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Wind Structure of the Atmospheric Boundary Layer in Low Pressure Systems in Sapporo —— Downdraft Signature ——

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Abstract

Wind structures of the atmospheric boundary layer in low pressure systems were studied using a Doppler sodar in Sapporo. During the observation period from September to October, 1988 and from March to June, 1989, nineteen cases of the approach of low pressure systems were observed. Wind fields of nineteen cases were classified into two regions, southerly region and northerly region, and wind signatures of the boundary layer of both regions were analyzed in detail. In the southerly period, remarkable characteristics as follows were observed in most of the cases, and these characteristics showed a continuation of several hours. Strong wind shear was observed at an altitude from 200 m to 400 m in the southerly period. And turbulence of horizontal wind speed was large at that altitude, which was considered to be produced by a strong wind shear. Downdraft was prominent in the southerly region. Stable layer and jet were recognized during the downdraft period at an altitude from 1,000 m to 2,500 m, which suggests that the downdraft was a downslope wind.

1. Introduction

Wind structures of the atmospheric boundary layer are concerned with human lives, through the process of diffusion and transportation of air pollutions and sometimes with air safeties when the layer has strong winds and shears. Internal structures of planetary boundary layers are very important for meteorological understanding. Wind structures of planetary boundary layers were studied from the view point of the convective mixing in fair weather and land/sea breezes. In the observation of these phenomena, Doppler sodars played important roles. However the studies on the wind structures of the boundary layers during the passage of extra tropical lows are very limited.

Shapiro (1984) and Brümmer (1988) studied the wind structures of planetary boundary layers during the passage of cold front with tower data. However

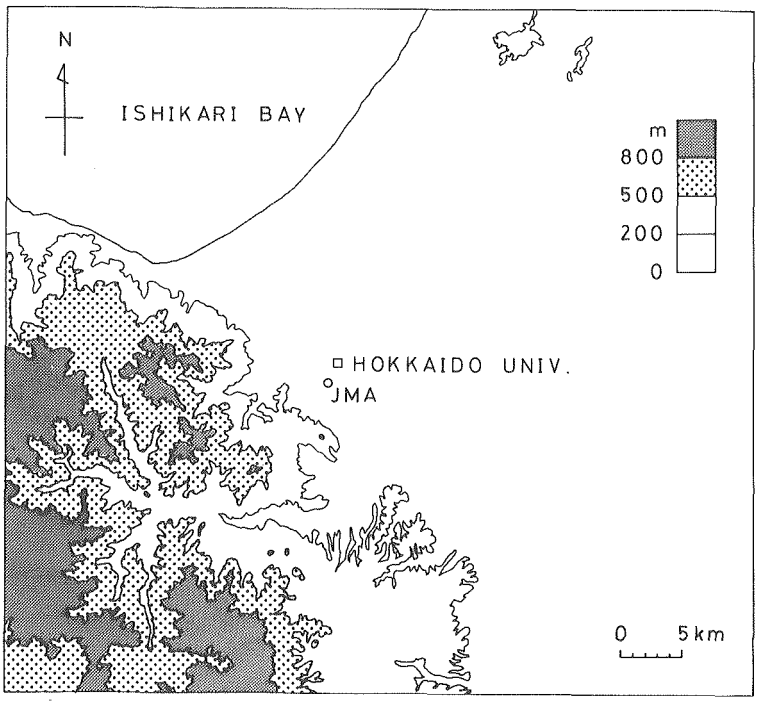

Fig. 1. Topographic map around an observation point. □: Doppler sodar observation point. ○: sonde site of Sapporo District Japan Meteorological Agency.

Table 1. Specification of the Doppler sodar.

Method of measurement	tri-monostatic
Carrier frequency	1,600 Hz
Output power	600 W
Antenna diameter	0.9 m
Pulse width	120 msec, 300 msec (mixed pulse)
Pulse repetition period	10 sec
Wind speed range	30 m/s
Wind speed accuracy	
Horizontal component	0.3 m/s or 5 % of wind speed
Vertical component	0.2 m/s or 2 % of wind speed
Wind speed resolution	0.1 m/s
Wind direction accuracy	5 deg
Wind direction resolution	1 deg

their observation period is rather short and their major interest was the structure of lower altitude of cold fronts. Gera and Weill (1987) studied the propagation speed, inclination and friction coefficient of fronts in the boundary layer with a Doppler sodar. However they did not mention about the wind fields.

In these situation, the authors considered that the studies of wind fields of planetary boundary layer during the approach and passage of extratropical lows with a Doppler sodar would give some clue for the understanding of the atmospheric boundary layer. Statistical analysis with numerous data is necessary for the understanding of general structure of atmospheric boundary layers. The most profitable equipment for this study is Doppler sodars.

The Doppler sodar observation at Sapporo in winter by Ohmoto et al. (1990) showed that the Doppler sodar is available for the observation of planetary boundary layer below 500 m.

The authors carried out observation for several months of the boundary layer with a Doppler sodar in order to reveal the wind structures of atmospheric boundary layer during the approach and passage of extratropical lows at Sapporo.

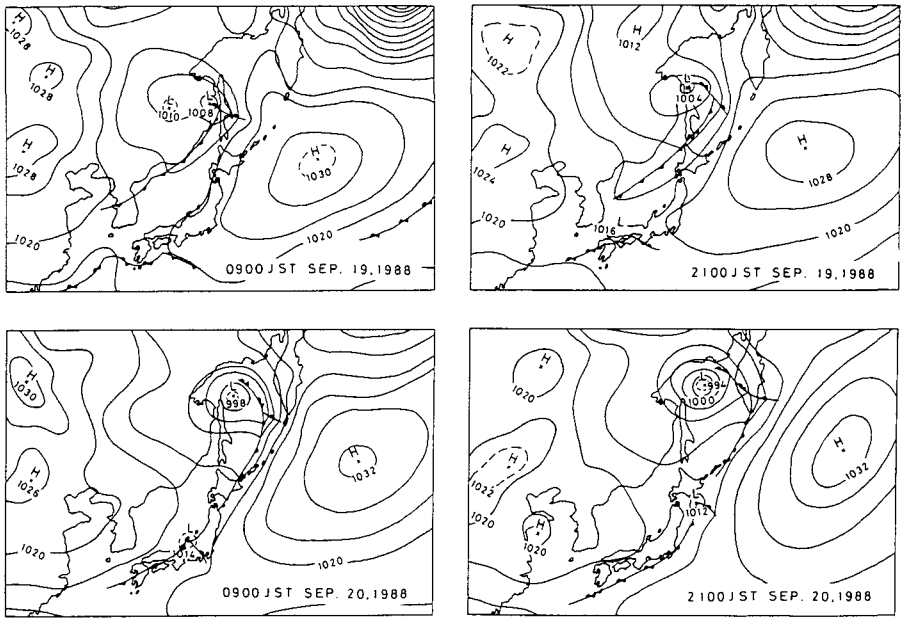

Fig. 2. Surface weather charts from 0900 JST 19 September to 2100 JST September 1988.

2. Method of Observation

Observation of wind structure of the atmospheric boundary layer in Sapporo was carried out with a Doppler sodar in September and October, 1988 and from March through to June, 1989. The Doppler sodar was set on the roof (22 m from the ground) of a building in the campus of Hokkaido University at the point of the square in Fig. 1.

The specification of the sodar is shown in Table 1. Ten minutes averaged horizontal wind speed (U), wind direction (D), vertical wind speed (W) and their standard deviations (σU, σD and σW) were recorded every ten minutes. The data were identified to be effective when more than 20% of total 20 pulses in 10 minutes satisfied the threshold of the signal to noise ratio. Further details of the calculation methods of the wind is presented by Ito et al. (1986).

Sounding data by Sapporo district of Japan Meteorological Agency (the location is shown by a circle in Fig. 1) were utilized to run a the comparison with the sodar data. In this area, orographic effect is assumed to be observed in the

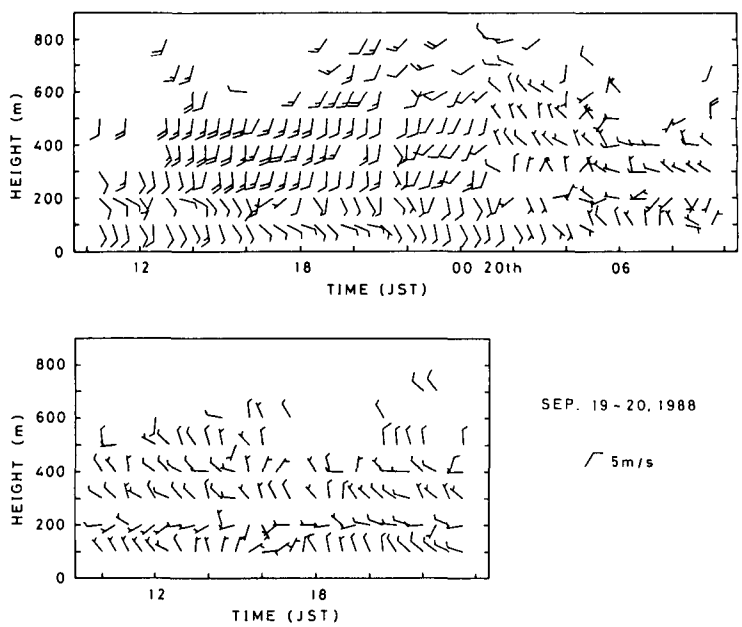

Fig. 3. Time height cross section of horizontal winds measured by a Doppler sodar at the campus of Hokkaido University in Sapporo. Winds at every hundred meters and at 30 minutes intervals are plotted from 1000 JST 19 September to 2330 JST 20 September 1988. Full barb is 5 m/s.

atmospheric boundary layer.

The topographic specification around the observation point is that plane extends from north to east and close mountains from south to west. Mountains about 1,000 m lies to the west of the observation point.

Nineteen cases of the approach of low pressure were observed continuously and analyzed for the wind characters of the planetary layer.

3. A Case study

As an example of wind variation during the approach of low pressure to the observation point, a case of 19-20 September 1988 is presented. A cold front crossed around 01 JST, 20 September as shown in Fig. 2. Horizontal wind measured by a Doppler sodar shifted from south to north-west around 0130 JST at the altitude over 200 m as shown in Fig. 3. Southerly wind prevailed before the passage of the cold front. During the southerly winds, a down draft was prominent at each altitude as shown in Fig. 4. After the passage of the front, weak westerly prevailed and vertical winds were weak at each altitude.

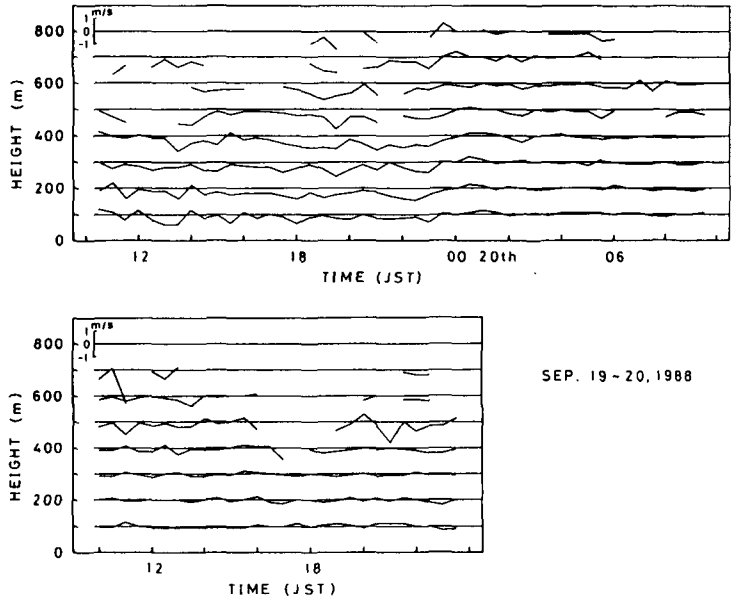

Fig. 4. Time height cross section of vertical winds for the same period as shown in Fig. 3. Folded line over the line of altitude at each hundred meter shows updraft by the scale shown at the top left of the squares.

Significant difference of wind structure was obvious in the two periods before (southerly) and after (northwesterly) the passage of the front. Therefore, long term averaged values of U, σU, σD, W, σW and wind rose at each altitude were plotted for the two periods (Fig. 5–Fig. 10).

In the southerly period, wind speed U increased abruptly from 200 m to 400 m as shown in Fig. 5 and standard deviation of the horizontal wind U was very large over 2 m/s as shown in Fig. 6. Prevailing wind direction before the front passage was SSW below 200 m and S over 200 m as shown in Fig. 7. The maximum of σD was at the altitude of 200 m as shown in Fig. 8. Vertical winds before the passage of the front are downdraft at all altitudes which increased with the altitude as shown in Fig. 9. The value of σW was large, larger than 0.6 m/s, at all altitudes and close to 1.0 m/s at the altitude of 100 m (in Fig. 10).

On the other hand, in the northwesterly period, both of the values U and σU were small and no wind shear from 200 m to 400 m nor peaks of σU were observed (Fig. 5 and Fig.6). Prevailing wind direction was NNW at the altitude of 100 m and W at the altitude of 200 m. Over the altitude of 200 m, the wind

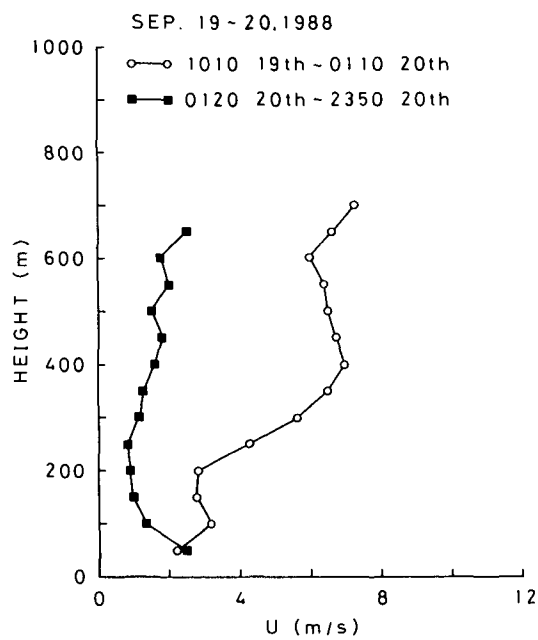

Fig. 5. Profile of averaged horizontal wind speed from 1010 JST, 19 Sep. to 2350 JST, 20 Sep., 1988. ○ : before the passage of the front (1010 19th-0110 20th). ■ : after the passage of the front (0120-2350 20th).

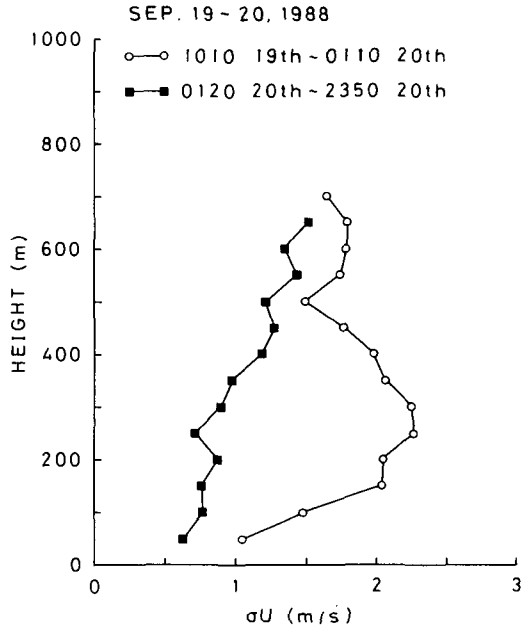

Fig. 6. Profile of averaged standard deviation of horizontal wind speeds σU. Symbols are the same as Fig. 5.

direction shifted from NW to N with the increase of the altitude (Fig. 7). The standard deviation of D, σD showed its maximum at an altitude of 200 m and large at all of the altitudes (Fig. 8). Vertical wind showed very small down drafts at all altitudes (Fig. 9) and σW was small at all altitudes (Fig. 10).

Sounding data of 09, 15 and 21 JST, 19 September at Sapporo are plotted in Fig. 11. These are during the period of southerly to southwesterly. Inversion is obvious from 900 to 850 mb at 09 JST and low altitude jet (950 mb at 09 JST and 850 mb at 15 JST) was prominent. However inversion and low altitude jet disappeared after 21 JST. After the passage of the front, wind speed was small at low altitudes below 800 mb.

4. Wind signature around low pressure system

Down drafts were prominent for most of the observed cases during the approach of low pressure systems as shown in the case of 19-20 September 1988. Averaged signature of winds observed for 19 cases of low pressure approach were analyzed in order to clarify the different structures of wind in the southerly

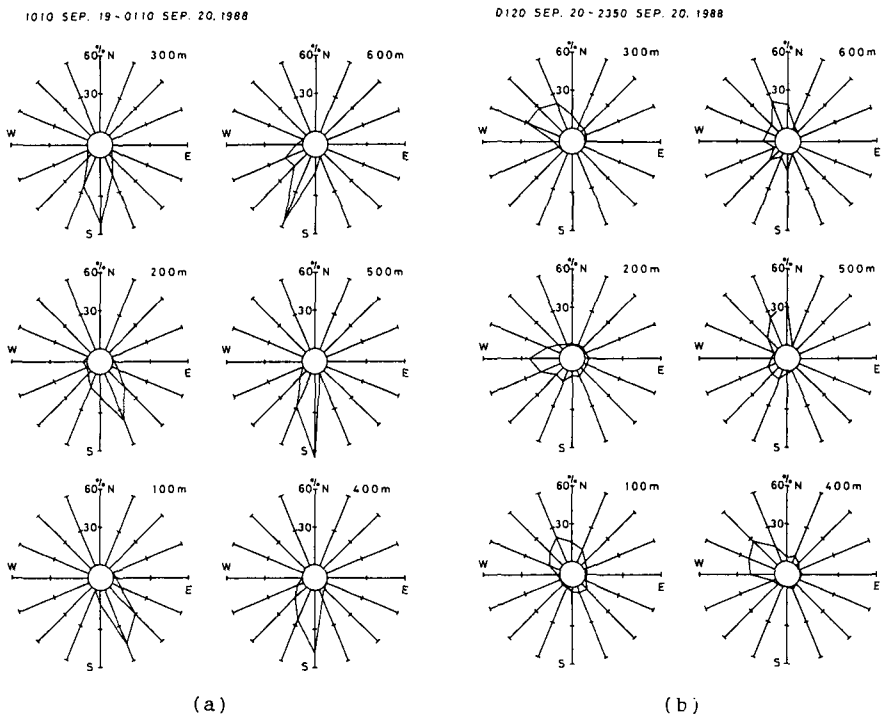

Fig. 7. Wind rose at 100, 200, - - -, 600 m (a) before the passage of the front and (b) after the passage of the front.

and northerly period. The criterion adopted as the division of southerly and northerly period is a sudden wind shift at the altitude from 200 to 400 m.

Table 2 shows the general signature of the observed low pressure system. The duration time of the downdrafts (< -0.3 m/s) are also shown. Histograms of horizontal wind speed at each hundred meters for all of the 19 cases is shown in Fig. 12. In the southerly region, frequency of wind speed decreases constantly to 8 m/s at 100 m and 200 m. Over the altitude of 300 m, frequency of each wind speed is close to constant and some percent is beyond the speed of 10 m/s. In the northerly region, the frequency of the wind-speed smaller than 3 m/s consitsts of more than 60% at each altitude. The frequency of the wind speed larger than 10 m/s is very small.

The vertical wind profiles of horizontal wind speeds in two periods is shown in Fig. 13. The large increase of wind speed from 200 m to 450 m is prominent during the southerly wind.

The vertical profile of standard deviation of horizontal wind, σU, is shown

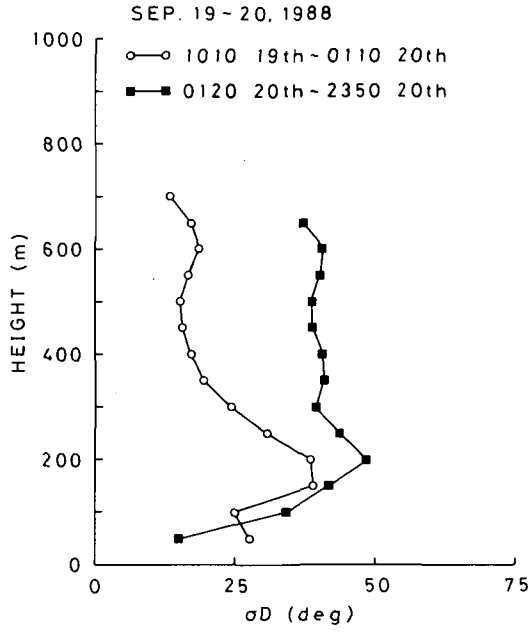

Fig. 8. Profile of averaged standard deviation of wind direction, σD Symbols are the same as Fig. 5.

in Fig. 14. The value of σU is also large during the southerly winds, particularly at the altitude from 250 to 450 m.

The Wind rose is shown in Fig. 15 for two periods. In the southerly wind, the wind direction turned from SSE to SSW with the increase of the altitudes. In the northerly period, the wind direction prevailed WNW and NW below 400 m and N over 500 m. The standard deviation of wind direction, σD showed a peak at 200 m for both periods as shown in Fig. 16.

Histograms of vertical wind speed is shown in Fig. 17. The percentage of downdrafts was 70% at each elevation in the southerly period and was from 40 to 50% at each elevation in the northerly period. A few ten presents of downdrafts larger than 0.5 m/s was observed in the southerly period. On the other hand strong downdrafts lager than 0.5 m/s was rare in the northerly periods. The vertical wind profile of averaged vertical wind speed is shown in Fig. 18. Downdrafts are prominent during the southerly period. The vertical profile of σW is shown in Fig. 19. Standard deviation of W is larger at all altitudes measured in the southerly period than in the northerly period.

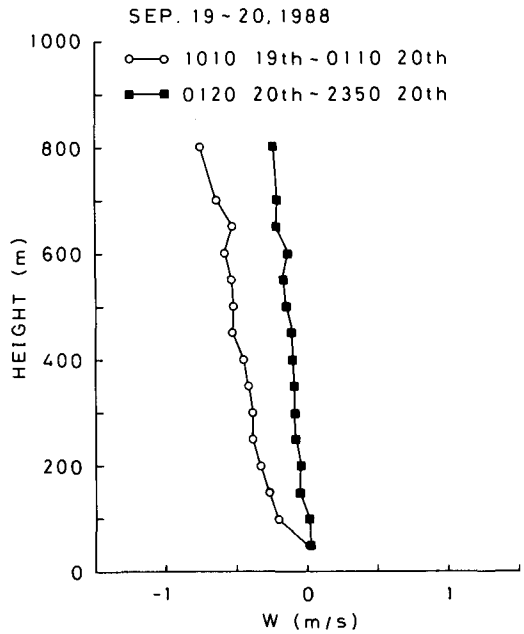

Fig. 9. Profile of averaged vertical wind speed W. Symbols are the same as Fig. 5.

5. Downdrafts during the southerly winds

Downdrafts are significant when the low pressure system approaches as shown in the previous chapters. Detailed signature of the downdraft during the southerly period is analyzed in this chapter.

Continuous downdrafts (< -0.3 m/s, which is the averaged downdraft of all altitudes of effective values) lasting more than two hours was observed in 16 cases among the 19 cases as shown in Table 2. Fig. 20 is the hourly histogram of downdraft occurrence in 16 cases. Significant diurnal variation was not obvious. However, relatively large frequencies from 14 to 16 JST indicate thermally induced vortices which drag down upper winds and relatively large frequency during the night time indicates a possibility of down slope winds. Fig. 21 shows the histogram of duration time of downdrafts. The maximum duration time was 470 minutes and the duration time less than 160 minutes was frequent. The Wind rose during the downdraft analyzed with the Doppler sodar was almost the same as that of southerly wind shown in Fig. 15(a). The vertical profile of averaged horizontal wind is shown in Fig. 22. The averaged horizontal wind speed of downdraft period is one or two meters per second

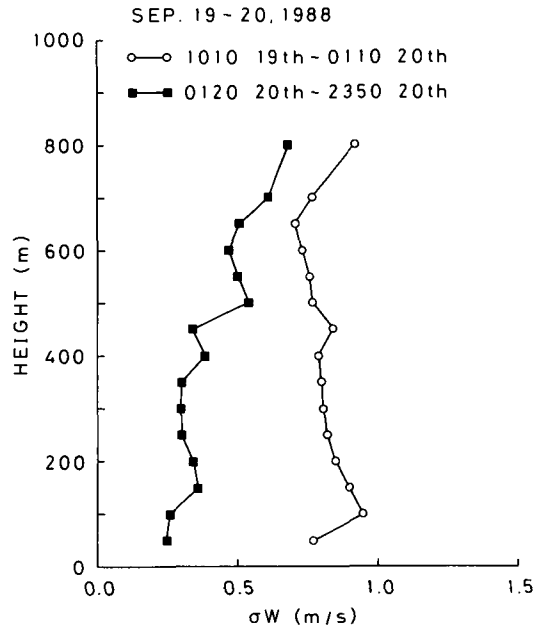

Fig. 10. Profile of averaged standard deviation of vertical wind speeds, σW. Symbols are the same as Fig. 5.

larger than that of southerly period although the pattern of the vertical profiles are almost the same. This indicates that this downdraft accompanies strong winds.

In order to investigate the vertical structure of the air, sounding data were analyzed. Fig. 23 shows vertical profiles of horizontal wind speed for 28 launchings during the downdraft periods. Here, the soundings in or within one hour of the observation of downdraft by the Doppler sodar were used for the plotting. Most of the soundings have wind jets from 900 mb to 750 mb. Fig. 24 is wind rose at standard levels during the downdrafts. Southeast wind prevails at the surface. Two peaks are significant at 900 mb (SSE and SSW), 850 mb (SSE and SW) and 800 mb (SSE and SW). At 700 mb and 600 mb, winds of SW and WSW prevail.

Temperature profiles of the same soundings of Fig. 23 are shown in Fig. 25. In many soundings, inversion of stable layers are recognized from 900 mb to 750 mb.

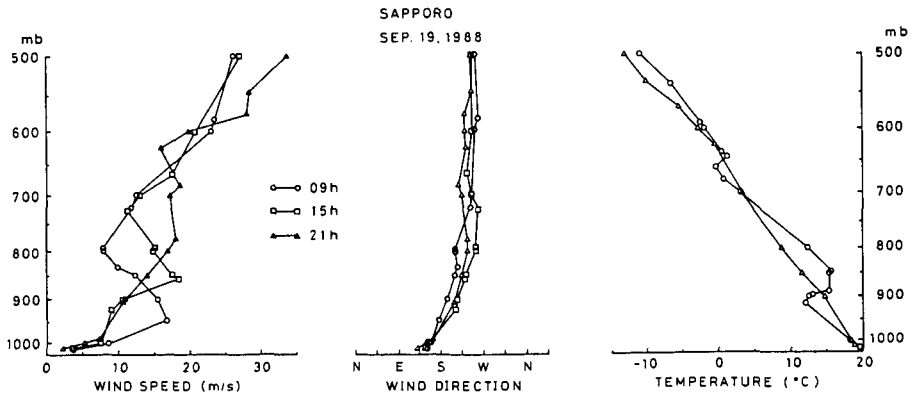

Fig. 11. Vertical profile of wind speed, wind direction and temperature at Sapporo on, 19 September 1988. (○) 09, (□) 15, and (△) 21 JST

Table 2. Observation period of low pressure approach. Signature of low pressures and length of duration of downdraft is shown.

Date	Signature of low	Down Draft duration (min)	Obsearvation hour (min)
Sep. 11-Sep. 13, 1988	Nihon-Kai low with occluded front	300	2390
Sep. 19-Sep. 20, 1988	Enkaisyu low with cold fron	440	2270
Oct. 5-Oct. 8, 1988	Nihon-Kai low	290	3880
Oct. 11-Oct. 12, 1988	Enkaisyu low with cold front	430	1480
Mar. 30-Apr. 1, 1989	Enkaisyu low	230	2620
Apr. 7-Apr. 9, 1989	Enkaisyu low	360	2590
Apr. 14-Apr. 15, 1989	Enkaisyu low	—	1400
Apr. 22-Apr. 23, 1989	Enkaisyu low with cold front	220	720
Apr. 26-Apr. 28, 1989	Nihon-Kai low	—	2690
May. 4-May. 5, 1989	Enkaisyu low with cold front	—	1120
May. 7-May. 8, 1989	Enkaisyu low with cold front	150	3480
May. 8-May. 10, 1989	Enkaisyu low with cold front	400	
May. 12-May. 15, 1989	Nihon-Kai low with occluded front	630	3520
May. 16-May. 17, 1989	Enkaisyu low	1200	2650
May. 19-May. 22, 1989	Enkaisyu low	1120	3280
Jun. 6-Jun. 7, 1989	Nihon-Kai low with occluded front	360	1240
Jun. 14-Jun. 18, 1989	Nihon-Kai low	1440	5670
Jun. 24-Jun. 26, 1989	Nihon-Kai low	1470	2830
Jun. 28-Jun. 29, 1989	Nihon-Kai low	180	1680

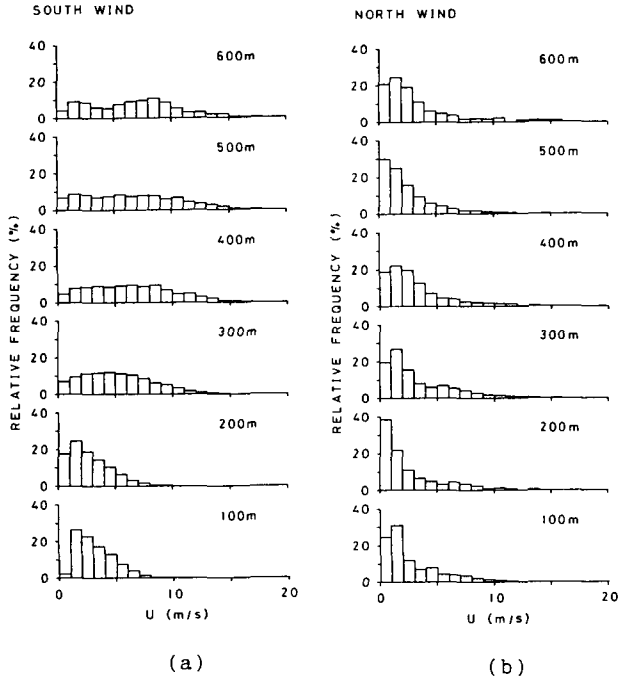

Fig. 12. Histogram of horizontal wind speed at each altitude of hundred meters. (a) southerly period (b) northerly period.

6. Consideration

In the observation of wind structure with a Doppler sodar in Sapporo, significant wind fields were classified into two periods. In the southerly period, strong horizontal wind and continuous downdraft were observed. In the northerly period, a wind speed was relatively weak.

In the northerly period, wind direction shifted unticlockwise from 100 m to 200 m although the direction shifted clockwise over 200 m as usual. The prevailing wind direction of NW and NNW at 100 m is parallel to the row of mountains to the west of Sapporo. In the southerly period, the wind direction shifted clockwise and the prevailing wind direction at 100 m was SE and SSE. The wind direction in the southerly wind is also parallel to the mountains range to the west of Sapporo. The wind directions at 100 m indicates that winds at the altitude around 100 m is affected by the topography. The maximum variation of wind direction at 200 m in both periods of southerly and northerly wind also indicates the orographic effect to the wind structure of the boundary layer.

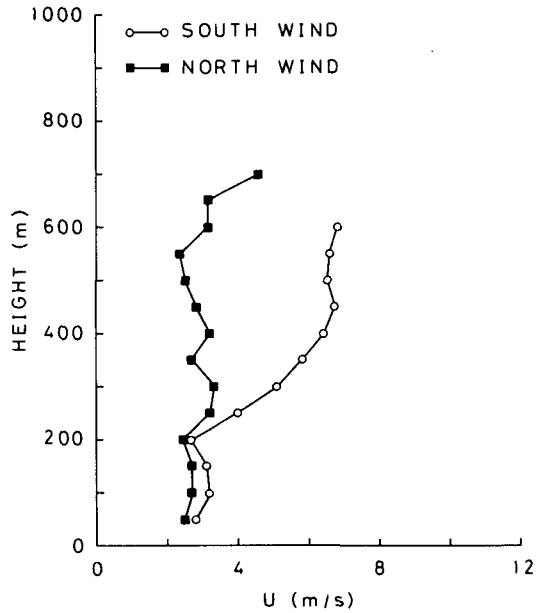

Fig. 13. Vertical profile of the averaged horizontal wind of 19 cases. Open circle indicates southerly winds and solid square indicates northerly winds.

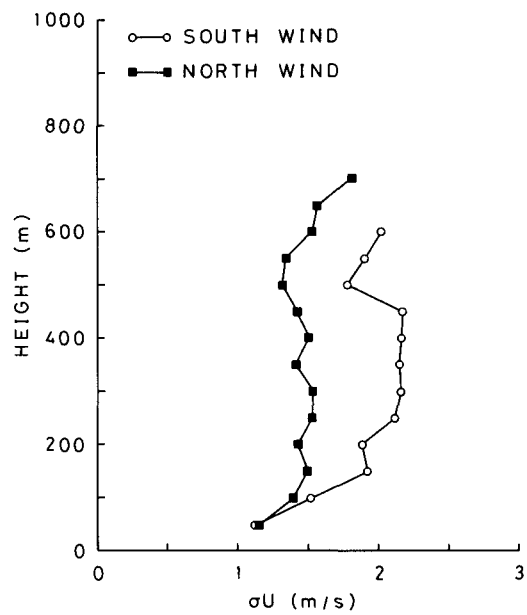

Fig. 14. Vertical profile of the averaged σU. Symbols are the same as Fig. 13.

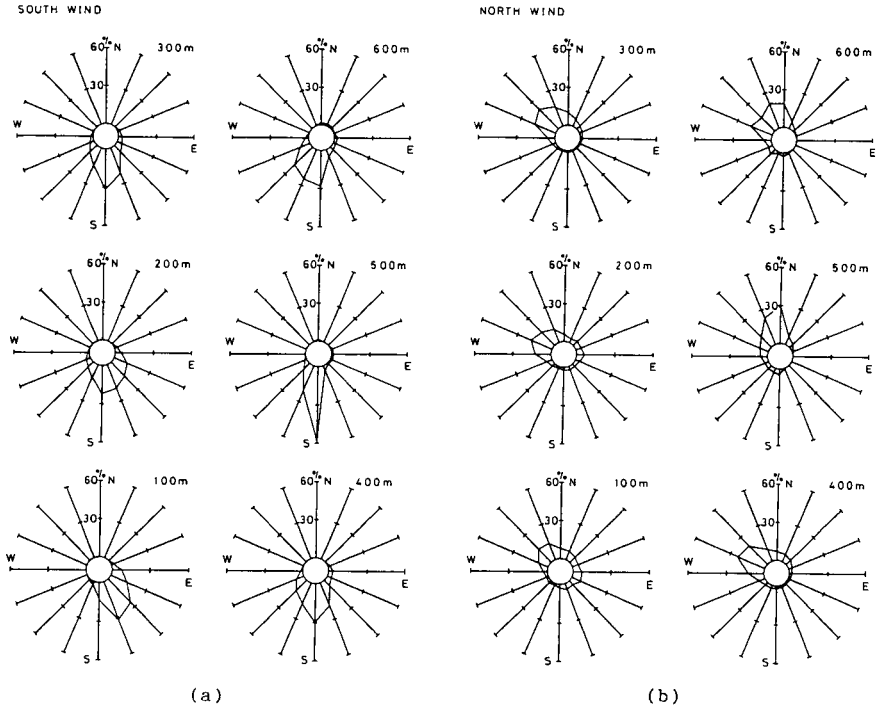

Fig. 15. Wind rose in 19 cases at each hundred meters. (a) southerly period and (b) northerly period.

At an altitude from 200 to 400 m, a strong wind shear was observed in the southerly periods. Also the value of σU was large from 250 to 450 m. The variation of horizontal wind speed at an altitude from 250 to 450 m is considered to be produced by the strong wind shear. However the reason for the strong shear was not clarified in the present observation, one of the probable mechanism involves frictional deceleration of wind speed over urban Sapporo.

In the period of southerly winds, Downdrafts were prominent throughout the observation heights of the Doppler sodar. The characteristics are summarized as follows ; a) the downdrafts have a continuity lasting for more than one hour, sometimes up to several hours, b) during the period of downdraft, a strong horizontal wind was observed, c) Maximum wind speed, inversion or stable layer was observed at an altitude from 900 mb to 750 mb (from 1,000 m to 2,500 m) and the prevailing wind direction there were SW and SSE. The winds of SW and SSE are the wind crossing over the mountains. Therefore, the strong winds and downdrafts in the southerly period are assumed to be downslope

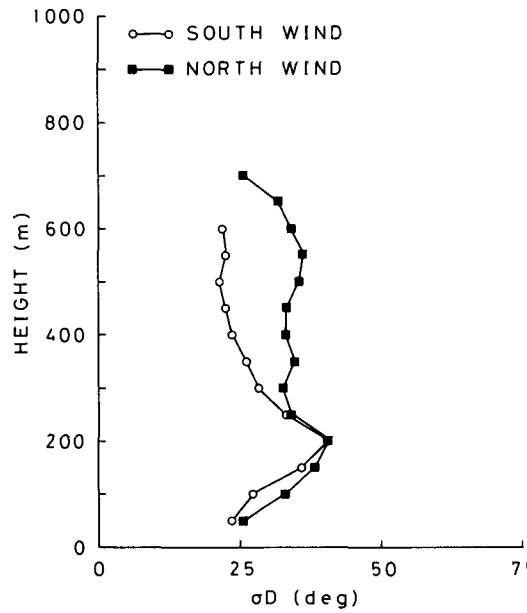

Fig. 16. Vertical profile of averaged σD of 19 cases. Symbols are the same as Fig. 13.

winds.

Studies on lee waves by many researchers are summarized by Smith (1979) and Atkinson (1981). Vergeiner and Lilly (1970) observed lee wave of Colorado Rocky and classified them into two types; mountain lee waves and hydraulic jumps. In a hydraulic jump, strong winds are observed on down wind slopes. It is known that an inversion layer is necessary at the altitude of a mountain or a somewhat higher than a mountain (Long, 1953; Arakawa, 1969; Brinkmann, 1974; Klemp and Lilly, 1975). Compared with these knowledges, the strong wind and downdraft observed by a Doppler sodar at Sapporo is considered to be downslope winds of the mountain ranges to the west and south of Sapporo.

7. Conclusions

Observation of wind structure of boundary layer in Sapporo was carried out in September and October, 1988 and from March to June in 1989 using a Doppler sodar during the approach of low pressure system. The signatures of wind structures in southerly period and northerly period are summarized as follows.

1) Strong wind shear was observed at the altitude from 200 m to 450 m in

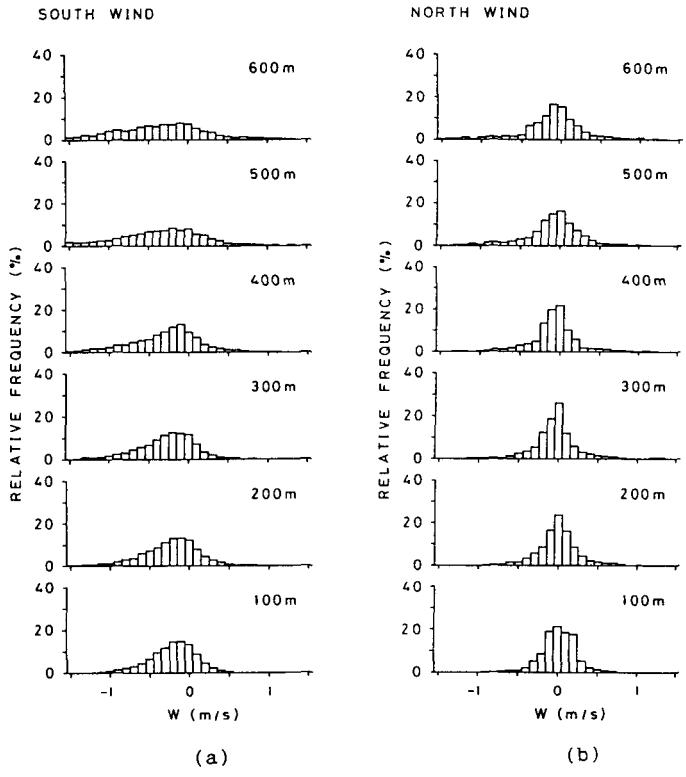

Fig. 17. Histogram of averaged horizontal wind speeds at each altitude of hundred meters. (a) southerly period (b) northerly period.

southerly period. On the other hand, in the northerly period, significant characteristics were not observed in the shear profile. Averaged horizontal wind speed of southerly period was larger than that of the northerly winds.

2) The value of σU was large at the altitude from 250 m to 450 m. This is considered to be produced from the large shear of U at this altitude.

3) Prevailing wind direction below 100 m were affected by orographic effect of mountains to the west and south of Sapporo.

4) Maximum value of σD was observed at the altitude of 200 m in both of the southerly and northerly periods.

5) Significant downdrafts were observed in the southerly period. Stable layer and jet were recognized in sounding data during the downdrafts from 1,000 m to 2,500 m. Therefor the downdrafts are considered to be downslope winds.

6) The values of σW were large at the altitude from 100 m to 200 m in both

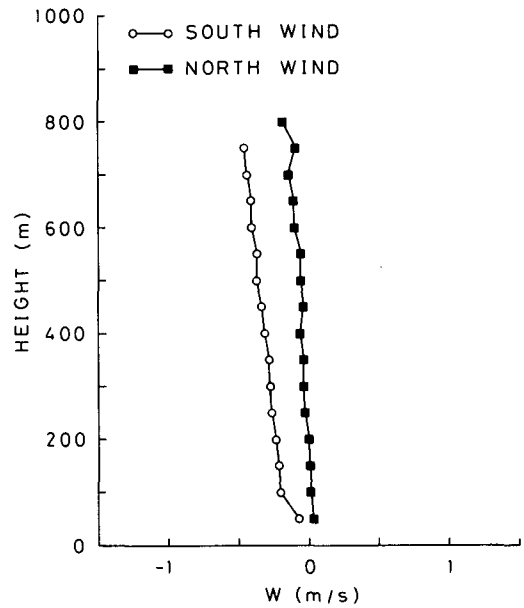

Fig. 18. Vertical profile of the averaged vertical wind speed of 19 cases. Symbols are the same as Fig. 13.

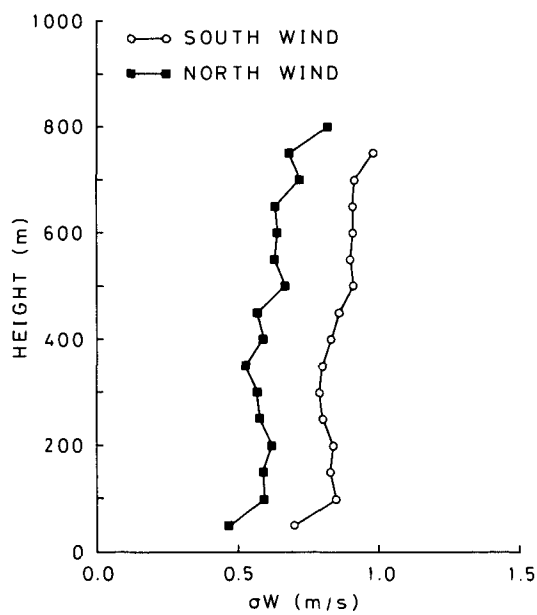

Fig. 19. Vertical profile of the averaged σW of 19 cases. Symbols are the same as Fig. 13.

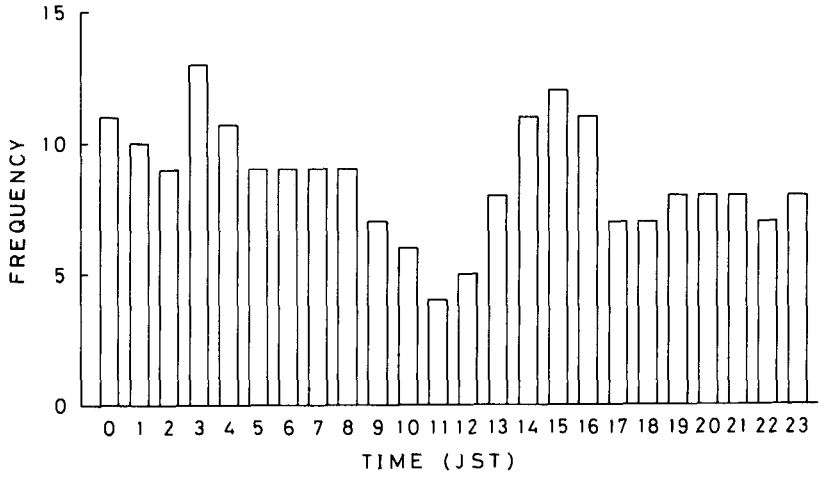

Fig. 20. Hourly frequency of downdraft occurrence.

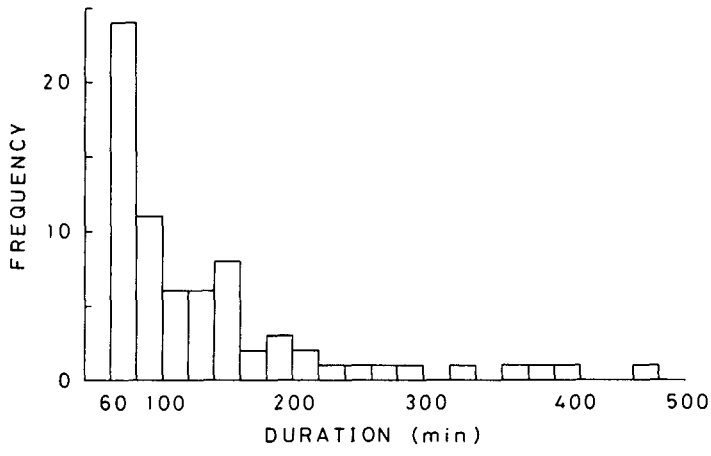

Fig. 21. Frequency in number of the duration time of downdrafts.

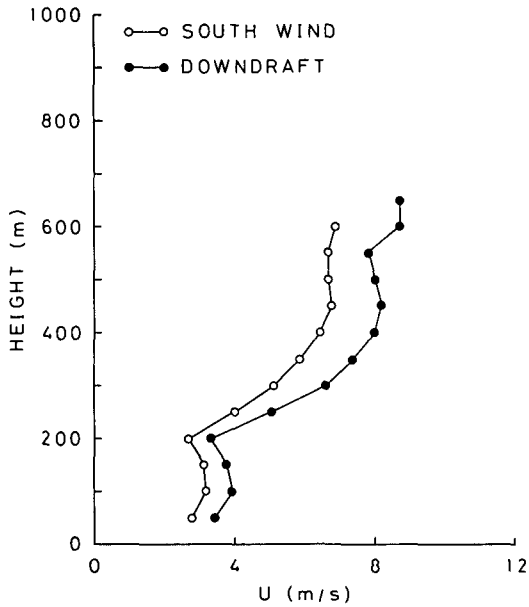

Fig. 22. Vertical profile of the averaged U during downdrafts (●). The profile of southerly wind is shown by open circles.

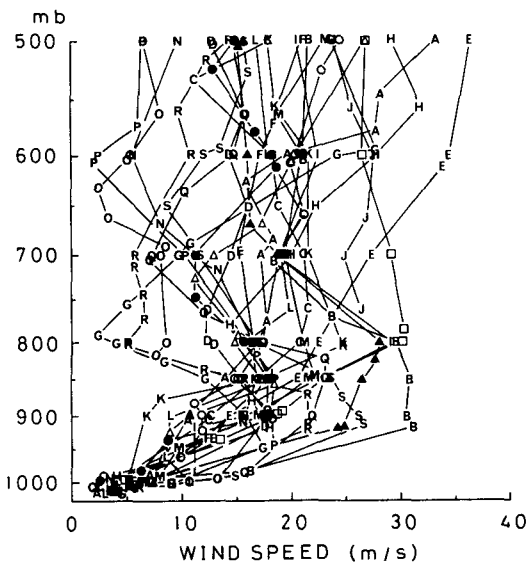

Fig. 23. Vertical profile of horizontal wind speeds of sounding at Sapporo during the downdrafts observed by the Doppler sodar.

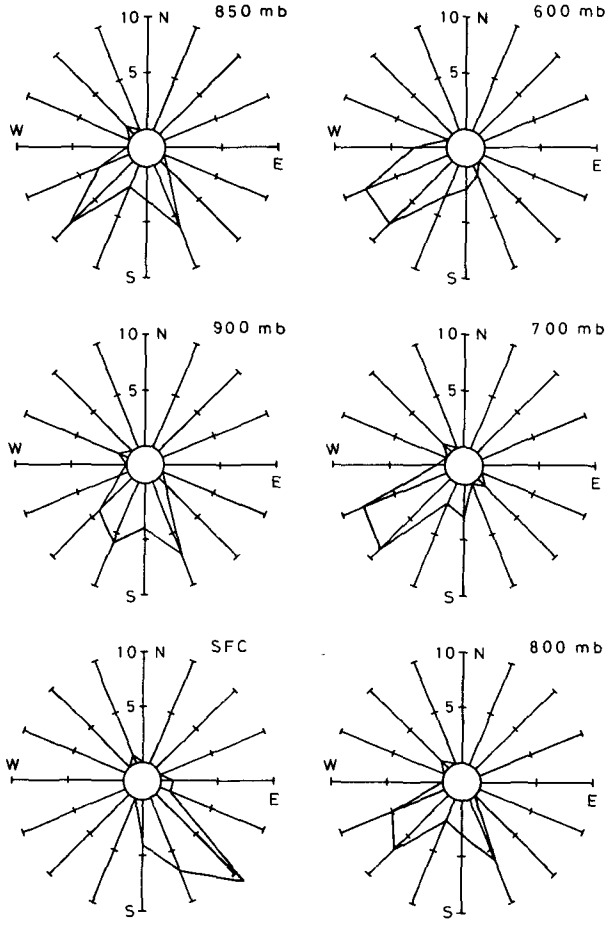

Fig. 24. Wind rose of sounding data at the standard levels at the same time with that of Fig. 23.

periods. The value in the southerly period was larger than that of northerly period.

In the present study, significant downdrafts were observed in the southerly period during the approach of low pressure system at Sapporo. The downdraft and strong horizontal wind are considered to be associated with downslope wind. In the northerly period, though a clear signature a such as seen in the southerly period was not observed, wind fields in particular horizontal winds are affected by the surrounding topography.

In the present study, one Doppler sodar was utilized, in order to clarify the

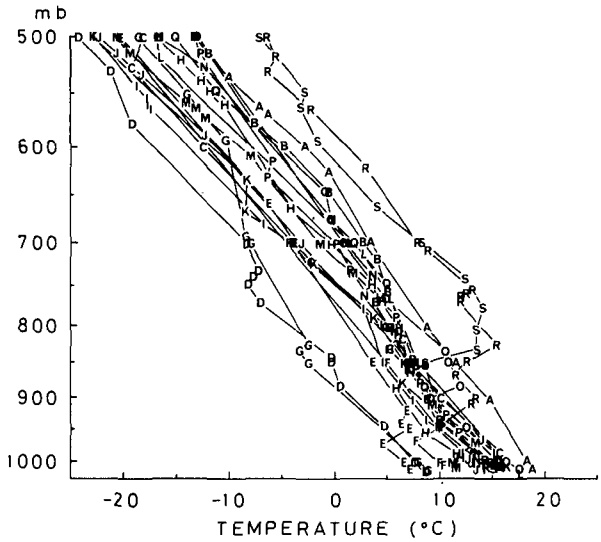

Fig. 25. Vertical profile of temperature of sounding at the same time with Fig. 23.

wind structure, three dimensional structure should be observed and higher altitude must be observed at the same time.

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