OBSERVATIONS OF AN ATMOSPHERIC GRAVITY WAVE BY SHEAR INSTABILITY IN KATABATIC WIND AT MIZUHO STATION, EAST ANTARCTICA

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Abstract: Measurements were made of vertical wind speed components, using two sonic anemothermometers on the snow surface at Mizuho Station in 1980 by the present authors who were members of the 21st Japanese Antarctic Research Expedition (JARE-21). The two anemothermometers were mounted at the fixed heights of 3 m and 30 m on a 30-m-high micrometeorological tower.

The existence of shear instability (Kelvin-Helmholtz) waves with period of about 20 s was revealed as a result. The maximum amplitude of the K-H waves was found when the surface layer had a local gradient Richardson number smaller than 0.25; the instability regime was in agreement with DRAZIN's criterion (J. Fluid. Mech., **4**, 214, 1958). Such gravity waves were observed when a strong surface inversion was progressing above the snow surface after the katabatic wind had been disturbed by a synoptic scale disturbance.

1. Introduction

In 1980 the present authors, belonging to the 21st Japanese Antarctic Research Expedition (JARE-21), carried out glaciometeorological observations at Mizuho Station (70°42′S, 44°20′E, 2230 m above sea level) as the second-year program of the Japanese POLEX-South (KUSUNOKI, 1981). About 270 km inland from the coast of the Antarctic Continent, this station is located on the slope of the ice sheet. A 30-m-high micrometeorological observation tower was erected at this station in January 1979. The details of installation and performance of the measurement systems in that year are described by MAE *et al.* (1981). In the austral summer of 1980 the present authors installed two sonic anemothermometers on the tower and measured vertical wind speed components.

WADA *et al.* (1981) reported large temperature fluctuations at the heights of 30 m and 16 m at Mizuho Station. According to their observations, when the wind speed at the height of 30 m was not stronger than that at 16 m, a strong surface inversion existed between the surface and 30 m, and shear instability waves called Kelvin-Helmholtz waves were found to exist. The existence of such waves above various surfaces has been reported by a large number of investigators, including GOSSARD and MUNK (1954), EMMANUEL (1973), HOOKE *et al.* (1973), STILKE (1973), READINGS *et al.* (1973), SETHURAMAN (1977), EINAUDI and FINNIGAN (1981) and SOMMERS (1981). This paper also suggests that the transfer of heat as a result of the breaking of gravity waves becomes increasingly important in the formation of a katabatic wind layer on the slope of the ice sheet.

2. Instruments

Fluctuating values of vertical wind speed components and air temperature were simultaneously measured with two one-dimensional sonic anemothermometers (referred to as S.A.T. hereafter) manufactured by Kaijo Denki Co., Ltd. in Japan. These were mounted on the 30-m-high tower at the heights of 3 m and 30 m. Electric signals of the wind component from the S.A.T. were recorded on a two channel rectigraph with a width of 40 mm per channel and a chart speed of 160 mm/min, the response time of the recorder being about 0.03 s.

Profiles of the mean wind speed and air temperature were obtained from data of measurements with seven anemometers of the 3-cup type manufactured by Makino Instrument Co., Ltd. in Japan, and with seven platinum resistance thermometers with a stainless steel shelter made by Toho Electric Co., Ltd. in Japan, respectively. The sensors of the anemometers and thermometers were mounted on the arms of the tower at the heights of 29.5, 15.5, 7.5, 3.5, 1.5, 1 and 0.5 m.

3. Results of Measurements

3.1. Air temperature variations in the surface boundary layer

When a developed katabatic wind is disturbed by a synoptic scale disturbance near Mizuho Station, the wind in the surface layer will be weakened. At that time,

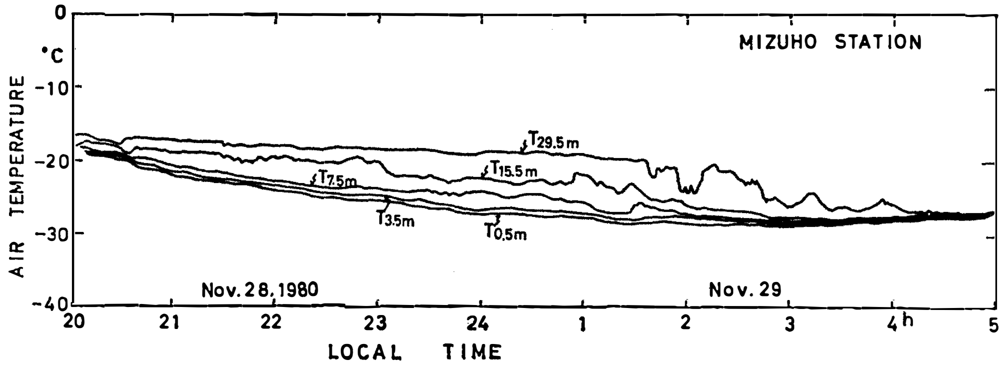

Fig. 1. Variations in air temperature at the heights of 29.5, 15.5, 7.5, 3.5 and 0.5 m from November 28 to 29, 1980.

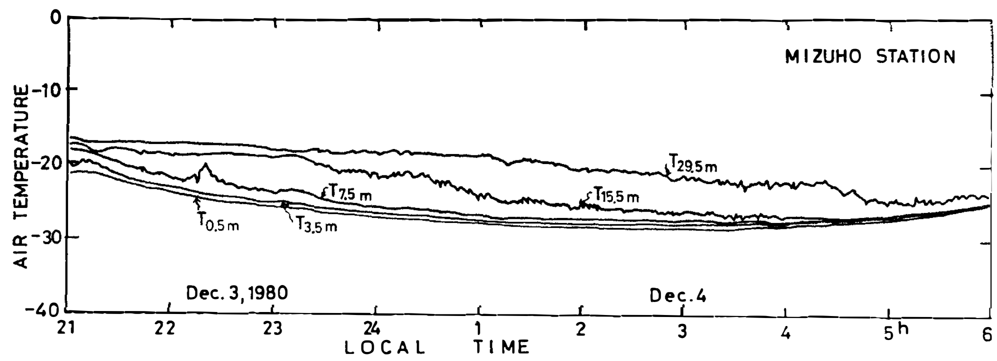

Fig. 2. Variations in air temperature at the same heights as in Fig. 1 from December 3 to 4, 1980.

if the skies are clear, then a strong surface inversion will occur near the snow surface. The distribution of frequency in such cases of strong inversion was reported by WADA *et al.* (1981). They defined a strong inversion to exist when the air temperature at 30 m is higher than that at 4 m plus 5°C. They found that this condition occurs much more frequently in winter than in summer.

Figures 1 and 2 show two typical variations in air temperature at five heights ranging from 0.5 m to 30 m from November 28 to 29 and from December 3 to 4 in 1980, respectively. A strong inversion of 10°C in temperature difference between the heights of 29.5 m and 0.5 m occurred in both cases. However, in the former case there were large variations in air temperature at the heights of 15.5 and 29.5 m associated with large-scale convection. On the other hand, in the latter case small variations were observed in larger numbers at the same heights. Such a surface inversion accompanied by a low katabatic wind occurred from 5 to 10 days per month.

3.2. *Vertical profiles of wind speed and air temperature under surface inversion*

Figures 3 and 4 show the vertical profiles of wind speed and air temperature

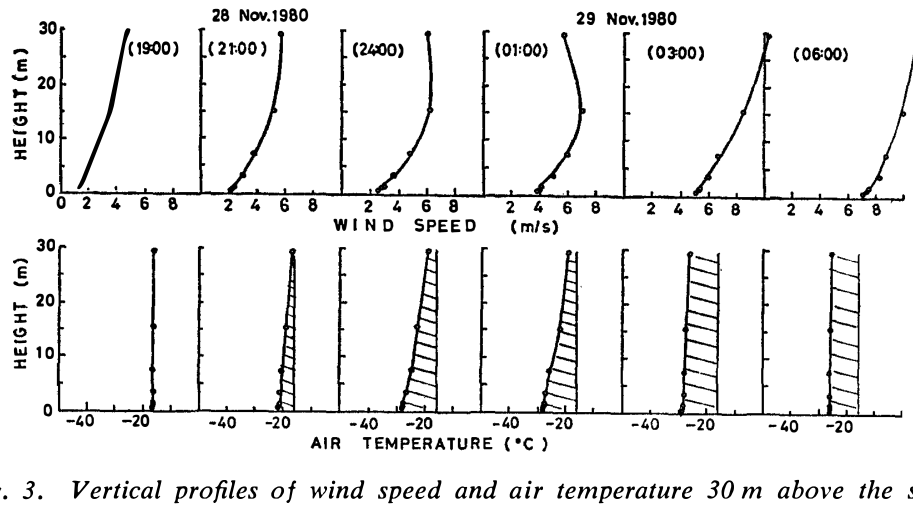

Fig. 3. Vertical profiles of wind speed and air temperature 30 m above the snow surface in the same period as in Fig. 1. The hatched part shows an increased thickness of the layer of cold air which allows a katabatic wind to develop sufficiently.

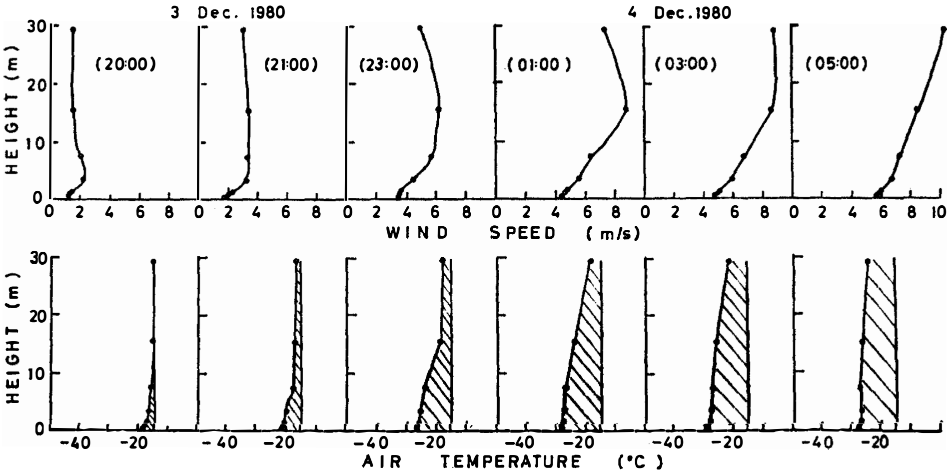

Fig. 4. *Vertical profiles in wind speed and air temperature 30 m above the snow surface in the same period as in Fig. 2. The hatched part has the same meaning as in Fig. 3.*

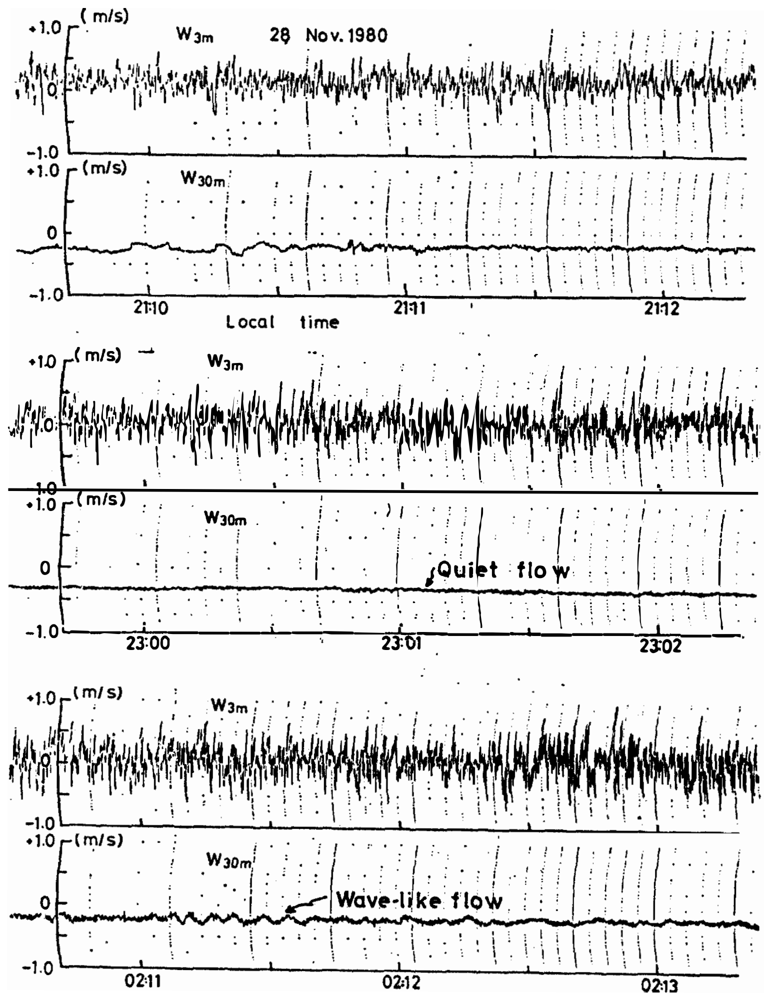

Fig. 5a.

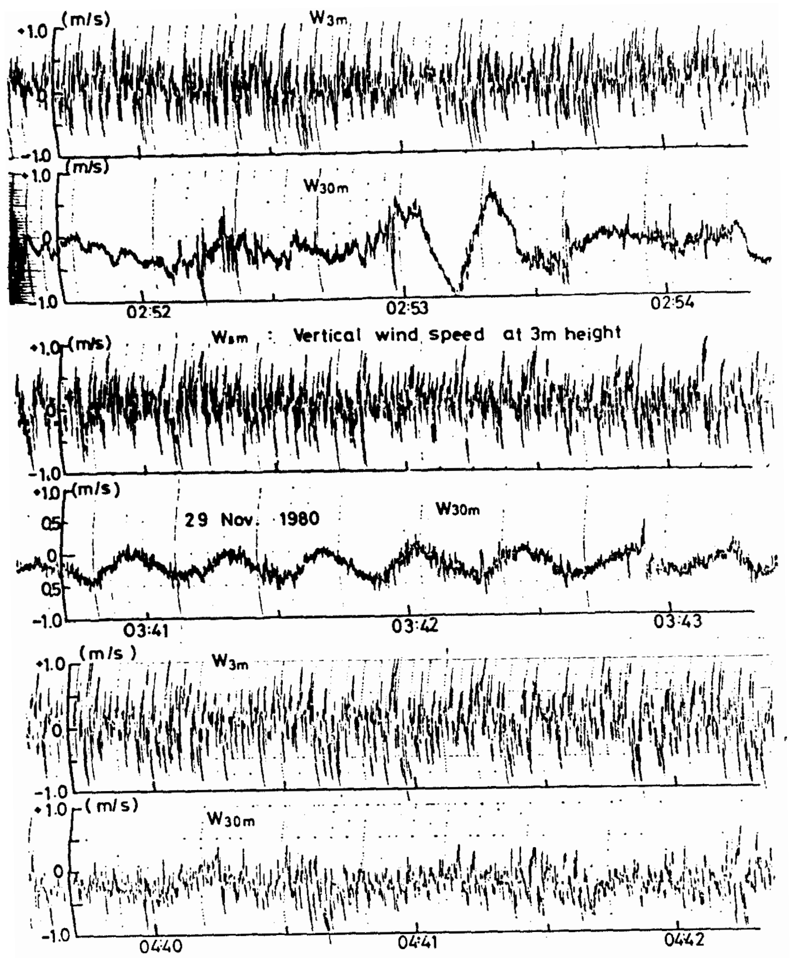

Fig. 5b.

Fig. 5a, b. Variations in vertical wind speed (W_{3m}, W_{30m}) measured by two sonic anemothermometers mounted at the heights of 3 m and 30 m from November 28 to 29, 1980.

up to 29.5 m at Mizuho Station in both cases described in the above section. As shown in these figures, the wind speed shows a maximum speed at heights lower than 20 m when a surface inversion develops. The present authors use the term "low katabatic wind" compared with the "high katabatic wind" which has a maximum wind speed between the heights of 40 m and 100 m (KOBAYASHI and YOKOYAMA, 1976). However, when the low katabatic wind is well enough developed; *i.e.*, the layer of cold air above the snow surface increases its thickness (see the hatched area of the temperature profiles in the figures), then the wind speed increases with increasing height. During the inversion, the wind speed structure over the snow or ice surface is not represented by a logarithmic profile. But the inversion is ultimately destroyed when strong winds develop and the lapse rate becomes adiabatic near the surface layer; *i.e.*, the wind profile can be approximated by a logarithmic law in a neutral condition. LILJEQUIST (1958) found a marked reduction in inversion intensity when the wind speed at the height of 10 m reaches 8 to 9 m/s.

3.3. *Fluctuating vertical wind speed components measured by sonic anemothermometers*

Direct measurements were made of vertical wind speed components using two sonic anemothermometers installed on the 30-m-high tower. Figures 5 and 6 illustrate the fluctuating vertical wind speed components obtained simultaneously at the heights of 3 and 30 m from November 28 to 29 and from December 3 to 4 in 1980, respectively. In Fig. 5 the data at 30 m (W_{30m}) show that laminar flow or "quiet flow" is maintained up to 0300 LT, November 29. Early on the morning of the 29th wave-like motion appears with a period of 20 s. When the wind is strong, the waves break down. However, the data at the height of 3 m (W_{3m}) always show turbulent flow created by surface friction. On the other hand, in Fig. 6 the data at the heights of 3 m and 30 m at the beginning of development of a surface inversion show a transition from laminar to turbulent flow as well as the appearance of the wave-like motion only at W_{30m} early on the morning of December 4 in 1980. The propagation of such waves and their break down is important in the question of mixing of an air mass between the surface layer (cold) and the free atmosphere (warm) above it. Consequently, the question of an atmospheric gravity wave generated by shear instability in a stable air layer will be discussed in the following chapter.

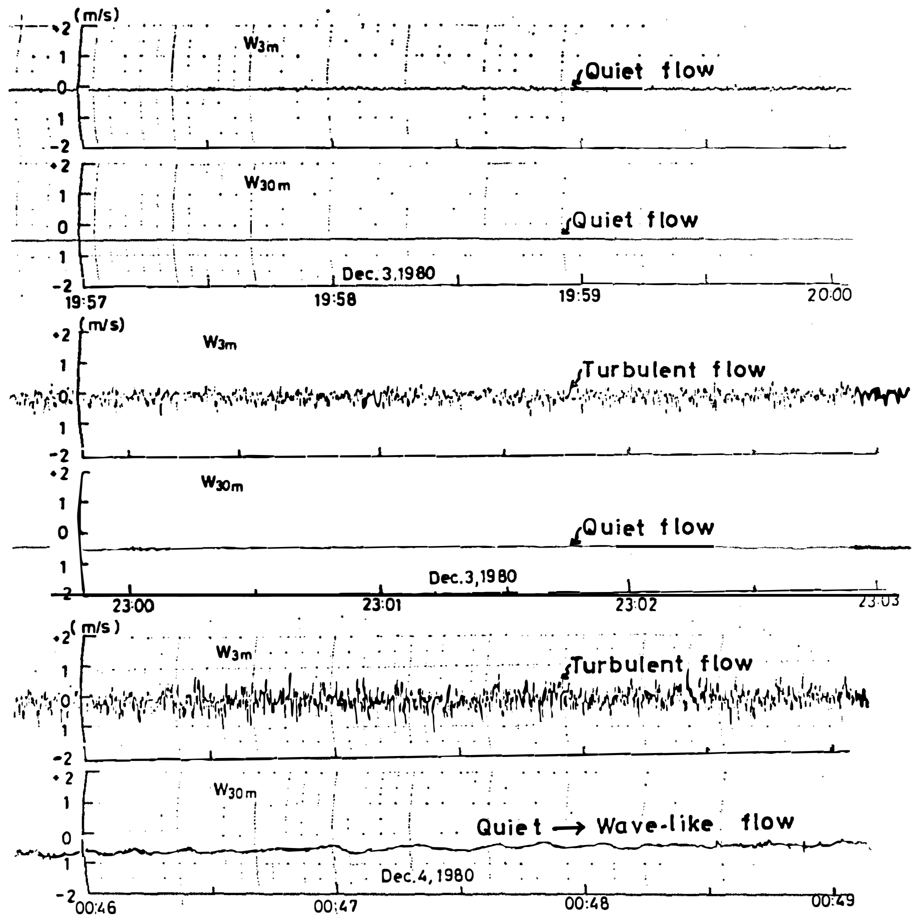

Fig. 6a.

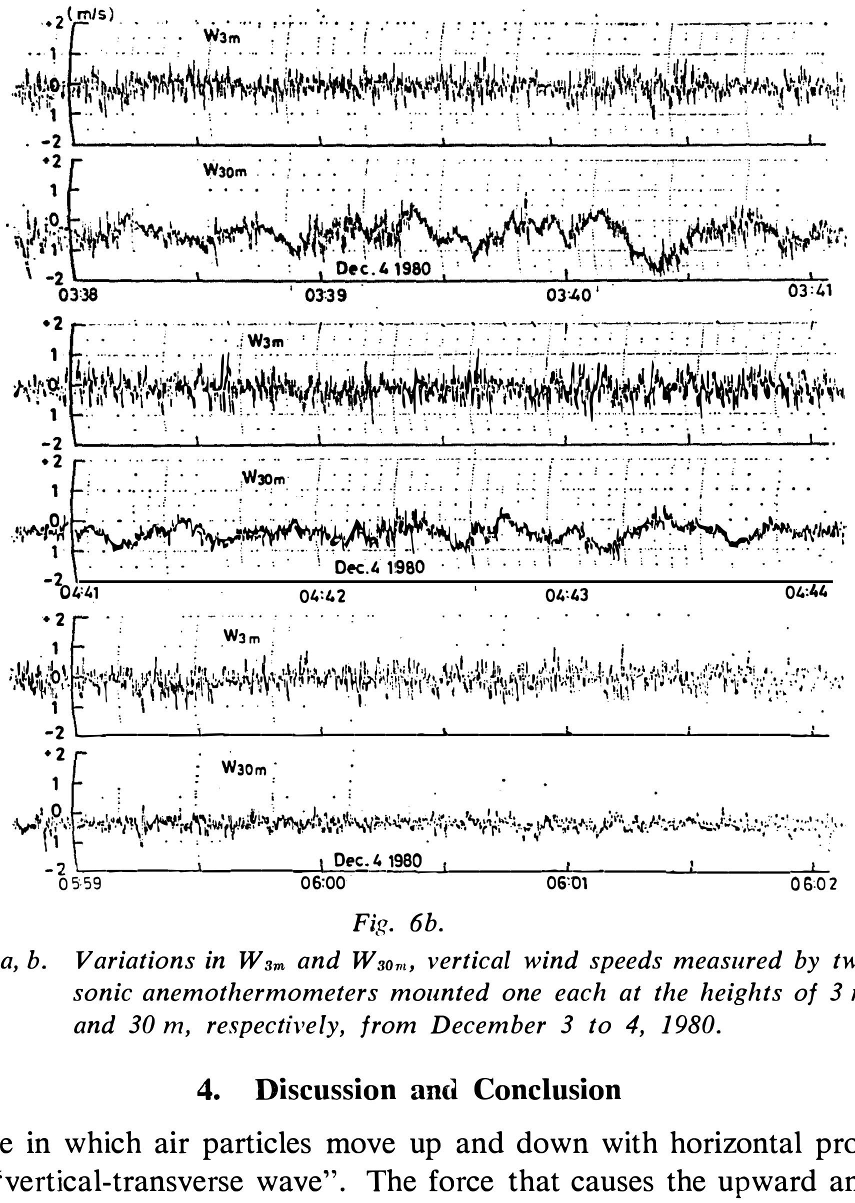

Fig. 6b.

Fig. 6a, b. Variations in W_{3m} and W_{30m}, vertical wind speeds measured by two sonic anemothermometers mounted one each at the heights of 3 m and 30 m, respectively, from December 3 to 4, 1980.

4. Discussion and Conclusion

A wave in which air particles move up and down with horizontal propagation is called a "vertical-transverse wave". The force that causes the upward and downward movement in the vertical-transverse wave is buoyancy; *i.e.*, this force is ultimately due to the action of gravity. For this reason vertical-transverse waves are widely known as gravity waves (see in Chapter 7, ATKINSON, 1981). According to the present measurements, wave-like motion with a period of 20 s appeared at 0340 LT, November 29, as shown in Fig. 5. Among various parameters, the Brunt-Väisälä frequency (B-V frequency) is indispensable in all studies of stably stratified media. The B-V frequency N is given by

$$N=\left(\frac{g}{\theta}\frac{\partial\theta}{\partial z}\right)^{1/2}, \tag{1}$$

where g is the acceleration of gravity, θ is the mean absolute potential temperature of a layer and $\partial\theta/\partial z$ is the vertical gradient of θ. According to the present authors' calculation, the B-V frequency was 0.07 Hz, *i.e.*, the period $T=2\pi/N=1.5$ min. The observed frequency with the period of 20 s is less than the period of 1.5 min of the B-V frequency. The discrepancy between observed and B-V frequencies indicates that the gravity wave is strongly influenced by vertical wind shear.

To illustrate the observed period of the wave we shall consider a simple two-dimensional wave equation. The basic momentum equation is, following the linearized perturbation equation:

$$\frac{\partial \boldsymbol{u}}{\partial t}+\bar{u}\nabla_H \boldsymbol{u}=-\frac{1}{\bar{\rho}}\nabla_H p\,, \tag{2}$$

where $\bar{\rho}$ = mean density of air
$\boldsymbol{u}$, p = horizontal wind speed perturbation and pressure perturbation
$\bar{u}$ = mean horizontal wind speed
∇_H = horizontal gradient operator.

Looking for a two-dimensional wave solution of eq.(2) we have:

$$\begin{pmatrix} \boldsymbol{u} \\ p \end{pmatrix}=\begin{pmatrix} A_{\boldsymbol{u}} \\ A_p \end{pmatrix}\exp\left[i(\boldsymbol{k}\cdot x-\omega t)\right]\,, \tag{3}$$

where ω = frequency measured at a fixed point
$\boldsymbol{k}$ = wave number
x = position in the horizontal
t = time
$A_{\boldsymbol{u}}$, A_p = amplitude of $\boldsymbol{u}$ and p, respectively
i = square root of -1.

Substituting eq.(3) into eq.(2) gives

$$\bar{\rho}(\omega-\boldsymbol{k}\bar{u})\boldsymbol{u}=\boldsymbol{k}\cdot \boldsymbol{P}\,. \tag{4}$$

Thus the intrinsic frequency(n) in a general stream is given by

$$n=\omega-\boldsymbol{k}\cdot\bar{u}\,. \tag{5}$$

The observed apparent period of the wave (T) is given by

$$T=\frac{2\pi}{\omega}=\frac{\lambda}{\bar{u}+c_i}\,, \tag{6}$$

where λ is the wavelength (*i.e.*, $\lambda=2\pi/k$) and c_i is the phase velocity (*i.e.*, $c_i=n/k$). According to CAUGHEY and READINGS (1975), T is nearly constant with height, and if it is accepted that λ is a weak function of height, it follows that $\bar{u}+c_i$ is nearly constant. If the values $T=20$ s and $\bar{u}+c_i=10$ m/s are inserted in eq.(6), it follows that $\lambda=200$ m. KANETO (1982) observed some wave-like clouds at Mizuho Station which were similar to beautiful K-H waves on the interface between layers of dense brine and fresh water generated by THORPE (1978) in a laboratory. The wavelength and height of billow clouds were about 300 to 500 m and 200 m, respectively.

Finally, to illustrate the occurrence of turbulence we shall consider the Richardson number. The combined effects of stability and shear are conveniently expressed in the form of the gradient Richardson number, Ri, as follows:

$$Ri=\frac{g}{\theta}\frac{\partial\theta}{\partial z}\Big/\left(\frac{\partial\bar{u}}{\partial z}\right)^2=\left(\frac{N}{S}\right)^2\,, \tag{7}$$

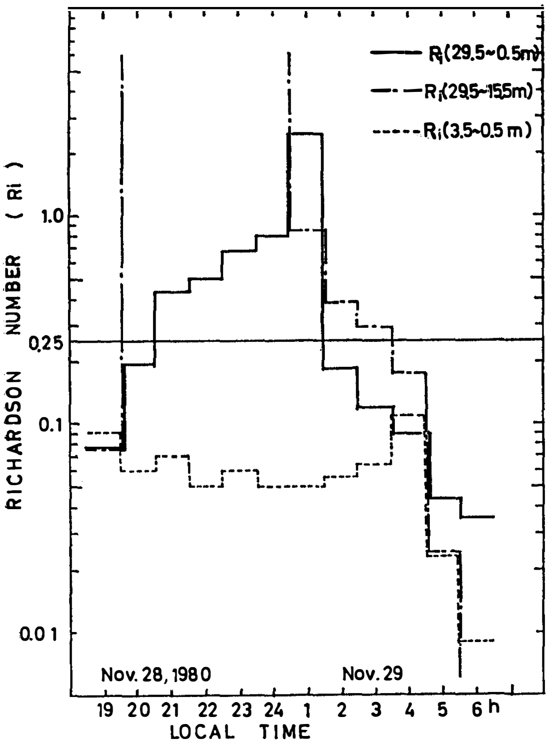

Fig. 7. Profiles of local Richardson numbers analyzed from data of profiles given in Fig. 3 from November 28 to 29, 1980.

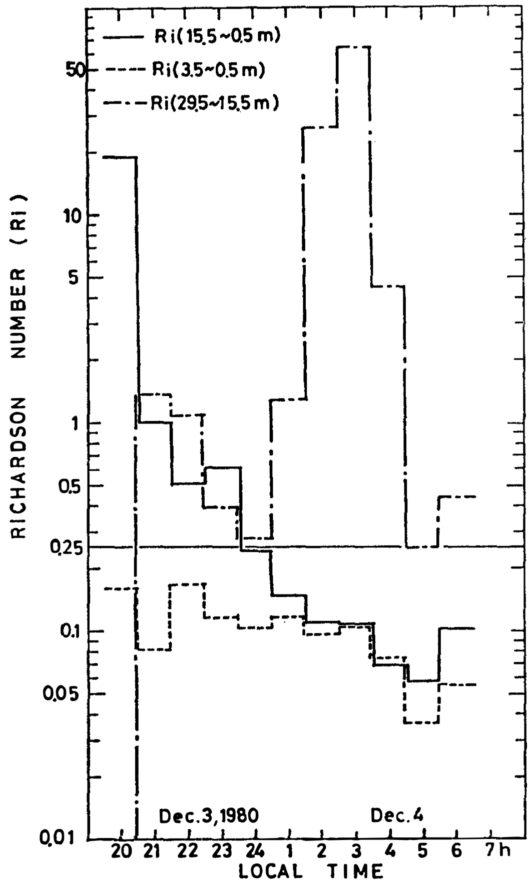

Fig. 8. Profiles of Richardson numbers from data given in Fig. 4 from December 3 to 4, 1980.

where S is the vertical wind shear $\partial \bar{u}/\partial z$. Figures 7 and 8 illustrate the local Richardson number calculated over three layers between 0.5 and 29.5 m in both cases from November 28 to 29 and from December 3 to 4, respectively. According to DRAZIN (1958), all disturbance of wave are stable for $Ri > 1/4$, whereas for $Ri \leq 1/4$ those disturbances are unstable. If the Richardson number is larger than 0.25, then turbulence is basically not important. But if the Richardson number should fall to a value of about 0.25, the so-called "intermittency" or atmospheric turbulence occurs and is deformed into smaller waves, which grow spontaneously (KONDO *et al.*, 1978). These smaller waves are known as Kelvin-Helmholtz waves; should they eventually "roll up" and "break down (cat's-eye)", the phenomenon is known as a Kelvin-Helmholtz instability (*e.g.* EMMANUEL, 1973; HOOKE *et al.*, 1973; ATKINSON, 1981). However, the present measurements roughly show that these quiet flows are stable in the layer between 15.5 and 29.5 m corresponding to the value of large Richardson number ($Ri > 0.25$), while they are unstable in the layer between 0.5 and 3.5 m with a Richardson number of less than 0.2. KONDO *et al.* (1978) found that the atmosphere was essentially nonturbulent for $Ri > 2$;

therefore, such data will correspond to the vertical wind data with nonturbulent flow observed at the height of 30 m, as shown in Figs. 5 and 6.

A more detailed treatment of transfer of heat by breaking of gravity waves will be reported in another paper in the same issue (KOBAYASHI *et al.*, 1982).

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