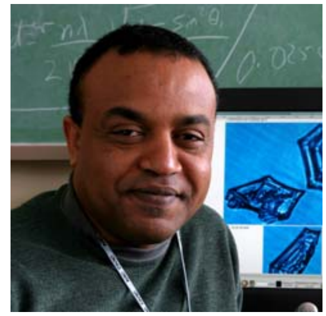
Characterization of supercooled and mixed phase clouds using airborne dual-frequency radar and G-band radiometer

Mengistu Wolde[1], David Hudak[2], Andrew L. Pazmany[3]
[1]*NRC Aerospace, Ottawa, Canada, Mengistu.wolde@nrc-cnrc.gc.ca*
[2]*Environment Canada, Toronto ON, Canada*
[3]*ProSensing Inc.,* Amherst MA, *USA*



Mengistu Wolde

1. Introduction

Characterization of aircraft icing environments and microphysical process leading to supercooled clouds and freezing drizzle conditions have been a subject of many research studies over the last 25 years (e.g., Sand et. al., 1984, Rasmussen et. al., 1992; Ashenden and Martwiz, 1998; Isaac et. al., 2001, 2005 and Cober and Isaac, 2012). Some of these studies explored the use of ground based and airborne remote sensing sensors for characterization and detection of aircraft icing environments using multiple-frequency radars (e.g., Vivekanandan et al., 1991; Lohmeier, et al., 1997), radar Doppler spectra (Zawadzki etl. al., 2001), radar polarimetry (e.g., Wolde et al., 2005 and Plummer et al. , 2010), radar and radiometer (e.g., Dong and Mace, 2003), radar and lidar (e.g., Hogan et al., 2003).

This paper presents an analysis of near coincident airborne in-situ cloud physics, W and X-band polarimetric radar and a G-band 183 GHZ water vapour radiometer data collected in supercooled and mixed phase environments. Two different flights were selected in which the aircraft sampled extended regions of supercooled and/or mixed phase conditions at temperature of -16°C to 0°C. The supercooled clouds occurred in layers with thickness less than 500 m, with a horizontal extent of over 60 km. The near-coincident measurement of the in-situ and remote sensing data allowed for determination of remote sensing signatures associated with different particle types including supercooled drops.

2. Data and Instrumentation

The data used in this paper were collected during the Canadian CloudSat and CALPSO satellite Validation Project (C3VP) that was conducted between October 31, 2006 and March 01, 2007 over Ontario, Canada (Hudak et al., 2007; www.c3vp.org) using the NRC Convair-580 (CV580) research aircraft. For the C3VP field campaign, NRC and Environment Canada (EC) jointly instrumented the CV580 with its standard suite of in-situ and remote sensing probes. The extensive in-situ cloud measurement capabilities of the CV580 for characterization of icing environments and midlatitude weather systems are well documented (e.g., Isaac et al., 2001). The in-situ data that are used in this study are all averaged over 1 Hz and include liquid water content (LWC) measured by the PMS King hot wire probe, the Rosemount Icing Detector (RID), concentration and mean volume diameter (MVD) from one of the PMS Forward Scattering Spectrometer Probes (FSSP, 5-95 μm) and particle images measured by the PMS 2DC probe, which images cloud particles up to 800 μm with a 25 μm bin resolution. In addition to the in-situ probes, the CV580 was equipped with three radars, a lidar and radiometers during the C3VP. For this study only data from the NRC W and X-band radar system (NAWX) and the 183 GHz G-band water Vapor Radiometer (GVR), developed by ProSensing Inc. (Pazmany, 2007) were used. The NAWX radar system (Wolde and Pazmany, 2005; www.nawx.nrc.gc.ca) has polarimetric and Doppler capabilities at both frequencies and can switch electronically between zenith, nadir and side looking antennas. The equivalent radar reflectivity (Z_e) and the Differential Radar Reflectivity Factor (ZDR) are used to characterize cloud structures in icing environments. The Liquid Water Path (LWP) and Precipitable Water Vapour (PWV) were estimated from the up-looking GVR brightness temperature measurements using a neural network technique described by Cadeddu et al. (2007). More technical detail of the airborne GVR can also be found from Pazmany and Wolde (2008).

3. Case Studies

3.1 Case 1- Dec 06, 2006

The CV580 sampled a multi-layer cloud system with significant supercooled drops and/or freezing drizzle conditions in the vicinity of the project ground site near Toronto, Canada. Two different segments of the flights were selected to highlight performance of the remote sensing instruments in various icing conditions.

3.1.1. Segment 1 - Multi-layer cloud with high LWC

In the first segment (16:30-18:00), the aircraft sampled a multi-layer cloud system (AC, SC types) around EC's Center for Atmospheric Research Experiment (CARE) site located in Egbert, Ontario. Fig. 1 shows time series of T, altitude, LWC, GVR derived LWP and RID voltage and samples of PMS 2D-C images taken during the repeated sampling of the multi-layer cloud system. Fig. 2 shows samples of pictures taken during the initial sampling of the multi-layer cloud system. The aircraft first made a spiral descent from 4 km to 1 km and then made repeated porpoising maneuvers between 2 and 3 km for nearly an hour. A visual inspection of the time series plot and the sample 2D-C images show some repetitive patterns:

- The maximum LWC (0.4 g m^{-3}) and LWP (0.5 mm) were observed within about 200 m of the lowest aircraft altitude.
- During the porpoising maneuver, the maximum LWP (LWC) values were repeatedly measured whenever the aircraft was at the lowest (middle point of the porpoising maneuver at ~ 2.7 km) altitude.
- The upper layer clouds (~2.5 km) were mixed phase with rimed ice crystals with sizes of up to 600 µm, while the lower layer clouds were all liquid with no indications of ice particles or large freezing drizzle drops.

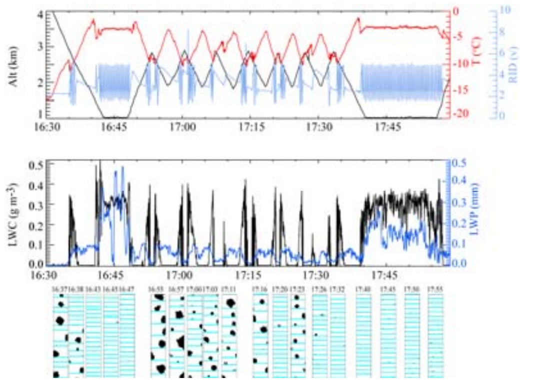


Fig. 1. Top: time series plots of aircraft altitude (black), Temperature (red) and Rose Mount Icing Detector (RID – blue). Middle: Liquid Water content measured by King Probe (black) and LWP measured by the GVR (blue) during the CV580 on Dec 06, 2006. Bottom: Sample particle PMS 2D-C images. The width of the PMS 2D-C image strips is 800 µm.

Fig. 2. Samples of pictures taken above the top cloud layer (16:30:46 & 16:53:20) and in between the two cloud layers (16:40:06 & 16:51:18) as discussed in the text. Note a trace of icing at the bottom right corner of the picture taken at 16:53:20.

To highlight the vertical cloud structure, vertical profiles of T, T_d, LWC, LWP, particle concentration (N) and MVD during the initial descent are shown in Fig. 3. It is evident that there are at least two cloud layers (marked by a shaded grey color in Fig. 3). Both of the liquid layers have thicknesses of about 400 m, with a shallow inversion layer above the cloud tops and the two liquid layers are separated by a dry layer. Although the two liquid layers have approximately the same thickness, the particle compositions are distinctly different. As described above, the top layer (2.5 km – 2.9 km and T ranges of -10 to -5°C) was mixed phase and contained large drops (> 50 µm). The MVD in the top layer also increases with height. In contrast, the lower cloud layers (1 km to 1.5 km and T of -5 to -3°C) consisted of small supercooled drops with no ice crystals or large drops. The particle concentration of the lower liquid layer was nearly three times higher than the values observed at the upper mixed-phase layer.

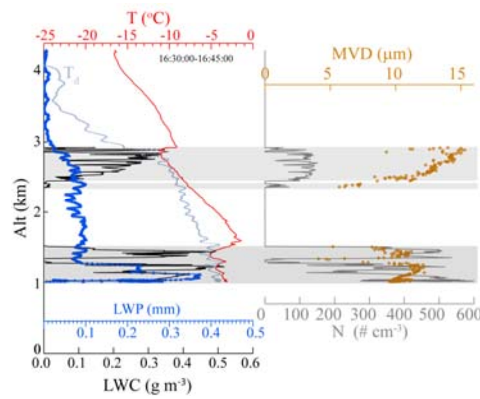


Fig. 3. Vertical profiles of Temperature (T), Dew Point (Td), Liquid Water Path (LWP), Particle Mean Volume Diameter (MVD) and Cloud Particle Concentration (N) during the Dec 06, 2006 CV580 flight around study area.

The profile presented in Fig. 3 is not unique, but what is unique in this case is the availability of remote sensing data to complement the in-situ data. We will now explore the performance of the remote sensing probes in these multi-layer clouds. The highly sensitive GVR (Fig. 3) probe provided very consistent measurements and allowed for a better interpretation of the in-situ cloud microphysics measurements. When the aircraft was between the two cloud layers (1.5 – 2.3 km), the LWP was nearly constant. After the aircraft entered the lower liquid layer, the LWP started to increase sharply. Note the near constant LWP value of 0.2 mm around 1.2 km, which is also consistent with the near zero LWC and particle concentrations at ~1.3 km altitude while the sharp increase in LWP when the aircraft descended to the lower level. For this flight, only the NAWX X-band (3 cm) radar was active. The radar detected the top layer sporadically and only at the closest range as the clouds consisted of relatively small particles (< 1mm) with low Z_e (<-20 dBZ), so that the X-band radar couldn't provide any additional information.

3.1.2. Segment 2 - Mixed phase cloud

During a transit flight from the C3VP CARE site to Ottawa, Canada, the aircraft sampled a mixed phase cloud. In this case, the cloud was detectable by the NAWX X-band radar. Fig. 4 shows the vertical cross-section of the NAWX X-band reflectivity and time series plots of the same parameters presented in Fig. 1. The sampled cloud was a single layer with precipitation reaching the ground. The Z_e values range from near -15 dBZ to about 20 dBZ, with a general tendency of higher Z_e values near the ground suggesting crystal aggregation. The LWC and RID traces show icing encounters between -10°C to -5°C. The in-cloud LWP is above 0.01 mm throughout this flight segment, indicating the presence of liquid above the flight level. The radar reflectivity shows a fine-scale organization, where a high Z_e cores (< 10 km) extend from cloud top to the ground. These high Z_e cores are likely narrow ice generating cells that remained intact through the depth of the cloud, in particular during the first ten minutes of the leg. Fig. 5 shows vertical profiles of LWC, T, T_d, and LWP during one of the porpoising maneuver. The vertical profiles in this case are much more complex than the profiles presented in the multi-layer cloud system over the CARE site. The maximum LWP was not observed at the lowest altitude, indicating the complexity and fine-scale organization of the cloud system. One of the interesting aspects of this case is how the LWP and LWC are correlated to Z_e. The patches of cloud with high LWC and LWP corresponds to weaker Z_e values (in between a high Z_e cores; e.g., ~18:27). So the LWC content is not purely a function of altitude.

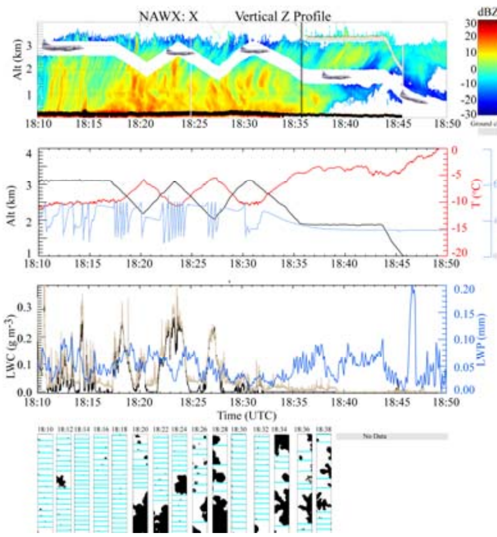


Fig. 4. Top: Vertical Z cross-sections measured by the NAWX X-band radar during the Dec 06, 2006 C3VP flight. The aircraft symbols and the white thick line show the aircraft altitude. Bottom 3 panels: Same as Fig. 3, except the LWC measured by the Nevzorov probe (brown) is also plotted.

3.2 Case 2- Feb 26, 2007

On February 26, the CV580 flight again targeted cloud systems around the EC CARE ground sites. Icing was encountered during both the outbound flight to the CARE project site as well as during the return flight to Ottawa. Fig. 6 shows a time series of the in-situ microphysics and thermodynamic data as well as LWP measured by the GVR. The sampled clouds include, mixed phase, all liquid as well as completely glaciated clouds. Icing was prevalent at a temperature range of -15°C to – 5°C. The highest LWC (~0.5 g m^{-3}) was measured at T of about -5°C and altitude of 1 km (~17:40), just above where the GVR measured the maximum LWP (~0.2 mm). As shown in the 2D-C sample images, the ice crystals sampled during this flight include, irregular shape, columnar and dendritic types. In order to correlate the remote sensing measurements with the in-situ data, three different segments of the flights were selected.

3.2.1 Segment 1- Multi-layer mixed phase cloud

Fig. 7 shows vertical profiles of T, T_d, LWC, LWP, cloud particle concentrations and MVD sampled during a spiral ascent between 17:18 and 17:25 UTC. The corresponding Z_e vertical cross-section obtained by the NAWX W-band radar is shown in Fig. 8. At the lowest aircraft altitude, the particles were all ice crystals (mixtures of irregular shape and needle type crystals). The dew point temperature at this ice crystal dominated cloud volume is less than the dry bulb temperature indicating that the environment is below water saturation. The maximum LWP (~ 0.2 mm) was observed at the lowest aircraft altitude where the LWC is zero, indicating the presence of liquid cloud above the flight level. Within a couple of hundred of meters of climb, the aircraft entered a supercooled cloud layer. The LWC and MVD values increased sharply and reached maximum values of 0.35 g m^{-3} and 15 µm respectively after 200 m of entering the supercooled regions, at the same time the LWP and cloud particle concentration decreased sharply. As the aircraft continued to the spiral ascent it continued to encounter shallow pockets of (< 200 m) of supercooled clouds up to the cloud top. It is important to point out that the LWP measured above the 2 km altitude was less than < 0.05 mm, which is consistent with the much reduced LWC and cloud depth observed above this altitude. From the vertical profile of the in-situ cloud physics measurements shown in Fig. 7 alone, it is difficult to determine the cloud structure. The LWC data suggest the presence of at least four liquid layers. Like the LWC and cloud particle measurements, the temperature and humidity profiles also show a complex structure with multiple isothermal and/or temperature inversion layers of variable thicknesses. One might interpret these complex vertical profiles as representative of the cloud vertical organizations assuming the cloud conditions are relatively homogenous in the horizontal. However, a careful examination of the

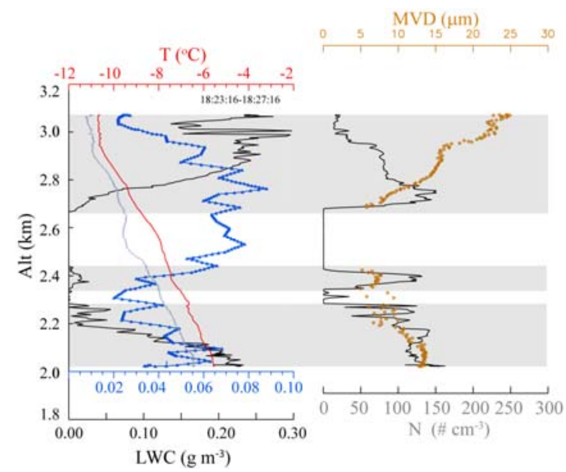


Fig. 5. Same as Fig. 3, except for profiles corresponding to the time segment shown in Fig. 4.

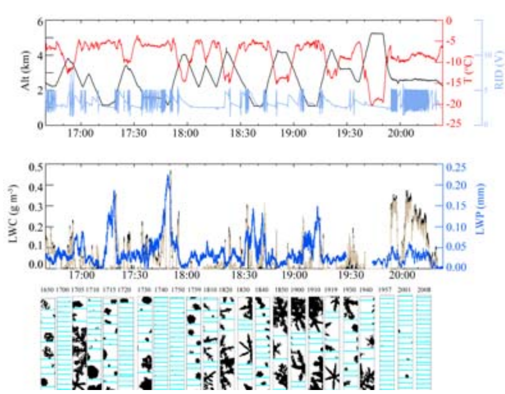


Fig. 6. Same as Fig. 1, except for the C3VP flight segment on Feb 26, 2007.

reflectivity field shows, there were three different types of clouds. A solid cloud layer below 2 km, a discontinuous middle layer cloud between (2-3.5 km), and a shallow upper cloud layer between 3.5 and 4 km. Supercooled drops were present in all of these three different layers, with the maximum icing condition confined to the top of the bottom cloud deck at ~1.8 km. Note the temperature inversion at the top of this lower cloud deck, but the humidity level remained high. In this particular case, the radar image provided a means to interpret the in-situ data better.

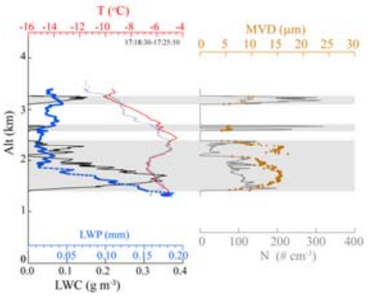


Fig. 7. Same as Fig. 3, except for a profile obtained during the CV580 spiral ascent on Feb 26, 2007.

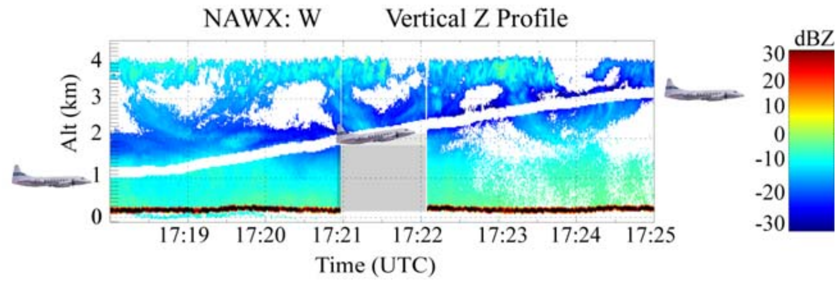


Fig. 8. Vertical Z cross-section, obtained by the NAWX W-band radar corresponding to the aircraft spiral ascent time segment presented in Fig. 7. The W-band nadir antenna was not active between 17:21 and 17:22 (indicated by the grey scale below the aircraft picture).

3.2.2 Segment 2 – Multi-layer cloud

Fig. 9 shows vertical profiles of in-situ and GVR data obtained north east of the CARE site as the CV580 made a spiral descent inside a 4 km deep cloud system. The corresponding vertical and horizontal Z_e cross-sections as well as the ZDR measurement from the side-looking NAWX W-band radar are presented in Fig. 10. Similar to the clouds sampled around the CARE site, the cloud contained mixed phase, glaciated or all liquid cloud volumes. A sample 2D-C image is also included with the radar images as a reference of particle types encountered during the spiral descent. As can be inferred from the vertical Z_e cross-section, the cloud top is relatively uniform with cloud top height of around 4 km, which is very similar to the cloud top height identified during the sampling around the CARE site (Fig. 7). What is different in this case is that the three layers observed at the CARE site now appear as one solid cloud deck extending from ground up to 4 km. However, the cloud microphysical properties, and hence the radar signatures, of the three cloud layers are still distinctly different. Similar to the previous case, there was a liquid layer near the upper cloud layer, just below the temperature inversion at around 4 km. As the radar reflectivity structure shows, there are fine-scale cloud organizations in the top layer. The reflectivity in this zone generally above 0 dBZ indicates the presence of ice crystals mixed with the supercooled cloud drops. This is consistent with the 2D-C images that show pristine dendrites. Because of the high aspect ratio of these crystals, the ZDR values are very high (> 3 dB). These polarimetric signatures are very similar to what is being observed in previous studies in pristine planar ice crystals (e.g., Wolde and Vali, 2001). The upper shallow liquid layer has maximum LWP of 0.04 mm, which is similar to what was measured at the CARE site (Fig.7). In the middle cloud layer, there was no liquid and, like the top mixed-phase layer, the crystals were mainly dendertic types with much reduced reflectivity values. There is again a fine-scale organization of ice particles that resulted in alternating minima and maxima in Z_e and ZDR values (e.g., 19:00-19:01) within the layer. The aircraft then entered into a supercooled liquid layer starting at 2.5 km altitude and continued to experience icing conditions until it descended to 1.8 km altitude. Note that the temperature and humidity profiles are very similar to the profiles presented in Fig. 7. Unlike the mixed phase condition near the top of the upper cloud layer, the ice crystals in this layer are bigger in size and also appear to be heavily rimed, which explains the near 0 dB ZDR values and higher reflectivity (>5 dBZ). Below 1.8 km (19:06), the aircraft sampled cloud volumes with no liquid in a sub-water saturated environment. The ice crystals composition was a mixture of small needle type crystals and some large aggregates. The near 0 dB ZDR and a higher Z values suggest the large aggregates dominate the reflectivity field. In this particular case, the availability of on-board radar and radiometer data allowed adequate characterizations of the vertical profiles of the supercooled liquid and mixed phase

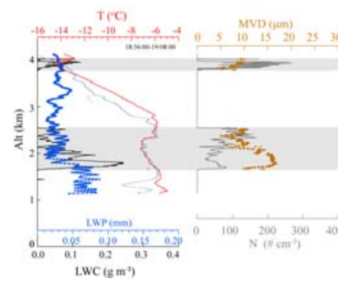


Fig.9. Same as Fig. 7, except for data obtained during a spiral descent between 1856 and 1908 on Feb 26, 2007.

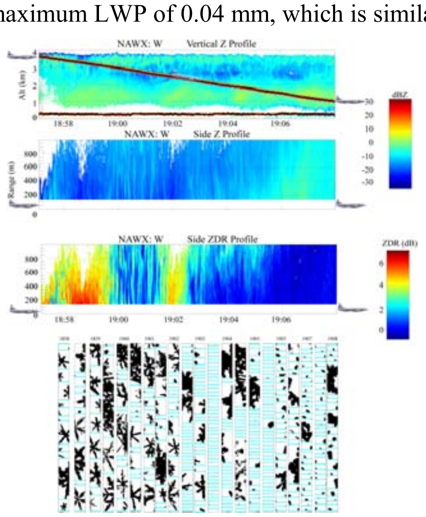


Fig. 10. Vertical (top) and horizontal Z cross-sections (middle image) and Horizontal cross-section of ZDR measured by the NAWX W-band radar (bottom image) corresponding to the time segments used in Fig. 9. Samples of the 2D-C image corresponding to the images are also shown.

conditions, which would have been difficult to do with just an in-situ data from a single aircraft. Three cloud layers were identified based on distinctly different radar and radiometer signatures.

3.2.3 Segment 3 – Single liquid layer

The third segment shows measurement made during a transit flight back to Ottawa where the aircraft experienced moderate to heavy icing condition. Fig. 11 shows traces of the NAWX W-band radar reflectivity at the nearest usable radar range gates (~200 m range) and measurements of LWC, LWP, T and T_d during this horizontal transect. The aircraft encountered sustained icing conditions at an altitude of 2.5 km and T of -10°C (19:55 – 20:20). When the aircraft entered the icing region, the LWC and LWP gradually increased from near 0 to a maximum of about 0.4 g m^{-3} and 0.06 mm respectively. During that time, the reflectivity increased from the detection limit of the radar (~ -30 dBZ) to a value of -25 dBZ. The same ranges of LWP, LWC and Z values and the reverse trend were observed when the aircraft exited the system. Outside the edges, the reflectivity values fluctuated between -28 dBZ and -24 dBZ, while the LWC values varied between 0.2 and 0.3 g m^{-3}. The reflectivity trace closely follows the LWC trace, matching even the small-scale (<0.05 g m^{-3}) LWC fluctuations indicating that all of the reflectivity comes from the liquid drops. In this particular case, the LWP measured at the flight level is lower than the 0.1mm, even if the LWC is high and the ice accretion on the aircraft and some of the probes were significant (Fig. 12). The NAWX radar was able to detect the cloud just within the 500-1000 m range so it is difficult to determine the cloud depth. But judging from the vertical profiles and the LWP values observed prior to entering this cloud, it is likely that the integrated LWP below the cloud layer were likely be much higher than 0.04-0.06 mm LWP measured at flight altitude.

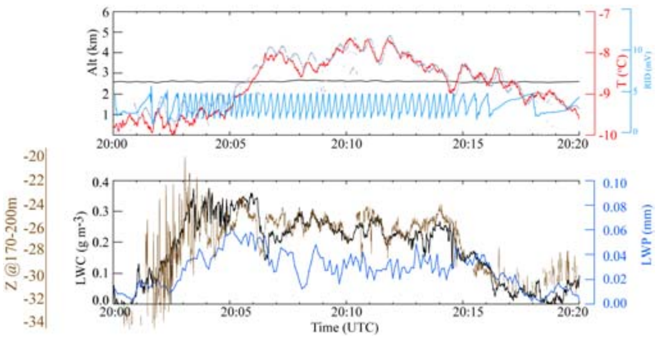


Fig. 11. Top: Time series of T, T_d, altitude (alt) and RID and Bottom: LWC, LWP, and NAWX W-band reflectivity at about 200 m range gate of segment 3 of the Feb. 26, 2007 flight.

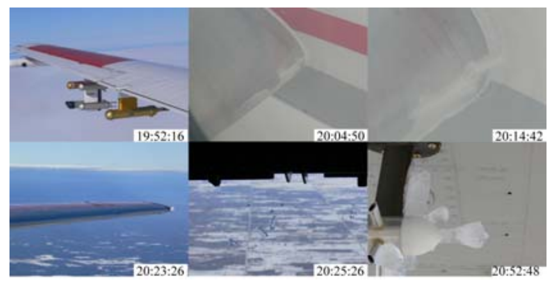


Fig. 12. Sequences of images taken during segment-3 of the Feb. 26, 2007 CV580 flight.

4. Concluding Remark

This paper presented five flight segments of airborne radar, radiometer and in-situ observations of icing encounters in winter clouds with temperature range of -16°C to 0°C. The data were collected during the Canadian CloudSat and CALIPSO Validation project conducted in Southern Ontario Canada in winter of 2006 and 2007. The near coincident measurements of in-situ cloud microphysics, radar and radiometer data allowed characterizations of the icing environments well beyond the research aircraft altitude. The main summaries of this study are:

- The depths of the liquid layers in all of the cases included in this study are less than 500 m. This is not unusual and has been routinely observed in both convective and stratiform clouds (e.g., Rauber and Tokay, 1991; Korolev et. al., 2007). Most of the cloud systems had more than one liquid and/or mixed phase layers. The GVR radiometer data clearly identified the cloud layering structures and also determining the LWP contribution of each of the layer. In the multi-layer clouds included in the study, the top layers were mixed phase. The LWP of just below the top-liquid layers range from 0.05 mm to 0.1 mm , with the maximum LWC of 0.3 g m^{-3} and radar reflectivity of typically >-20 dBZ. In contrast, all of low-level cloud layers contained no ice crystals and had high LWC (up to 0.5 g m^{-3}) and LWP (up to 0.2 mm). These all-liquid shallow layers are barely detectable by the radars as the reflectivity values are typically < -20 dBZ.
- During both flights continuous observation of supercooled clouds with sustained LWC of 0.2 to 0.3 g m^{-3} were observed for over 60 km during horizontal transects.

The airborne remote sensing data (radiometer and radar) provided invaluable information that are complementary to the in-situ cloud physics probes documenting the horizontal and vertical structure of the icing events. The near-coincident measurement of the in-situ and remote sensing data allowed determination of the remote sensing signatures associated with the different particle types including the supercooled regions to a scale that is not feasible from ground based systems. In one of the cases, the high LWC regions appear in close proximity to cloud layers consisting of pristine dendritic crystals with no liquid present. The radar polarimetric signature readily identifies this pristine ice crystal dominated layer from the liquid clouds that was sampled just below the ice crystal layer. Similar observation of high ZDR at proximity of the high LWC was documented by Wolde et al. (2005) in deep Ns cloud. More cases need to be analyzed to characterize the frequency of occurrences and the scales of high LWC in clouds with high ZDR values, which has a potential to identify supercooled drops in mixed phase environments.

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