P.192 **An investigation of wintertime midlevel mixed-phase clouds with supercooled water droplets using in-situ measurements**

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1. INTRODUCTION

In general, the number of aircraft accidents due to weather hazards has been declining with the technology advancement over the past decades. However, In-flight icing is still very challenging and remains a serious aviation hazard. Mixed-phase clouds containing both supercooled liquid water droplets and ice particles are relatively common in the Earth's atmosphere (Deeter and Vivekanandan, 2004) and have been observed to contain liquid droplets at temperatures down to -40°C (Cober et al., 2001). Aircraft flying through these mixed-phase clouds can result in rapid ice accretion on the wings and frames, which can directly cause aircraft crashes. Many efforts have been made to develop reliable techniques for identifying and forecasting icing conditions using various data sources, but our limited knowledge of these mixed-phase clouds has been responsible for the uncertainties in retrievals from both satellites and surface radar observations, as well as numerical weather prediction models that these techniques rely on. Although detailed understanding of the characteristics and microphysical properties of mixed-phase clouds is essential in aviation safety, studies of these clouds have been significantly limited particularly due to lack of extensive in-situ measurements. For instance, several studies of mid-latitude mixed-phase clouds (e.g., Fleishauer et al., 2002; Niu et al., 2008; Carey et al., 2008) show that a large number of liquid droplets and a small number of ice crystals are concentrated at or near cloud-top whereas ice virga can be found in the middle and bottom portions within these clouds. However, the cloud structure and hydrometeor quantities are not properly represented yet in many present numerical models and satellite retrieval algorithms that are using temperature thresholds to distinguish cloud phases.

In this study, spaceborne radar/lidar data and aircraft in-situ measurements are analyzed in order to better understand the structures and microphysical characteristics of non-precipitating midlevel mixed-phase clouds such as altostratus and altocumulus. We take advantage of rich data sources from in-situ aircraft measurements during an intensive field campaign that took place during 2006-2007 winter season over the Southern Ontario region of Canada. Multi-satellite measurements are also used. The cloud features detected by various sensors are represented for the cases showing mixed phase signatures. The spatial distributions of liquid/ice phase hydrometeors and corresponding atmospheric sounding data are also investigated.

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2. DATA

We use rich data from in-situ aircraft measurements during an intensive field campaign. The tenth Cloud Layer Experiment (CLEX-10) is part of an ongoing research project for a study of non-precipitating midlevel mixed-phase clouds at CIRA/Colorado State University funded by the Department of Defense's Center for Geosciences/Atmospheric Research (Fleishauer et al. 2002; Carey et al. 2008). It collaborated with the Canadian CloudSat/CALIPSO Validation Project (C3VP; refer to www.c3vp.org) that took place from 31 October 2006 to 1 March 2007 over Southern Ontario and Southwestern Quebec. These two field experiments (C3VP/CLEX-10) worked together during 2006-2007 winter season to target A-Train (the Afternoon satellite constellation led by NASA's Aqua satellite; Stephens et al., 2002) overpasses of wintertime clouds and precipitation over the areas shown in Fig. 1.

The distributions and various properties of supercooled liquid water droplets and ice particles in the clouds during C3VP/CLEX-10 were measured by the Convair-580 research aircraft that was equipped with a number of observational instruments such as the Particle Measurement System (PMS) Forward Scattering Spectrometer Probes (FSSP-100) (Knollenberg, 1981) for droplet effective radius, a King hot-wire probe (King et al., 1978) for liquid water content (LWC), the Nevzorov probe (Korolev et al., 1998) for total water content (TWC), and many other instruments for measuring thermodynamic parameters and aircraft geo-location information (Barker et al., 2008). All these measurements are analyzed in order to better understand the microphysical structures of supercooled liquid water droplets in mixed-phase clouds.

In addition, various kinds of satellite data are also used to investigate responses of these mid-level mixed-phase clouds in satellite microwave channels. MODIS (Moderate-Resolution Imaging Spectroradiometer) data of the Aqua satellite are used to examine cloudy areas of interest. For studying the vertical structure of clouds, data from the recently launched CloudSat (Stephens et al. 2002) are used together with coincidental aircraft observations. CloudSat is designed to measure the vertical structure of clouds and precipitation from space with a 94-GHz cloud profiling radar (CPR), which observes most of the cloud condensate and precipitation within its nadir field of view and provides profiles of these properties with a vertical resolution of 240 m. CloudSat release-version 04 data are used in this study (refer to http://cloudsat.cira.colostate.edu/ for more details). The CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation) satellite (Winker et al. 2009) also provide direct observations of thin clouds and aerosols from space with two channels of 532 nm and 1064 nm, which is sensitive to thin liquid cloud layers. These satellites together will provide more detailed observations of mixed-phase clouds.

3. AIRCRAFT MEASUREMENTS

During C3VP/CLEX10, the vertical structure and microphysical properties of several mixed phase clouds were sampled using in-situ probes and remote sensing instruments onboard the National Research Council of Canada's Convair-580 aircraft. Figure 2 shows 12 vertical profiles of temperature and liquid/ ice water content (LWC and IWC) obtained from the aircraft measurements. It is noted that LWC and IWC are from the King liquid water and Nevzorov LWC-TWC probes, respectively, following the procedure described by Korolev et al. (2003). In the figures, it is found that the cloud observed on 31 October 2006 consisted of two layers with an upper-layer cloud top temperature of -21°C, and a significant amount of supercooled liquid water droplets (up to 0.3 gm^{-3}) still exists near cloud top at very low temperatures around –20 ~ - 30°C as shown in 05 November 2006 and 25 February 2007 profiles. It also is found that LWC and IWC significantly vary in each profile and show no linear correlation between two. In Fig. 3, LWC and temperature data shown in Fig. 2 are represented as Liquid Fraction (LF) described in Eq. (1) to explore more detailed relationship between these two variables. These results reconfirm previously observed results (e.g., Fleishauer et al., 2002) that many cases of mixed-phase clouds are dominated by supercooled liquid droplets in very low temperature conditions (< -20°C) at or near cloud top while IWCs are very small. However, any significant correlation between liquid water contents and temperature is not found for the profiles.

$$LF = \frac{LWC}{IWC + LWC} \qquad (1)$$

4. SATELLITE OBSERVATIONS

Satellite observations of two cases (05 November 2006 and 25 February 2007) are presented here. Figure 4 shows MODIS IR cloud phase data (MYD06) for the cases. On 5 November 2006, a warm front had moved over Southern Ontario leaving behind a large area of mid-level cloud cover. Mid-level clouds were observed at a C3VP ground station continuously for over ten hours. During the C3VP/CLEX-10 flight targeting the CloudSat overpass around 1830 UTC, a mixed phase cloud layer, with nearly 3 km of thin cirrus above and scattered clouds below, was observed. While broad areas of 'Uncertain' category are found over the target region in Fig. 4a, the target mixed-phase cloud has cloud top temperatures down to -22°C and a significant amount of liquid up to 0.3 gm^{-3} in the cloud (4-4.7 km) as shown in Fig. 2 (183714-184833 UTC on 05 November 2006). CloudSat data shows the vertical cross-section (Fig. 5b) of the 'Altocumulus' cloud over the target region (Fig. 5a). The current CloudSat algorithm (http://cloudsat.cira.colostate.edu/ICD/2B-CLDCLASS/2B-CLDCLASS_PDICD_5.0.pdf) classifies clouds into stratus (St), stratocumulus (Sc), cumulus (Cu), nimbostratus (Ns), altocumulus (Ac), altostratus (As), deep convective (DeepC), or high cloud (Ci) by combining space-based active (CPR and CALIPSO lidar) and passive remote sensing (MODIS) data. The high cloud class consists of cirrus, cirrocumulus, and cirrostratus. CALIPSO clearly detects a supercooled liquid water layer at cloud top and cirrus above the cloud layer as shown in Fig. 5c.

On 25 February 2007 a large low-pressure system over the central US continued to move slowly toward the northeast, near southern Ontario (Fig. 4b). Ahead of the system, a band of cirrus and a large area of mid-level cloud cover were observed over our target area. During the flight, layers of altostratus cloud were sampled, which is consistent with CloudSat cloud classification data in Fig. 6a. CALIPSO observed supercooled liquid water layers in the cloud (Fig. 6c), and a selected flight leg during C3VP/CLEX-10 plotted in Fig. 2 (183254-184510 UTC on 25 February 2007) shows a maximum of LWC of about 0.17 gm^{-3} at the cloud top where the temperatures throughout the cloud (5.8-6.7 km) are all below -20°C. In this case, IWC has the highest value of 0.07 gm^{-3} at the top.

5. SUMMARY AND CONCULUSIONS

In this study, analyses of aircraft and satellite measurements of wintertime mid-level mixed-phase clouds are presented. During C3VP/CLEX-10, a great combination of observations of midlevel mixed-phase clouds was obtained from aircraft, satellites, and surface observations, and the data are used to understand the characteristics and microphysical features of the mixed-phase clouds. The analysis of vertical distributions of liquid/ice using satellite and aircraft measurements confirmed again the existence of supercooled liquid water droplets at very low temperatures (< -20°C) and often near or at cloud top, which has been also frequently observed in mixed-phase clouds over the Arctic region (Shupe et al., 2006) and in the previous CLEXs (Fleishauer et al., 2002; Carey et al., 2008). Since this cloud vertical structure has a great effect particularly on shortwave heating rates, an accurate representation of the cloud structure and properties is critical for the cloud lifetime forecast, as well as the global estimate of cloud-radiative forcing in climate studies. It also is found that the amount of cloud water content (LWC and IWC) significantly varies in each case. However, no linear correlation is found between LWC and

IWC. Also, any significant correlation between water contents and temperature is not found.

From the present study, it is apparent that intensive observations such as C3VP/CLEX-10 are necessary to improve our understanding of the detailed cloud microphysical features of these clouds and thus to develop reliable techniques for identifying and forecasting icing conditions. In particular, signals from liquid and ice phases of the mixed-phase clouds in many satellite measurements are relatively weak and so complicated because many midlevel mixed-phase clouds are thin and temporally unstable compared to deep convective precipitating clouds. Our results also show that multi-frequency and multi-instrument analyses (e.g. CloudSat + CALIPSO + MODIS) are essential to clearly detect and properly retrieve midlevel mixed-phase clouds from a satellite remote sensing perspective. Together they make it possible to accurately profile these mixed phase clouds.

We continue to analyze satellite and aircraft in-situ measurements during C3VP/CLEX-10 and investigate the characteristics of midlevel mixed-phase clouds such as LWC/IWC vertical distributions, detailed microphysics, and radiative properties. Also, we have been validating satellite retrievals including CloudSat and MODIS products by using intensive in-situ observations. This study will provide an observational basis for the improvement of numerical model schemes and satellite retrieval algorithms of midlevel mixed-phase clouds and thus have significant benefits to the aviation community.

6. ACKNOWLEDGMENTS

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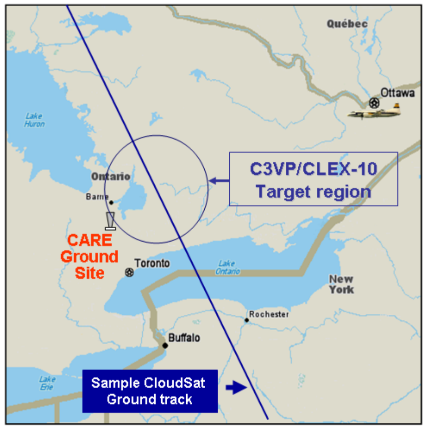

Figure 1. Map of a sample C3VP/CLEX-10 target region.

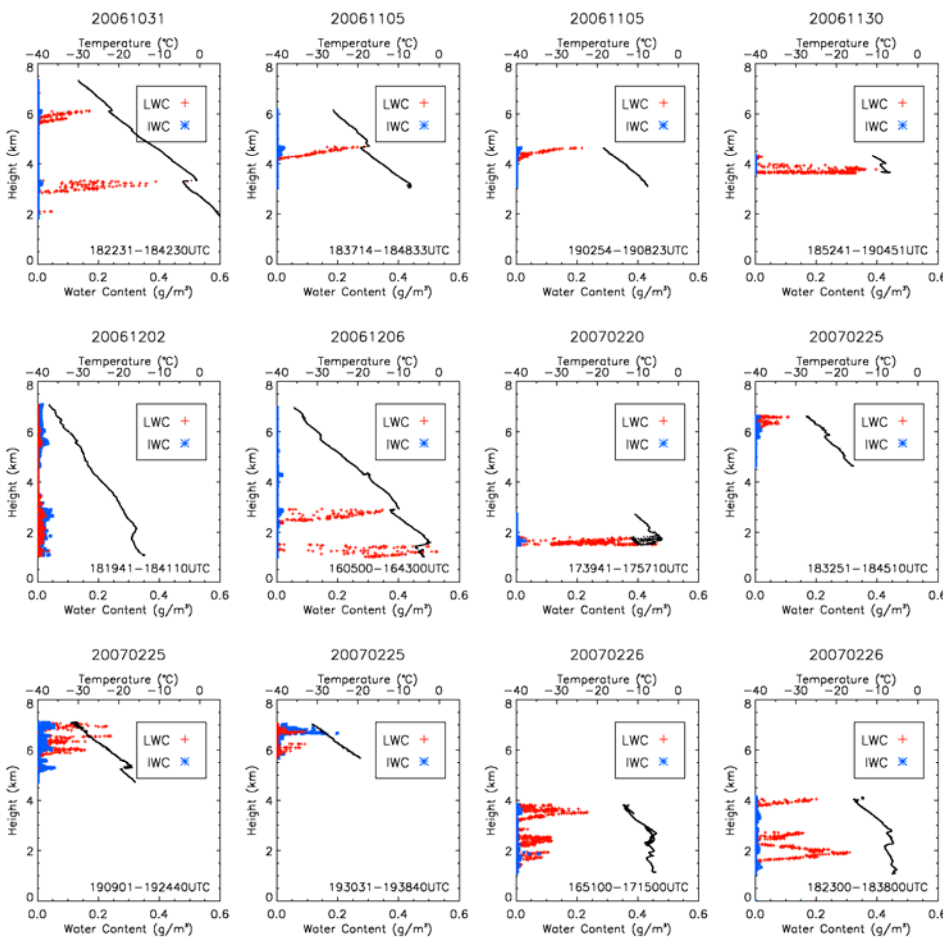

Figure 2. Vertical profiles of LWC/IWC and temperatures (black dots) for 12 selected flight tracks during C3VP/CLEX-10.

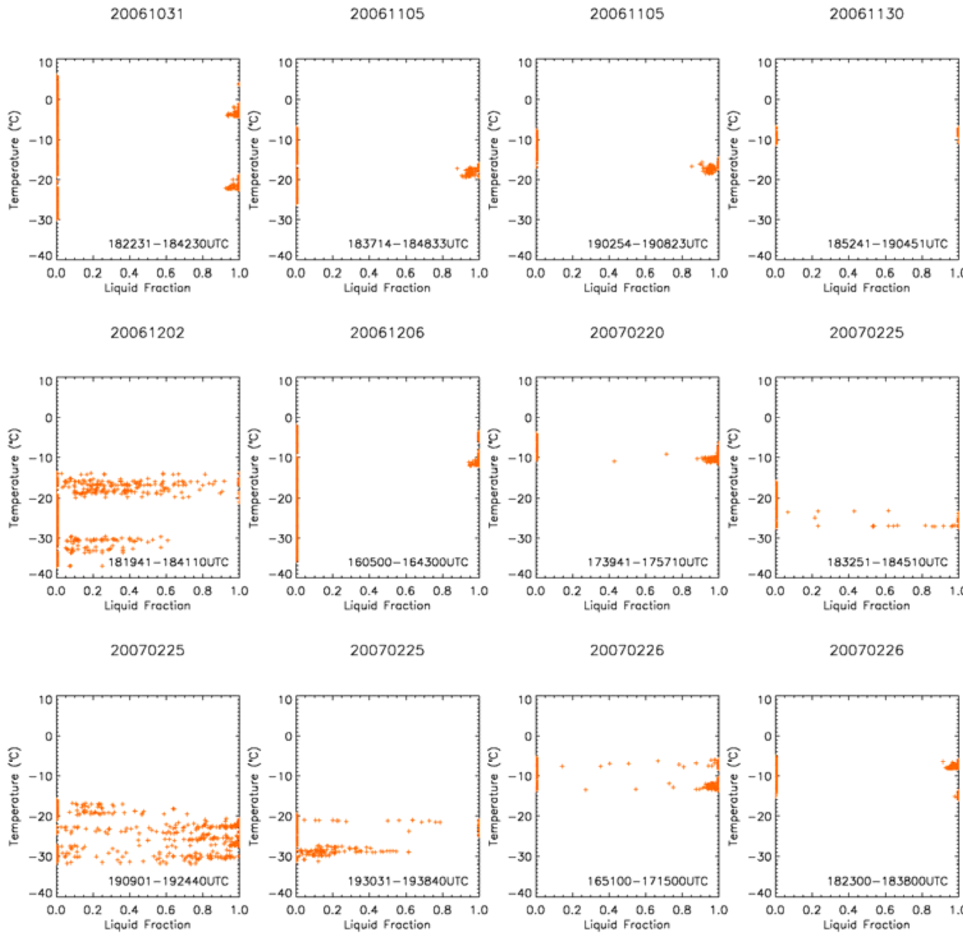

Figure 3. Scatter plots of liquid fractions vs. temperatures.

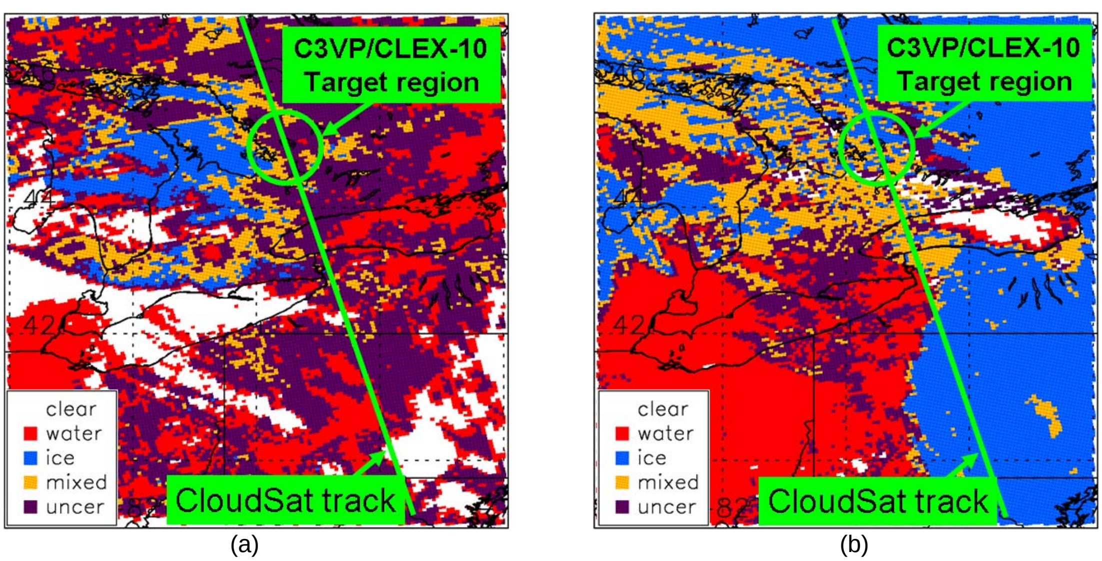

Figure 4. Auqa MODIS cloud phase (IR) products (a) at 1825 UTC on 05 November 2006 and (b) at 1825 UTC on 25 February 2007.

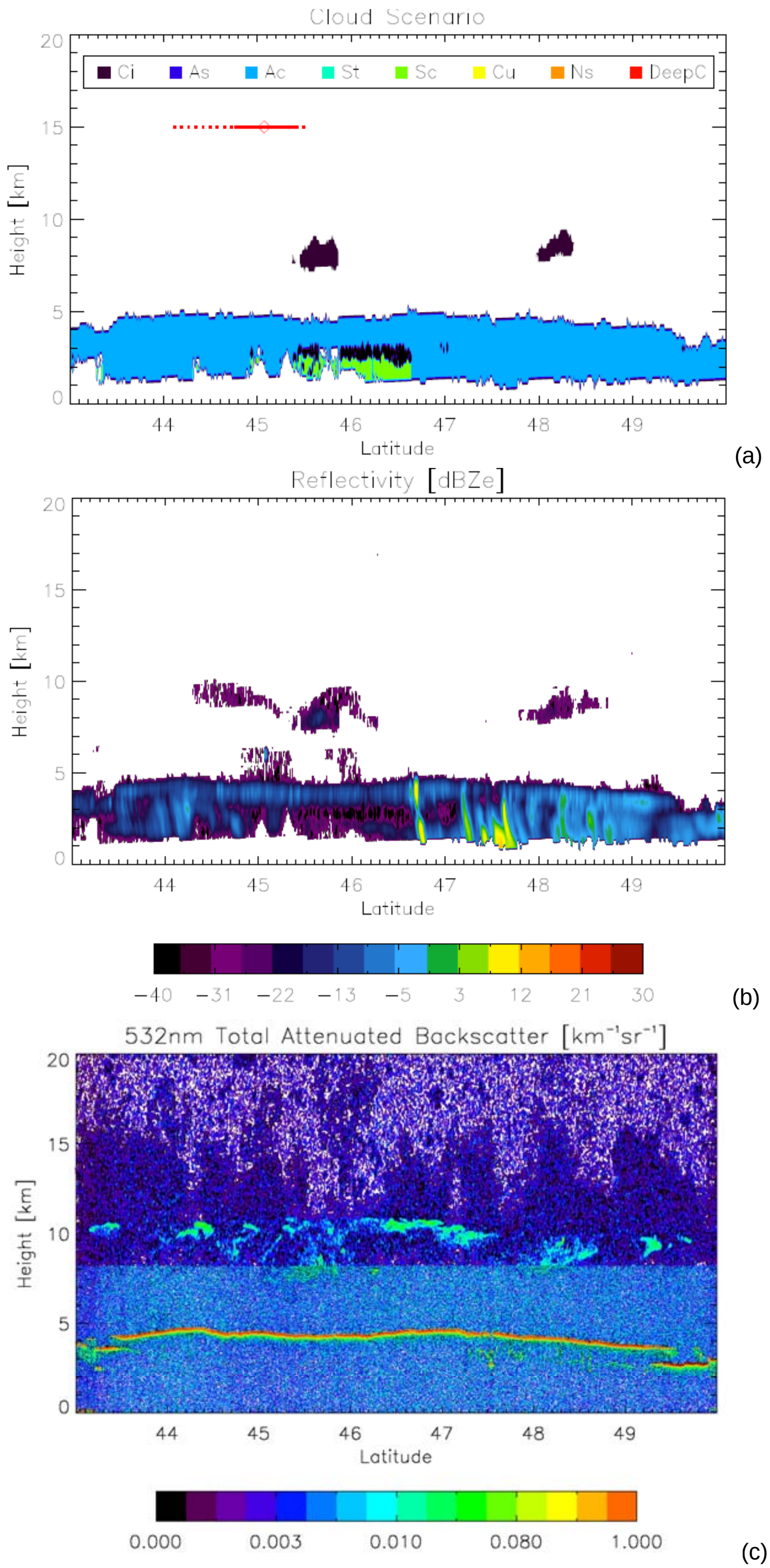

Figure 5. CloudSat data of (a) cloud classification with C3VP/CLEX-10 target area (red solid line) and the aircraft location (red diamond) during the CloudSat overpass and (b) CPR reflectivity [dBZe], and (c) CALIPSO 532 nm total attenuated backscatter on 05 November 2006.

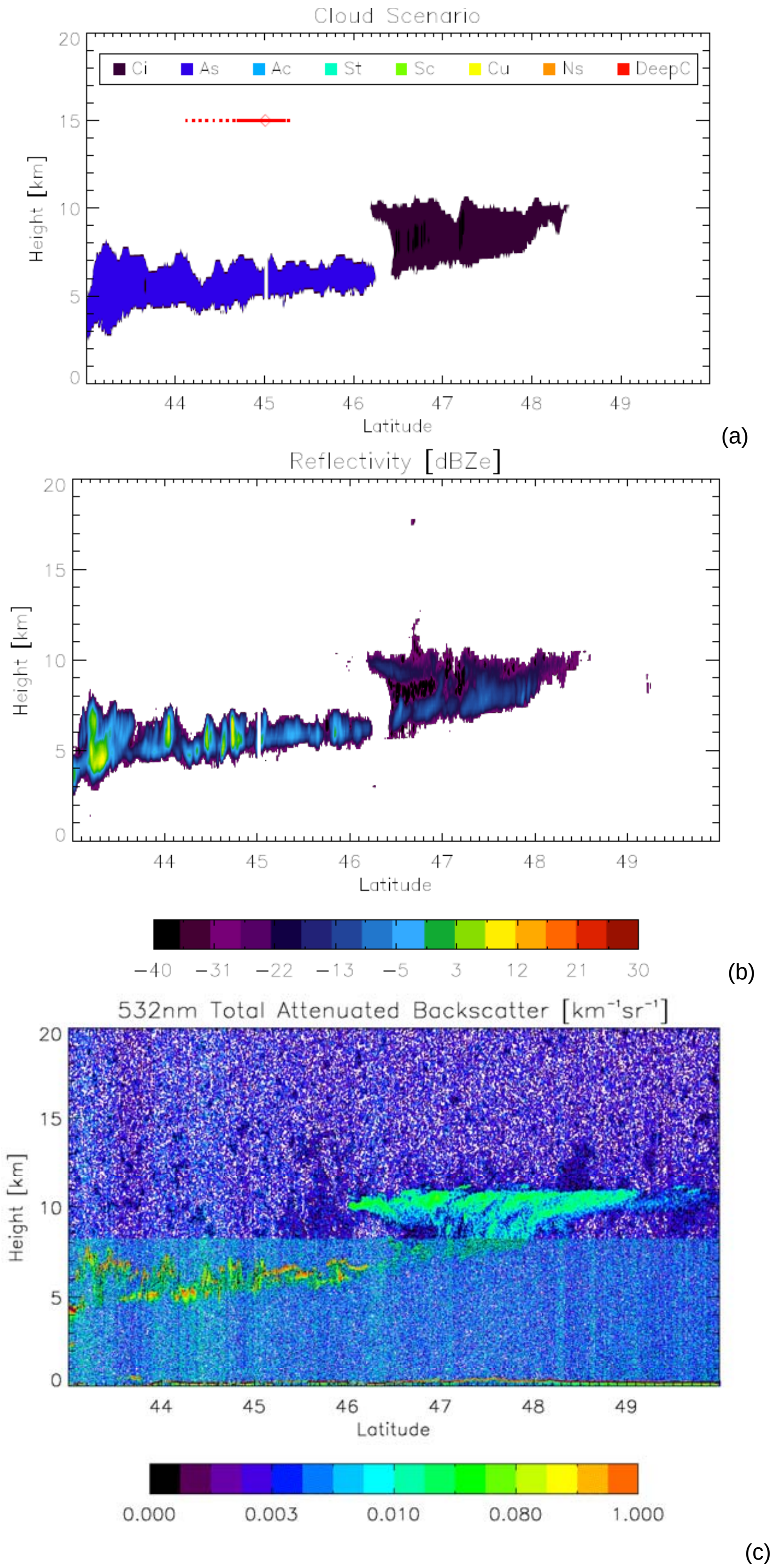

Figure 6. Same as Fig. 5 but for 25 February 2007.