Some Characteristics of Turbulence in Katabatic Winds over Mizuho Plateau, East Antarctica*

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南極みずほ高原上の斜面滑降風の乱流*

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要旨: 超音波風速計による斜面滑降風 (katabatic wind) の乱流特性が調べられた．観測地点は，みずほ基地の雪原上とやまと裸氷原上の２点であり，前者は，定常的な斜面滑降風域，後者は斜面滑降風のハイドロリックシャンプ (hydraulic jump) 域として特徴づけられる．２つの地域の乱流特性の差は，自己相関係数から計算した特性時間スケールとパワースペクトルに著しく表れた．

***Abstract*:** Wind turbulence was observed, using sonic anemometers, on a snow surface at Mizuho Station (2230 m above sea level, Lat. 70°41.9′S, Long. 44°19.9′E) and on a bare ice field near the Yamato Mountains (1700 m above sea level, Lat. 71°18′S, Long. 35°40′E) in the Mizuho Plateau in 1973 by the party of the 14th Japanese Antarctic Research Expedition (JARE-14). Observations revealed, as to katabatic winds blowing above the two places, that the one above the latter is characterized by the presence of a hydraulic jump generated by nunataks there, resulting in a stronger turbulence than the one above the former which is stationary. Hence, a comparison is made in this paper between characteristics of turbulence and a hydraulic jump in a katabatic wind

1. Introduction

An atmospheric turbulence constituting stable stratification above the sea ice area around Syowa Station was first observed by MAKI (1974a, b), a member of the wintering party of the 11th Japanese Antarctic Research Expedition (JARE-11), in Antarctica during the period from February to December 1970. ADACHI (1973, 1974) also made observations of the same atmospheric turbulence in this area in 1971 (JARE-12). They measured atmospheric turbulence using a 3-dimensional sonic anemometer-thermometer (referred to as S. A. T. hereafter) which was mounted on a meteorological tower at the height of 20 m. As the observation site is about 4 km away from the rim of the Antarctic Continent, however, it is not suited to observe turbulence in stationary katabatic winds. Then, SASAKI (1979) first observed atmospheric turbulence in stationary kata-

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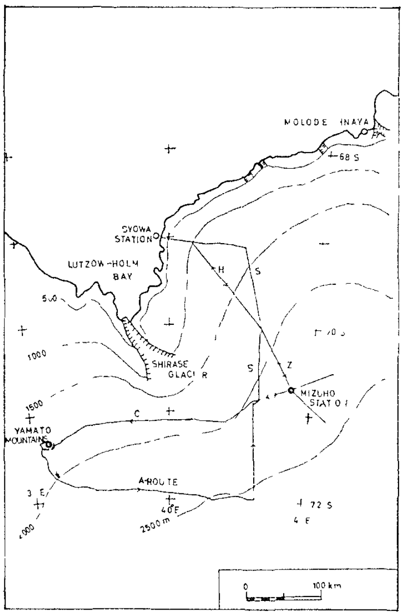

Fig 1. A map of two observation sites, Mizuho Station and bare ice field near the Yamato Mountains

batic winds at Mizuho Station (Fig. 1) in 1972 (JARE-13), also using the same S.A T. as the above, which was mounted on the meteorological tower at the height of 10 m

One of the present authors (KOBAYASHI) made observations of wind and temperature fluctuations at the same tower in 1973 (JARE-14). Additionally, he analyzed the data obtained at the bare ice field near the Yamato Mountains (Fig. 1) to measure turbulence due to a hydraulic jump in a katabatic wind.

2. Measurements

2.1. Observations on Mizuho Station snow surface

A series of micrometeorological measurements was made on a katabatic wind slope (mean surface slope: 3×10^{-3}) at Mizuho Station (2230 m above mean sea level, Lat 70°41.9′S, Long. 44°19 9′E) in the periods from August 28 to September 23, 1972, and from April 15 to April 21, 1973. Meteorological conditions at this station are characterized by stationary katabatic winds within the inversion layer over the surface slope. The mean profile of wind velocity was obtained by measurements with five small anemometers of the 3-cup type manufactured by Makino Instrument Company. They were installed on the tower at the respective heights of 8, 4, 2, 1 and 0 35 m above the snow surface. Rotations of the anemometers were counted by automatic magnetic digital counters. The profile of temperature was obtained by the use of platinum resistance thermometers each with a shelter, which were set on the same tower at the respective heights of 4, 2, 1 and 0.5 m above the snow surface. Outputs of the thermometers were automatically recorded every minute on a 6-channel recorder. Fluctuating wind components and air temperatures were simultaneously measured with a 3-dimensional S.A.T. manufactured by Kaijo Denki Ltd., which was mounted at the height of 4.5 m. Electric signals from the S.A.T. were recorded on a 4-channel rectigraph with the width of 40 mm per channel and the chart speed of 50 mm/s, the response time of the recorder being about 0.03 s. The sampling interval was between 0.1 s and 0.2 s, while the recording time for each run was about 5 min.

2.2. Observations on Yamato bare ice field

Micrometeorological observations were carried out on the bare ice field near the Yamato Mountains from December 1 to 7, 1973. The observation site was located on the leeward of the massifs E and F of the Yamato Mountains. The prevailing wind direction near the surface was nearly easterly. This area is marked by a hydraulic jump accompanied by a strong turbulence generated by nunataks. Five sets of 3-cup anemometers were installed at the heights of 3.35, 1.85, 0.86, 0.55 and 0.35 m respectively. Air temperatures were measured using thermister thermometers instabled at the heights of 3.15, 1.65 and 0.15 m respectively.

Some results of analyses of these data have been reported (KOBAYASHI, 1978, 1979), in which the atmosphere showed an unstable condition (negative Richardson number) with the decrease of wind speed, as the bare ice surface was heated by solar radiation. Wind turbulence was observed by means of a 1-component sonic anemometer, which was mounted at the height of 2.2 m. Electric signals from the sonic anemometer were recorded on a strip chart recorder. The sampling interval was 0.83 s, while the recording time for each run was about 10 min. Results of vertical wind components are described in this paper.

3. Data Analyses

Calculated in the present paper are standard deviations of turbulence, Eulerian auto-correlation coefficients, power spectral densities of vertical wind components and temperature fluctuations The last two data were calculated with the maximum entropy method programed by SAITO (1974). According to INOUE (1952), the auto-correlation coefficient $R_j(t)$ at the small time lag t may be approximated by

$$R_j(t)=1-(t/T_j)^{m_j}, \tag{1}$$

where T_j is the characteristic time taken for the "largest turbulence" to pass through a measuring point, m_j is the numerical constant, and j is the subscript representing any one of three components, longitudinal (u), lateral (v) and vertical (w).

Turbulence can be generated either thermally or mechanically. For a convenient stability parameter, a gradient Richardson number Ri was calculated from the vertical air temperature gradient $\Delta\theta/\Delta Z$ and the vertical wind velocity gradient $\Delta U/\Delta Z$ for each averaging period:

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

where g is the acceleration of gravity and $\bar{\theta}$ is the mean absolute potential temperature of a layer.

A very important parameter is indispensable in all studies of stably stratified media; *i. e.*, it is called the Brunt-Väisala frequency (B–V frequency). Denoted by N, it is given by

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

4. Observation Results

4.1. Eulerian auto-correlation coefficients on Mizuho Station snow surface

As examples of Eulerian auto-correlation coefficients, those obtained at Mizuho Station are shown in Fig. 2. The figures represent a relation between the lag time t and $1-R_j(t)$ $(j=u, v, w)$. Solid lines in the figure are drawn so as to fit eq. (1). Since t equals T_j when $1-R_j(t)$ is unity, each of characteristic times is obtained from the point of intersection of a solid line and the line of $1-R(t)=1$ in Fig. 2. Thus, we have characteristic times as shown in Table 1. The characteristic times are smaller than those in katabatic winds obtained and reported by MAKI (1974b) at Syowa Station. It is already known that the katabatic winds observed at Syowa Station are affected by a weak hydraulic jump in a katabatic flow, *i. e.*, MORITA (1968), who described some characteristics of katabatic winds at Syowa Station, reported that their effect reaches Syowa Station only when the katabatic flow is of the "type 2" in Ball's theory (BALL, 1956, 1960) in which a jump can occur inland. Meanwhile, ADACHI (1979) reported differences in power spectrum of katabatic winds at Syowa Station between those stationary winds

Table 1. Mean and turbulent parameters.

Run	Date 1973	Time (L.T.)	U(4.5 m) m/s	U_* m/s	Ri(3 m)
M1	Apr 20	1810–1815	13.2	0.58	0.003
M2	Sep 7	1409–1514	15.5	0.61	0.004
M3	Sep 8	0907–0915	10.2	0.38	0.024
M4	Sep 9	1458–1505	15.2	0.56	0.004

U_*: Friction velocity, Ri: Gradient Richardson number, $\sigma_u, \sigma_v, \sigma_w$: Standard deviations of T_u, T_v, T_w: Characteristic times (u, v, w: same as above), m_u, m_v, m_w: Values of exponent in

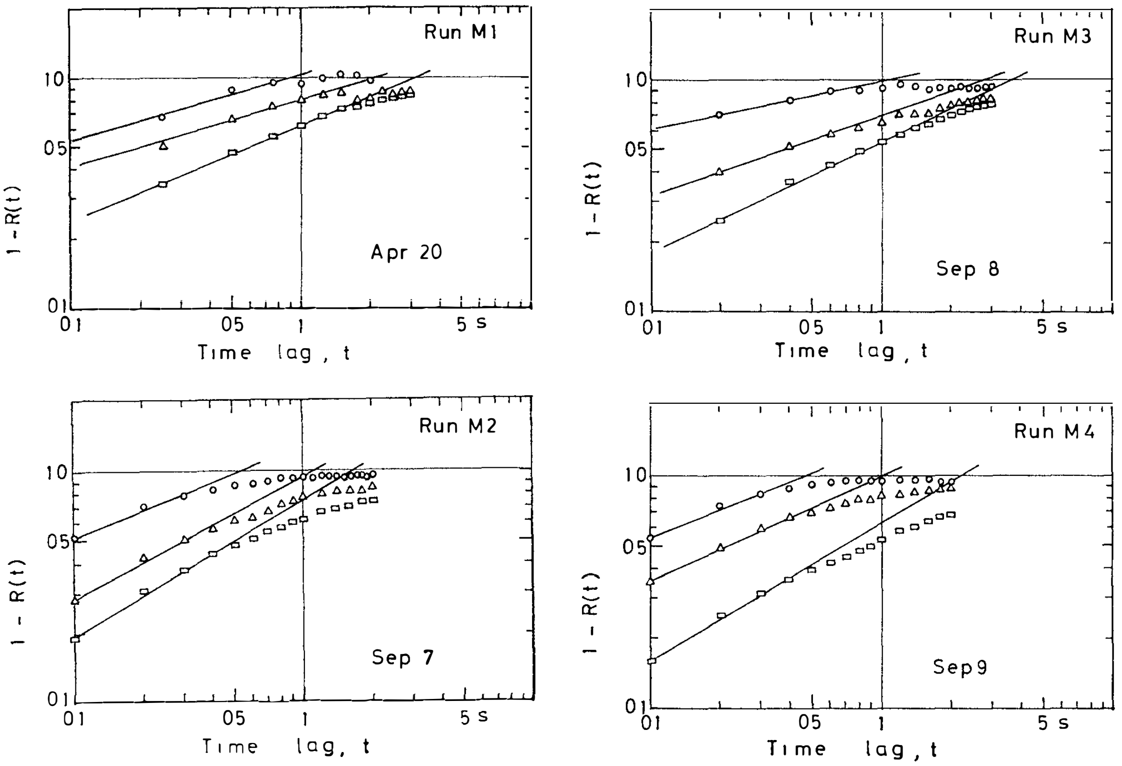

Fig. 2. Eulerian auto-correlation coefficients of longitudinal (□), lateral (△), and vertical (○) wind velocity [1–R(t)] against time lag [t] in stationary katabatic winds obtained at Mizuho Station

and those winds affected by a hydraulic jump inland. According to these characteristic times, the mean scale of the "largest turbulon" (INOUE, 1952) represents an ellipsoid like a long and narrow visionary vortex having the dimensions of length, breadth, and height in 3.7: 2.3: 1.

4.2. Power spectral densities obtained at Mizuho Station

Four examples given in Figs. 3–6 show power spectral densities of vertical wind

obtained at Mizuho Station

σ_u	σ_v m/s	σ_w	σ_w/U_*	T_u	T_v s	T_w	m_u	m_v	m_w
1 18,	0.93,	0 72	1.24	3.0,	2.1,	0.9	0.42,	0.30,	0 28
1.29,	0 94,	0.78	1 28	1.6,	1.1,	0.5	0 60,	0.53,	0.40
0 66,	0 53,	0.45	1 18	3.7,	2.7,	1.1	0 48,	0 36,	0.21
1.32,	1.03,	0.75	1.34	2.2,	1.0,	0.5	0 59,	0.46,	0.41

wind velocity (u, v, w· representing respectively longitudinal, lateral and vertical components), eq (1) (u, v, w: same as above) speed fluctuation and air temperature fluctuation obtained in the period of stationary katabatic winds at Mizuho Station. In recent years, wave-like motions have been frequently observed in stably stratified atmospheric conditions; the interpretation of atmospheric data obtained in such conditions may well be complicated by the coexistence of two types of motions, *i. e.* turbulence and internal gravity waves. One way of distinguishing between the two was proposed by AXFORD (1971) who drew on spectral characteristics of temperature and velocity fields. Meantime, CAUGHEY and READINGS (1975) described a wave-like phenomenon within 183 m above the earth's surface during nocturnal inversions over land; according to their results, all the spectra have pronounced peaks in the frequency range of $0.002<n<0.003$ Hz corresponding to a period lying between 5 and 8 min. The value of 0.002 Hz given by SETHURAMAN (1977) for internal gravity waves at a height of 23.5 m over the ocean in surface-based inversions is in agreement with the above results. The values obtained by the present authors, however, are

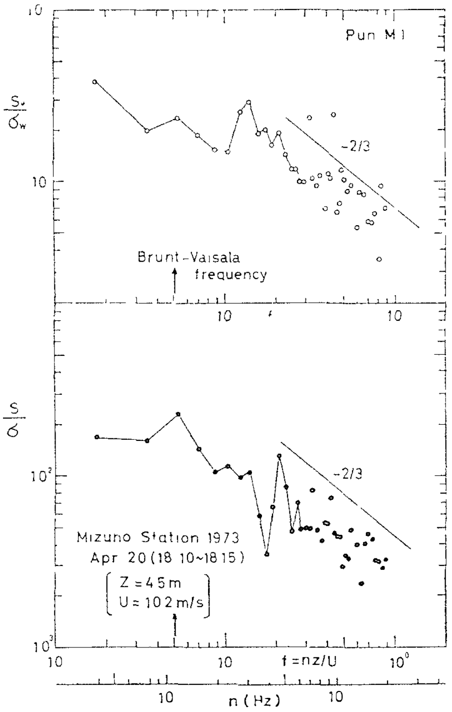

Fig 3.

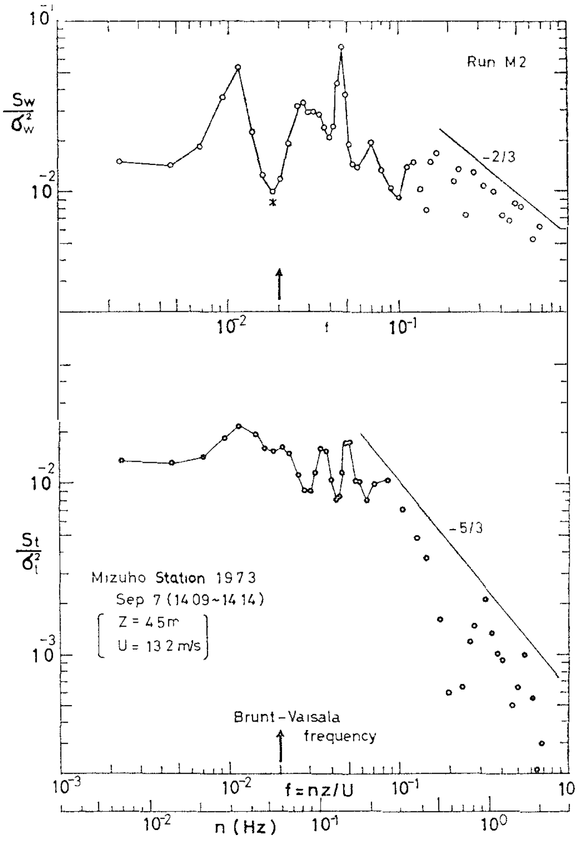

Fig 4

Figs 3 and 4 Normalized power spectral densities of vertical wind fluctuation and air temperature fluctuation against nondimensional frequency [$f=nZ/U$] and frequency [n] in stationary katabatic winds obtained at Mizuho Station. Arrows denote positions of Brunt-Vaisala frequencies

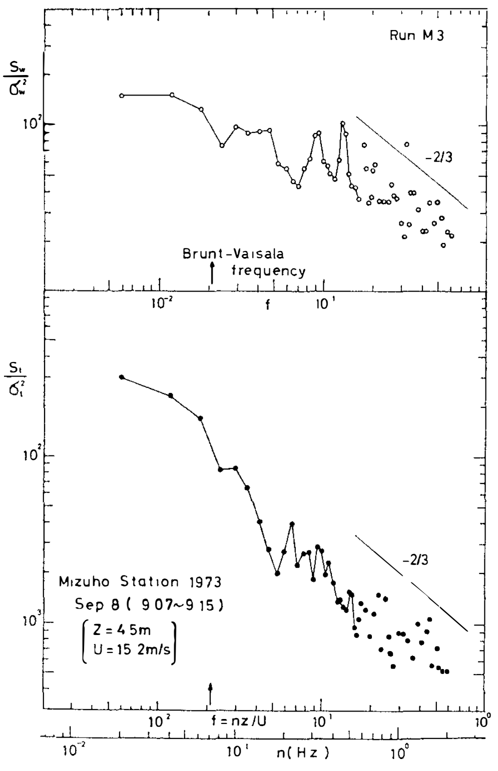

Fig. 5.

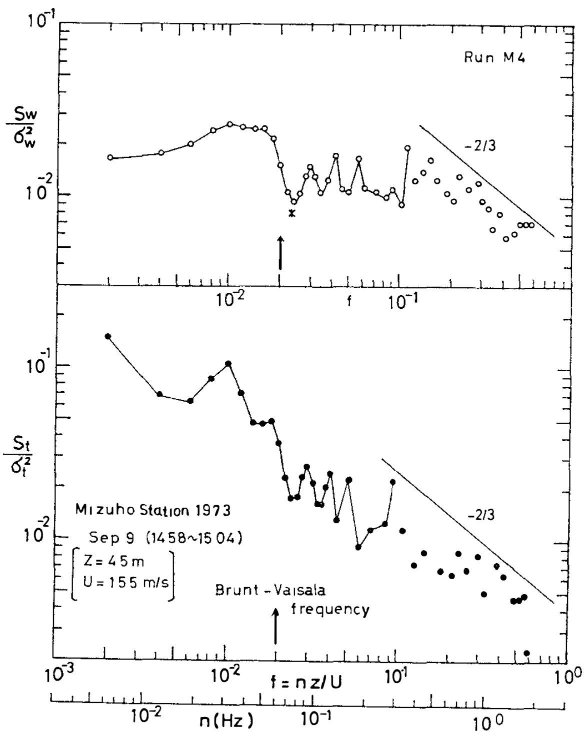

Fig. 6.

Figs 5 and 6. Normalized power spectral densities of vertical wind fluctuation and air temperature fluctuation against nondimensional frequency [$f=nZ/U$] *and frequency* [n] *in stationary katabatic winds obtained at Mizuho Station. Arrows denote positions of Brunt-Väisälä frequencies*

larger than those of the above results.

The peaks may shift to the high frequency side when strong shears are present. Using instrumented aircraft, MASCART *et al.* (1978) reported that the frequency of peak is close to 0.03 Hz within a low-level inversion where the gradient Richardson number is small, *i. e.* shear production is present. The general slope of spectra falls, approximating to $n^{-2/3}$ on the high frequency side. The $-5/3$ power law is rarely seen applicable at temperature spectra, the exception being shown in Fig. 4. In general, the slope of spectra in a stable surface layer began to approximate to $n^{-2/3}$ (KAIMAL, 1973; RAYMENT and CAUGHEY, 1977). In Figs. 3–6 arrows denote the positions of B–V frequencies calculated at 4.5 m. The depression of a peak (marked with an asterisk in Figs. 4 and 6) at the low frequency in the vertical wind component (see Run M2 and Run M4) is in the neighborhood of the B–V frequency. However, the trough in the neighborhood of the B–V frequency is not remarkable in Run M1 and Run M3. Since the observed frequencies of any waves will have been Doppler-shifted by the mean flow (CAUGHEY, 1977), it cannot be expected that the B–V frequency will correspond to the position of internal waves when a strong shear is present in the flow.

4.3. Eulerian auto-correlation coefficients on Yamato bare ice field

For a comparison between the data of stationary katabatic winds and the data of katabatic winds accompanying a hydraulic jump, observations were made of vertical wind fluctuations at the Yamato bare ice field, which is marked by the presence of a

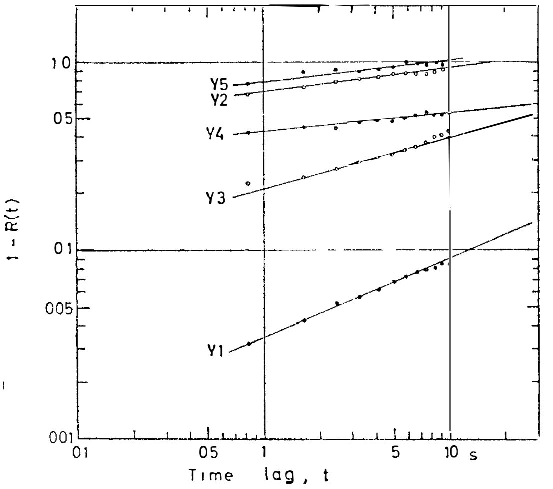

Fig 7

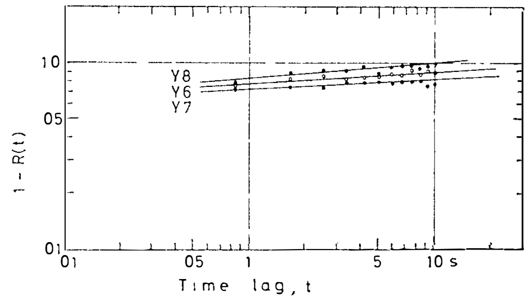

Fig. 8.

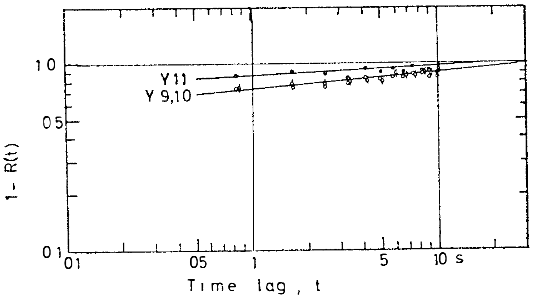

Fig 9.

Figs 7–9. Eulerian auto-correlation coefficients of vertical wind velocity [1–R(t)] against time lag [t] in a hydraulic jump of a katabatic wind obtained at Yamato bare ice field

Table 2. Mean and turbulent parameters obtained at Yamato bare ice field

Run	Date 1973	Time (L.T.)	U(2.2 m) m/s	U_* m/s	Ri(1.7 m)	σ_w m/s	σ_w/U_*	T_w s	m_w
Y 1	Dec. 1	1400–1412	9.2	0.46	−0.005	0.71	1.54	2700	0.11
Y 2	〃	1658–1718	11.7	0.52	−0.001	0.13	0.24	15	0.13
Y 3	〃	1752–1802	11.7	0.52	−0.001	0.32	0.61	350	0.26
Y 4	〃	2037–2051	10.1	0.50	0.013	0.31	0.63	5000	0.39
Y 5	〃	2350–2403	10.1	0.50	0.013	0.14	0.28	8	0.11
Y 6	Dec. 2	0530–0543	12.5	0.60	−0.006	0.19	0.32	60	0.06
Y 7	〃	0900–0916	11.6	0.65	−0.005	0.34	0.53	320	0.06
Y 8	〃	1025–1041	10.1	0.52	−0.002	0.15	0.29	11	0.08
Y 9	〃	1343–1359	10.1	0.52	−0.018	0.22	0.43	15	0.13
Y10	〃	1540–1557	10.1	0.52	−0.010	0.21	0.40	15	0.13
Y11	〃	1745–1759	10.1	0.52	0	0.34	0.66	17	0.05

U_*: Friction velocity, Ri: Gradient Richardson number, σ_w: Standard deviation of vertical wind velocity, T_w: Characteristic time, m_w: Value of exponent in eq. (1)

strong hydraulic jump associated with vortexes, using a one-component ultra sonic anemometer.

Eleven examples of Eulerian auto-correlation coefficients are shown in Figs. 7–9. The characteristic times given in Table 2 show a wide change over the range from 8 to 5000 s. There are many vortexes varying in size in the hydraulic jump. The larger vortexes may be Karman vortexes generated by the Yamato Mountains. The vortexes contribute to the expansion of the bare ice field on the leeward of the Yamato Mountains, playing an important role in preservation of the bare ice surface which results in an energy exchange between the vortexes and the ice.

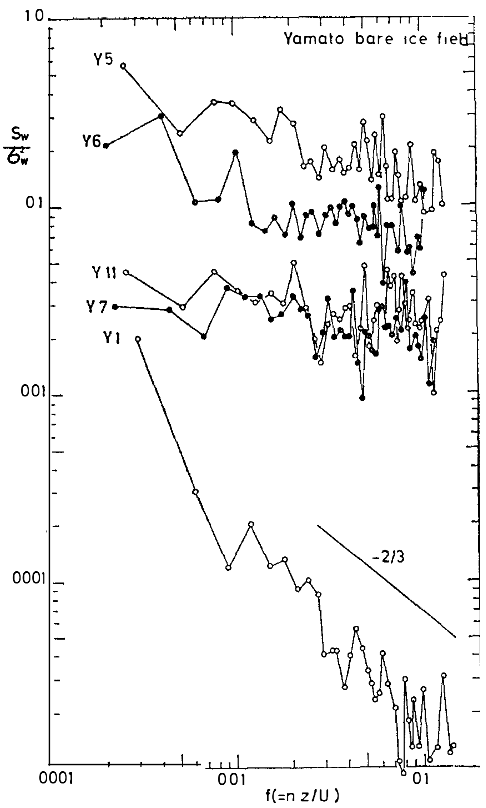

Fig. 10.

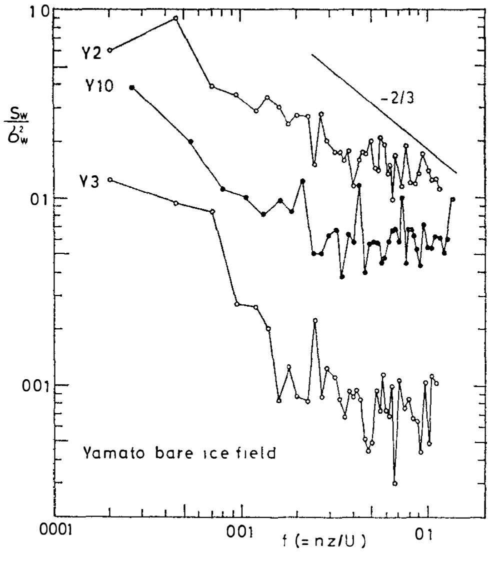

Fig 11.

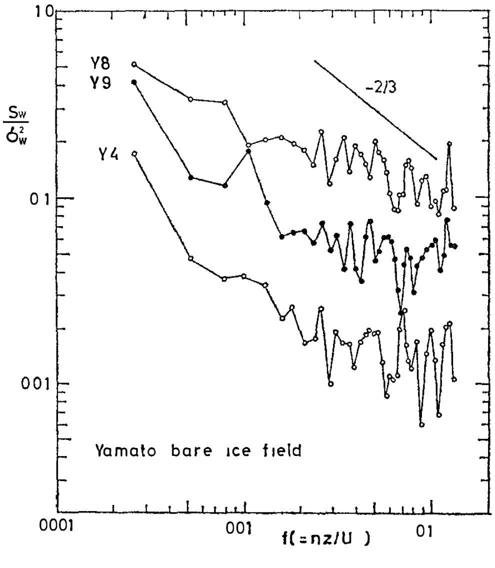

Fig. 12.

Figs. 10–12. Normalized power spectral densities of vertical wind fluctuation against nondimensional frequency [$f=nZ/U$] in a hydraulic jump of a katabatic wind obtained at Yamato bare ice field

4.4. Power spectral densities on Yamato bare ice field

Figs. 10–12 show some examples of normalized power spectral densities of vertical wind velocity fluctuation in a hydraulic jump in katabatic winds obtained at the Yamato bare ice field. The magnitudes of spectral estimates have large differences among the runs As pointed out in section 4.3, it is suggested that many vortexes of various sizes are present in the flow. We cannot identify peaks that are not associated with a hydraulic jump On the other hand, ADACHI (1979) reported the depression of the peak in smoothed power spectra observed at Syowa Station. In spite of the unstable conditions, the slope of spectra falls roughly to $n^{-2/3}$ over the frequency range. In general, the levels of power obtained at the Yamato bare ice field were higher than those obtained at Mizuho Station.

5. Concluding Remarks

Unfortunately, a fairly precise knowledge is lacking about turbulence in the katabatic winds flowing over the sloped ice sheet in Antarctica Katabatic winds in the neighborhood of Mizuho Station are steady in both speed and direction. According to radiosonde observations, the katabatic winds are accompanied by a relatively thin layer of cold air, *i. e.* it is associated with a surface inversion Since internal gravity waves can be supposed at the top of an inversion layer, turbulences and waves co-exist near the surface layer. In a spectral analysis, dominant troughs sometimes have been seen corresponding to the positions of Brunt-Vaisala frequencies Propagation of gravity waves and their breaking are important phenomena for mixing of an air mass between the surface layer and the free atmosphere above it. Meanwhile, a pressure jump (hydraulic jump) will occur near the foot of the ice slope on the leeward of nunataks In regions where strong katabatic winds occur, for example in the Yamato bare ice field, there often occur strong vortexes which are rendered visible by drift snow.

The characteristic times estimated from Eulerian auto-correlation coefficients obtained at the Yamato bare ice field showed that there are large-scale vortexes. These large and strong vortexes will contribute to the keeping of the bare ice field free from snow accumulation.

Acknowledgments

The authors are grateful to Mrs. Yasuko UEMATSU for her assistance in preparing the manuscript.

Statistical calculations given in this paper were computed by aid of an electronic computer, FACOM 230–75, of Hokkaido University Computing Center.

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(Received April 14, 1979)