An Investigation of Glaciated Cloud Capabilities in the NASA Glenn Icing Research Tunnel

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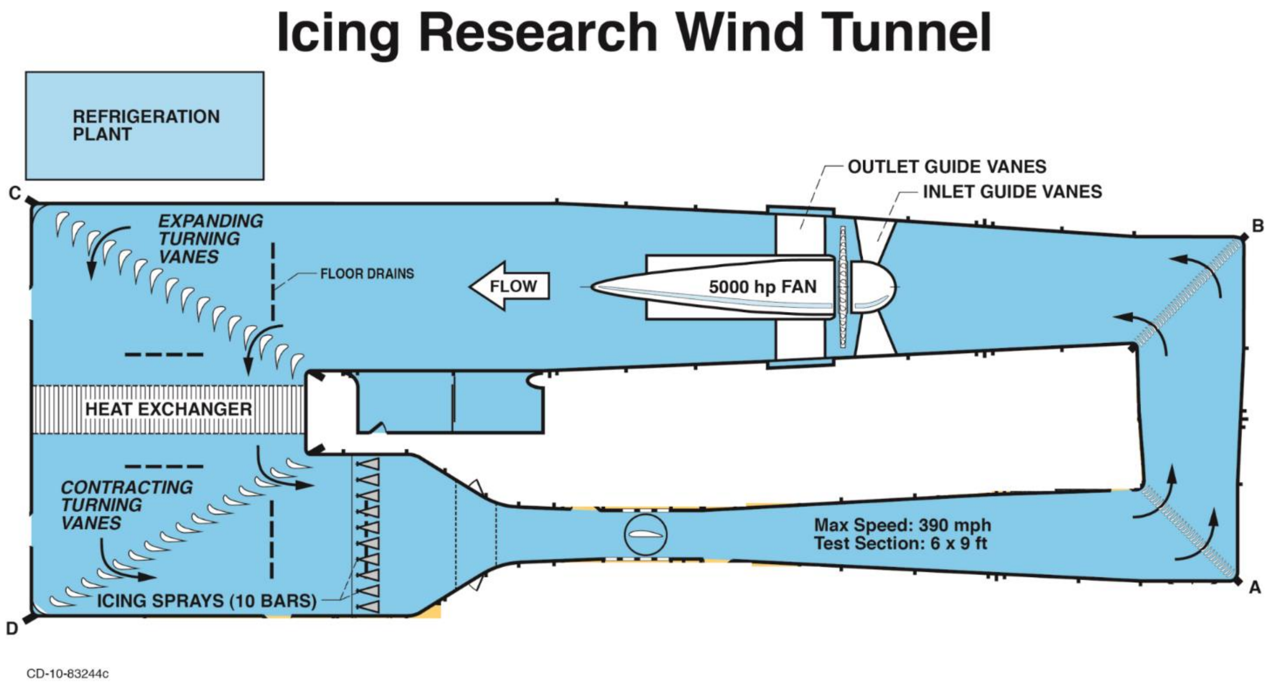
The Problem:

- *In 2015 the FAA Added Appendix D to Part 33 engine certification requirements that included Mixed Phase and Ice Crystal Icing to aircraft engine certification*
- *The Icing Research Tunnel (IRT) at NASA Glenn historically has operated almost solely with a super-cooled liquid water cloud. However, NASA researchers expressed interest in investigating the IRT's capabilities to create a fully glaciated cloud as a potentially less-expensive alternative to creating ice crystals in an engine icing facility*
- *The purpose of this test was ONLY to see if the IRT can create a fully-glaciated cloud, not to explore mixed-phase capabilities. Mixed-phase could be a future goal, but is beyond the scope of the present work.*

Test Facility



- **Test section size: 6 ft. x 9 ft. (1.8 m x 2.7 m)**
  - All water content measurements are made in the center of the test section
- **Calibrated test section airspeed range: 50 – 325 kts**
- **Air temperature: -40 ^{o}C static to +10 ^{o}C total**
- **Calibrated MVD range: 14 – 270 µm**
- **Calibrated LWC range: 0.15 – 4.0 g/m^3 (function of airspeed)**
- **This test only utilized the Mod1 nozzles (lower water flow rate)**

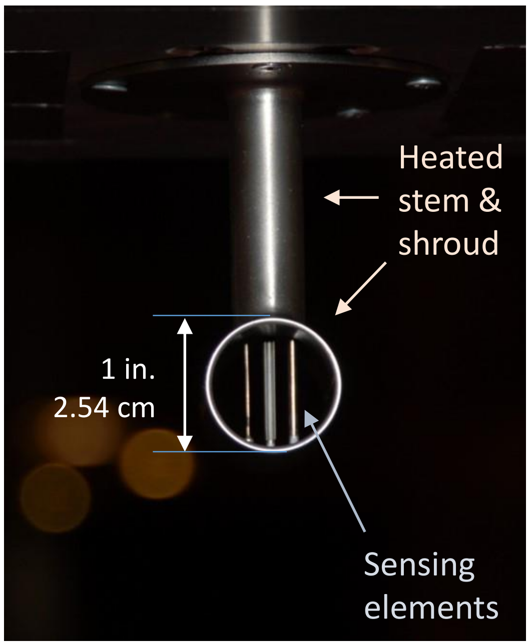
Developing a Hypothesis

IRT spraybars as seen from the top of the contraction section, facing upstream

- IRT Spraybars are supplied with air and water. The pressures of each are controlled to create the desired water content and drop-size distribution.
- Air & Water are typically heated to 80-85 ^{o}C in order to avoid freezing the water drops
  - So we asked ourselves, ***what happens if we don't heat it?***
  - Air & Water are heated, but cannot be actively cooled, so the best we can do is to run the air and water "unheated"
- Pumps contribute to the water heat
  - Operating temperature of spraybar air was around 30 ^{o}C
  - Operating temperature of spraybar water was around 43 ^{o}C

The Multi-Element Sensor

From Science Engineering Associates, Inc.



Commonly known as “the Multi-Wire”

Typical Multi-Wire shrouds contain 3 sensing elements of various sizes; Different element types are designed for better response to different conditions

- 2mm forward-facing half-pipe: “TWC”
  - Total Water Content sensor, responds to liquid water and ice crystals
- 2mm reverse-facing half-pipe “2mm”
  - responds to liquid water, approx. 10% “false-response” to ice crystals*
- 0.5mm wire, “0.5mm”
  - responds to liquid water, and approx. 10% “false-response” to ice crystals*
- There is also a compensation wire, located behind the central element
  - measures changes coming only from airspeed, air temperature, air pressure, and relative humidity: “dry” conditions

Given the different responses, we can compare data from the different element to determine if the cloud is glaciated

*Struk, P.M., Bencic, T., Tsao, J., Fuleki, D., Knezevici, D.C., “Preparation for Scaling Studies of Ice-Crystal Icing at the NRC Research Altitude Test Facility,” 5th *AIAA Atmospheric and Space Environments Conference,* AIAA-2013-2675, 2013.

Multi-Element Sensor Theory of Operation

- A voltage is applied across each of the elements to maintain them at a temperature of 140 ^{o}C
  - Elements are cooled by convection and impinging water
- Data system records the power required to maintain each element at constant temperature.
- The compensation wire is shielded to stay dry; changes during a spray are reflected in the calculated water content
- The recorded powers are used to calculate water content—the below equation has been adapted to assume the cloud is made of ice crystals rather than being purely liquid

$$P_{elem,wet} = P_{elem,tot} - \overbrace{(offset + slope * P_{comp,dry})}^{\text{Subtract off cooling from dry air, correlated to comp wire}}$$

Conversion factor

$$IWC = \frac{P_{elem,wet}(watts) * 2.389 \times 10^{5}}{\underbrace{\left[C_{p,IWC}(T_{melt} - T_{IWC}) + L_{fus} + C_{p,LWC}(T_{evap} - T_{melt}) + L_{vap}\right]}_{\text{Amount of energy required to raise the ice particle to its evaporative temperature and then evaporate it (cal/g)}} * \underbrace{TAS\frac{m}{s} * l_{elem}mm * w_{elem}mm}_{\text{Sample volume of sensing element } (m^3/s)}}$$

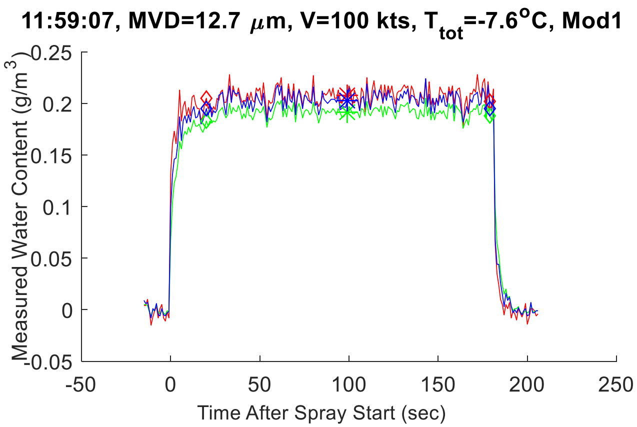
For this presentation, all data from the 3 vertical sensors (TWC, 2mm, 0.5mm) were calculated using this equation, regardless of how the cloud was ultimately classified

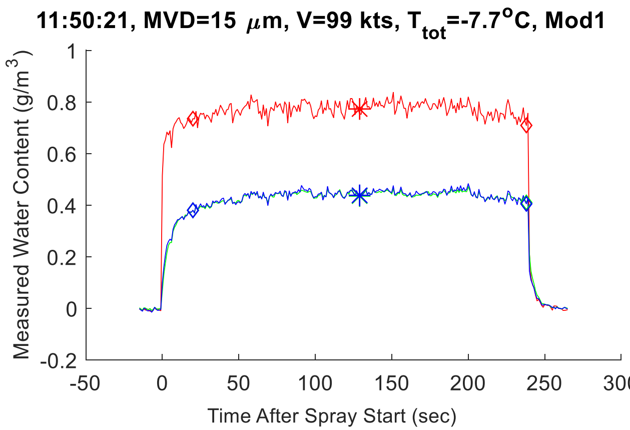
Source: the SEA User’s Manual

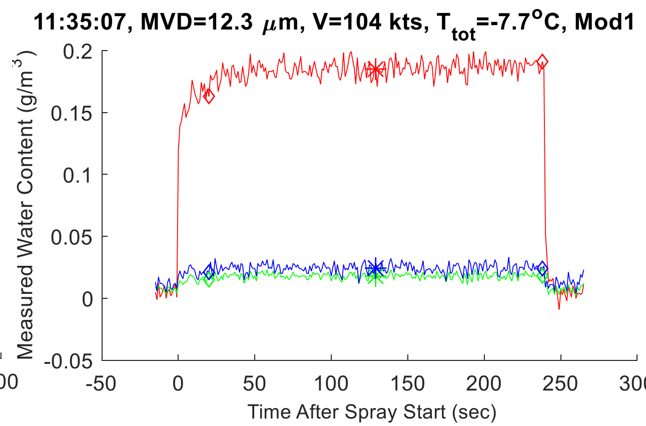
Test Procedures

- The air and water supply in the spraybars were left unheated
  - Air temps were around 30 ^{o}C
  - Water temps were around 43 ^{o}C
- Spray time = 4 minutes
- Initial facility setpoint: highest total temperature and lowest airspeed, with nozzle settings to create our smallest possible drops (MVD approx. 12.7 µm):
  - Ttot = -7 ^{o}C
  - Airspeed = 100 knots
  - Pair = 60 psig
  - DelP = 10 psid
- Once it was confirmed this created a glaciated cloud, tunnel parameters were varied to explore how cloud glaciation was affected by the following:
  - Increasing drop size — from 12.7 up to 30 µm MVD
  - Decreasing nozzle air pressure — 60, 40, 30 psig
  - Increasing airspeed — 100, 150, 250 knots
  - Decreasing tunnel total temperature — -7, -15, -25 ^{o}C

Example “Good” Data Traces







TWC_{raw} (IWC)	0.21 g/m^3
2mm / TWC	0.92
0.5mm / TWC	0.97

Fully Liquid

TWC_{raw} (IWC)	0.78 g/m^3
2mm / TWC	0.56
0.5mm / TWC	0.57

Mixed Phase

TWC_{raw} (IWC)	0.18 g/m^3
2mm / TWC	0.06
0.5mm / TWC	0.07

Fully Glaciated

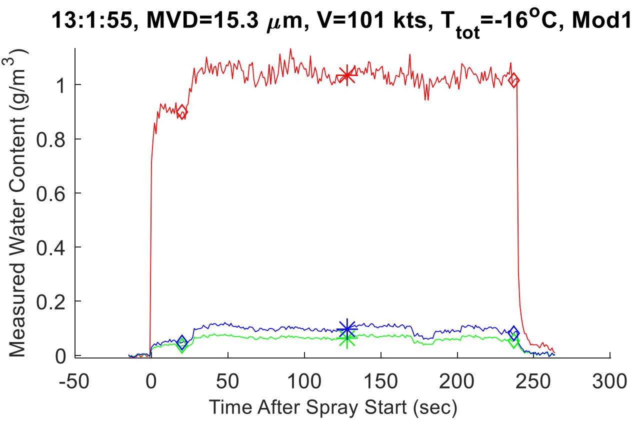
10 sprays in this test were stable for the duration of the spray, out of 27 fully glaciated sprays measured

Data Processing Notes:

- Data are averaged for each element, starting 20 sec after spray begins, until 2 sec before spray ends

- The ratio values of each of the side cylinder elements to the center TWC element are used to determine if the cloud is liquid, glaciated, or mixed phase
- Ice water content from the TWC element was also corrected for collection efficiency and compared to the expected (IRT calibrated) LWC

Other Example Traces

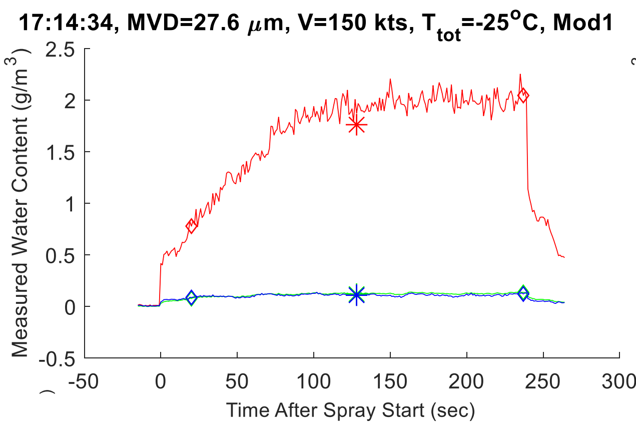


Step-Increase, then Stable

Cause: Recirculating crystals, non-compounding

4 sprays

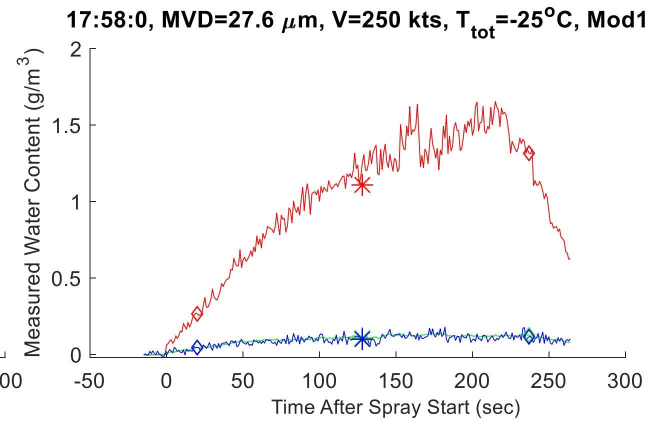
Only observed at 100 knots, for which the loop transit time is approximately 25 seconds. Presumably, then, the step-increase is due to cloud recirculation that for some reason only lasts for one loop around the tunnel



Ramp-up, then Stable

Cause: Recirculating crystals, compounding & eventually "stabilizing"

9 sprays



Continuous Ramp-up, Never Stabilized

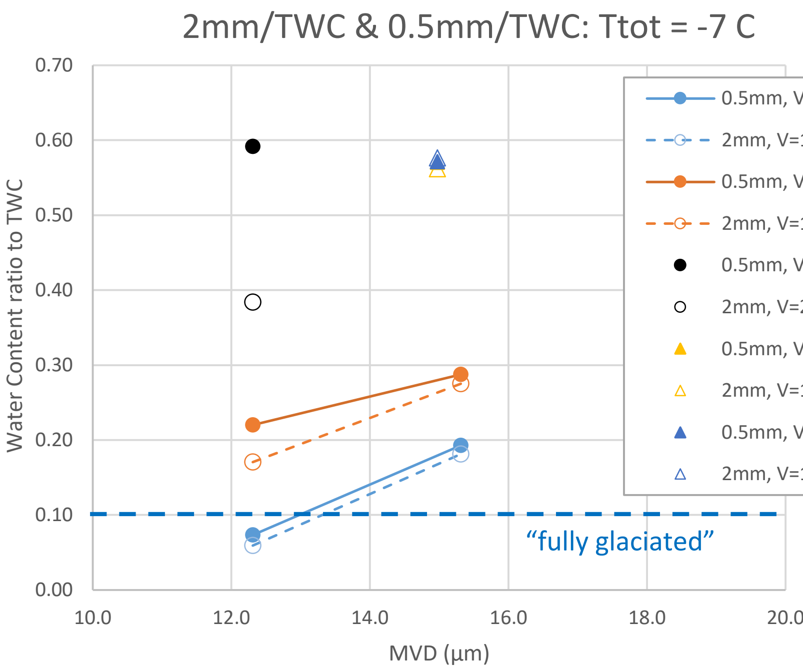
Cause: Recirculating Crystals, continually compounding

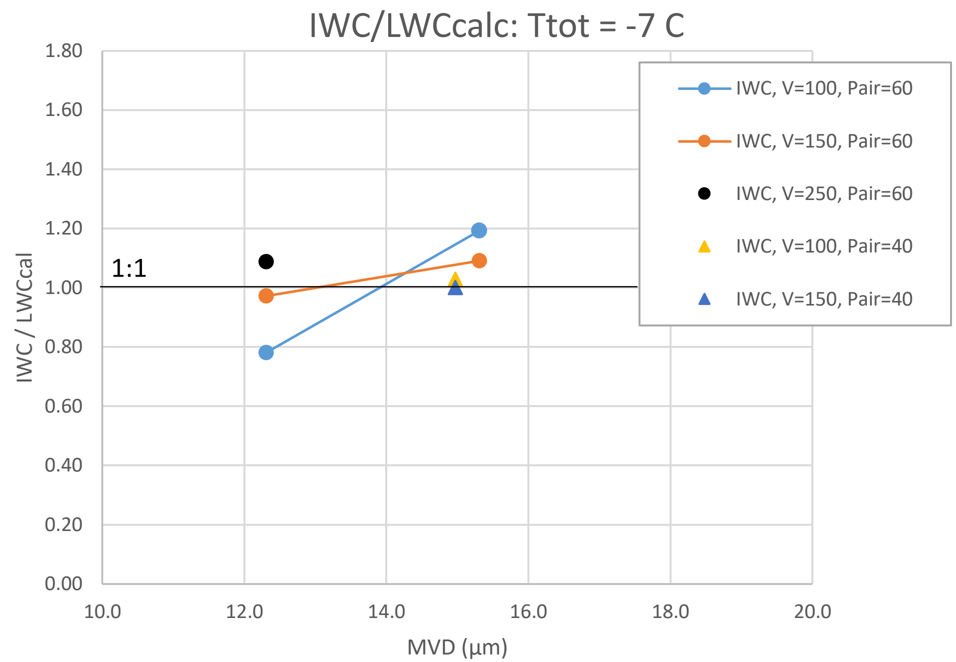
3 sprays

- For all such cases, if the readings were stable for more than 1 minute, the data were averaged across the stable segment.
- If there was no stable segment, the condition was not included in the subsequent plots

Warm temperatures: T_{tot} = -7 °C

There was only one condition observed to be fully glaciated at Ttot = -7 °C, but there was still information to be found in the observed trends.

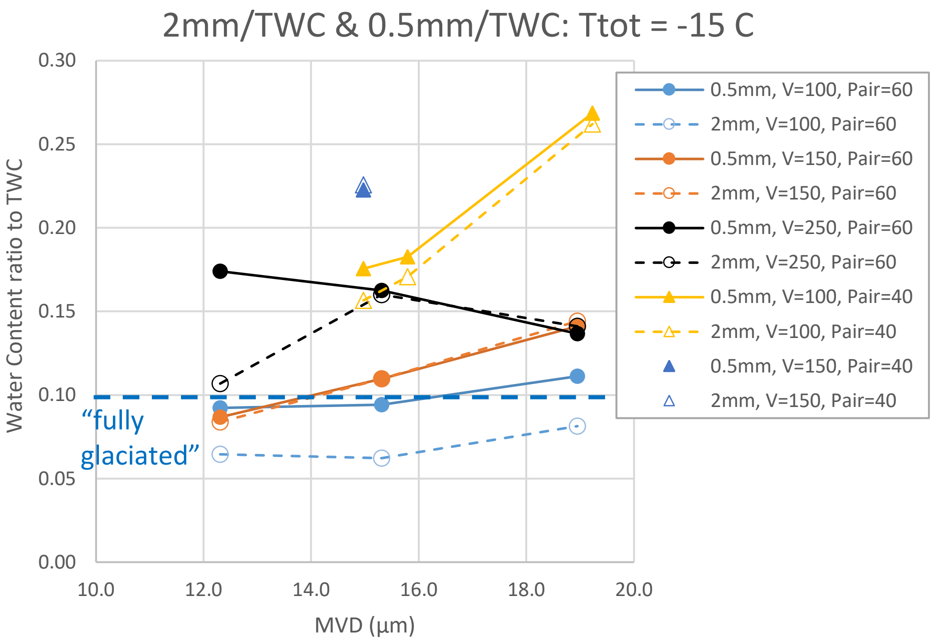


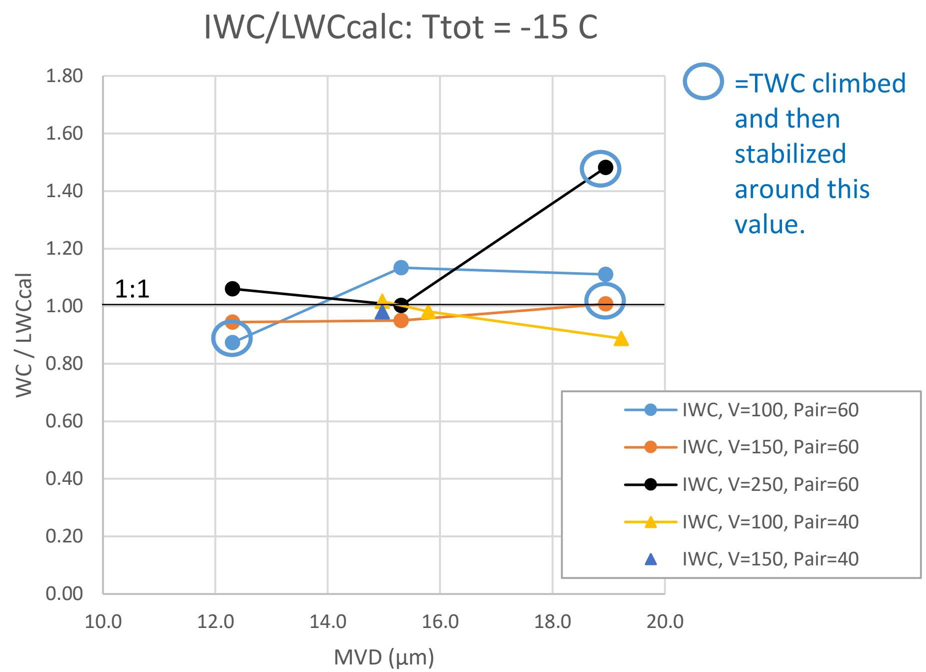


Observations from 2mm and 0.5mm element ratios:

- Glaciation is more likely at lower air speeds
  - Suggests that drop residence time is more important than static temperature
- For a given air pressure, glaciation is more likely for low MVD (deltaP) values
- Glaciation is more likely for a higher air pressure than for a smaller drop size
  - Suggests that the cooling effect of the spray nozzle air pressure plays a substantial role in cloud glaciation.

Colder temperature: T_{tot} = -15 ºC

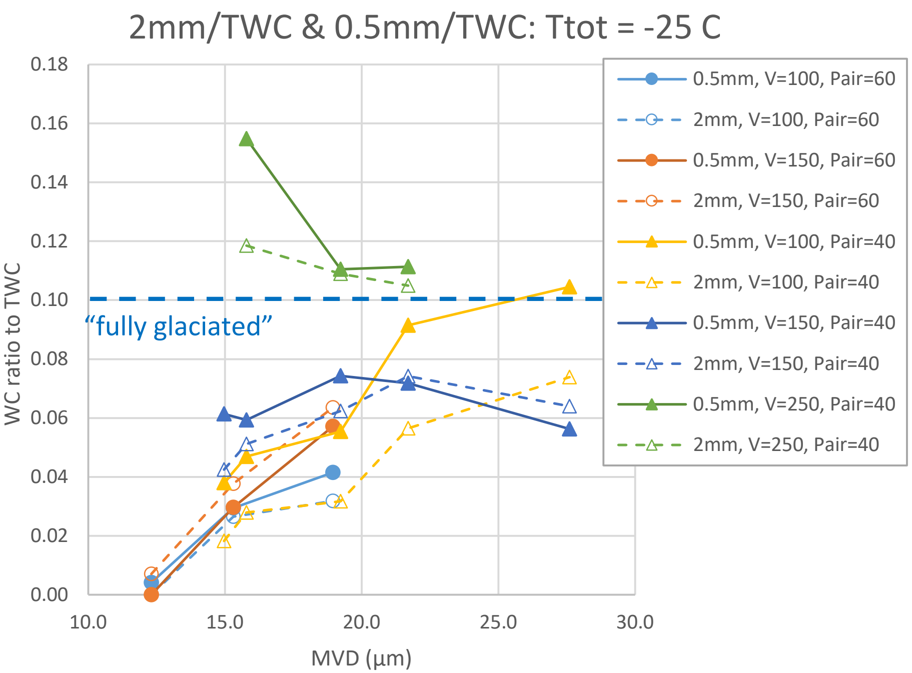


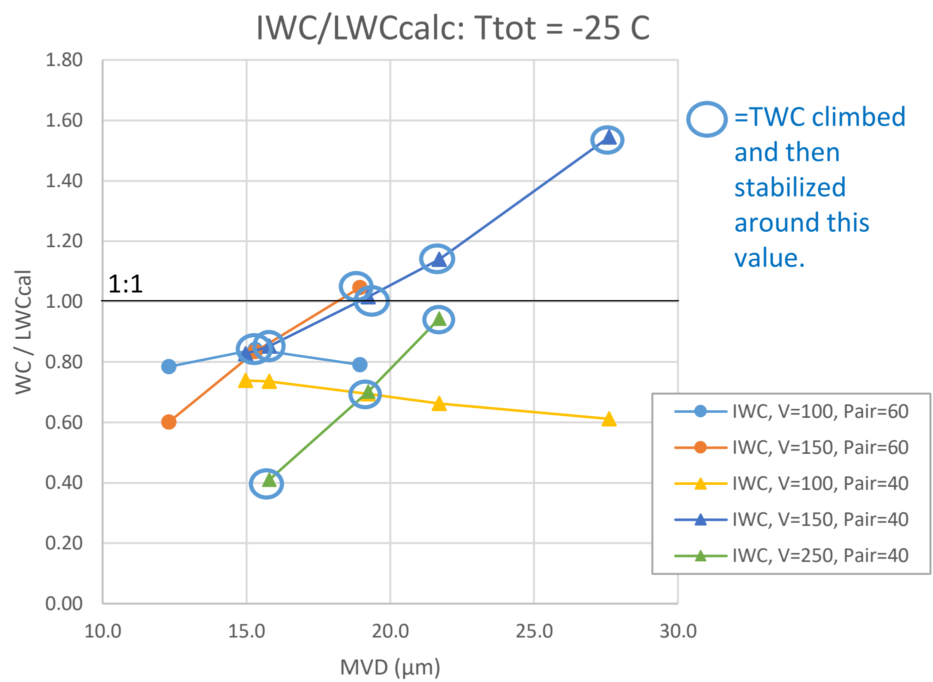


- As expected, glaciation is more likely at a colder temperature: more data points are showing full glaciation
- Similar observations as seen at -7 ºC:
  - Glaciation more likely at lower air speeds
  - For a given air pressure, glaciation is more likely for low MVD (deltaP) values
  - Glaciation is more likely for a higher air pressure than for a smaller drop size

- The 250 kt (black) data breaks trend, in that glaciation appears to be <u>more</u> likely for larger MVD values. However, this may be driven by uncharacteristic TWC values

Cold temperature: T_{tot} = -25 °C

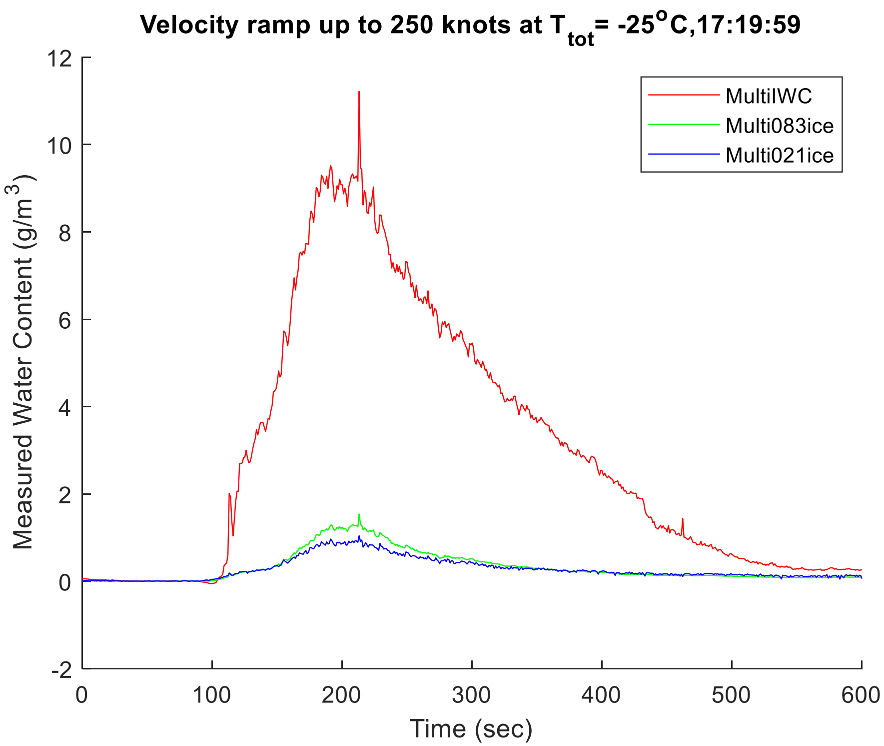




- As expected, glaciation is more likely at a colder temperature: more data points show full glaciation
- Conditions were less stable at -25 °C.
- The data points for V=250 kts, Pair=60 were removed from these plots—IWC was steadily increasing and did not stabilize.
- Similar observations as seen at -7 °C and -15 °C :
  - Glaciation more likely at lower air speeds
  - For a given air pressure, glaciation is more likely for low MVD (deltaP) values
  - Glaciation is more likely for a higher air pressure than for a smaller drop size
- The 40-psia data at 150 and 250 kts (blue & green triangles) break trend, in that glaciation appears to be more likely for larger MVD values. However, this may be driven by uncharacteristic TWC values
  - This does not seem to have the same impact on the 150 kt, Pair=60 (orange) data

What happened when we increased airspeed to 250 knots at -25 C:

- Later in the day, after we had measured a several glaciated conditions at -25 °C and 150 knots
- Plot at right shows water contents measured by the 3 elements, in between sprays as we increased speed from 150 to 250 knots
- We saw lots of ice crystal recirculation. Most likely we “kicked up” a lot of the ice particles that had been settling around the tunnel loop over the course of the day.
- **The ice crystals appeared to “settle out” within about 10 minutes of holding airspeed**, which is about as much time as it would take the IRT to get onto condition for the next point. Hence, we do not expect the creation of new ice crystals to be a problem for test points later in the day.



Summary of Results

We measured a total of 27 conditions for which the 2mm/TWC and/or 0.5mm/TWC ratios were less than 11%, indicating a glaciated cloud

- 10 of these showed stable readings from the TWC, 2mm, and 0.5mm elements, indicating a stable glaciated cloud
- 4 of these showed a step increase about 25 seconds into the spray, followed by stable reading. Presumably, the step-increase is due to cloud recirculation that for some reason does not continually compound.
- 9 of these showed TWC increasing for the first 1-2 min while the 2mm and 0.5 mm remained flat (an effect of ice crystal recirculation), then the TWC leveled off, suggesting perhaps the cloud reached a sort of "equilibrium" at the test section
- 3 of these (only at coldest temp and highest airspeed) never leveled off, but continued increasing over the spray's duration (not included in the previous plots)
- 1 spray was started too early after increasing tunnel velocity, and showed TWC decrease (by about 0.03 g/m^3, or 5%) for 1 min and then stabilize

Conclusions

- Still many things that are unknown, but we did learn a few things:
- The IRT can create a fully glaciated cloud by running unheated spraybar air and water
    - This has to happen from the start of a test day, as the air and water cannot be actively cooled.
- Full glaciation was observed for select conditions at:
    - Total air temperatures of -7, -15, and -25 ^{o}C
    - Airspeeds of 100, 150, and 250 knots
    - Nozzle air pressures of 40 and 60 psig
    - MVD values between 13 and 28 µm
- In the IRT, cloud glaciation is more likely at:
    - Colder total temperatures
    - Lower airspeeds (suggests that residence time is more important than static temperature)
    - Higher nozzle air pressures
    - Smaller drop sizes
        - Nozzle air pressure was also shown to be a greater driver for glaciation than drop size

Remaining Work:

- Check repeatability of these conditions
  - Characteristics of the spray (is it still stable?)
  - Element readings for the spray (is the water content consistent?)
- Further characterization of the cloud:
  - Uniformity & Particle Size
  - No current means in the IRT to measure these for an ice crystal cloud

Acknowledgements

- Funding for IRT cloud calibration and cloud capability expansion testing comes from the NASA Aerosciences Evaluation and Test Capabilities (AETC) Project
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- Paul Tsao & Peter Struk
- IRT engineers and technicians

Questions?

HX5 SIERRA

JOINT VENTURE

NASA