

# Assessing the Usage of Unmanned Aircraft Systems (UASs) for Conducting Cloud Seeding for Fog Abatement



Left: Images showing the TIMMS in March 2023 at Ice Crystal Engineering.



Left: Images showing ice on plates of octocopter UAS after a super-cooled fog flight in March 2023 at Ice Crystal Engineering.



Right: Images showing ice on the TIMMS after fog event taken on in March 24 2023 at Ice Crystal Engineering.

# Definition of Mist and Fog

- An assortment of small hydrometeors suspended at the Earth's surface that reduces horizontal visibility.
- Mist results in visibility of between 7 statute miles (11.2 km) and 5/8 statute miles (1 km)
- Fog results in visibility below 5/8 statute miles (1 km).



Images showing fog on May 8, 2023 outside of East Grand Forks, MN. Courtesy of David Delene.

# Hazards of Fog

- Fog causes 38,700 vehicle crashes annually, with 16,300 injuries and over 600 fatalities. (U.S. Department of Transportation 2022)
- The transportation (land, sea, air) economic losses for fog are similar to those of severe weather. (Gultepe et al. 2007)
- Visibility reductions is responsible for majority of weather-related aviation accidents. (Gultepe et al. 2007, 2017)
- Of fatal weather-related aviation accidents, fog and low ceilings are the most prevalent factors. (Capobianco and Lee 2001)



Images showing a multi-car wreck near Jamestown. Photo courtesy of North Dakota Highway Patrol and the Jamestown Sun.

# Types of Fog Dispersal (Abatement)

-40 °C

-20 °C

0 °C

**Ice Fog**

**Ice and  
Supercooled Fog**

**Supercooled  
Fog**

**Warm Fog**

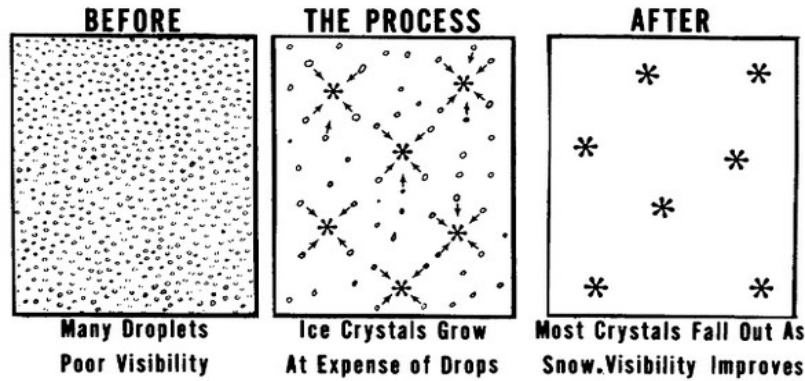
Stable

Metastable

Metastable

Stable

- Dispersal largely preventative.
- Conventional aircraft downwash has limited effectiveness.
- Success is limited to transportation of anthropogenic vapor sources.



Credit: Lease and Zeigler (1972)

Least common, most  
accomplished dispersal  
operationally.

- Most common in the mid-latitudes.
- Physical Removal
  - Sound waves
  - Sprays
  - Air-mass Removal
- Evaporation
  - Heat
  - Hygroscopic Materials

# Conceptual Model for Supercooled Fog Dispersal

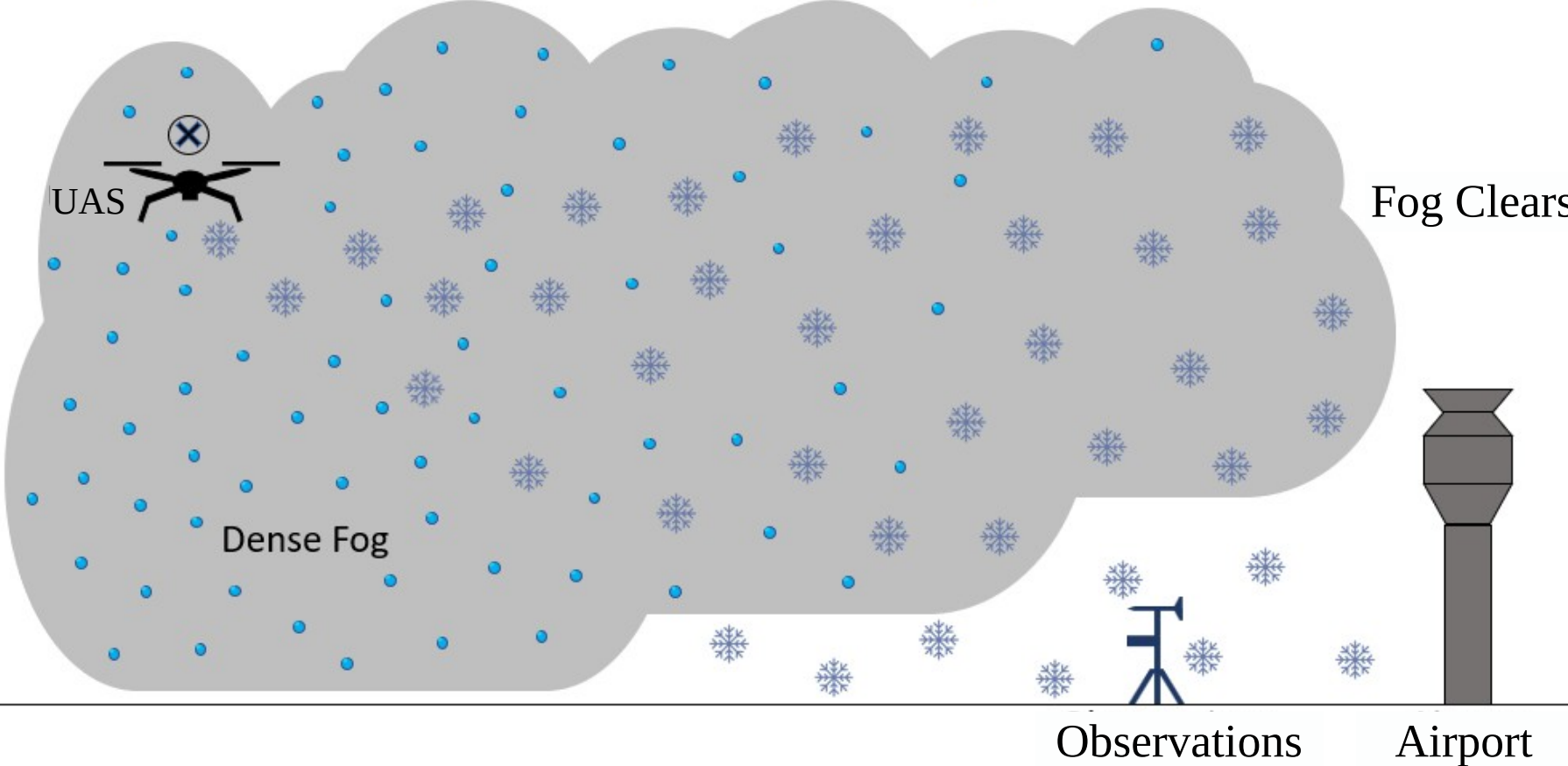
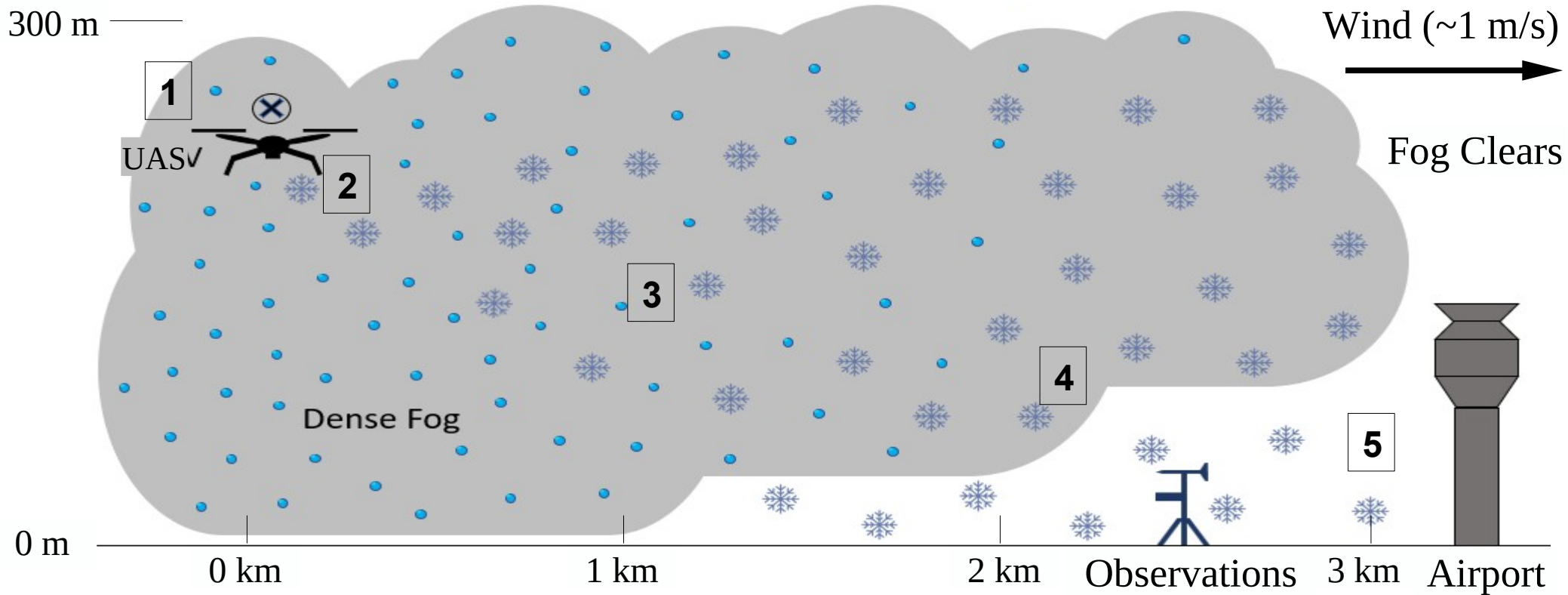


Image illustrating the conceptual model for using Unmanned Aircraft Systems (UASs) to conduct cloud seeding for fog abatement.

# Conceptual Model for UAS Operations



1. UAS flies upwind of airport, just below top of fog layer.
2. UAS releases seeding material that instigating ice crystal growth.
3. Ice crystals grow at expense of droplets.
4. Ice crystals fall through the extent of fog layer.
5. Cloud bases rise and dispersal commences.

# Objectives for UAS Fog Research

- **Research:** Efficacy of the UAS platform to acquire in-situ microphysical data.
- **Abatement:** Feasibility of a supercooled fog dispersal project in the Red River Valley
  - Determine an operational period based on fog climatology.
  - Obtain FAA approval for UAS platform operations.
  - Test an UAS for conducting fog missions.
  - Employ and evaluate miniaturized instrumentation for fog measurements.
  - Conduct UAS platform missions.



Image showing the hexacopter manufacturer by Botlink, which has a 1,620 mm diameter, 25 kg maximum takeoff weight (up to 6 kg payload), and 28 min flight duration.

# Location: North Dakota – Red River Valley

- The Red River Valley was formed by glacial effects.
- Flat smooth, low-elevation terrain
- Rock/sediment deposition along edges
- The intracontinental, high-latitude location allows for seasonal snowpack buildup.

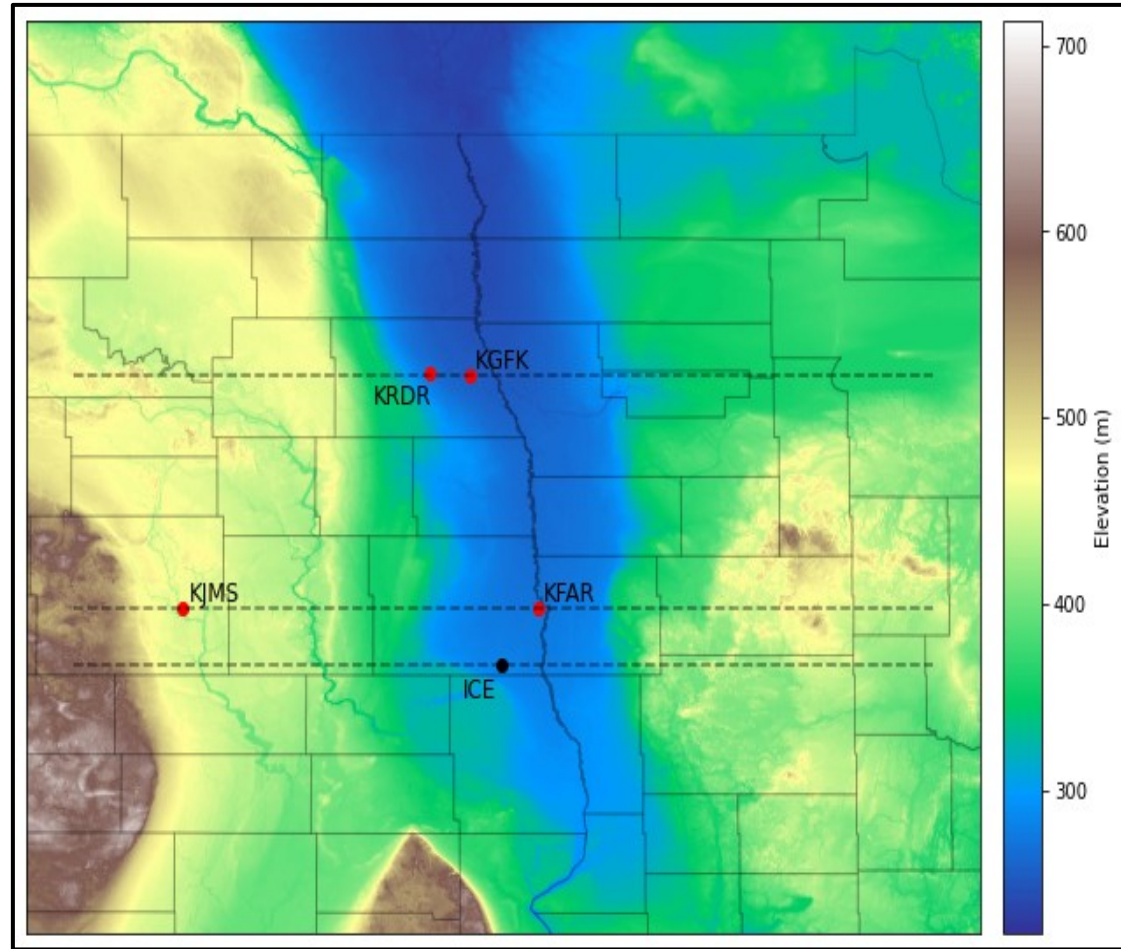


Image showing the topography of the Red River Valley in North Dakota and Minnesota.

# Surface and Flight Station Locations

- **Surface Locations**

- KGFK:
  - Grand Forks International Airport
- KFAR
  - Hector International Airport
- KRDR
  - Grand Forks Air Force Base
- KJMS
  - Jamestown Regional Airport

- **Flight Operations**

- ICE
  - Ice Crystal Engineering

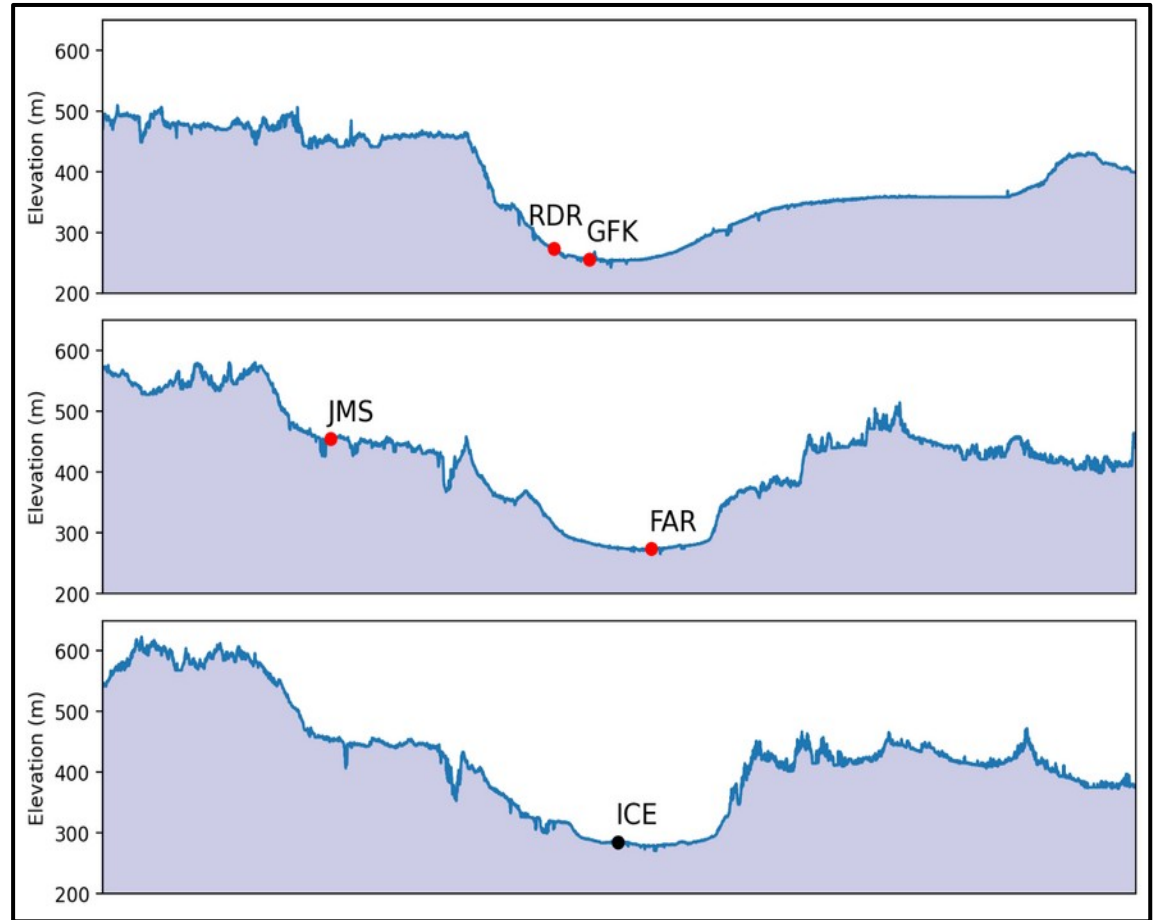
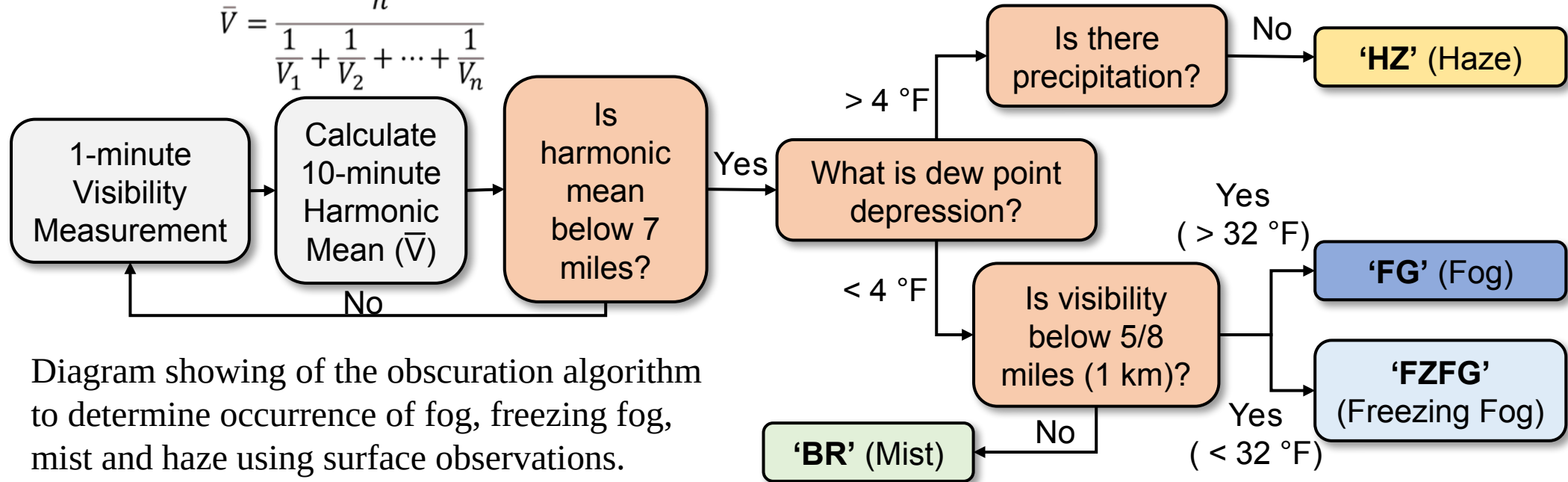


Image showing the location of surface and flight operations stations in terms of elevation in the Red River Valley.

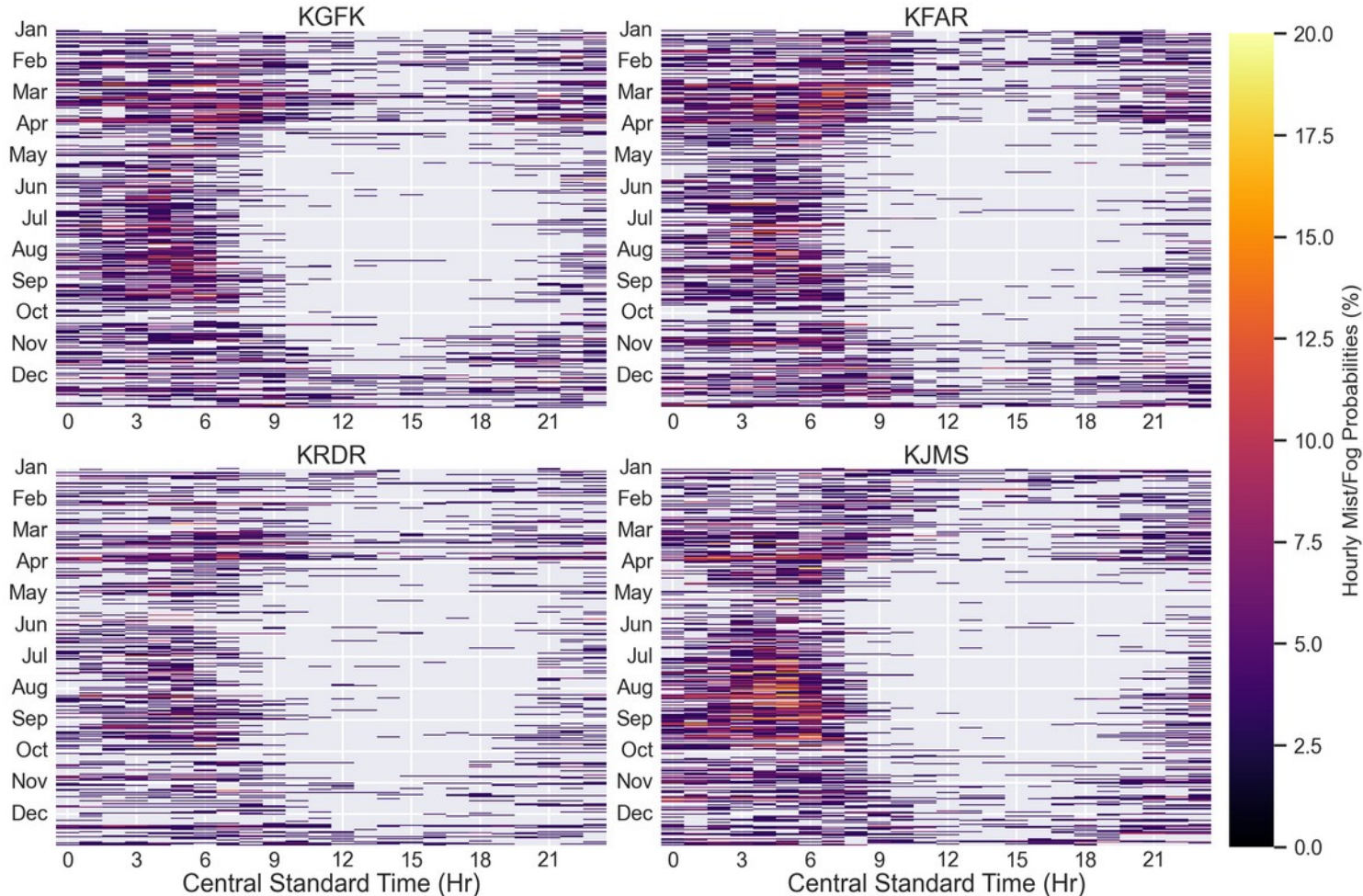
# ASOS Obscuration Algorithm

- 30-year (1989-2019) sampling from ASOS (Automated Surface Observing System)
- Occurrences of fog ('FG') and/or mist ('BR') in present weather are grouped by hour.
- Concurrent hydrometeor occurrences are excluded (i.e. rain, snow, drizzle, etc).
- Only the first occurrence during each hourly period is included.
- Wind (< 10 m/s) and temperature (< 0 °C) thresholds are applied.

$$\bar{V} = \frac{n}{\frac{1}{V_1} + \frac{1}{V_2} + \dots + \frac{1}{V_n}}$$

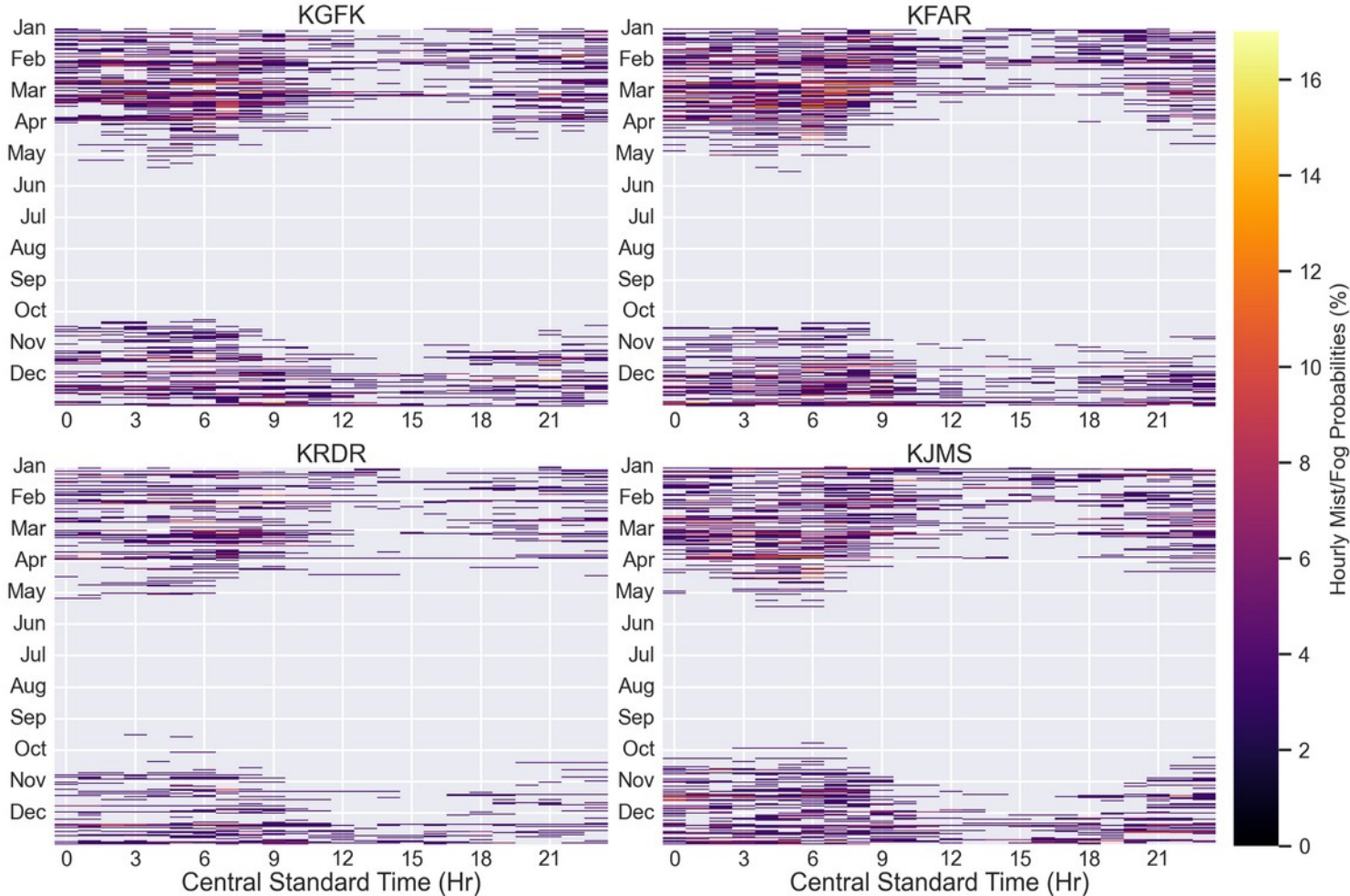


# Low Visibility, Low Wind Speed (Mist/Fog)



- Applied Wind Threshold  $< 10$  m/s
- Wind threshold likely filters out blowing snow events.

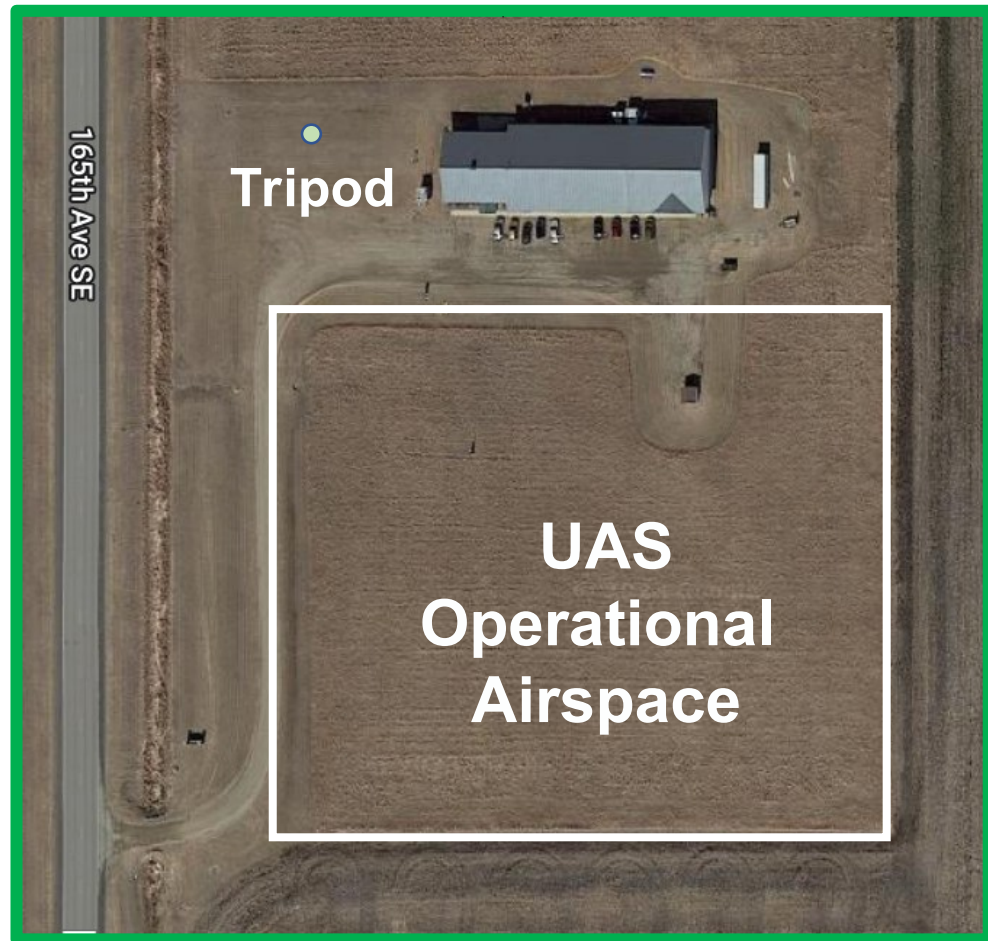
# Low Visibility, Low Wind Speed Supercool (Mist/Fog)



- Applied Wind Threshold  $< 10$  m/s
- Applied Temperature Threshold  $< 0$  °C
- Maximum during March coincides with seasonal snow melt.

# UAS Operational Area (Ice Crystal Engineering)

- FAA UAS Operations Waiver (2 years).
- Located 21 miles SW of Hector International Airport (KFAR).
- Located within the eastern Red River Valley at Ice Crystal Engineering (ICE) headquarters.



# Hexacopter Description and Performance

Diameter	1620 mm
Maximum Takeoff Weight	25 kg
Maximum Takeoff Payload	6 kg
Flight Time Estimates	32.5 min (4 kg Payload) 28.9 min (6 kg Payload)
Battery Capacity	4 x 30,000 mAh
Autopilot	Pixhawk Cube
Radio Control (RC) Controller	2.4 GHz, 8 km range
Datalink	900 MHz, Botlink XRD LTE
Lighting	6x Firehouse ARC XL Strobes
Landing Gear	Fixed and Removable
Arms	Removable
Propellers	29" Lightweight Carbon Fiber



Image showing the Botlink hexacopter flying at ICE during March 2023.

# UAS Instrumentation: IMet-XQ2

- Second-generation radiosonde quality instrument (InterMet Systems)
- Parameters: Temperature, Relative Humidity, Pressure and GPS Location
- Proper aspiration is vital for temperature, relative humidity sensors.

Measurement	Sensor	Range	Accuracy	Resolution	Response
Temperature	Bead Thermistor	-90 – 50 °C	± 0.3 °C	0.01 °C	1.0 s
Humidity	Capacitive	0 – 100 %	± 5 %	0.1 %	0.6 – 10.9 s
Pressure	Piezoresistive	10-1200 hPa	± 1.5 hPa	0.01 hPa	0.01 s
GPS Location	Ublox CAM-M8	0 – 50 km	12 m (vert.)	2.5 m	1.0 s



Credit: InterMet Systems, [intermetsystems.com](http://intermetsystems.com)

# UAS Instrumentation: MiniOFS

- Low-cost miniaturized instrument.
- Optical receiver is sensitive to backscattered light around 25 cm.
- Sensitive to direct solar radiation; easy oversaturation.
- Visibility measurements up to 4000 m.

<b>Analog Output</b>	Analog 0-5 Volt
<b>Digital Output</b>	RS 232
<b>Update Time</b>	30 s
<b>Warmup Time</b>	60 s
<b>Operational Range</b>	-20 °C to +50 °C
<b>Visibility Range</b>	20 m to 4,000 m
<b>Wavelength</b>	850 nm
<b>Housing</b>	Anodized Aluminum



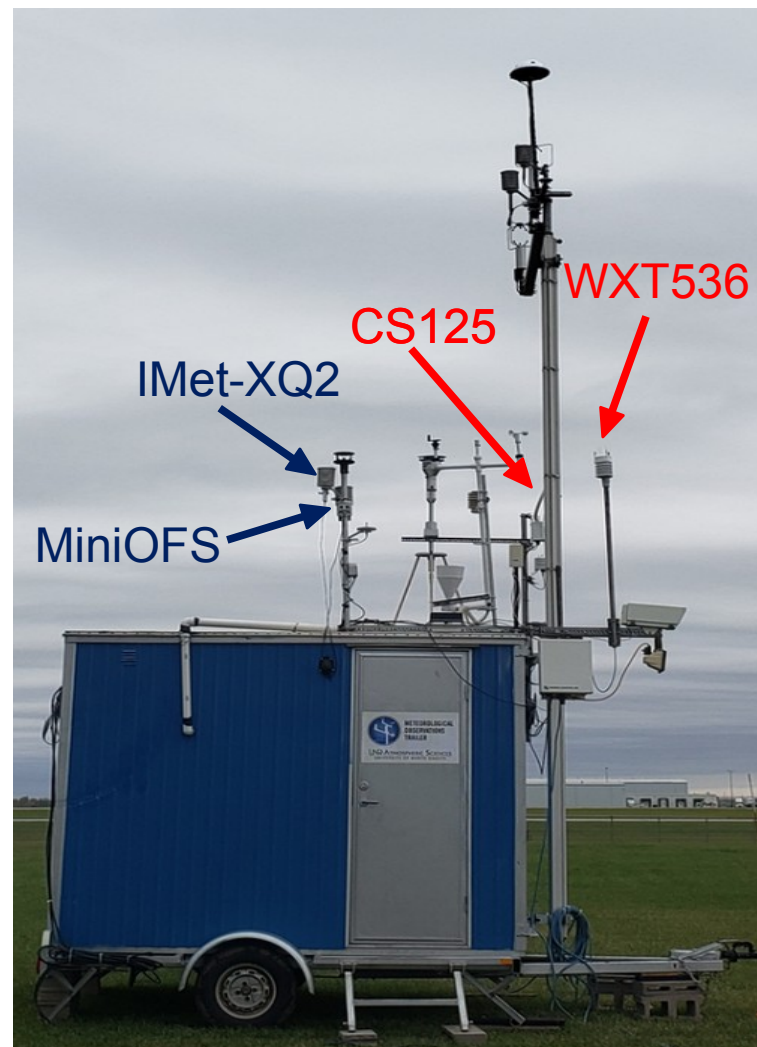
Credit: Optical Sensor Inc.

# Miniaturized UAS Instrumentation Comparison

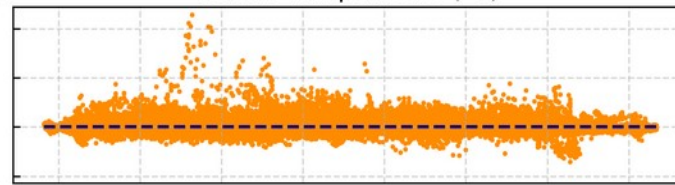
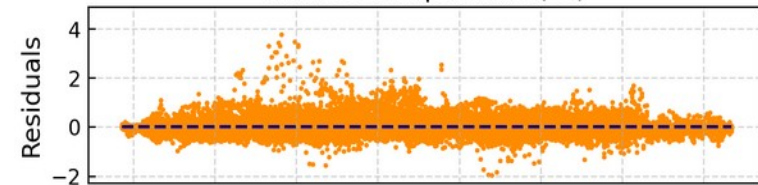
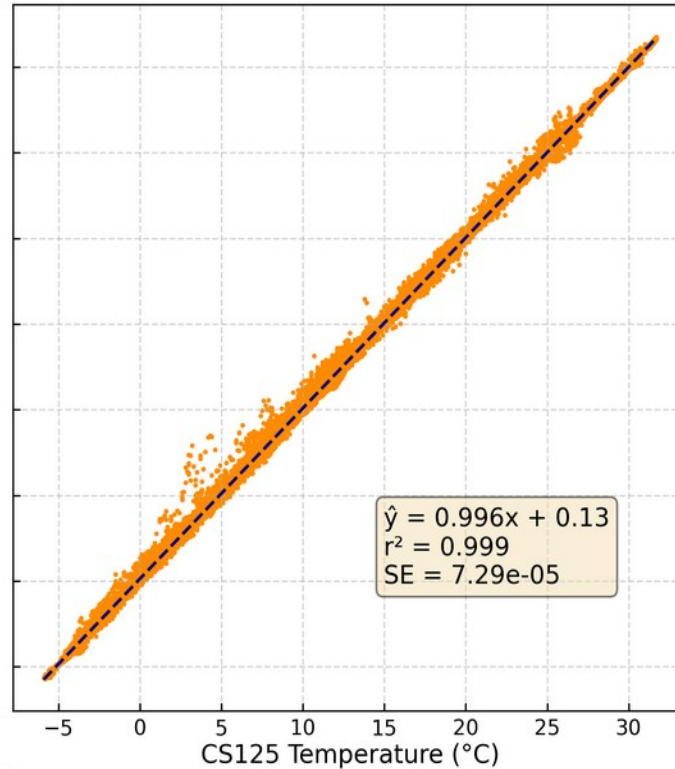
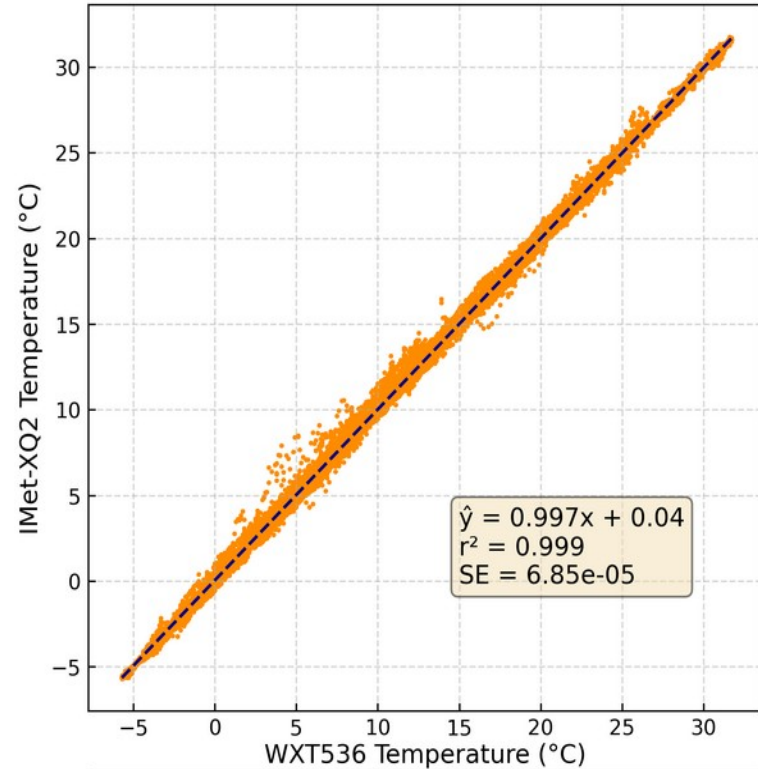
- Sampling period was from September 1st, 2021 to December 9th, 2021

Response (Dependent) vs. **Predictor (Independent)**

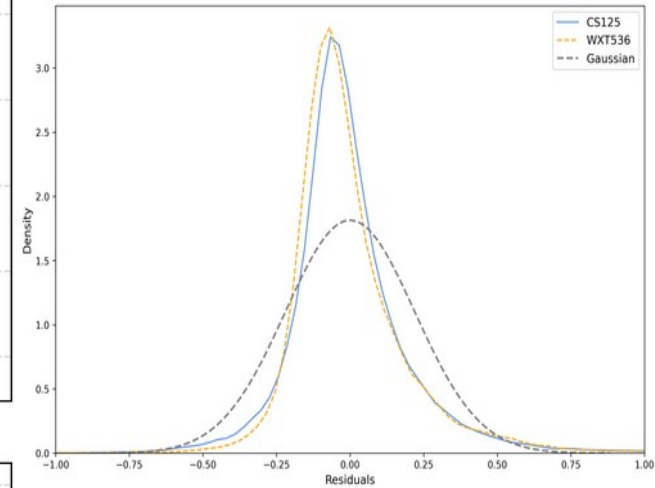
	Temperature	Relative Humidity	Visibility
IMetXQ2	Yes	Yes	No
MiniOFS	No	No	Yes (Backwards Scattering)
<b>WXT536</b>	Yes	Yes	No
<b>CS125</b>	Yes	Yes	Yes (Forward Scattering)



# IMet-XQ2 Temperature Sensor Comparison

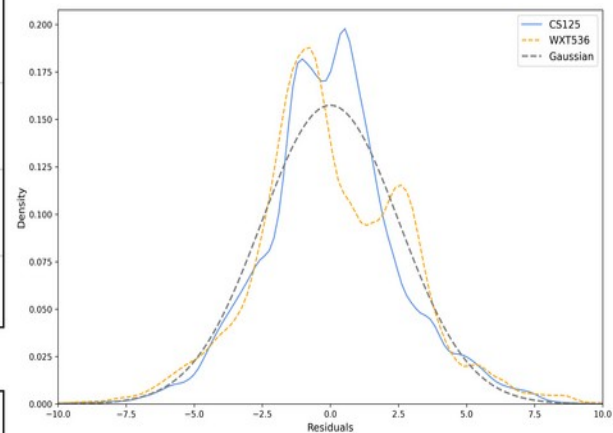
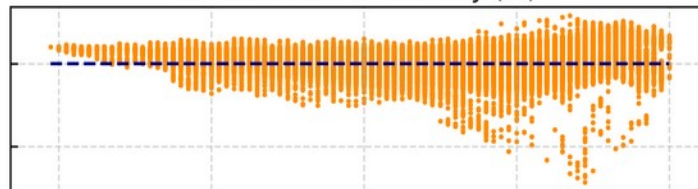
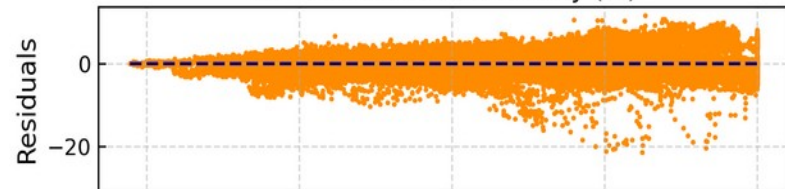
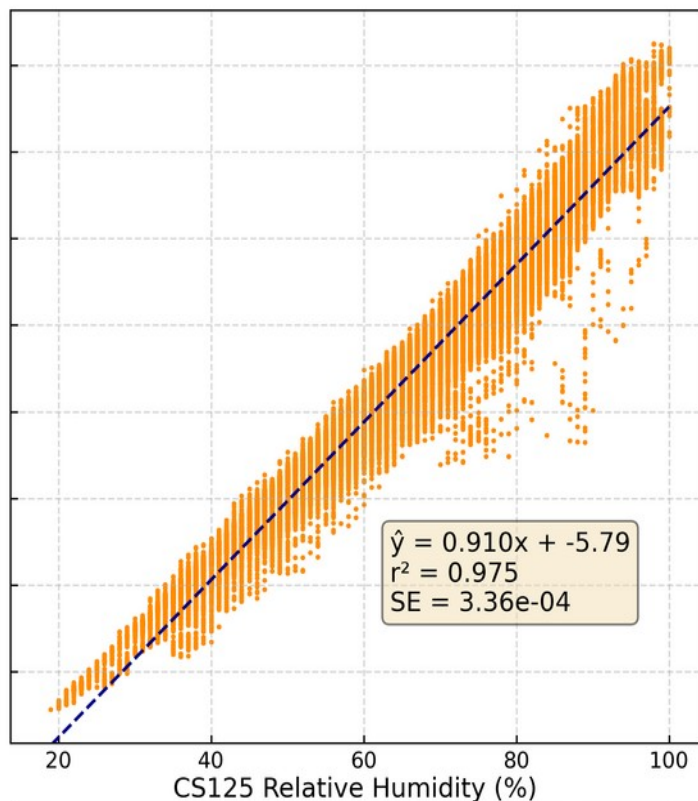
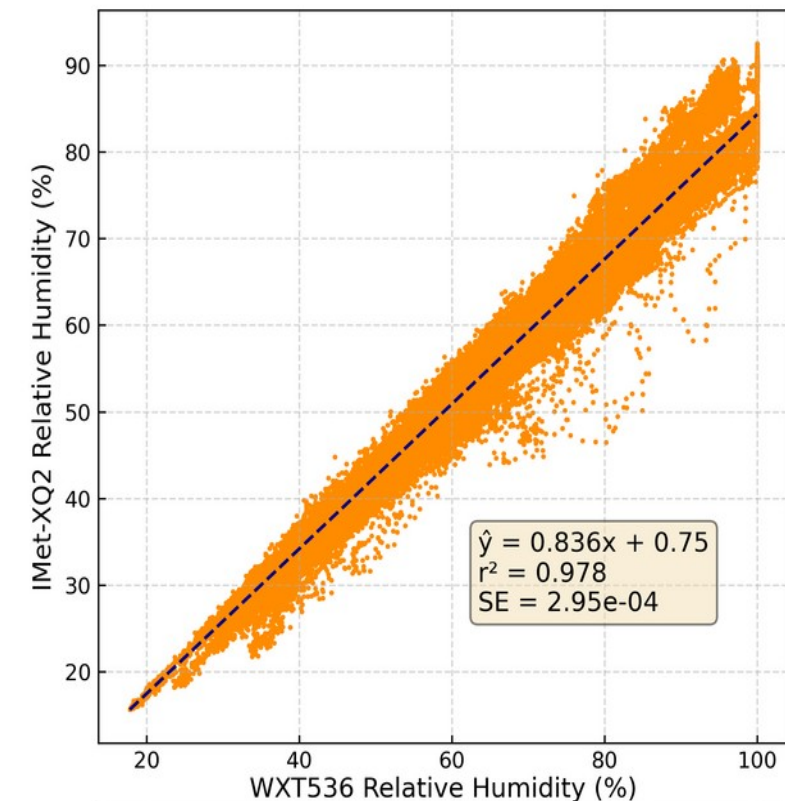


**Takeaway:** The IMet-XQ2 temperature sensor displays high accuracy and precision.



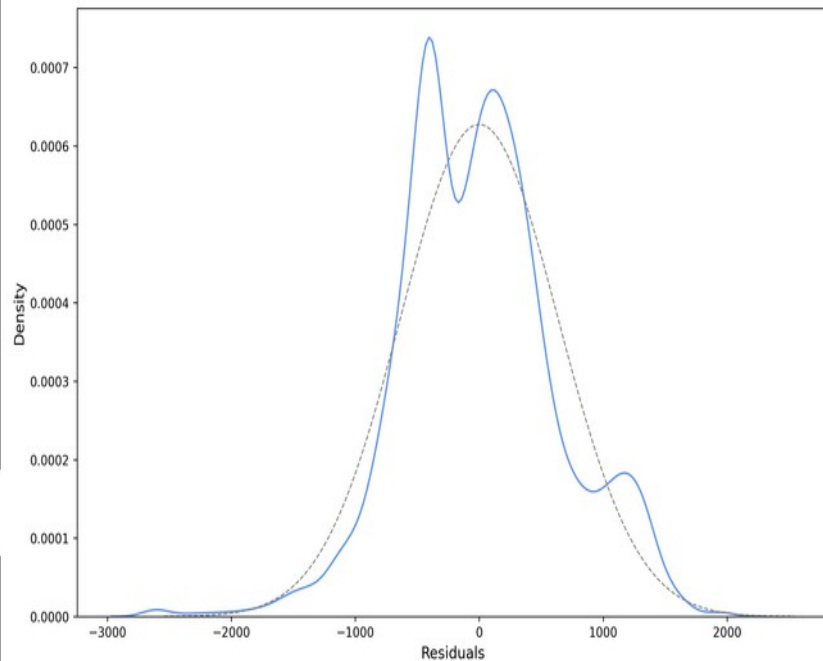
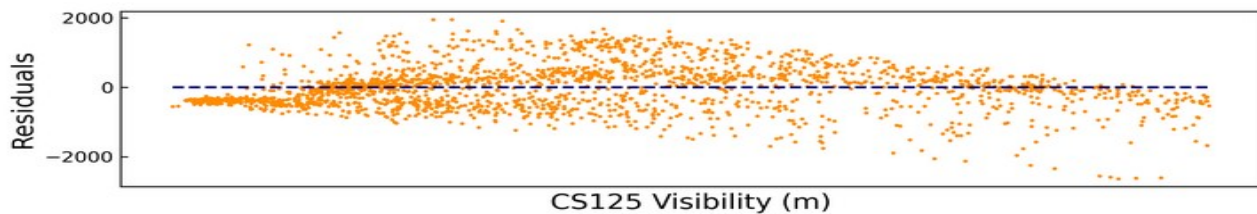
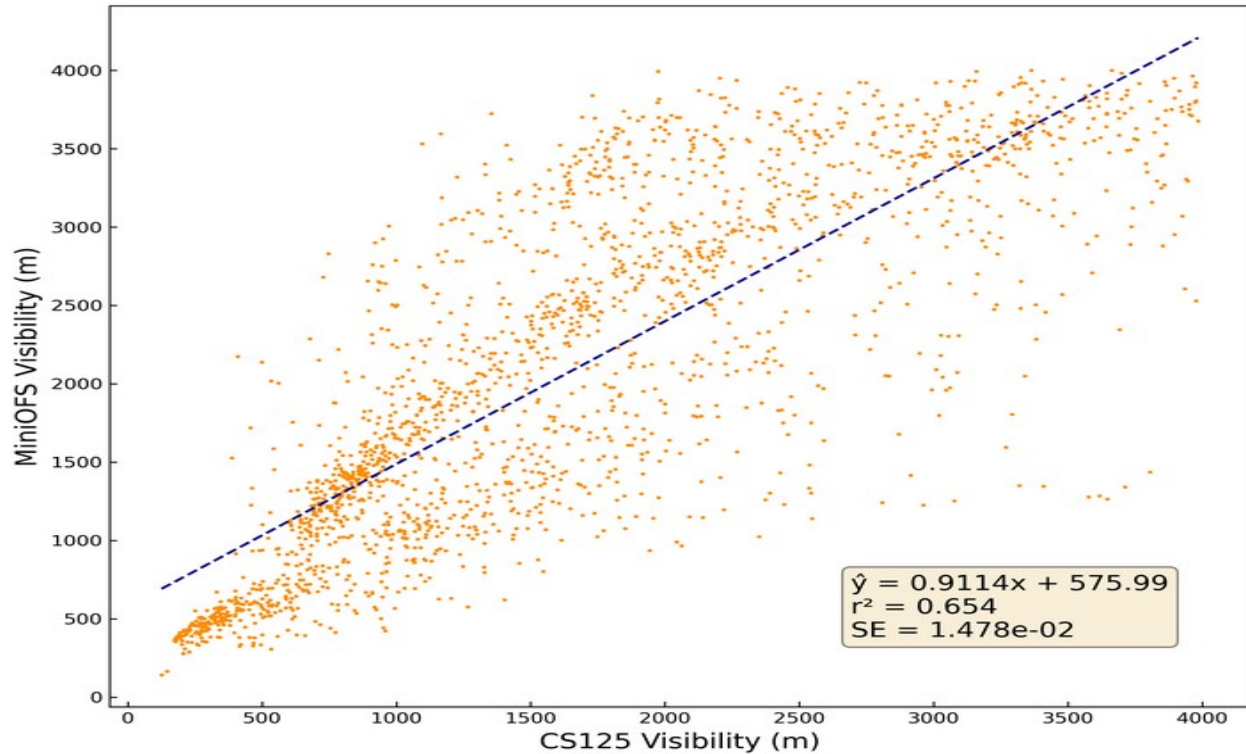
# IMet-XQ2 Relative Humidity Sensor Comparison

**Takeaway:** The IMet-XQ2 RH sensor consistently underestimates. Increased variability of measurements.



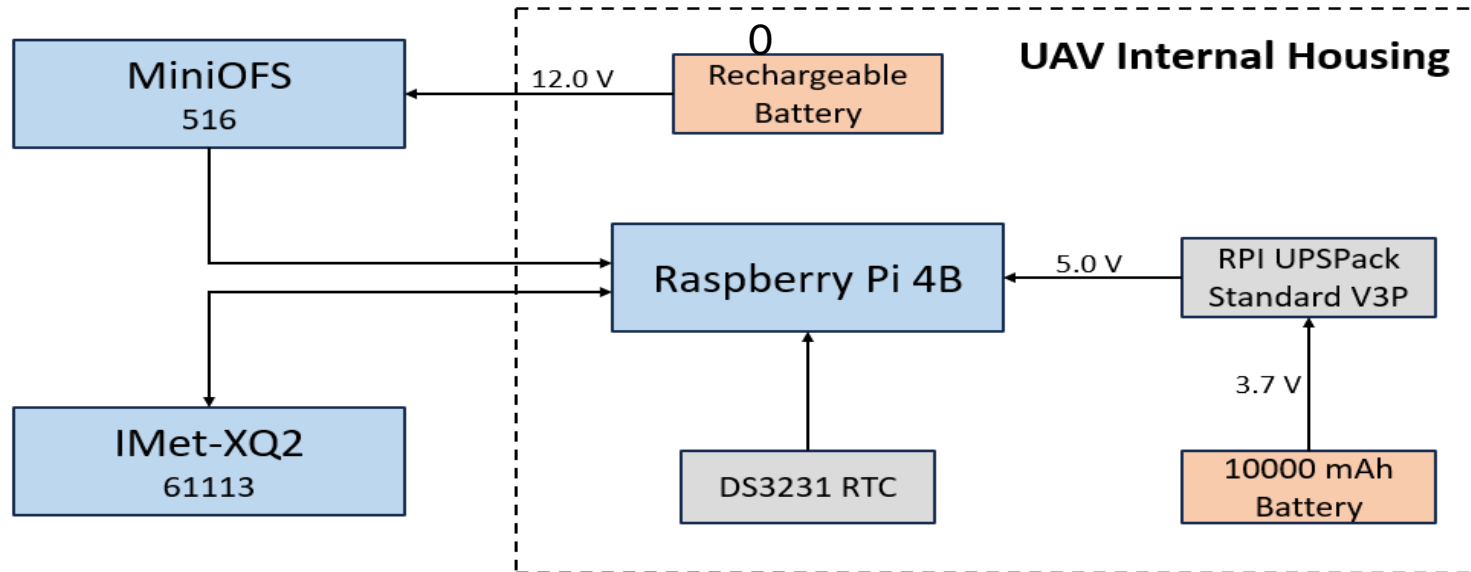
# MiniOFS Visibility Sensor Comparison

**Takeaway:** Poorer correlation.  
MiniOFS has larger visibility than CS125.

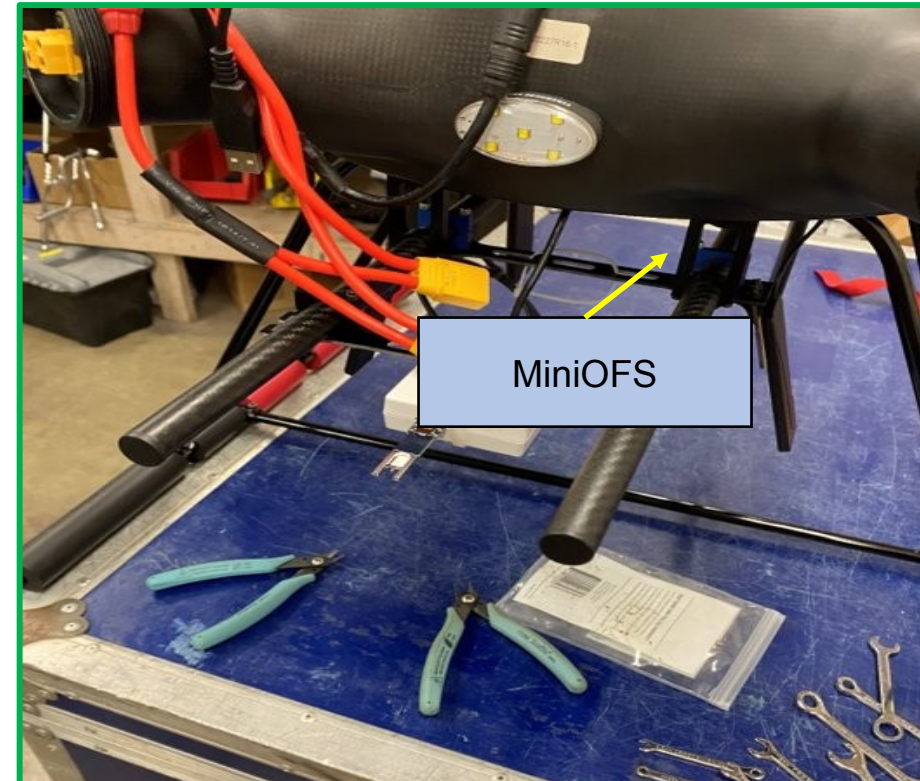
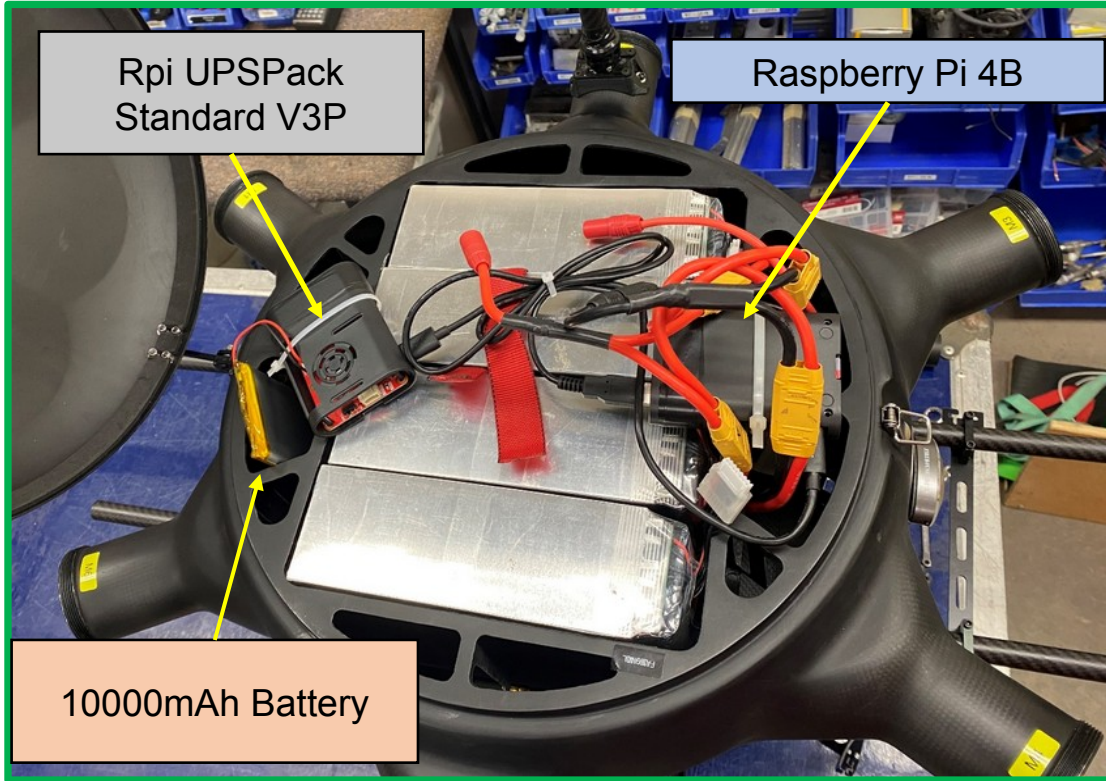


# Equipment Deployed on UAS Platform

- Instrumentation: IMet-XQ2, MiniOFS
- Raspberry Pi 4B: Stores instrument data
- DS3231: Real-time clock module
- 10000 mAh Battery: Power Instrument System
- Rpi UPSPack Standard V3P: Converts 3.7V to 5V
- Rechargeable Battery: Power source for MiniOFS.



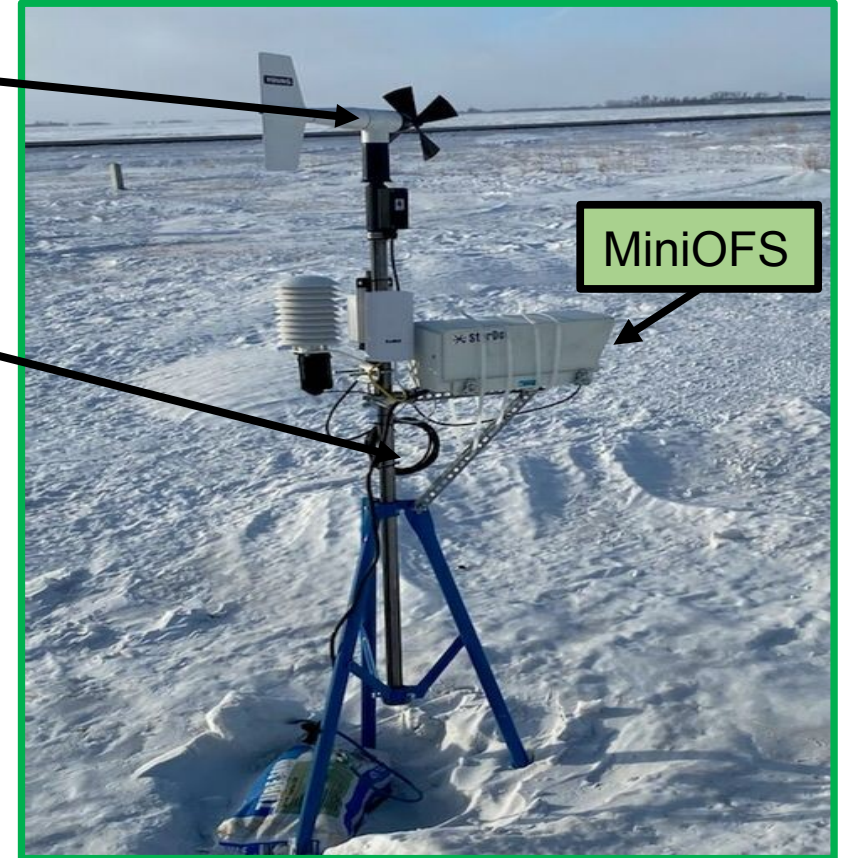
# Instrument Integration with UAS Platform



Images showing the integration of instrument and equipment on the Botlink hexacopter for deployment in fog during field operations in March 2023.

# Surface Instrument: Tripod System

- ***Young Anemometer***
  - Wind Speed
  - Wind Direction
- ***IMet XQ2 UAV Sensor***
  - Pressure
  - Temperature
  - Humidity
- ***MiniOFS Optical Sensor***
  - Visibility
  - Solar Irradiance
  - Extinction Coefficient

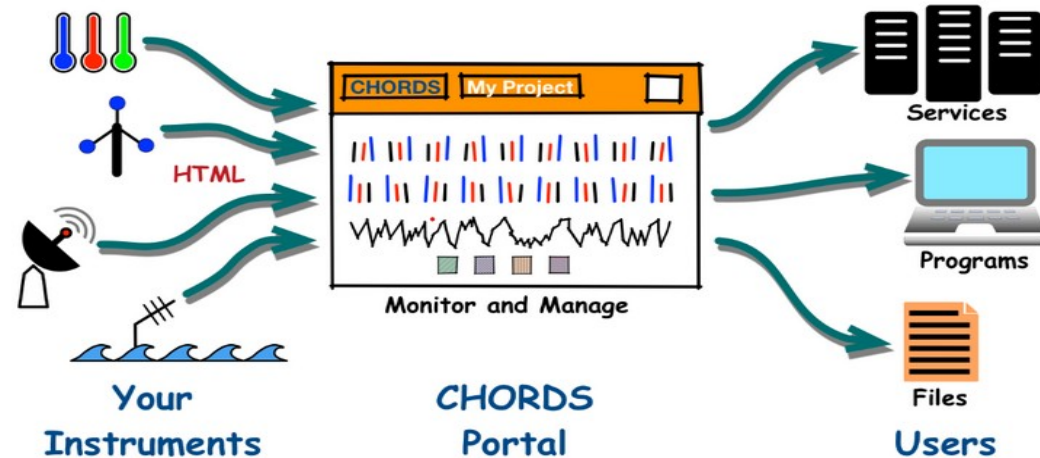


Images showing the tripod mounted instruments deployed at Ice Crystal Engineering during the March 2023 field project.



# Data Acquisition and Real-time Display

- All instrument data is recorded and stored on a Raspberry Pi 4B on both platforms.
- Python-based instrument acquisition scripts available through the Airborne Data Processing And Analysis (ADPAA) software package.



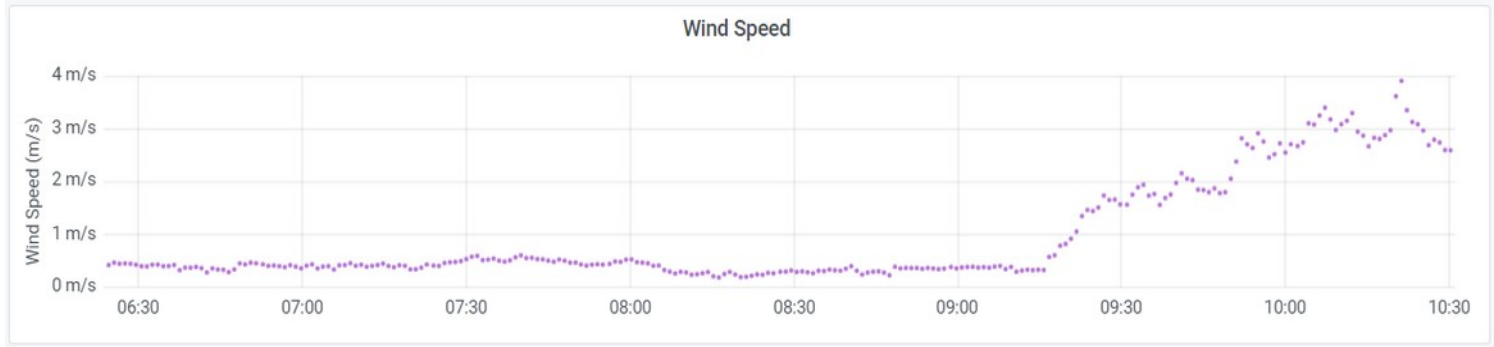
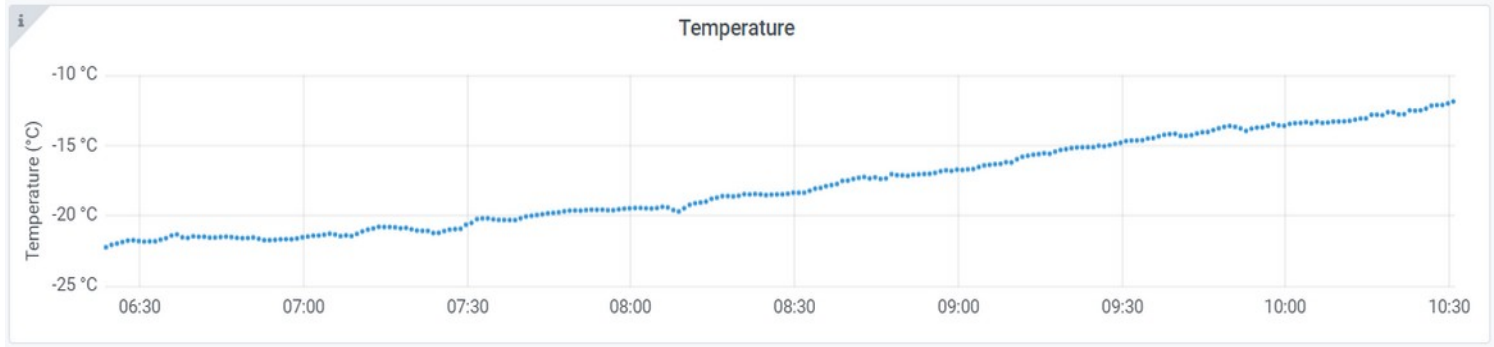
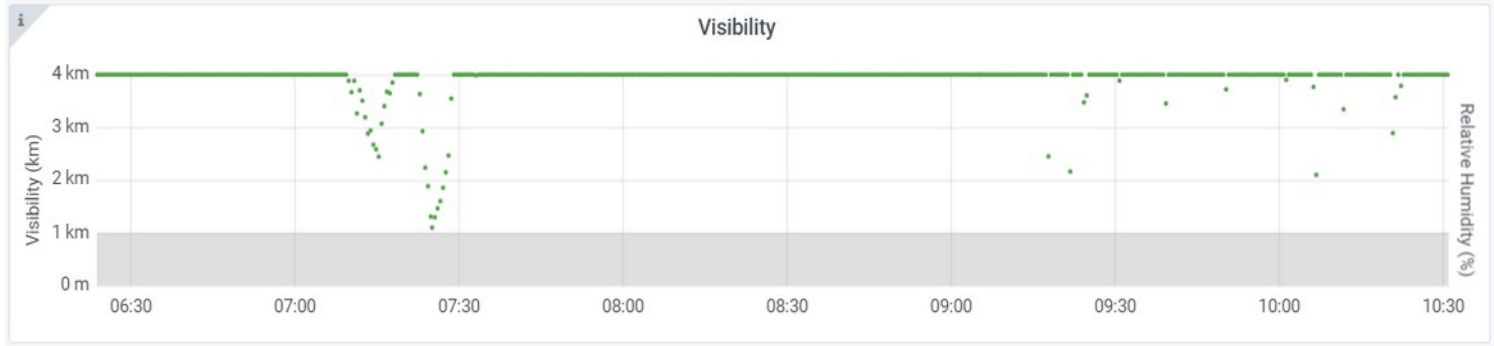
Instrument	Baudrate	Data Bits	Parity	Stop Bit	Sampling
IMet-XQ2	57,600 bits/s	8	No	1	1 s
MiniOFS	1,200 bits/s	8	No	1	30 s
Young	9,600 bits/s	8	No	1	1 s



# UAS Field Project Mission Summary

Date	Visibility Conditions	Vertical Profiles	Surface Wind Speed	Ascent Start	Ascent End	Descent Start	Descent End	Instrument Status
3/7/2023	No Fog	1	~ 5.0 m/s	17:59:48	18:00:58	18:01:12	18:02:54	Both
3/13/2023	No Fog	2	~ 1.0 m/s	15:14:26	15:18:03	15:18:21	15:22:42	Both
				15:22:50	15:26:36	15:27:00	15:32:07	
3/15/2023	Elevated Fog	4	< 0.5 m/s	08:07:28	08:10:12	08:10:27	08:15:15	MiniOFS only
				08:16:29	08:18:16	08:18:39	08:23:46	
				08:46:32	08:49:28	08:50:35	08:53:43	
				08:52:49	08:55:16	08:55:00	08:56:16	

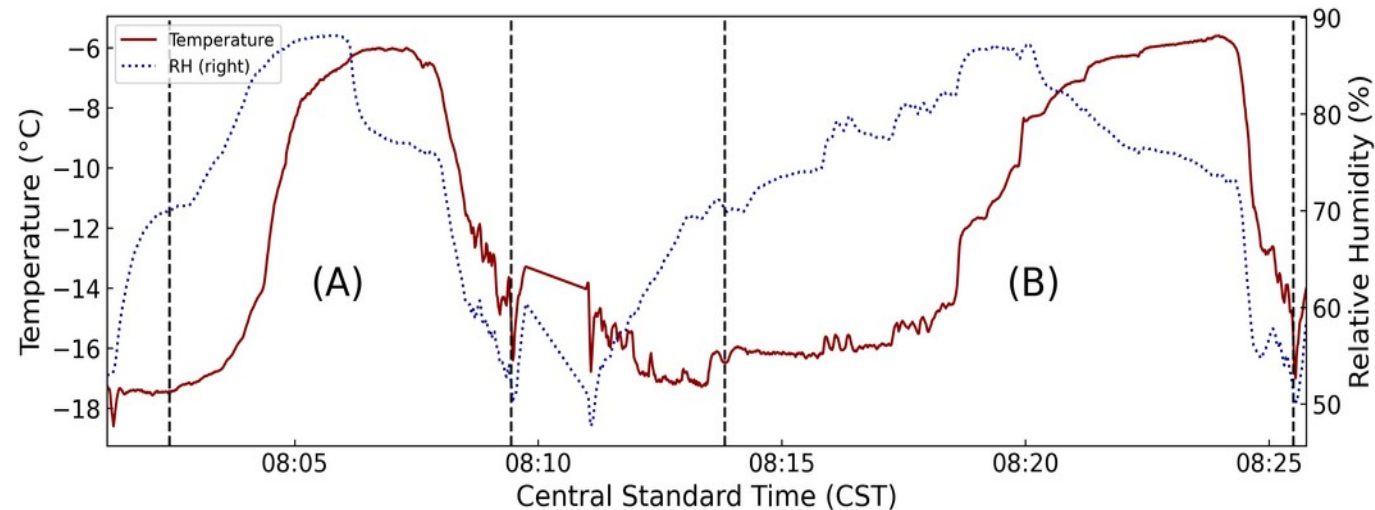
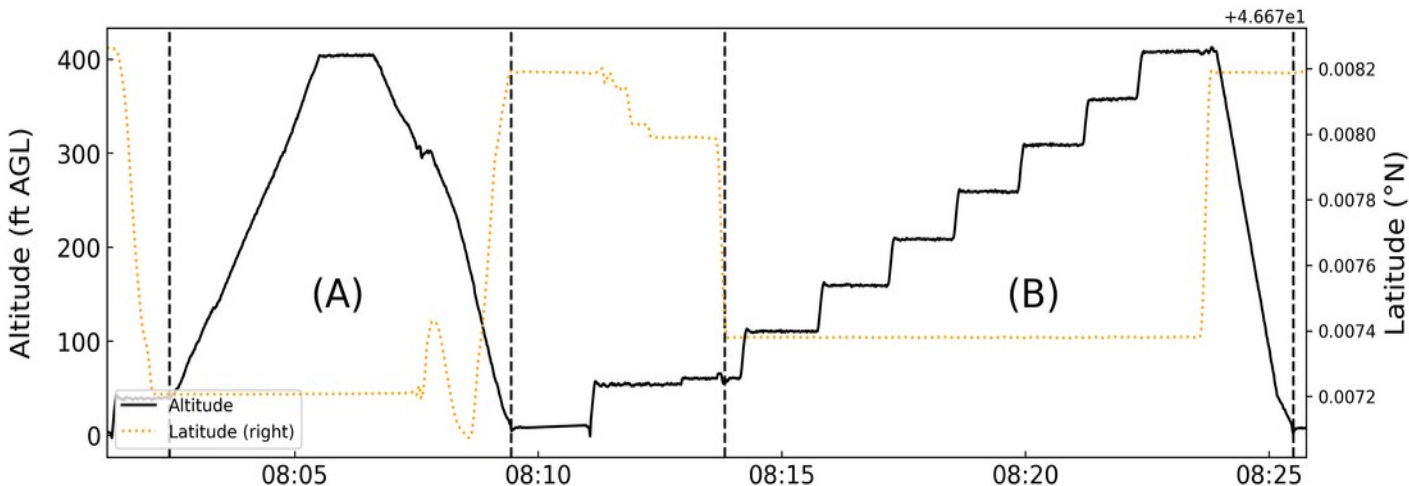
# March 24<sup>th</sup> 2023 Fog Event: Surface Measurements



**Takeaway:**

- Fog/cloud layer not captured within surface observations.

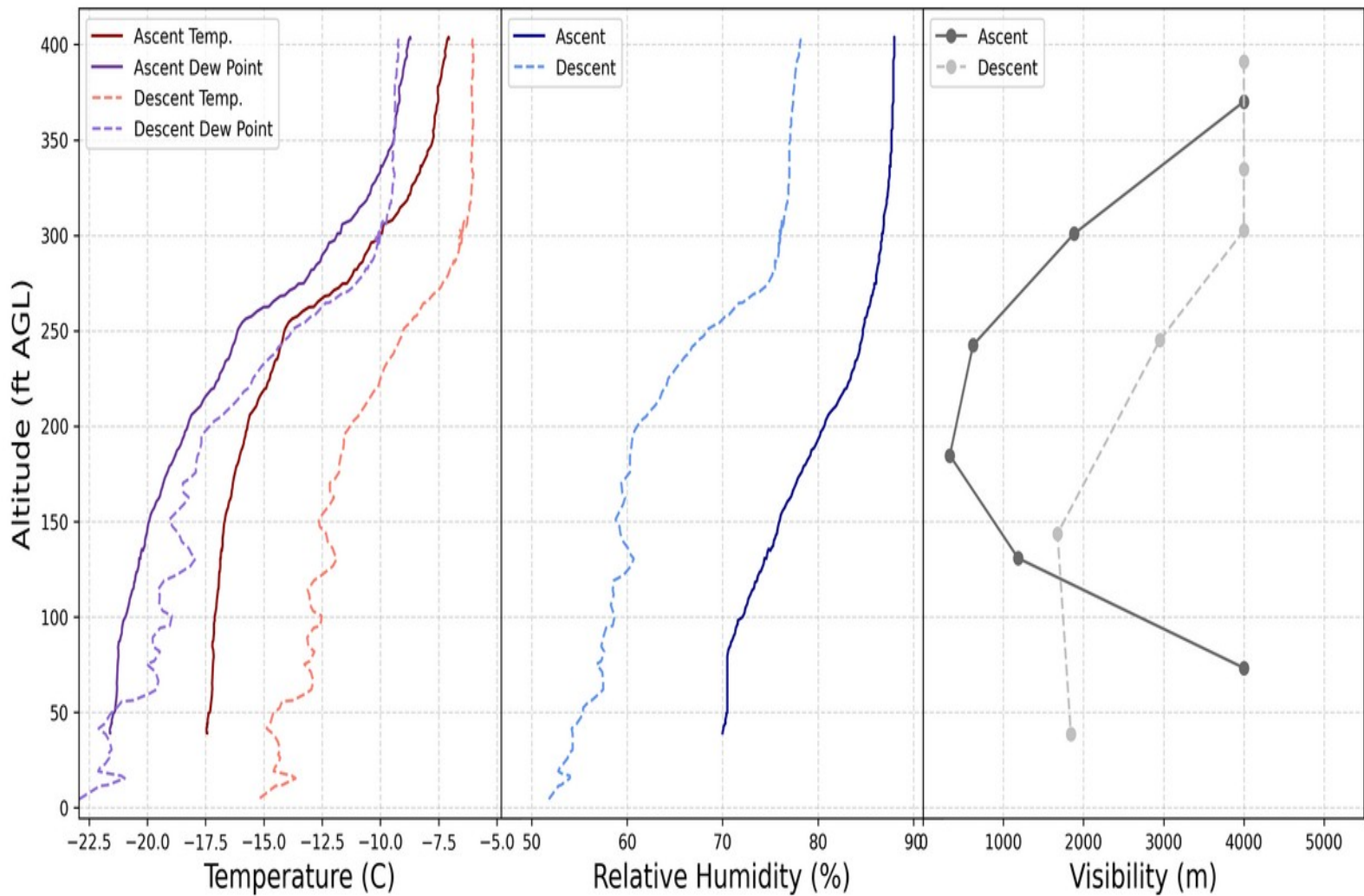
# March 24<sup>th</sup> 2023 Fog Event: UAS Mission



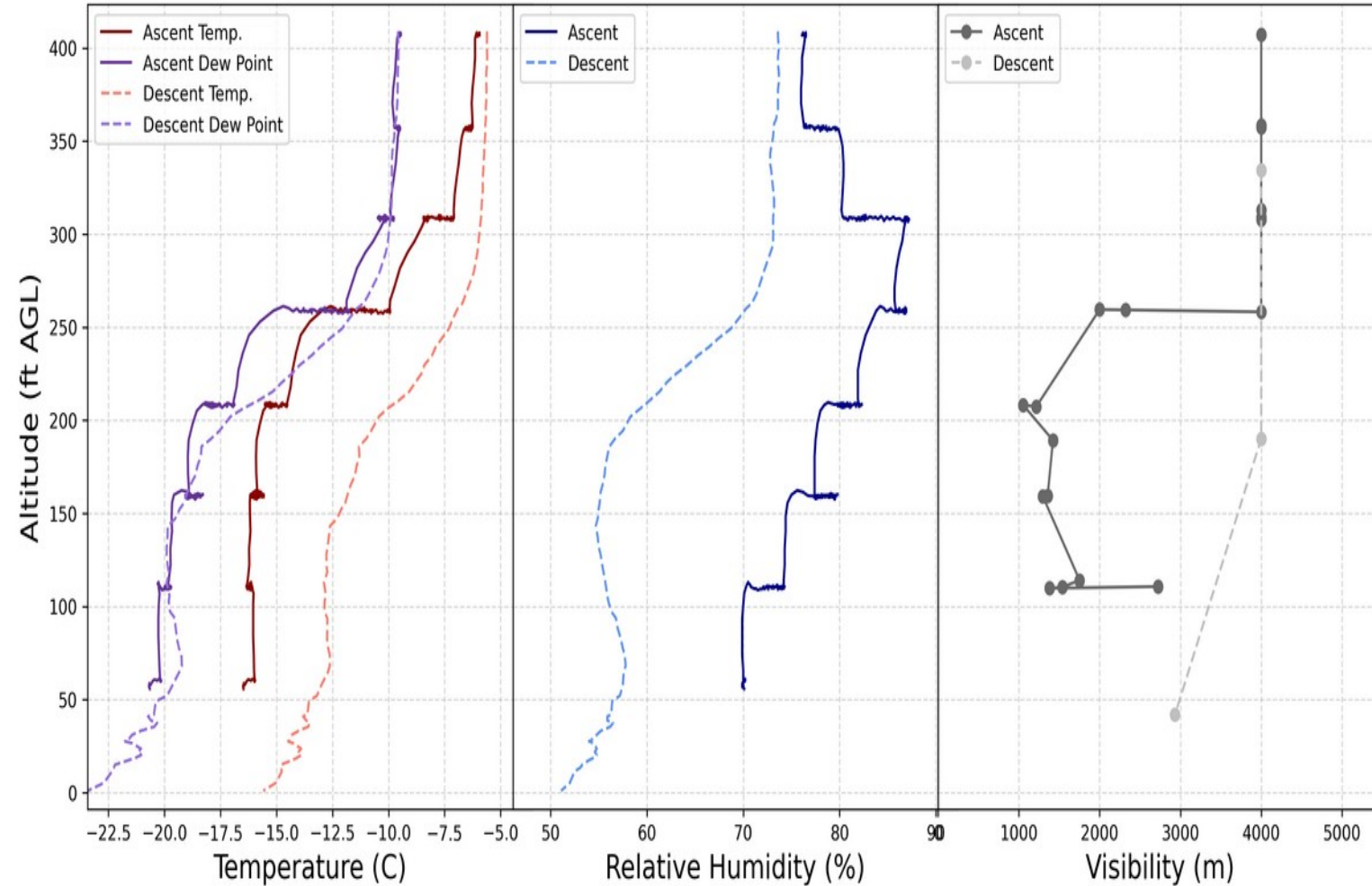
## Takeaway:

- Ascent during vertical profiling maneuver in B used hovering periods to sample specific altitudes

# March 24<sup>th</sup> 2023 Fog Event: Vertical Profile A



# March 24<sup>th</sup> 2023 Fog Event: Vertical Profile B



## Takeaways:

- Elevated nature of cloud layer not captured on ground-based station.
- Cloud layer depth 100 – 250 ft AGL.
- Inversion observed at top of fog layer.

# Summary of UAS Field Project Missions

- The UAS platform performed remarkably well during low visibility and supercooled conditions.
- Vertical Profiling Maneuvers
  - High resolution profiling of boundary layer.
  - Successful identification of the top of multiple fog layers (constrained by 400 ft AGL limit).
  - Discrepancies in temperature/relative humidity profiles are related to sensor aspiration, sensor response times, heat contamination issues.
  - While significant ice buildup occurred, no noticeable performance degradation was observed
- Racetrack Maneuvers
  - Response of temperature sensor reveals UAV speed/direction bias.

# Feasibility of the Red River Valley

- A potential operational period of supercooled fog occurs from November through the beginning of April; peaking in March.
- Successful targeting of supercooled fog required appropriate forecasting days prior to the onset of event.
- UAS platform sufficient in determination of top of fog layer for efficient abatement methods.
- The bigger question: Does supercooled fog occur often enough?

KGFK	"FG" and/or "BR"		"FG" only	
	All (hours/year)	$\leq 0$ °C (hours/year)	All (hours/year)	$\leq 0$ °C (hours/year)
$\leq 10$ m/s	129	61	80	37
$\leq 7.5$ m/s	88	41	54	24
$\leq 5.0$ m/s	53	24	32	14