Evaluation of the Performance of a Rosemount Icing Detector During IMPACTS 2020

Greg Sova

M.S. Thesis Defense

University of North Dakota

Grand Forks, ND

12/03/2021

Committee:

Dr. David Delene, UND (Chair)

Michael Poellot, retired UND

Dr. Andy Detwiler, UND

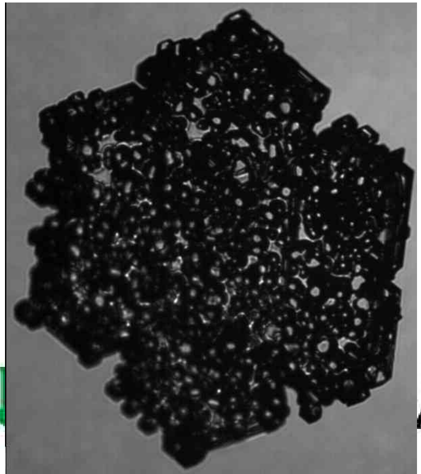
Introduction and Data

Supercooled Water

- Definition: Water that exists below 0 °C (32 °F)
- Supercooled Liquid Water Content (SLWC) measured in g/m^3
- Measurements important for Wegener-Bergeron-Findeisen Process, modeling, remote sensing retrievals, particle riming, and aircraft icing

Left: NRC Canada Convair 580 during ICICLE 2019

Right: CPI image of a rimed crystal during IMPACTS 2020

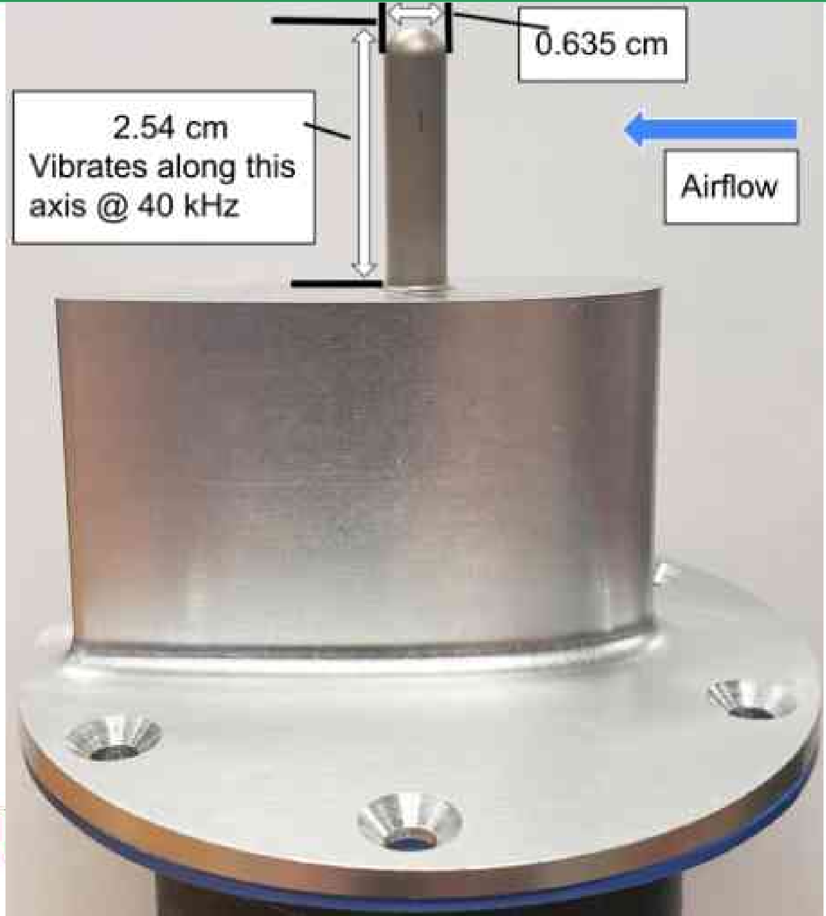


Other LWC Probes

- Right: King Liquid Water Sensor (King Probe), 1.5 mm hot wire probe
  - Sensitive to ice, drop size bias with MVD > 40 µm
- Left: Cloud Droplet Probe (CDP), forward scattering optical probe
  - Sensitive to ice, coincidence bias, shattering

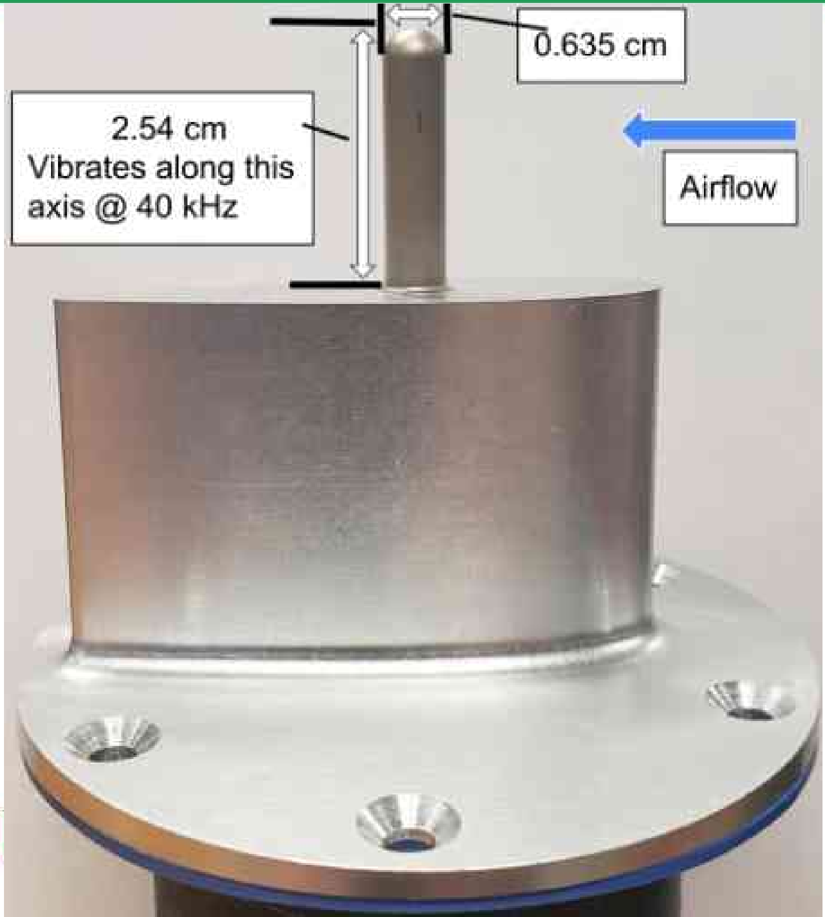
Rosemount Icing Detector

- AKA: RICE Probe
- Nickel cylinder 2.54 cm long, 0.635 cm in diameter
- Vibrates at 40 kHz in clear conditions
- Frequency decreases as ice accretes in presence of SLWC
- At 0.5 m of accretion (39.5 kHz), a heater trips and the ice is shed



Rosemount Icing Detector

- Advantages: Insensitive to ice, no known particle size limits
- Disadvantages: Only detects supercooled water, and is limited by Ludlam Limit
- NOTE: RICE Probe was *not* designed as a SLWC measuring probe, but as an aircraft icing measuring probe

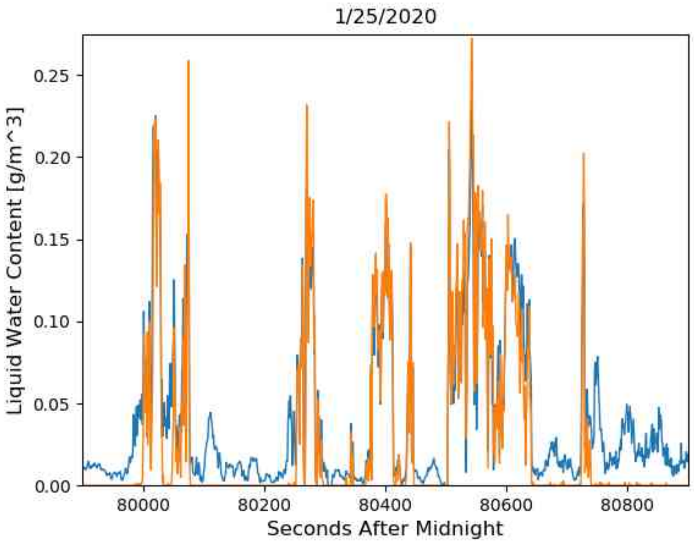


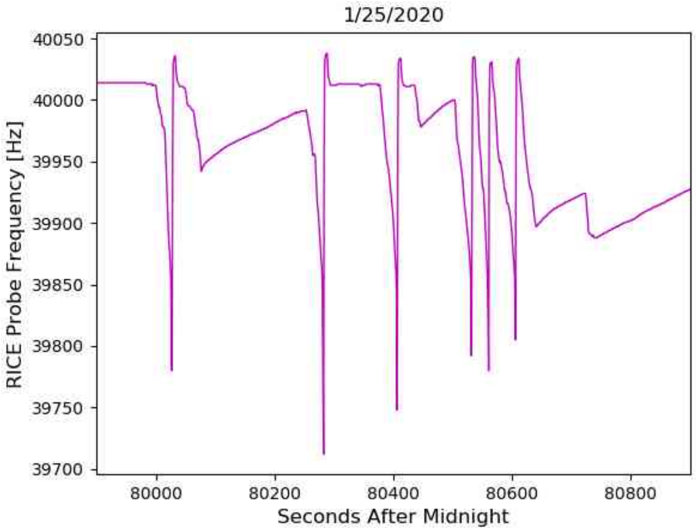
Ludlam Limit

- Defined as the critical LWC above which the supercooled water will incompletely freeze (the freezing fraction is <1)
- Multiple thermodynamic processes will cause RICE Probe surface temperature to rise above freezing even when the surrounding air is cooler than freezing, inhibiting ice accretion
- Main two processes are adiabatic compression ahead of the probe and the release of heat in the freezing process

Objectives

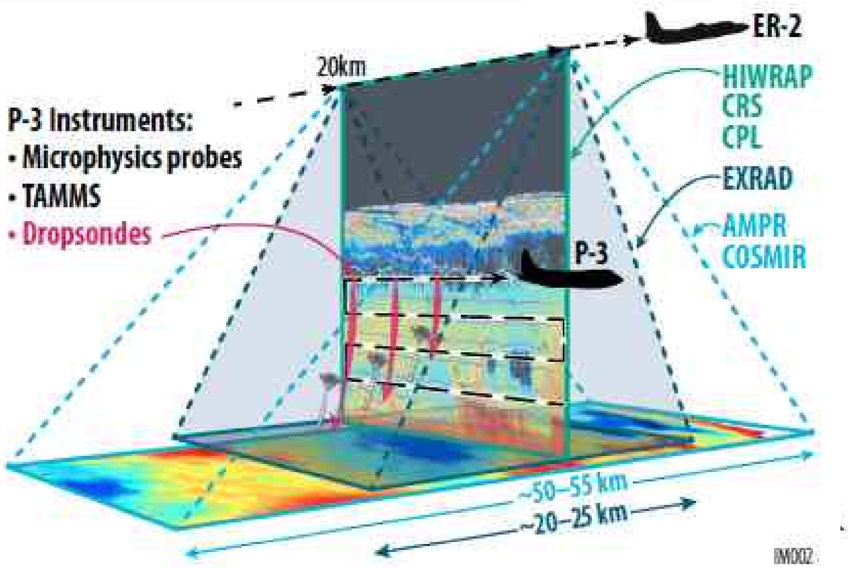
- In 2020, Frequency is all we had (right) for a qualitative idea of SLWC
- Goal: derive a quantitative SLWC product
- Once derived, will compare SLWC product to LWC products from CDP and King (orange and blue, left) to explore valid conditions in which RICE Probe performs





IMPACTS 2020

- Investigation of Microphysics and Precipitation of Atlantic Coast Threatening Snowstorms
- NASA P-3 Orion for in-situ measurements collocated with the “satellite simulating” NASA ER-2 aircraft.



NASA P-3 Orion


PHIPS/2DS


RICE

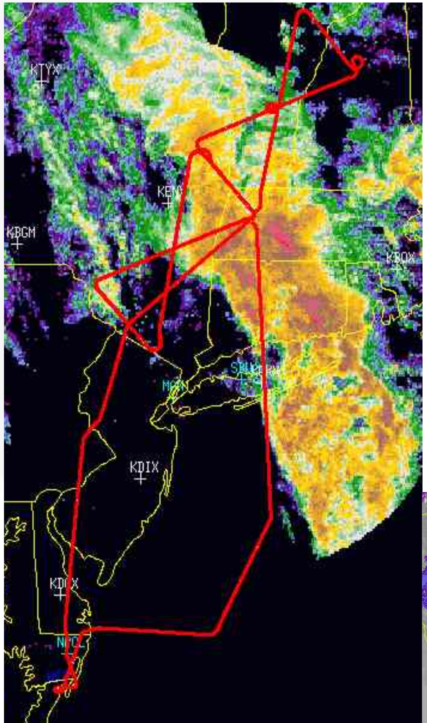

Hotwire Boom:
CDP
King
Nevzorov

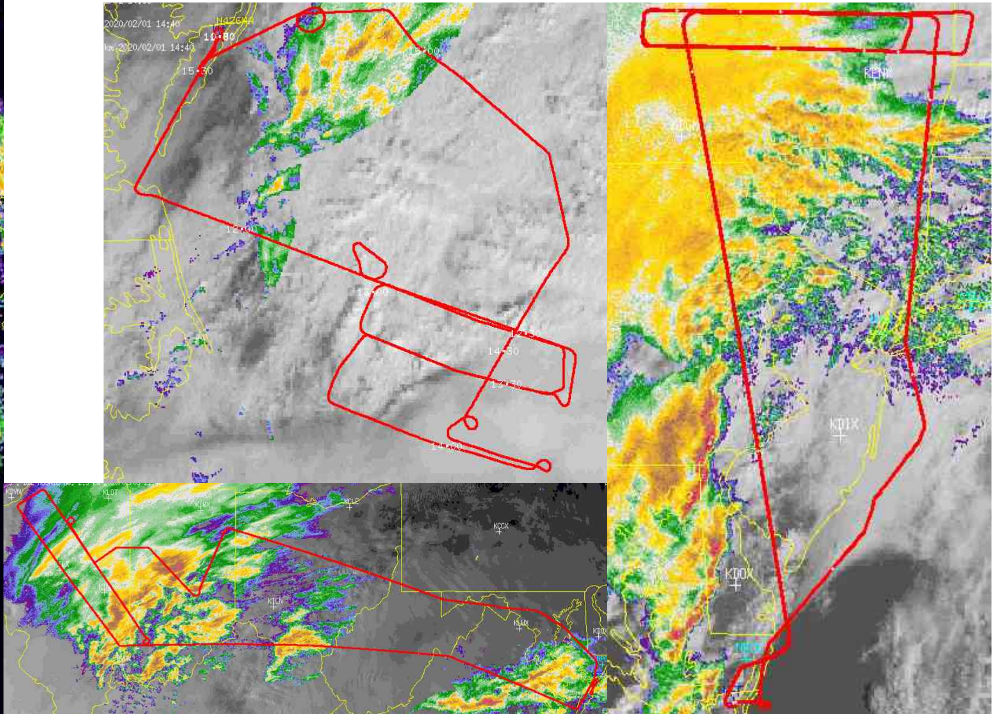

Hawkeye


HVPS-3 B/A

2020 Flights

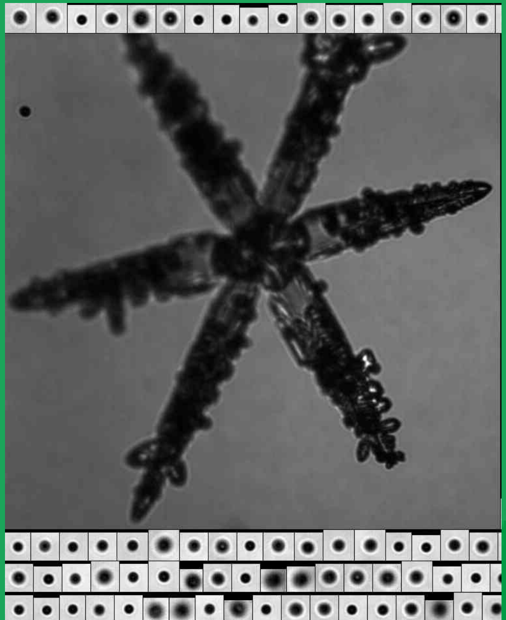
- P-3 was involved in 9 flights in 2020
- CDP, King Probe, and RICE Probe all available on flights 2-5





UNIVERSITY OF NORTH DAKOTA

Methods and Results Part 1: Supercooled Liquid Water Content Derivation



SLWC Overview

- SLWC Derivation via comparison technique
- From Mazin et al (2001):

$$W_m = \frac{\frac{-dF}{dt} \cdot k}{2 R_c l U}$$

- Only unknown on RHS is the k coefficient
- k coefficient must be empirically defined

Constant /Variable	Description	Unit
W_m	SLWC	g/m^3
-dF/dt	Negative change in Freq. over time	Hz/s
k	Coefficient	unitless
R_c	Cylinder radius	m
l	Cylinder length	m
U	True Air Speed	m/s

SLWC Overview

- Rearrange Mazin et al (2001):

$$k = 2 R_c l U W_m * -\frac{dt}{dF}$$

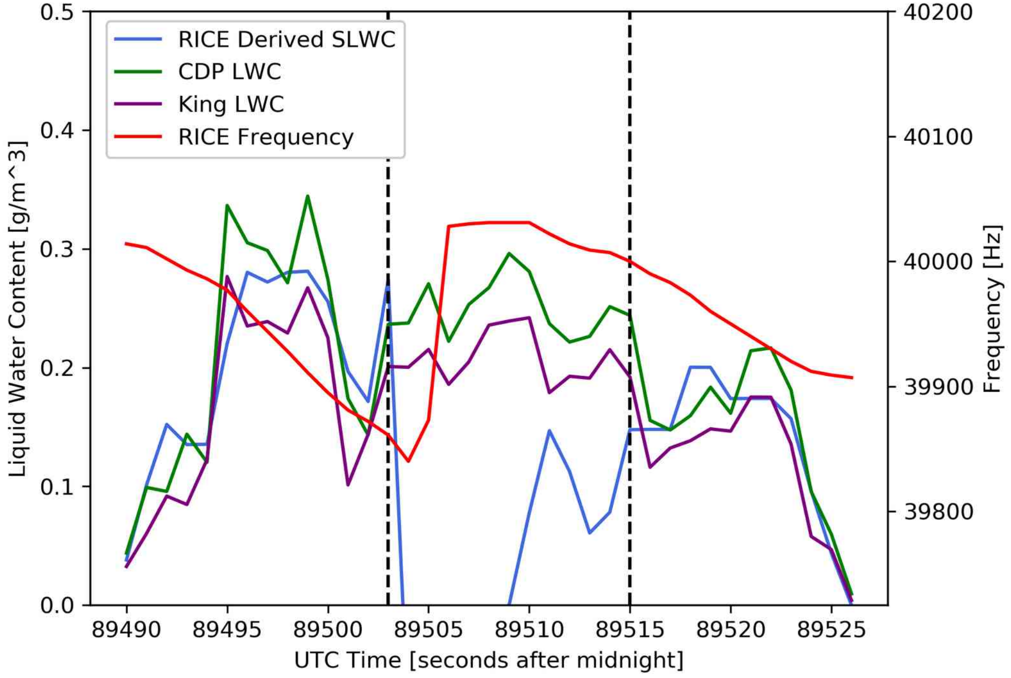
- For W_m, LWC values are taken from King Probe or CDP in cases of:
  - strong ice accretion
  - ice-free conditions
  - sufficiently cold enough to assume LWC = SLWC

Constant /Variable	Description	Unit
W_m	LWC	g/m^3
-dF/dt	Negative change in Freq. over time	Hz/s
k	Coefficient	unitless
R_c	Cylinder radius	m
l	Cylinder length	m
U	True Air Speed	m/s

UND UNIVERSITY OF NORTH DAKOTA

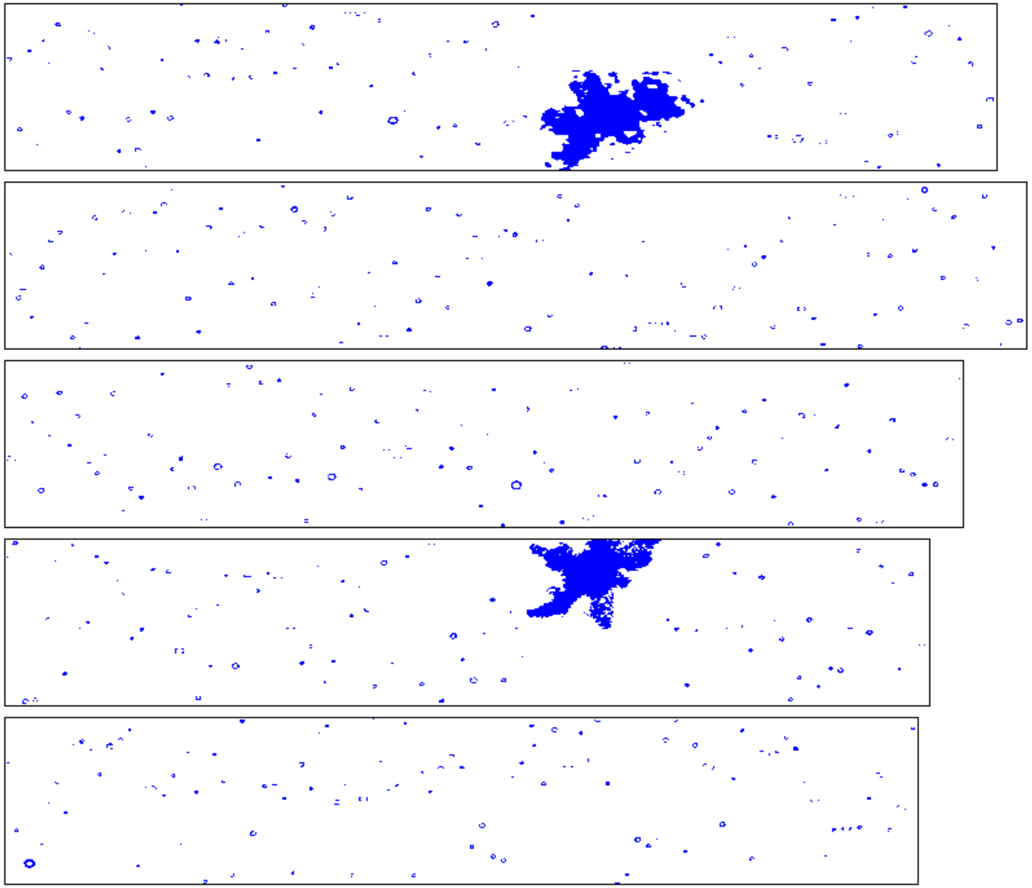
Case Selection

- Strong ice accretion: when RICE Probe accreted ~0.5 mm of ice to trigger a de-icing heater cycle (when frequency sharply goes from ~39.8 kHz to 40 kHz)
- Consecutive cases joined, time from when heater tripped to probe cooling off was omitted
- Cases through 4 flights: 60



Case Selection

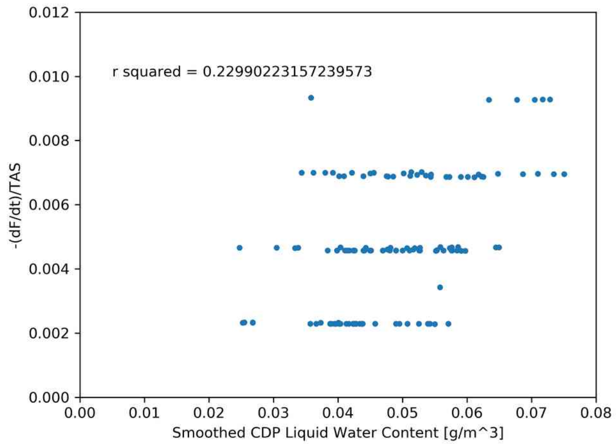
- Ice-free conditions: particles on 2D-S probe mostly spherical, concentration of particles >100 µm <10^4 m^{-3}, mean volume diameter (MVD) <50 µm
- Right: a case that had some ice particles but still within concentration threshold
- Cases through 4 flights: 9



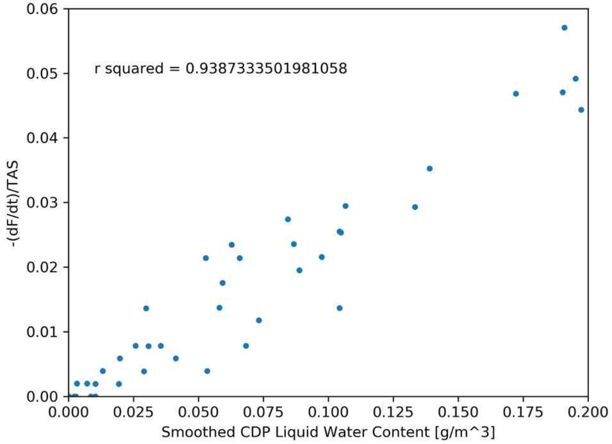
Case Selection

- Cold enough: At warmer sub-zero °C temperatures, RICE will incompletely freeze due to the Ludlam Limit
- Based on precedent from Cober et al (2001), -3 °C was chosen as an upper limit for cases
- Cases through 4 flights: 8

Above: Omitted case with max temp above -3 °C



Below: Typical case with max temp below -3 °C

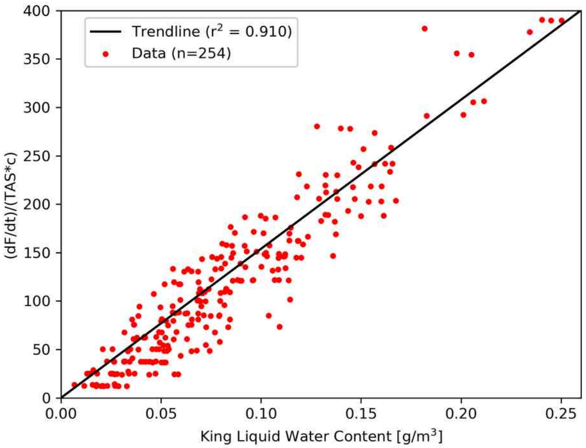


SLWC Derivation

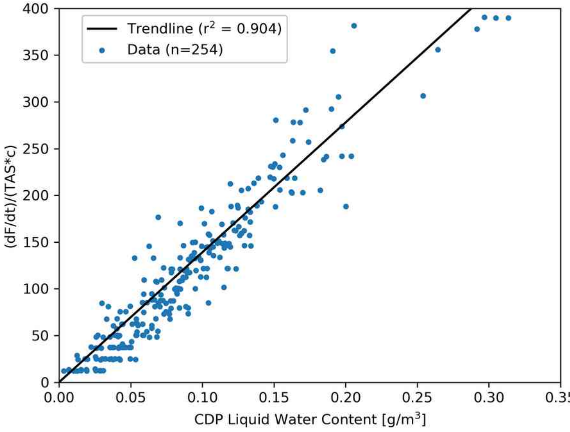
- After some QC, k is empirically derived
- Scatterplots made of the 254 data points of the 8 valid cases, k is the slope of the trendline
- X axis: LHS of Mazin et al (2001)
- Y axis: RHS of Mazin et al (2001) except k

$$W_m = \frac{\frac{-dF}{dt} \cdot k}{2 R_c l U}$$

Above: Scatterplot using King Probe LWC



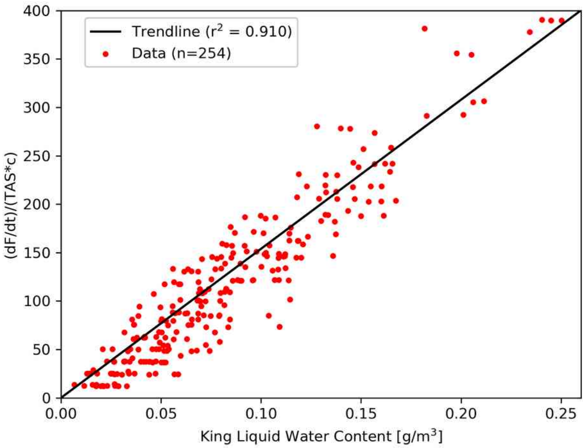
Below: Scatterplot using CDP LWC



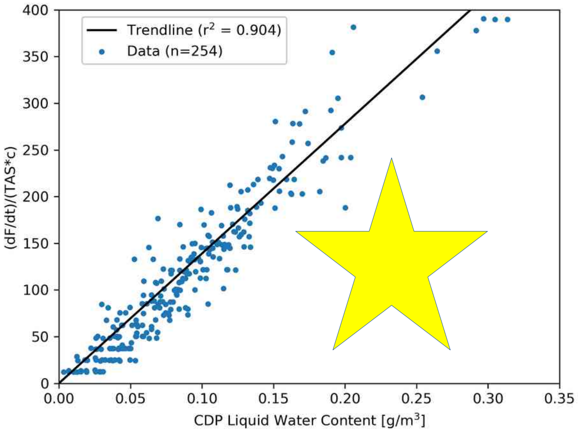
SLWC Derivation

- King Probe derived k = 6.496×10^{-4}
- CDP derived k = 7.195×10^{-4}
- CDP chosen, as King Probe was theorized to suffer from a drifting baseline from long in-cloud periods
- Plots from now on will compare CDP and RICE Probe

Above: Scatterplot using King Probe LWC



Below: Scatterplot using CDP LWC

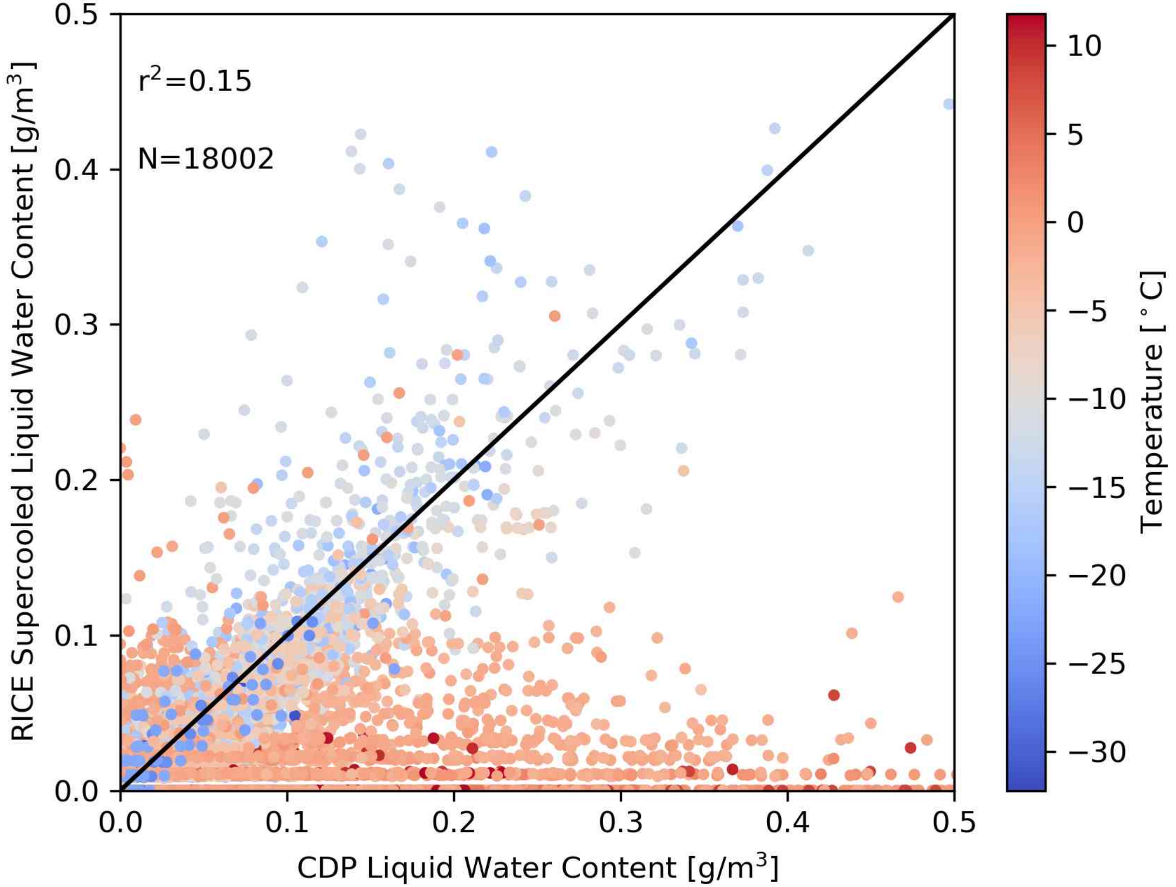


Methods and Results Part 2: Environmental and Aircraft Tests

Joe O'Brien, Greg Sova, Martin Schnaiter, and Kendra Sand working on Cloud Probes.

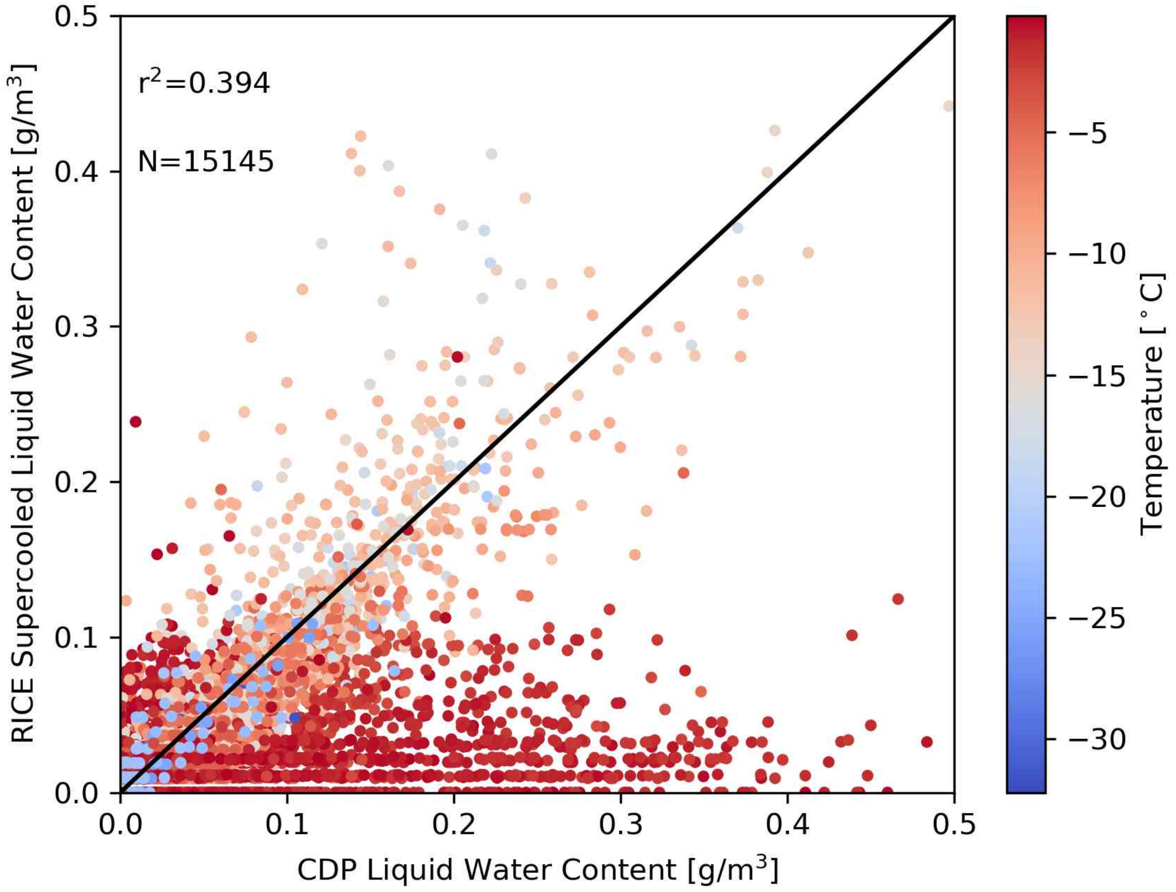
Temperature

- RICE SLWC vs CDP, no filters



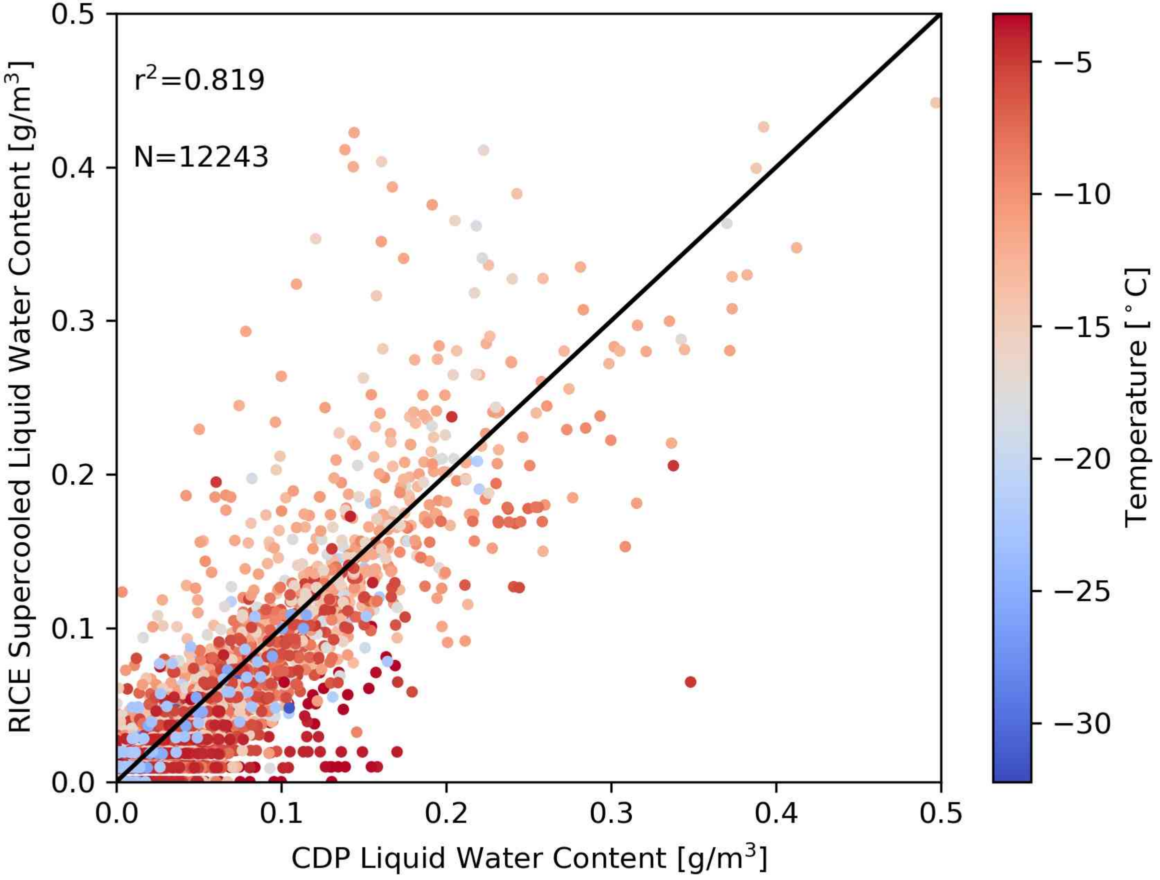
Temperature

- RICE SLWC vs CDP, 0 ℃ maximum temperature



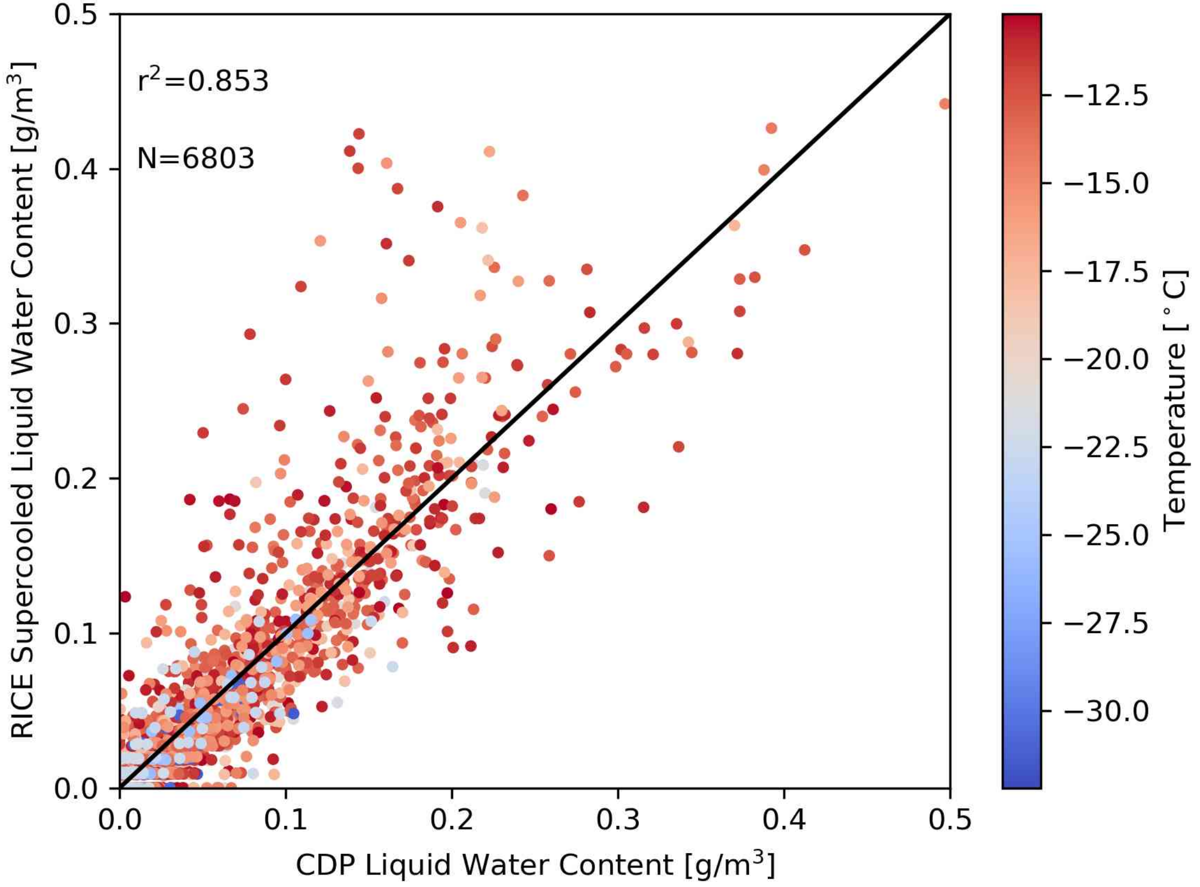
Temperature

- RICE SLWC vs CDP, -3 °C maximum temperature



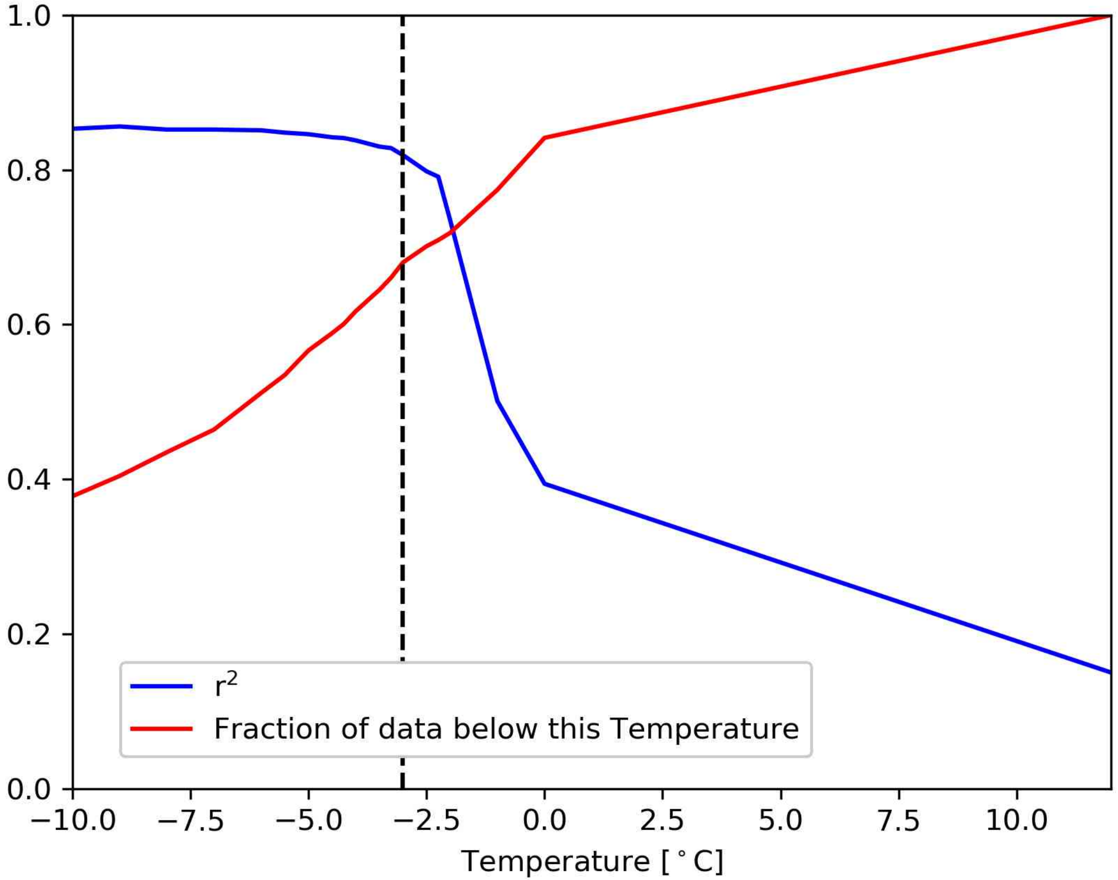
Temperature

- RICE SLWC vs CDP, -10 °C maximum temperature

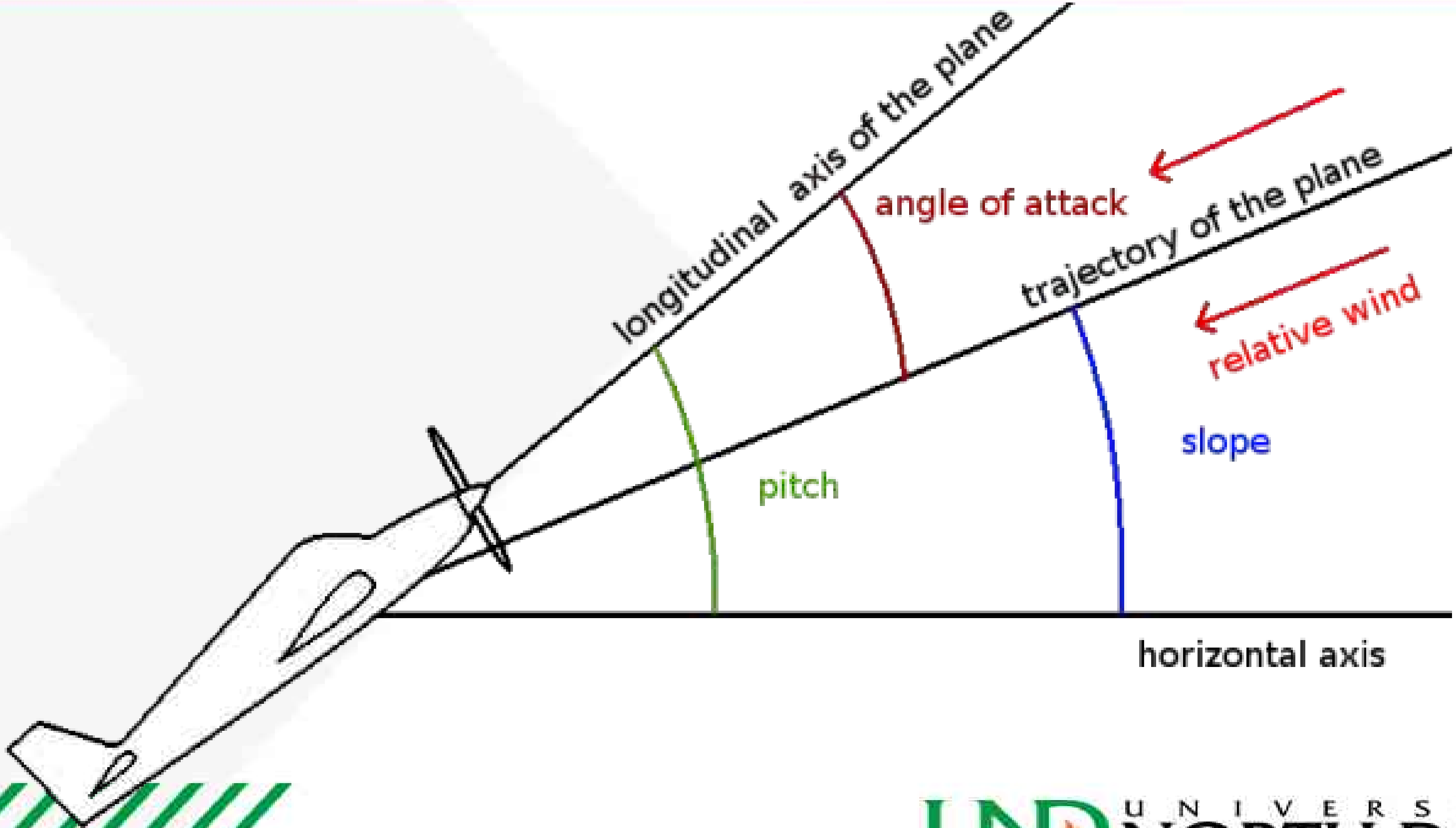


Temperature

- -3 °C optimal for a maximum temperature threshold
- Warmer, and RICE Probe was undermeasuring (Ludlam Limit)
- Cooler, and the correlation was not improving enough to justify loss of data

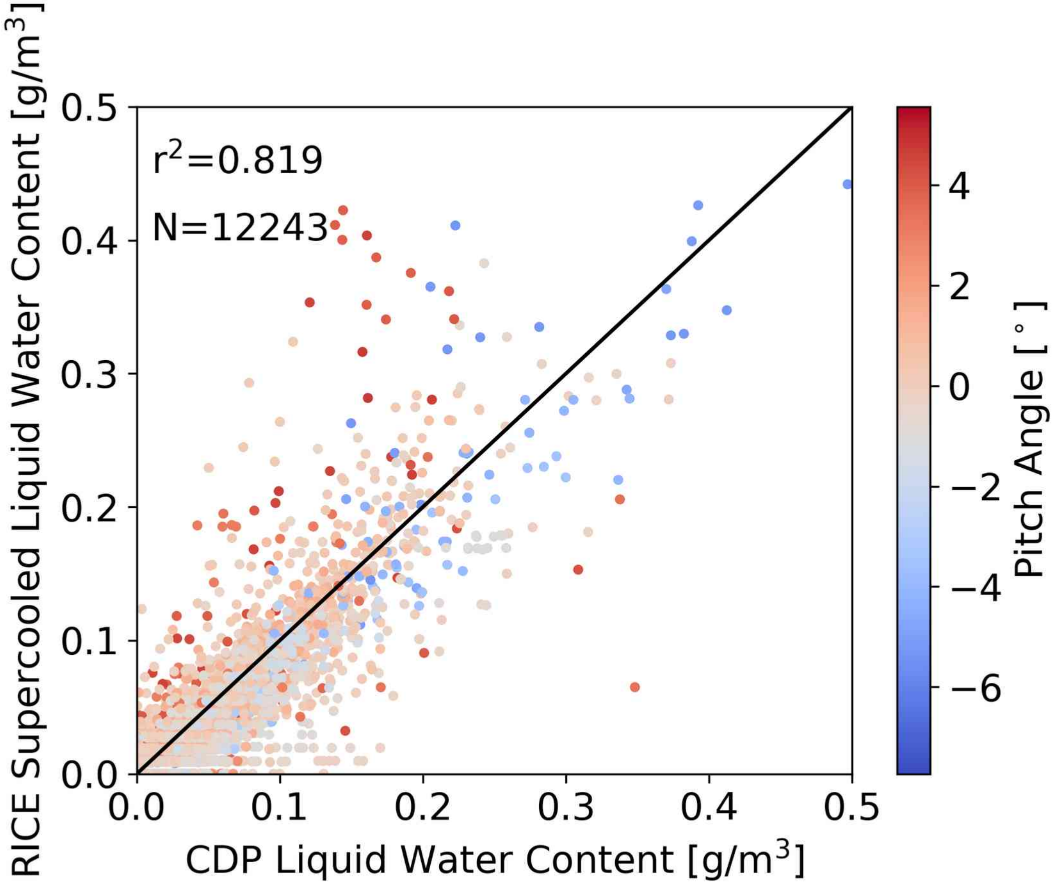


Pitch Angle


longitudinal axis of the plane
angle of attack
trajectory of the plane
relative wind
slope
pitch
horizontal axis

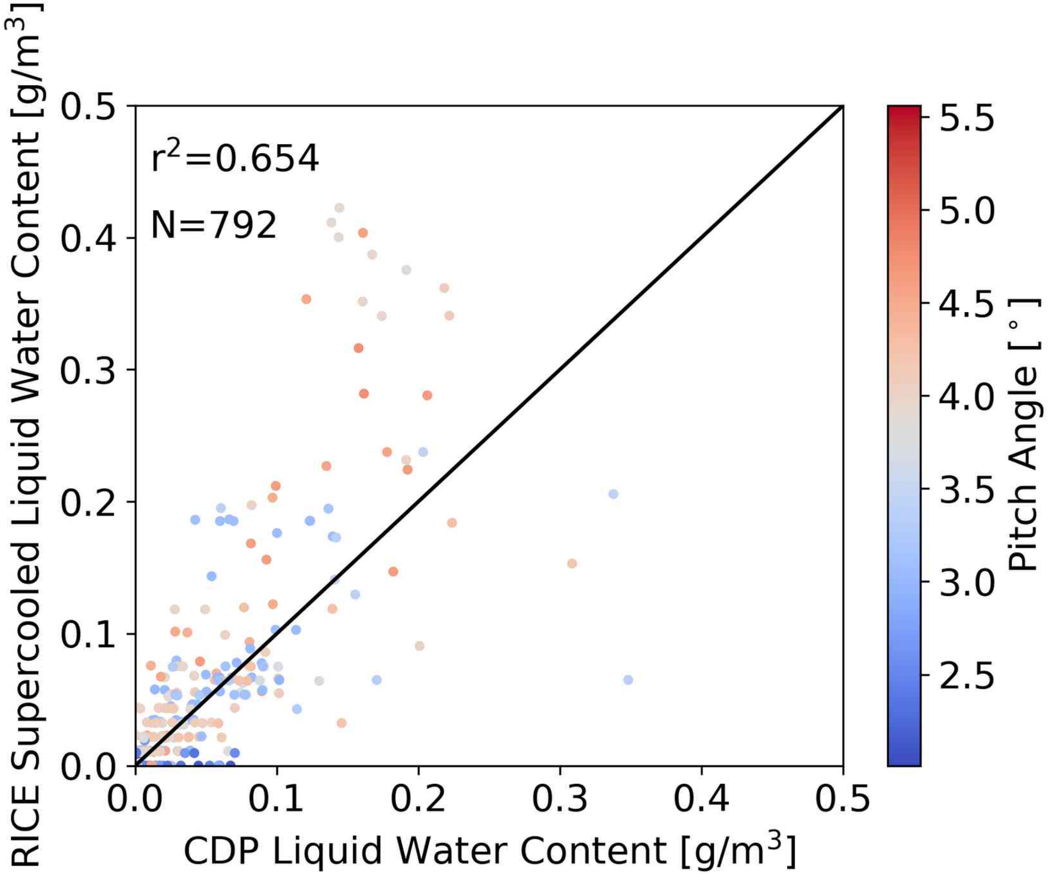
Pitch Angle

- RICE SLWC vs CDP, -3 °C maximum temperature, all pitch angles



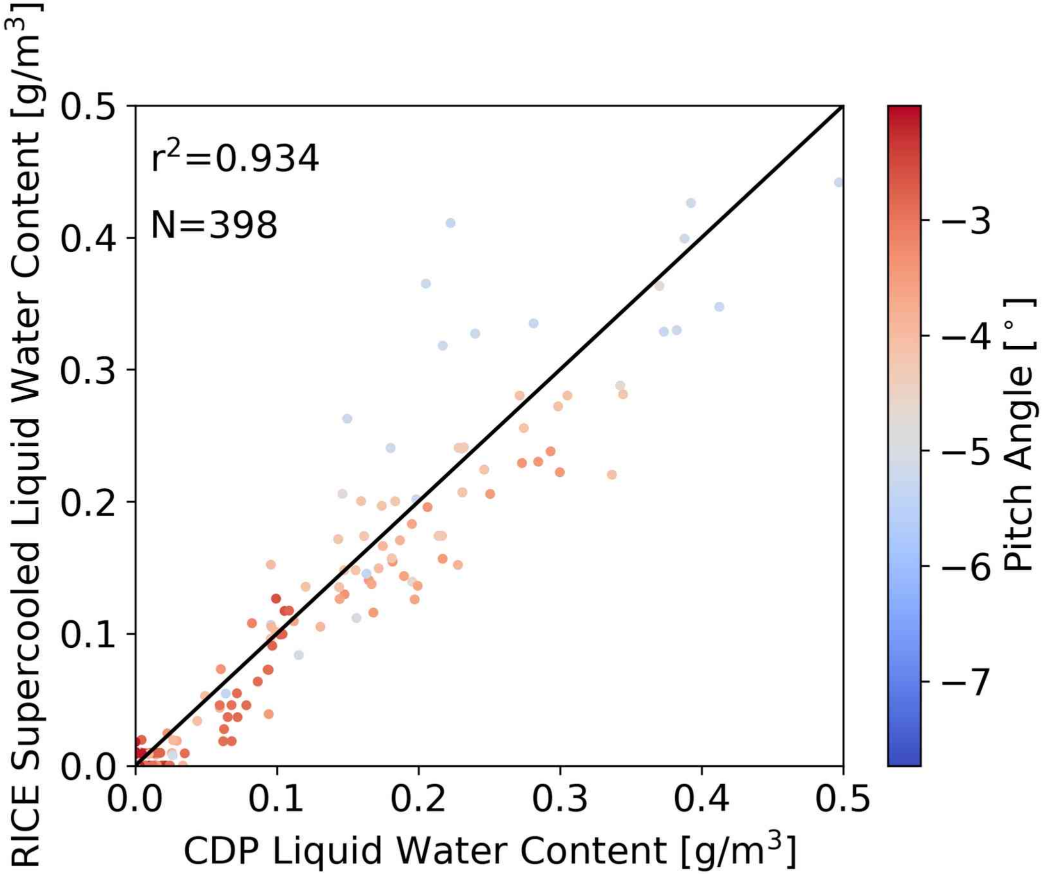
Pitch Angle

- RICE SLWC vs CDP, -3 °C maximum temperature, upward pitch angles (2° and above)



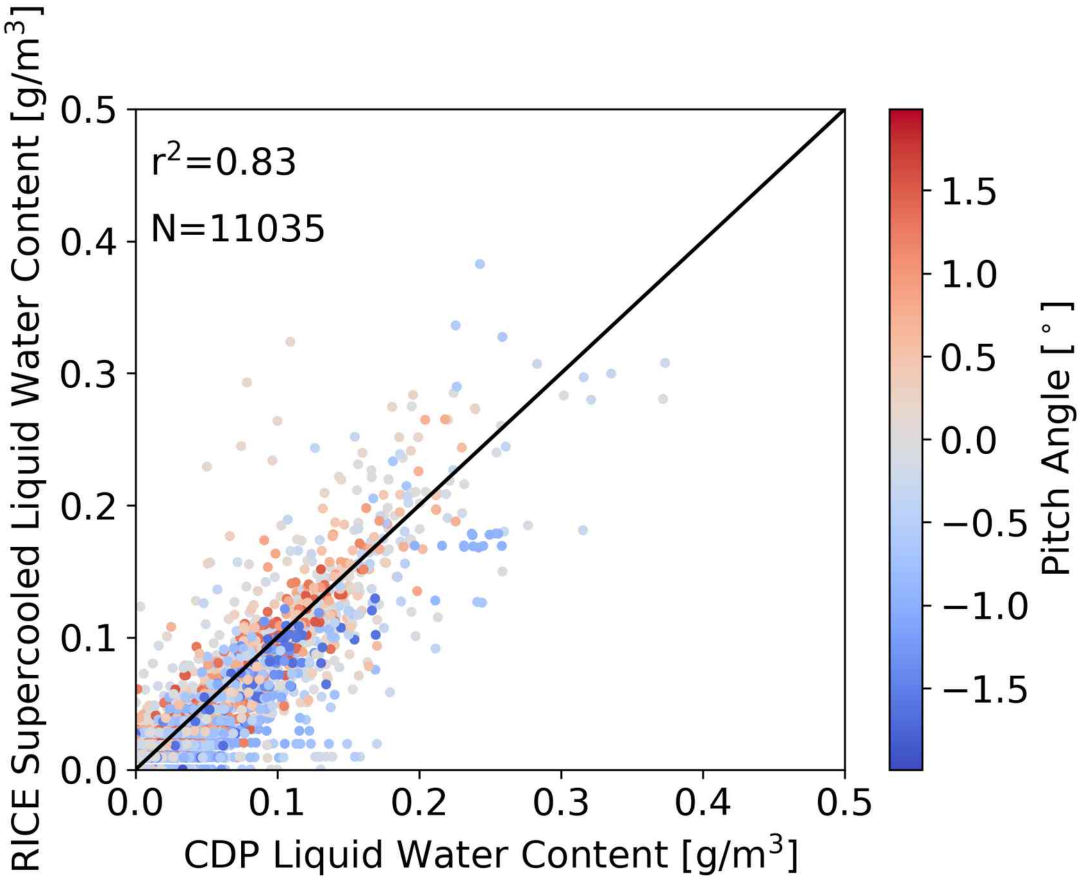
Pitch Angle

- RICE SLWC vs CDP, -3 °C maximum temperature, downward pitch angles (-2° and below)



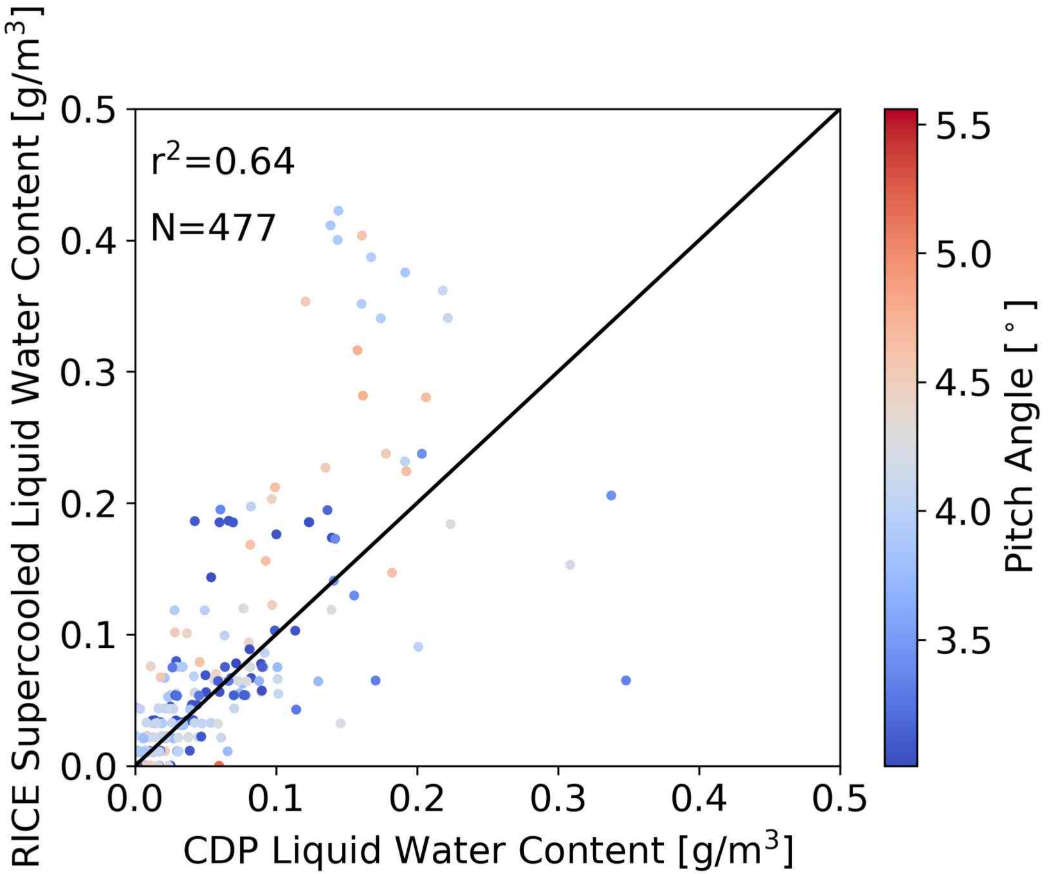
Pitch Angle

- RICE SLWC vs CDP, -3 ℃ maximum temperature, level pitch (±2°)



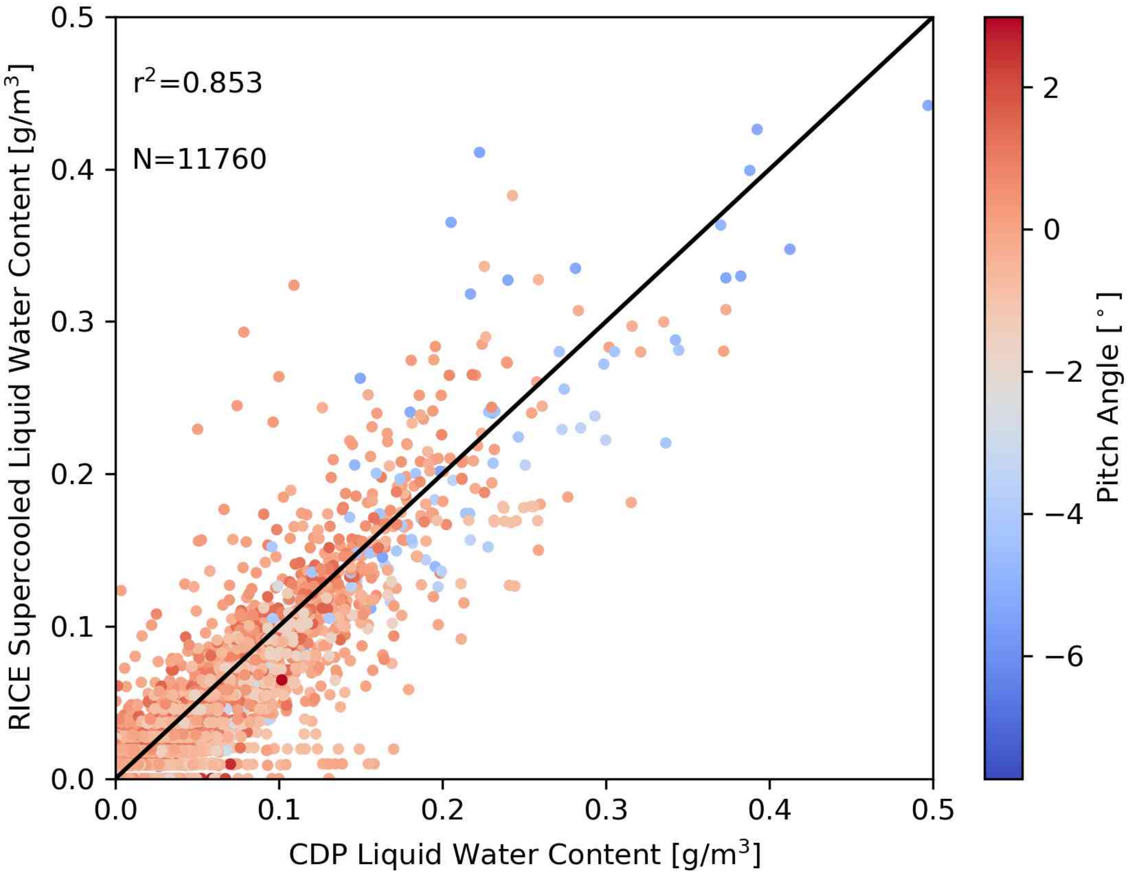
Pitch Angle

- RICE SLWC vs CDP, -3 °C maximum temperature, pitch 3° and above

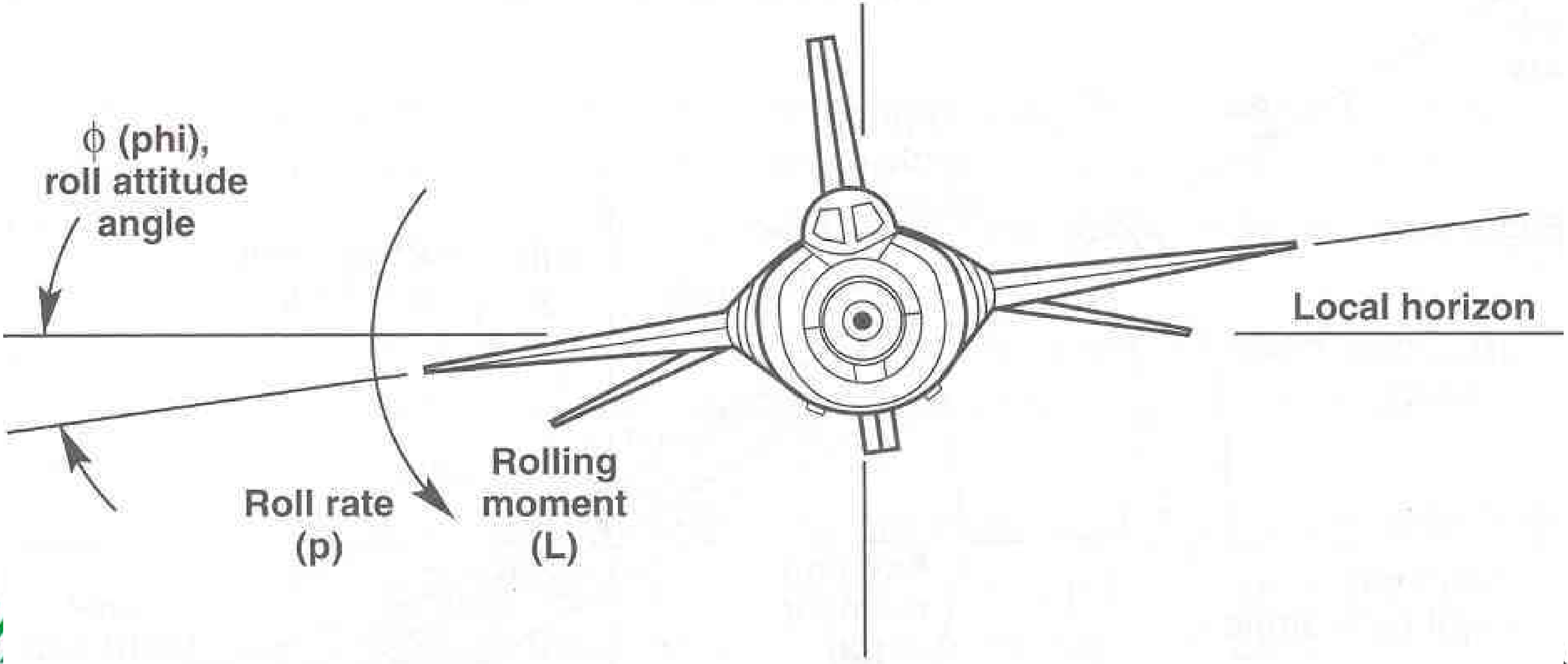


Pitch Angle

- RICE SLWC vs CDP, -3 °C maximum temperature, pitch 3° and below

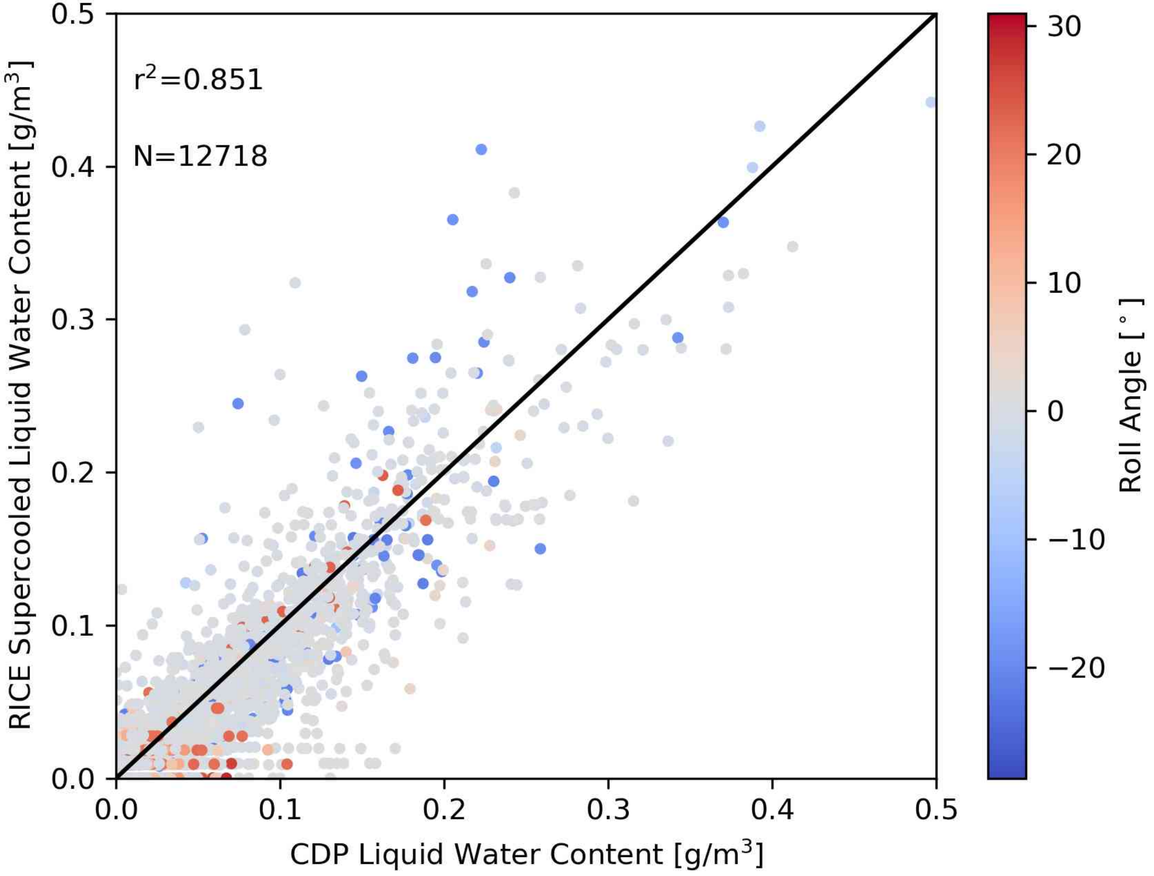


Roll Angle


ϕ (phi),
roll attitude
angle
Local horizon
Roll rate
(p)
Rolling
moment
(L)

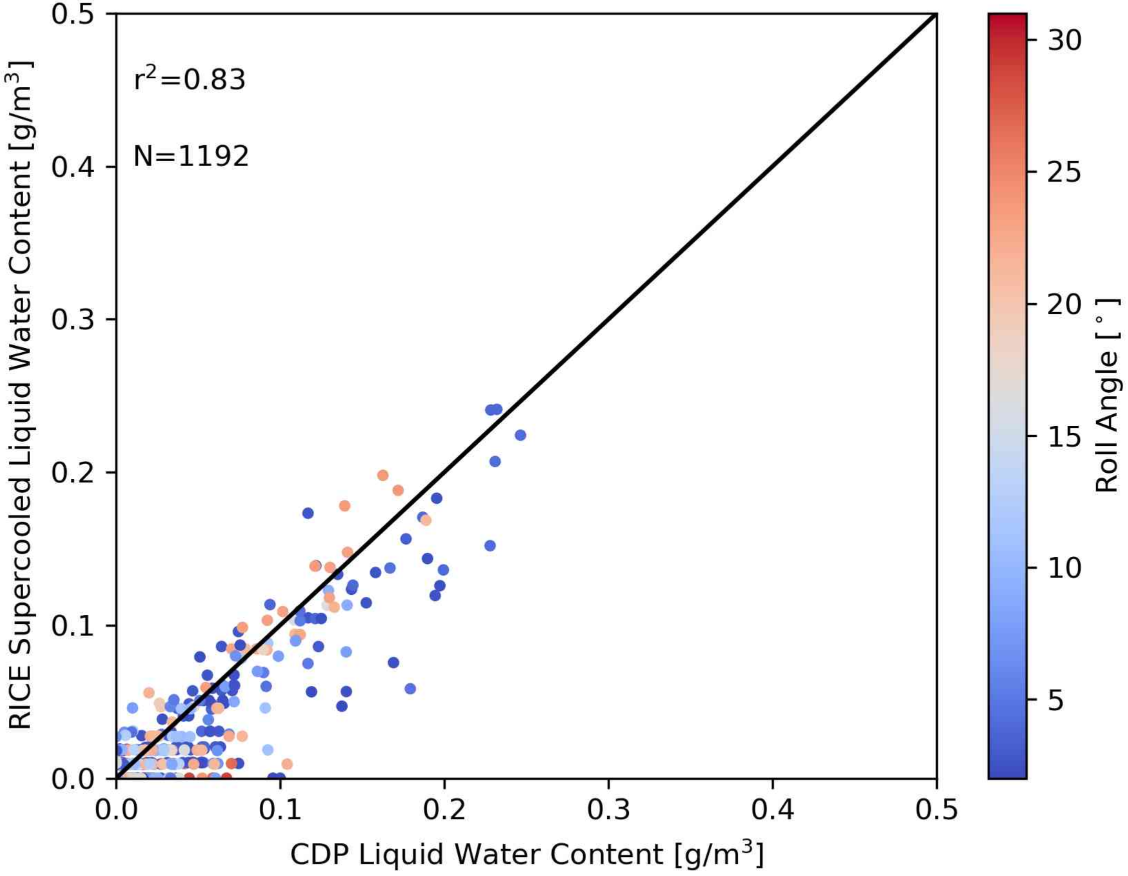
Roll Angle

- RICE SLWC vs CDP, -3 °C maximum temperature, pitch 3° and below, all roll angles



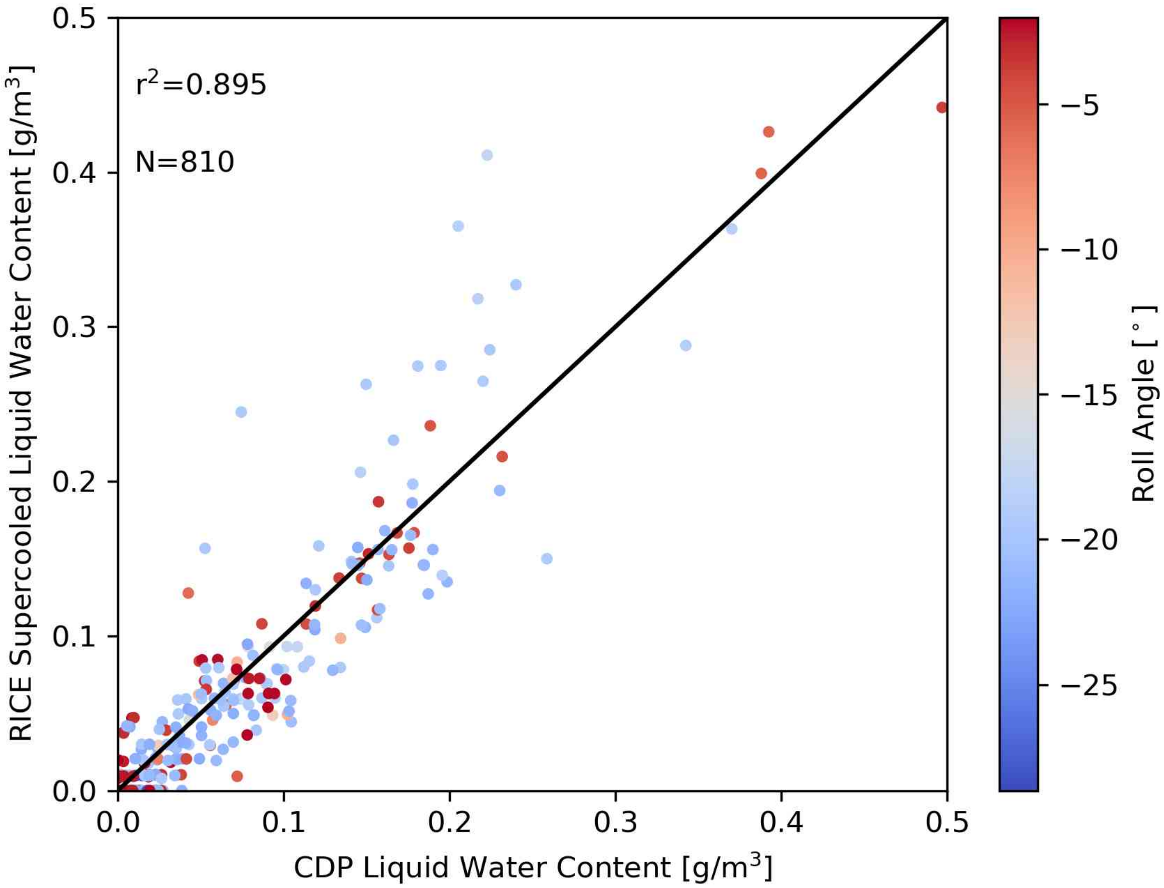
Roll Angle

- RICE SLWC vs CDP, -3 °C maximum temperature, pitch 3° and below, left roll angles (2° and above)



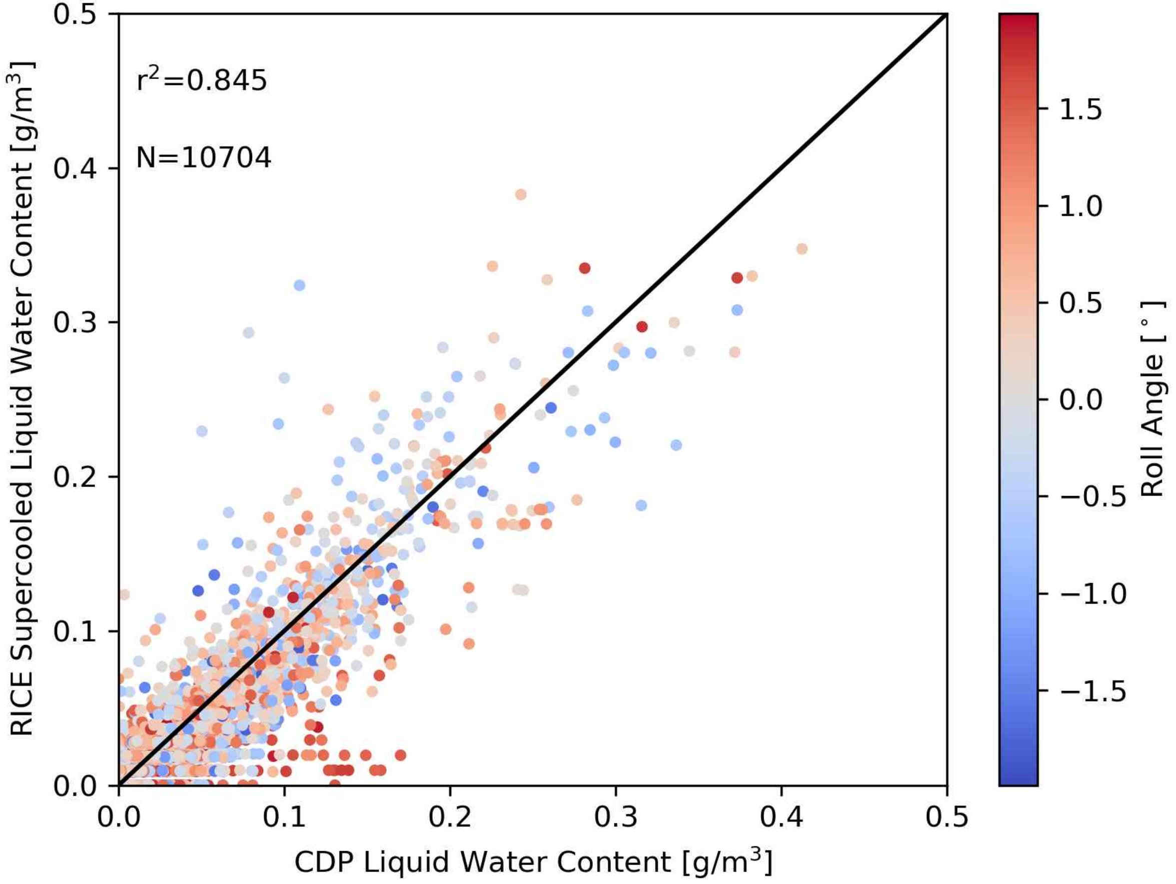
Roll Angle

- RICE SLWC vs CDP, -3 °C maximum temperature, pitch 3° and below, right roll angles (-2° and below)



Roll Angle

- RICE SLWC vs CDP, -3 °C maximum temperature, pitch 3° and above, level roll angles ($\pm$2°)

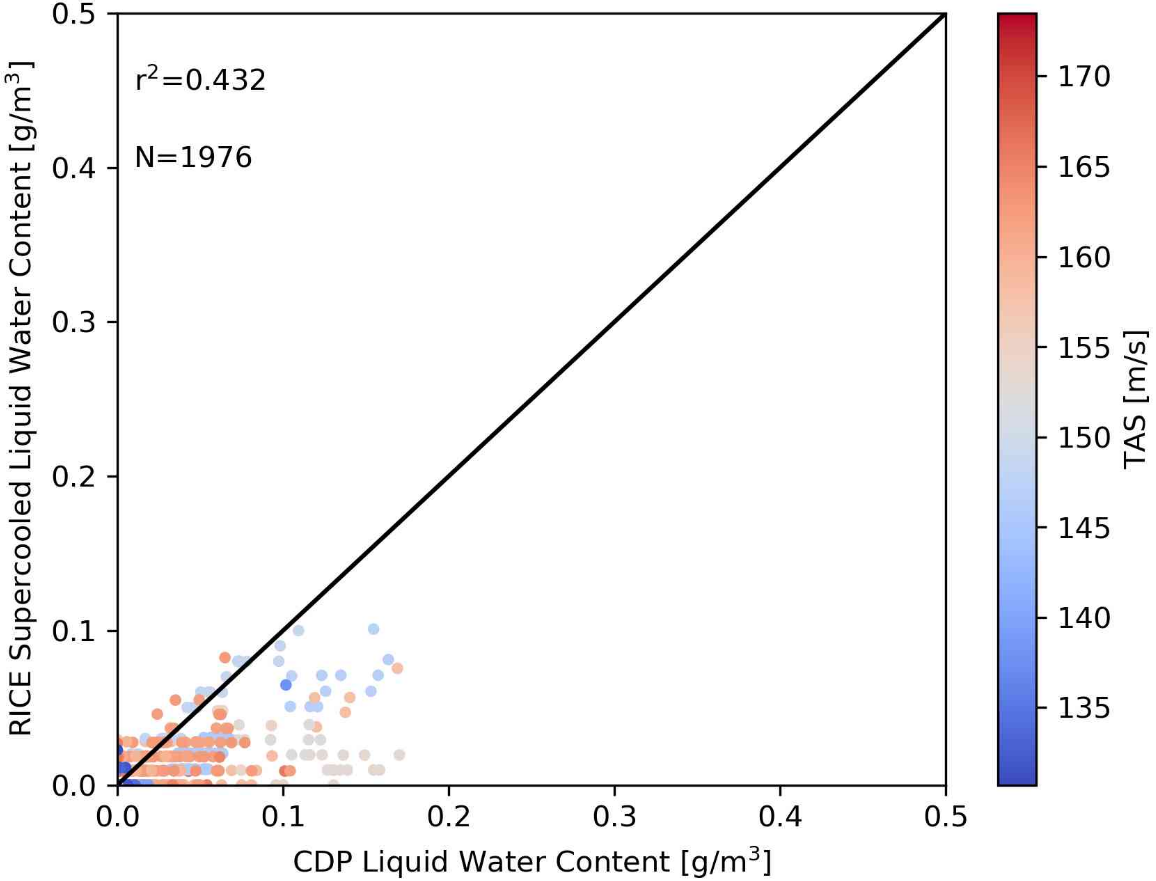


True Air Speed (TAS)

- Air speed relative to the airmass, or air speed corrected for pressure
- Ludlam limit is linked to TAS
  - Higher TAS = higher volume of supercooled water at a given time
    - Higher volume of water = more heat released in phase transition
  - Higher TAS = adiabatic compression is higher, thus more heat added
- Therefore, when near the temperature threshold, slower TAS should be more effective

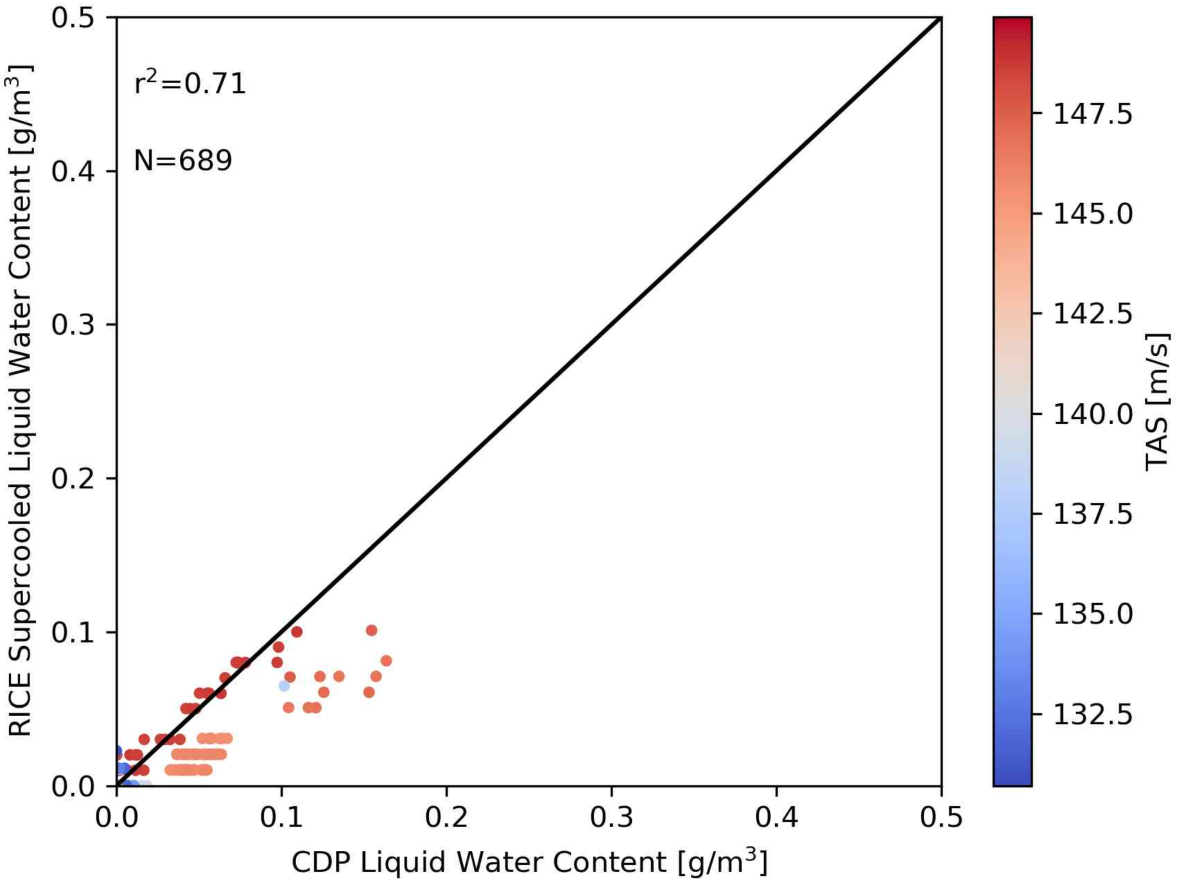
True Air Speed (TAS)

- RICE SLWC vs CDP, pitch 3° and below, no TAS limit, -5 °C < T < -3 °C



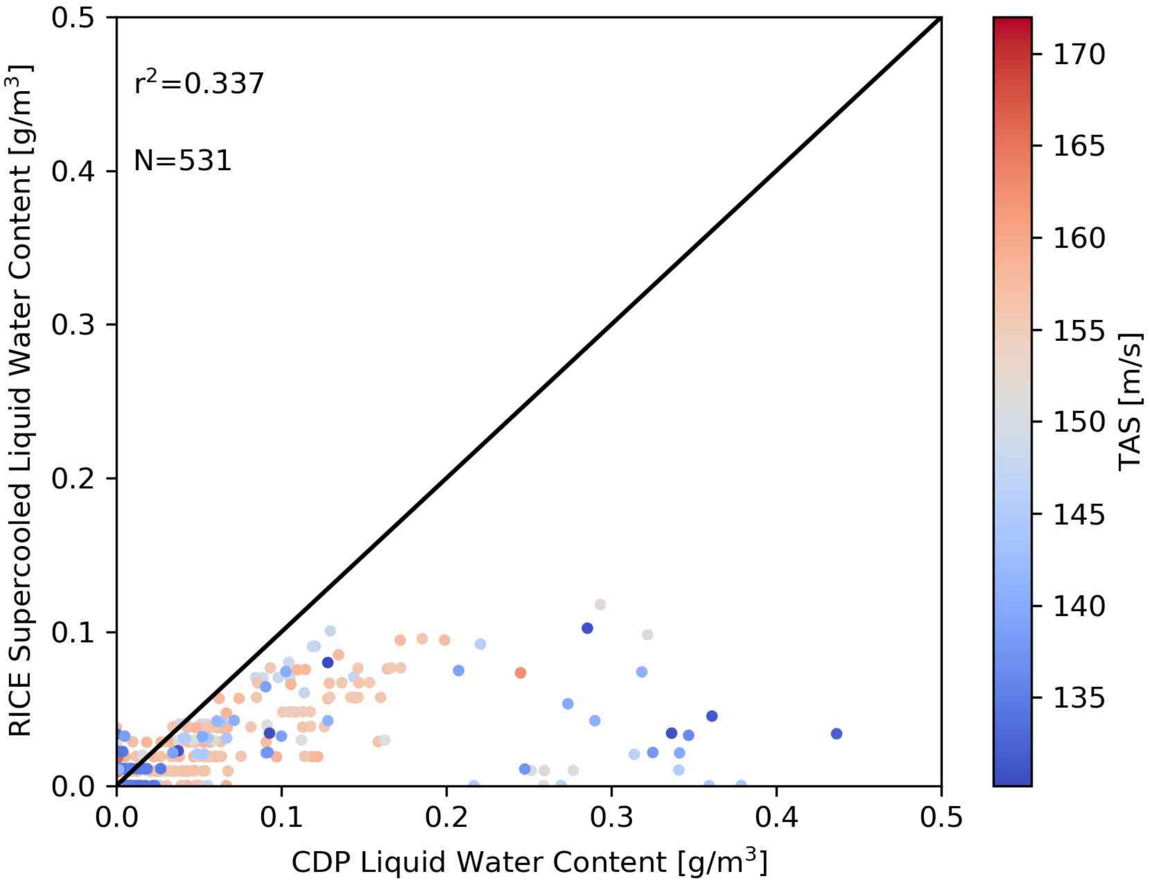
True Air Speed (TAS)

- RICE SLWC vs CDP, pitch 3° and below, TAS < 150 m/s,
  -5 °C < T < -3 °C



True Air Speed (TAS)

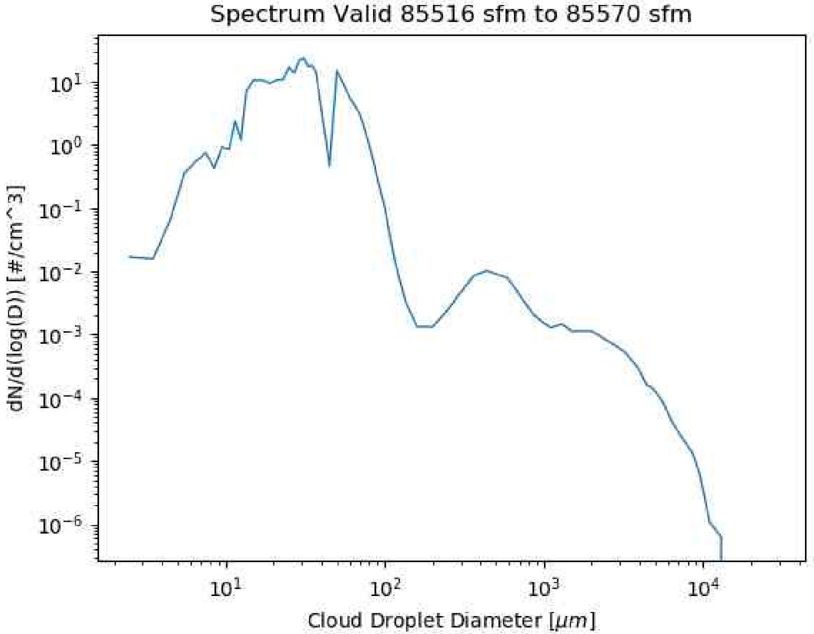
- RICE SLWC vs CDP, pitch 3° and below, no TAS limit, -3 °C < T < -2 °C



Mean Volume Diameter (MVD)

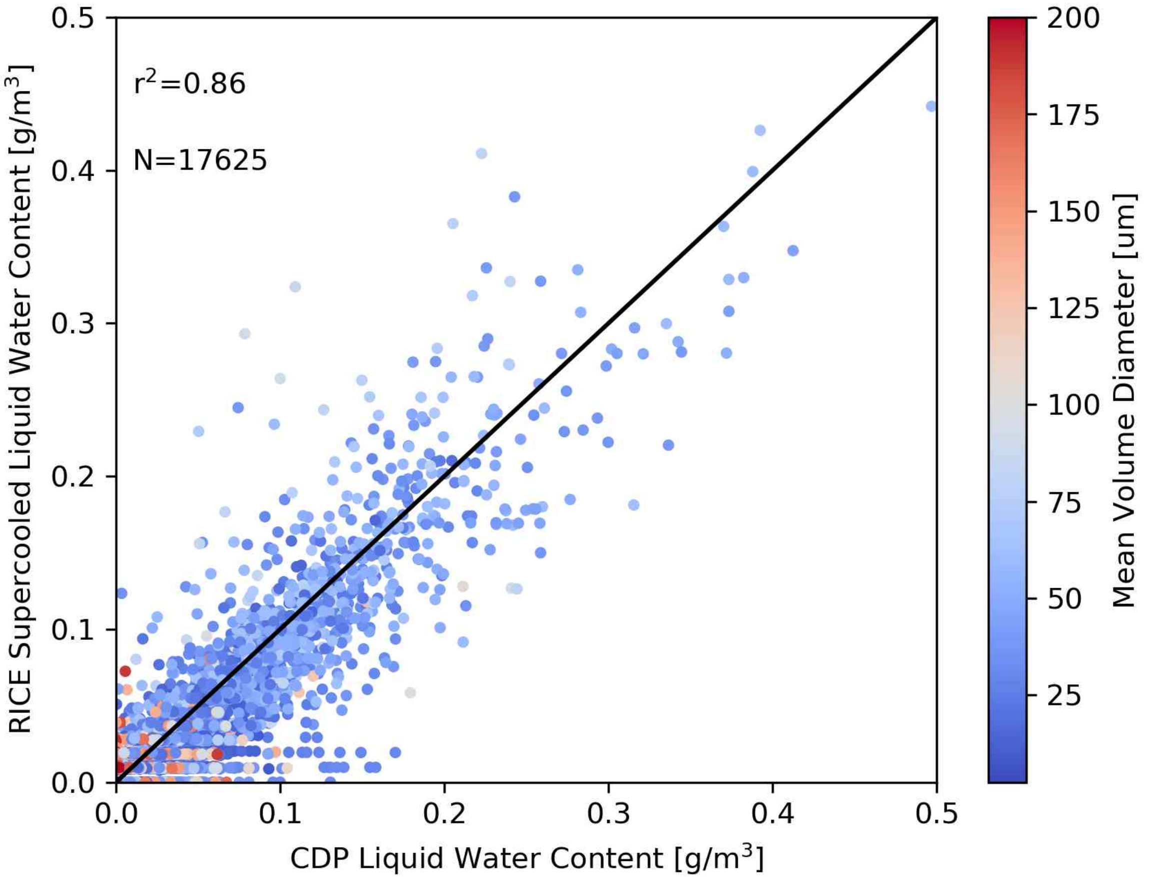
- The mean diameter weighted by volume
- Increases the contribution of larger particles in the mean diameter calculation
- MVD and Total Concentration calculated for particles under 200 µm to reduce the influence of ice

$$MVD = \frac{\sum_{i=1}^{m} V_i d_i}{\sum_{i=1}^{m} V_i}$$



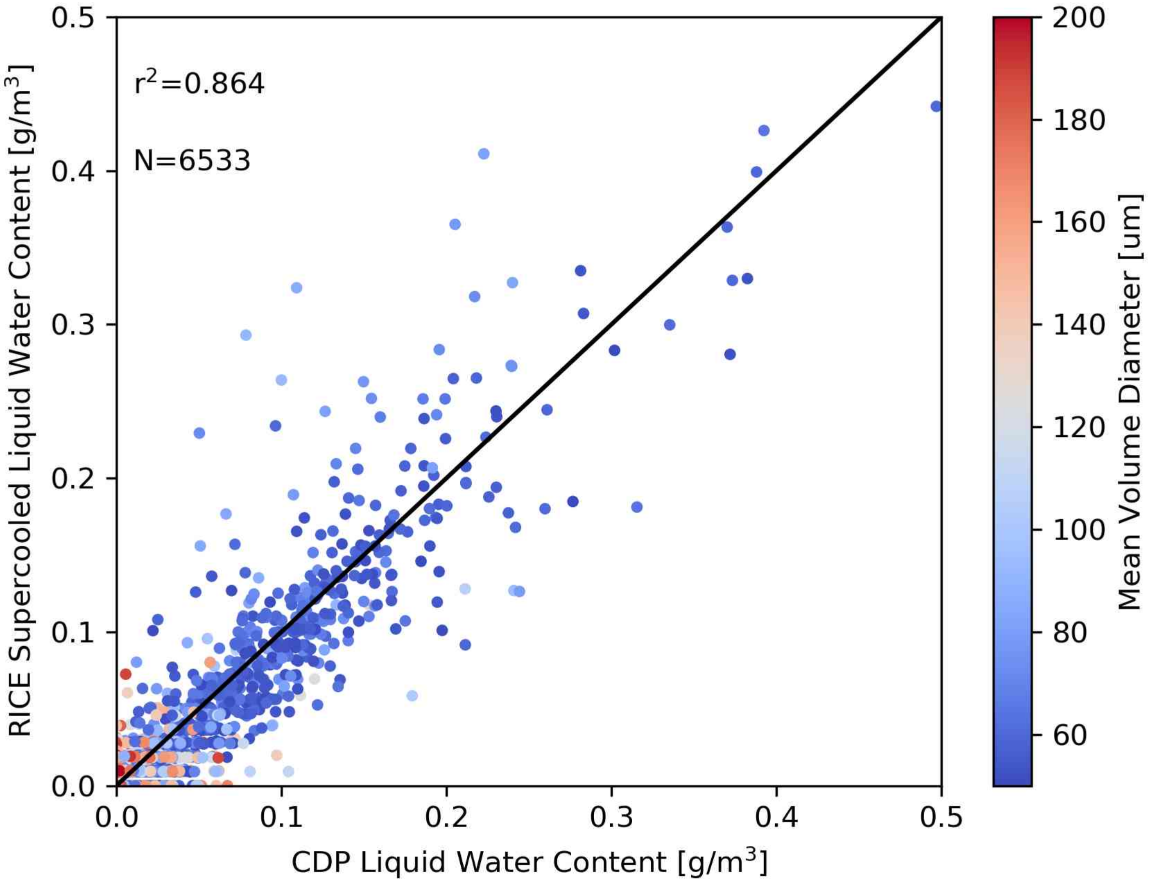
Mean Volume Diameter (MVD)

- RICE SLWC vs CDP, -3 °C maximum temperature, pitch 3° and below, no MVD threshold



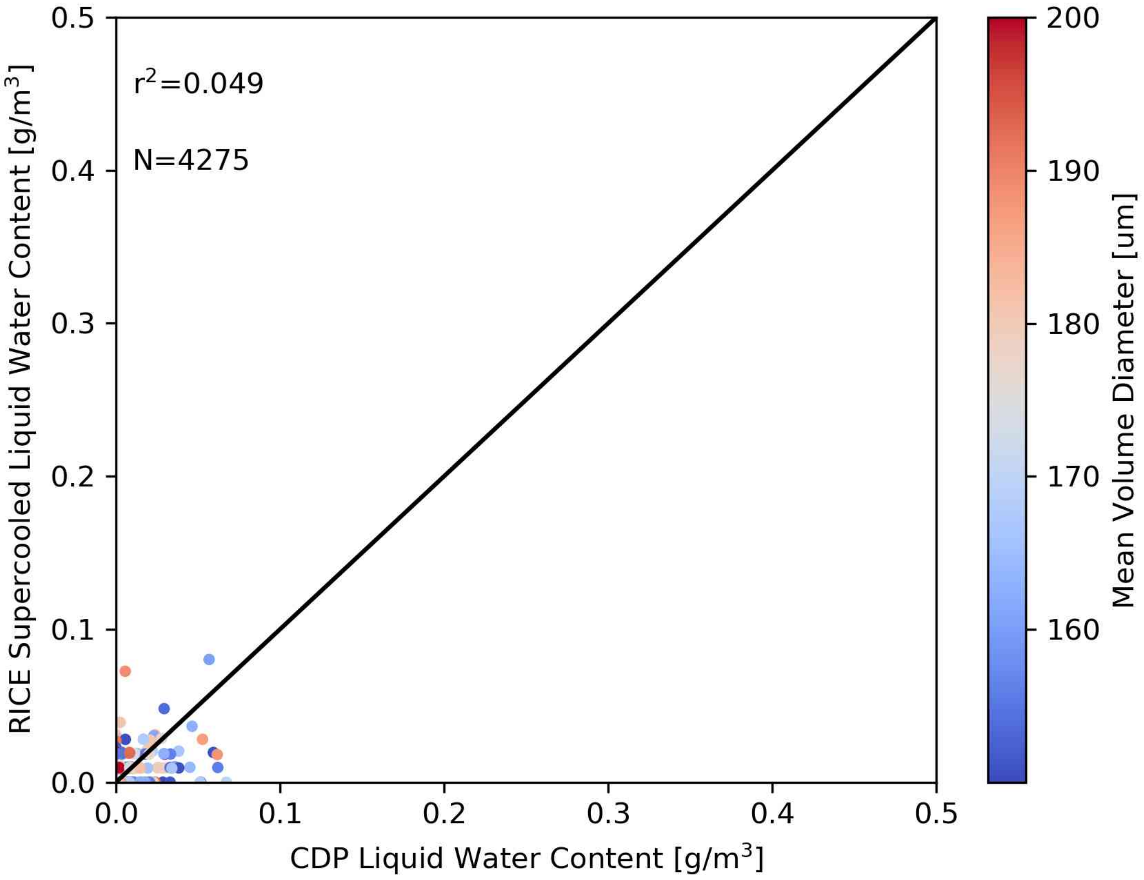
Mean Volume Diameter (MVD)

- RICE SLWC vs CDP, -3 °C maximum temperature, pitch 3° and below,
  50 µm < MVD < 200 µm



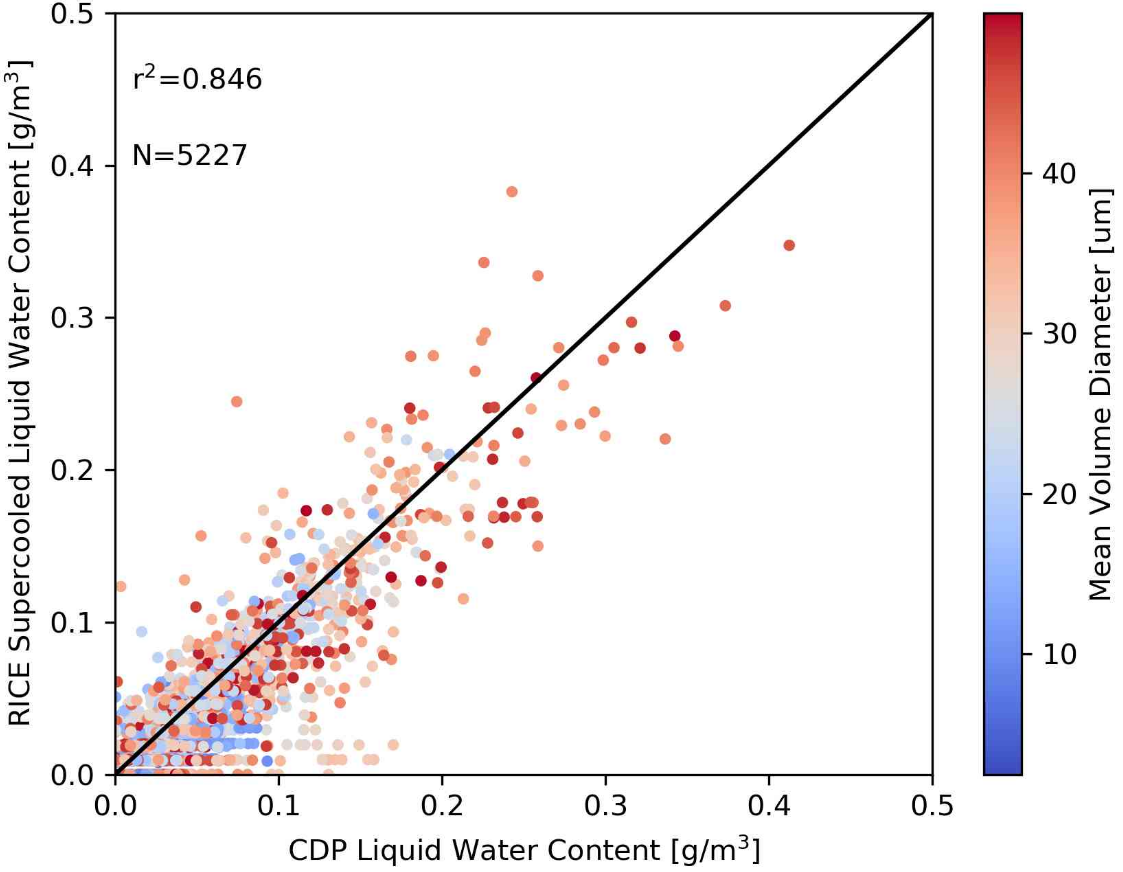
Mean Volume Diameter (MVD)

- RICE SLWC vs CDP, -3 °C maximum temperature, pitch 3° and below,
150 µm < MVD < 200 µm



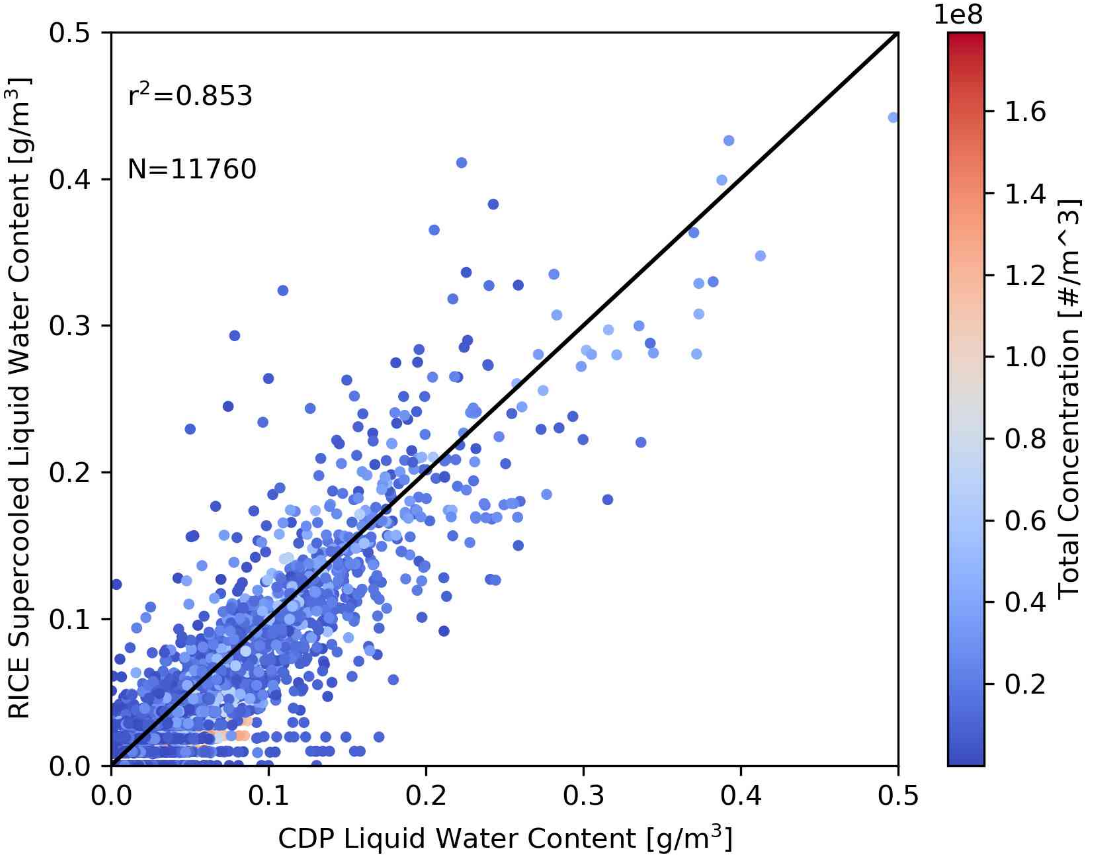
Mean Volume Diameter (MVD)

- RICE SLWC vs CDP, -3 °C maximum temperature, pitch 3° and below, MVD below 50 µm



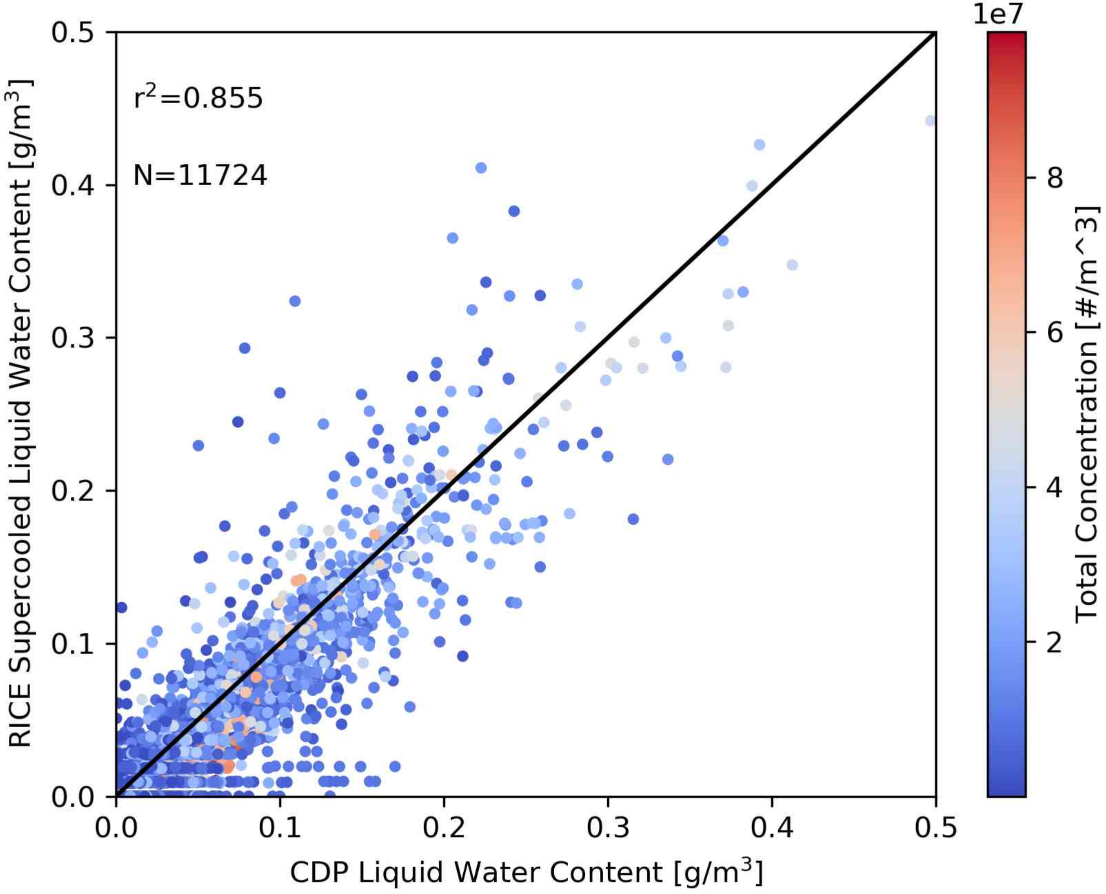
Total Concentration

- RICE SLWC vs CDP, -3 °C maximum temperature, pitch 3° and below, no concentration limits



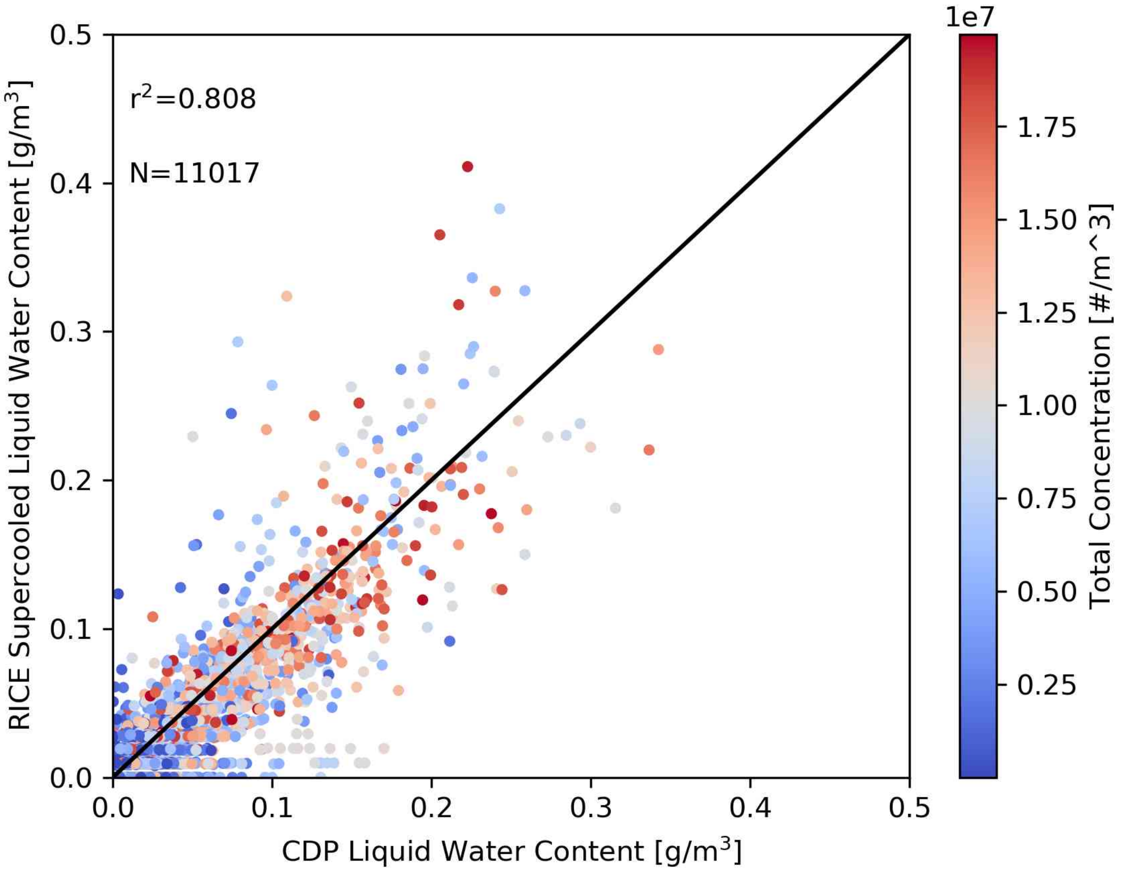
Total Concentration

- RICE SLWC vs CDP, -3 °C maximum temperature, pitch 3° and below, concentration less than $10^8/m^3$



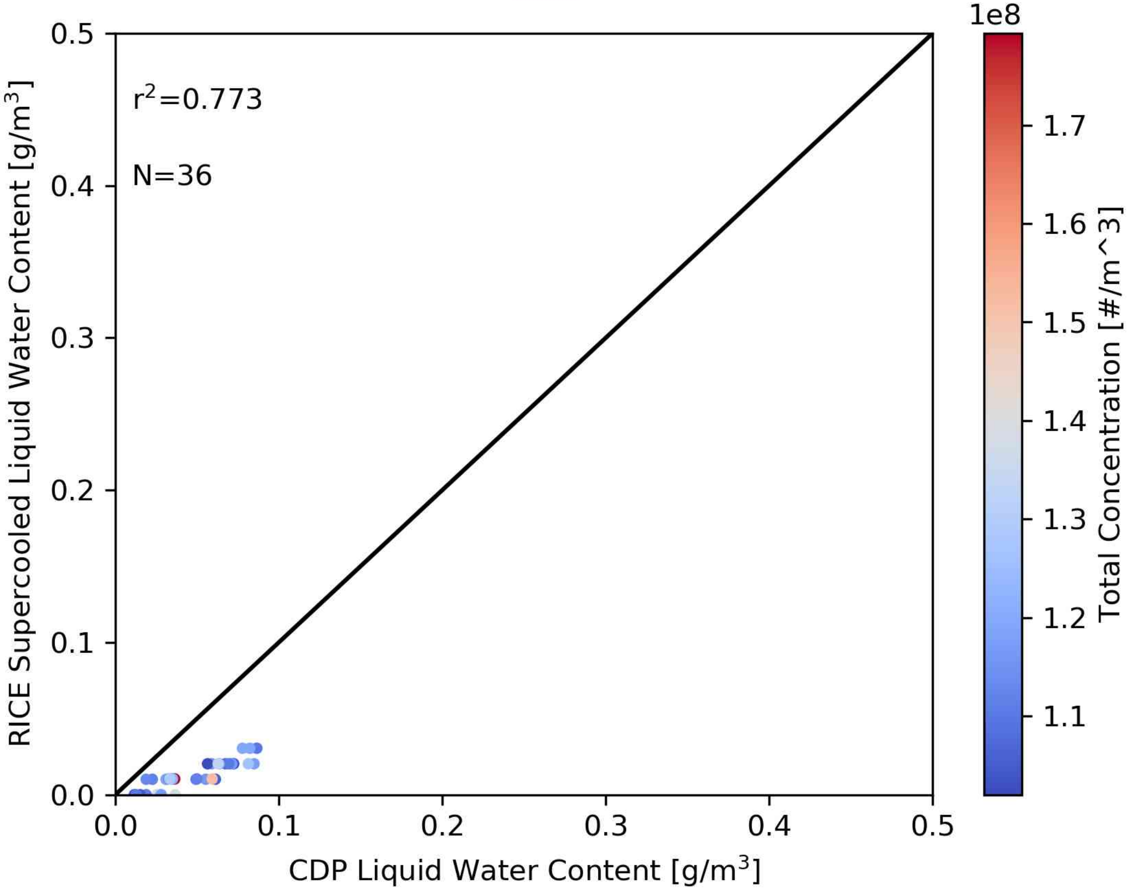
Total Concentration

- RICE SLWC vs CDP, -3 °C maximum temperature, pitch 3° and below, concentration less than $2x10^7/m^3$



Total Concentration

- RICE SLWC vs CDP, -3 °C maximum temperature, pitch 3° and below, concentration greater than $10^8/m^3$



Minimum Detection Threshold

- Goal: What is the lowest possible and reasonable value for W_m from Mazin et al (2001) equation (right)?

$$W_m = \frac{\frac{-dF}{dt} \cdot k}{2 R_c l U}$$

- $W_m(max) = 0.007\ g/m^3$
- $W_m(avg) = 0.021\ g/m^3$

Constant/ Variable	Description	Unit	Value
W_m	LWC	g/m^3	?
-dF/dt	Negative change in Freq. over time	Hz/s	-1/3
k	Coefficient	unitless	7.195×10^{-4}
R_c	Cylinder radius	m	0.00317
l	Cylinder length	m	0.0254
U	True Air Speed	m/s	Max: 208.5 Avg: 139.2

Summary and Conclusions

Discussion/Importance

- Even if use is limited to certain environment conditions, every measurement can add value
- Redundancy is vital to field campaigns, such as IMPACTS
- Use of this k value may not be valid for other RICE's
  - But the derivation process is valid!
- For other airplanes that mount the RICE, this analysis is valid with some caveats
  - Different mount = different pitch/roll analysis
  - Different TAS could make TAS effect and temperature threshold different

UND UNIVERSITY OF NORTH DAKOTA

Summary of Conclusions

- Temperature: -3 °C maximum temperature
- Pitch Angle: 3° maximum, no minimum
- Roll Angle: No limits necessary
- TAS: No limits, but slower air speeds improve quality near -3 °C
- MVD: No limits, need data in SLD environments
- Concentration: No limits, need more data in concentration > $10^8/m^3$
- Minimum Detection: TAS dependent, average is around 0.02 g/m^3, could be as low as 0.007 g/m^3

Acknowledgments

- My beautiful, loving wife Allison
- Mike Poellot, advisor 2019-early 2021 and current committee member
- Dr. David Delene, advisor and committee chair mid 2021-present
- Dr. Andy Detwiler, committee member
- NASA
- Dr. Alexei Korolev
- Trece Hopp
- Wanda and Sue
- Family and Friends, (especially the “Finer Things Club”)

References (1/?)

Bain, M., and J. F. Gayet, 1982: Aircraft Measurements of Icing in Supercooled and Water Droplet/Ice Crystal Clouds. *J. Appl. Meteorol. Climatol.*, **21**, 631–641, https://doi.org/10.1175/1520-0450(1982)021<0631:AMOIIS>2.0.CO;2.

Baumgardner, D., and A. Rodi, 1989: Laboratory and Wind Tunnel Evaluations of the Rosemount Icing Detector. *J. Atmospheric Ocean. Technol.*, **6**, 971–979, https://doi.org/10.1175/1520-0426(1989)006<0971:LAWTEO>2.0.CO;2.

Bernstein, B. C., R. M. Rasmussen, F. McDonough, and C. Wolff, 2019: Keys to Differentiating between Small- and Large-Drop Icing Conditions in Continental Clouds. *J. Appl. Meteorol. Climatol.*, **58**, 1931–1953, https://doi.org/10.1175/JAMC-D-18-0038.1.

Biter, C. J., J. E. Dye, D. Huffman, and W. D. King, 1987: The Drop-Size Response of the CSIRO Liquid Water Probe. *J. Atmospheric Ocean. Technol.*, **4**, 359–367, https://doi.org/10.1175/1520-0426(1987)004<0359:TDSROT>2.0.CO;2.

Borque, P., K. J. Harnos, S. W. Nesbitt, and G. M. McFarquhar, 2019: Improved Parameterization of Ice Particle Size Distributions Using Uncorrelated Mass Spectrum Parameters: Results from GCPEx. *J. Appl. Meteorol. Climatol.*, **58**, 1657–1676, https://doi.org/10.1175/JAMC-D-18-0203.1.

Brown, E. N., 1981: *An Evaluation of the Rosemount Ice Detector for Aircraft Hazard Warning and for Undercooled Cloud Water Content Measurements*. UCAR/NCAR,.

Claffey, K. J., K. F. Jones, and C. C. Ryerson, 1995: Use and calibration of Rosemount ice detectors for meteorological research. *Atmospheric Res.*, **36**, 277–286, https://doi.org/10.1016/0169-8095(94)00042-C.

Cober, S., and G. Isaac, 2006: Estimating Maximum Aircraft Icing Environments Using a Large Database of In-Situ Observations. *44th AIAA Aerospace Sciences Meeting and Exhibit*, *Aerospace Sciences Meetings*, American Institute of Aeronautics and Astronautics.

——, A. Korolev, and G. Isaac, 2001a: Assessing characteristics of the Rosemount Icing Detector under natural icing conditions. *39th Aerospace Sciences Meeting and Exhibit*, *Aerospace Sciences Meetings*, American Institute of Aeronautics and Astronautics.

Cober, S. G., G. A. Isaac, and A. V. Korolev, 2001b: Assessing the Rosemount Icing Detector with In Situ Measurements. *J. Atmospheric Ocean. Technol.*, **18**, 515–528, https://doi.org/10.1175/1520-0426(2001)018<0515:ATRIDW>2.0.CO;2.

——, ——, and J. W. Strapp, 2001c: Characterizations of Aircraft Icing Environments that Include Supercooled Large Drops. *J. Appl. Meteorol. Climatol.*, **40**, 1984–2002, https://doi.org/10.1175/1520-0450(2001)040<1984:COAIET>2.0.CO;2.

Cropper, M., 2021: P-3 Orion - WFF | NASA Airborne Science Program. https://airbornescience.nasa.gov/aircraft/P-3_Orion_-_WFF (Accessed June 28, 2021).

Delene, D., K. Hibert, M. Poellot, and N. Brackin, 2019: *The North Dakota Citation Research Aircraft Measurement Platform*. SAE International,.

——, A. Skow, J. O'Brien, N. Gapp, S. Wagner, K. Hibert, K. Sand, and G. Sova, 2020: *Airborne Data Processing and Analysis Software Package*. Zenodo,.

Delene, D. J., 2011: Airborne data processing and analysis software package. *Earth Sci. Inform.*, **4**, 29–44, https://doi.org/10.1007/s12145-010-0061-4.

Fraser, D., C. K. Rush, and D. Baxter, 1953: Thermodynamic Limitations of Ice Accretion Instruments. *Bull. Am. Meteorol. Soc.*, **34**, 146–154, https://doi.org/10.1175/1520-0477-34.4.146.

Heymsfield, A., M. Krämer, N. B. Wood, A. Gettelman, P. R. Field, and G. Liu, 2017: Dependence of the Ice Water Content and Snowfall Rate on Temperature, Globally: Comparison of in Situ Observations, Satellite Active Remote Sensing Retrievals, and Global Climate Model Simulations. *J. Appl. Meteorol. Climatol.*, **56**, 189–215, https://doi.org/10.1175/JAMC-D-16-0230.1.

Heymsfield, A. J., and L. M. Miloshevich, 1989: Evaluation of Liquid Water Measuring Instruments in Cold Clouds Sampled during FIRE. *J. Atmospheric Ocean. Technol.*, **6**, 378–388, https://doi.org/10.1175/1520-0426(1989)006<0378:EOLWMI>2.0.CO;2.

——, and ——, 1993: Homogeneous Ice Nucleation and Supercooled Liquid Water in Orographic Wave Clouds. *J. Atmospheric Sci.*, **50**, 2335–2353, https://doi.org/10.1175/1520-0469(1993)050<2335:HINASL>2.0.CO;2.

Isaac, G., S. G. Cober, J. W. Strapp, A. Korolev, A. Tremblay, and D. L. Marcotte, 2001: Recent Canadian Research on Aircraft In-Flight Icing. *Can. Aeronaut. Space J.*, **44**, 213–222.

References (1/?)

Jackson, D., D. Cronin, J. Severson, and D. Owens, 2001a: Ludlam limit considerations on cylinder ice accretion - Aerodynamics and thermodynamics. *39th Aerospace Sciences Meeting and Exhibit*, *Aerospace Sciences Meetings*, American Institute of Aeronautics and Astronautics.

——, D. Owens, D. Cronin, and J. Severson, 2001b: Certification and integration aspects of a primary ice detection system. *39th Aerospace Sciences Meeting and Exhibit*, *Aerospace Sciences Meetings*, American Institute of Aeronautics and Astronautics.

Jackson, D. G., J. Y. Liao, and J. A. Severson, 2003: An Assessment of Goodrich Ice Detector Performance in Various Icing Conditions. FAA In-flight Icing / Ground De-icing International Conference & Exhibition, 2003-01–2115.

Jeck, R. K., 2007: Calibration and Use of Goodrich Model 0871FA Ice Detectors in Icing Wind Tunnels. *J. Aircr.*, **44**, 300–309, https://doi.org/10.2514/1.23543.

Korolev, A., 2007: Limitations of the Wegener–Bergeron–Findeisen Mechanism in the Evolution of Mixed-Phase Clouds. *J. Atmospheric Sci.*, **64**, 3372–3375, https://doi.org/10.1175/JAS4035.1.

Korolev, A., and Coauthors, 2017: Mixed-Phase Clouds: Progress and Challenges. *Meteorol. Monogr.*, **58**, 5.1-5.50, https://doi.org/10.1175/AMSMONOGRAPHS-D-17-0001.1.

Lance, S., 2012: Coincidence Errors in a Cloud Droplet Probe (CDP) and a Cloud and Aerosol Spectrometer (CAS), and the Improved Performance of a Modified CDP. *J. Atmospheric Ocean. Technol.*, **29**, 1532–1541, https://doi.org/10.1175/JTECH-D-11-00208.1.

Lance, S., C. A. Brock, D. Rogers, and J. A. Gordon, 2010: Water droplet calibration of the Cloud Droplet Probe (CDP) and in-flight performance in liquid, ice and mixed-phase clouds during ARCPAC. *Atmospheric Meas. Tech.*, **3**, 1683–1706, https://doi.org/10.5194/amt-3-1683-2010.

Mazin, I. P., A. V. Korolev, A. Heymsfield, G. A. Isaac, and S. G. Cober, 2001: Thermodynamics of Icing Cylinder for Measurements of Liquid Water Content in Supercooled Clouds. *J. Atmospheric Ocean. Technol.*, **18**, 543–558, https://doi.org/10.1175/1520-0426(2001)018<0543:TOICFM>2.0.CO;2.

McMurdie, L. A., G. Heymsfield, J. E. Yorks, and S. A. Braun, 2020: IMPACTS Field Campaign Data Collection. https://doi.org/10.5067/IMPACTS/DATA101.

Plummer, D. M., G. M. McFarquhar, R. M. Rauber, B. F. Jewett, and D. C. Leon, 2014: Structure and Statistical Analysis of the Microphysical Properties of Generating Cells in the Comma Head Region of Continental Winter Cyclones. *J. Atmospheric Sci.*, **71**, 4181–4203, https://doi.org/10.1175/JAS-D-14-0100.1.

Rogers, R. R., and M. K. Yau, 1989: *A Short Course in Cloud Physics*. 3rd ed. Elsevier, 290 pp.

Rosenfeld, D., and W. L. Woodley, 2000: Deep convective clouds with sustained supercooled liquid water down to -37.5 °C. *Nature*, **405**, 440–442, https://doi.org/10.1038/35013030.

Storelvmo, T., and I. Tan, 2015: The Wegener-Bergeron-Findeisen process – Its discovery and vital importance for weather and climate. *Meteorol. Z.*, 455–461, https://doi.org/10.1127/metz/2015/0626.

Strapp, J., P. Chow, M. Maltby, A. Bezer, A. Korolev, I. Stromberg, and J. Hallett, 1999: Cloud microphysical measurements in thunderstorm outflow regions during Allied/BAE 1997 flight trials. *37th Aerospace Sciences Meeting and Exhibit*, 498.

Stull, R. B., 2000: *Meteorology for Scientists and Engineers*. 2nd ed. Gary Garlson, 502 pp.

Twohy, C. H., and D. Rogers, 1993: Airflow and Water-Drop Trajectories at Instrument Sampling Points around the Beechcraft King Air and Lockheed Electra. *J. Atmospheric Ocean. Technol.*, **10**, 566–578, https://doi.org/10.1175/1520-0426(1993)010<0566:AAWDTA>2.0.CO;2.

Walter J Boyne, 2014: P-3 Orion. *Air Force Mag.*, **97**, 88-.

Questions?

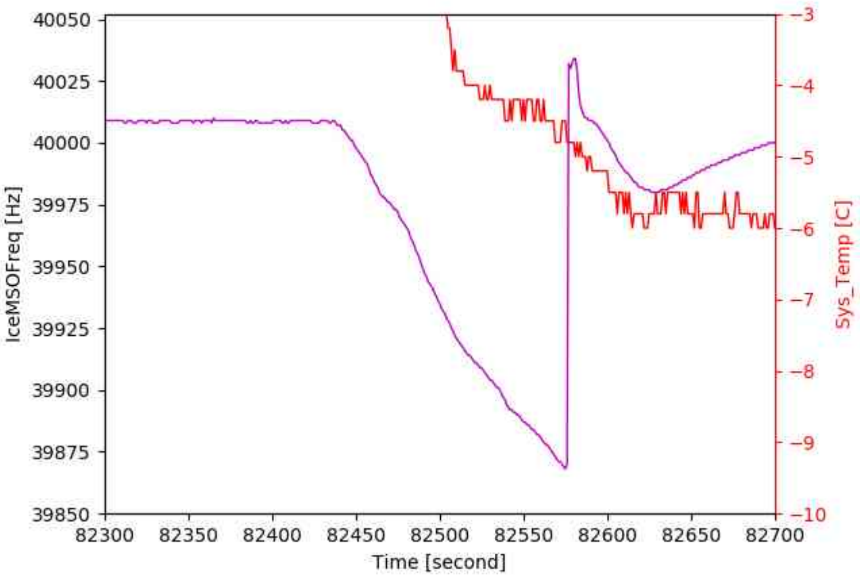

GREG SOVA
UNIVERSITY OF NORTH DAKOTA RESEARCHER
REAL-TIME WEATHER ALERTS IN THE NBC10 APP
5:47
71°
10
2:28 / 2:58

Supplemental: Ludlam Thermodynamics

- Mazin et al (2001) lists 6 mechanisms:
  1) Adiabatic heating due to compression
  2) Cooling due to ice sublimation
  3) Cooling from supercooled water warming to 0 ℃ to freeze
  4) Heating from water freezing
  5) Heating due to ice cooling from 0 ℃ to the original temperature
  6) Heating due to the collision of particles
- 1 and 3-5 discussed earlier, 2 is very situational, 6 is neglected

Supplemental: High Concentration, Low (S)LWC

- If the number of water particles is so high, why is LWC so low? More water particles =/= more water?
- Environments with extremely high concentration are dominated by small particles



Left: RICE Probe Frequency (magenta) and temperature (red)

Right: MVD (black) and concentration (red)