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Results and Conclusions From the NASA Isokinetic Total Water Content Probe 2009 IRT Test

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Abstract

The NASA Glenn Research Center has developed and tested a Total Water Content Isokinetic Sampling Probe. Since, by its nature, it is not sensitive to cloud water particle phase nor size, it is particularly attractive to support super-cooled large droplet and high ice water content aircraft icing studies. The instrument comprises the Sampling Probe, Sample Flow Control, and Water Vapor Measurement subsystems. Results and conclusions are presented from probe tests in the NASA Glenn Icing Research Tunnel (IRT) during January and February 2009. The use of reference probe heat and the control of air pressure in the water vapor measurement subsystem are discussed. Several run-time error sources were found to produce identifiable signatures that are presented and discussed. Some of the differences between measured Isokinetic Total Water Content Probe and IRT calibration seems to be caused by tunnel humidification and moisture/ice crystal blow around. Droplet size, airspeed, and liquid water content effects also appear to be present in the IRT calibration. Based upon test results, the authors provide recommendations for future Isokinetic Total Water Content Probe development.

Introduction

The purpose, detailed design, and previous testing results of the Total Water Content Isokinetic Sampling Probe are described in Reference 1 and except where noted, the system discussed in this document is unchanged from what was described in that document.

As NASA became involved with the study of hazards associated with super-cooled large droplets (SLD) and high ice water content (HIWC) flight conditions, it became apparent that the current water content instrumentation would be inadequate. Existing liquid water content (LWC) instrumentation was susceptible to significant errors when measuring SLD clouds due to large droplet breakup, splashing, and bouncing. Due to its basic design, existing water content instrumentation suffered the effects of ice particle bouncing and inadequate heater capacity when tasked to measure HIWC conditions.

One solution option that eliminates droplet splash, bounce, and breakup effects of SLD conditions and ice particle bounce effects for HIWC conditions is a heated isokinetic cloud particle sampler. By its nature, a properly functioning heated isokinetic cloud particle sampler should not be influenced by the size or phase of the cloud particle. By sufficiently heating the sampling probe, all water particles sampled (ice and liquid) are evaporated into the air sample. An additional benefit of this heating is that the exterior of the probe remains free of ice accretion. When all of the water is evaporated, the cloud's total water content (TWC) can be calculated for a known air sample flow rate by differencing the measurement of the absolute humidity of the sampled air from the measurement of the absolute humidity of the ambient air.

The NASA Total Water Content Isokinetic Sampling Probe is made up of three subsystems (1) Sampling Probe, (2) Sample Flow Control, and (3) Water Vapor Measurement. The Sampling Probe subsystem consists of the Sample and Reference Probes. The forward facing Sample Probe is intended to ingest a volume of air with all cloud particles present, while the rear facing Reference Probe is intended to ingest only the ambient air, with no cloud particles. The Sample Probe is heated such that all ingested water (liquid and ice) is evaporated. The Sample Flow Control subsystem consists of a thermal mass flow meter (to measure the actual Sample Probe air flow rate), a suction source, and control valves.

The Water Vapor Measurement subsystem consists of Infrared (IR) Gas Analyzers and the Chilled Mirror hygrometers that measure the absolute water vapor levels of both the Sample and Reference air sources. Only the measurements from the IR Gas Analyzers were used in this report.

System Changes Made for This Test

A possible error source that was identified in earlier work (Ref. 1) was the uncertainty of the level of super-saturation of the ambient air in the wind tunnel test section. Since the wind tunnel's spray system is located in the low-speed settling chamber, after the airflow is rapidly accelerated through the bell mouth into the test section, it is very likely that the ambient air is super-saturated. In the previous report, it was theorized that to ensure an accurate measurement of the ambient water vapor in the test section, that the Reference Probe needed to be heated. This was accomplished for this test by wrapping a heater element around the outside of the Reference Probe. During most of the testing, there was no difference between the ambient water vapor measurements and those from earlier tests. However, since the Reference Probe was heated, liquid water occasionally was able to run back on the exterior of the probe to the inlet and be ingested. As will be discussed later, based on the system measurements it was obvious when this occurred. Since for most of the cases examined there was no difference between the heated and unheated Reference Probe ambient water vapor measurements, and the heated probe would occasionally ingest liquid water, the heating of the Reference Probe was discontinued and is not recommended for future testing.

The other change made to the system was generated by concerns of the accuracy of the water vapor measurements from the IR Gas Analyzers. The Analyzers' manufacturer released a newsletter (Ref. 2) in which they described the need for care when measurement pressures varied significantly from calibration pressures. Since during operation of the system the pressures in the IR Gas Analyzers vary with wind tunnel airspeed, the authors were concerned that this effect would introduce error into the water vapor measurements. A bench test was conducted by varying the restriction of the exit flow of the pumped air sample passing through the IR Gas Analyzer's measurement cell. Figure 1 shows the full range of the data gathered from this bench test and Figure 2 shows the data close to the ambient pressures. The air sample for these measurements was maintained at a constant humidity with a reference dew point generator. As can be seen from these figures, there is a small band where pressure variations are adequately compensated and no error occurs, but significant error can be introduced at pressure variations outside this band. To eliminate this potential error source, the IR Gas Analyzer's measurement cell was monitored during all subsequent testing and the exit flow rate was controlled to maintain the measurement cell at the pressure recorded during the instrument's daily calibrations.

Test Results

The NASA Total Water Content Isokinetic Sampling Probe was tested in the NASA Glenn Icing Research Tunnel (IRT) during January and February 2009. The comparison of measured TWC to wind tunnel calibrated liquid water content (LWC) with varying airspeed, LWC, droplet median volumetric diameter (MVD), and temperature was of particular interest for this test. The test matrix of this testing is shown in Table 1. Test section temperature was between –20 °C and –2 °C, airspeed was between 51 and 104 m/s, wind tunnel calibrated LWC was between 0.3 and 1.5 g/m^3, and wind tunnel calibrated MVD was between 14 and 192 μm.

Typical Measurements

The two primary outputs of the system are TWC and 10 sec averaged TWC. A typical example output over a spray is shown in Figure 3. The horizontal axis is time-of-day and the vertical axis is TWC in g/m^3. The level of variability shown is representative of that seen in all cases.

One potential source of error for an isokinetic sampling probe is not operating the probe at the proper flow rate. The NASA system is constantly calculating the target mass flow rate required to ensure isokinetic sampling (dependant on wind tunnel airspeed, temperature, and the probe orifice size) and the actual corrected sample mass flow rate. This data is available in the system output and is displayed on the data system's user screen, and allows for the manual control of the sample mass flow rate. Figure 4 shows typical values when the mass flow rate was maintained properly during a wind tunnel water spray test run.

As discussed earlier, it is important to maintain the IR Gas Analyzer's measurement cell pressure at the same pressure used during calibration. Figure 5 includes plots of the sample and reference IR Gas Analyzers' measurement cell pressures. The variability seen in the sample cell's pressure here is acceptable since it falls within the pressure compensated band that results in no measurement error.

Figure 6 shows representative raw water vapor measurements for the sample and reference air sources. As can be seen in this plot, most of the variability of the TWC output is caused by variability in the sample's water vapor measurement. There is one point where the reference's water vapor level changes, and this results in an obvious change in the TWC output. Since the sample and reference air sources are pulled to the IR Gas Analyzers at different rates (the sample is pulled most of the physical distance at the isokinetic-required flow rate and the reference is pulled at the slower rate driven by the IR Gas Analyzer's pump), there is a possible error in the final TWC value. However, since this is a time dependent error, it would be completely eliminated in the averaged TWC values. The best means of removing this measurement phase error would be to locate the IR Gas Analyzers as close to the sampling ports as possible. In the NASA IRT, this could be accomplished by locating the IR Gas Analyzers at the test section overhead hatch on the third floor.

Examples of Probe Generated Measurement Phenomena

The most easily recognized measurement phenomenon occurs when the Sample port ingests a piece of shed ice. The ice provides additional water load to the baseline value so that the measured TWC spikes up (Fig. 7). For a small piece of ice, the TWC spike is very sharp and the TWC measurements very quickly return to the previous level. However, in cases where larger pieces of ice are ingested, it may take many seconds for the ice to completely evaporate within the probe and allow the measurement to return to the proper level. In all cases, the ingestion of ice shows a recognizable initial step increase in TWC.

A somewhat similar measurement error occurs when liquid water is pulled into the Reference port. For the 2009 IRT test, the Reference Probe was initially heated as discussed above. The downside to heating the Reference Probe is that it occasionally allowed liquid water to flow back on the exterior of the probe and be ingested along with the ambient air sample. When this occurred a recognizable initial step decrease in TWC occurred. The Reference-side error could be confirmed by checking the raw Reference water vapor measurement (Fig. 8). Since the Reference port had much lower heat and flow rates than the Sample port, these Reference port water ingestion events were slower to clear themselves and allow the resultant TWC measurement to return to the proper level. Because of the potential for liquid water ingestion, the Reference Probe heat was discontinued during this 2009 IRT test.

Another dramatic measurement error occurs when the Sample Probe tip became blocked with ice. This can easily occur if insufficient heat is provided to the probe when running at high airspeeds, very low temperatures, or very high water loading (the combination of all three is the worst-case). But again, as with all probe failure modes, this condition is easily recognized by examining the Sample Probe flow rate. Figure 9 shows the TWC and Sample Probe flow rate for a case when the probe tip was blocked with ice. The flow rate and then the TWC measurements clearly respond to the ice blockage. For this case, the blockage was recognized and additional heat was applied, with the probe clearing and all measurements returning to normal after approximately 1 min.

While these probe operation problems (ice ingestion into the Sample port, liquid water ingestion into the Reference port, and ice blockage of the Sample port) can introduce significant error into the measurements, they are easily recognizable by the user. For this reason, any future system should always include in its user display plots of the TWC, Sample and Reference ports raw water vapor measurements, and Sample Probe flow rate.

Examples of Wind Tunnel Generated Measurement Phenomena

During this test two wind tunnel phenomena became apparent that influence the measurements of the TWC measurement system. The first can result in TWC measurements that are significantly higher than the calibrated LWC expected for a given spray configuration. Figure 10 shows the TWC output from the system during such a run. At the beginning of the spray, the initial TWC is close to the calibrated tunnel LWC (in this case the wind tunnel was configured to run at a temperature of –18 °C, an airspeed of 102.8 m/s (200 knots), an LWC of 0.9 g/m^3, and a cloud droplet median volumetric diameter (MVD) of 19 μm). However, almost immediately the TWC began to ramp up and continued to increase until it reached a level of over 250 percent of the calibrated LWC. Also significant is that at spray-off, the TWC rapidly drops an amount very close to the calibrated LWC and then gradually decays back to zero. Although not shown here, the settling chamber and test section water vapor levels remain relatively constant throughout the spray. Taking these points together, the authors theorize that this measurement phenomenon is caused by ice crystal buildup during the spray. If a portion of the spray freezes out into ice crystals and then continues to blow around the wind tunnel's full circuit, the TWC measurements would appear similar to what is exhibited in this figure. Again, it is important to look at the raw water vapor measurements during such events. In this case, the Reference water vapor measurements remained roughly steady, with all of the increase in TWC being contributed by an increase in the Sample water vapor measurements.

Figure 11 shows what appears initially to be a similar phenomenon to ice crystal blow-around and that occurred several times during this test. Unlike the ice crystal blow-around situation, in this case the initial TWC starts off lower than the calibrated LWC condition, and importantly, at spray-off, the TWC drops to zero immediately. By examining this figure, you can see that the final time averaged TWC is quite close to the wind tunnel LWC calibration value of 0.55 g/m^3. It appears that there is something occurring at the beginning of this spray that is restricting the development of the cloud. Also shown in the figure are the settling chamber (upstream of the spray bars) and Reference Probe Dew Point measurements (the settling chamber measurement was made with the facility's capacitive hygrometer). The cases when this occurred were either the first spray of the night or following a wind tunnel cool-down period where the refrigeration heat exchanger was running colder than the ambient air temperature to effect a decrease in air temperature and the tunnel was running for an extended time with no spray. To further study this phenomenon, it is recommended that future testing closely examine the water vapor levels at various locations in the wind tunnel circuit and verify that the capacitive hygrometer's time response is adequate for this application.

Results of Parameter Study

Figures 12 to 30 will examine the effects of changing key wind tunnel parameters on measured TWC. The parameters that were individually varied are: MVD, airspeed, LWC, temperature, sprayed particle phase, and droplet size between Appendix C and SLD sizes. To compare the TWC to the IRT's calibrated LWC for each of these cases, the TWC was averaged over the period of the spray (or the period of stable output for cases where there was a perturbation, as described above).

Figures 12 to 14 will examine the effect of spray cloud MVD on the agreement between the measured TWC and the calibrated facility LWC. Figure 12 shows the TWC measured for three sprays in which airspeed was held at 51.4 m/s (100 knots), LWC was 1.4 g/m^3, and Total Temperature was –8.9 °C. From the left to the right, the three TWC traces are for 30, 40.9, 49.4 μm MVD. Relative to the IRT calibration LWC, the TWC for these three sprays are 18 percent low, 5 percent low, and 8 percent high, respectively.

Figure 13 is also showing the effects of changing cloud droplet size. These traces are for an airspeed of 77.2 m/s (150 knots), an LWC of 0.9 g/m^3 and a temperature of –8.9 °C. From left to right, the trace's

MVD are 19.6, 45.8, and 35.9 μm. Note that these are in time order and not in order of increasing MVD. The traces' corresponding averaged TWC agreement with the IRT's LWC calibration are 18, 52, and 48 percent high, respectively.

Figure 14 shows the examination of droplet size effect for 102.8 m/s (200 knots). Again the LWC was 0.9 g/m^3 and the temperature was –8.9 °C. From left to right, the traces represent the TWC for 20.1, 34.7, and 50.7 μm. Compared with the IRT LWC calibration, they are 45.7, 68.3, and 91.2 percent high, respectively.

Based on these three sets of comparisons, there seems to be a consistent trend of effects from increasing droplet MVD. It should be noted that this effect is present even though these charts are for Appendix C conditions (the larger MVD cases for each figure are very close to the upper bound of Appendix C conditions).

We will next examine the effects of airspeed on the agreement between the measured TWC and the IRT LWC calibration. Figure 15 shows the airspeed effects when the LWC is held at 0.55 g/m^3, the droplet size is held at an MVD of 16 μm, and the temperature is held at –18 °C. The traces from left to right are for 51.4 m/s (100 knots), 38.6 m/s (75 knots), and 102.8 m/s (200 knots). Their corresponding agreement with the IRT LWC calibration is 3.2, 6.6, and 43 percent high, respectively.

Figure 16 shows a similar chart for an LWC of 0.99 g/m^3, a droplet MVD of 19 μm, and a temperature of –18 °C. For this figure the corresponding airspeeds, from left to right, are 77.2 m/s (150 knots), 51.4 m/s (100 knots), 38.6 m/s (75 knots), and 102.8 m/s (200 knots). Compared to the IRT LWC calibration for each spray, the first three had a TWC that was 25.7, 14.4, and 16.3 percent high. The two higher speed runs, 77.2 m/s (150 knots) and 102.8 m/s (200 knots), had evidence of the ice crystal buildup as described above in reference to figure 10. In fact, this effect was so powerful for the 102.8 m/s (200 knots) run, that no TWC averaging was possible. The maximum TWC measured for this high speed run was approximately 250 percent higher than the corresponding IRT LWC calibration value.

Figure 17 shows varying airspeed results for an IRT calibration LWC of 1.46 g/m^3, droplet MVD of 21.1 μm, and temperature of –18 °C. The left trace is for 51.4 m/s (100 knots) and the right is for 38.6 m/s (75 knots). The left trace's comparison to IRT LWC is 19.4 percent high and the right's is 10.2 percent high.

While not as obvious as the trend seen in the examination of MVD trends, increasing airspeed also seems to generally increase the value of TWC over the corresponding value of IRT calibrated LWC. This trend is not particularly evident for airspeeds below 51.4 m/s (100 knots), but becomes more obvious for airspeeds above this.

The next five figures will examine the effects of varying LWC on the agreement between the isokinetic probe's measured TWC and the IRT's LWC calibration. Figure 18 shows the TWC measured for three sprays where the airspeed was held at 38.6 m/s (75 knots), the droplet MVD was held in the range between 15 and 21 μm, and the temperature was maintained at –18 °C. The left trace had an IRT calibrated LWC of 0.55 g/m^3, the center had 1.0 g/m^3, and the right had 1.5 g/m^3. Compared to the IRT LWC calibration, the TWC was 6.6 percent high for the left trace, 16.3 percent high for the center trace, and 10.2 percent high for the right trace.

Figure 19 shows the TWC measurements for a set of sprays where the LWC was varied and the airspeed was held at 51.4 m/s (100 knots), droplet MVD was held in a range between 14 and 21 μm, and temperature was held at –18 °C. From the left to right, the IRT calibrated LWC was 0.55, 1.0, 1.5, and 0.3 g/m^3 (note that again the sprays are not in order of increasing LWC, but rather in order of the time of the spray). The corresponding agreement of the measured TWC to the IRT calibrated LWC, again from left to right, is 3.2, 14.4, 19.4, and 6.0 percent.

Figure 20 shows the TWC measurements at 77.2 m/s (150 knots), 19.3 μm, and –18 °C where the LWC was 0.52 g/m^3 for the left trace and 1.0 g/m^3 for the right trace. Compared to the IRT calibrated LWC, the measured TWC for the left trace was 30.8 percent high (TWC was averaged over the stable period in the middle of the spray) and for the right trace was 25.7 percent high.

Figure 21 shows a similar set of traces for an airspeed of 77.2 m/s (150 knots), an MVD of 19.3 µm, and a temperature of –8.9 °C. The spray for the left trace had an IRT calibrated LWC of 0.52 g/m^3 and the right had 1.0 g/m^3. For the left trace, the TWC was 25.2 percent high compared to the IRT calibrated LWC, and the right trace was 20.9 percent high.

Figure 22 is the final chart of the series of varying LWC comparisons. This figure is for an airspeed of 102.8 m/s (200 knots), an MVD between 16 and 19 µm, and a temperature of –18 °C. The LWC for the left trace was 0.55 and 1.0 g/m^3 for the right. The left trace had the measured TWC 43 percent higher than the IRT calibrated LWC. The right trace was for the run examined earlier where the TWC increased through the entire spray. However, there is a brief stable period right after an initial increase, where the TWC is approximately 1.3 g/m^3, which is 44 percent higher than the spray's IRT calibrated LWC.

Of these five figures, the 51.4 m/s (100 knots) case (Fig. 19) is the only one that seems to exhibit a clear trend of increasing TWC elevation over IRT calibrated LWC with increasing LWC. It is possible that 51.4 m/s (100 knots) is near the threshold where a physical process such as droplet splashing, bouncing, or breakup begins to occur depending on the spray's LWC. Both below and above this airspeed, varying the LWC does not seem to have an effect.

The next five figures will examine the effect of wind tunnel temperature on the comparison between the isokinetic probe measured TWC and the calibrated LWC. Figure 23 shows three TWC measurement traces from 51.4 m/s (100 knots), 0.55 g/m^3, and 16 µm runs with the temperature varying from –8.9 °C (left) to –14 °C (center) and –18 °C (right). The TWC measurements were 2.6, 7.6, and 0.8 percent low (respectively) compared to the IRT calibration of 0.55 g/m^3. It should be noted that, as discussed earlier, immediately after decreasing the temperature in the IRT, the next measured TWC of the next spray is often low. This is the situation for these three cases. The comparison to IRT calibrated LWC was made near the end of each of these sprays, but this effect may explain the relatively low TWC measurements seen here.

Figure 24 shows the measured TWC at 77.2 m/s (150 knots), 0.52 g/m^3, and 18.7 µm sprays with the temperatures of –18 °C (left) and –8.9 °C (right). The averaged TWC for the left trace (over the stable period during the middle of the spray) was 30.8 percent high compared to the IRT calibrated LWC and was 25.2 percent high for the right trace (over the stable period near the end of the spray).

Figure 25 shows data from two similar runs, but this time with a calibrated liquid water content of 1.0 g/m^3. Compared to the tunnel's calibrated LWC, the left trace (–18 °C) is 25.7 percent high (averaged over the beginning stable period) and the right trace (–8.9 °C) is 20.9 percent high (averaged over the center stable period).

Figure 26 shows four TWC traces for sprays at 102.8 m/s (200 knots), 0.5 g/m^3, and 20.3 µm. The left trace was run at –2.2 °C and is 49 percent high compared to the calibrated wind tunnel LWC. 2nd from the left (–8.9 °C) was 32.4 percent high. 3rd from the left (–14 °C) was 23 percent high. And the right trace (–18 °C) was 25.3 percent high.

Figure 27 shows 3 TWC traces for cases at 102.8 m/s (200 knots), 0.9 g/m^3, and 19.1 µm. The left trace was run at –2.2 °C and is 43.9 percent high compared to the calibrated wind tunnel LWC. The center trace (–8.9 °C) was 34.8 percent high (the TWC was averaged using the stable data after the ice ingestion anomaly). The right trace was recorded for a test section temperature of –18 °C and was the case with increasing TWC throughout that is thought to be caused by ice crystals blowing around the wind tunnel circuit (note that the TWC measurements at the beginning of this spray have similar magnitude to the other two traces).

The preceding five charts examining varying test section temperatures display no clear trends on the TWC measurements. If one considers the parameters that might influence droplet splash, bounce, or breakup (the phenomena that are most likely to cause LWC measurement error), then it makes sense that temperature does not seem to influence the agreement between the isokinetic probe measured TWC and the IRT's calibrated LWC.

Figure 28 shows a comparison between two sprays. The spray that was used for the left tracing is a 'freeze out' condition that is known to generate ice particles. The spray that was used for the right tracing produces a normal, liquid cloud. Both had similar water contents, particle size, temperature, and airspeed. The left (freeze out condition) had a TWC that was 1.7 percent higher than the calibrated LWC and the right was 7.7 percent high. Based upon the stability of the measured conditions, the TWC measurement appears to have no effect caused by the particle phase (ice or liquid water), as would be expected.

The next two charts examine the influence of cloud droplet size on the agreement between the measured TWC and IRT calibrated LWC like the earlier comparison, except these charts include SLD conditions. Figure 29 shows the TWC tracings for 77.2 m/s (150 knots) and –18 °C. The left tracing was from a 0.6 g/m^3 LWC and 78.2 µm MVD SLD spray. The averaged TWC was 45.7 percent higher than the calibrated LWC. The right tracing was from a 0.52 g/m^3 LWC and 20.4 µm MVD spray. Its average TWC was 29.9 percent higher than the calibrated LWC.

Figure 30 shows the measured TWC traces for 77.2 m/s (150 knots), 0.7 g/m^3, and 18 °C sprays. The left TWC tracing is for the 191.5 µm SLD spray and was 83.2 percent higher than the corresponding calibrated LWC. The center tracing (20.4 µm) was 24.5 percent high. And the right tracing (42.4 µm) was 68.1 percent high.

As we saw with the earlier MVD comparison cases at 77.2 m/s (150 knots) (Fig. 13), there seems to be a consistent trend of effects from increasing droplet MVD into the SLD sized range. It is important to note that while the droplet size effect continues into the SLD regime, the effect appears to begin within the Appendix C range of MVD.

Results of Bulk Comparison Between Measured TWC and LWC Calibration

Finally, Figure 31 shows the average TWC values for each spray plotted against the corresponding IRT calibrated LWC. As has been seen in previously reported test results (Ref. 1), the TWC is quite consistently higher than the IRT calibrated LWC. Similar results have also been seen and with the Canadian Isokinetic Total Water Content Probe (Ref. 3).

Conclusions

Based upon the January and February 2009 testing and previous testing (Ref. 1), the NASA Isokinetic Total Water Content Probe appears to be making valid measurements. While a long-term goal of isokinetic probe development is to provide data up to 200 m/s, this speed is beyond the capability of the IRT. The probe was previously tested to 129 m/s and 2.48 g/m^3 (at a lower airspeed) (Ref. 1). Based on these past results, the data gathered here, and the theory of isokinetic sampling, there should be no limitation to the functionality of an isokinetic TWC probe up to 200 m/s. Providing sufficient heat to anti-ice the sample probe at high speed and low temperature conditions and providing additional sample flow (which is merely a matter of scaling up the current configuration) are the only issues that would need to be addressed. Bench testing conducted in 2008 (Ref. 1) demonstrated that the water vapor measurement and flow control subsystems resulted in repeatable results accurate within 5 percent. And droplet trajectory analysis (Ref. 1) showed negligible errors caused by the sampling probe for realistically sized cloud particles and flight speeds. The testing performed in January and February of 2009 further supports the validity of this system.

Heating the Reference Probe was discontinued because it was found to allow the ingestion of cloud water and adversely affect the measurements and was also shown to be unnecessary.

Control of the pressure in the IR Gas Analyzers' measurement cell was found to be important and was accomplished by controlling their exit flow rates.

During the testing of the NASA Isokinetic Total Water Content Probe, several cases had ice particle ingestion, water ingestion into the reference port, or probe tip ice contamination. What is particularly noteworthy is that these measurement malfunctions are easily recognized and have distinct, identifiable signatures.

At relatively low liquid water content and moderate airspeed, the NASA Isokinetic Total Water Content Probe has been shown to agree well with the liquid water content calibration of the IRT. At some conditions there is an obvious ice crystal blow-around effect that results in dramatically elevated TWC measurements. For other conditions there appears to be some other effect (which the authors theorize is caused by sub-saturation test section humidity) that results in temporarily lowered TWC measurements. Specifically, the first spray of the day and the first spray after lowering the wind tunnel temperature seems to exhibit lower TWC than would normally be expected.

The NASA Isokinetic Total Water Content Probe data from this and previous tests suggest that there is a droplet size effect in the IRT liquid water content calibration. This is particularly evident for SLD sprays. Wind tunnel airspeed above 51.4 m/s (100 knots) also seems to adversely effect the agreement between the measured total water content and the wind tunnel's calibrated liquid water content.

Recommendations

If further development and testing of the NASA Isokinetic Total Water Content Probe is pursued, the authors recommend the following actions:

- Acquire or fabricate a new sampling probe that uses resistive heater elements to provide anti-icing and sample evaporation heat. The current probe requires a low-voltage, high current power supply and very large power conductors. It also appears susceptible to internal electrical shorts that may limit its future utility.
- To simplify and speed-up the measurement process, improved water vapor measurement cell flow rate valves should be installed and control of this subsystem should eventually be automated.
- To allow the automation of the main sample flow rate control, a digitally controlled bypass valve should be added to the main sample line. The current configuration requires manual adjustment of the ejector to accurately control the sample flow rate.
- To minimize the lag between the sample and reference water vapor measurements, the IR Gas Analyzers should be relocated closer to the sampling probe.
- To further examine the effects of wind tunnel humidity, the water vapor levels at various locations in the wind tunnel circuit should be monitored (particularly after the temperature has been lowered).

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3. Davison, Craig, "Naturally Aspirating Isokinetic Total Water Content Probe (IKP) 2009 Testing," presented at High Ice Water Campaign Instrumentation Meeting, Cleveland, OH, November 25, 2009.

TABLE 1.—AS-RUN TESTMATRIX

Date	Time	Run #	Cond #	IRT Total Temp (deg C)	IRT True A/S (knots)	IRT Cal LWC (g/m3)	IRT Cal MVD (microns)
30-Jan	19:10:00	6	5	-18.02	150.3	0.52	18.7
30-Jan	19:38:00	7	6	-17.94	150.07	1	19.3
30-Jan	19:52:00	8	8	-18.12	75.06	0.55	15.1
30-Jan	20:03:00	9	9	-18.02	75.22	1	18.5
30-Jan	20:11:00	10	10	-18.04	76.17	1.5	21.4
30-Jan	20:25:00	11	11	-18.04	200.7	0.55	15.9
30-Jan	21:02:00	12	12	-18.00	199.4	0.9	19.1
30-Jan	21:30:00	13	30	-18.01	150.83	0.6	78.2
30-Jan	21:41:00	14	31	-18.03	150.04	0.73	191.5
30-Jan	21:50:00	15	32	-18.01	149.04	0.52	20.4
30-Jan	22:01:00	16	33	-17.96	150.12	0.7	20.4
30-Jan	22:08:00	17	34	-18.00	148.53	0.7	42.5
30-Jan	22:20:00	18	35	-19.96	151.36	0.42	11.8
30-Jan	22:31:00	19	39	-20.04	150.1	0.4	14
2-Feb	16:50:00	20	19	-2.25	198.5	0.5	20.3
2-Feb	17:11:00	21	41	-2.21	199	0.9	19.1
2-Feb	17:22:00	22	13	-8.92	100.66	0.55	16
2-Feb	17:37:00	23	18	-8.70	200.55	0.5	20.3
2-Feb	17:56:00	24	40	-8.89	199	0.9	19.1
2-Feb	18:06:00	25	14	-14.12	100.06	0.55	16
2-Feb	18:24:00	26	17	-13.90	200.37	0.5	20.3
2-Feb	18:36:00	27	15	-17.97	100.1	0.55	16
2-Feb	18:50:00	28	16	-18.04	199.33	0.5	20.3
2-Feb	19:40:00	31	1	-18.07	100.57	0.55	16
2-Feb	19:50:00	32	2	-18.16	99.58	0.99	19
2-Feb	20:01:00	33	3	-18.07	100.31	1.46	21.1
2-Feb	20:12:00	34	4	-18.06	100.29	0.3	14.1
2-Feb	20:46:00	35	26	-8.98	99.8	1.4	19.9
2-Feb	21:07:00	36	27	-8.90	100.7	1.4	30
2-Feb	21:14:00	37	28	-8.98	100	1.4	40.9
2-Feb	21:09:00	38	29	-8.95	99.83	1.4	49.4
2-Feb	21:30:00	39	42	-8.72	150.6	0.52	18.7
2-Feb	21:46:00	40	43	-8.77	149.49	1	19.3
2-Feb	21:52:00	41	20	-8.91	150.57	0.89	19.6
2-Feb	21:57:00	42	21	-9.02	149.35	0.98	45.8
2-Feb	22:02:00	43	22	-9.01	150.87	0.9	35.9
2-Feb	22:17:00	44	23	-9.02	200.63	0.9	20.1
2-Feb	22:35:00	45	24	-8.91	201.37	0.9	34.7
2-Feb	22:41:00	46	25	-9.00	201.16	0.9	50.7

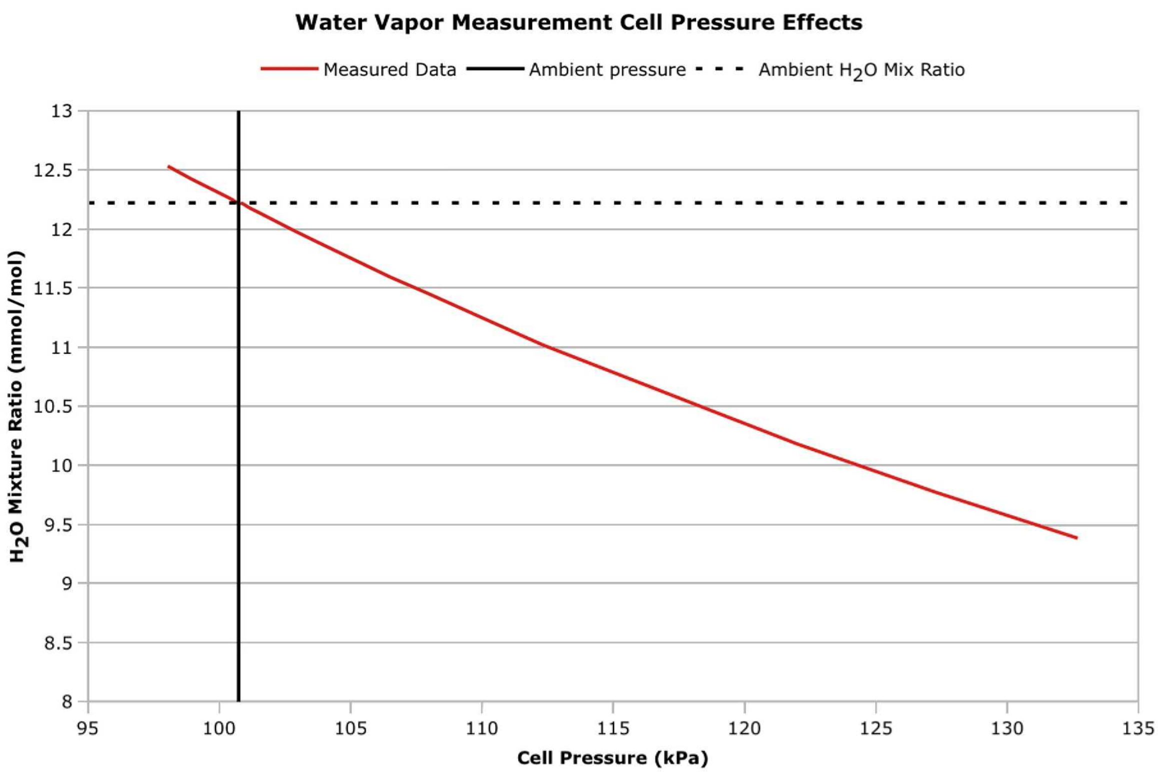

Figure 1. —Water vapor measurement cell bench test pressure effects.

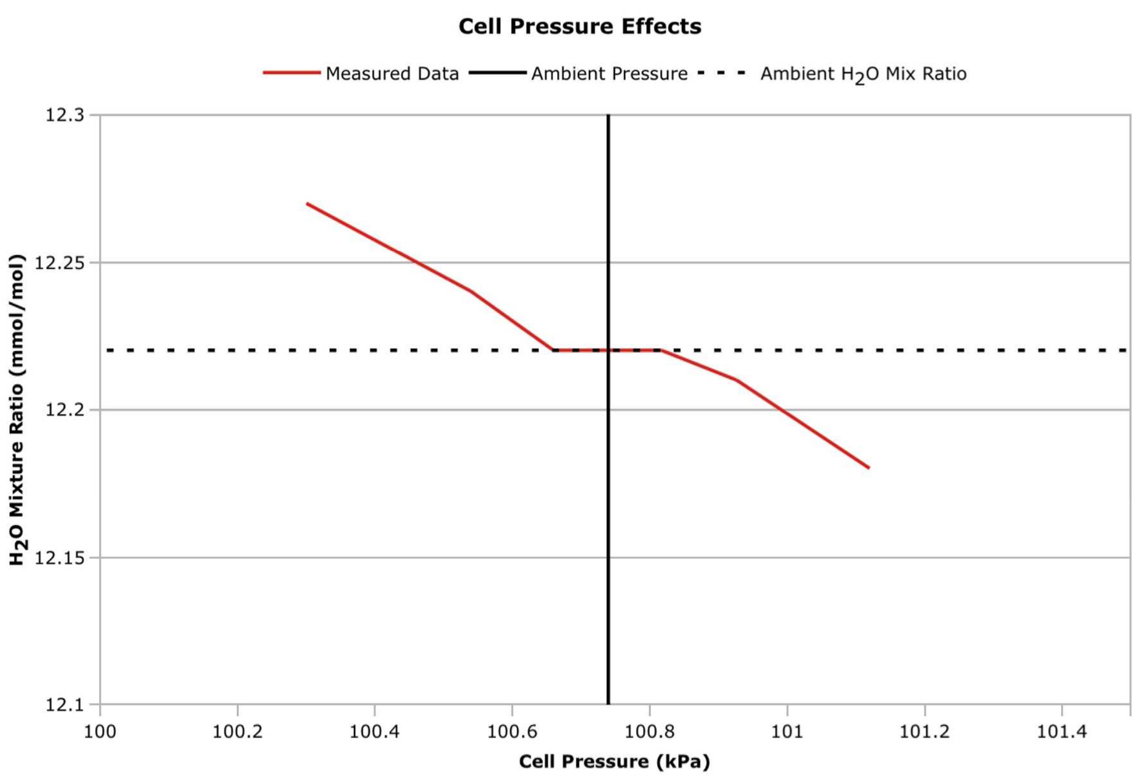

Figure 2. —Water vapor measurement cell bench test pressure effects (zoomed in).

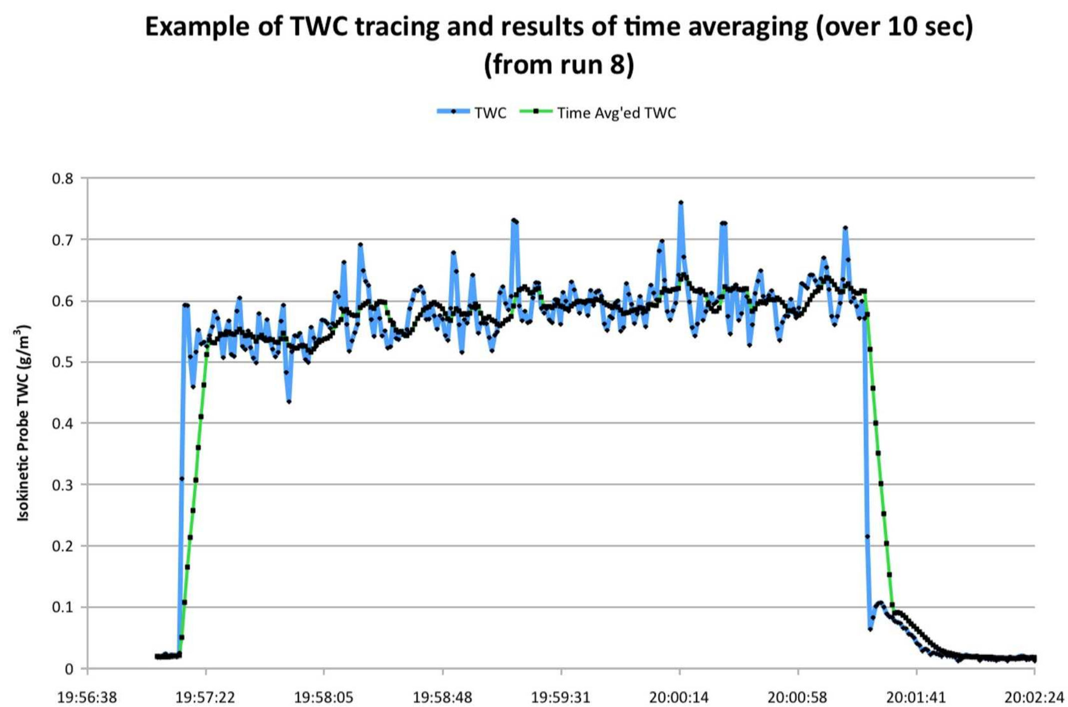

Figure 3.—TWC tracing.

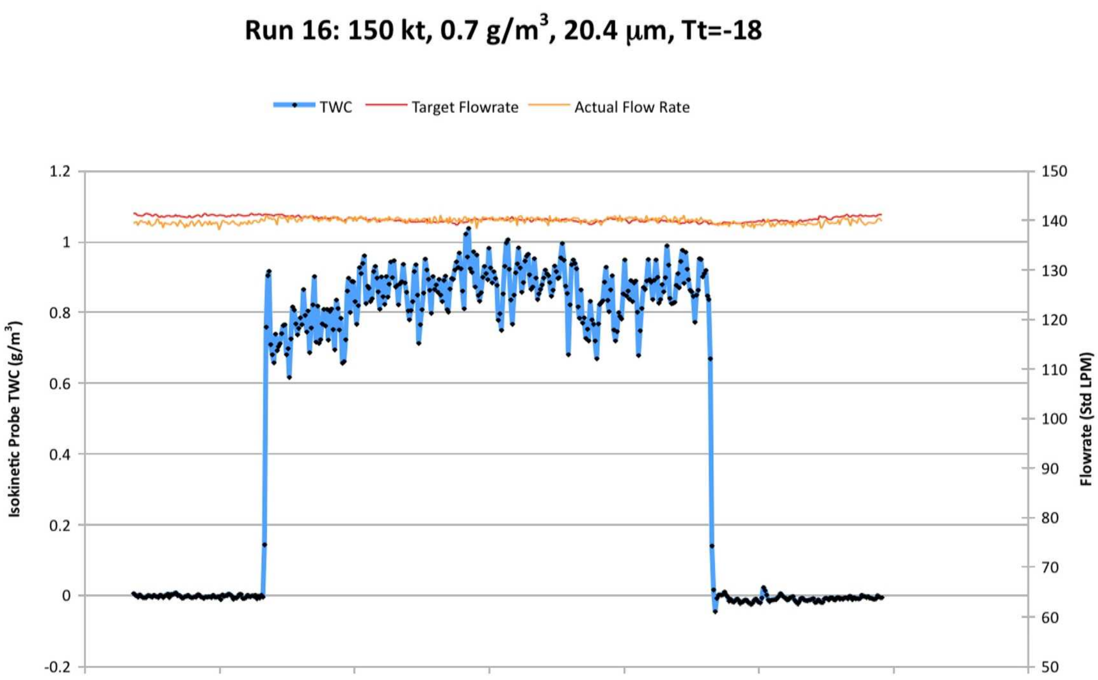

Figure 4.—Flow rate tracings (target and actual).

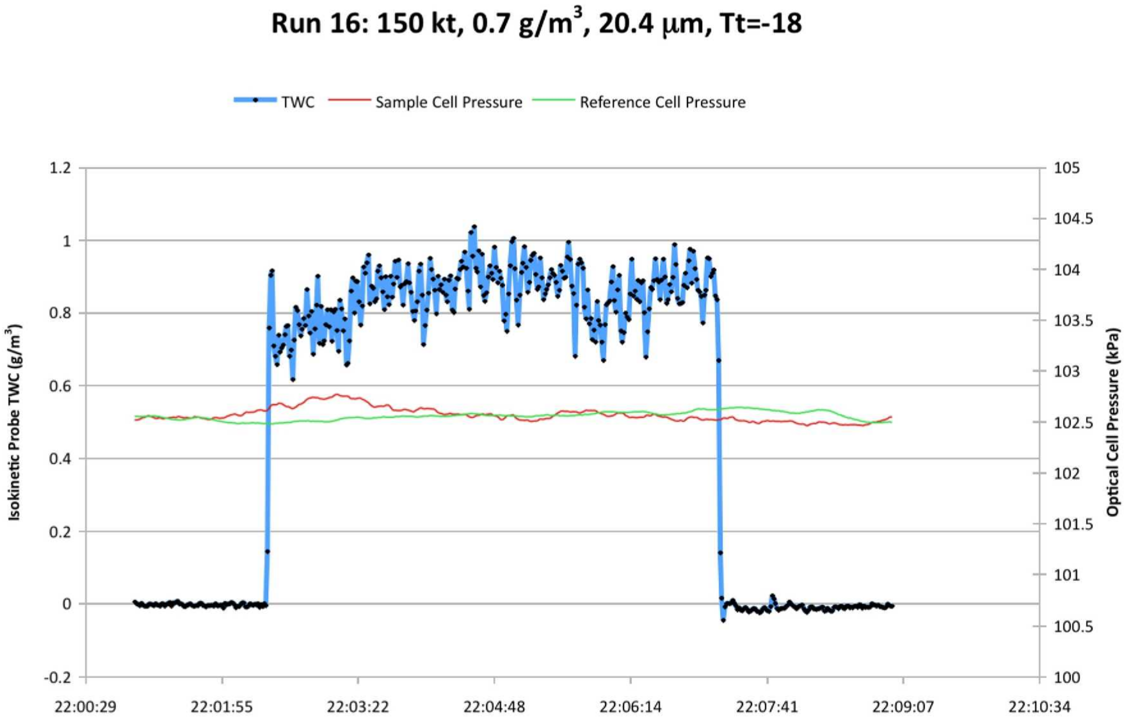

Figure 5.—Measurement cell pressure tracings.

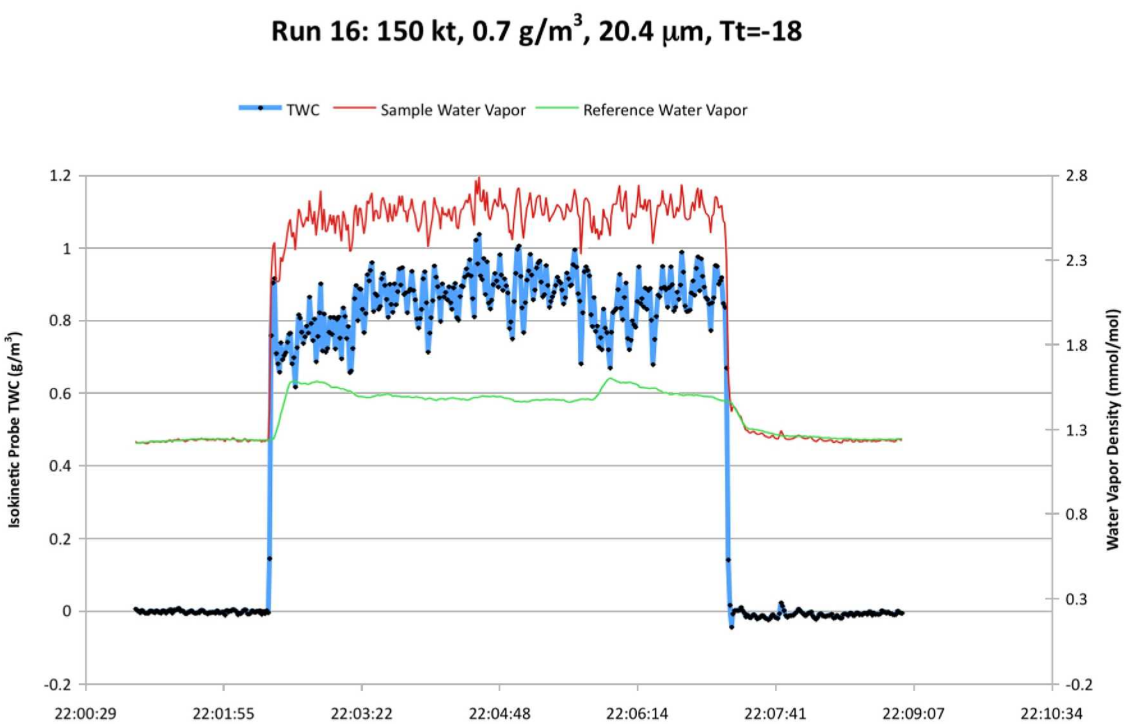

Figure 6.—Water vapor tracings.

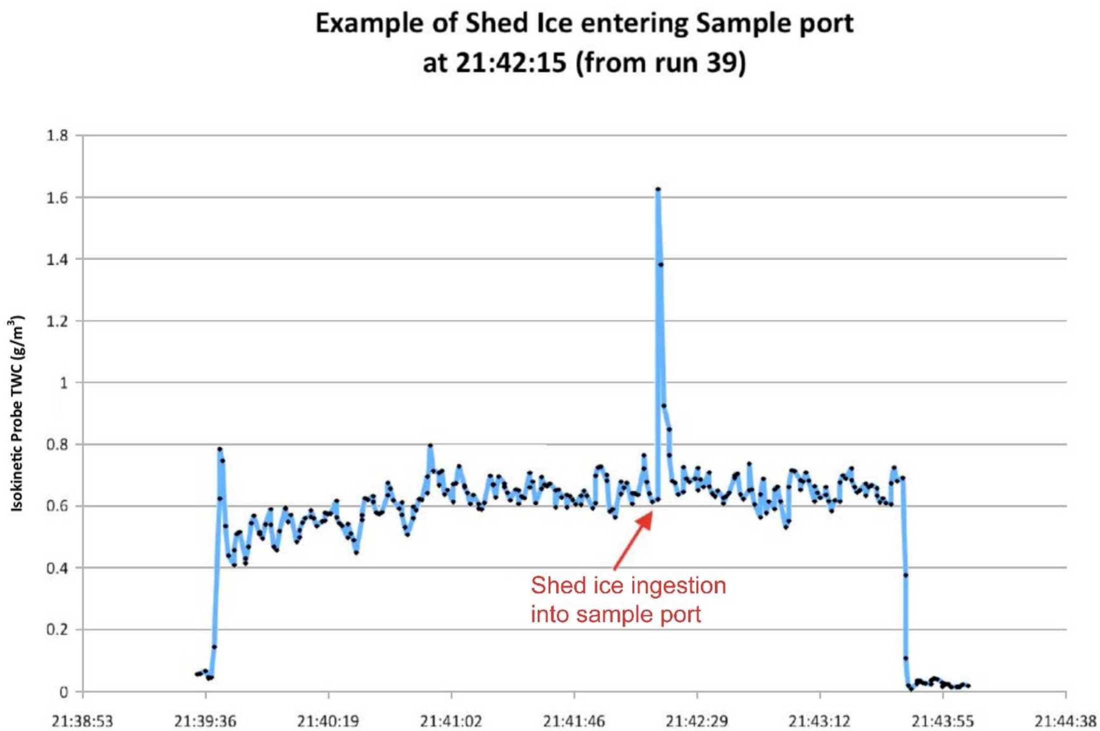

Figure 7.—Ingested ice ‘chunk’ into sample port (run 39).

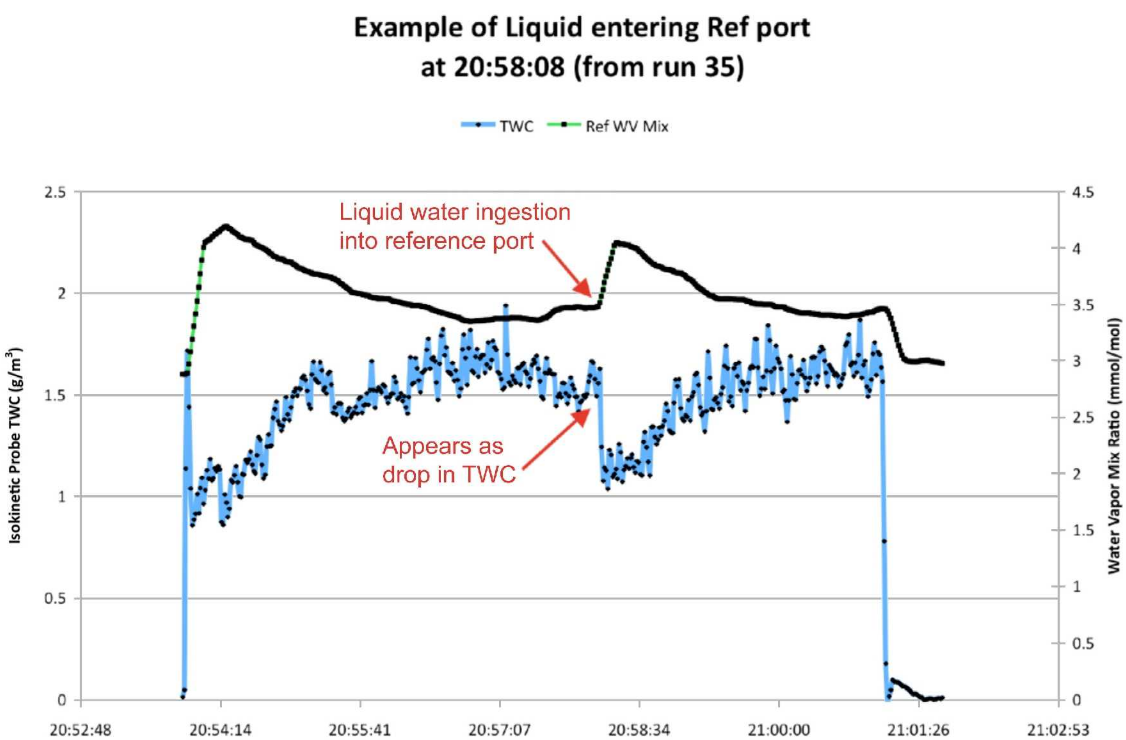

Figure 8.—Ingested water into reference port (run 35).

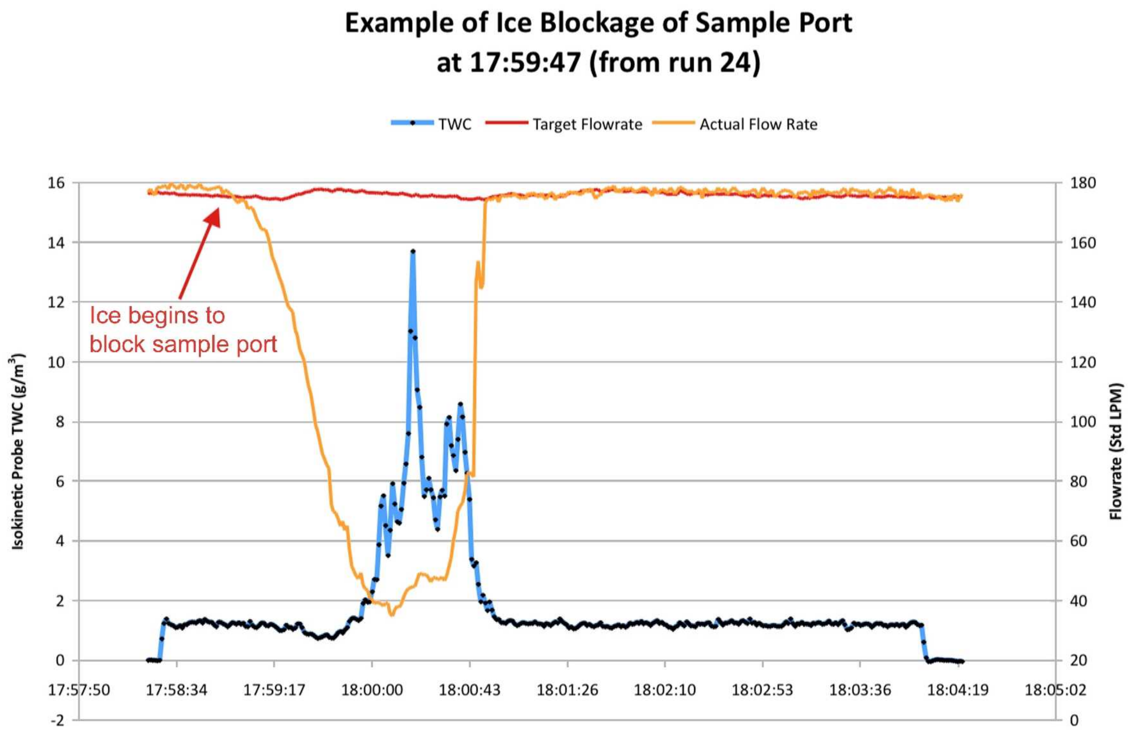

Figure 9.—Probe tip ice blockage (run 24).

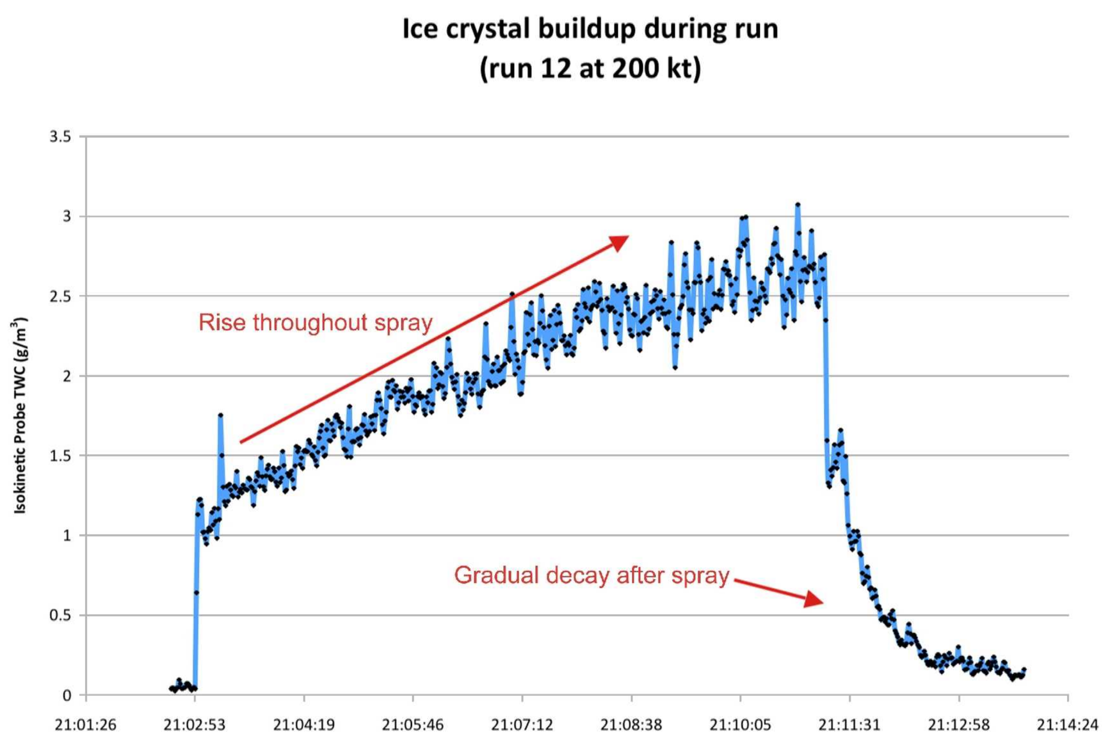

Figure 10.—Ice crystal buildup during run (run 12).

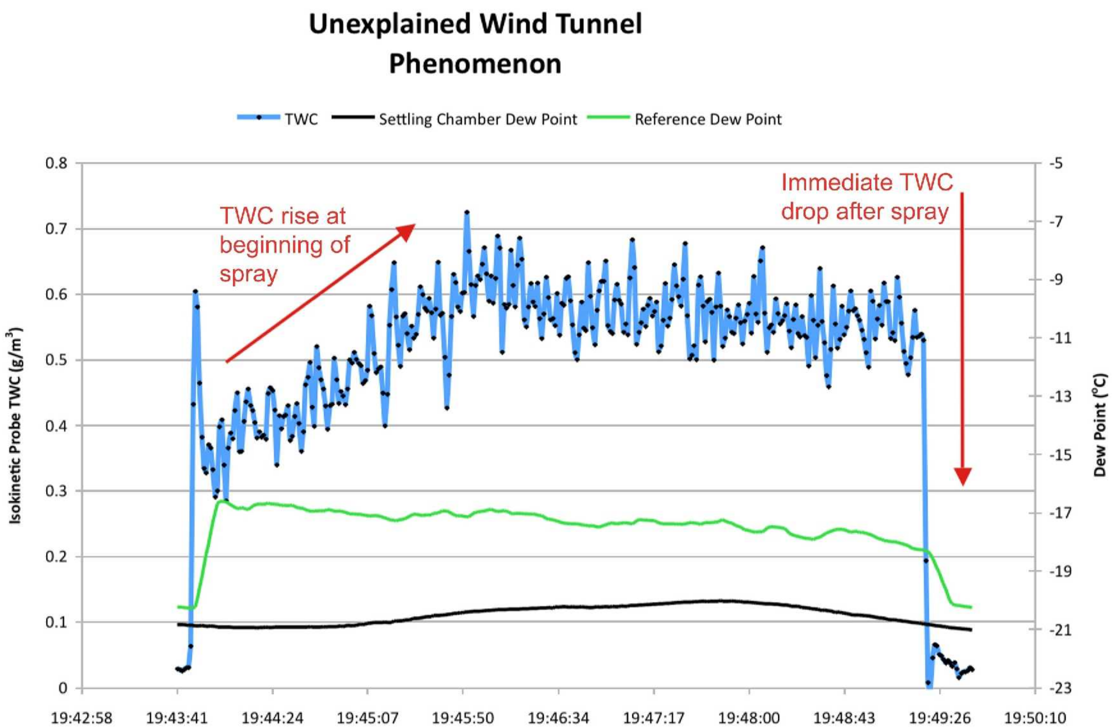

Figure 11.—Unknown wind tunnel phenomenon (run 31).

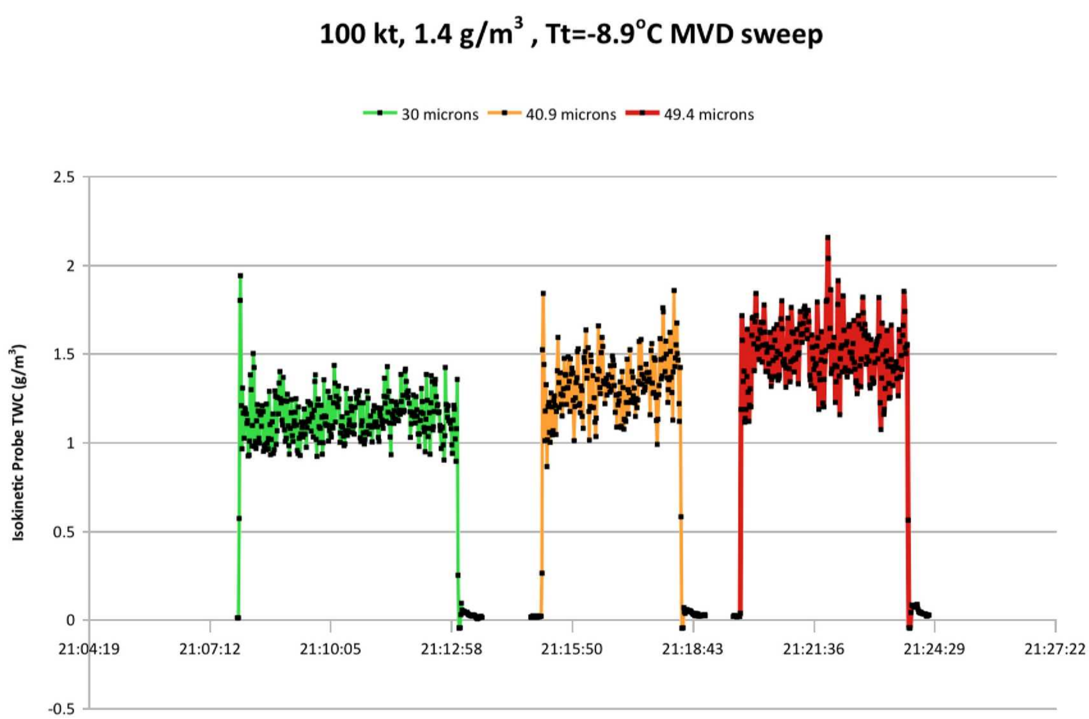

Figure 12.—MVD sweep at 100 kts.

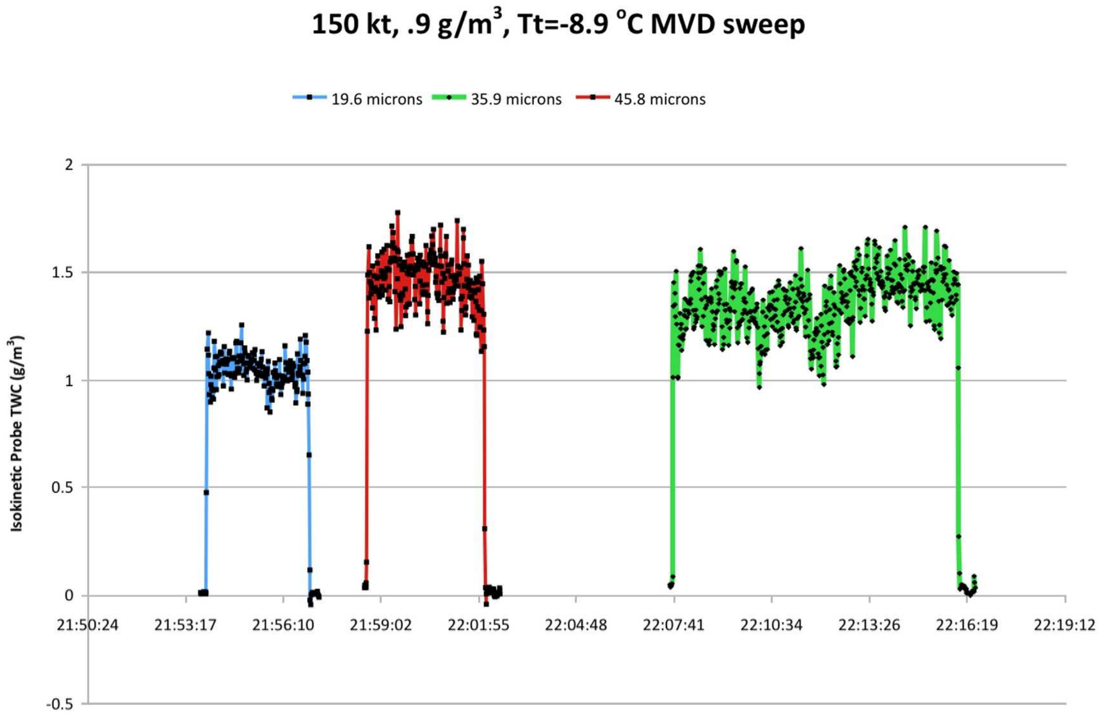

Figure 13.—MVD sweep at 150 kts.

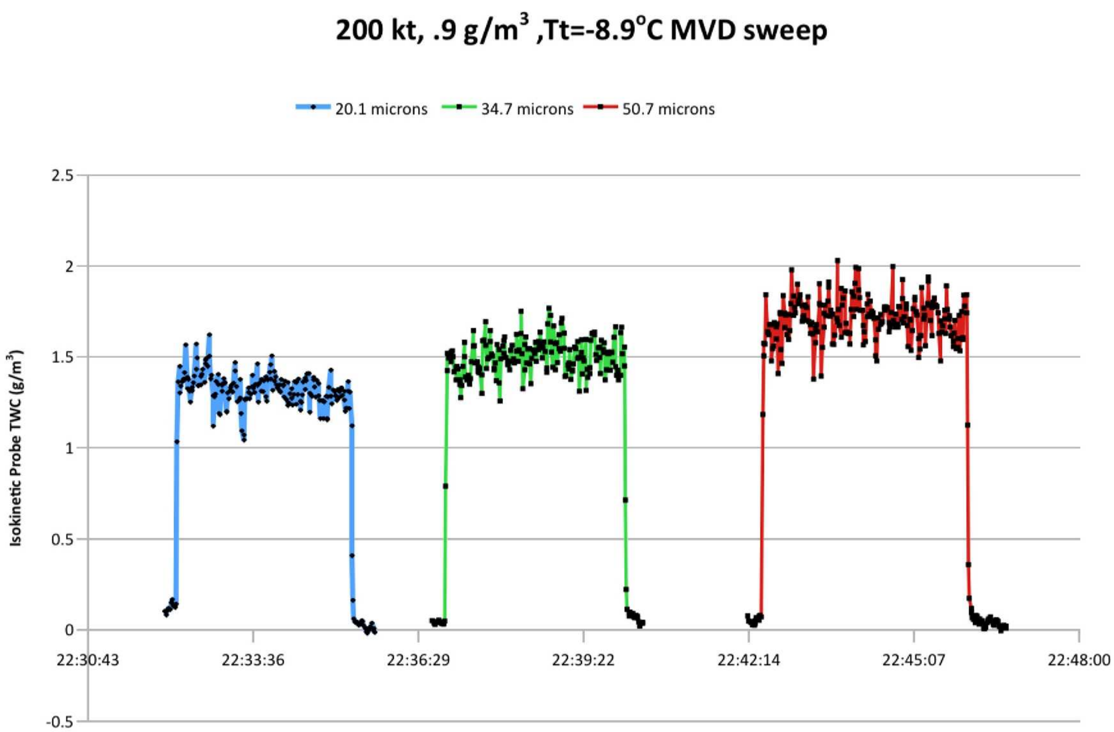

Figure 14.—MVD sweep at 200 kts.

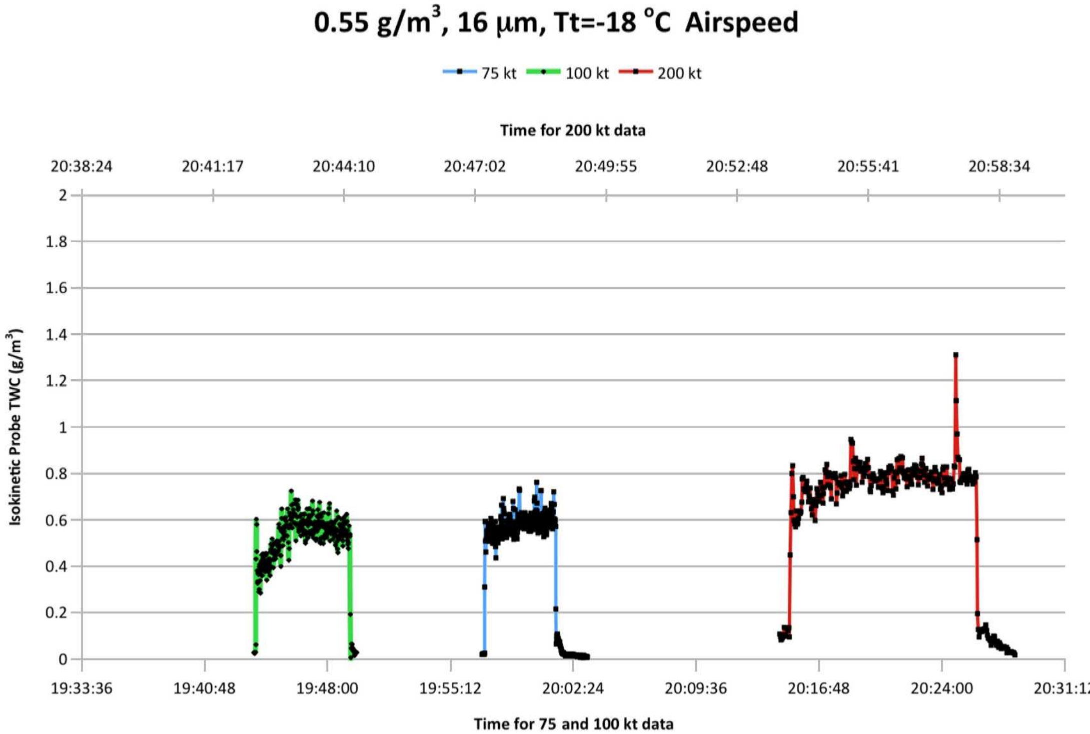

Figure 15.—Airspeed sweep at 0.55 g/m^3.

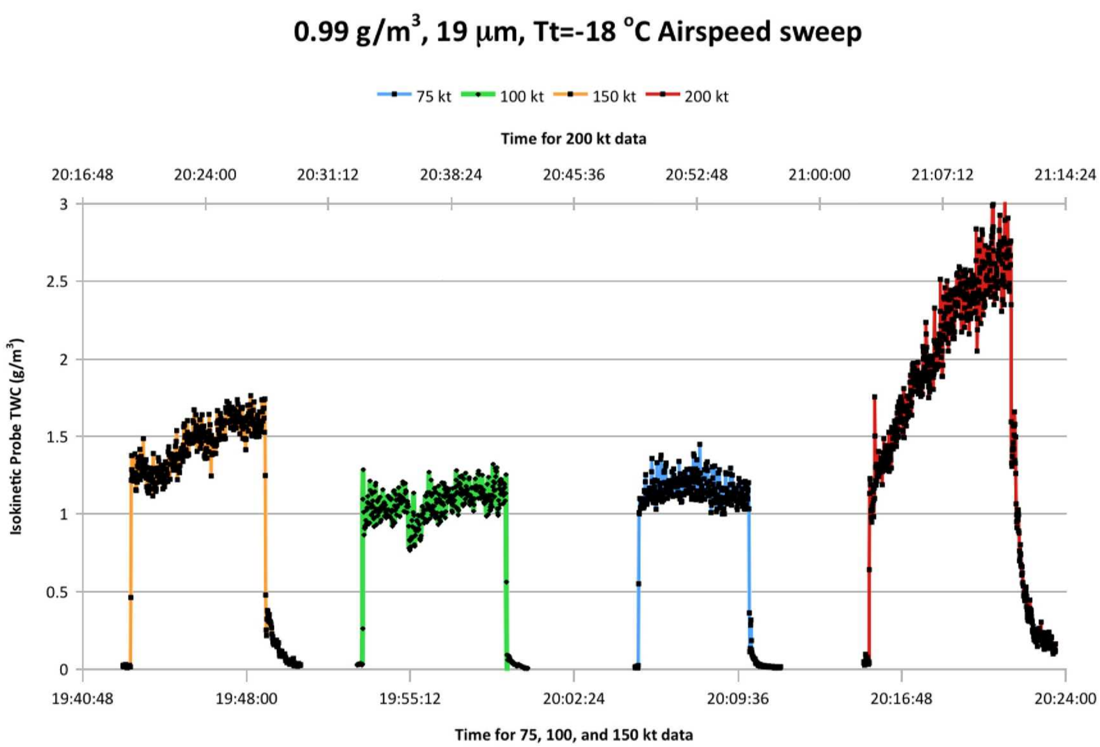

Figure 16.—Airspeed sweep at 0.99 g/m^3.

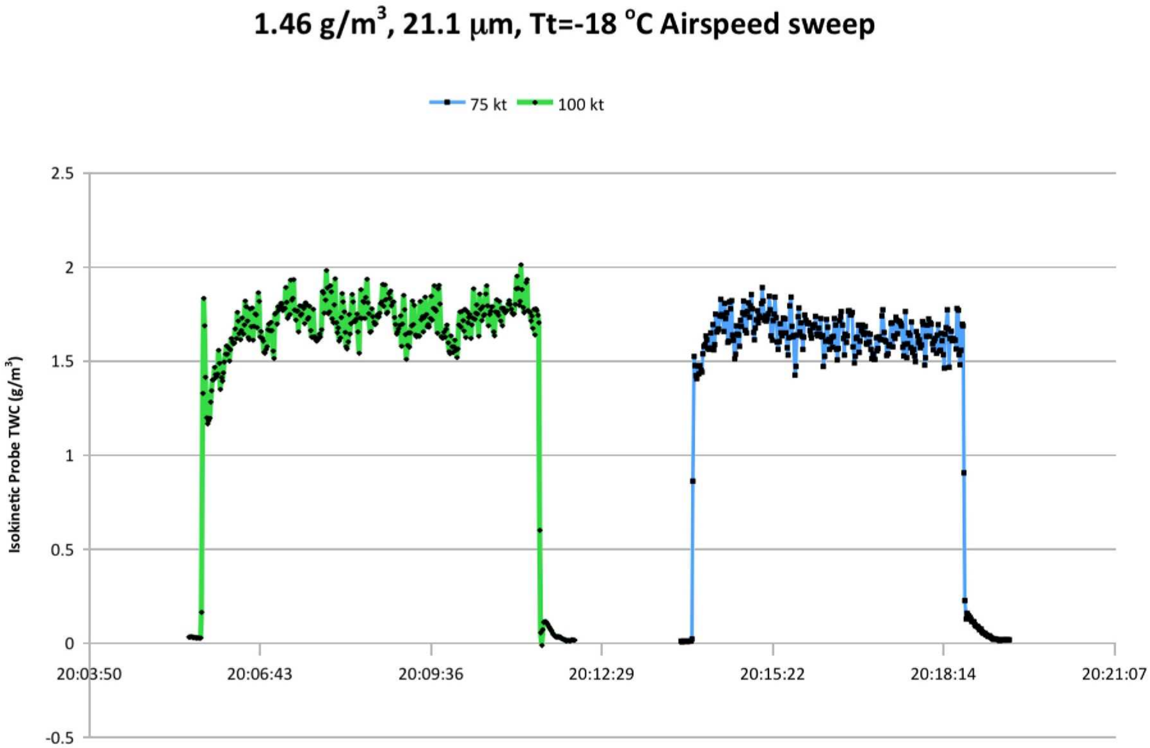

Figure 17.—Airspeed sweep at 1.46 g/m^3.

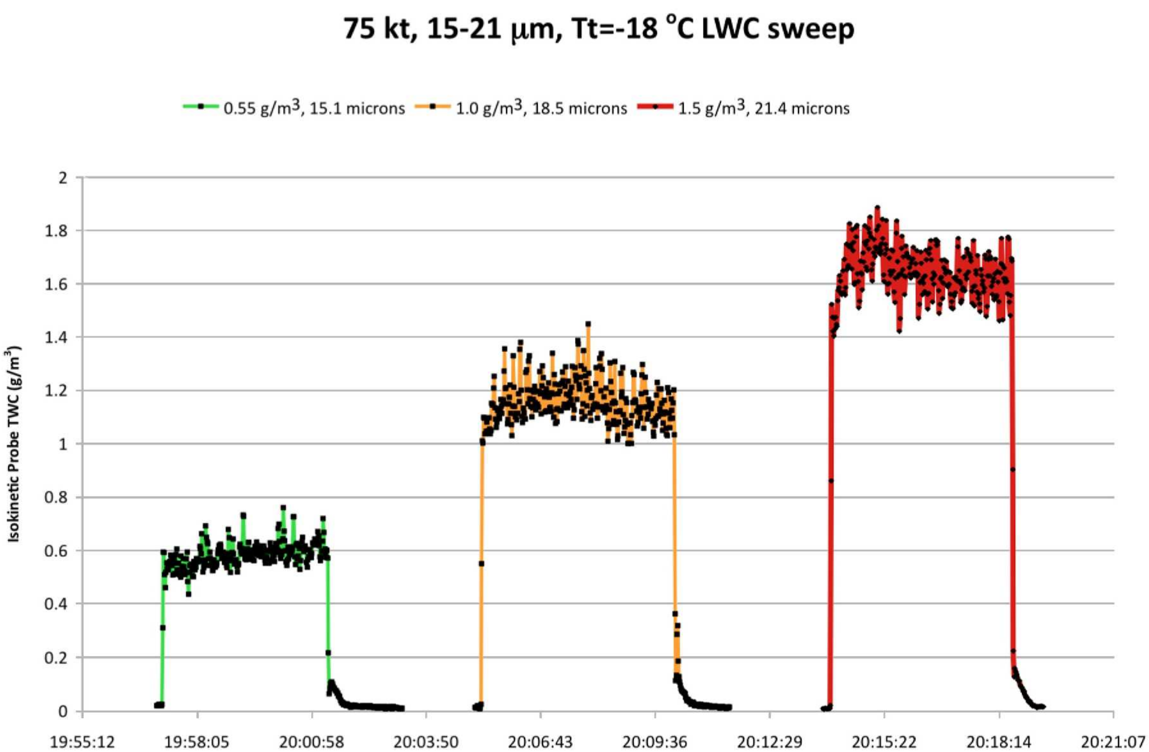

Figure 18.—LWC sweep at 75 kts.

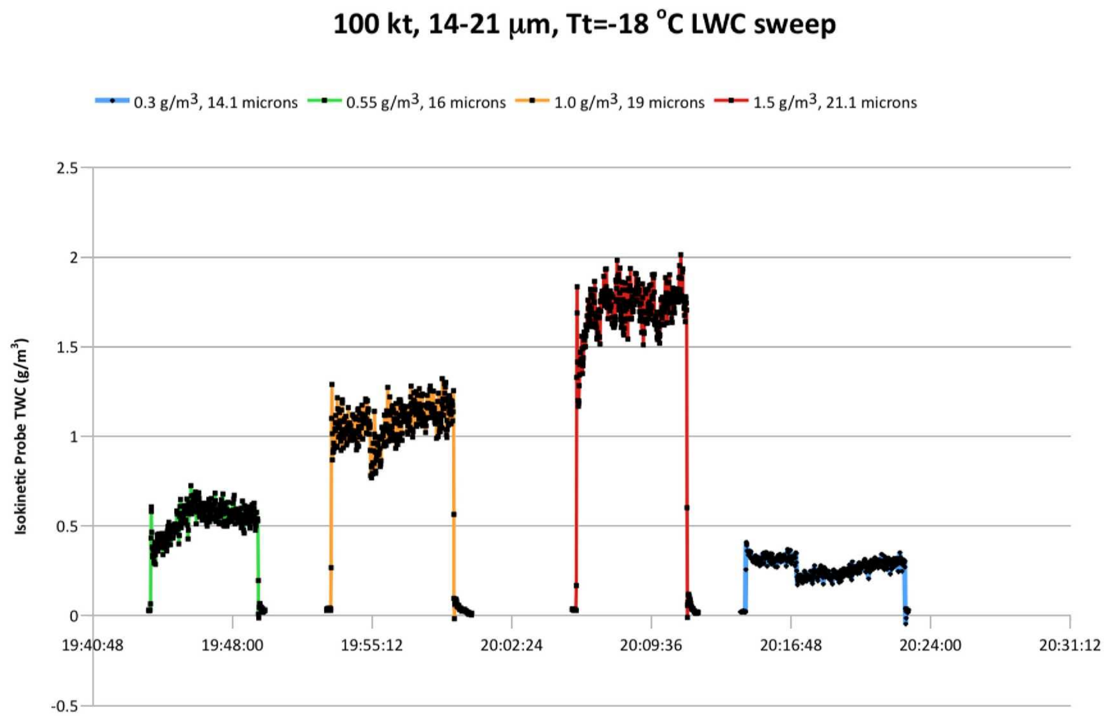

Figure 19.—LWC sweep at 100 kts.

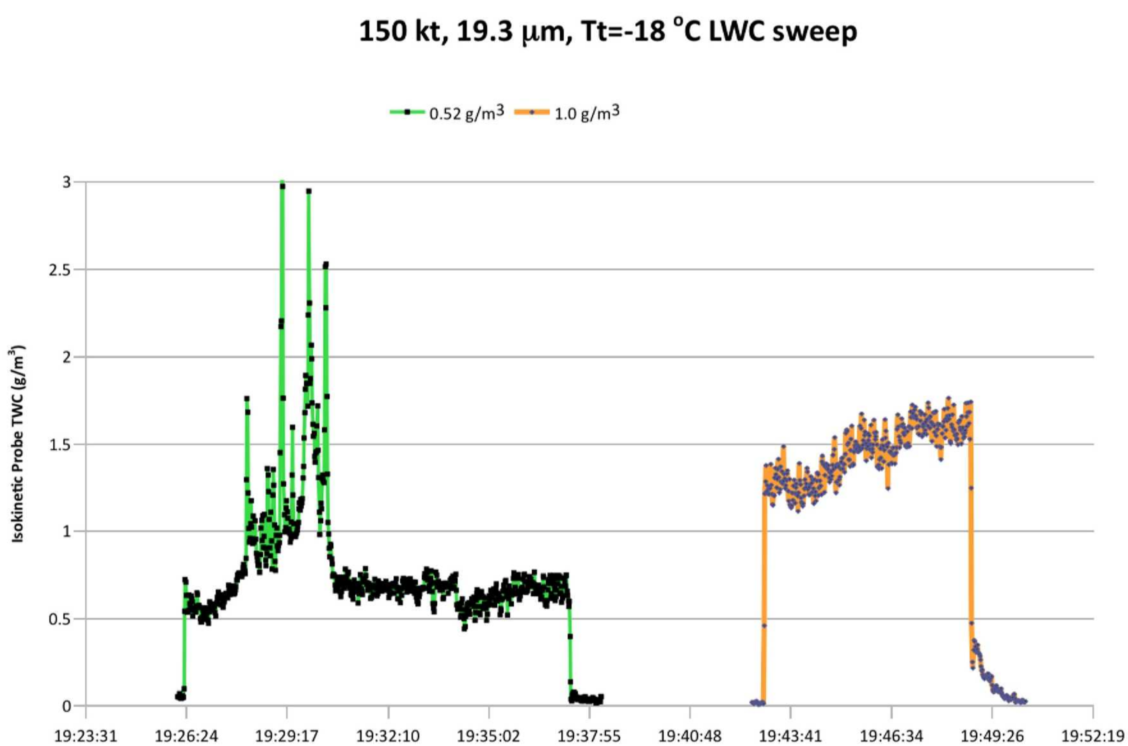

Figure 20.—LWC sweep at 150 kts and –18 °C.

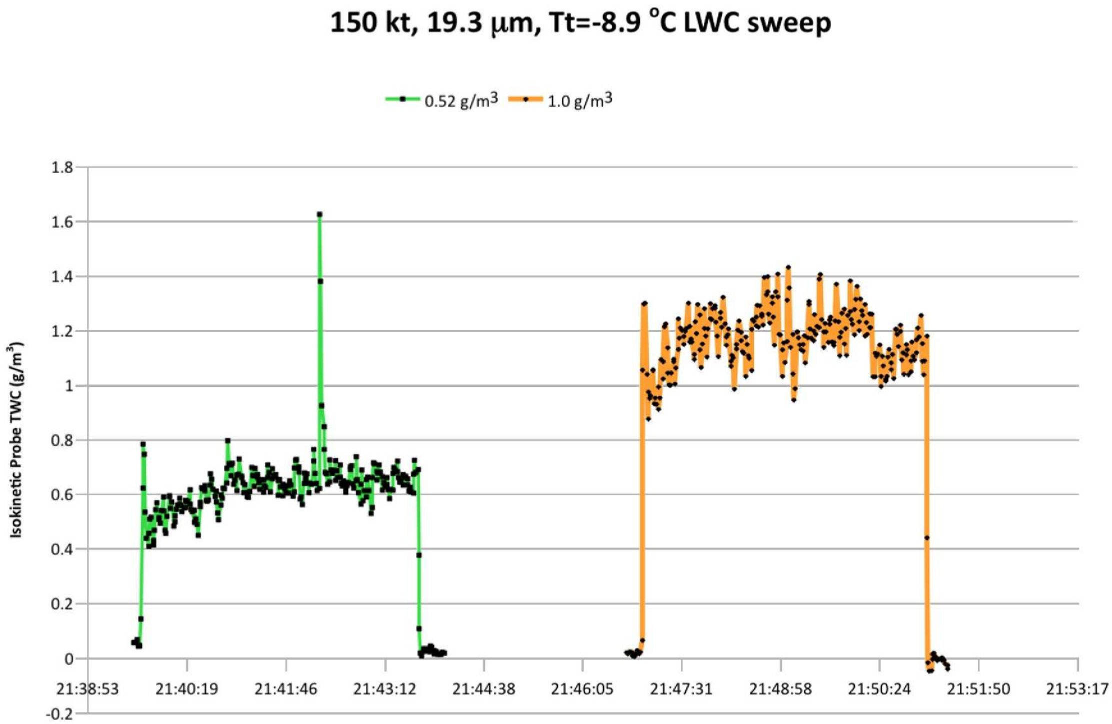

Figure 21.—LWC sweep at 150 kts and –9 °C.

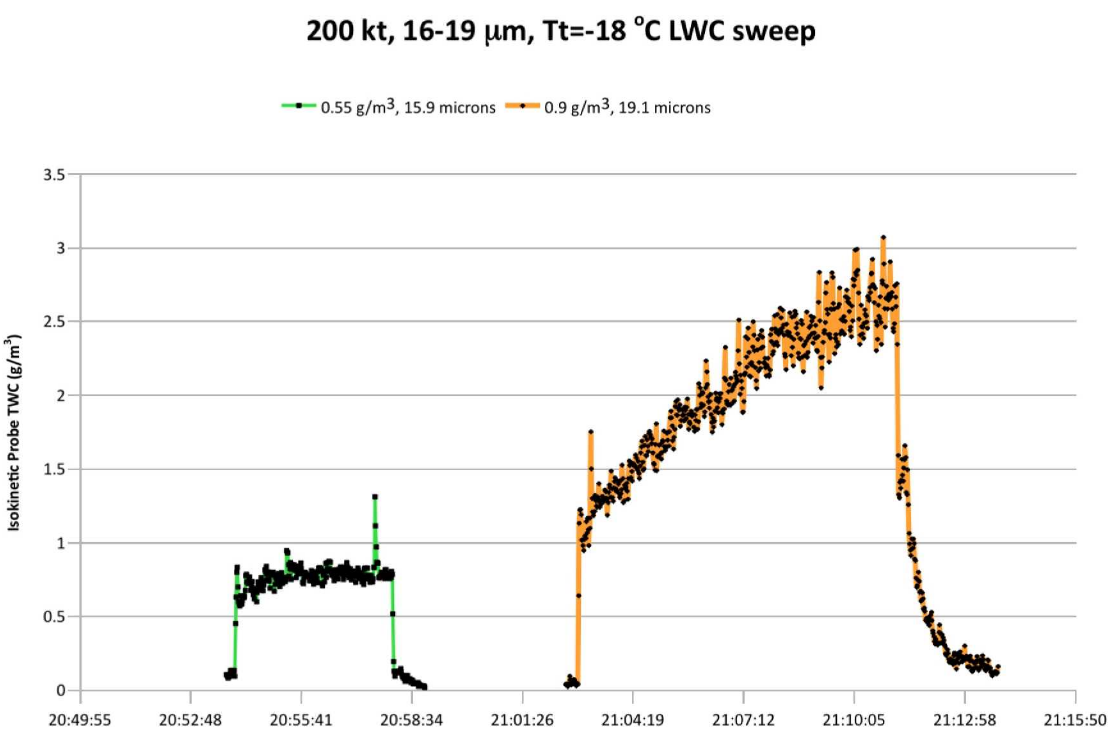

Figure 22.—LWC sweep at 200 kts.

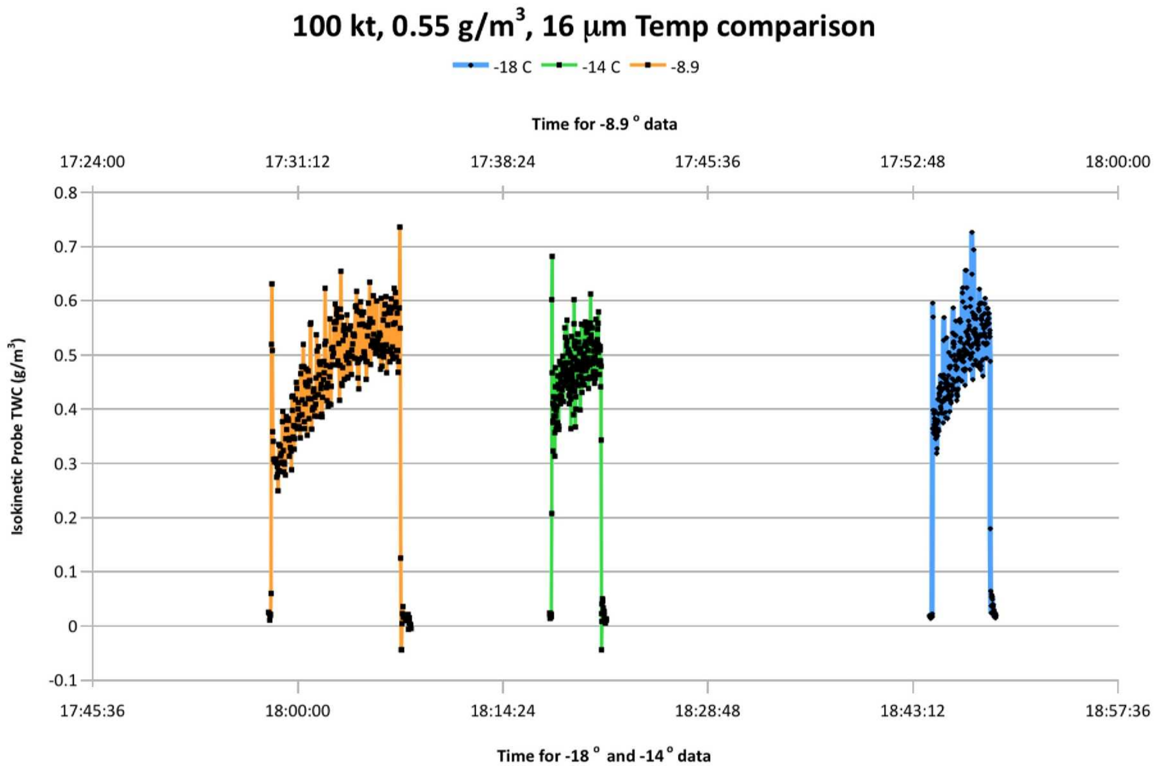

Figure 23.—Temperature comparisons at 100 kts.

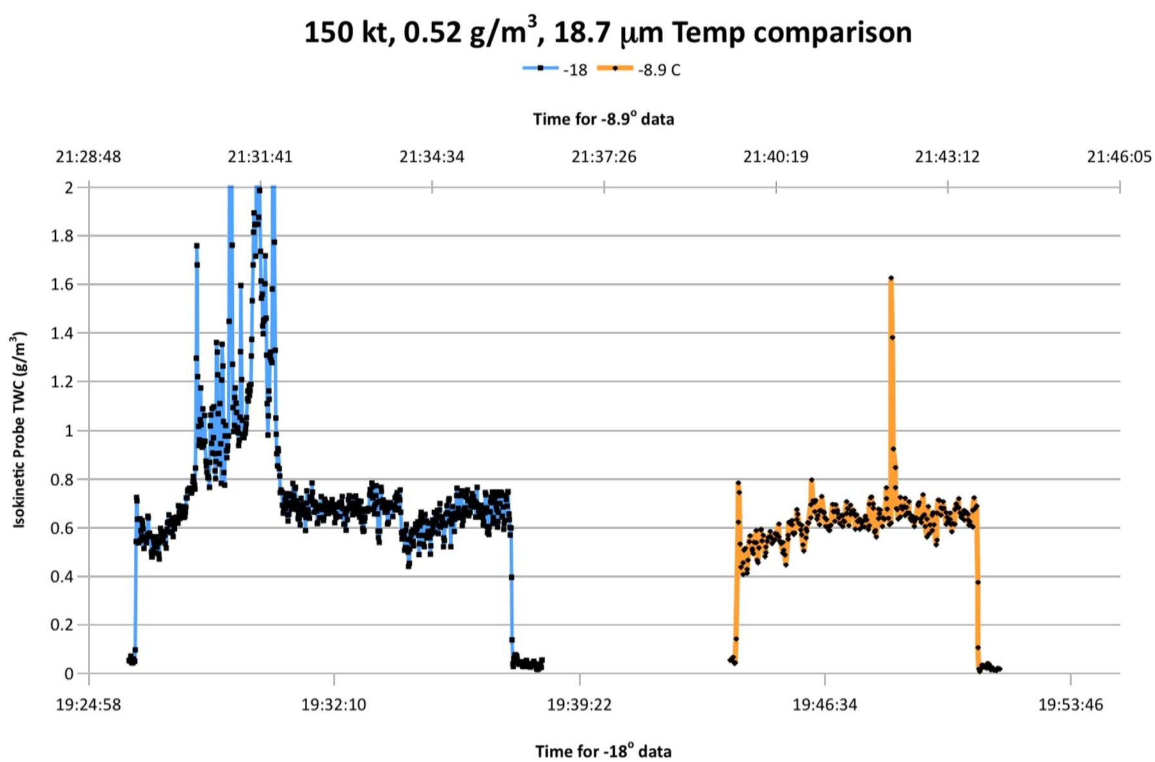

Figure 24.—Temperature comparisons at 150 kts and 0.5 g/m^3.

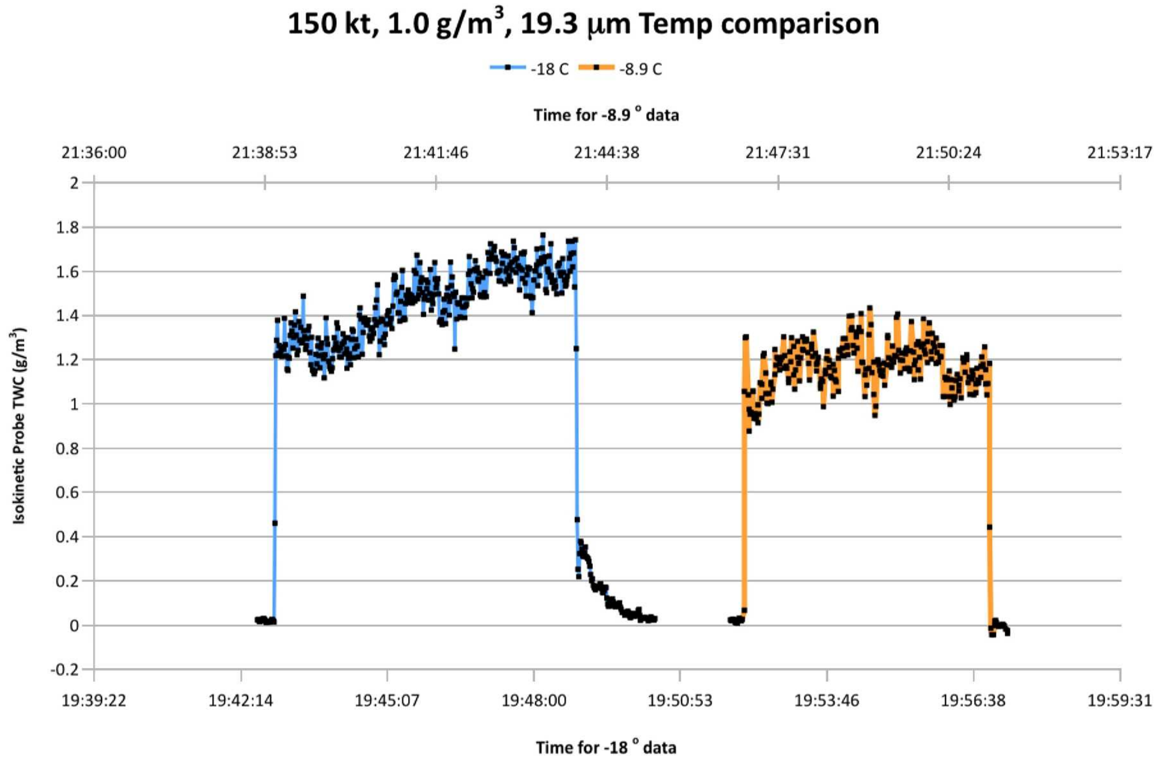

Figure 25.—Temperature comparisons at 150 kts and 1.0 g/m3.

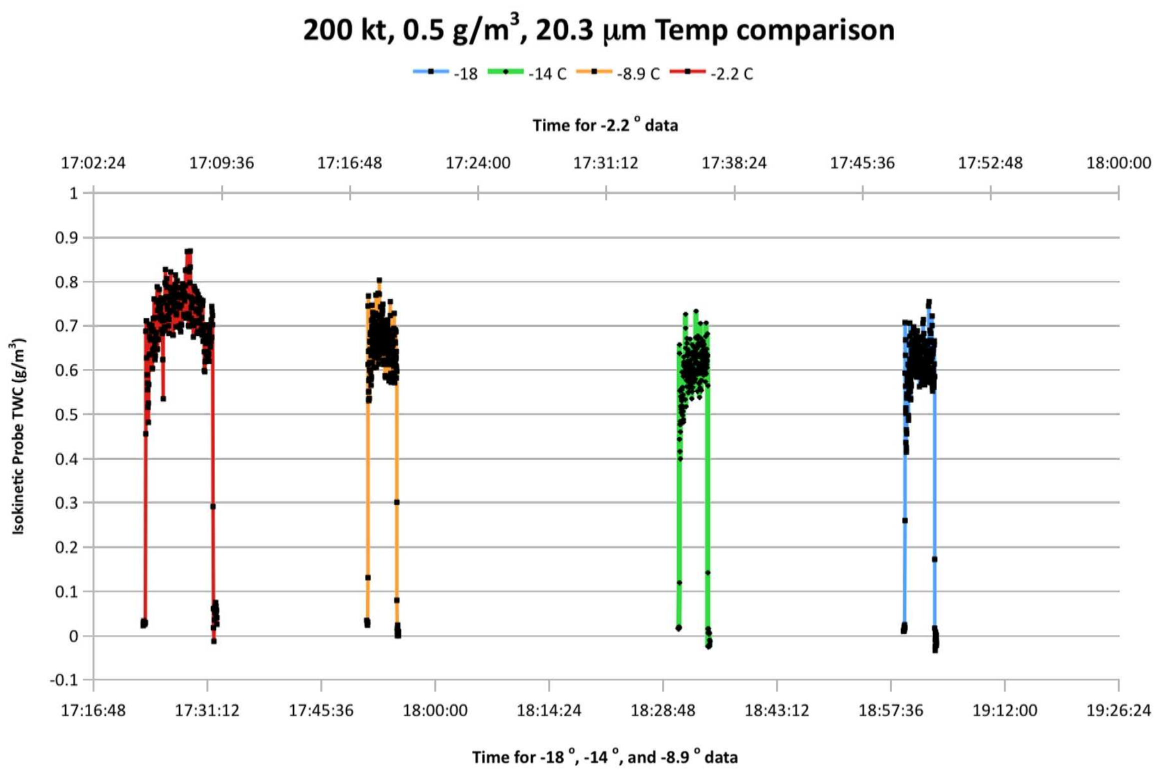

Figure 26.—Temperature comparisons at 200 kt and 0.5 g/m3.

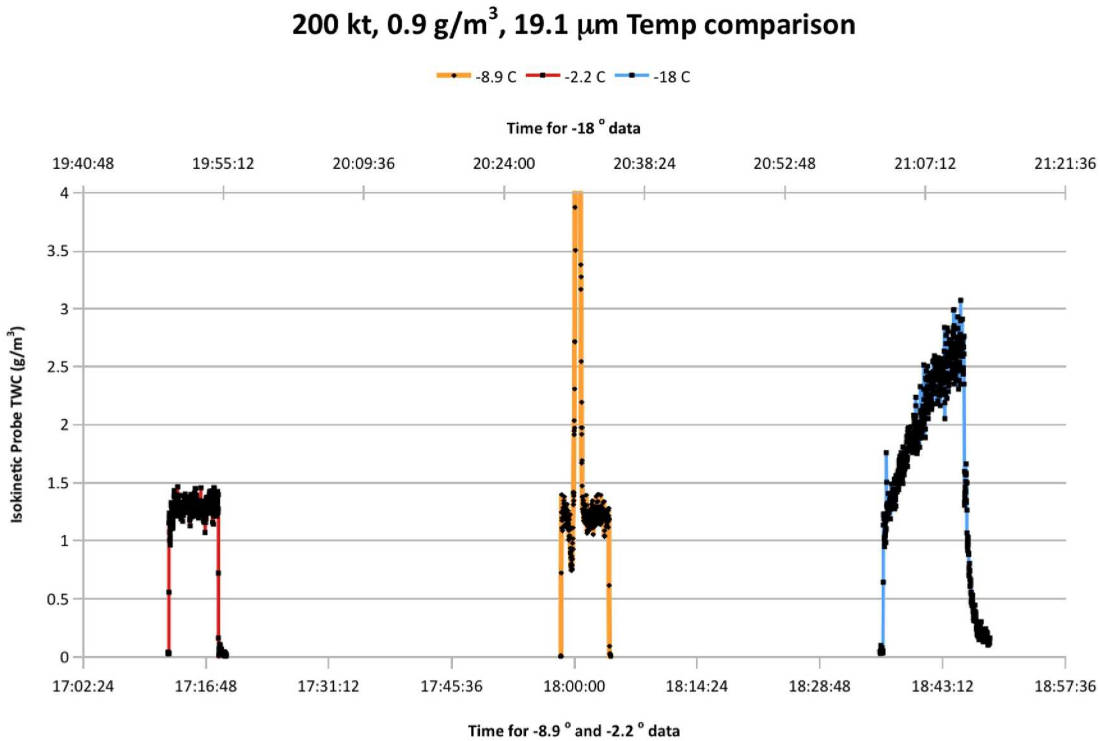

Figure 27.—Temperature comparisons at 200 kts and 0.9 g/m^3.

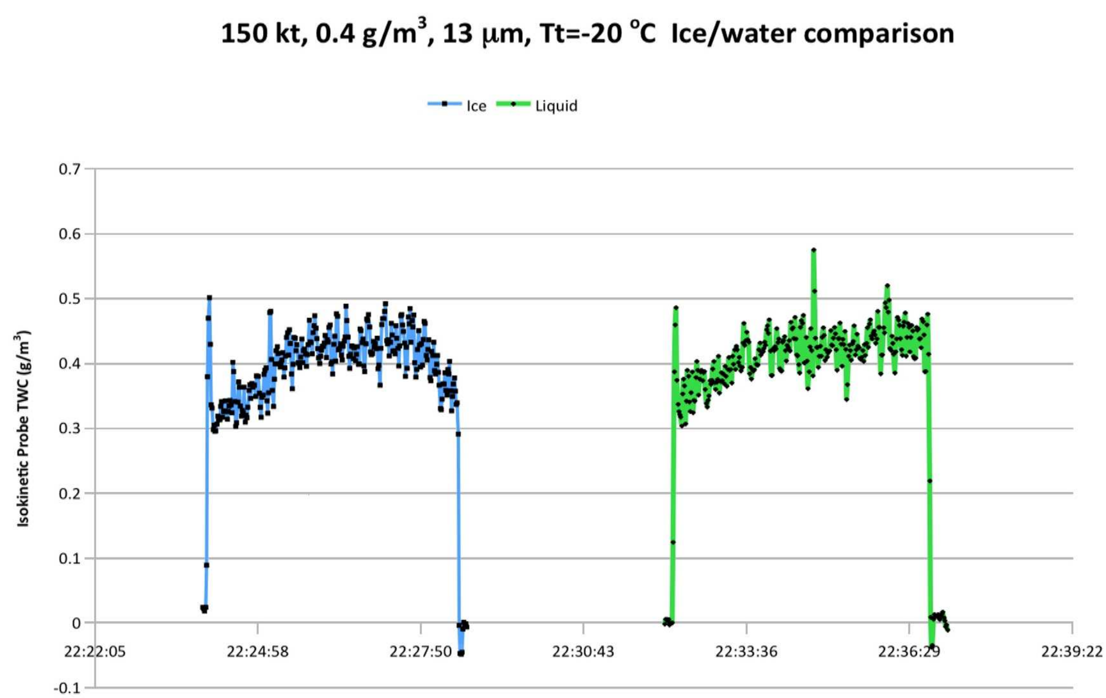

Figure 28.—Ice crystal/liquid water comparison.

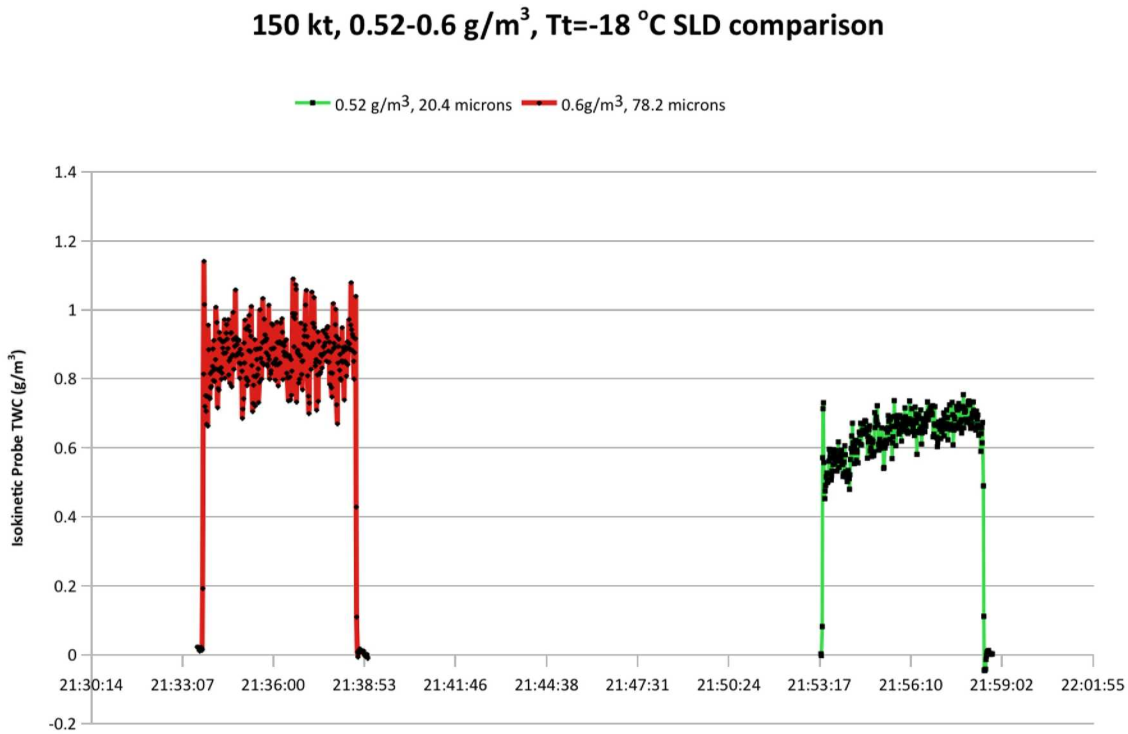

Figure 29.—Appendix C/SLD comparisons at around 0.5 g/m^3.

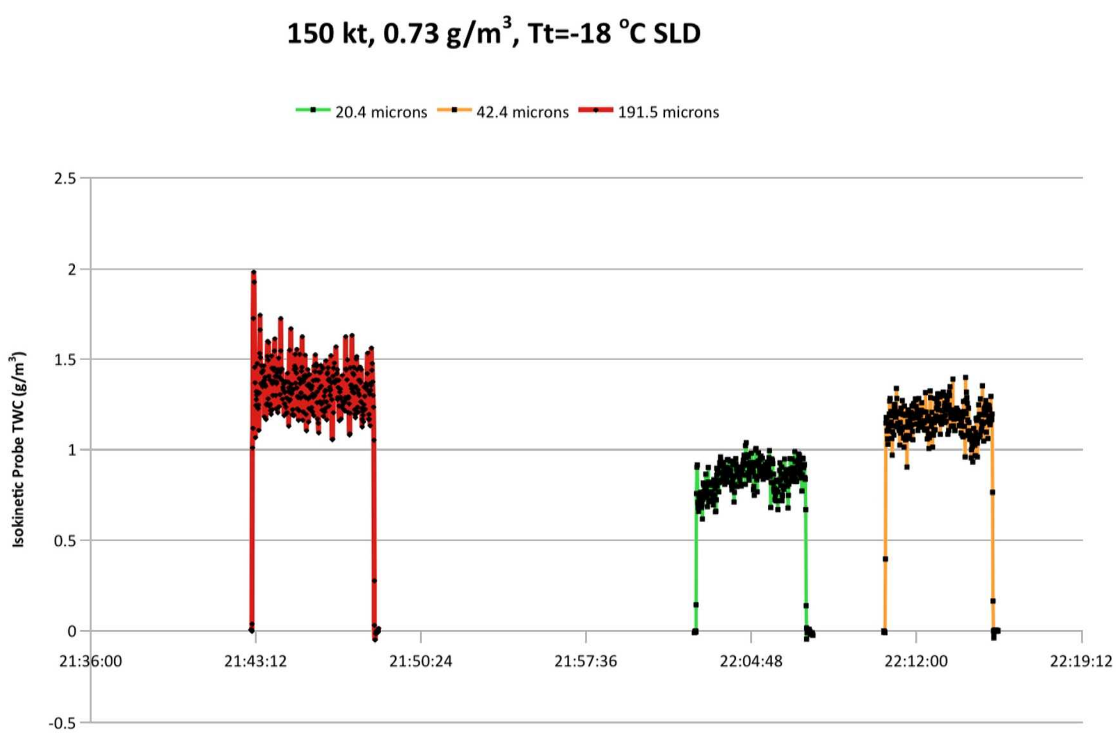

Figure 30.—Appendix C/SLD comparisons at 0.7 g/m^3.

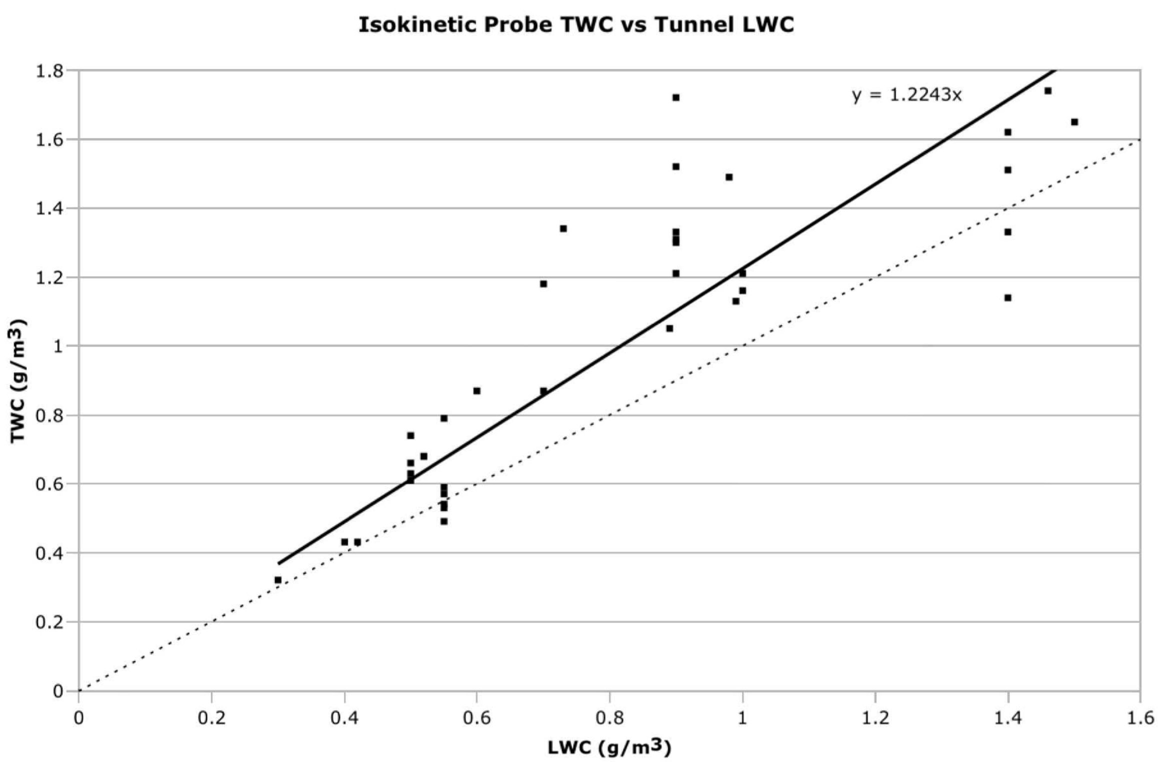

Figure 31.—Bulk comparison of isokinetic probe TWC to wind tunnel LWC calibration.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
The NASA Glenn Research Center has developed and tested a Total Water Content Isokinetic Sampling Probe. Since, by its nature, it is not sensitive to cloud water particle phase nor size, it is particularly attractive to support super-cooled large droplet and high ice water content aircraft icing studies. The instrument comprises the Sampling Probe, Sample Flow Control, and Water Vapor Measurement subsystems. Results and conclusions are presented from probe tests in the NASA Glenn Icing Research Tunnel (IRT) during January and February 2009. The use of reference probe heat and the control of air pressure in the water vapor measurement subsystem are discussed. Several run-time error sources were found to produce identifiable signatures that are presented and discussed. Some of the differences between measured Isokinetic Total Water Content Probe and IRT calibration seems to be caused by tunnel humidification and moisture/ice crystal blow around. Droplet size, airspeed, and liquid water content effects also appear to be present in the IRT calibration. Based upon test results, the authors provide recommendations for future Isokinetic Total Water Content Probe development.

15. SUBJECT TERMS
Aircraft icing; Aircraft safety; Hygrometers; Flowmeters; Wind tunnel calibration

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