OBSERVATIONS OF AN ATMOSPHERIC BOUNDARY LAYER AT MIZUHO STATION USING AN ACOUSTIC SOUNDER

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***Abstract*:** Acoustic sounding was used in observing a katabatic wind layer at the lowest few hundred meters over Mizuho Station (70°42′S, 44°20′E, 2230 m above sea level), East Antarctica. Some examples of acoustic echo return showed the structure of surface inversions in connection with a katabatic wind and the behavior of breaking waves, *e.g.* a "herringbone" type structure described by EMMANUEL *et al.* (J. Atmos. Sci., **29**, 886, 1972) as an unstable wave. Observations disclosed that wave-like motion exists in a layer between the heights of 100 and 300 m and it has a shorter period than the calculated value from the Brunt-Väisälä frequency. This discrepancy was explained by a simple two-dimensional wave equation, considering the presence of mean atmospheric flow.

1. Introduction

A study was made of an atmospheric boundary layer at Mizuho Station (70°42′S, 44°20′E) under the program of the Japanease Polar Experiment in Antarctica (POLEX-South). This station is located at about 250 km from the coast of East Antarctica on the slope of the ice sheet at an elevation of 2230 m above sea level. Its climate is characterized by two main features: the prevalence of such a katabatic wind in the atmospheric boundary layer that blows continuously at a speed of 11 m/s on the annual average; and low air temperature below −32°C on the annual average (OHATA *et al.*, 1981). Radiosonde observations show that the katabatic wind is accompanied by a relatively thin layer of cold air; *i.e.*, it is associated with a surface inversion (KOBAYASHI and YOKOYAMA, 1976).

Acoustic sounding and observations by low-level radiosondes have been provided to study this thin katabatic layer at the station. Acoustic sounding is a remote sensing technique which may be employed not only for studying the structure of the lower atmosphere, but also for measuring wind velocity using the acoustic Doppler shift

(BERAN *et al.*, 1973; HOLMGREN *et al.*, 1975). In Antarctica, the lowest few hundred meters of the atmosphere over Amundsen-Scott Station at the geographical South Pole have been subjected to an acoustic sounding study by NEFF (1981).

Results on the surface inversion above Mizuho Plateau recently have been reported by KAWAGUCHI *et al.* (1982) using the low-level radiosonde. According to them, the thickness of the surface inversion layer was not larger than 500 m and its intensity became stronger steadily from 3°C in February to about 20°C in May.

This paper describes especially the facsimile records obtained by an acoustic sounder for *in-situ* measurements as well as the characteristics of gravity waves generated by instability in wind shear in the katabatic wind layer.

2. Instruments

2.1. Acoustic sounder

An acoustic sounding system (AR-100) manufactured by Kaijo Denki, Ltd., was used to study the dynamics of the formation and dissipation of the katabatic winds on the Antarctic ice sheet. Its basic function is to measure the intensity of a reflected echo and to make a height-time chart of it using a facsimile recorder. The system is

Table 1. Parameters of the acoustic sounder.

(a)	Sound wave packet	
	Carrier frequency	1600 Hz
	Power	300 W
	Packet width	50 ms
	Beam direction	vertical
(b)	Data processor	
	Antenna diameter	1.2 m
	Receiver bandwidth	1600±50 Hz
	Range on facsimile recorder	0–600 m

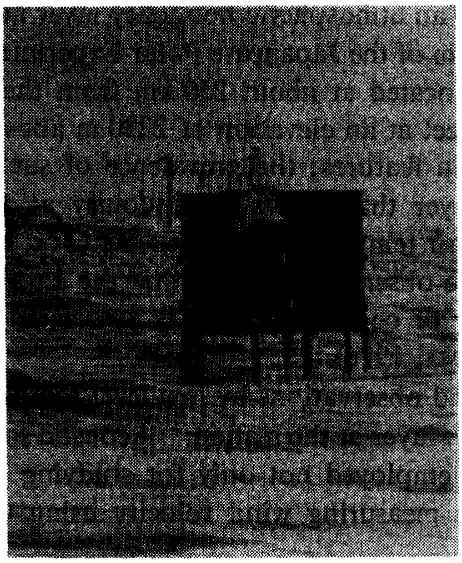

Fig. 1. An acoustic sounder installed on a platform above snow surface.

the monostatic type, with receiving and transmitting antennas collocated. The details of the block diagram of the system have been described by HAYASHI *et al.* (1978), and its specifications are summarized in Table 1. A sound beam is set in a vertical position as shown in Fig. 1. In order to prevent a snow drift from accumulating around the instrument, the driver/receiver horn assembly is enclosed by an integral shield lined with lead and polyurethane foam on a platform constructed by angle iron.

2.2. *Low-level radiosonde*

A low-level radiosonde used for the present study consisted of an aneroid (JWA-75TWS Type: Meisei Electric Co., Ltd.) and a semiconductor (JNL-78TP Type: Nissho Iwai Co.), a barometer, and a thermister. The trajectory of a rubber balloon inflated with helium gas, hanging a sonde, is obtained automatically using a receiving system (Meisei rawinsonde system, RD-65A Type). The number of releases of radiosondes at Mizuho Station was about 80 times throughout the year (KAWAGUCHI *et al.*, 1982). Sounding data obtained, especially temperature profiles in the katabatic layer, were compared each time with the facsimile record of the acoustic sounder.

2.3. *Observations of static stability of surface layer*

An aluminum walk-up tower 30 m in height was erected at Mizuho Station to measure the vertical profiles of air temperature and mean wind speed in the surface boundary layer (MAE *et al.*, 1981). In order to obtain the profiles, seven anemometers of the three-cup type and seven platinum resistance thermometers with a stainless steel shelter were mounted on the arms of the tower each at the heights of 29.5, 15.5, 7.5, 3.5, 1.5, 1 and 0.5 m. Using these data, we calculated the Richardson number, *Ri*, which is a measure of the static stability

$$Ri=\frac{g}{\bar{\theta}}\frac{(\Delta\theta/\Delta Z)}{(\Delta U/\Delta Z)^2}, \tag{1}$$

where g is the acceleration of gravity, $\bar{\theta}$ is the mean absolute potential temperature of the profile, $\Delta\theta/\Delta Z$ is the vertical gradient of potential temperature, and $\Delta U/\Delta Z$ is the vertical gradient of horizontal wind speed.

3. Results

3.1. *General characteristics of acoustic echo return*

Figure 2 shows the facsimile record from the vertically oriented antenna and the Richardson number calculated from eq. (1) at the heights between 29.5 and 0.5 m from 1500 LT, January 20, to 1100 LT, January 21, 1980. Multilayered echoes are seen at the lower layer of the atmospheric boundary layer in the period of evening and nighttime, when a surface inversion layer is developing, corresponding to an increase in the Richardson number in positive values. Then the echoes extend in the vertical direction, as observed in the period of nighttime and morning. Regarding atmospheric stratification, HAYASHI and IKEDA (1979) proposed a classification of the facsimile records of acoustic soundings basically into vertical (weed) type, horizontal (layered) type and non echo (white) type, the first one being observed in the case of thermal convection, *i.e.*, unstable stratification. MAHONEY *et al.* (1973) observed an acoustic sounding record of thermal plumes and vertical wind velocity using a Doppler shift techniqe. According to their measurments the peak upward velocity is approximately 2 m/s. The layered echoes come from the stable stratified atmosphere, *e.g.* an inversion layer. A weak echo return comes from a layer with a temperature gradient between the dry adiabatic lapse rate and the equitemperature gradient (0°C/m), in which case the facsimile record becomes "white" (HAYASHI and IKEDA, 1979).

However, the echo patterns in Mizuho Station were slightly different from the above description. Echoes mixed of layered and weed types were seen during radiative cooling between 1700 LT, January 20 and about 0800 LT, January 21, as shown in Fig. 2. The layered echoes appeared at heights lower than 60 m and the weed echoes were seen until a height of 150 m. In this case a mixing would be seen at a boundary between cold air and warm air above it, and a decaying process of the surface inversion layer occurred in the morning. Accordingly, the stable layer remained in the upper part and the unstable layer existed in the lower part of the atmosphere, because the surface was heated by solar radiation. Then, the Richardson number changed from the positive to the negative values at 0600 LT, January 21, as shown in Fig. 2. Therefore, the time lag between the variation of echo return and the Richardson number was about two hours. A similar acoustic sounding record from 1400 LT, January 24, to 1100 LT, January 25, 1980, is given in Fig. 3. The above are examples in late summer. The layered echoes were seen at heights lower than 75 m and the weed echoes reached a height of 200 m between 0200 LT and 0500 LT, January 25. The end of the echoes mixed of the layered and the weed types agreed

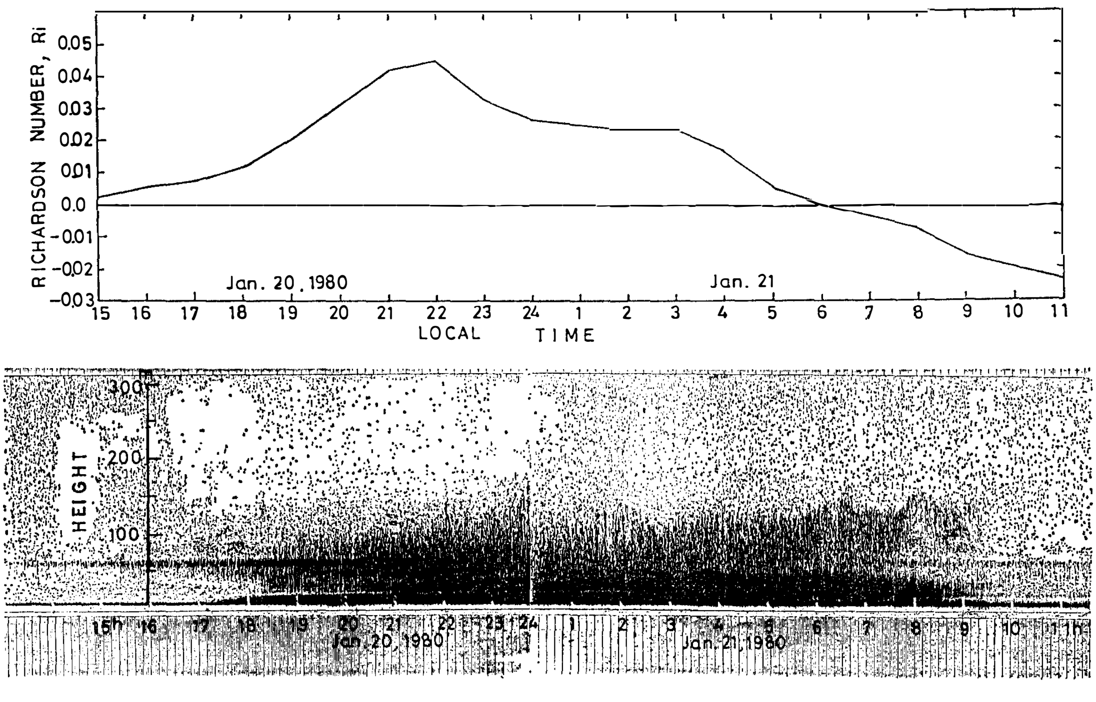

Fig. 2. Developing and decaying process of surface inversion as indicated by the acoustic sounder's facsimile record (lower). Richardson number (upper) was calculated at the heights between 29.5 and 0.5 m. Period: 1500 LT, January 20, to 1100 LT, January 21, 1980.

with the time of transition. These cases of acoustic echo returns existed in summer, *i.e.*, these acoustic returns may be associated with formation and dissipation of surface inversion resulting from radiative cooling and heating of the surface.

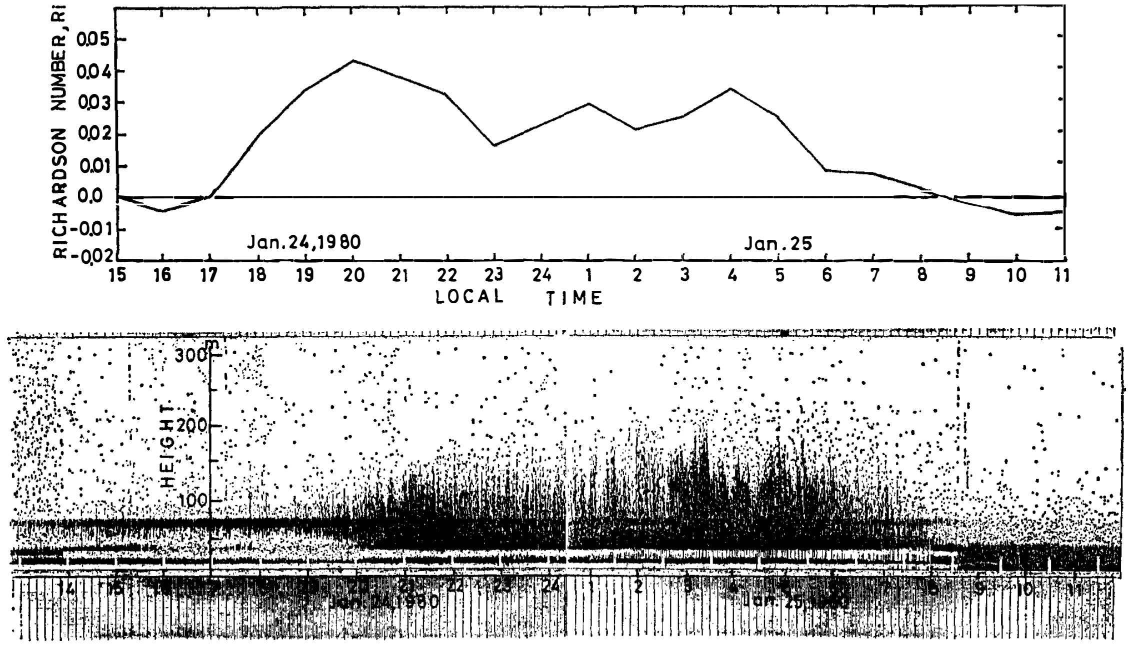

Fig. 3. Same as Fig. 2. Period: January 24 to 25, 1980.

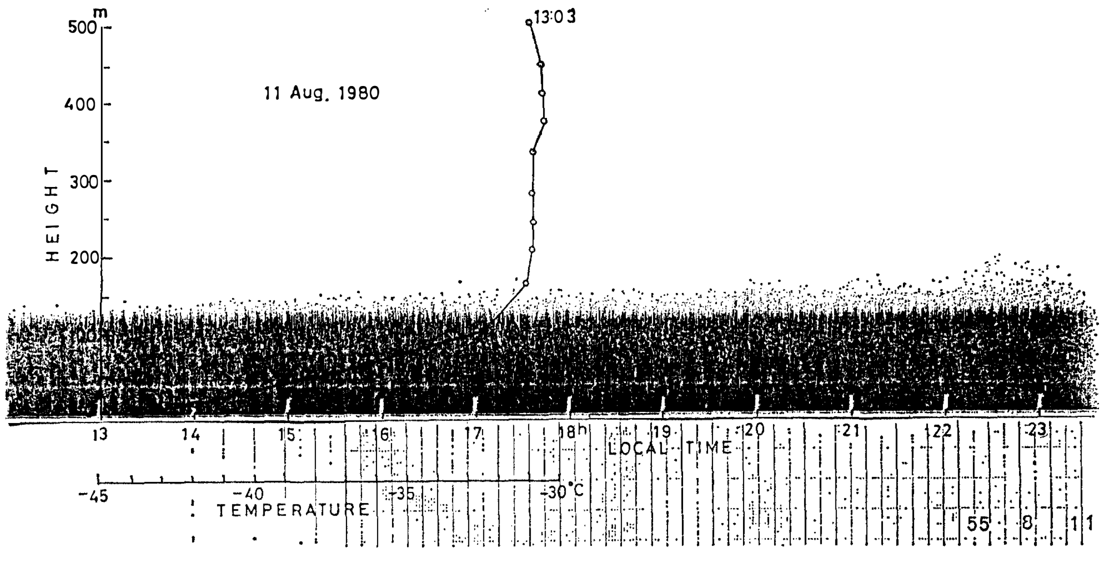

Fig. 4. Acoustic sounder's facsimile record during strong surface inversion. Period: 1300 LT to 2300 LT, August 11, 1980. Temperature profile was obtained by a low-level radiosonde at 1303 LT.

Then, in winter, as shown in Fig. 4, no scattering echo is observed with a strong low-level inversion. Meanwhile, in spring, as shown in Fig. 5, layered echoes in an elevated position are seen in a large number coming from the more stable but weak region aloft. In winter, a day variation as in summer is not clear. According to NEFF

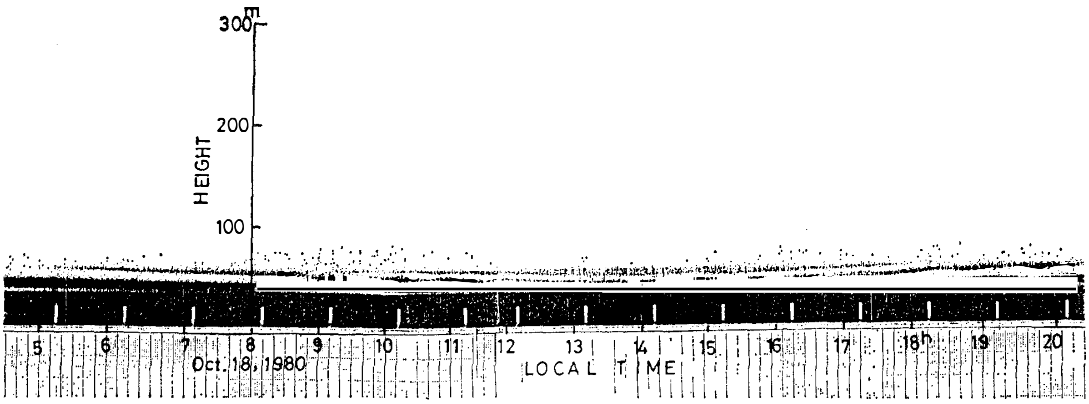

Fig. 5. Acoustic sounder's facsimile record during stable stratification. Period: 0500 LT to 2000 LT, October 18, 1980.

(1981), the echo in this lowest layer is classified as "stable-continuous", whereas the echoes within the remainder of the inversion layer are classified as "stable-sporadic" mainly with wave-associated turbulence.

3.2. Acoustic echo return in relation to temperature gradient

Studied next are the relationships between the depth of the echo return and the vertical temperature gradient obtained by low-level radiosondes. The facsimile records of acoustic soundings in Figs. 6 and 7 illustrate that in the case of unstable stratification plume-like structures as classified by HAYASHI and IKEDA (1979) are not observed. However, in Fig. 6 acoustic soundings were recorded on February 4, 1980, when the weather was cloudy in the sky and calm at the surface (3 m/s). The acoustic record of Fig. 7 was obtained under the condition in which surface winds were at the

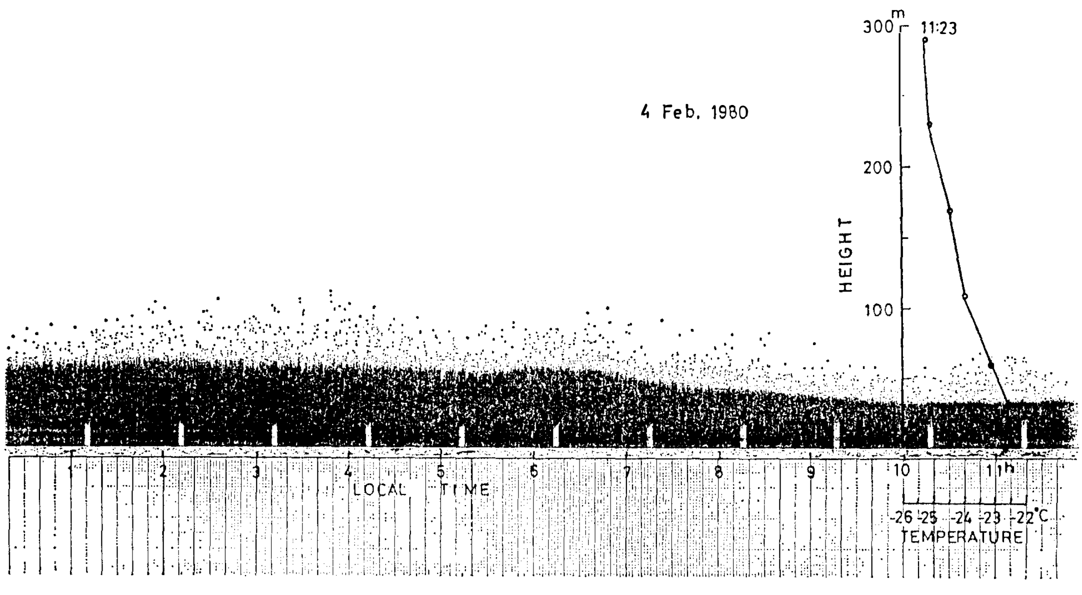

Fig. 6. Acoustic sounder's record during unstable stratification under the weather condition of a cloudy sky and a calm wind. Period: 0100 LT to 1100 LT, February 4, 1980. Temperature profile was obtained by a low-level radiosonde at 1123 LT.

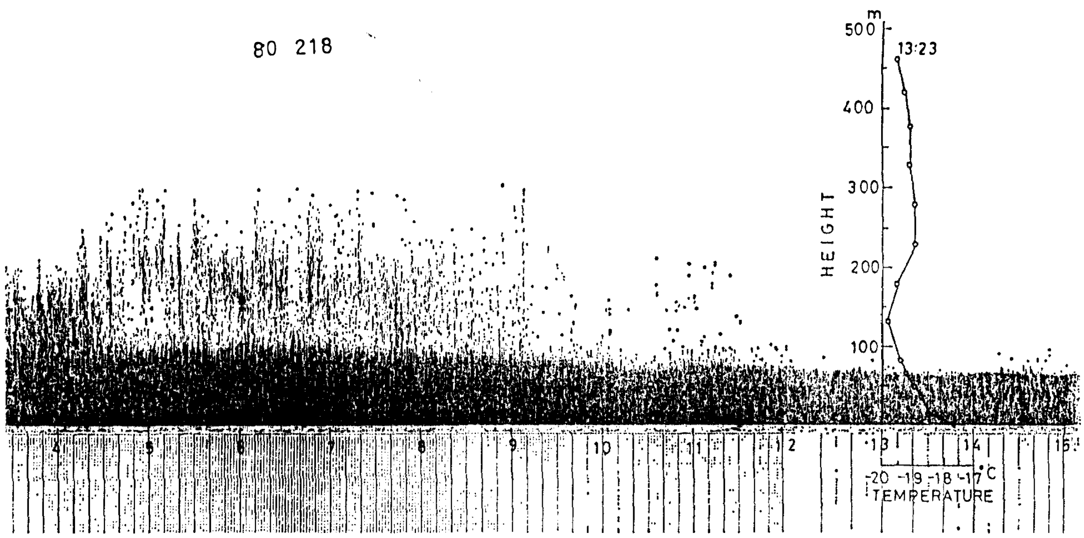

Fig. 7. Acoustic sounder's facsimile record in a period from a strong katabatic wind to a rising inversion. Period: 0400 LT to 1500 LT, February 18, 1980. Temperature profile was obtained by a low-level radiosonde at 1323 LT.

speed of 7 m high, changing from strong winds (10 m/s) early in the morning to moderate winds (10–7 m/s) in the daytime. The temperature profile in Fig. 7 shows a weak rising inversion between 130 and 270 m. Consequently, a surface inversion in connection with the development of a katabatic wind may have existed in the morning, resulting in a vertical orientation of the echo patterns in the upper part. This indicates a rising temperature inversion, following a transition from stable conditions immediately after sunrise to the beginning of convective conditions (BEAN *et al.*, 1973). The same pattern is seen in Fig. 8.

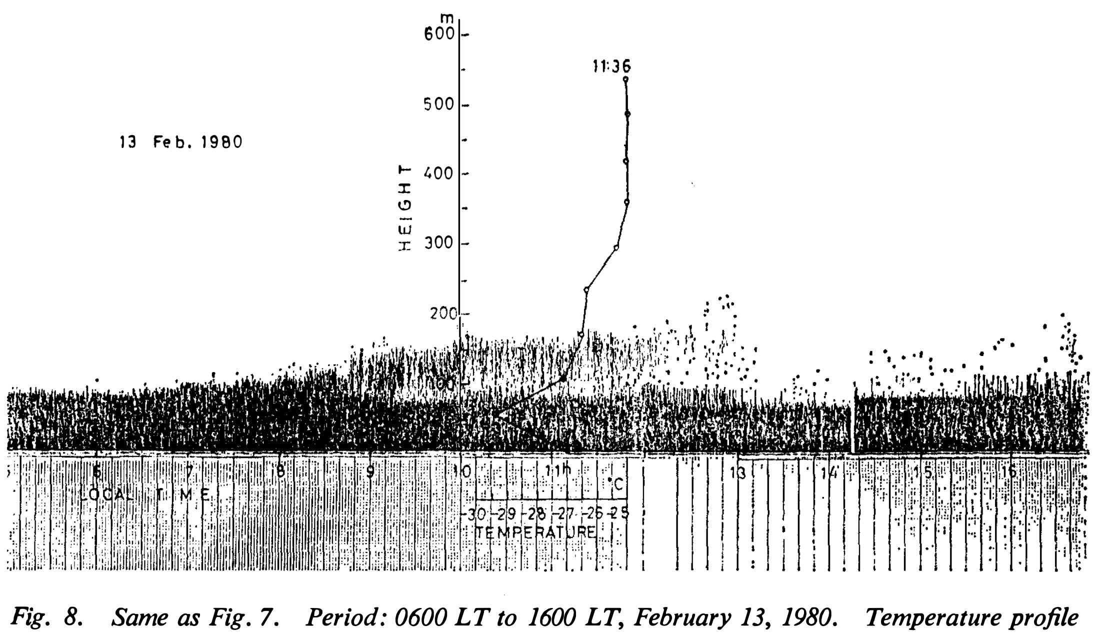

Fig. 8. Same as Fig. 7. Period: 0600 LT to 1600 LT, February 13, 1980. Temperature profile was obtained by a low-level radiosonde at 1136 LT.

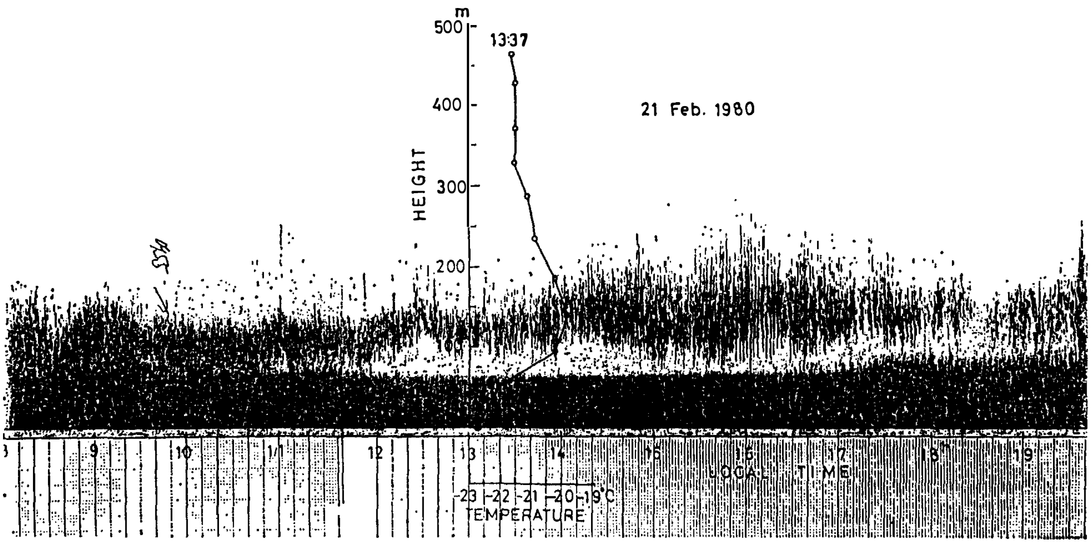

Fig. 9. Acoustic sounder's record during surface inversion. Period: 0900 LT to 1900 LT, February 21, 1980. Temperature profile was obtained by a low-level radiosonde at 1337 LT.

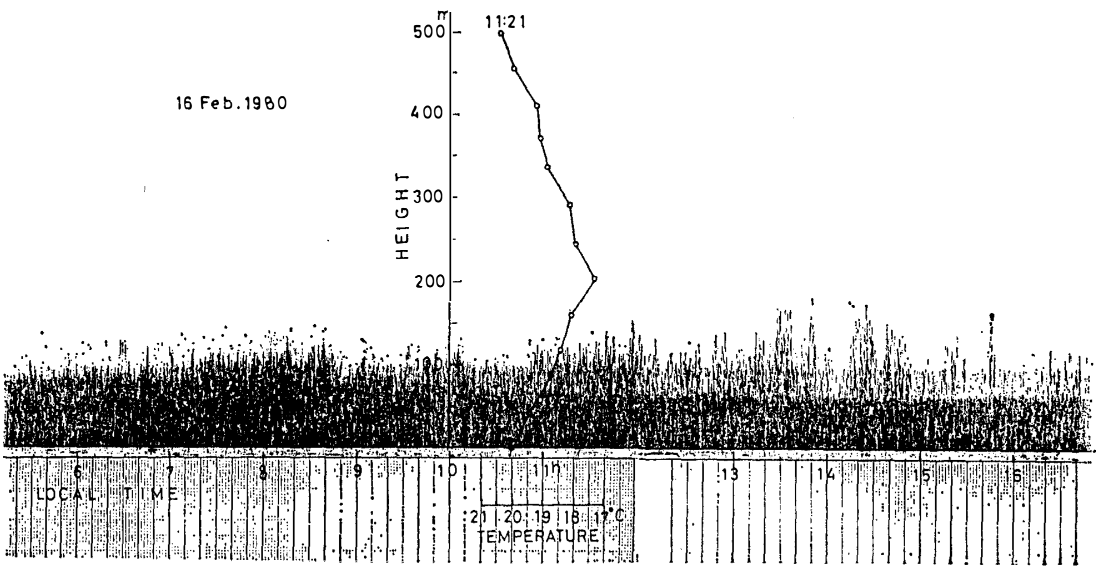

Fig. 10. Same as Fig. 9. Period: 0600 LT to 1600 LT, February 16, 1980. Temperature profile was obtained by a low-level radiosonde at 1121 LT.

In the case of stable stratification the vertical patterns in the upper part exist continuously, as shown in Figs. 4, 9 and 10. These echo patterns are associated with the breaking waves. The breaking wave structure, shown in Fig. 9, appears between 1600 LT and 1700 LT, February 21, 1980. These almost vertical acoustic returns were described by EMMANUEL *et al.* (1972) as an unstable wave and they defined it as a "herringbone" type structure. In contrast, the stable wave motion, as shown in Fig. 5, has a long period in the horizontal direction and it is relatively unimportant in the transfer of heat and momentum in the vertical direction. However, an unstable or breaking wave has a strong vertical component, and as a result, this type of wave is important in the question of mixing of an air mass between the cold surface layer and the warm layer above it. Consequently, the wave behavior in a stable layer will be discussed in the following section.

3.3. Wave-like motion in a katabatic wind layer

Wave-like motion with a period of 2.3 min in the weed echo type appeared from 1600 LT to 1700 LT, February 21, 1980, as shown in Fig. 11. The wave-like motion also appeared at the heights between 100 and 300 m. Since this vertical acoustic echo return may be that of an unstable wave, it has a short lifetime with about one hour.

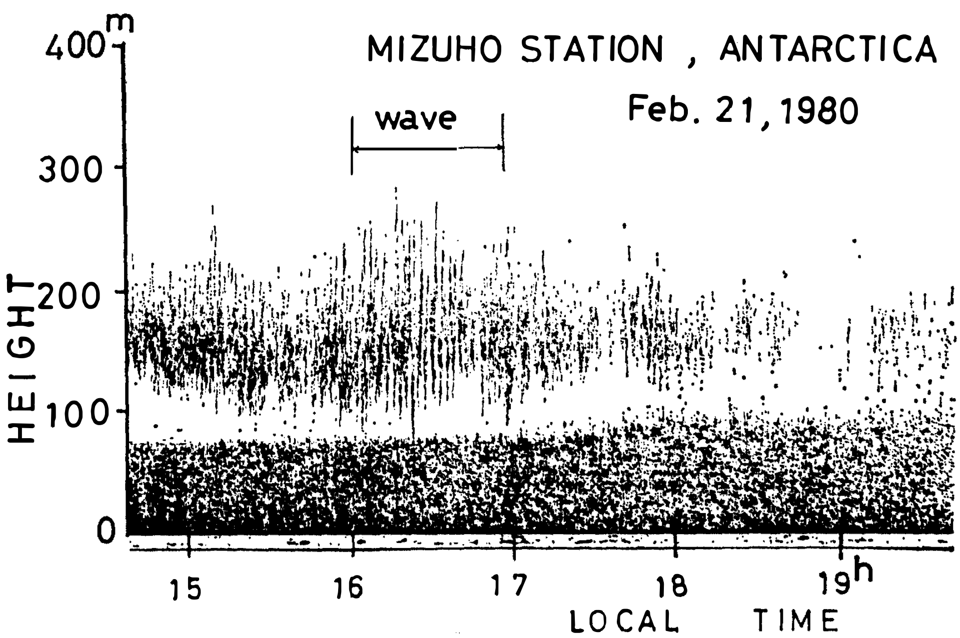

Fig. 11. Wave-like motion, expanded from Fig. 9, has a period of 2.3 min, appearing at the heights between 100 and 300 m.

Figure 12 shows aerological sounding data at 1337 LT, February 21, 1980. A profile of the Brunt-Väisälä period, T_N, is given in the figure. The B-V period is converted by the following equation:

$$T_N = 2\pi/N\,, \tag{2}$$

where N is the B-V frequency which is given by

$$N = \left(\frac{g}{\bar{\theta}}\frac{\Delta\theta}{\Delta Z}\right)^{1/2}. \tag{3}$$

The potential temperature in eq. (3) was obtained from the observations by a low-level radiosonde. The B-V period at a lower height than 400 m showed values between 2.8 and 8.7 min. As a result, the observed period was less than the B-V period. According to the present authors' measurements of the vertical components of wind speed using two sonic anemothermometers installed on a 30-m high tower, the wave-like motion with a period of 20 s appeared at the beginning of development of a surface inversion on the morning of December 4, 1980, and at the same time the B-V period

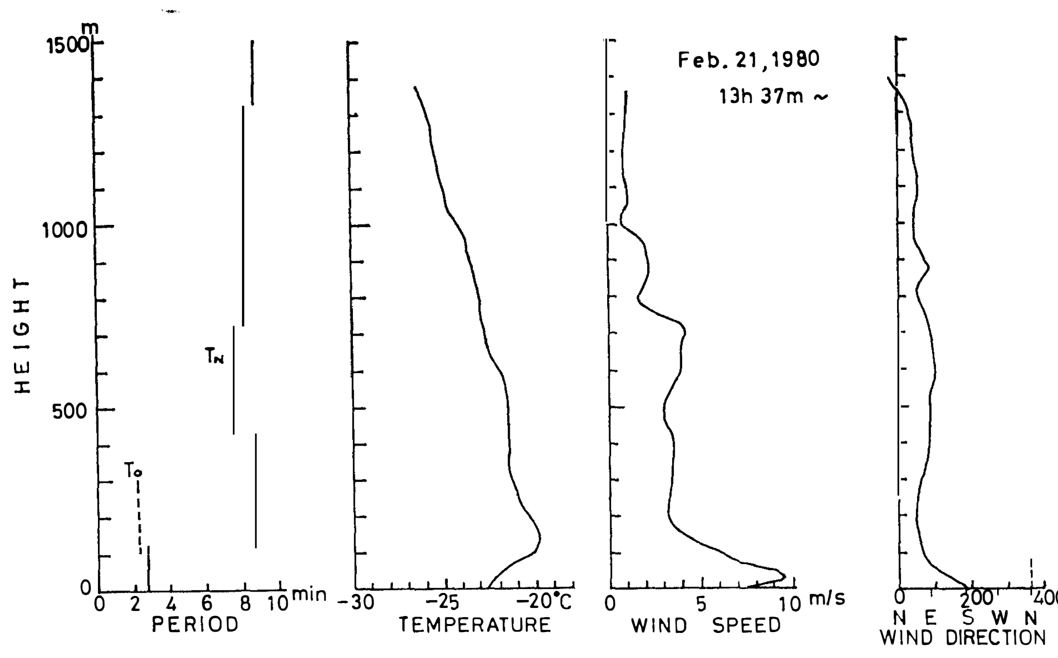

Fig. 12. Profiles of Brunt-Väisälä period, T_N, temperature, wind speed and wind direction obtained from data of a low-level radiosonde at 1337 LT, February 21, 1980. Observed period, T_0, seen in Fig. 11 is shown in a dashed line.

was 1.5 min (KOBAYASHI *et al.*, 1982). The discrepancy between the observed period and the B-V period indicates that the period of wave-like motion is strongly influenced by horizontal wind speed.

To illustrate the observed period of wave-like motion will be considered next a simple two-dimensional wave equation. The basic momentum equation follows the linearized perturbation equation (ARAKAWA, 1973):

$$\frac{\partial \boldsymbol{u}}{\partial t}+U\cdot\nabla\boldsymbol{u}=-\frac{1}{\bar{\rho}}\nabla p\,, \tag{4}$$

where $\boldsymbol{u}$ and p are the horizontal wind speed perturbation and the pressure perturbation, respectively, U is the mean horizontal wind speed, $\bar{\rho}$ is the mean density of air, and ∇ is the horizontal gradient operator. The wave solution of eq. (4) is assumed as follows:

$$\begin{pmatrix} \boldsymbol{u} \\ p \end{pmatrix}=\begin{pmatrix} A_u \\ A_p \end{pmatrix}\exp\left[i(kx-\omega t)\right]\,, \tag{5}$$

where A_u and A_p are the amplitudes of $\boldsymbol{u}$ and p, respectively, k is the wave number, x is the position in the horizontal, ω is the frequency measured at a fixed point, t is the time, and i is the square root of -1. Substitution of eq. (5) into eq. (4) leads to

$$\bar{\rho}(\omega-k\cdot U)\boldsymbol{u}=k\cdot p\,. \tag{6}$$

Thus the intrinsic frequency, n, denoted by an observer drifting with the zero-order flow, is given by

$$n=\omega-k\cdot U\,, \tag{7}$$

and the observed apparent period of the wave, T_0, is given by

$$T_0=\frac{2\pi}{\omega}\,. \tag{8}$$

Assuming that n is nearly equal to the B-V frequency, N, the value of the B-V period, T_N, is obtained as follows:

$$T_N=\frac{2\pi}{n}=\frac{2\pi}{\omega-k\cdot U}\,. \tag{9}$$

Comparing eq. (8) with eq. (9), as a result, if a general stream exists, then the observed period is less than the B-V period.

4. Discussion

The wavelength, $\lambda=2\pi/k$, and the phase velocity, $C_i=n/k$, were not considered in the foregoing chapter. KANETO (1982) observed billow clouds at Mizuho Plateau, which were wave-like similar to Kelvin-Helmholtz waves, and found that their wavelength ranged between 300 and 800 m. Now to illustrate the phase velocity the following equation is obtained from eqs. (6) and (7):

$$\rho\cdot n\cdot \boldsymbol{u}=k\cdot p\,. \tag{10}$$

Therefore, from eq. (10) the phase velocity is given by

$$C_i\equiv\frac{n}{k}=\frac{p}{\bar{\rho}\cdot \boldsymbol{u}}\,. \tag{11}$$

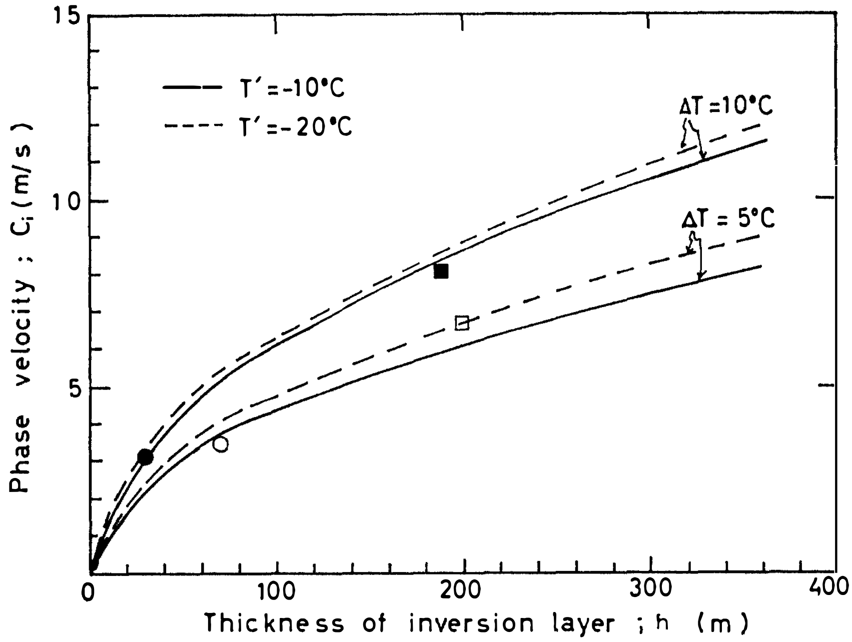

Fig. 13. Relation between phase velocity and thickness of an inversion layer, derived from eq. (12). T′: temperature of a warm layer above a cold layer; ΔT: intensity of inversion; ■,□: observed data in Antarctica; ●, ○: observed data in Hokkaido, Japan (KOBAYASHI and ISHIKAWA, 1982).

The equation has been termed the "impedance equation" by GOSSARD and MUNK (1954). Although a wave phase velocity (measured relative to a moving medium) is given by the above relation, we have no data on the wave-associated pressure perturbation. However, BEAN *et al.* (1973) showed the atmospheric gravity waves can be revealed by the acoustic Doppler shift and the pressure trace from four microbarographs. We now will consider another approach to the phase velocity. Concerning the motion of waves in the atmosphere in question, FREEMAN (1951) assumed that the waves include transverse waves traveling along the interface of two quasi-incompressible (homogeneous) fluid layers of the density ρ_1 (cold) and ρ_2 (warm). As a result, according to him, the phase velocity is given by

$$C_i=[gh(1-\rho_2/\rho_1)]^{1/2}\ , \tag{12}$$

where g is the acceleration of gravity, and h is the thickness of an inversion layer. Theoretical results agree well with the data obtained in field observations, as shown in Fig. 13 (KOBAYASHI and ISHIKAWA, 1982). KUHN *et al.* (1977) also pointed out that the transfer of momentum and heat by vertical transverse waves becomes increasingly important at Plateau Station and anywhere else in the interior of the Antarctic Continent.

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