Cloud-Top Supercooled Liquid Droplets in Stratiform Clouds Observed during Winter in Inland Hokkaido, Japan

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Abstract

Supercooled liquid droplets (SLDs) not only play important roles in precipitation formation processes but they also affect the radiation budget. Therefore, it is important to clarify the distribution and quantity of SLDs. Hydrometeor videosenode observations were performed in February 2011 at Rikubetsu in inland Hokkaido, Japan. Five hydrometeor videosenodes were released in ice precipitations in stratiform clouds and SLDs were detected in three cases. The clouds in these three cases had SLDs at the cloud tops. The microphysical quantities of the SLD layers were within the ranges of those observed in Arctic mixed-phase clouds. The cloud-top SLDs had potential to cause radiative cooling, which contributed to the formation of upward motion generating ice precipitation. Small water vapor amounts above the cloud tops cannot contribute to moisture supply. Vertical profiles of temperature and moisture showed that the SLD layers were decoupled from surface moisture sources. The absence of additional moisture supply was consistent with short lifetimes, compared with persistent Arctic mixed-phase clouds.

1. Introduction

Supercooled liquid droplets (SLDs) exist within a temperature range between 0 and −40°C. In most situations, SLDs collocate with ice particles in clouds that are referred to as mixed-phase clouds. In the mixed-phase condition, ice particles grow rapidly by diffusion because of the difference in saturation water vapor pressure between the liquid and solid phases, i.e., the Wegener–Bergeron–Findeisen mechanism (Storelvmo and Tan 2015). In small contents of SLDs in small upward motion, this mechanism contributes to growth of ice crystals (Korolev 2007). In large contents of SLDs in strong updrafts associated with convective clouds, growth by riming is effective and graupels are frequently formed. Therefore, SLDs play important roles in the precipitation formation processes of both stratiform and convective clouds. Differences in radiation between liquid- and solid-phase water particles can affect estimations of the radiation budget of the earth (e.g., Choi et al. 2014; Sun and Shine 1994; Tsushima et al. 2006). Therefore, it is important to clarify the distributions and quantities of SLDs to understand precipitation formation processes and to estimate earth’s radiation budget for determining the temperature of the earth.

SLDs are consumed continuously in mixed-phase conditions by the growth of ice particles through the Wegener–Bergeron–Findeisen mechanism. Frequent detection of SLDs in the atmosphere can be indicative of their continuous generation, compensating the continuous depletion. The generation of SLDs is related to the cooling of air through processes such as ascent and radiation. In cloud systems such as extratropical cyclones (e.g., Murakami et al. 1992; Ikeda et al. 2007) and mesoscale convective clouds (e.g., Murakami et al. 1994; Rosenfeld and Woodley 2000; Takahashi 2010) and orographic clouds (e.g., Kusunoki et al. 2004), SLDs are formed because of ascent owing to synoptic-scale or mesoscale atmospheric instability and external dynamical forcing. Around the Japanese Islands, there were only a few reports for stratiform mixed-phase clouds without synoptic-scale disturbance, convection, and orographic lifting (Meteorological Research Institute 1992). In this study, we focus on maintenance processes of those stratiform mixed-phase clouds.

In the Arctic, SLDs are frequently observed in stratiform clouds in boundary layers (e.g., Morrison et al. 2011a; Shupe et al. 2006, 2008; Verlinde et al. 2007). The SLDs at the tops of Arctic mixed-phase clouds could be maintained from a period of less than one hour to a maximum of several days (Shupe et al. 2006). The SLDs at the cloud tops cause strong radiative cooling that drives vertical air motions (Pinto 1998). Moisture inversions are frequently formed by large-scale advection near cloud tops. Vertical mixings arising near the cloud tops supply moisture from above the cloud into the cloud layers (Solomon et al. 2011). In addition, longwave radiation of SLDs can induce decreasing static stability and increasing surface heat and moisture fluxes (Morrison and Pinto 2004). These processes can contribute to the maintenance of clouds. Thus, in the Arctic mixed-phase clouds, the presence of SLDs is essentially related to the processes of their formation and maintenance, which differ to those in clouds systems such as extratropical cyclones, convective clouds, and orographic clouds. The quantities of SLDs are controlled by the balance between the processes of their generation and depletion. High number concentrations of ice particles facilitate to consume SLDs (Morrison et al. 2011b). Large uncertainties in cloud microphysical processes such as ice nucleation cause differences in numerical simulations of Arctic mixed-phase clouds (e.g., Morrison et al. 2011b; Ovchinnikov et al. 2014). Furthermore, the environments favorable for Arctic mixed-phase clouds are also unclear, which could cause their poor representation in climate models. Therefore, it is important that the quantities and distributions of SLDs are measured observationally.

In February 2011 in inland Hokkaido, which is located in northeast Japan (Fig. 1), we conducted observations of precipitating stratiform clouds using hydrometeor videosondes (HYVISs). In the HYVIS observations, clouds with SLDs at their tops were observed. In this paper, we present the characteristics of those stratiform mixed-phase clouds with SLDs at their tops, without synoptic-scale disturbance, convection, and orographic lifting.

2. Observations and data

We performed observations of precipitating clouds from 8 to 28 February 2011 at Rikubetsu in Hokkaido. The Nagoya University X-band radar was installed at the Rikubetsu Observatory of the Institute for Space-Earth Environmental Research, Nagoya University (43.46°N, 143.77°E; 376 m above sea level). The release point of the HYVIS instrument (43.46°N, 143.76°E; 230 m above sea level) was located 1.0 km northwest (azimuth: 325°) of the radar site. HYVIS was developed at the Meteorological Research Institute of Japan (Murakami and Matsuo 1990) and it is manufactured by the Meisei Electric Co. HYVIS collects particles on a transparent film coated with silicon oil and it takes alternate images using

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both microscopic and close-up cameras that have fields of view of 1.4 and 7−9 mm, respectively. Particles with diameters > 7 μm can be recognized using the microscopic camera. Another type of HYVIS was developed that has a suction fan to measure particles in clouds with low number concentrations (Orikasa and Murakami 1997). Both types of HYVIS were used in this study.

A radiosonde was attached to the HYVIS to measure temperature, humidity, and horizontal wind. The types of the collected particles were identified from the HYVIS images and their lengths and numbers were quantified. A sample image of the SLDs observed by HYVIS released at 1802 JST on 27 February 2011 is shown in Fig. 2. A diameter of SLD was defined as an average of major and minor axes of a best fit ellipse. Number concentration \( N \) was given by

\[
N = \frac{N_{\text{count}}}{EV},
\]

where \( N_{\text{count}} \) is number of observed particles, \( E \) is collection efficiency, and \( V \) is sampling volume. Collection efficiencies of SLDs and snows were given as an equation by Murakami and Matsuo (1990) and 0.5 (Orikasa et al. 2005), respectively, for an original HYVIS. For a HYVIS with a suction fan, a collection efficiency was given as unity (Orikasa and Murakami 1997). Sampling volumes of air were estimated from ascent velocity for an original HYVIS and from Orikasa and Murakami (1997) for a HYVIS with a suction fan. In order to derive liquid water content (LWC), mass of a SLD was calculated as a sphere with a defined diameter. HYVISs were used to observe a variety of clouds (e.g., Murakami et al. 1992, 1994; Kasunoki et al. 2004; Orikasa et al. 2013; Orikasa and Murakami 2015; Oue et al. 2015).

The specifications of the X-band radar were given in Morotomi et al. (2012) and Ohigashi et al. (2014). The radar was operated with 11 or 12 plan position indicator scans every 5 min. Constant altitude plan position indicator (CAPPI) data were derived using 5-min volume scan data with a horizontal spacing of 0.5 km.

In the HYVIS observations, eight vertical profiles were obtained for precipitating stratiform clouds. Five of the observed clouds were not associated with extratropical cyclones, and SLDs were found in three of those cases. The common characteristics of these three cases are explained using the HYVIS released at 1802 JST on 27 February 2011.

### 3. Characteristics of SLDs observed on 27 February 2011

Figure 1 shows the surface pressure and wind fields from the Japan Meteorological Agency (JMA) Climate Data Assimilation System and an infrared channel 1 image from Multifunctional Transport Satellite (MTSAT) 2 at 1500 JST on 27 February 2011. An extratropical cyclone center is located to the west of the Korean Peninsula. High clouds shown as low brightness temperatures, which are associated with a warm front, extend about 1000 km to the east and north from the cyclone center but they do not reach Hokkaido. An infrared image acquired at 1800 JST on 27 February (not shown), close to the time of release of the HYVIS, also indicated that the high clouds did not cover the HYVIS observation area. Another small low can be seen over Hokkaido at 1500 JST on 27 February.

A close-up view around Hokkaido at 1500 JST on 27 February 2011 is shown in Fig. 3. Relative humidity at 800 hPa (around a height of 1900 m) from the JMA mesoscale analysis (Fig. 3a) is above 90% around the small low. Wind vectors at the same level around the HYVIS observation site is directed from the high relative humidity area toward the observation site. An infrared satellite image shows low-level clouds, which is categorized as stratus, over Hokkaido (Fig. 3b). Note that the gray levels in Fig. 3b are different from those in Fig. 1. The stratus coexists with the high relative humidity region around the surface small low. It is inferred that weak upward motion was present around the surface small low and can cause the high humidity region at low levels, which resulted in stratus.

The radar reflectivity at a height of 1.25 km is shown in Fig. 4. It can be seen that the radar echoes between 15 and 25 dBZ are scattered, although a region of relatively stronger reflectivity (of around 30 dBZ) can be seen to the northwest of the radar at 1810 and 1835 JST. The HYVIS was released into a radar echo that was identified at 1620 JST and which moved toward the southeast. It is inferred that the southerly part of the echo (13 dBZ) was located over the HYVIS observation site at the release time, although CAPPI data were unavailable at upper levels around the radar site. At the passage of the echo, snow aggregates were observed at the surface. SLDs were observed at 1811−1812 JST by the HYVIS when it was located at 43.44°N, 143.79°E. The CAPPI at a height of 1.25 km at 1810 JST showed that the HYVIS ascended into the southern part of the 13-dBZ echo. The target radar echo was

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**Fig. 1.** Infrared channel 1 image from MTSAT-2 (gray shading, °C), sea-level pressure (red lines, hPa), and surface winds (vectors, m s\(^{-1}\)) at 1500 JST 27 February 2011.

**Fig. 2.** Microscopic camera image of supercooled liquid droplets observed by HYVIS released at 1802 JST 27 February 2011 at Rikubetsu. Pressure (p, hPa), temperature (T, °C), height (z, m), and relative humidity (RH, %), at which the image were taken, are shown below the image.
Fig. 3. Distribution of humidity and clouds. (a) Relative humidity (shadings, %) and horizontal wind (vectors, m s\(^{-1}\)) at 800 hPa, and sea-level pressure (white contours, hPa). (b) Infrared channel 1 image from MTSAT-2 (gray shading, °C). Closed marks indicate the HYVIS observation point at Rikubetsu. Note that gray levels in Fig. 3b are different from those in Fig. 1.

Fig. 4. Radar reflectivity (dBZ) at a height of 1.25 km every 25 min between 1630 and 1835 JST 27 February 2011. The data were obtained by the Nagoya University X-band radar installed at Rikubetsu. Red solid ellipses indicate a precipitation echo into which a HYVIS was released. Purple dotted ellipses show ground clutter. Black crosses denote the location of the HYVIS observation site located 1.0 km northwest (at an azimuth of 325°) of the radar. CAPPI data at this altitude were unavailable within black solid circles.
observed for 140 min until 1840 JST. Figure 5a shows the profiles of potential temperature, equivalent potential temperature, and saturation equivalent potential temperature, as well as the layer in which SLDs were present. The 230-m-thick SLD layer, extending from 2975 to 3205 m, corresponds to a temperature range of −25.5 to −23.8°C. The potential temperature indicates high stability above the SLD layer, where the proximity of the equivalent potential temperature indicates very low relative humidity. Therefore, no moisture inversion was present. Above the SLD layer, almost no particles were observed by the HYVIS observation and therefore, the SLDs must have been present at the cloud top. A microscopic camera image (Fig. 2) shows a number of tiny round particles showing SLDs near the top of the SLD layer (a height of 3000 m). Another significant stable layer is present at 910 hPa (Fig. 5a).

The particle size distribution of the SLDs within the layer is shown in Fig. 6. The mode of the diameters is 10–20 μm and the mean diameter and the effective radius are 13 μm and 7 μm, respectively (Table 1). No SLDs with a diameter > 32 μm were observed. The number concentration is 4 cm$^{-3}$ and the liquid water content through the SLD layer is 0.006 g m$^{-3}$. In the SLD layer, no ice particle was observed in microscopic camera images nor close-up camera images. This indicates an ice number concentration < 0.1 L$^{-1}$, which was the minimum detected concentration derived from Eq. (1) using $N_{\text{count}} = 1$.

![Fig. 6. Size distribution of supercooled liquid droplets between heights of 2975 and 3205 m obtained by the HYVIS released at 1802 JST 27 February 2011.](image)

Table 1. Characteristics of clouds in which cloud-top supercooled liquid droplets (SLDs) were observed. Date and time indicate HYVIS release time. $T_s$ is surface air temperature at release time. Parameters $T$ and LWC are temperature and liquid water content, respectively, in the layer in which SLDs were observed. It was not possible to measure the average diameter, effective radius, maximum diameter, and number concentration of cloud-top SLDs for the case of 11 February 2011 because SLDs filled the HYVIS images.

<table>
<thead>
<tr>
<th>Date</th>
<th>Release time (JST)</th>
<th>$T_s$ (°C)</th>
<th>Height (Thickness) (m)</th>
<th>$T$ (°C)</th>
<th>Average diameter (μm)</th>
<th>Effective radius (μm)</th>
<th>Maximum diameter (μm)</th>
<th>Number concentration (cm$^{-3}$)</th>
<th>LWC (g m$^{-3}$)</th>
<th>Number concentration of ice in cloud-top SLD layers (L$^{-1}$)</th>
<th>Cloud-top height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>27 Feb.</td>
<td>18:02</td>
<td>−3.2</td>
<td>2975–3205 (230)</td>
<td>−25.5 to −23.8</td>
<td>13</td>
<td>7</td>
<td>32</td>
<td>4</td>
<td>0.006</td>
<td>0 (&lt; 0.1)</td>
<td>3205</td>
</tr>
<tr>
<td>11 Feb.</td>
<td>19:45</td>
<td>−4.7</td>
<td>2660–2860 (200)</td>
<td>−23.3 to −21.5</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>3</td>
<td>2880</td>
</tr>
<tr>
<td>25 Feb.</td>
<td>19:53</td>
<td>−3.2</td>
<td>2570–2630 (60)</td>
<td>−21.6 to −21.0</td>
<td>27</td>
<td>14</td>
<td>40</td>
<td>4</td>
<td>0.045</td>
<td>15</td>
<td>2785</td>
</tr>
</tbody>
</table>
4. Comparisons with Arctic mixed-phase clouds

The clouds in which the SLDs were observed were not associated with synoptic-scale extratropical cyclones. High relative humidity regions and stratus in the low levels were formed around mesoscale lows (cases on 11 and 27 February) and in the lee of clouds developed in a cold-air outbreak over sea (a case on 25 February). The characteristics of the clouds are shown in Table 1. The surface temperatures at the times of release of the HYVISs (−4.7 to −3.2°C) were considerably higher than the February climatic values of mean temperature (−10.0°C) and mean daily minimum temperature (−19.2°C) at the Rikubetsu observation point, as provided by the JMA. The horizontal extents of the precipitation echoes were within several tens of kilometers. Lifetimes of precipitation echoes were several hours, which were comparable to the Arctic mixed-phase clouds (Shupe et al. 2006). However, the lifetimes were considerably shorter than long-lived Arctic mixed-phase clouds maintained for a maximum of several days. During passages of echoes over the HYVIS observation site, snow aggregates were observed at the surface. The clouds had SLDs at the cloud tops just below strong stable layers, as shown in Figs. 5a, 5b, and 5c. For the case of 11 February, two further SLD layers were observed in addition to the cloud-top SLD layer. The ranges of the temperatures and heights of the cloud-top SLD layers were −25.5 to −21.0°C and 2570−3205 m, respectively. The thicknesses of the SLD layers ranged from 60 to 230 m. Air above the cloud tops was dry. Other significant stable layers were present at 950−870 hPa. This indicates that the cloud-top SLD layers were decoupled with the surface.

The average diameter, effective radius, and maximum diameter of the SLDs were 13−27, 7−14, and 32−40 μm, respectively. Supercooled drizzle drops > 100 μm in diameter, which have been observed in the Arctic (Kajikawa et al. 2000), were not observed in this case. The number concentration and LWC in the SLD layers were calculated at 4 cm−3 and 0.006−0.045 g m−3, respectively, for the cases on 25 and 27 February 2011. For the HYVIS released on 11 February 2011, a number of SLDs overlapped on the images. Therefore, it was not possible to measure the sizes of the SLDs. If the relative distribution of particle size on 11 February 2011, was assumed the same as on 25 and 27 February 2011, the number concentration and LWC could be estimated as 80−340 cm−3 and 0.47−0.93 g m−3, respectively. Number concentration of ice particles in the SLD layers were 0−15 L−1. Although an ice concentration of 0 L−1 is small, those of 3−15 L−1 are also within the range observed in the Arctic mixed-phase clouds (Hobbs and Rangno 1998; McFarquhar et al. 2007; Verlinde et al. 2007).

Liquid particles at cloud tops tend to cause greater radiative cooling than solid particles. Morrison et al. (2011b) showed that cloud-top radiative cooling rates were mostly determined by the liquid-dominated water contents from intercomparison of model simulations. The SLD-layer-averaged LWCs of 0.03 and 0.15 g m−3 corresponded to peak radiative cooling rates of −30 and −85 K day−1, respectively. While radiative cooling rates remain to be estimated quantitatively, especially for the relatively small LWC in the case on 27 February, the clouds observed in inland Hokkaido had potential to cause cloud-top radiative cooling comparable to those in the Arctic. This cooling can destabilize stratification, which causes upward motion generating ice precipitation. On the other hand, sounding profiles showed neither moisture inversion near the cloud top nor dynamical coupling to the surface. Therefore, no moisture supply was expected from above the cloud tops nor the surface. This leads to depletion of moisture by ice precipitation soon. This is consistent that the lifetimes of clouds observed in Hokkaido were short, compared with long-lived Arctic mixed-phase clouds maintained for a maximum of several days.

5. Summary

HYVIS observations were performed in February 2011 at Rikubetsu in inland Hokkaido, Japan. SLDs were detected in three of five HYVIS launches into precipitating stratiform echoes that were not associated with extratropical cyclones; these SLDs were observed at the cloud tops. Microphysical characteristics within the SLD layers were similar to mixed-phase clouds in the boundary layer in the Arctic. The SLDs observed at the cloud tops had potential to cause cloud-top radiative cooling comparable to those in the Arctic, which contributes to the formation of ice precipitation. On the other hand, no additional moisture supply expected from absence of moisture inversion and decoupling to the surface was consistent with short lifetimes of precipitating clouds in Hokkaido, compared with long-lived Arctic mixed-phase clouds persisting for a maximum of several days. This study contributes to understanding of structures and maintenance mechanisms of low-level stratiform precipitating clouds formed in subfreezing temperature. We only launched HYVISs into clouds that were accompanied by substantial precipitation, as confirmed by the X-band radar. To clarify the statistical characteristics of clouds with SLDs at their tops in this region, long-period and continuous observations acquired by remote sensing instruments will be needed for both precipitating and non-precipitating clouds. To understand complex processes associated with presence of SLDs as shown in Morrison et al. (2011a), average microphysical quantities including SLDs must be derived using in situ measurement instruments as well as multiple remote sensing instruments such as millimeter-wave radar, lidar, and microwave radiometers, which could enable the quantitative estimation of radiation using a radiative transfer model.

Acknowledgments

We thank Dr. T. Murata of Rikubetsu Space Earth Science Museum and Dr. K. Shimizu of the Meisei Electric Co. for their cooperation with the observations. We are also grateful to Dr. H. Minda, T. Kouketsu, H. Okamoto, H. Takeuchi, Y. Hyuga, S. Miyai, and R. Furuhata of Nagoya University for conducting the observations. Thanks are extended to reviewers for their valuable comments. This study was supported jointly by the Japan Society for the Promotion of Science KAKENHI Grant Nos. 22340136 and 15K05285, and the “Virtual Laboratory for the Earth’s Climate Diagnostics” program.

Edited by: R. Misumi

References


Kusunoki, K., M. Murakami, M. Hoshimoto, N. Orikasa, Y. Yamada, H. Mizuno, K. Hamazu, and H. Watanabe, 2004: The characteristics and evolution of orographic snow clouds


Manuscript received 24 February 2016, accepted 14 May 2016

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