A new SLWC-sonde compared to research aircraft flights

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1. Introduction

2. Liquid water with a temperature below the 0°C is termed 'supercooled liquid water' (SLW) and can be a danger to aircraft. SLW that comes in contact with an aircraft's superstructure freezes onto it and can negatively impact a plane's aerodynamic characteristics. The aviation community therefore has an interest in the capability to detect and warn on in-flight icing hazards.

No single instrument has yet been developed which can remotely and unambiguously detect in-flight icing conditions within a volume of airspace. For this reason, combinations of ground-based remote sensors and/or numerical weather prediction models have been under development for some time to detect in-flight icing (Politovich et al., 1995, Reehorst et al., 2003, Bernstein et al., 2005). These algorithms need to be verified against in situ data to gain acceptance in the aviation safety community, so either expensive research flights need to be conducted or comparison to subjective pilot reports of icing needs to occur.

A new avenue for verification and calibration of these ground-based in-flight icing detection systems is now available. An updated version of Hill and Woffinden's (1980) vibrating wire sonde for measurement of SLW content (SLWC) profiles along a weather balloon's trajectory has been under development by Anasphere Inc., which is based in Bozeman, Montana (Bognar et al., 2011).

In this work, several SLWC-sondes were launched into Lake-Effect snow systems in upstate New York while a specially outfitted research aircraft flew through the clouds which contained SLWC. The main goal of this study is to determine how closely the SLWC derived from the SLWC-sonde agree with the values obtained from the in-situ probes aboard the research aircraft.

Section 2 describes the field campaign that these SLWC-sonde launches were a part of. A description of how the SLWC profile is derived from the time series of vibrating wire frequency is presented in Section 3. A sample case study detailing four SLWC-sonde flights is discussed in Section 4. The findings on how the sonde SLWC profile compared to the University of Wyoming KingAir (UWKA) in-situ microphysical measurements is in Section 5. Finally, the paper is summarized in Section 6.

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2. OWLeS Field Campaign

The Ontario Winter Lake Effect Systems field campaign (Kristovich et al., 2013) was sponsored by the National Science Foundation and conducted around Lake Ontario during winter 2013-2014. The goals of the campaign were to study the formation mechanisms, dynamics and cloud microphysics of lake-effect storm (LES) systems. OWLes had at its disposal several mobile radars, surface-launched weather balloons and the fully outfitted UWKA aircraft available to collect standard meteorological and microphysical parameters.

3. SLWC-sonde

Working from a previous design in the literature (Hill and Woffinden, 1980), which had at one time been offered commercially, instrument development began with the intent to employ an improved version of a vibrating wire sensor for SLWC measurement. Goals for the redesign were to make the sensor smaller and lighter than the preceding design, to improve performance, and to reduce power consumption. A full discussion on the redesigned specifications can be found in Serke et al., 2014. The SLWC sonde is shown in Figure 1. A length of wire is exposed to the ambient environment and excited into vibration with an electromagnet, and the resulting vibration frequency of the wire is measured. As ice builds up from freezing of impacting SLW, the vibration frequency of the wire is reduced. Using mathematical approaches described in the Hill and Woffinden (1980) paper and with subsequent refinements described in Hill (1994), the supercooled liquid water concentration is computed using (1).

$$SLWC = -\frac{2b_0 f_0^{\,2}}{\varepsilon D \omega f^3}\frac{df}{dt} \tag{1}$$

where f_0 is the pre-launch un-iced wire frequency, ε is the drop collection efficiency, D is the wire diameter, ω is the air velocity relative to the wire, f is the wire frequency at a given time during flight, df/dt is the time rate of change in frequency and b_0 is a measure of steel wire weight per unit length as 44.366 g cm^{-1} (for the tested configuration). The drop collection efficiency for the specific wire diameter of 0.61 mm used on the SLW sonde was computed using the method discussed in Lozowski et al., (1983) and is shown for a relevant range of drop diameters and relative velocities between sonde and the ambient airmass in Figure 2. The mean relative velocity from the case study shown in Section 4 is roughly 5 m s^{-1}.

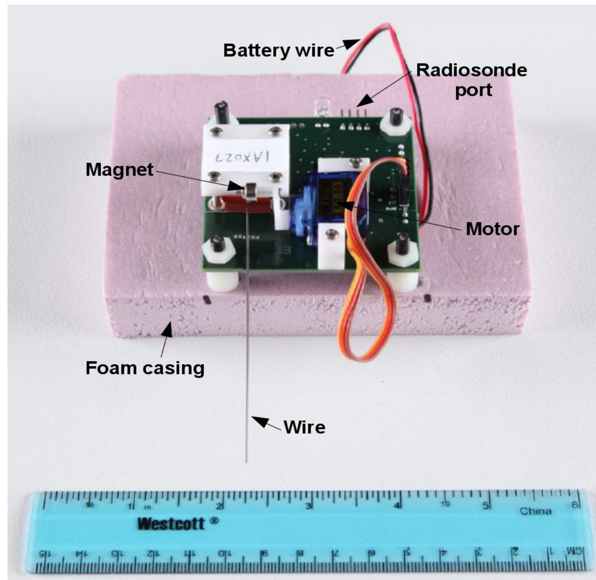


Figure 1. *SLWC sonde.*

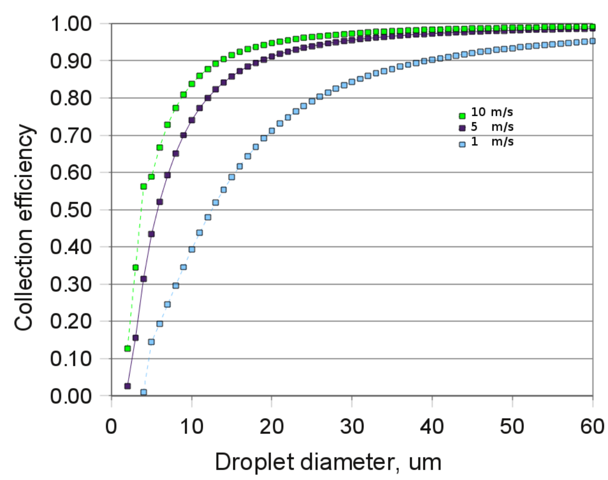
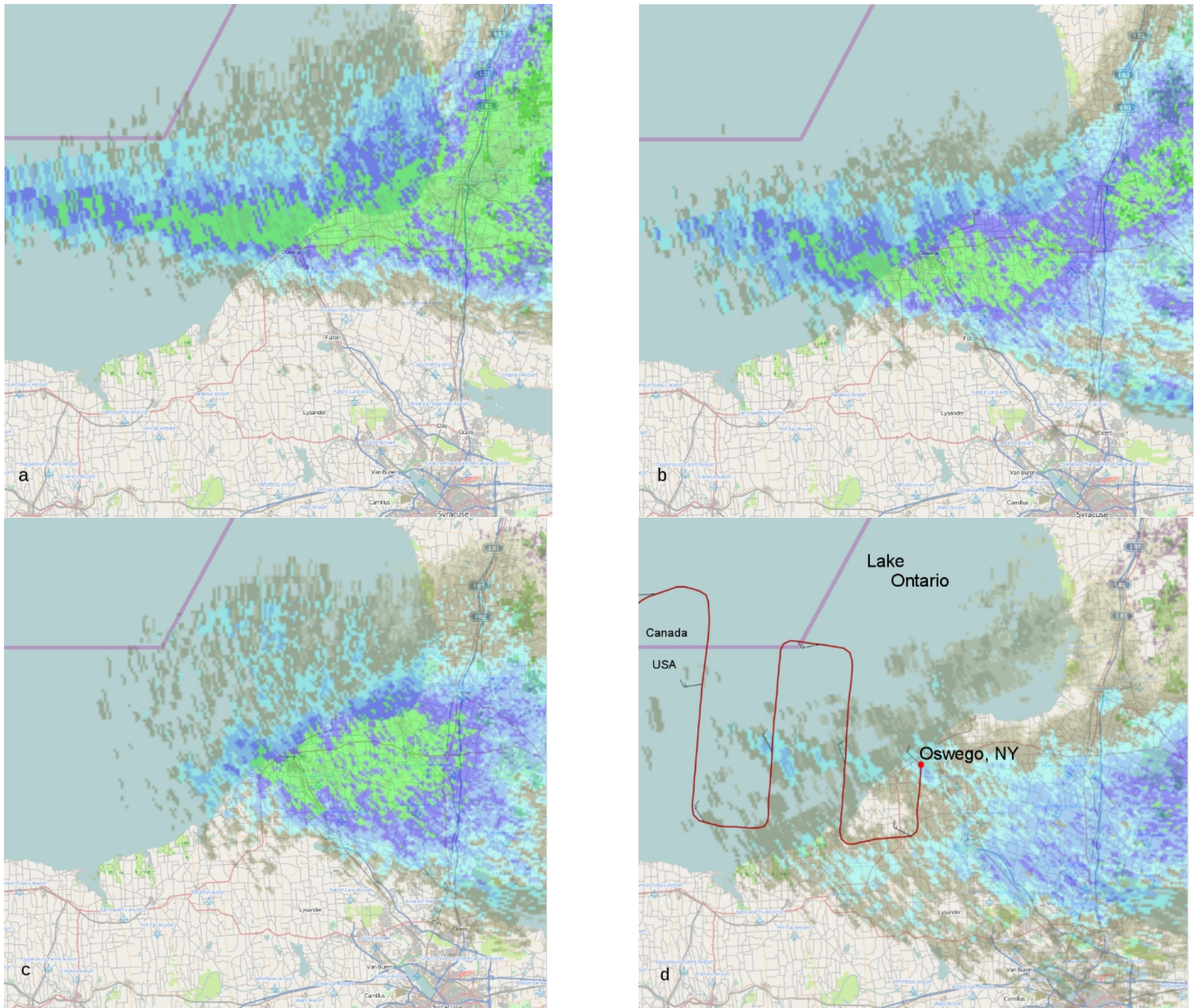


Figure 2. *SLWC sonde collection efficiency.*

4. Case Study

On January 8th, 2014, intense LES setup down the long-axis of Lake Ontario that lasted over 24 consecutive hours, delivering more than 60 inches of snow to some locations. On the morning of the 9th, the band sagged southward from Watertown, NY toward Oswego, NY and dropped 6 inc of snow in 90 min (Figure 3 a through c) before the LES band's intensity weakened (Figure 3d



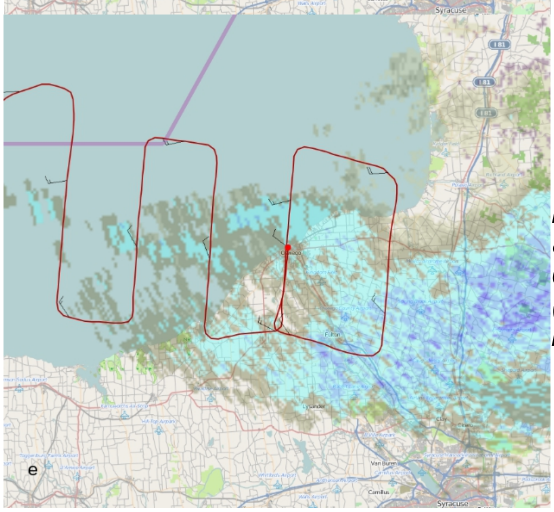


Figure 3. *Reflectivity from Montague, NY WSR-88D radar (KTYX) and UWKA flight track (red line) from 06:00 (a), 07:01 (b), 8:17 (c), 14:23 (d) and 14:43 UTC (e) on 1/8/2014. Values of reflectivity range from 3 dBZ in grey to 25 in green.*

and e).

Before the UWKA was aloft, two SLWC-sondes were launched at 07:01 and 08:17 UTC, which correspond to NEXRAD reflectivity the images in Figure 3b and c, respectively. Using the mean particle diameter of 10 μm detected by the UWKA in the later 14:23 and 14:43 UTC launches to find the collection efficiency, SLWC profiles from 7:01 UTC are shown in Figure 4. The frequency of the sonde wire (Figure 4a, blue line) is smoothed with an 11-point moving average (red line). Next, df/dt is calculated (Figure 4b) from the smoothed frequency. These values along with the sonde's ascent rate (Figure 4e) are inputs to Equation 1, and the SLWC profile (Figure 4c) is the output. Temperature, (Figure 4d, red line) dewpoint temperature with respect to ice (blue line) and the resulting relative humidity (Figure 4f) are included to complete the meteorological profile. At this time, the profile is saturated with respect to ice up to 2.0 km AGL, as the blue ice saturation temperature profile is warmer (to the right of) the red ambient temperature profile. A temperature inversion at 2 km caps the LES event in height. This time was very near the maximum intensity snow rate at the Oswego sonde launch site. The SLWC (Figure 4c) shows a layer between 0.4 and 0.9 km and a more significant layer that peaks near 0.4 gm^{-3} near 1.9 km. These liquid layers are detected by wire frequency and the change in wire frequency with time decreasing as ice is accreted to the wire during the balloon's ascent. Areas of maximum detected SLWC correspond to minimum ascent rate (Figure 4e) as the accreted ice decreases the balloon's relative buoyancy.

As the LES band begins to weaken in intensity and begins to zonally break up at 8:17 UTC, the depth of the SLWC layer shallows to 1.4 km AGL (Figure 5c). The lowest 0.6 km are no longer saturated (Figure 5d, blue line now left of red line). Again, the ascent rate is inversely related to the presence of SLWC.

The UWKA flew flight legs that were perpendicular to the long axis of the band, roughly north-south, for about three hours on this date from 12:52 to 16:07 UTC. Several different aircraft overpasses of Oswego occurred during this period, two of which were coincident with launches of SLWC-sonde balloons from the campus of SUNY Oswego. Figure 3d shows the UWKA location (red dot) as over Oswego at 14:23 UTC and the northward flight leg (red line) that will be examined in the next few plots. The LES band is clearly much weaker and less continuous than at previous launch times, based on the KTYX reflectivity imagery. Time series from three different SLWC measurement instruments are shown in Figure 6a, including the CDP, PVM-100 and FSSP-100. This time series begins when the UWKA begins the northward flight leg and ends just north of the LES band several kilometers out over Lake Ontario, with time=120 s being directly over the Oswego launch site. The UWKA flew at a constant altitude of about 1.2 km above Oswego's mean surface altitude. The CDP (black line) iced up and ceased to report good data soon after entering the southern edge of the LWS band at about 40 s into the flight leg. Both the PVM and FSSP had values between 0.3 and 0.6 gm^{-3} in the band (before 200 s). Mean particle diameters as measured by the CDP (Figure 6b, black line), FSSP (red) and FSSP effective radius (times 2, magenta) indicate the preponderance of 10-12 μm-diameter drops. At 14:18 UTC, the third SLWC-sonde of the event was launched with a goal to be as close as possible in time and space to the aircraft and its in situ microphysical measurements. Figure 7c shows a decayed SLWC profile compared with previous launches, and a maximum SLWC value of 0.25 gm^{-3} near 1.2 km. A reasonable value for the UWKA's SLWC over the Oswego launch site is about 0.4 gm^{-3} (black star) and the range of detected SLWC values is represented by the horizontal black line. As with the previous launch, the lowest 0.6 km are no longer saturated (Figure 7d), and thus no SLWC exists there. Ascent rate is still inverse to SLWC in the cloud layer, and a weak inversion caps the detected liquid at 1.4 km. The difference in aircraft and sonde SLWC values at flight level is not unreasonable considering the differences in detection methodology and temporal/spatial differences.

Figure 3e shows the UWKA location (red dot) as over Oswego at 14:43 UTC and a new northward flight leg (red line) that will be examined in the next few plots. The LES band is of similar or slightly enhanced intensity as the previous launch time, based on the KTYX reflectivity imagery. This time series begins when the UWKA begins the northward flight leg at just over 0.8 km AGL and ends just north of the LES band several kms out

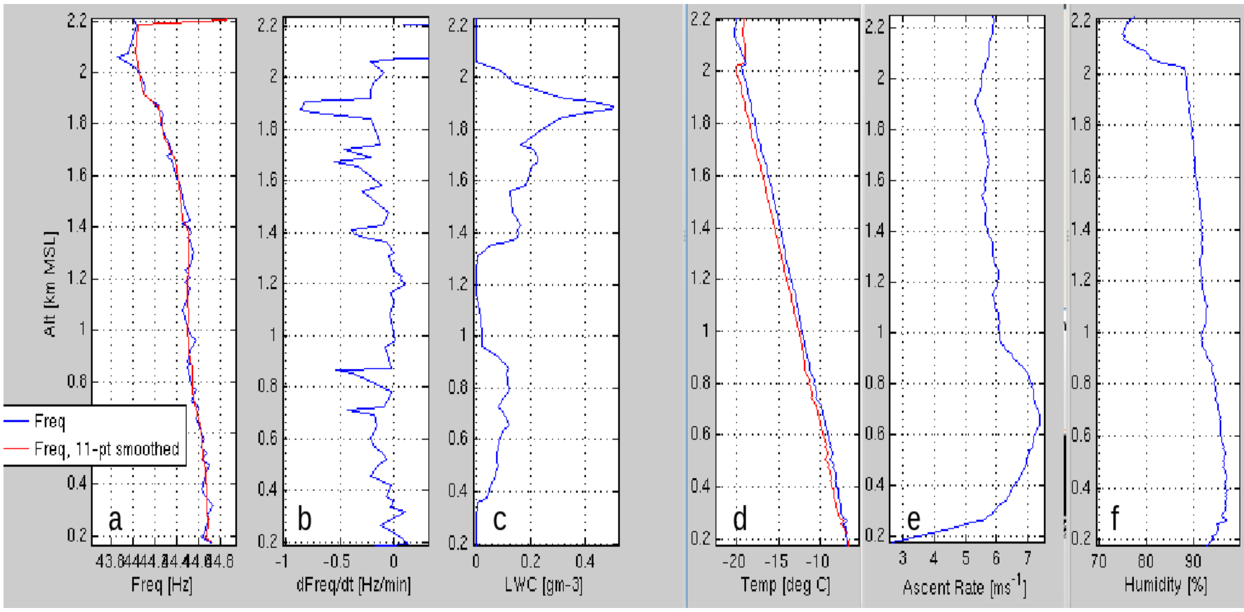


Figure 4. *SLW-sonde frequency (a), change in frequency with time (b), resulting LWC (c), radiosonde temperature (d), ascent rate (e) and humidity (f) from the flight at 07:01 UTC on 1/9/2014.*

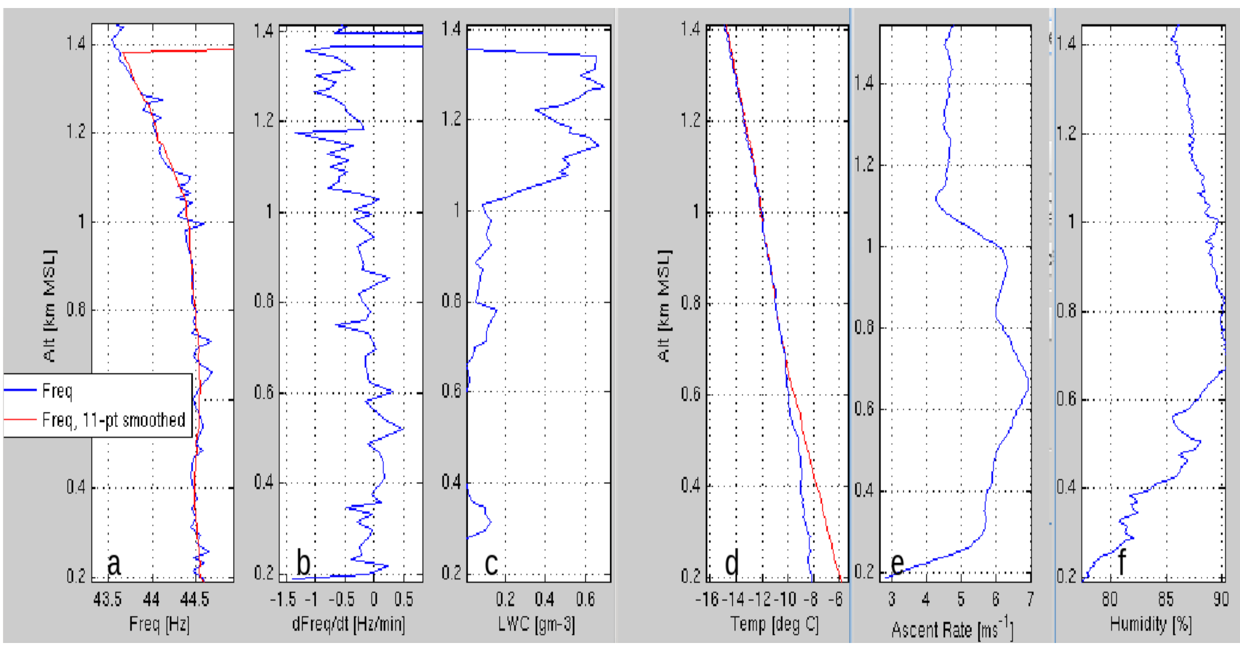


Figure 5. *As for Fig. 4,except at 08:17 UTC on 1/9/2014.*

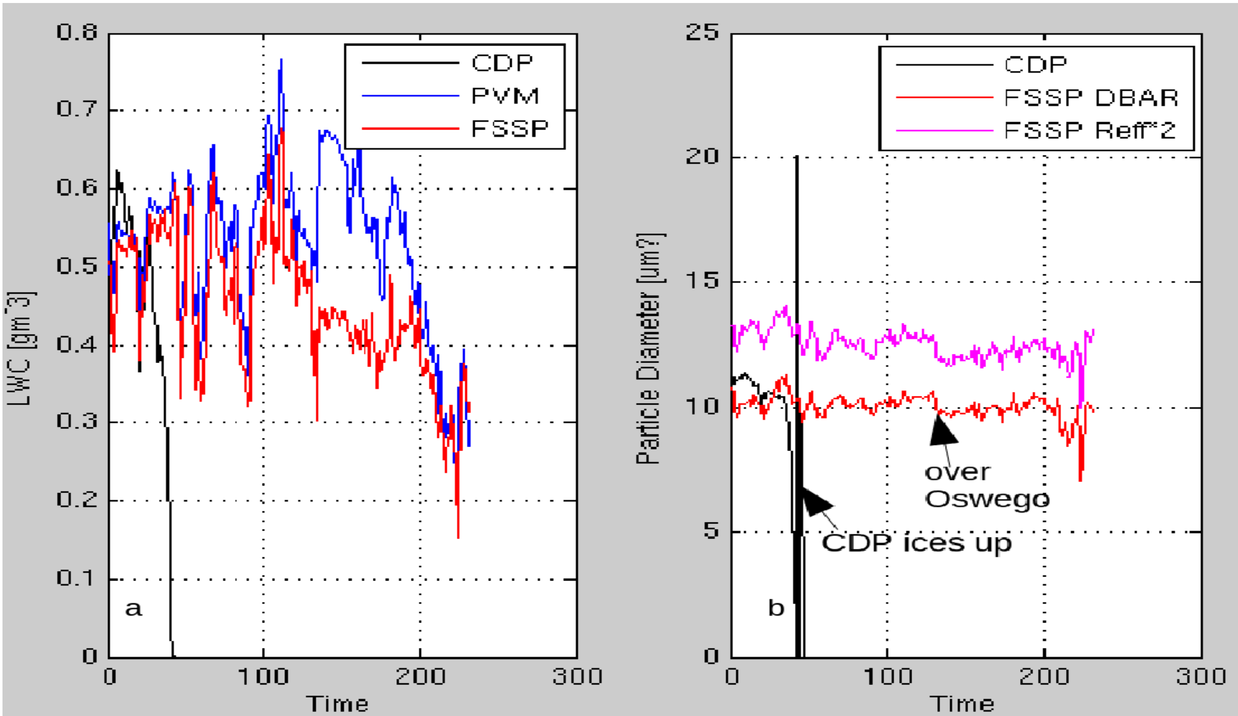


Figure 6. *UWKA LWC (left) and particle diameter (right) during flight track shown in Figure 3 part d on January 9th, 2014 over Oswego, NY.*

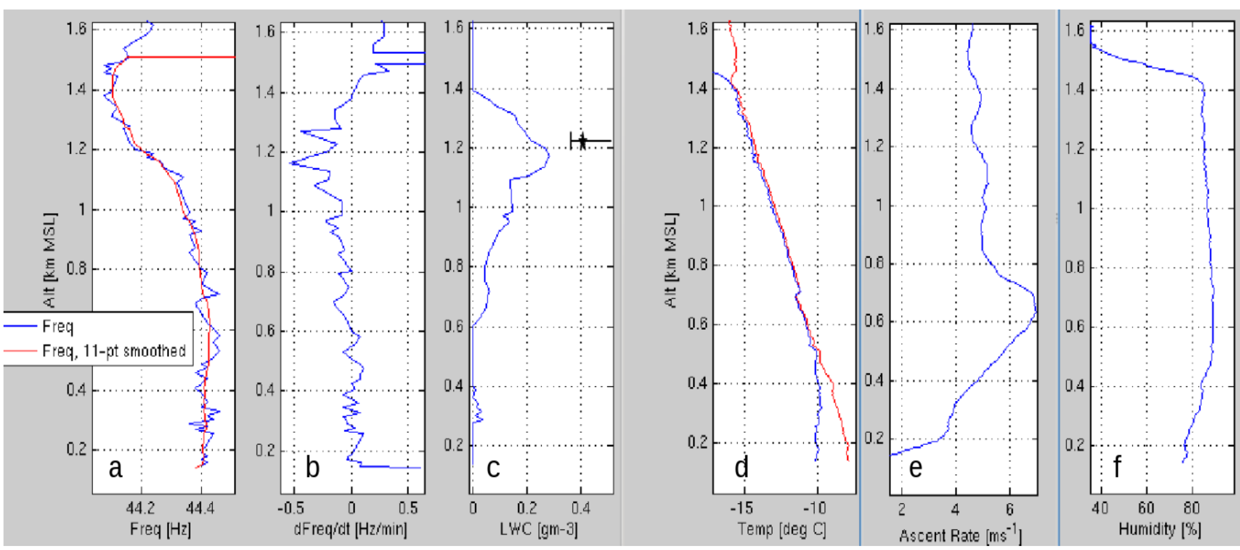


Figure 7. *As for Fig. 4, except at 14:18 UTC on 1/9/2014. Comparable UWKA values plotted on c as a star indicating the average and bar indicating the range. .*

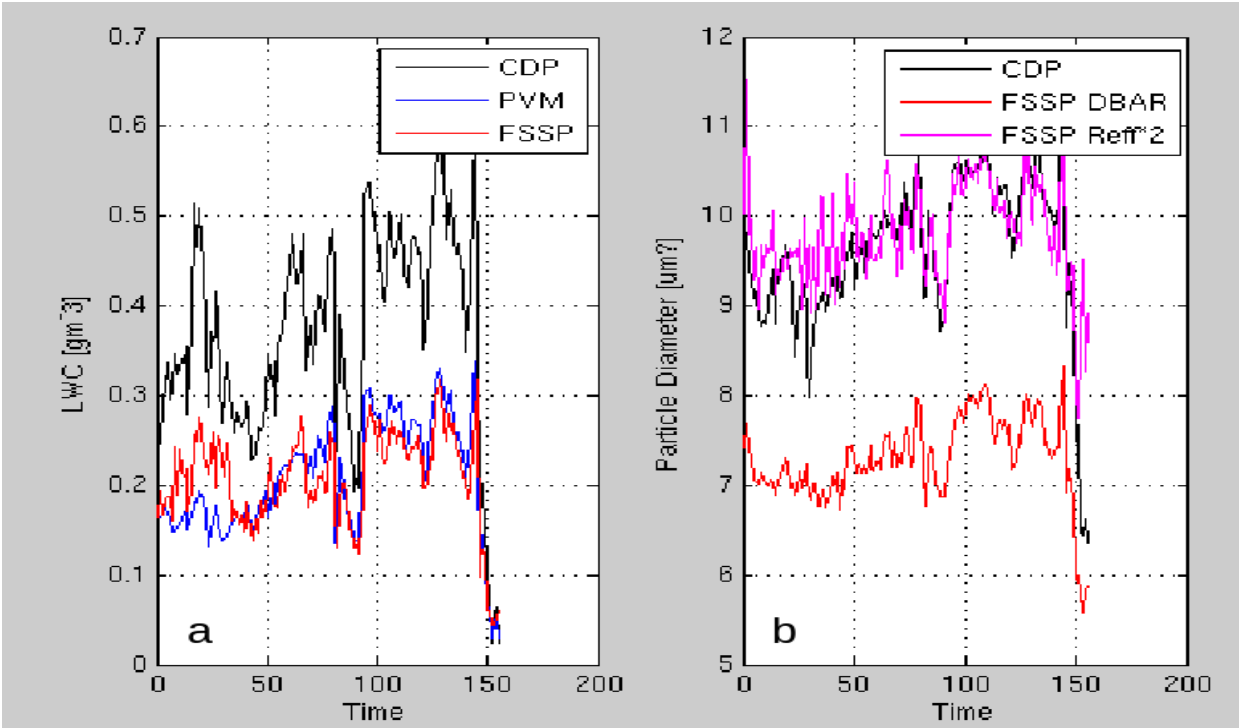


Figure 8. *UWKA LWC (left) and particle diameter (right) during flight track shown in Figure 3 part e on January 9th, 2014 over Oswego, NY.*

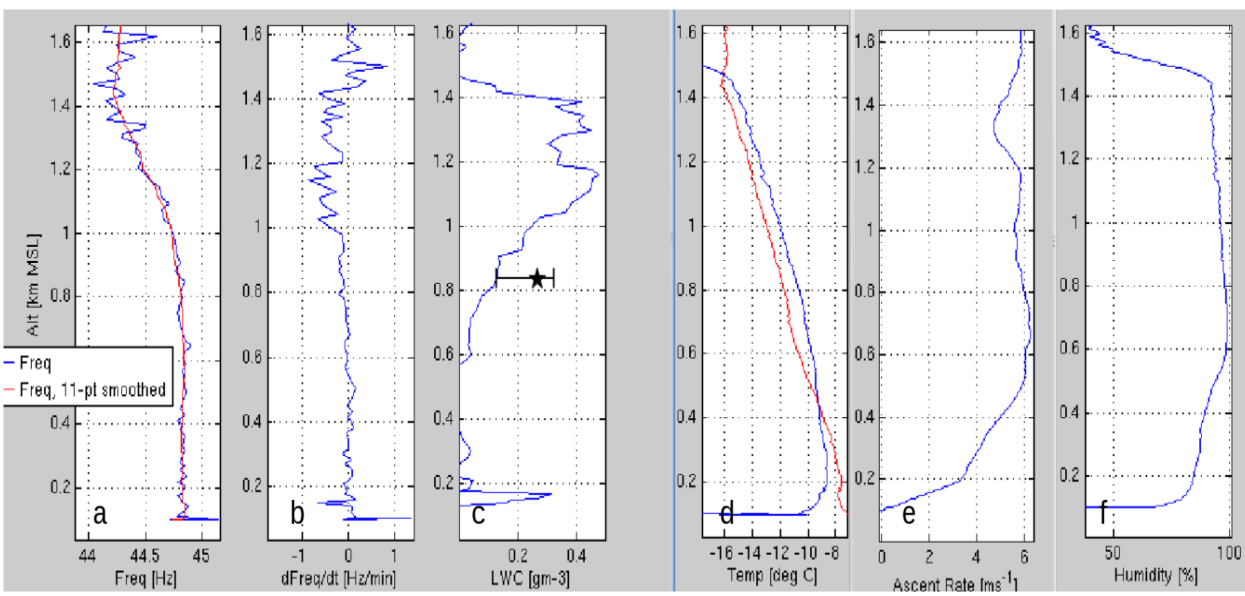


Figure 9. *As for Fig. 4, except at 14:46 UTC on 1/9/2014.*

over Lake Ontario, with time=90 s being directly over the Oswego launch site. The CDP (Figure 8a, black line) is no longer iced up, and records higher SLWC than the PVM and FSSP. Both the PVM and FSSP have values between 0.15 and 0.3 gm^{-3} in the LES band (before 140 s). Mean particle diameters as measured by the CDP (Figure 8b, black line), FSSP (red) and FSSP effective radius times 2 (magenta) indicate the preponderance of 7-11 micron diameter particles. At 14:46 UTC, the fourth and final SLWC-sonde of the event was launched. Figure 9c shows an enhanced SLWC profile compared with the prior 14:23 UTC launch, and a maximum SLWC value of 0.45 gm^{-3} above 1.1 km. A reasonable value for UWKA LWC at the 0.85 km flight level over the Oswego launch site is about 0.25 gm^{-3} (black star). As with the previous launch, the lowest 0.5 km are no longer saturated (Figure 9d), and thus no SLWC exists there. Ascent rate is still inverse to SLWC in the cloud layer, and a weak inversion caps the detected liquid just above 1.4 km. The difference in aircraft and sonde SLWC values at flight level is again not unreasonable considering the differences in detection methodology and temporal/spatial differences. Similar to the 7:01 UTC launch time when the LES dynamics were enhanced over Oswego, the profile is supersaturated with respect to ice (Figure 9d). This is an environment where SLWC is allowed to increase, as witnessed by the somewhat enhanced SLWC values at 14:43 as compared to 14:23 UTC.

5. Results

During the two SLWC-sonde launches that were coordinated with UWKA overflights during this LES event, SLWC-sonde liquid values were found to be comparable but biased slightly lower than the mean in-situ aircraft values at comparable heights (Table 1). It is currently unknown why the SLWC sonde low bias appears in these two cases compared to the in situ instrumentation which will require further analysis.

Table 1. *Sonde SLWC [gm^{-3}] compared to UWKA at flight level on 1/9/2014.*

Time [UTC]	Sonde	UWKA
1423	0.24	0.36 – 0.60
1443	0.17	0.15 – 0.30

6. Summary

Icing instrumentation research was able to piggyback with the 2013-2014 OWLeS field campaign based in Oswego, NY with launches of a newly redesigned vibrating wire SLWC-sonde attached to a radiosonde and weather balloon. When these sondes were launched during UWKA overflights, direct comparison of SLWC at the aircraft's flight level revealed reasonable but slightly low-biased liquid values by the sonde. These differences could be due to spatial and temporal differences of the respective SLWC measuring instruments in the highly dynamic LES environment and also fundamental differences in the measuring techniques.

SLWC is seen to be bounded vertically at cloud top by temperature inversions, with maximum SLWC near cloud tops. No SLWC is detected by the sonde in areas below cloud where temperature and dewpoint indicate subsaturation. Relative minima in the balloon ascent rates correspond to maxima in SLWC as the balloon accretes ice and loses some of its relative buoyancy. SLWC is also seen to increase over short time periods as the LES experiences pulses of growth. This small number of SLWC sonde profiles appear microphysically realistic when compared to research aircraft data from this and previous studies (Politovich et al., 1996). The SLWC sondes will require more validation in a laboratory environment, but the overall theory behind the vibrating wire appears to be soundly reaffirmed and the recent redesign by Anasphere Inc. seems to have led to a relatively inexpensive, accurate and reliable method to detect SLWC profiles in the free atmosphere.

A field campaign designed specifically for the study of in-flight icing conditions, involving research aircraft, ground-based remote sensing and SLWC-sonde launches, is planned for the winter of 2014-2015 in the Cleveland, Ohio area. SLWC-sondes will be launched in support of any research flight days to advance the verification and validation of all icing related instrument platforms.

Acknowledgments

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