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Structures of Planetary Boundary Layers Observed by a Doppler Sodar in a Cold Season at Sapporo, Japan

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Abstract

Observations of planetary boundary layers in Sapporo city in a winter monsoon season were carried out from December 1987 to February 1988 with a Doppler sodar. Two typical cases in winter, cold air flows from inland and northwesterly winter monsoon with snowfall, were analyzed in detail. The cold air flows of February 16, 1988 showed two upward rising (up to the altitude of 700 m) echo patterns. Wind direction shifted from southwest to east during the period of the two echo patterns. The prominent updrafts of 1. 2 and 0.7 m/sec were recorded at the first and the second echo patterns respectively. They corresponded to the first shallow (<90 m) and the second thick (>120 m) cold air flows that penetrated into Sapporo. Effects of snowfalls on planetary boundary layers were examined in the case of February 11, 1988. Wind direction shifted from east to northwest with the beginning of snowfalls. At the same time, the height of strong wind region descended gradually to the ground. Heavy snowfalls produced maximum downdraft speed of 1.6 m/sec. Two rapid mixing processes in winter, from the ground upward by cold air flows and from cloud base to the ground by snowfalls, were revealed by the Doppler sodar observation at Sapporo, Japan.

Key Words: Planetary boundary layers, Doppler sodar, Cold air flows, Snowfalls, Upward rising echo pattern, Updraft, Downdraft, Mixing process in winter.

1. Introduction

Recent studies have revealed that Doppler acoustic echo sounding system, Doppler sodar (SOund Detection And Ranging), is useful to measure the planetary boundary layer structures. Many studies of mixing depth, stability conditions and other parameters of the lower atmosphere with Doppler sodar have been carried out by Talonet et al.(1983), Kobayashi et al. (1984), Neff(1987), Spanton et al. (1988) and others. Gera and Weil(1987) made observation of front structures at lower atmosphere. However, the observations of boundary layers with Doppler sodar in very cold region are limited. Also the structure changes of boundary layer by the effects of snowfalls are interesting problems to be solved. Though heavy rainfall prevents observation of sodar by sound noises produced by rain drops, snow does not make such problems. Furthermore, Taniguchi et al. (1983) made observations of reflection echoes from snowflakes with conventional sodar (non Doppler).

In order to make observations of planetary boundary layers in winter, Sapporo city is very suitable place. Sapporo is close to Japan sea having northwesterly wind of winter monsoon and also it is affected by cold nocturnal air flows from inland plains. Around Sapporo, snow bursts from snow clouds were observed by Shirooka et al.(1988) and the effects of cold air flows from inland to snowfalls were observed by Fujiyoshi et al.(1988). The properties of aerosol concentrations of winter Sapporo were studied by Lee et al. (1988) and others. The study of wind structure of boundary layers in winter Sapporo is expected from many workers in several fields.

As a first step of Doppler sodar observation, data were recorded for three months in a winter season. Typical two cases were selected from the obtained data in order to analyze the detailed structures of planetary boundary layer in winter.

2. Method

Observations of planetary boundary layers in Sapporo city, Hokkaido island, Japan in the winter monsoon season were carried out from December 1987 to February 1988 with a Doppler sodar. The Doppler sodar (trimonostatic type) was set on the ground in the campus of Hokkaido university, about 2 km northwest from central Sapporo. The university campus is located about 15 km southeast from the sea coast of Ishikari Bay, the Sea of Japan as shown in Figure 1.

The specifications of the sodar are shown in Table 1. Wind components and their variances (σ U and σ W) were measured every 10 minutes at 50m intervals below 400m, and at 100m intervals above 400m. These values were averaged for 10 minutes with 20 pulses. Also facsimile records of reflective echo (intensity) were obtained up to 800m. Data were acquired continuously except the time of shoveling snow out from acoustic transmitters. However, buildings on the campus played a role as mirrors to the acoustic wave to produce strong reflection as shown in the record of return power (Figure 2). Therefore the data below 100 m were eliminated from the analyses.

From the data of three months, two typical cases were selected. For the detailed analyses, meteorological data obtained at the top of a building (27m above ground level) close to the observation site were used. The data measured by the Sapporo District Meteorological Observatory, Japan meteorological Agency and by the Health and Sanitation Bureau, Sapporo City were also utilized.

3. Results

Two typical cases in winter, cold air flow from inland and northwesterly winter monsoon with snowfalls, were analyzed in detail.

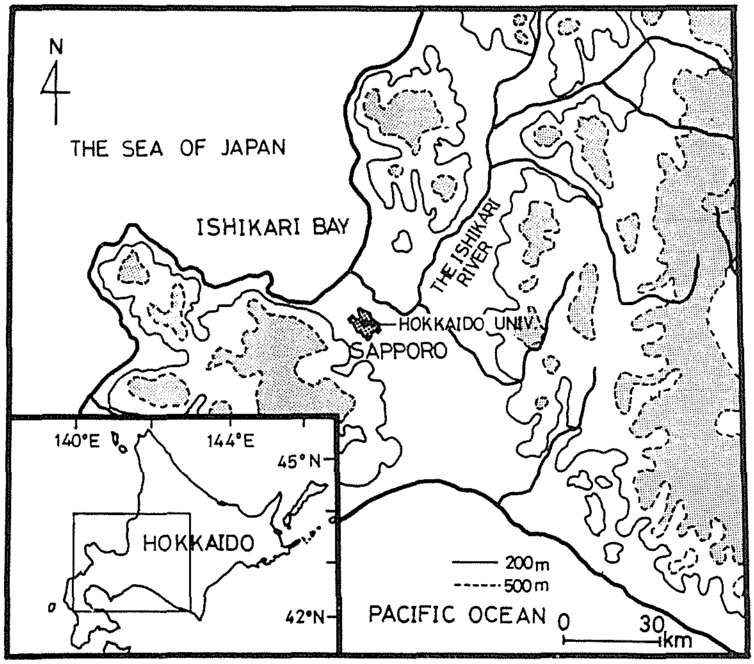

Figure 1. Map of observation area. The Doppler sodar was located in a campus of Hokkaido University.

Table 1 Doppler sodar specifications.

Model Name	AR410, Kaijodenki
Transmitter, Receiver-Antennas	Paraboric dish, 0.9mϕ
Transmitting Power	200 W
Transmitting Frequency	1600 Hz
Transmitting Pulse Width	120 msec, 300 msec
Repetition Interval	10 sec
Resolution of Heights	20 m, 50 m
Beam Width	10 deg
Accuracy of Speed	0.3 m/s (horizontal) 0.2 m/s (vertical)

3.1 Cold air flow The structures of cold air flows of February 16, 1988 were analyzed. Two intense and upward rising echo patterns (first and second) of sonic reflection were observed from 01 JST to 04 JST as shown in Figure 3. The time-height cross section of horizontal wind speed and direction is shown in Figure 4. The intense echo region in Figure 3 coincided well with the region of large wind speed (>3m/sec). The wind data obtained by sonde by the Sapporo District Meteorological Observatory, JMA are superposed on Figure 4. The wind speed coincided well with that of the Doppler sodar. The wind speed was measured up to 700 m by the Doppler sodar. The observed heights are rather high compared to the average height of possible wind measurement by sodars in winter Sapporo.

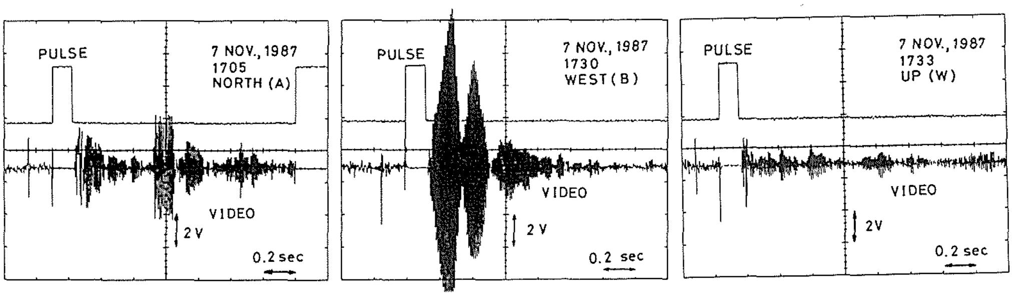

Figure 2. Return signals of acoustic wave transmitted from the transmitters facing north, west and upward. Large amplitudes aronud 600 sec (north) and before 400msec (west) indicate the reflection from a building at 100 m north from the sodar and trees near the sodar to the west.

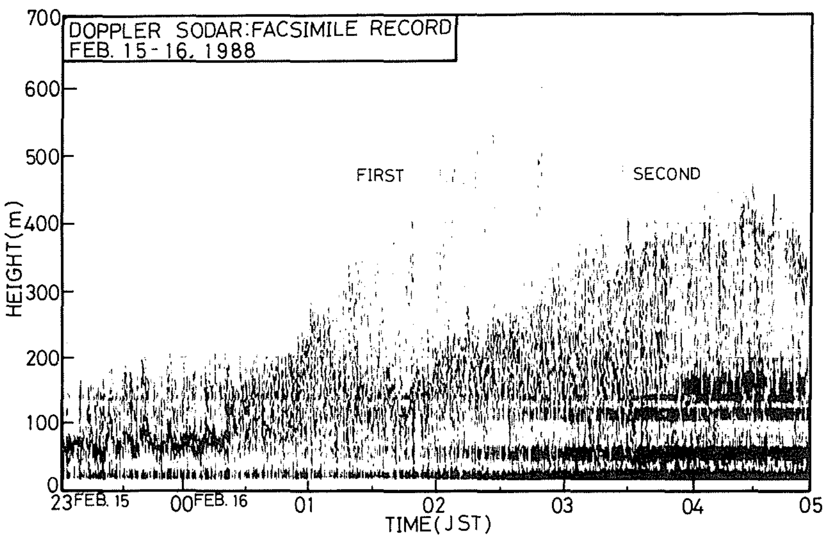

Figure 3. A facsimile record of reflective intensity from 23 JST, February 15 to 05 JST, February 16, 1988. Two iotense uprising echo patterns (First and Second) are prominent.

Vertical wind speeds are contoured on the figure of horizontal wind speed as shown in Figure 5. At the high speed region of the first rising echo pattern, updraft wind speed larger than 0.2 m/s (hatched with cross) spread widely and reached 1.2 m/s at 0110 JST in 250 m level. On the other hand, at the second rising echo pattern of high horizontal wind, the updraft region is rather narrow and reached 0.7 m/s at the most. Behind the second one, up -and down-drafts were observed alternately. The interval was about 28 minutes at the altitude from 250 to 400 m. The most turbulent regions are identified behind the first and second echo as shown in Figure 6 by the distribution of σW (0.6 m/s).

In order to examine the vertical structure of temperature, television tower data

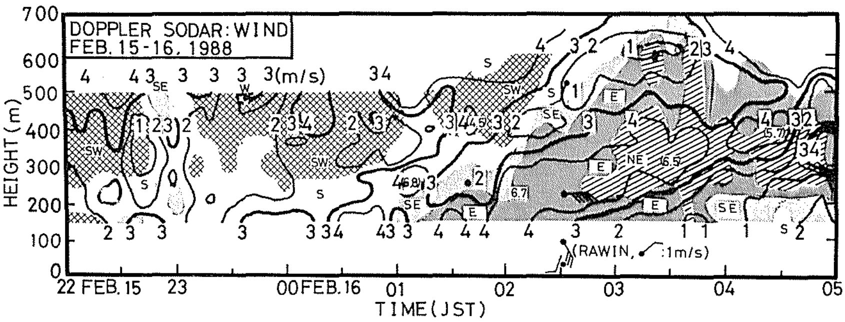

Figure 4. Time-height cross section of horizontal wind from 22 JST February 15 to 05 JST February 16, 1988. Winds are divided into eight directions by shades with symbols. Wind speed are shown by solid lines at 1 m/s intervals. The arrows with barbs at 0230 JST show the wind obtained from date by Sapporo Meteorological Observatory, Japan Meteorological Agency. The prevailing wind direction was south before the first echo pattern and east behind the second echo pattern.

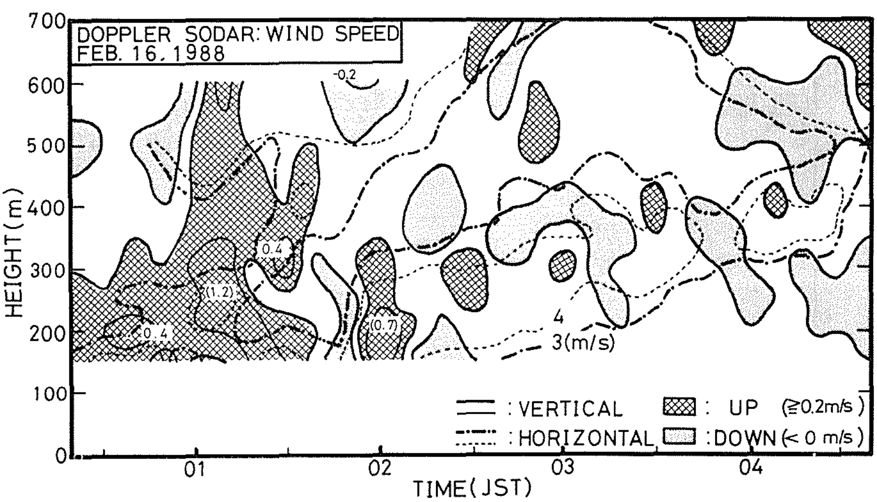

Figure 5. Tire-height cross section of vertical wind speed from 0020 to 0440 JST February, 1988. Updrafts and downdrafts are shown by cros-shatched and shades respectively. Dot-dash and dashed lines show horizontal wind speeds of 3 m/s and 4 m/s respectively.

obtained by Sapporo city were utilized. Temperatures are measured at surface, 30, 60, 90 and 120 m, and horizontal winds are measured at 30 and 90 m. Time-height cross section of them in February 15 and 16 is shown in Figure 7. The first cold flow is identified at around 2230 JST by the contour of -10°C and the wind shift. At 2300 JST, -12°C is observed at the altitude of 30 m. This flow was shallow below 90 m. However, the next flow at 0030 JST was thicker than the first one reaching over 120 m. The lowest temperature was below -12°C at 0040 JST at 60 m. After 0100 JST, the temperature below the altitude

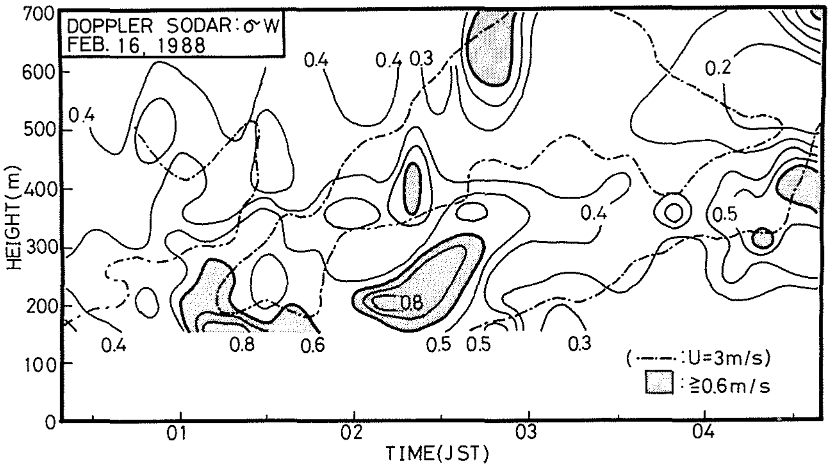

Figure 6. Comparison of horizontal wind speed (shown by dot-dash lines of 3 m/s) with variances of vertical wind (σ W, shown by solid lines and shades).

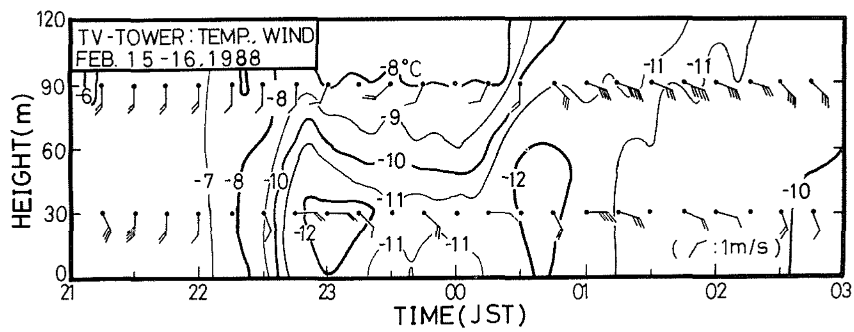

Figure 7. Vertical structure of cold air flow from 2100 JST, February 15 to 0300 JST, February 16, 1988 at TV tower. Solid lines show temperature. Wind at 30 and 90 m are shown by barbs.

of 90 m rose gradually.

Wind at 30 m level changed from south to west at 2230 JST. However, at 90 m level, apparent wind shift from south to west is identified around 0040 JST. These results indicate that there were two separate cold air flows.

As shown in the surface weather map of Figure 8, Hokkaido is under a local high pressure. The distributions of surface temperature were examined with the AMeDAS data. In Figure 9, surface temperatures of 2100 and 2300 JST 15 February and 0100 JST February 16 are shown. A cold region of -16°C approached Sapporo and the temperature at TV tower dropped to -11.5°C at 2300 JST. At 0100 JST 16 February, the cold region of -16° C spread widely. At this period the depth of cold air flow increased at central Sapporo. Figure 10 shows the detailed distribution of surface temperature of Sapporo. At 2300 JST, the first cold air flow that approached from east is clearly shown, though the temperature

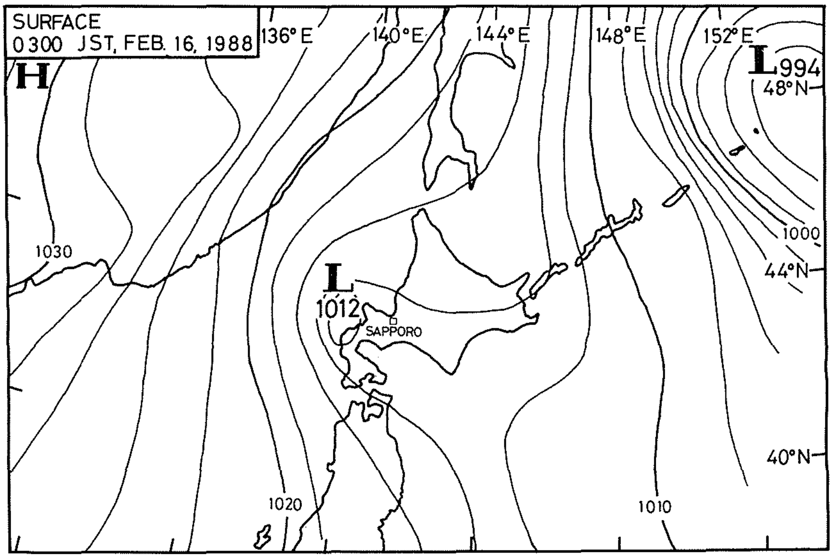

Figure 8. Synoptic weather chart ot 03 JST, February 16, 1988.

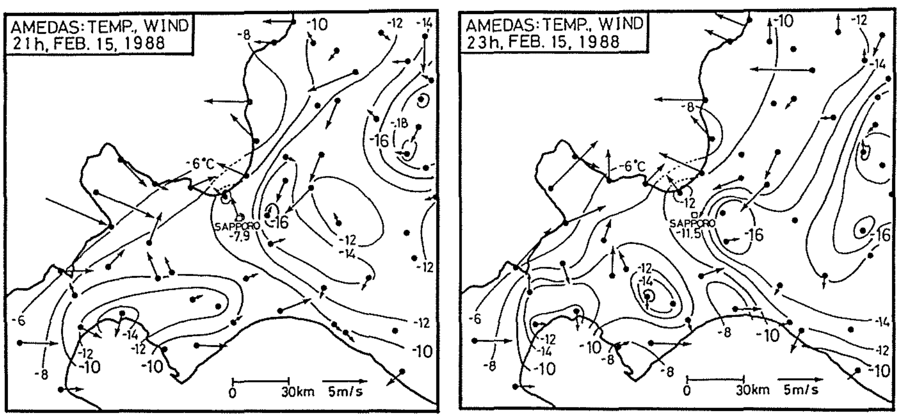

Figure 9. Distribution of surface temperature and wind by AMeDAS on 21 and 23 JST February 15, 1988. Contours of temperatures are shown in 2°C intervals.

at 2100 JST is rather high at the central Sapporo.

3.2 Effects of snowfalls Northwesterly winter monsoon brings snowfalls to Sapporo. At the beginning of a snowfall, the winds usually shift from east to northwest over the surface in Sapporo. The echo of the sodar in the case of onset of the northwesterly wind of winter monsoon (February 11) is shown in Figure 11. Echo height rose rapidly after 1210 JST. A time-height cross section of horizontal wind speed and direction is shown in Figure 12. An apparent wind shift from south to west around 12 JST before a heavy snowfall at surface

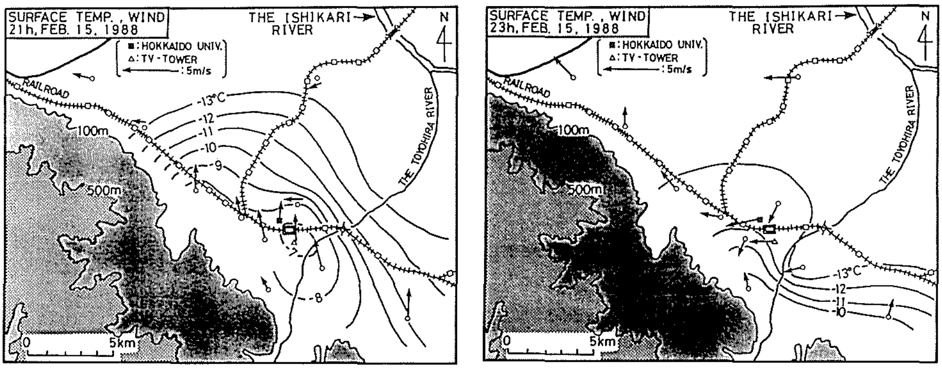

Figure 10. Distribution of surface terperature and wind at Sapporo city on 21 and 23 IST, February 15, 1988.

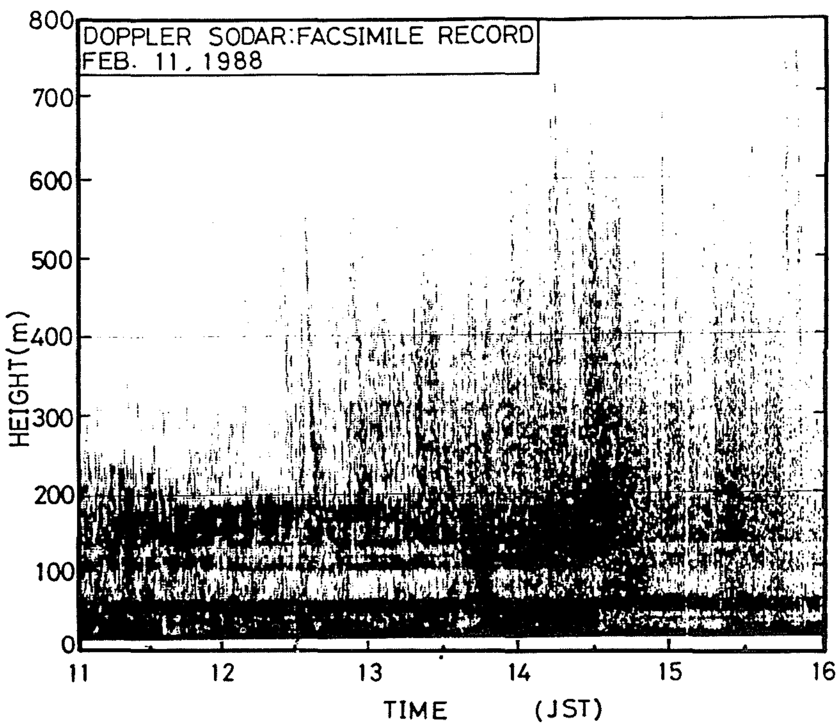

Figure 11. Facsimile record of reflective intensity from 11 to 17JST, February 11, 1988.

was observed around 1420 JST. Northwesterly winds prevailed after 1230 JST and strong horizontal wind (northwesterly) descended gradually to the ground.

Snowfall intensities were compared with the vertical wind signatures measured by the Doppler sodar. Snowfall intensity and vertical wind speeds are superposed in Figure 13. The snowfall intensity (shown by dotted column) was large (0.7 cm/10 minutes) around 1430

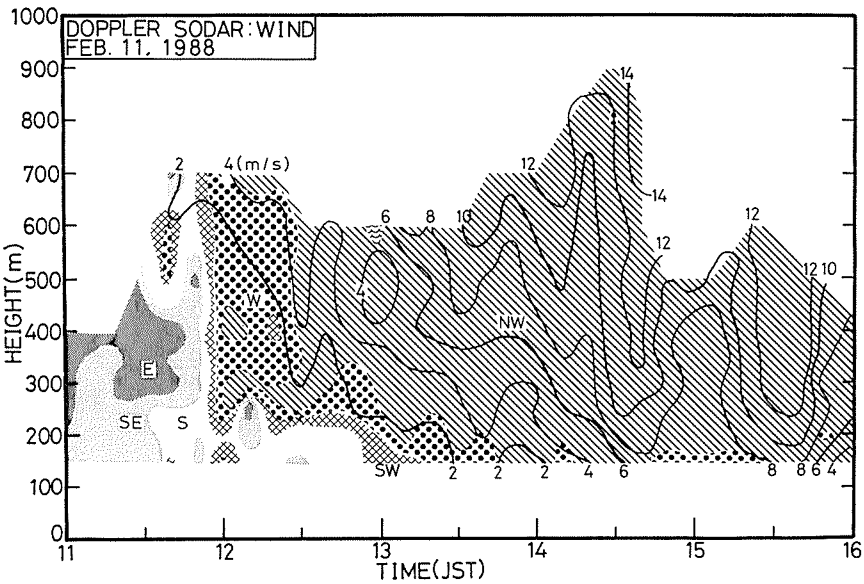

Figure 12. Time-height section of horizontal wind from 11 to 16 JST, February 11, 1988, Wind directions are divided into eight by shades with symbols. Horizontal wind speeds are shown by solid lines at 2 m/s intervals.

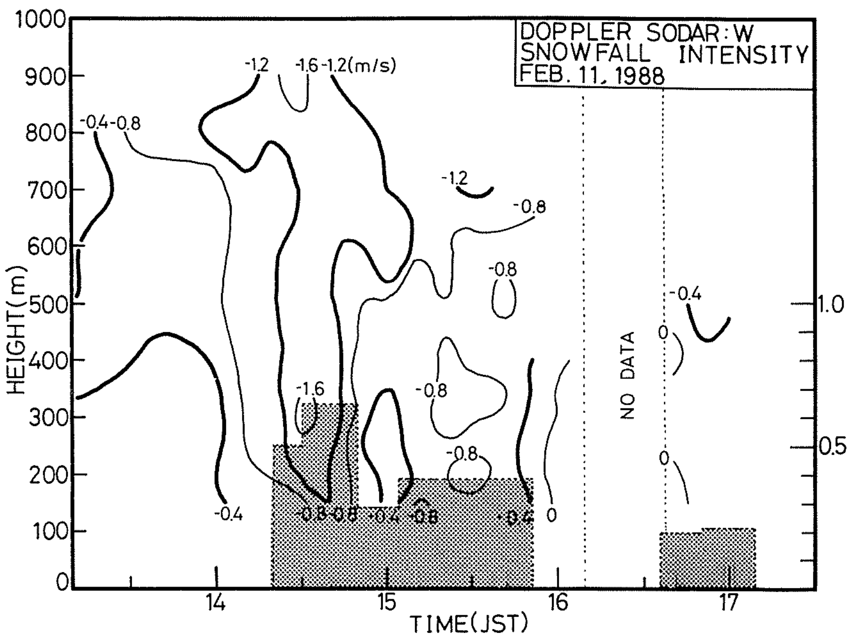

Figure 13. Time-height cross section of vertical wind speed and snowfall intensity (shown by shaded rectangles) from 13 to 17 JST, February 11, 1988.

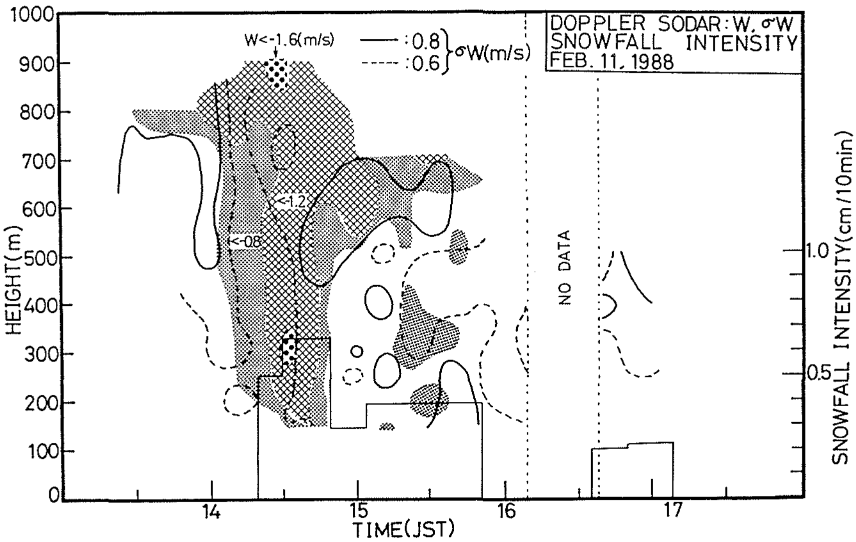

Figure 14. Time-height cross section of vertical wind speed, variance of speed and snowfall intensity from 13 to 18 JST, February 11, 1988. Vertical wind speed is shown by shades with numbers. Variance of vertical wind speed are shown by solid line (0.8 m/s) and dashed line (0.6 m/s). Snowfall intensity is shown by rectangles of solid line at the bottom of the figure.

JST. At that time, the descending wind speed was large reaching up to 1.6 m/s at the altitude of 350 m. On the average, descending wind speeds were large when snowfalls were observed. At the time of no-data region in Figure 13, snow in the cylindrical sound transmitter of the sodar was being shoveled out.

Figure 14 shows the variance of vertical wind speed (σW) superposed on Figure 13. The value of σW was relatively small in the area of strong downdraft. This indicates that turbulences are larger before and after the heavy snowfall.

4. Concluding Remarks

Two typical cases of Doppler sodar observations revealed the detailed structures of planetary boundary layers of winter Sapporo.

In the case of cold air flow, two penetrations of cold air currents from inland plains were observed at intervals of 2 hours. The areas of horizontal wind speed larger than 3 m/sec and updraft larger than 0.2 m/sec are shown in a composite of vertical temperature profiles at TV tower, (Figure 15). The first cold air flow was shallow and less than 90 m and the second one is thick with a depth of more than 120 m. The first air flow produced updraft up to the altitude of 800 m and, at the same time, it pushed up the boundary of temperature stratification up to 800 m as seen in the echo pattern of sodar. The second air flow produced a wave pattern which was assumed to be KHI (Kelvin Helmholtz Instability) wave as the Richardson number was estimated to be less than 0.25. The boundary layer is

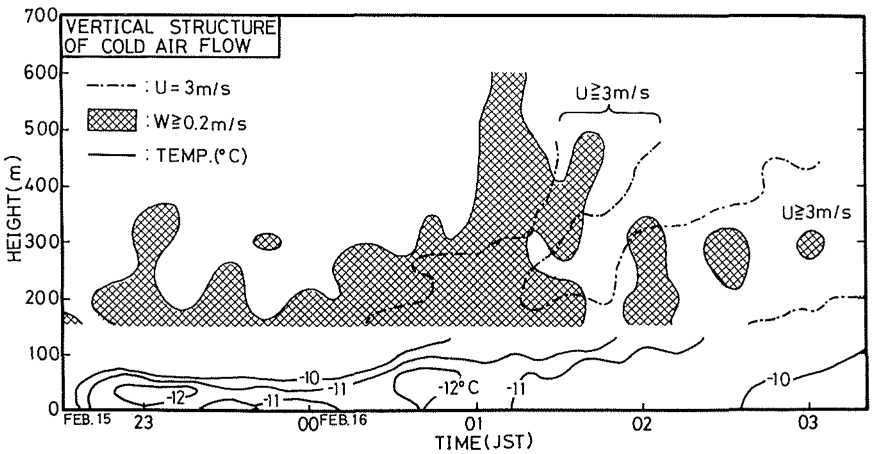

Figure 15. Schematic vemtical structure of cold airflow from 2230 JST February 15 to 0320 JST February 16, 1988. Lines bellow the altitude of 120 m show temperatures at TV tower about 2 km southeast from the sodar site. Dashed lines are horizontal wind speed of 3 m/s. Mesh regions show updraft areas (>0.2 m/s).

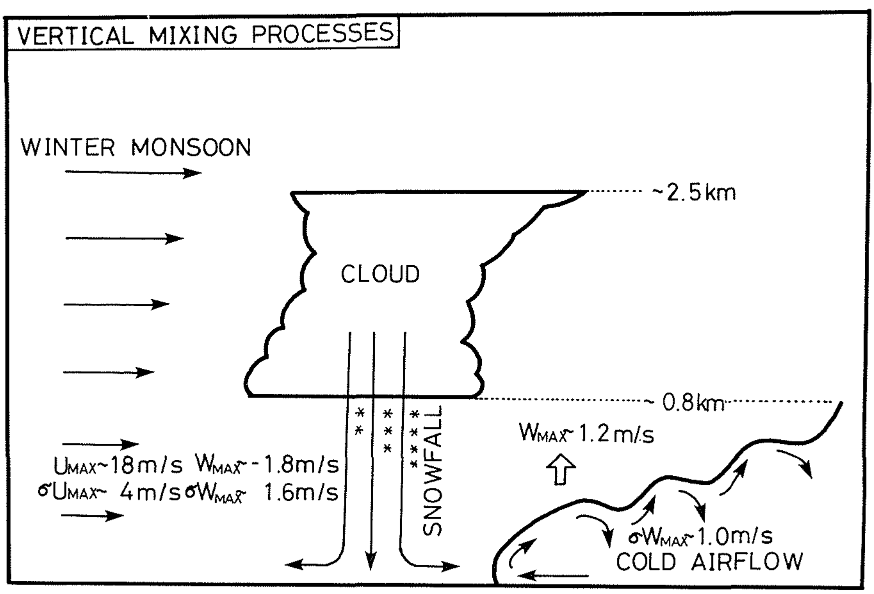

Figure 16. Schematic model of vertical mixing processes of planetary boundary layers in winter Sapporo summarized from the analyses of two cases.

considered to be mixed more rapidly than the known speed.

In the case of snowfall, the descending of the altitude of northwesterly wind was observed at the beginning of snowfalls. At the same time, wind structure during the snowfall was analyzed. The time and intensity of snowfalls measured at the ground close to the Doppler Sodar showed a good coincidence with the observation time of the strong descending currents. The maximum speed of the downdraft was 1.2 m/sec. However, it is considered that measured wind speed was composed with descending wind speed and speed of the snowfall. They could not be clearly differentiated since the falling speed of snowflakes are close to 1 m/sec. On the other hand, wind speed was observed up to very high altitudes during snowfalls. This may indicates that snowflakes reflected the sonic wave. Nevertheless, the wind measured is considered to be mainly from actual air motions as the major part of return signal is assumed to be from the air.

Through the observations with a Doppler sodar and their analyses, a variety of vertical mixing processes of winds in a cold season in Sapporo are shown quantitatively and a part of their mechanisms are clarified. Rapid mixings from surface to upward by cold air flow and from cloud base to surface by snowfall were confirmed. The planetary boundary layer structures of winter monsoon season are summarized schematically in Figure 16 from the analyses of two cases.

In order to to understand the atmospheric boundary layer in winter monsoon season in Sapporo, continuous data acquisition of Doppler sodar and comparison with the analyses of Doppler radar data are required.

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