-00071.1

Gultepe, I, R Sharman, PD Williams, B Zhou, G Ellrod, P Minnis, S Trier, S Griffin, SS Yum, B Gharabaghi, W Feltz, M Temimi, Z Pu, LN Storer, P Kneringer, MJ Weston, H-y Chuang, L Thobois, AP Dimri, SJ Dietz, GB Franca, MV Almeida, and FL Albquerque Neto. 2019. "A review of high impact weather for aviation meteorology." *Pure and Applied Geophysics* 176(5): 1869−1921, https://doi.org/10.1007/s00024-019-02168-6

Hoose, C, and O Möhler. 2012. "Heterogeneous ice nucleation on atmospheric aerosols: a review of results from laboratory experiments." *Atmospheric Chemistry and Physics* 12(20): 9817−9854, https://doi.org/10.5194/acp-12-9817-2012

Ireland, C. 2020. "Investing from Within: Exploring Environmental Interactions. Part 1 of a 3-Part Series." https://www.emsl.pnnl.gov/news/investing-from-within-part---of-a---part-series/1563).

Kim, CK, M Stuefer, CG Schmitt, A Heymsfield, and G Thompson. 2014. "Numerical modeling of ice fog in interior Alaska using the weather research and forecasting model." *Pure and Applied Geophysics* 171(8): 1963−1982, https://doi.org/10.1007/s00024-013-0766-7

Schmitt, CG, and AJ Heymsfield. 2009. "The Size Distribution and Mass-Weighted Terminal Velocity of Low-Latitude Tropopause Cirrus Crystal Populations." *Journal of the Atmospheric Sciences* 66(7): 2013−2028, https://doi.org/10.1175/2009JAS3004.1

4.0 Lessons Learned

The most important lessons were the utility and efficacy of the TBS system in making vertical profiles through a layer of ice fog, and the importance of ARM support personal and instrument mentors in conducting such logistically challenging field campaigns. The PIs are eager to conduct a full-blown ice fog campaign at the NSA site in January-February 2025, as a part of our continuing efforts to study the dynamics of ice fog.

Appendix A

Instruments and/or Platforms at IFFExO and other Information

Platform	Instrument	Measurements	Make	Notes
ARM-TBS	CPC (cloud particle counter)	CCN	TSI	>25 nm & <1 µm [uncertainty:±10%]
	TRAPS (time-resolved aerosol particle sampler)	IN chemical composition	CSU	1 nm-10 µm, 30 min averages (±30%)
(New – Prototype)	STAC (size and time-resolved aerosol collector)	IN chemical composition and spectra	PNNL	0.1-0.5µm & 1Hz (±20%)
	POPS, printed optical particle spectrometer	Ice nuclei 0.14-3 µm ASD	Handix	>0.3 µm (±10%)
	VIPS, Video Ice Particle Sampler	Droplet or ice crystal spectra and images	Nat. Sys. Res.	10-2000 µm (±50% at 10 µm)
	CDMS (Cloud Droplet Measurement System)	Droplet spectra	MesaPhotonics	10-1000 µm(±10%)
	TBI (tethered balloon impactor)	Aerosol composition	TSI	0.25,0.5,1.0,2.5 µm (±20%)
	3-D sonic anemometer	(x,y,z) wind vectors	Young	Not for icing (±8%)
	SLD (supercooled liquid droplet) sondes	Supercooled LWC	Anasphere	Entire size range (±15%)
	iMet XQ2 UAV sensor	Meteorology	InterMet	At the TBS (±10%)
	DTS (distributed temperature sensing)	Distributed temp. sensing system	Silixa	T at 0.5 m scales (±5%)
UOIT-Gondola	CDP (cloud droplet probe)	Droplet/ice spectra	DMT	(1-50 µm); 1 Hz; (±10%
(For TBS)	BCP (backscatter cloud probe)	Droplet/ice spectra	DMT	(5-75 µm); 1 Hz; Cloud icing and SLD (±20%)
ARM-AMF3	MWR (microwave radiometer)	T, LWP, and IWVP	Radiometrics	3 channels, not profiling (±20%)
	halo Doppler lidar	Doppler wind velocity	Metek	For ice fog and clouds (±10%)
	Ka-band radar	Radar reflectivity (Z) and Cloud properties	Metek	Profiling (±10%)
	nepholemeter	Aerosol extinction	TSI	(±10%)

Platform	**Instrument**	**Measurements**	**Make**	**Notes**
	ceilometer	Cloud base and ceiling, backscattering	Vaisala	Backscatter and visibility (±10%)
	PSAP (particle soot absorption photometer)	Absorption	DMT	(±20%)
	UHSAS (ultra-high-sensitivity aerosol spectrometer)	Aerosols size distribution	DMT	<0.5 µm, spectral ASD (±10%)
	(Pacific Northwest National Laboratory) aerosol impactor	Aerosol composition	AOS	0.25-2.5 µm (±10%)
	LPM (laser precipitation monitor); disdrometer	Snow spectra and type; hydrometeors	Metek	100 µm -1 cm (±30%)
	Sunphotometer	Optical thickness	Cimel Elect.	For aerosols (±10%)
	SRS (snow ranging sensor)	Snow depth	Metek	(±20%)
	MET tower	Met measurements		(various)
	DTS, fiber optic distributed temp sensing	T profile measured at 0.25-m intervals	ARM	30-60 sec profiles (±5%)
	AMC (Ameriflux Meas. Component System)	Up- and downwelling radiative fluxes	AMC Labs	(±10%)
	MAWS (Met Automatic Wx station)	Met measurements	Metek	Radiosonde profiles (±10%)

ARM

www.arm.gov

U.S. DEPARTMENT OF ENERGY

Office of Science