Evaluation of the Water Content Measurement Model 3000 Probe (WCM-3000) Using the NASA IMPACTS Dataset

Jennifer Moore

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Committee Members: Dr. David Delene, Dr. Jared Marquis, Prof. Michael Poellot

LIQUID WATER CONTENT (LWC)

The amount of liquid water contained in a unit volume of air
Units: g/m^3

History of Hot-wire Probes

Johnson-Williams Probe

1950's

Izmeritel Vodnosti Oblakov (IVO) '1st generation Nevzorov'

1970's

PMS King Probe

Nevzorov '2nd generation'

1990's

2000's

SEA WCM-2000

SEA WCM-3000

2010's

Other instrumental methods used to measure LWC:

- Forward Scattering Probes
- Optical Imaging Probes
- Evaporative Probes

MOTIVATION

What are LWC measurements used for?

- Aviation
  - Aircraft icing
  - Performance testing
- Icing Tunnel Research
- Verification purposes
  - Model studies
  - Remote sensing instruments
- Cloud Process Studies
  - IMPACTS data users

Ice accumulating on the nose of the NASA P-3 aircraft | Feb. 28, 2023

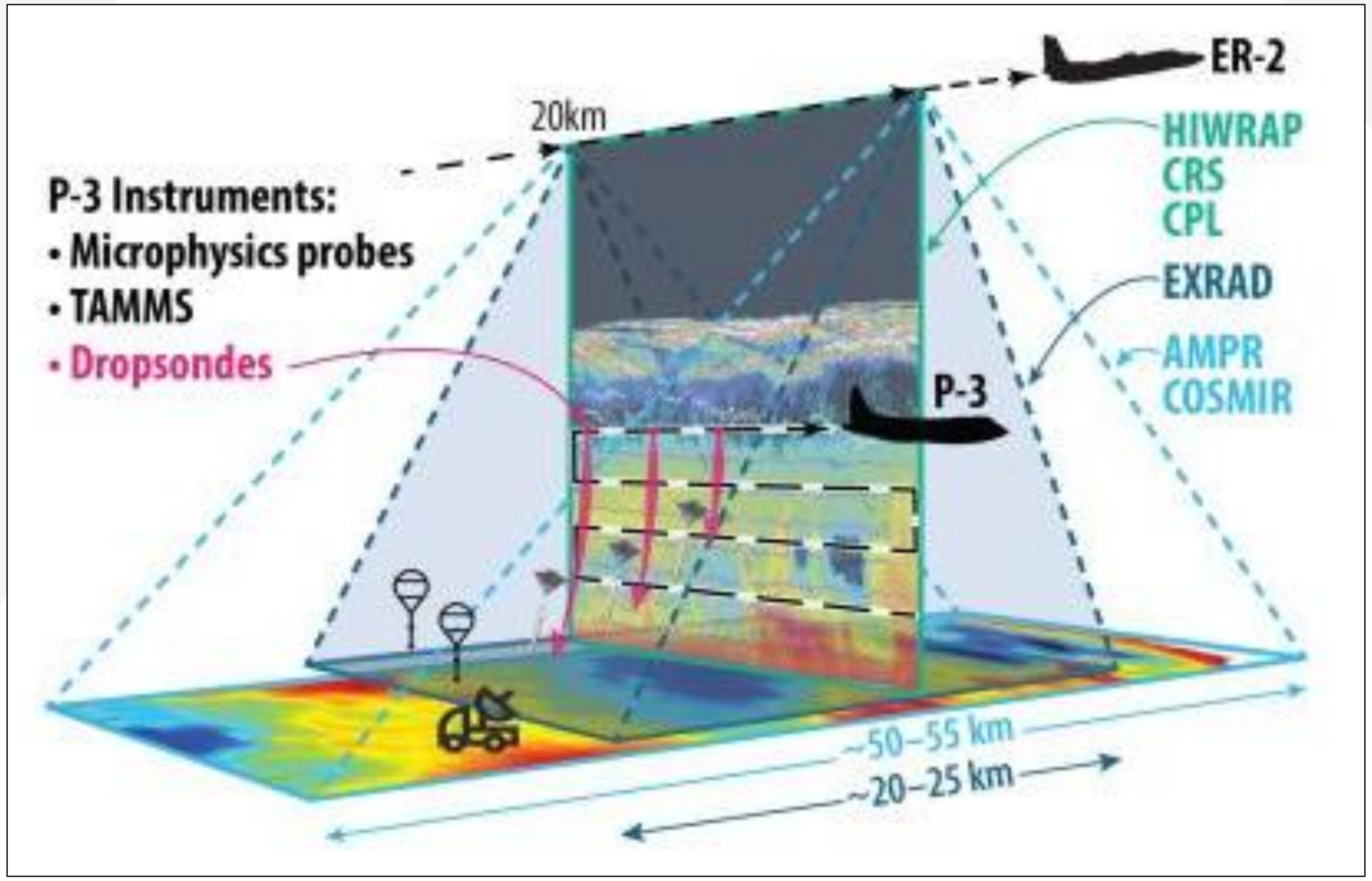
THESIS OBJECTIVE

To determine if the WCM-3000 values agree with the other probes within their measured uncertainties?

- What are some reasons to have instrument comparisons?
  - Determining instrument limitations
  - Interpreting measurements from different probes
  - Historical preservation
- Comparison is made using the NASA IMPACTS data set

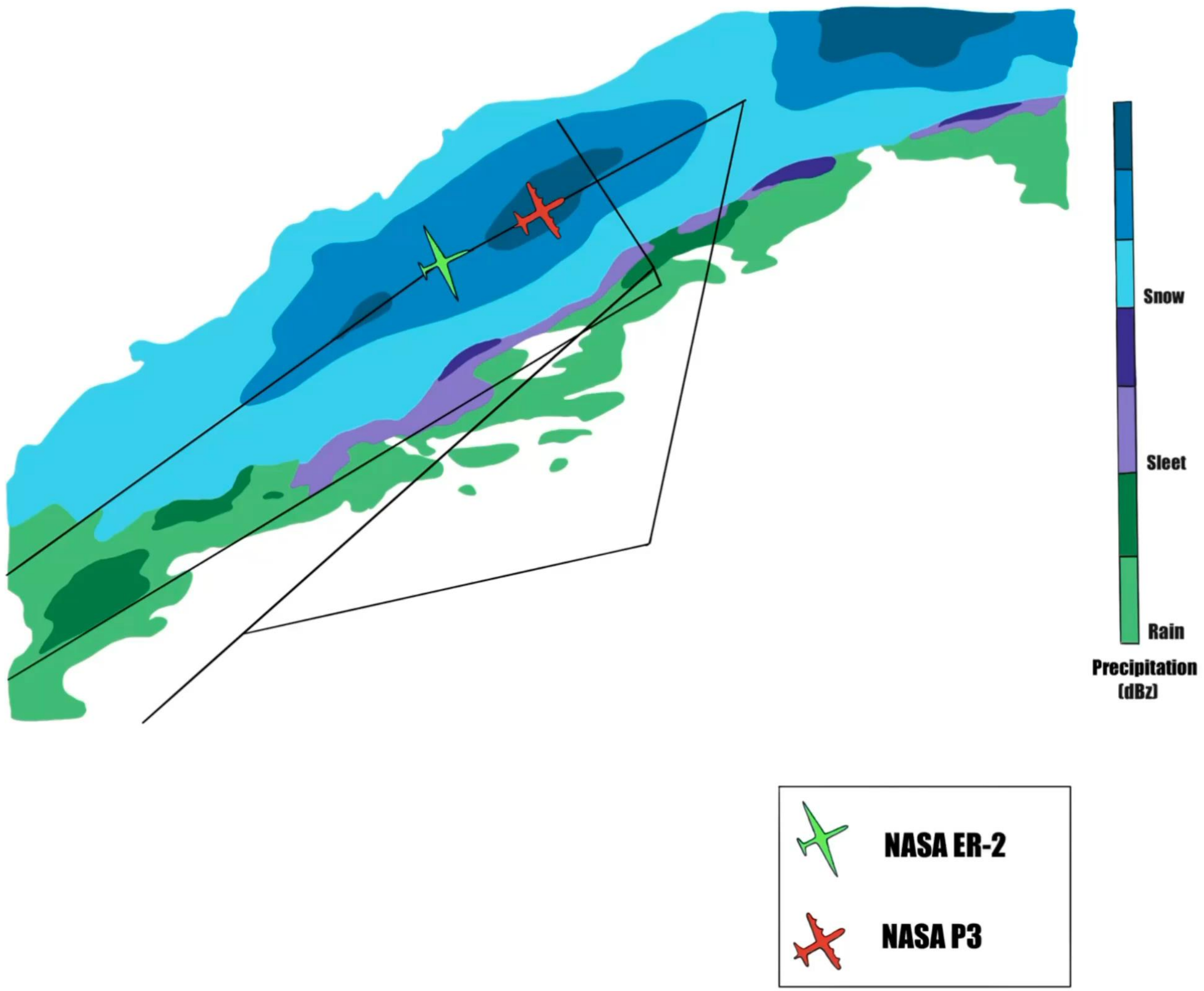
IMPACTS FIELD CAMPAIGN

- **I**nvestigation of **M**icrophysics and **P**recipitation in **A**tlantic **C**oast **T**hreatening **S**nowstorms
- NASA ER-2 – remote sensing
- NASA P-3 – microphysical/environmental
- Ground observations
- Coordinated flight legs



McMurdie et al., 2022

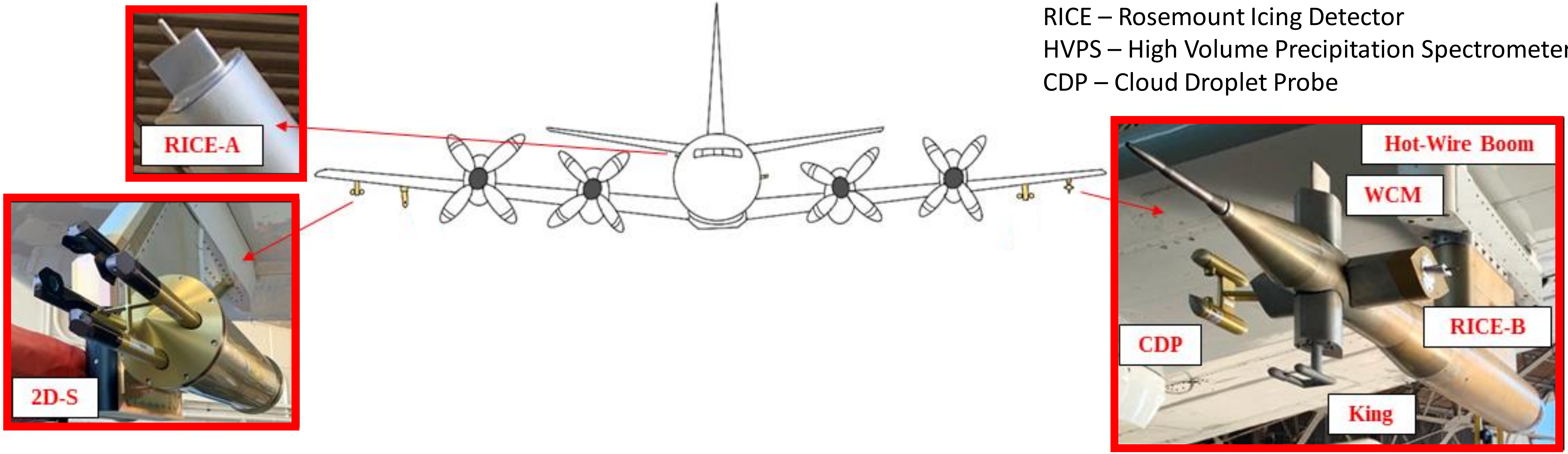
Goal: To better understand the precipitation process of winter storms (McMurdie et al., 2022)



Snow
Sleet
Rain
Precipitation (dBz)
NASA ER-2
NASA P3

P-3 MICROPHYSICAL INSTRUMENTS

2D-S – Two Dimensional stereo probe
RICE – Rosemount Icing Detector
HVPS – High Volume Precipitation Spectrometer
CDP – Cloud Droplet Probe



- Measurement size range overlap from 2 µm – 19.2 mm
- Measurement Methods: Forward scattering, hot-wire, optical imaging, vibrating cylinder

HOT-WIRE PROBES

- Droplet size range: 5 – 200 µm
- Wire is heated to a specific temperature
  - King : 185 °C
  - WCM : 140 °C
- Wire is maintained at the specific temperature by supplying enough power
- Wire is cooled by airflow, water evaporating, radiation, etc.
- Derive LWC from power

In this study, the WCM-3000 is compared to the King and CDP

HOT-WIRE PROBE THEORY

- Heat Transfer: heat loss from conduction, convection, and/or radiation
- Power supplied to the wire is represented by a dry term (P_{dry}) and wet term (P_{wet})

$$P_{total} = P_{dry} + P_{wet}$$

- Dry term – heat loss from mechanisms that cool the wire other than the evaporation of water
- Wet term – heat loss from the evaporation of water

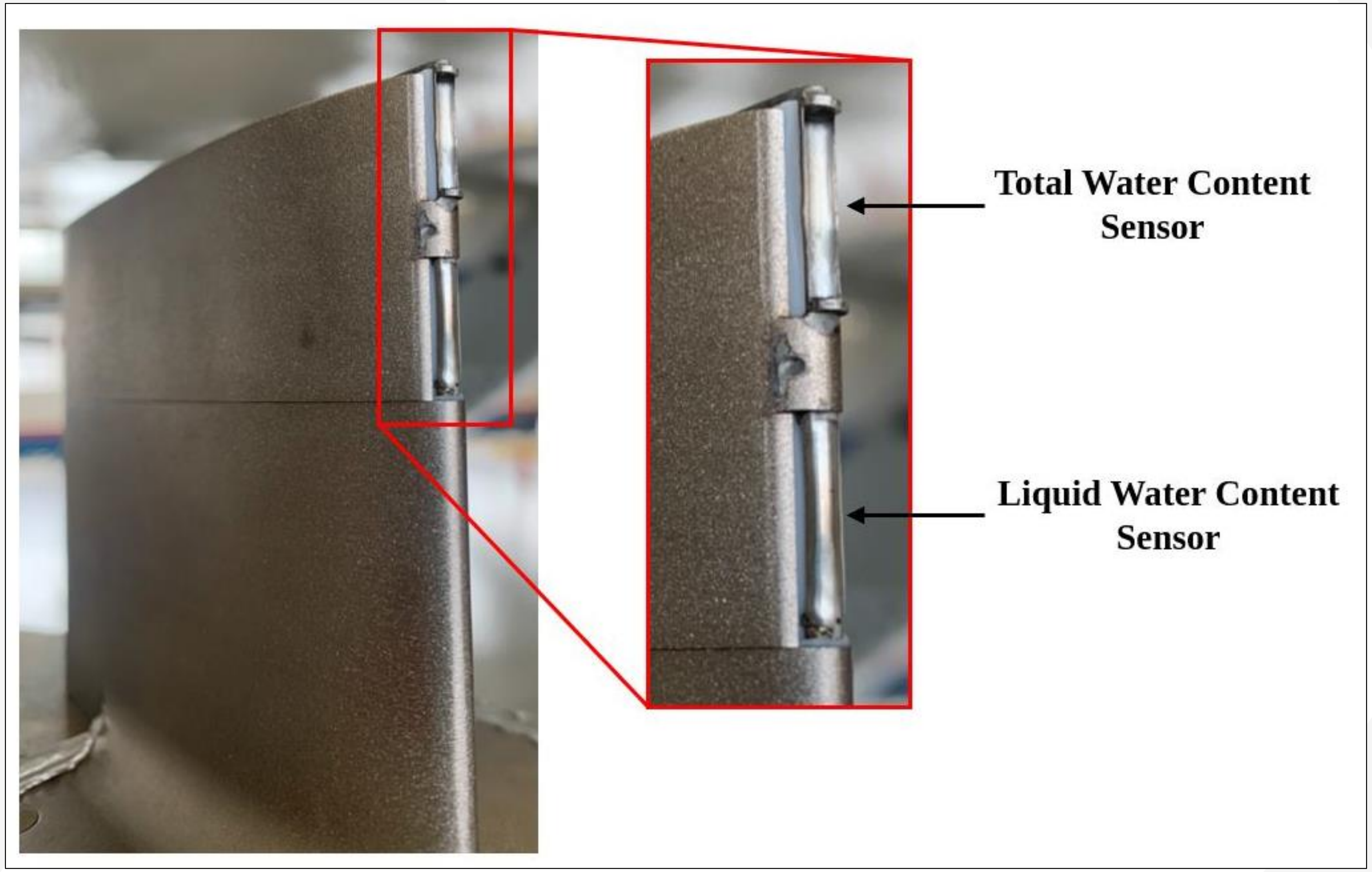
$$LWC\left(\frac{g}{m^3}\right) = \frac{P_{wet}\,(W) * 2.389x10^5}{\left[L_{evap}\left(\frac{cal}{g}\right) + 1.0\left(\frac{cal}{g°C}\right) * (T_{evap} - T_{amb})\right] * TAS\left(\frac{m}{s}\right) * l_s(mm) * W_s(mm)}$$

L_{evap} - latent heat of evaporation, T_{evap} - evaporative temperature, T_{amb} - ambient temperature, TAS - true air speed, l_s - length of the sensor, and W_s - width of the sensor

Close up of WCM-3000 elements

WCM-3000

- Concave Sensor – TWC
  - Measures both liquid droplets and ice particles
  - Cannot aerodynamically contain all ice particles
- Convex Sensor – LWC
  - Measures liquid droplets
  - Residual sensitivity to ice particles

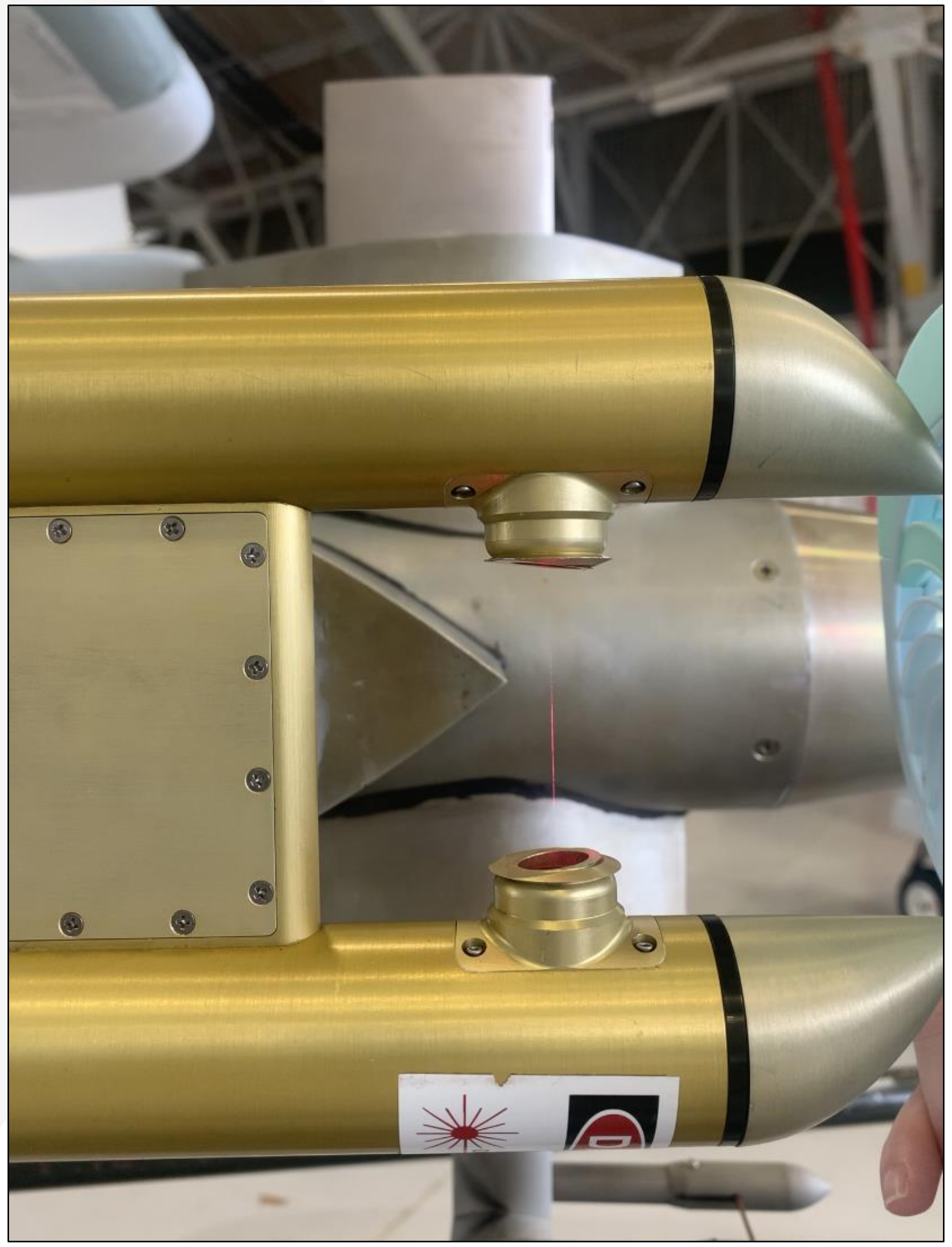


CLOUD DROPLET PROBE (CDP)

- Forward Scattering Probe
- Measures droplets between 2 – 50 µm
- Droplets scatter the laser's light within a range of 4 –12° into the detector
- Integrating droplet distribution to get LWC

$$\mathrm{LWC} = \sum \mathrm{n_i}\, \rho_{\mathrm{w}} \pi \frac{d^3}{6}$$

The CDP will be used in this study for:
(1) Comparison with WCM and King
(2) Droplet size distribution



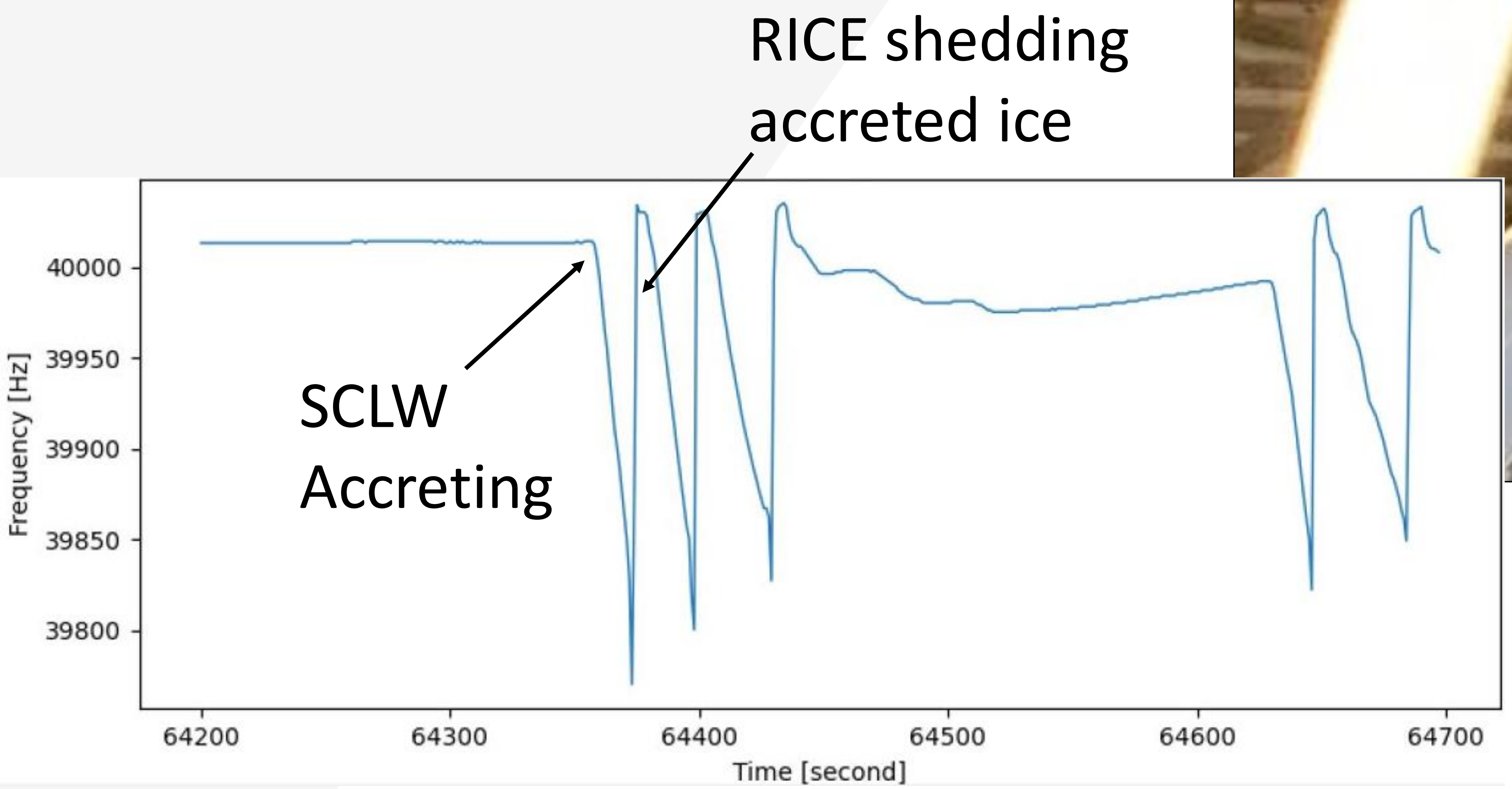
CDP measuring small liquid droplets

CDP on lab bench

ROSEMOUNT ICING DETECTOR (RICE)

- Vibrating Cylinder
- Measures supercooled liquid water (SCLW)
- SCLW freezes on contact with the metal vibrating cylinder
- As SCLW accretes, it dampens the frequency of the RICE

RICE is used in this study to verify periods of SCLW

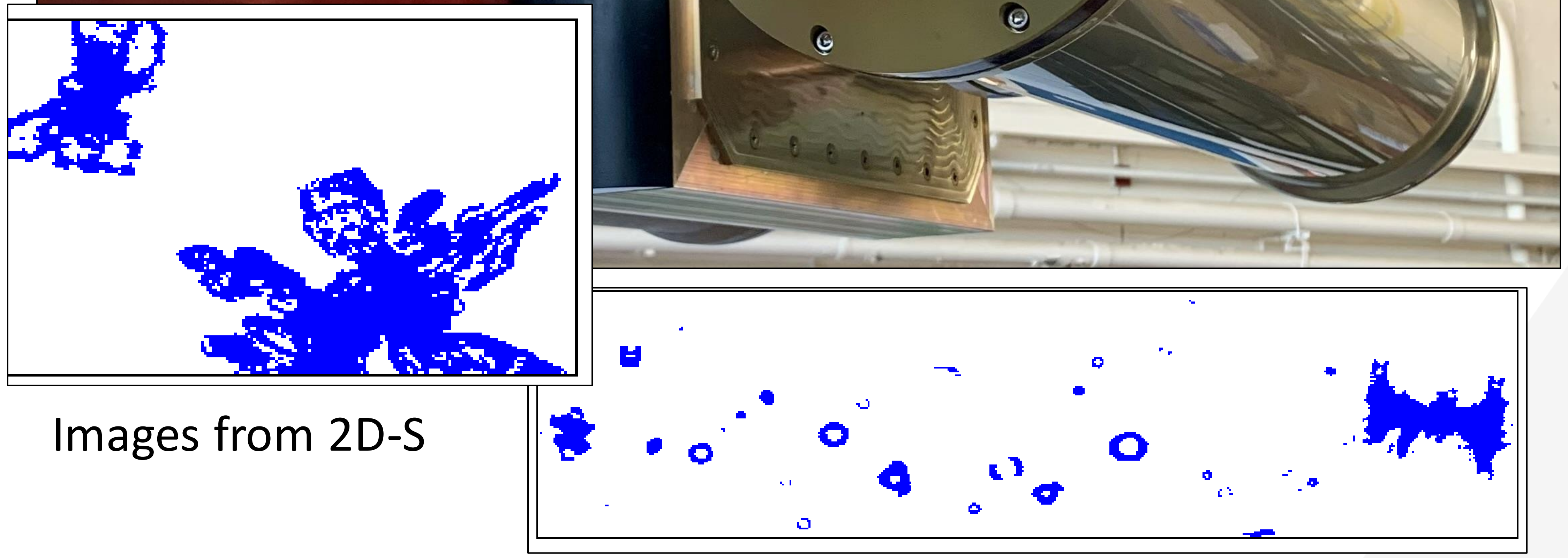


RICE Probe on NASA P-3 fuselage

2-DIMENSIONAL STEREO PROBE (2D-S)

- Optical Imaging Probe
- Size Range 10 µm – 1.280 mm
- Orthogonal lasers sample cloud particles
- As cloud particles pass in front of the laser beam, a shadow is casted on the 128-photodiode array resulting in an image

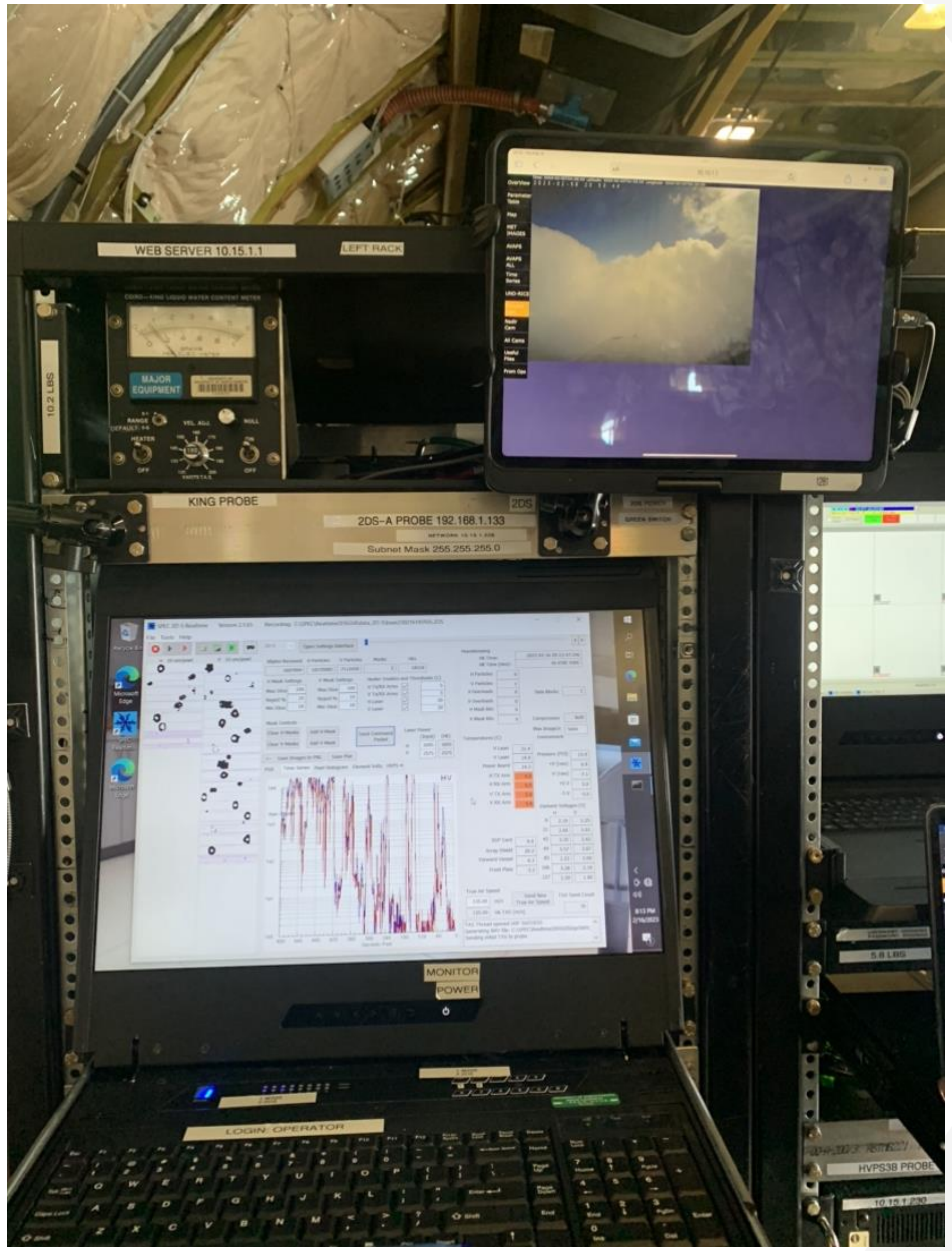
In this study the 2D-S will be used to verify particle types and droplet diameter sizes



Images from 2D-S

DATA PROCESSING

- Airborne Data Processing and Analysis (ADPAA) software package (Delene, 2011)
- Takes the instrument observations and processes them to derive analysis parameters
    - Calibrations (i.e. speed run calibrations, bead tests)
    - Correction (i.e. dry power term correction)
    - Quality Assurance



UND Instrument Rack on the NASA P-3

METHODOLOGY

- Evaluation of the WCM-3000 is done by comparing the LWC measurements to measurements taken by the CDP and King probe

- Flight conditions are defined to compare instruments in:
  - Cloud environments where probe measurements should agree
  - A typical cloud environment in IMPACTS science flights

- Uncertainty calculation

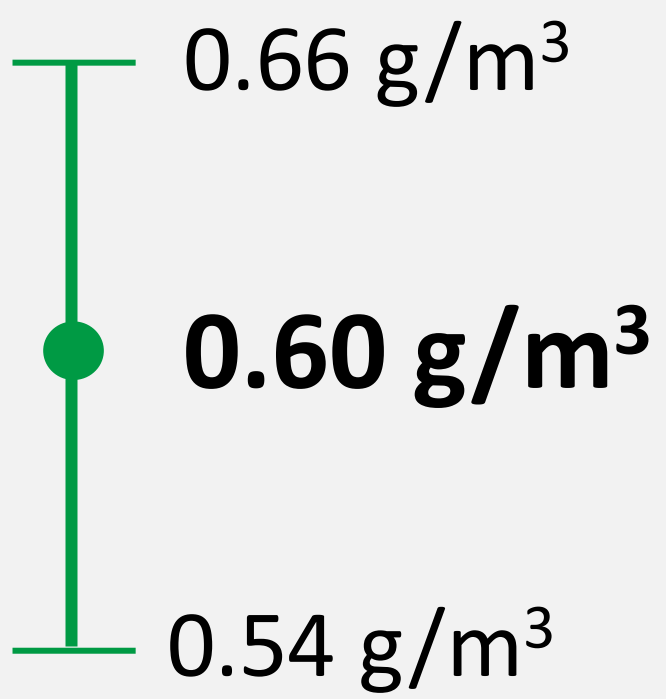
CLOUD CONDITIONS

- Relatively constant environmental parameters during time periods (i.e. TAS and altitude)
- **Liquid Water Cloud**
  - Temperatures > 0 °C
  - No SCLW and no ice particles
  - Droplet sizes < 50 µm
- **Supercooled Liquid Water Cloud**
  - Temperatures < 0 °C
  - No ice particles
  - Droplet sizes < 50 µm
- **Mixed Phase Cloud**
  - Temperatures < 0 °C
  - WCM TWC > LWC
  - Droplet sizes < 200 µm

UNCERTAINTY CALCULATION

$$Absolute\ Error = Measured\ Value * Relative\ Error$$

- Calculating the absolute error (uncertainty)
- Relative error – 10%
- Overlap in uncertainty shows agreement in probe measurements
- Where does error come from?
  - Hot-wires : dry term
  - CDP : limitation in sizing and counting of droplets

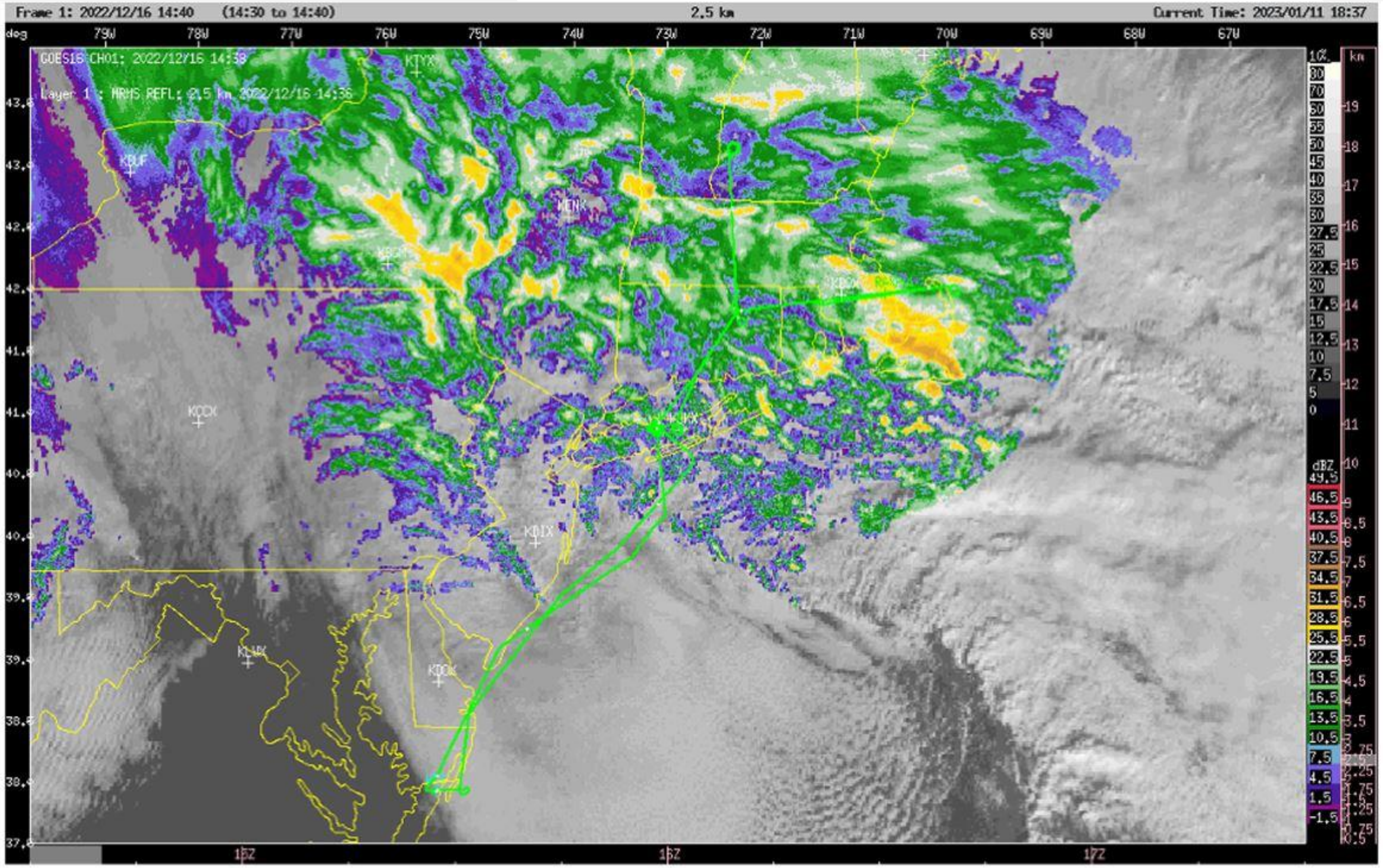


Abs error = (**0.60 g/m³**) * 10%

Abs error = ± 0.06 g/m³

LIQUID WATER CLOUD FLIGHT SEGMENT

- 16 December 2022
- Flight over Long Island, NY
- Low pressure system
- Observed clouds and precipitation
- Multiple segments of above freezing temperatures

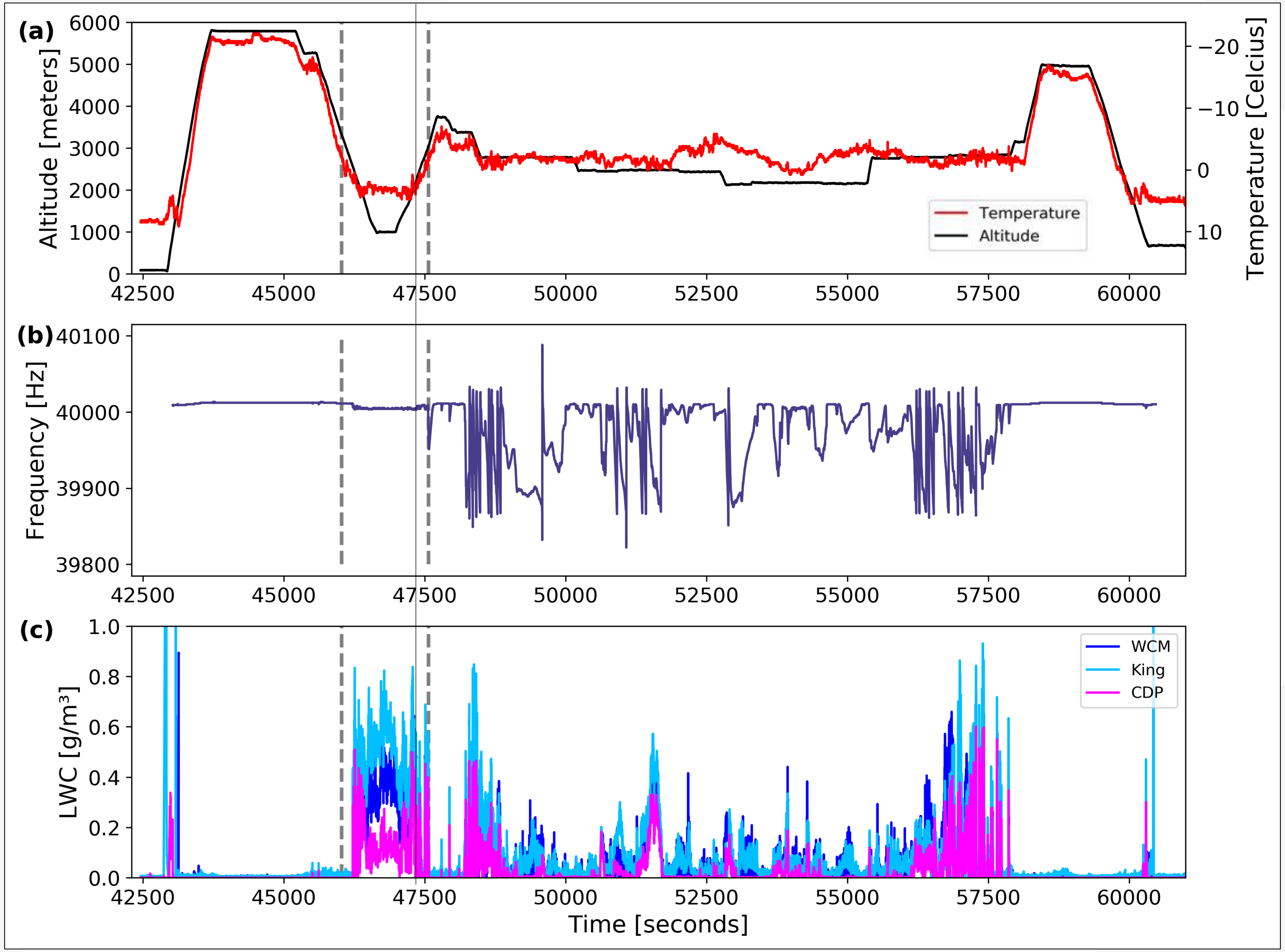


16 December 2022 Flight Track with GOES visible imagery and composite MRMS reflectivity overlaid © McMurdie

AIRCRAFT OBSERVATIONS

Liquid Water Cloud Criteria:

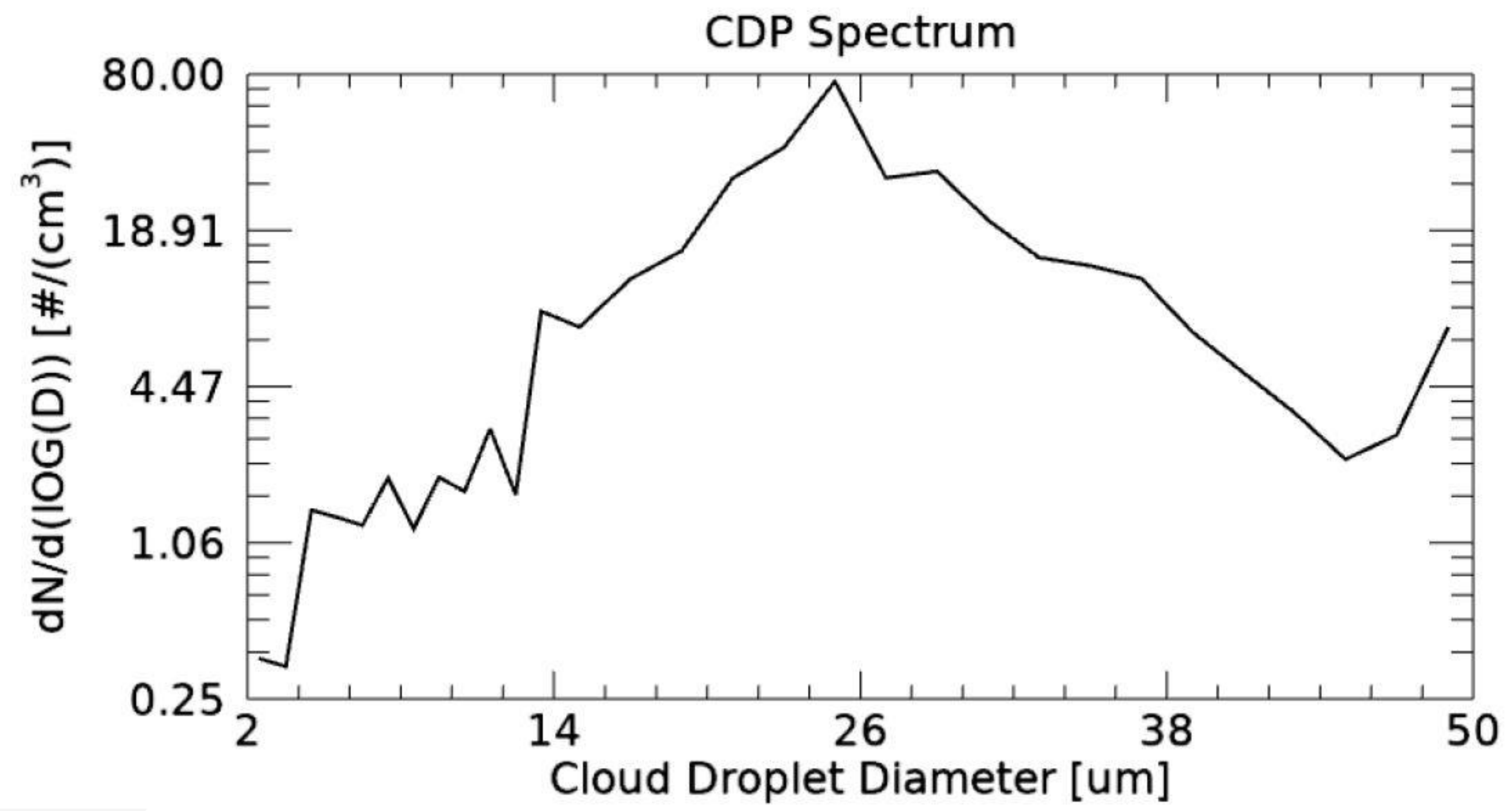
- ☒ Constant altitude
- ☑ Temperatures > 0 °C
- ☑ No SCLW and no ice particles
- ☐ Droplet sizes < 50 µm

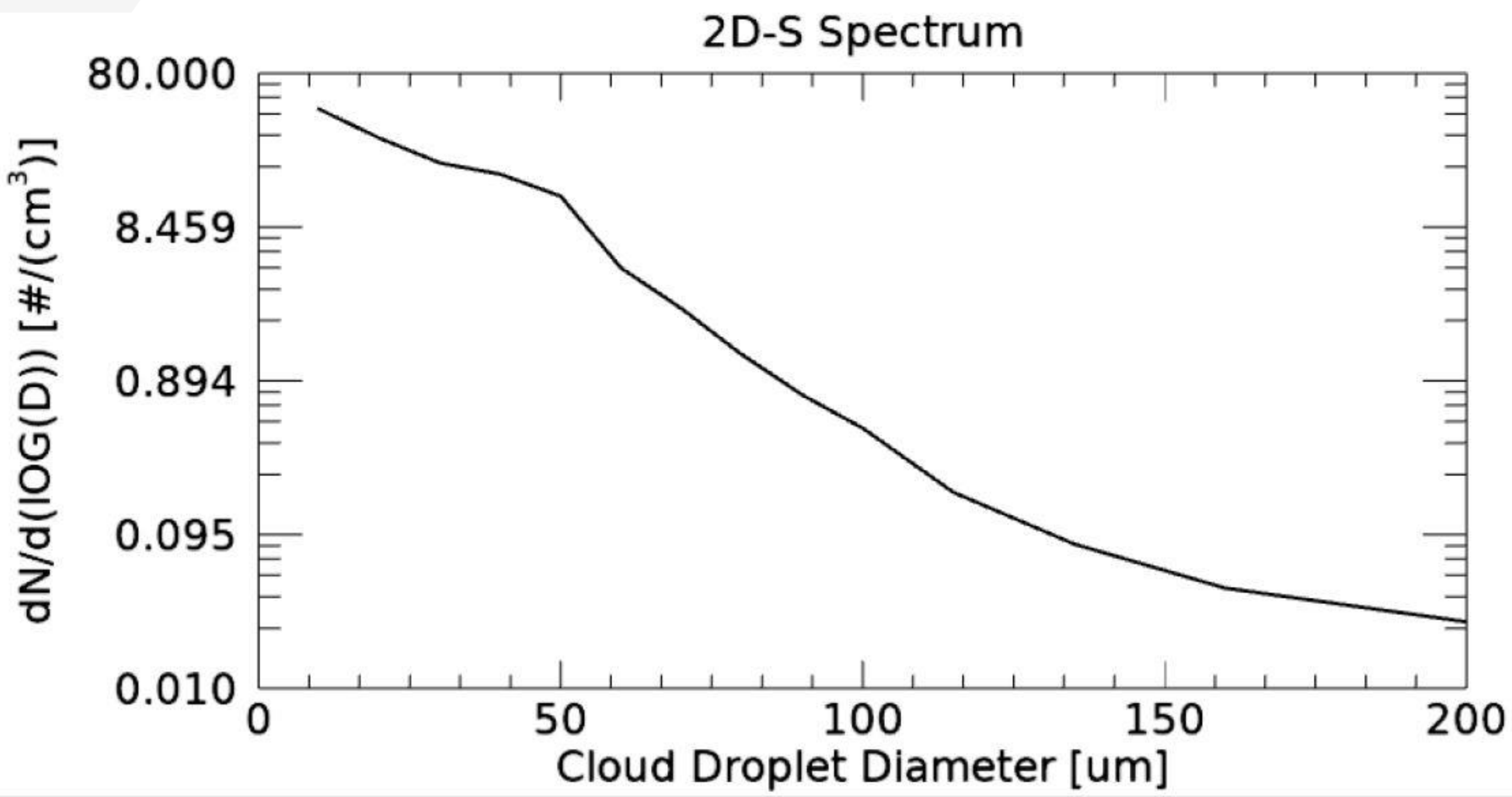


CLOUD DROPLET DIAMETERS

Liquid Water Cloud Criteria:

- ✗ Constant altitude
- ✓ Temperatures > 0 °C
- ✓ No SCLW and no ice particles
- ~~Droplet sizes < 50 µm~~

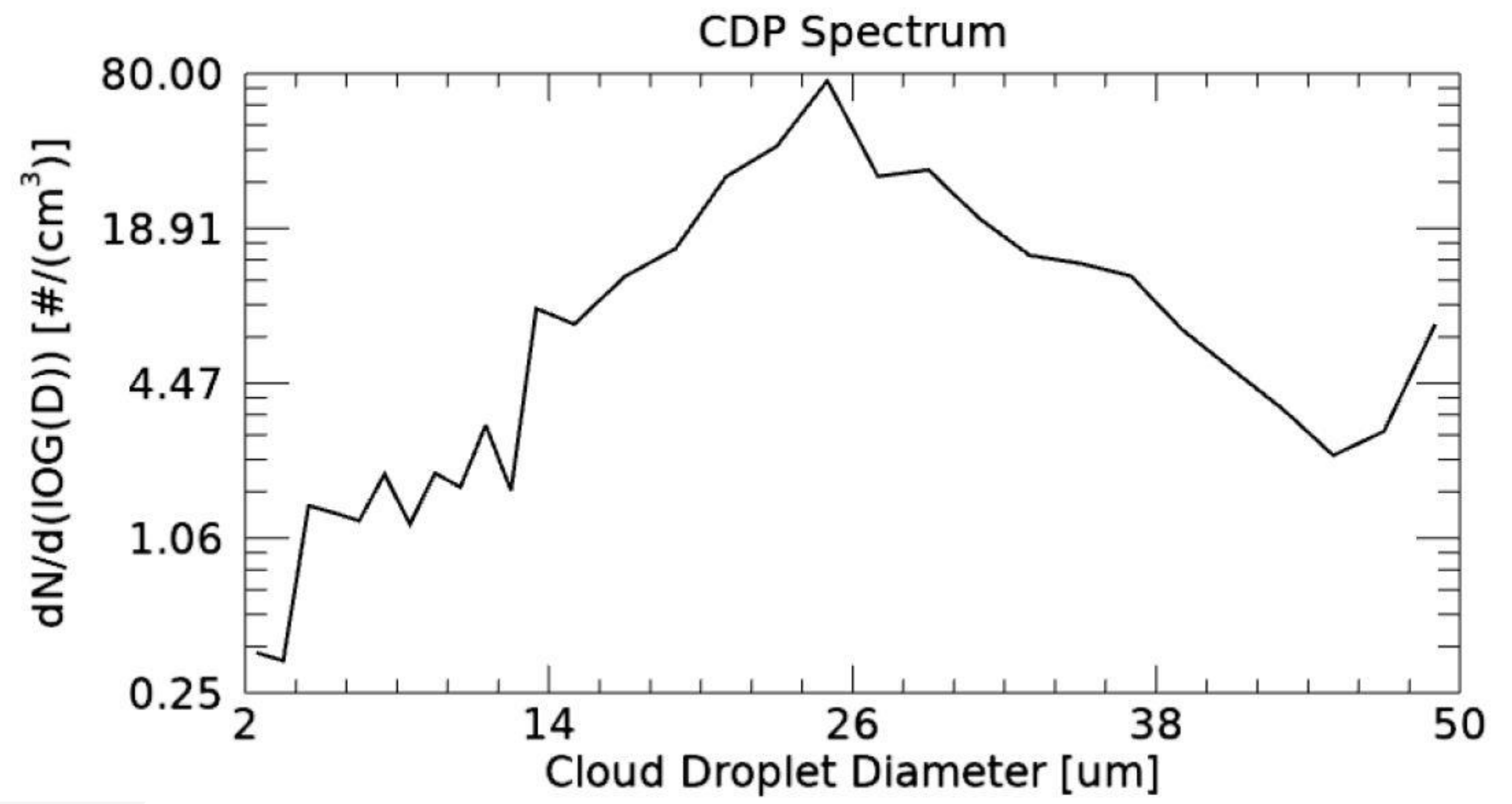


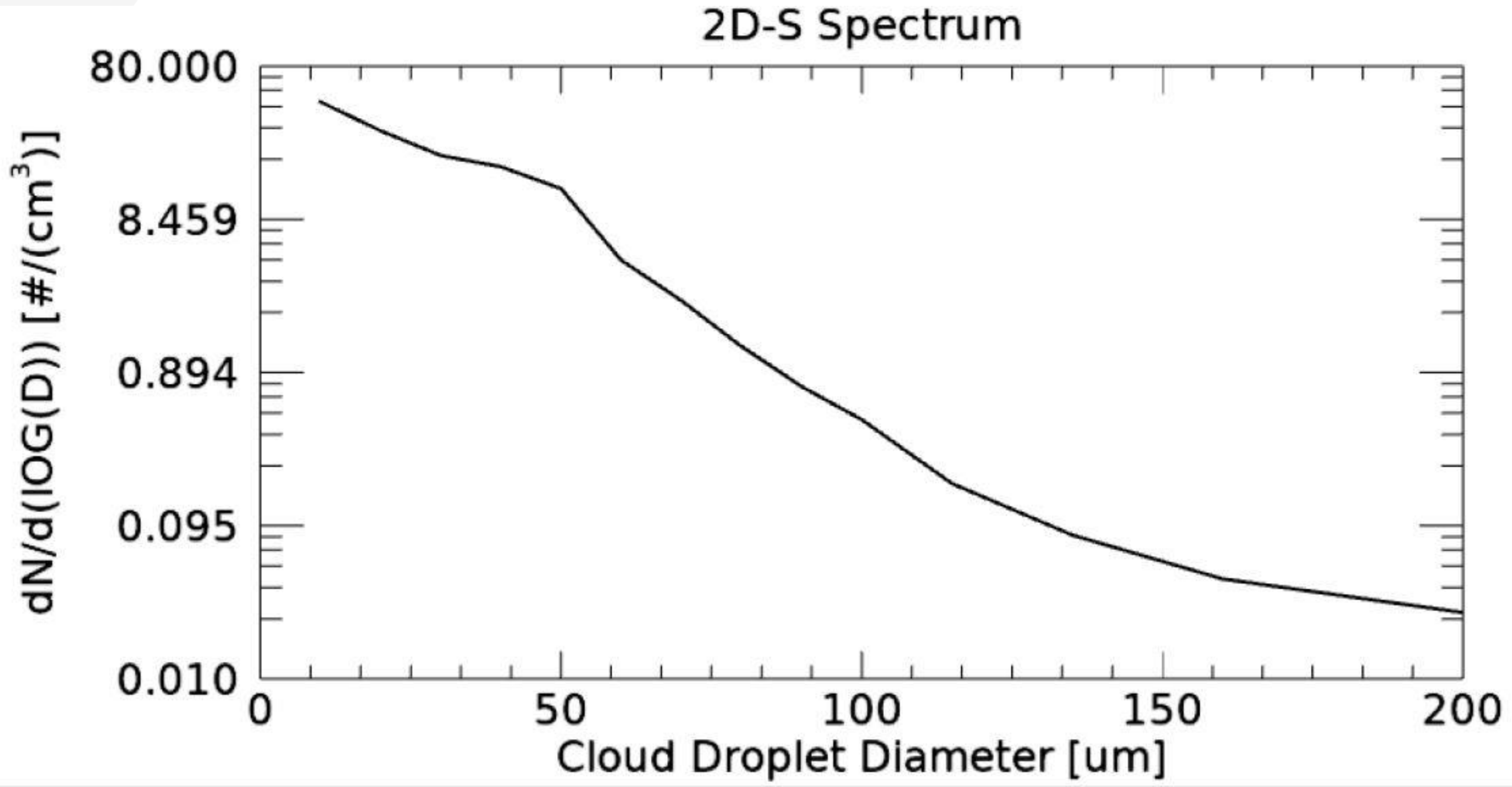


CLOUD DROPLET DIAMETERS

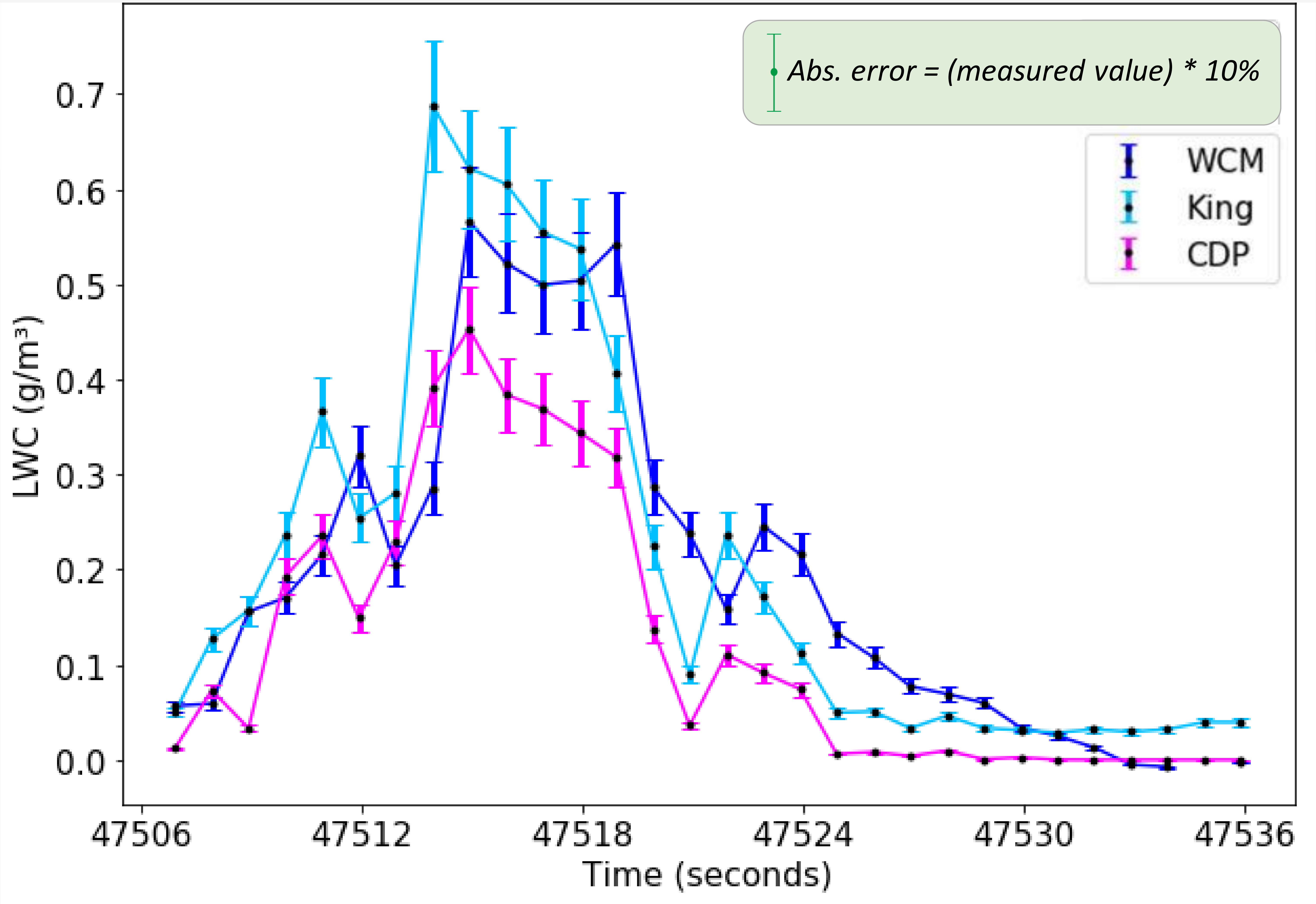
Liquid Water Cloud Criteria:

- ☒ Constant altitude
- ☑ Temperatures > 0 °C
- ☑ No SCLW and no ice particles
- ☑ **Small droplet sizes**
  - 2D-S shows particles up to 200 µm
  - Limited on above freezing cases





LIQUID WATER TIME SERIES



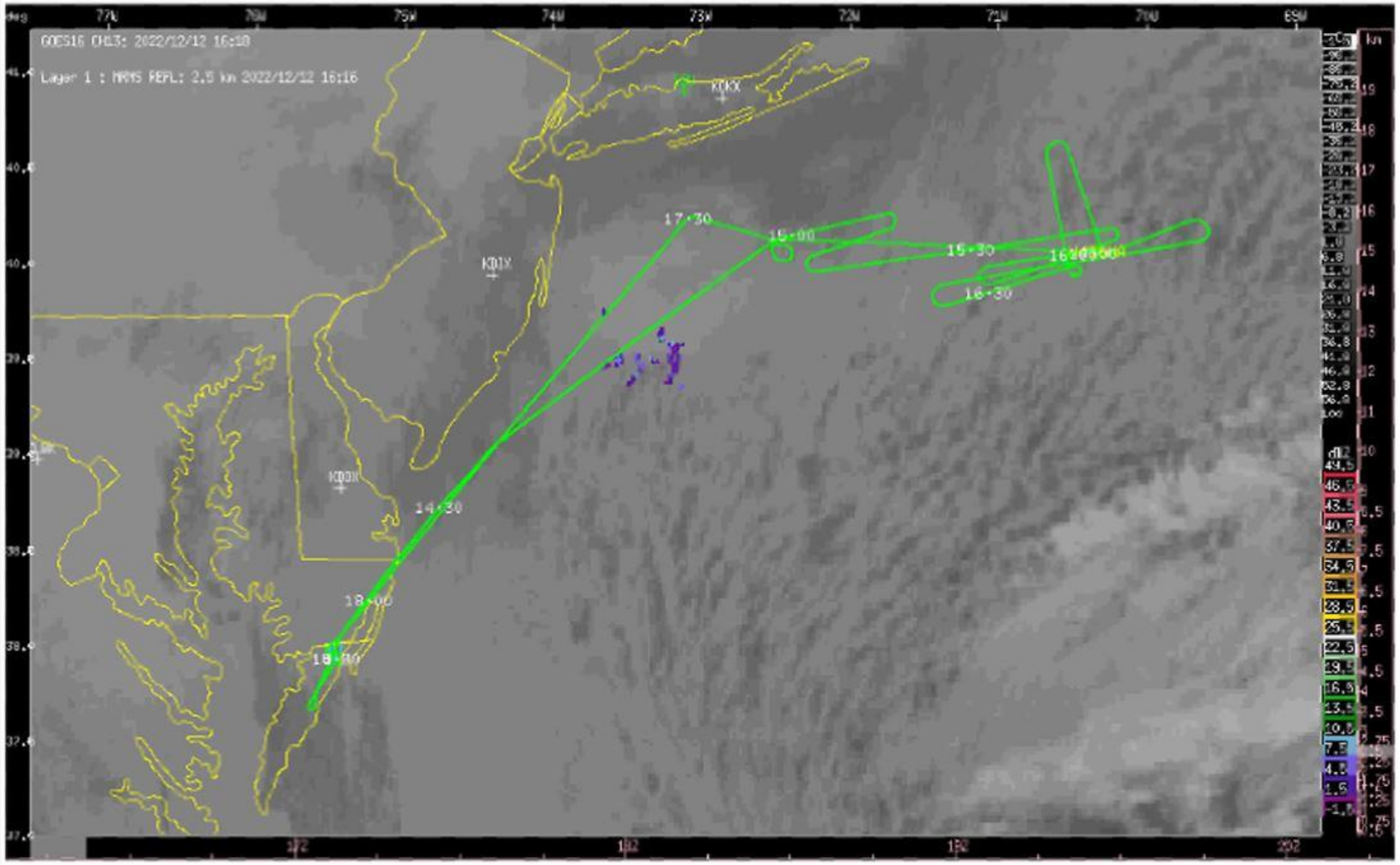
- Some overlap in uncertainties
- General trend
- WCM – Gradual decline in LWC once out of cloud
- CDP – Measuring less LWC
  - Larger droplets present
  - Calibration

Takeaway:

- **King and WCM do not always agree within measured uncertainty**

SUPERCOOLED LIQUID WATER CLOUD FLIGHT SEGMENT

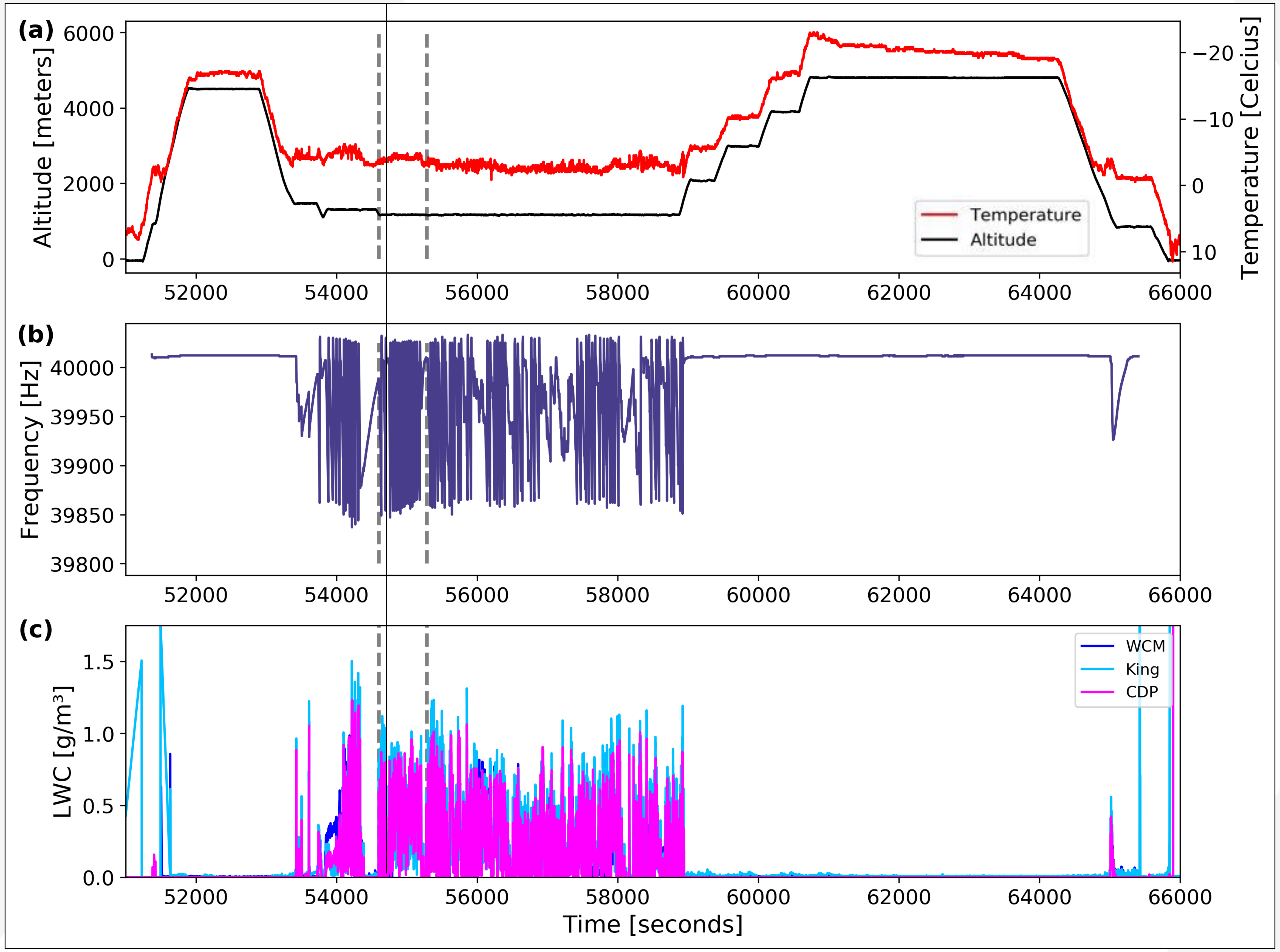
- 12 December 2022
- Flight off the New Jersey Coastline
- Observed stratocumulus clouds
- Clear air flight maneuvers



12 December 2022 Flight Track with IR channel 13 brightness temperatures overlaid © McMurdie

SCLW Cloud Criteria:

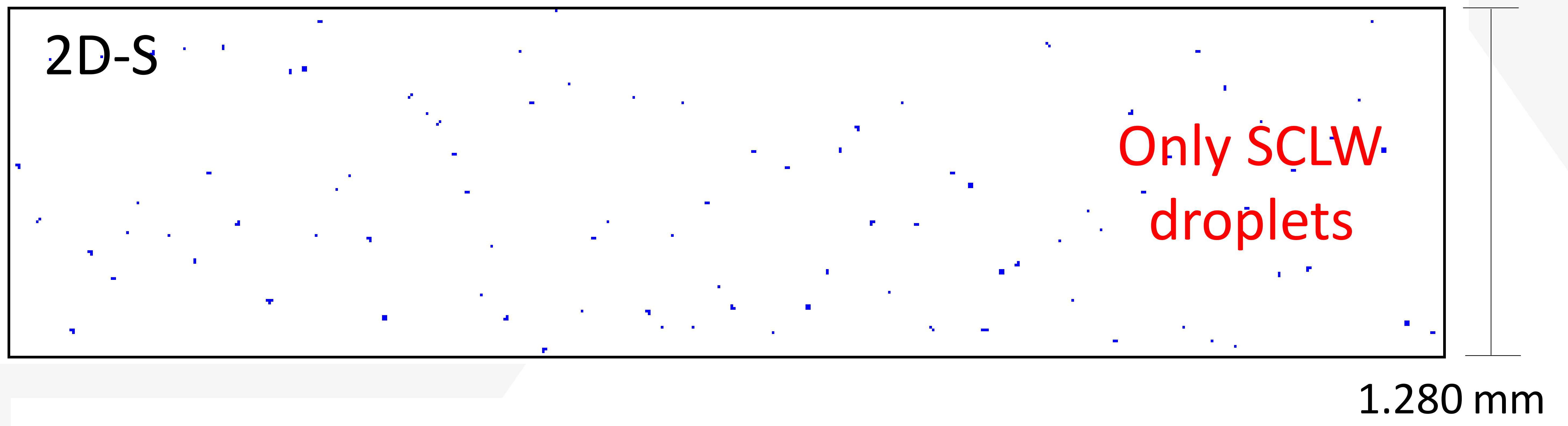
- ☑ Constant altitude
- ☑ Temperatures < 0 °C
- ☑ SCLW
- ☐ No ice particles
- ☐ Droplet sizes < 50 µm

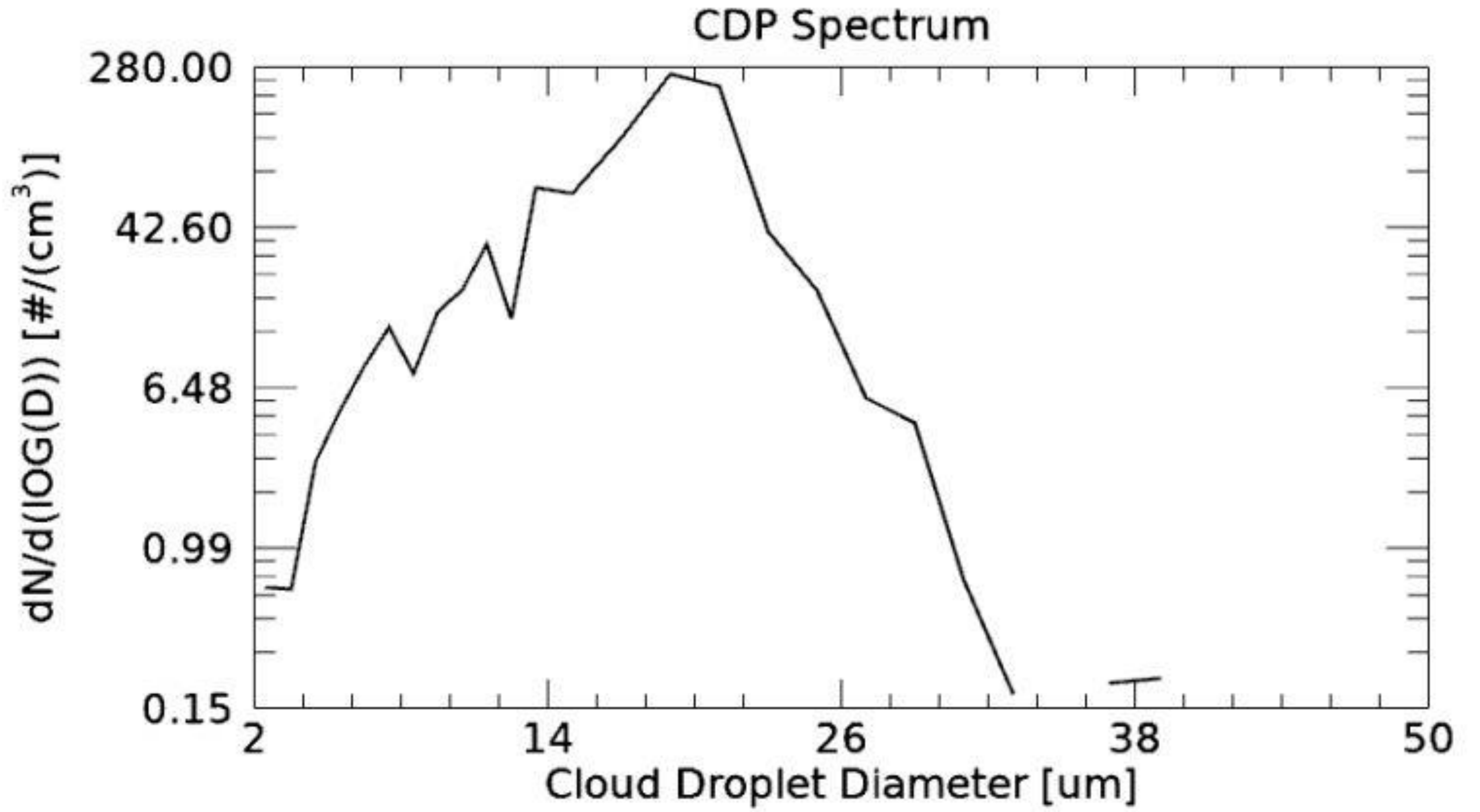


CLOUD DROPLET DIAMETERS

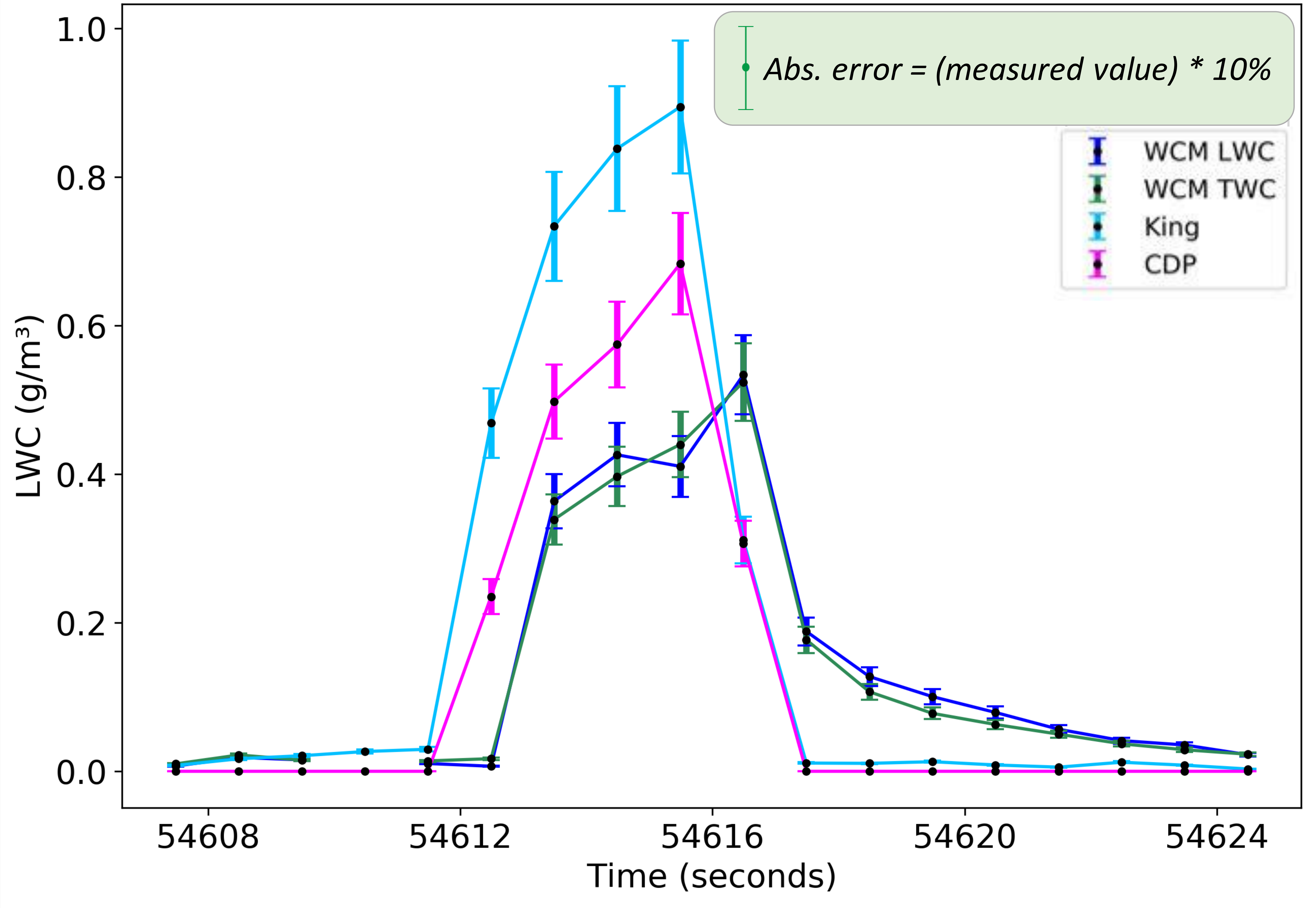
SCLW Cloud Criteria:

- ☑ Constant altitude
- ☑ Temperatures < 0 °C
- ☑ SCLW
- ☑ No ice particles
- ☑ Droplet sizes < 50 µm





SCLW TIME SERIES



- General trend
- WCM – Delay in response
- WCM – Gradual decline in LWC once out of cloud

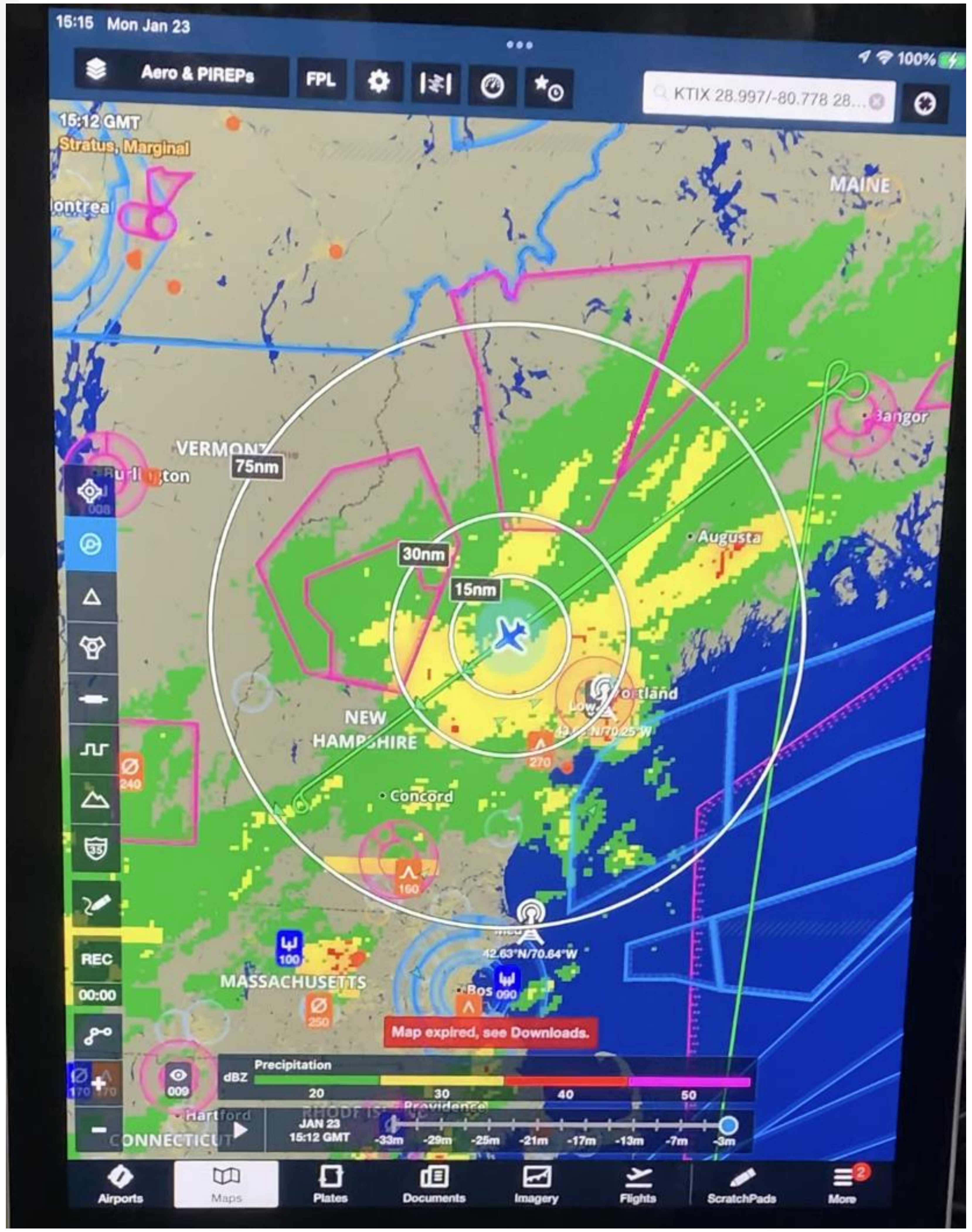
Takeaways:

- **Instruments do not agree within measured uncertainty**

MIXED PHASE CLOUD FLIGHT SEGMENT

ENVIRONMENT

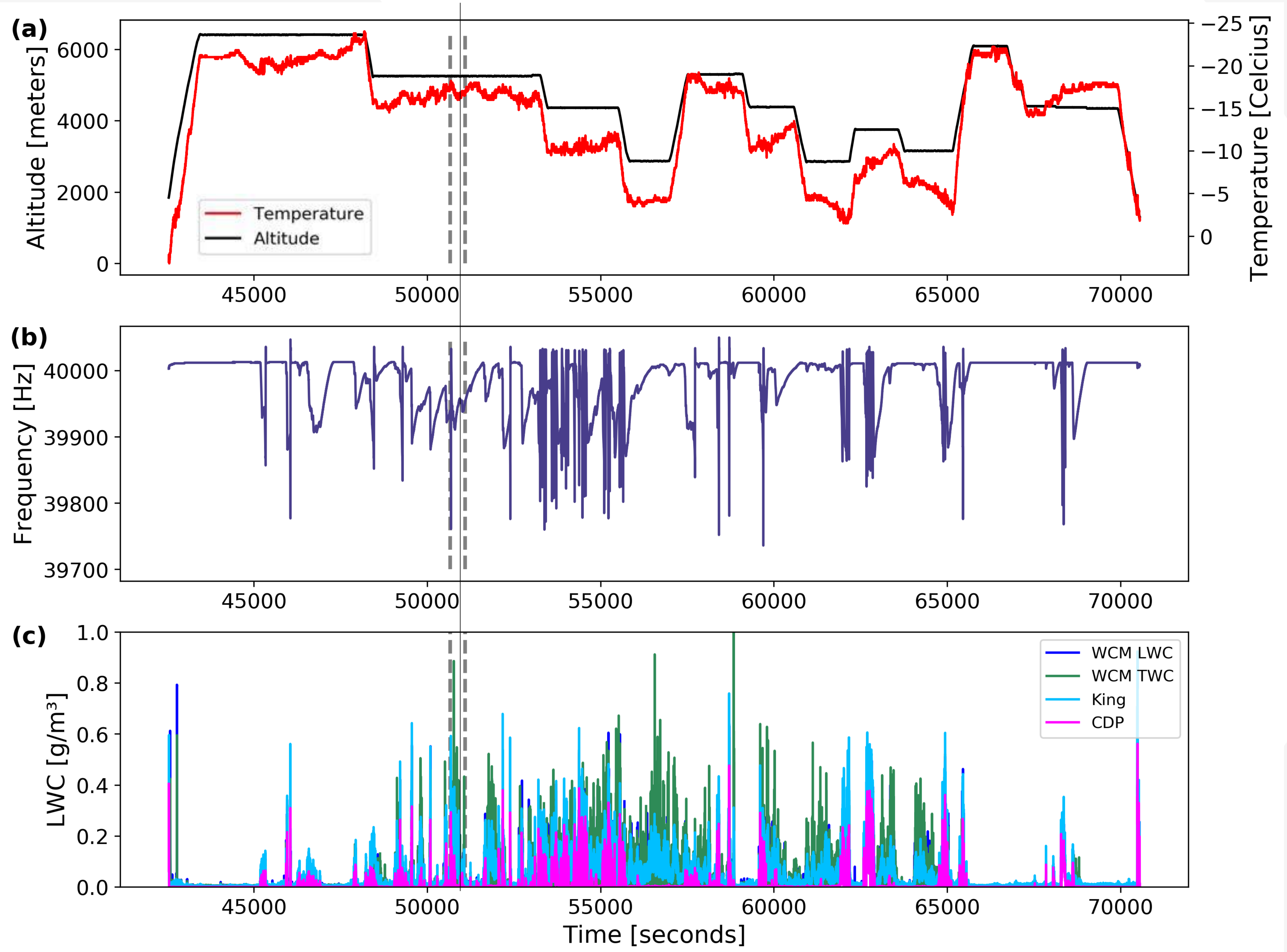
- 23 January, 2023
- Flight sampled a winter storm system over New England and Gulf of Maine
- Deepening surface low



23 January 2023 Flight Track with Radar Reflectivity overlaid

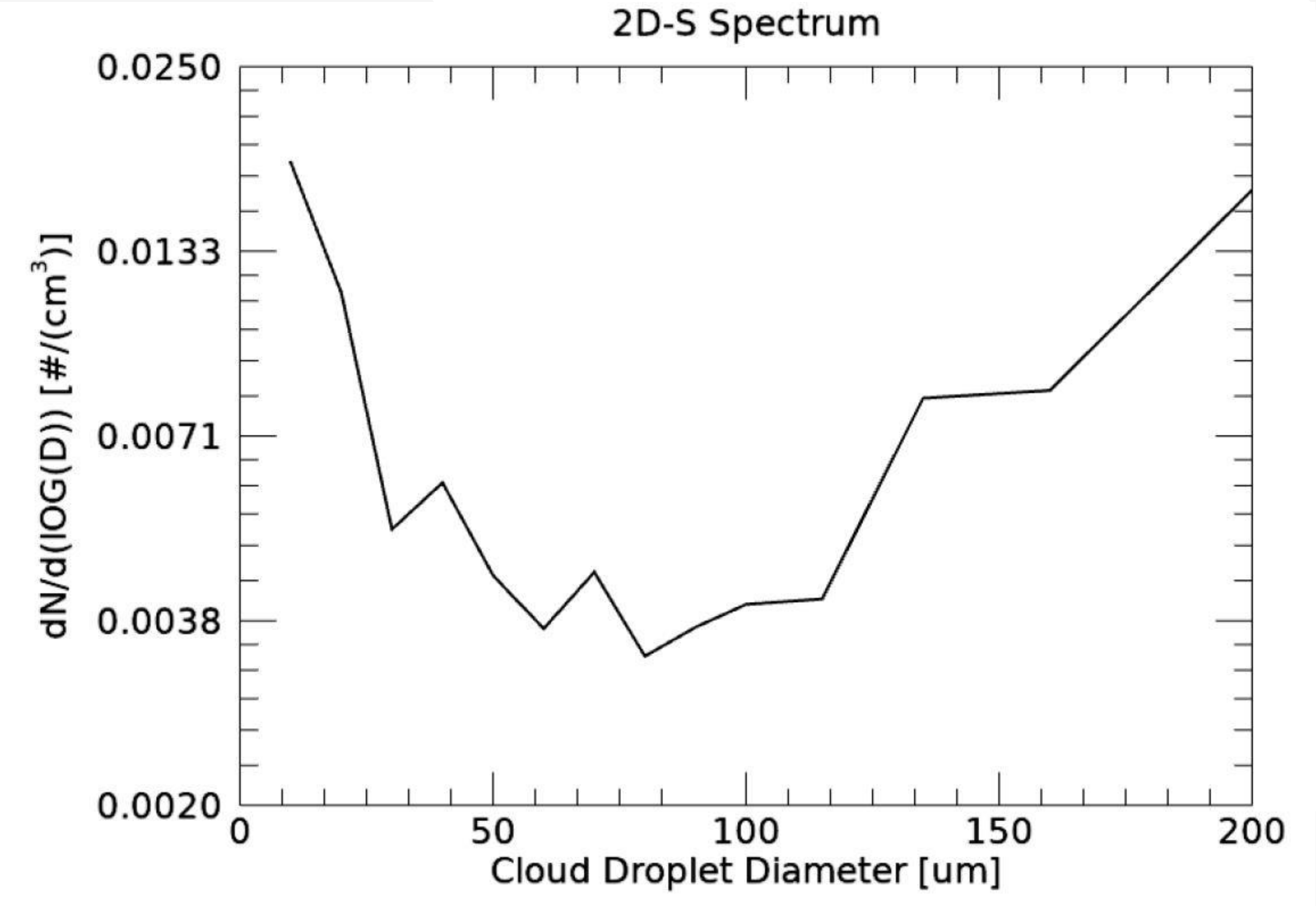
Mixed Phase Cloud Criteria:

- ☑ Constant altitude
- ☑ Temperatures < 0 °C
- ☑ TWC > LWC
- ☐ Droplet sizes < 200 µm



Mixed Phase Cloud Criteria:

- ☑ Constant altitude
- ☑ Temperatures < 0 °C
- ☑ TWC > LWC
- ☑ Droplet sizes < 200 µm

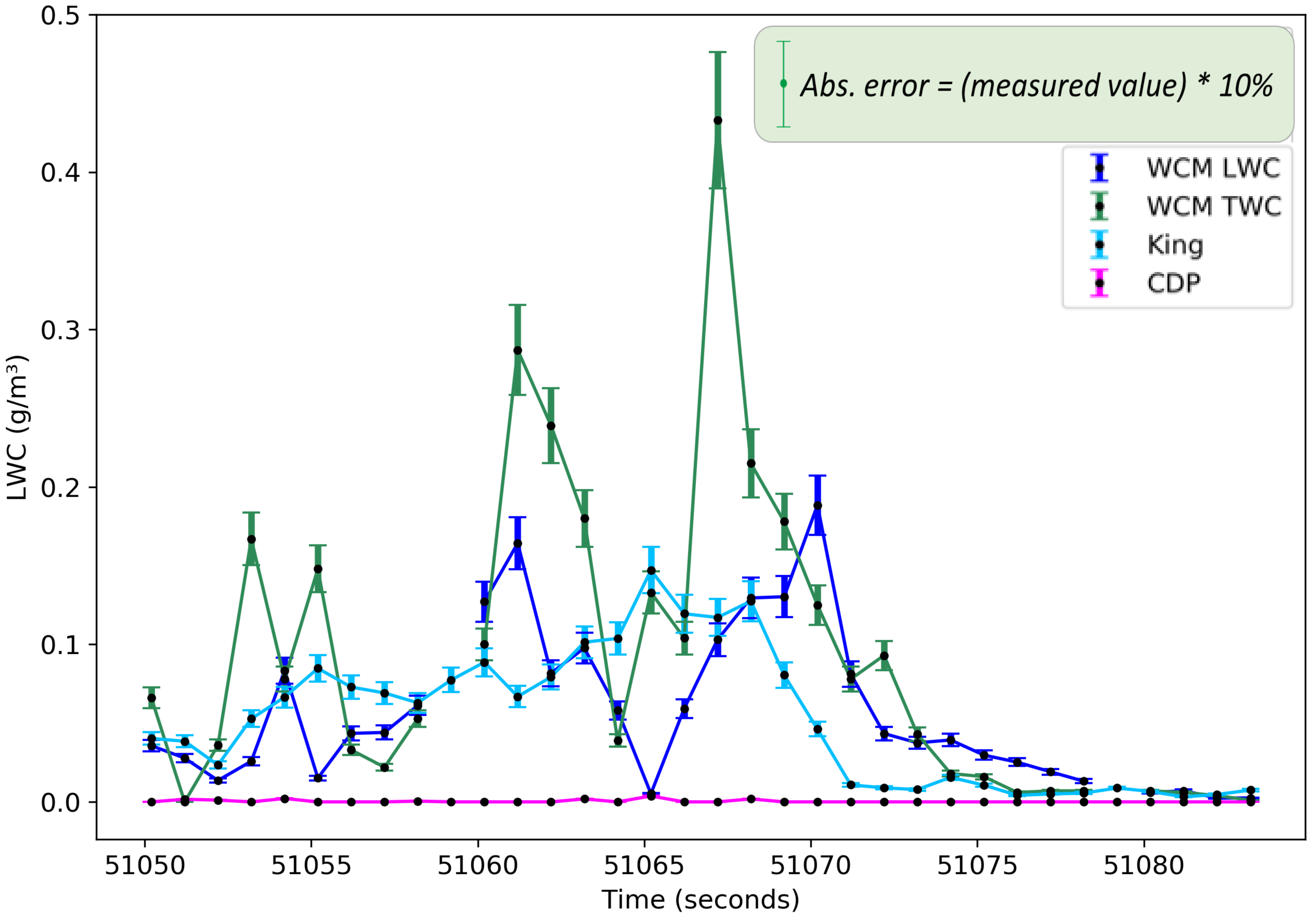


MIXED PHASE TIME SERIES

- 1 Hz data
- CDP is measuring no LWC
- King and WCM LWC – measuring small amounts of LWC
- WCM TWC is measuring the most amount of water contents

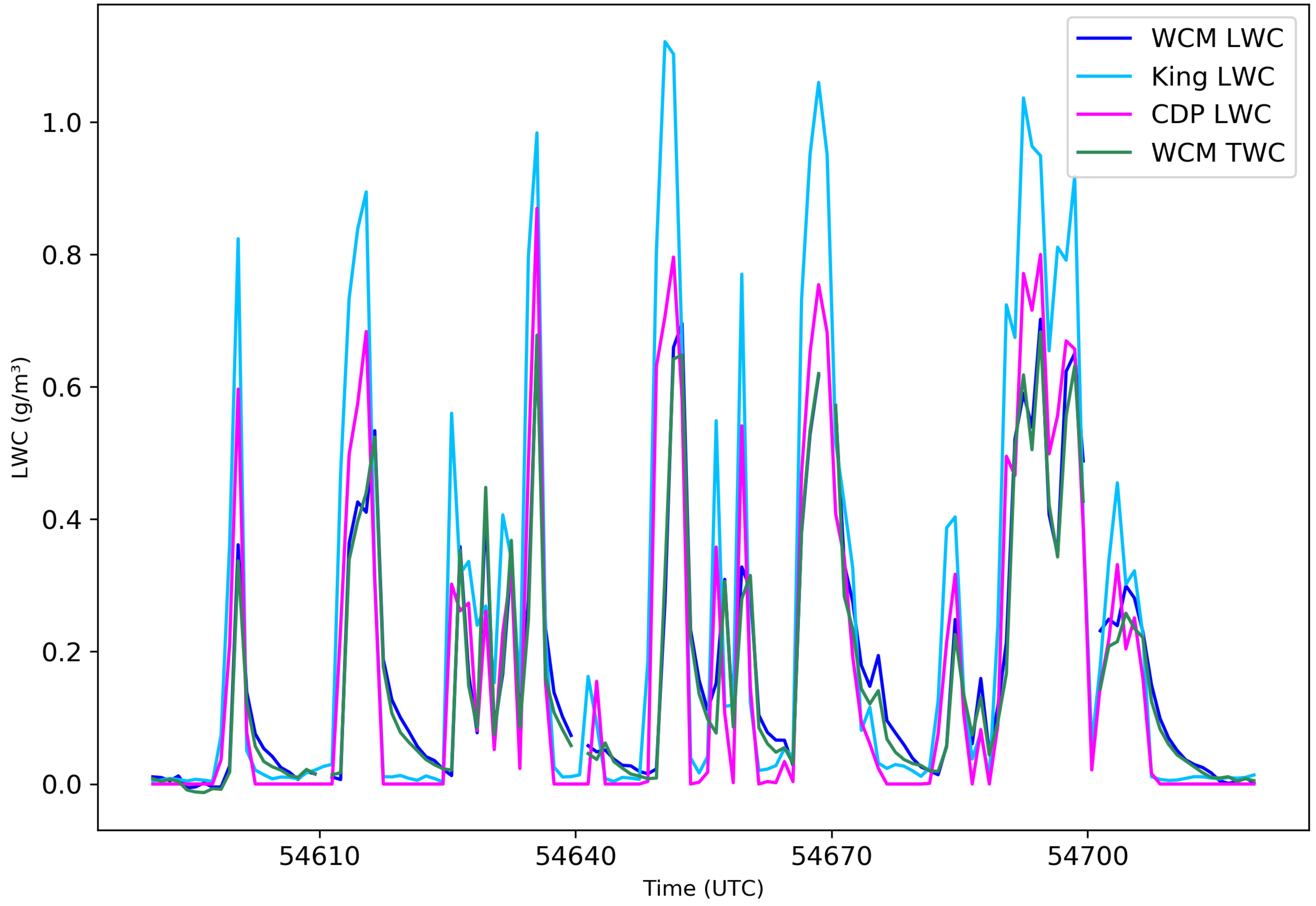
Takeaway:

- **WCM - Slow decline in water contents once out of cloud**



SUMMARY OF RESULTS

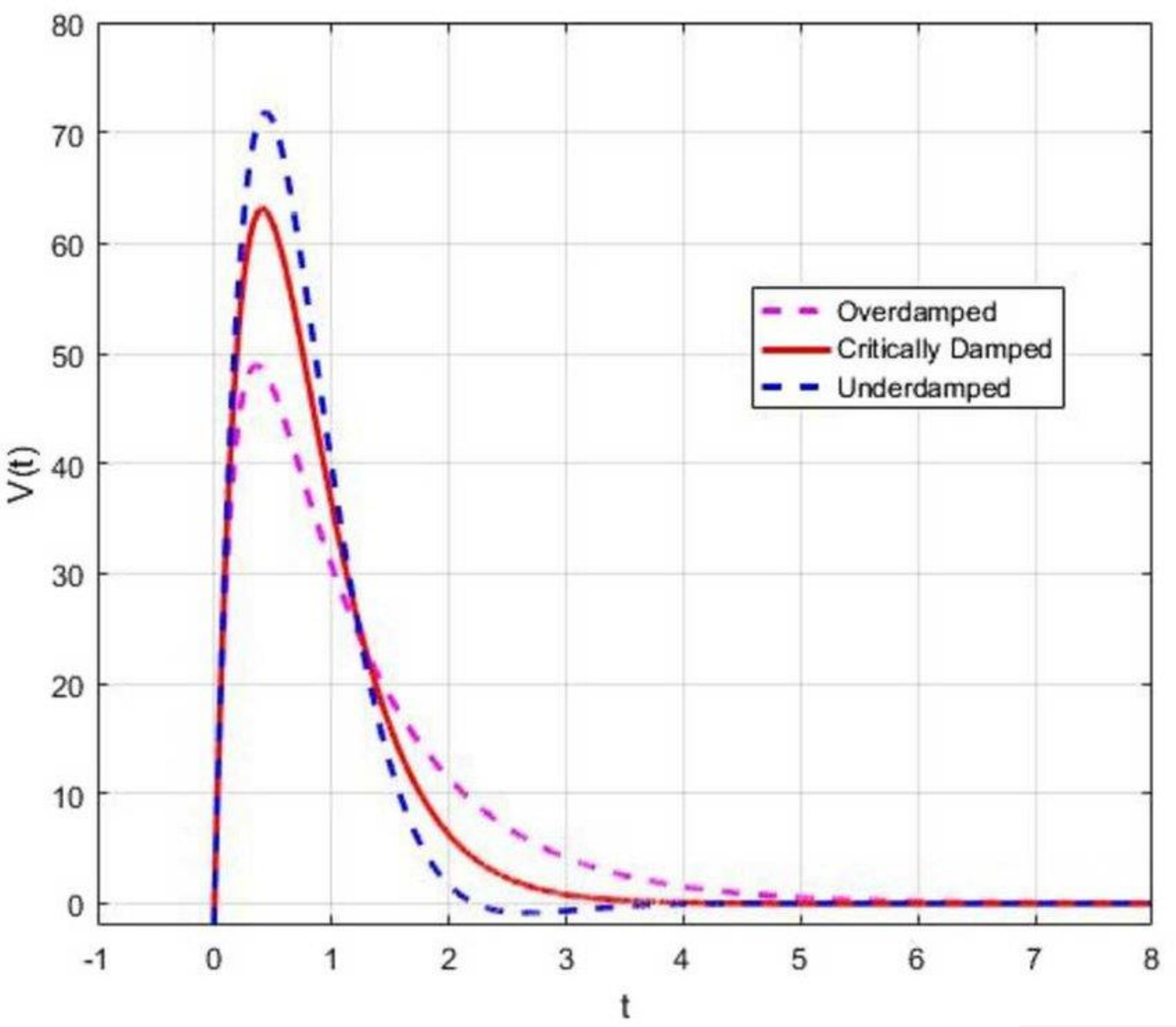
- Little agreement in measurement uncertainties
- Delay in WCM measurements once in cloud
- WCM - Slow decline in LWC once out of cloud
- King probe measures the most LWC
- CDP underrepresenting LWC
    - Calibrations
    - Measurement size range



Example of multiple cloud passes where WCM has slow decline in LWC once out of cloud

What could be causing WCM performance issues?

- ~~Time offset~~
  - Time series plot don't show a simple shift in time
- ~~Hysteresis effect~~
  - Residual water not evaporating fast enough
    - Gap in wire
- ~~Software issue~~
  - Tried different software, sensor heads, see on raw data
- Overdamped control system



Alizadeh et al. 2020

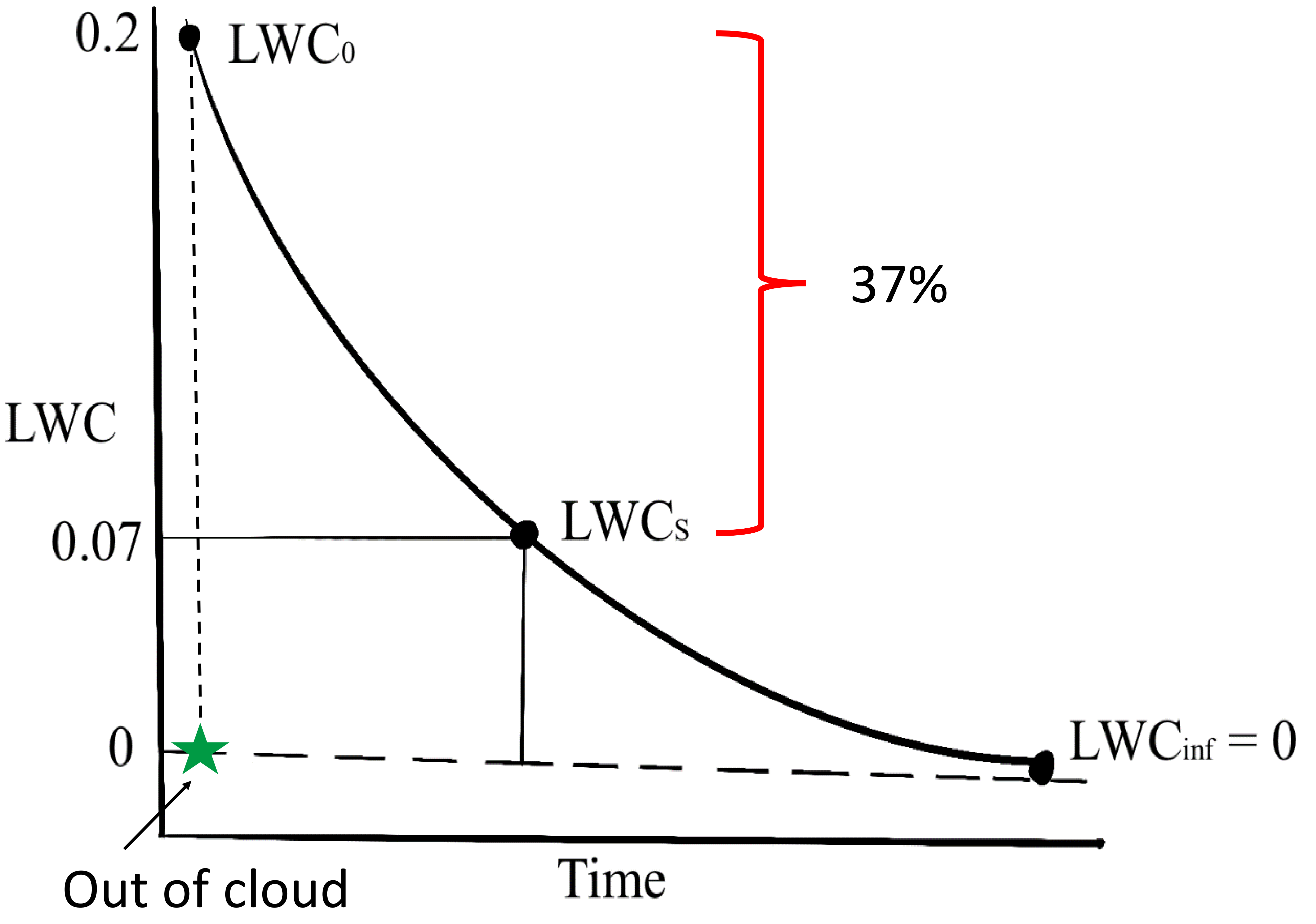
OVERDAMPED SYSTEM

- Time Constant (τ)
- Is there consistency in the duration of the slow response time?

$$\frac{LWC_s - LWC_\infty}{LWC_0 - LWC_\infty} = e^{-t/\tau}$$

- LWC: $\tau = 3.4$ s
- SCLW: $\tau = 3.4$ s
- Mixed: LWC $\tau = 3.6$ s, TWC $\tau = 2.9$ s

τ ~ 3 seconds



CONCLUSIONS

- **To determine if the WCM-3000 values agree with the other probes within their measured uncertainties?**
  - No, they do not agree
- Cases provide evidence that the WCM-3000 has performance issues
  - Slow WCM response upon entering cloud
  - WCM measures LWC after exiting cloud
- Time constant $\tau \sim 3$ s
- Most likely an overdamped control system

FUTURE WORK

- Improve WCM performance
- IMPACTS dataset
  - Process WCM dataset
    - As is, missing value codes, or correction algorithm

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- IMPACTS group
- AtSci Department
- Wanda and Sue
- Family and Friends


ALLEY OF LOVE
EXIT

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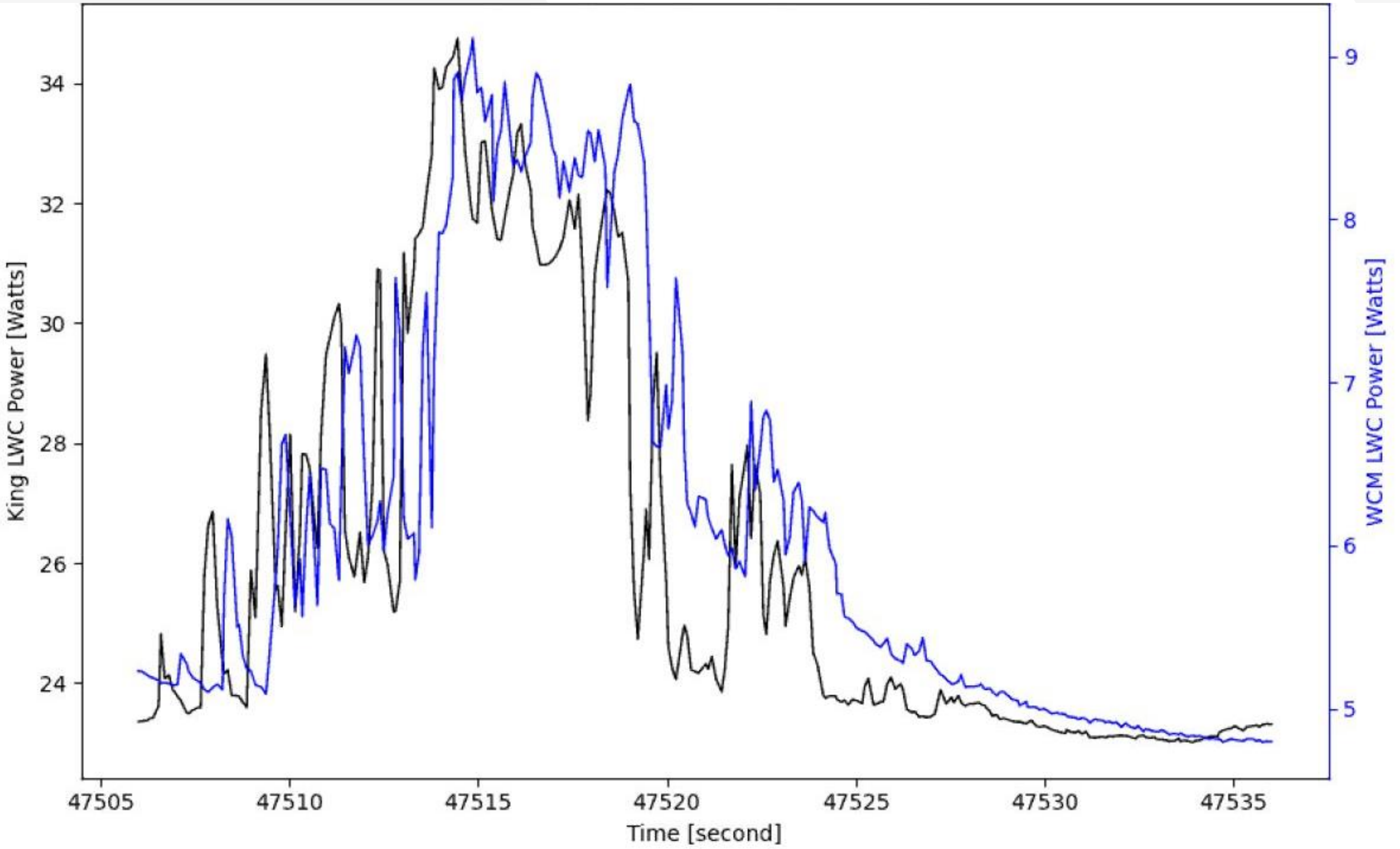
EXTRA SLIDES

POWER : LIQUID WATER

- Same delay in the increase of power
- Same gradual decline in power



Takeaway:

- **This provides insight into the performance issue being a probe issue and not a calculation issue in post processing**

FLIGHT SEGMENTS OF INTEREST

Type	Date	Time Span (hh:mm:ss)	Temp.	Altitude	Diam.
LW	20221216	13:11:38 – 13:12:14 UTC	-0.6 ±0.4 °C	2864 ±34.6 m	< 50 µm
SCLW	20221212	15:10:11 – 15:10:25 UTC	-3.5 ±0.3 °C	1154 ±3.7 m	< 50 µm
Mixed	20230123	14:09:38 – 14:11:30 UTC	-16.8 ±0.2 °C	5250 ±3.1 m	< 200 µm