TURBULENT CHARACTERISTICS OF THE VERTICAL WIND VELOCITY NEAR THE CRITICAL RICHARDSON NUMBER

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Abstract: From analysis of the vertical wind velocity at two heights (3 and 30 m) observed at Mizuho Station in Antarctica, intermittent turbulence was found under very stable conditions. In the range of gradient Richardson number from 0.2 up to about 2, wave-like flows with two groups of periods, in about the 10 and 20 s, play a predominant role. Taking the behavior of such waves into account, the standard deviation and the skewness of the vertical wind velocity component were estimated.

1. Introduction

From August 1980 to January 1981, KOBAYASHI, who is one of the present authors, observed the vertical wind velocity components using two sonic anemometers at two heights (3 and 30 m) at Mizuho Station (70°41′53″S, 44°19′54″E) in East Antarctica. A detailed description of the measurements, site and instrumentations has been given in KOBAYASHI *et al.* (1982a).

Some of the data obtained indicated some interesting features near the critical Richardson number beyond which, in a very stable surface layer, turbulence begins to decay because the buoyancy prevents its maintenance. For example, the traces of vertical wind velocity components at the height of 30 m show that wave-like flow is present frequently (Fig. 1a) and that transition takes place from quiet to turbulent flow (Fig. 1b). KOBAYASHI *et al.* (1982a) discussed the vertical wind velocity components observed at Mizuho Station. Some clearly reflect the presence of waves in strong stability.

The aim of this paper is to further analyze the vertical wind velocity component data to learn the characteristics of the flow.

2. Data Analysis

The vertical wind velocity components on the recording at two levels under stable conditions only were directly sampled at a rate of 2 per second by microcomputer (PS-80, TEAC/TANDY Co., Ltd.) and plotter (MIPLOT, GRAPHTEC Co., Ltd.),

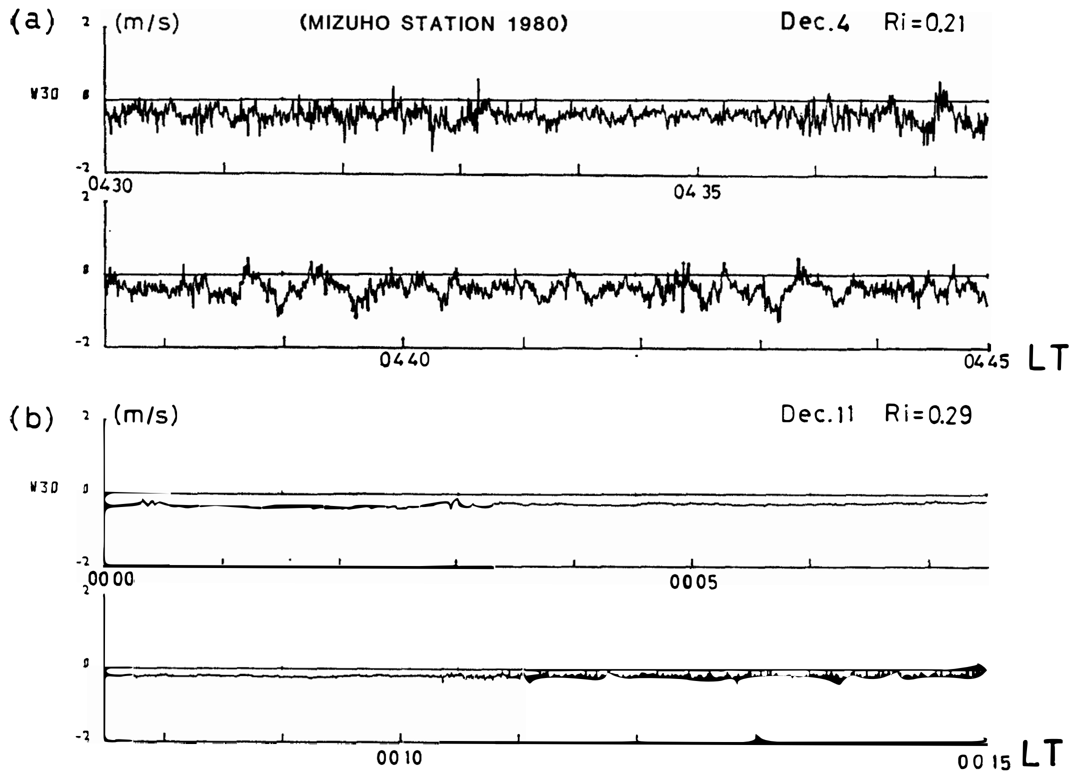

Fig. 1. (a) Time variation of vertical wind velocity at 30 m at Mizuho Station in the period 0430–0445, December 4, 1980 with Ri=0.21 and (b) in the period 0000–0015, December 11, 1980 with Ri=0.29.

and stored in digital cassette tapes. The sampling duration of a single run was 30 min, but the results to be presented were based on two successive 15 min runs. The number of runs to be discussed here is 13 at 3 m, and about 31 at 30 m, respectively.

The gradient Richardson number is a stability parameter, defined as

$$Ri = \frac{g}{\theta} \frac{\partial\theta/\partial z}{(\partial U/\partial z)^2}, \qquad (1)$$

where g is the acceleration of gravity, U the mean wind velocity, and θ the mean absolute potential temperature. The values of Ri were obtained in the following manner; profile data used here are based on hourly values of U and θ at seven levels (0.5, 1, 2, 4, 8, 16 and 30 m) reported by OHATA *et al.* (1983). By approximating profile data to the second-order polynomials in ($\ln z$) [$U = a(\ln z)^2 + b(\ln z) + c$ and $\theta = a'(\ln z)^2 + b'(\ln z) + c'$], numerical values ($a$, b, c and a', b', c') are obtained by the least-square method to fit the observed mean values of U and θ.

Figure 2 shows the vertical profiles of wind speed and air temperature at 0500 LT, December 11, 1980. The curves obtained by using the second-order polynomial, which are indicated by solid lines, fit the observed data (open circles). Therefore, it is concluded that the technique is satisfactory. The hourly gradients of mean wind

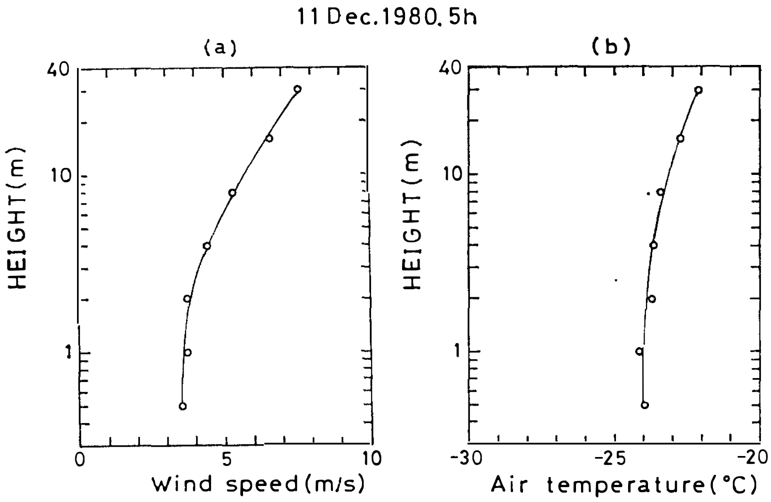

Fig. 2. Vertical profiles of wind speed (left) and air temperature (right) at 0500LT, December 11, 1980.

velocity $\partial U/\partial z$ and potential temperature $\partial \theta/\partial z$ were obtained by differentiating second-order polynomials in ($\ln z$), and finally Ri were estimated. The above method is the same as that of IZUMI (1971).

The normalized third-order moment (skewness, S_w) and fourth-order moment (kurtosis, K_w) for the vertical wind velocity are defined by

$$S_w = \overline{w^3}/\sigma_w^3, \tag{2}$$

$$K_w = \overline{w^4}/\sigma_w^4, \tag{3}$$

where w is vertical turbulent wind velocity and σ_w the r.m.s. of vertical wind velocity.

The relative error between the values of S_w (or K_w) for sampling duration 15 min and those for 30 min were investigated in order to check the statistical stationary of S_w and K_w. As a result, the underestimation in 15 min data was about 5% for S_w and about 2% for K_w. The small differences between them support the use of 15 min data in this study.

The apparent zero shift of the vertical wind velocity component was found in the time series as shown in Fig. 1. For this reason, KOBAYASHI *et al.* (1982b) suggested that the mean vertical wind velocity shows the mean subsidence velocity $\overline{w}$. In our results, the values of $\overline{w}$ for $0.05 < Ri < 1.0$ were about -10 cm/s at 3 m, and about -20 cm/s at 30 m, respectively. Of course this $\overline{w}$ was removed from the raw vertical wind velocity. Though the effect of $\overline{w}$ on other turbulence quantities is important, it will not be studied here.

3. Results and Discussion

3.1. *Turbulent intensity and intermittency factor of w component*

The vertical turbulent intensity σ_w/U at two levels are plotted with different symbols in Fig. 3 as a function of Ri. The values of σ_w/U at 3 m decay gradually for $Ri > 0.05$, while those at 30 m remain very small ($\simeq 0.015$), which is indicated

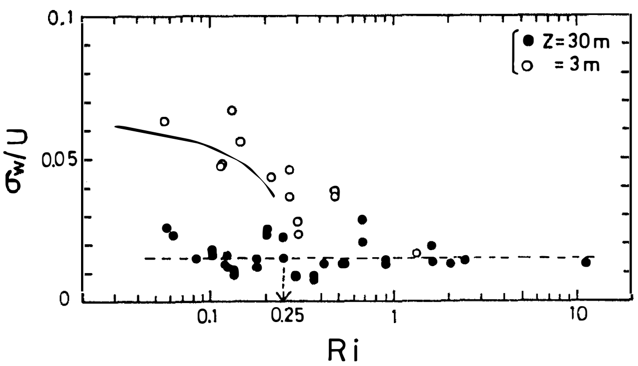

Fig. 3. Relationship between the vertical turbulent intensity (σ_w/U) and gradient Richardson number Ri in the range $0.05 < Ri < 12$. The solid line shows KONDO *et al.'s (1978) empirical relation at 3 m and the dashed line indicates $\sigma_w/U = 0.015$.*

by the dashed line, over a wide range ($0.05 < Ri < 11$). The former observed data (open circles) for *Ri* agree fairly well with the solid line, which represents KONDO *et al.*'s (1978) empirical relation:

$$\sigma_w/U = 1.1k/[\ln(z/z_0) + 7X/(1-7X)], \quad X = Ri/[6.873Ri + 1/(1+6.873Ri)],$$

where $k(=0.4)$ is the Karman constant, and roughness height $z_0 = 0.24$ cm (SASAKI, 1979). However, there is not any obvious reason for the independence of *Ri* at 30 m and this fact has not yet been known.

Two important points are presented from Fig. 3. First, it appears that the behavior of the vertical turbulent wind velocity is different at different levels. That is, the influence of wave-like motion on *w* component at 3 m is negligibly small as compared with that at 30 m (see, KOBAYASHI *et al.*, 1982b). Second, it is expected that σ_w at 30 m is about 15 cm/s at the lowest estimate if it is accepted that $\sigma_w/U = 0.015$ and $U = 10$ m/s characterized by the typical katabatic winds at Mizuho Station. This value of $\sigma_w = 15$ cm/s will be related to the threshold value of the intermittency factor shown later.

In a very stable surface layer, intermittent structure in which both quiet and turbulent flow simultaneously exist is frequently observed in the vertical wind velocity as well as the temperature fluctuation. Therefore, we should consider the intermittency factor (I_w) which indicates the degree of intermittent turbulence of the vertical wind velocity fluctuation.

Generally, I_w is defined as the ratio of the time during which turbulence is observed to the sampling duration (30 min). A detailed explanation of the intermittency factor has been given by KONDO *et al.* (1978).

We can consider the "turbulent state" to be the period when the r.m.s. σ_w, which is calculated continuously every 10 s, is larger than 10 cm/s. Our choice of the threshold level of 10 cm/s is selected for two reasons. One is that the accuracy obtained by reading raw *w* component data is greater than 1 cm/s. The other is connected with the value of $\sigma_w/U = 0.015$ mentioned above.

Intermittent turbulence is also closely related to the critical Richardson number

Ri_{crit}. In general, it can be said that Ri_{crit} is a useful parameter distinguishing between the range of turbulence and that of non-turbulence. There has been much research concerning Ri_{crit} and its existence (YAMAMOTO, 1975; KONDO *et al.*, 1978). OKE (1970) summarized the values of Ri_{crit}, but, from the observational point of view, this Ri_{crit} cannot be strictly determined because of its wide distribution from 0.05 to 0.4. In this sense it seems convenient for this study to use Ri ($=0.25$) derived from the theory (DRAZIN, 1958) as Ri_{crit}.

Figure 4 displays the relationship between I_w and Ri. The factor at 3 m (open circles) begins to rapidly decay beyond $Ri=0.2$. A similar tendency of the temperature fluctuation is suggested by KONDO *et al.* (1978).

On the other hand, the values of I_w at 30 m are divided into two regions in the vicinity of $Ri=0.4$. In one region ($Ri<0.4$), it appears that the values of I_w are approximated well by the following empirical formula:

$$I_w=\exp[-50(Ri-0.1)^2] \qquad \text{for } 0.1<Ri<0.4. \tag{4}$$

The data for $Ri>0.4$ (surrounded by the dashed line) have common characteristic in the raw data, which were observed during the periods of 0040–0240, 4 December and 0130–0430, 11 December 1980 when Ri continuously decreased. Namely, the data contain wave-like flow with a prevailing period of about 10 s. These waves were mostly found during the shift from quiet to turbulent flow while Ri varied from 2 to 0.4.

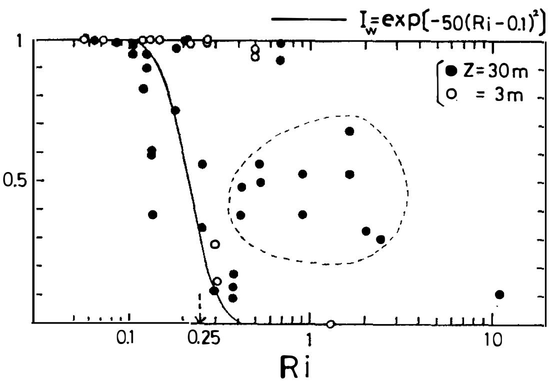

Fig. 4. Variation of intermittency factor I_w with Ri for stable condition. The solid line is from eq. (4) and the symbols are the same as those in Fig. 3.

Thus, two kinds of waves dominate the data observed at Mizuho Station; one has a period of about 20 s associated with shear instability previously reported by KOBAYASHI *et al.* (1982a).

One example of the w spectra under the range of $Ri>0.4$ is shown in Fig. 5, which plots the $nS(n)$ *versus* n, where $S(n)$ is the power spectral density at the frequency n. The peak of spectral energy is clearly discernible near $n\sim0.1$ Hz (corresponding to the period of 10 s).

Consequently, as shown in the result reported by YOKOYAMA *et al.* (1983), it seems clear that coexistence of wave-like motion and turbulence near Ri_{crit} is an inevitable

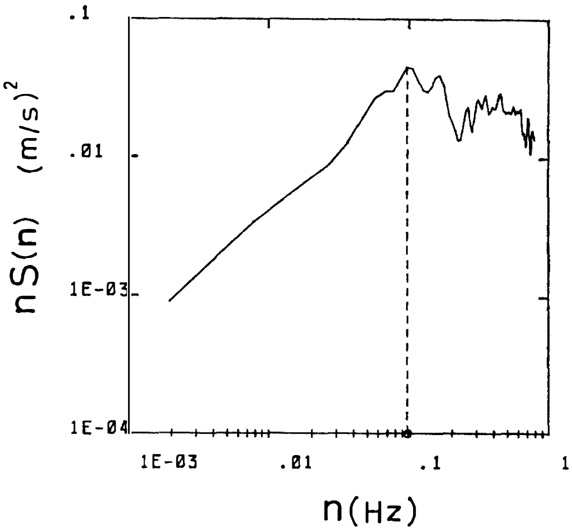

Fig. 5. Power spectra for the vertical wind velocity over the period 0300–0310, December 11, 1980 at 30 m at Nizuho Station. The peak frequency is indicated by the vertical dashed bar.

fact. For reference, the difference between the wave observed at Mizuho Station and that found by YOKOYAMA *et al.* (1983) is the strong mean wind velocity in the former case.

3.2. *Skewness and kurtosis of w component*

To date it has been suggested from several studies that S_w is around -0.2 in stable conditions (CHIBA, 1978; SASAKI, 1979), and K_w increases with stability (CHIBA and KIKUCHI, 1982). However, characteristics of S_w and K_w for strong stabilities cannot be thoroughly studied because of scattering due to the inherent nature of the higher-order moments. Moreover, the appearance of wave-like motion, which can be also ascertained by the Brunt-Väisälä frequency, may partially result in scatter.

In order to remove the effect of the wave with a period larger than 20 s to w component itself at 30 m only, the digital signals filtered with a 0.05 Hz high-pass filter were analyzed, and the results are shown in Figs. 6a–6c. Here in each figure the arrow denotes the position of Ri_{crit} $(=0.25)$.

The ratio of the filtered σ_w to σ_{wo} calculated directly from the raw data is shown in Fig. 6a against Ri. There is an obvious change near $Ri=0.25$, beyond which σ_w/σ_{wo} is about 0.85. Likewise, as shown by the dashed line in Fig. 6b, the value of the filtered S_w is about -0.3 for Ri up to 0.25, and gradually converges around zero with increasing Ri for $Ri>0.25$ although there are some scattering data. From the fact that the turbulence almost ceases with increasing stability, it seems reasonable that S_w approaches zero for $Ri>0.25$. These results indicate that, at $z=30$ m, a slowly-varying frequency with period larger than 20 s affects the estimates of σ_w and S_w.

Figure 6c shows the filtered values of K_w plotted against Ri. It seems that despite the abnormally scattered data near Ri_{crit}, the value of K_w gradually increases with increasing Ri as indicated by the dashed line. This qualitative dependence on

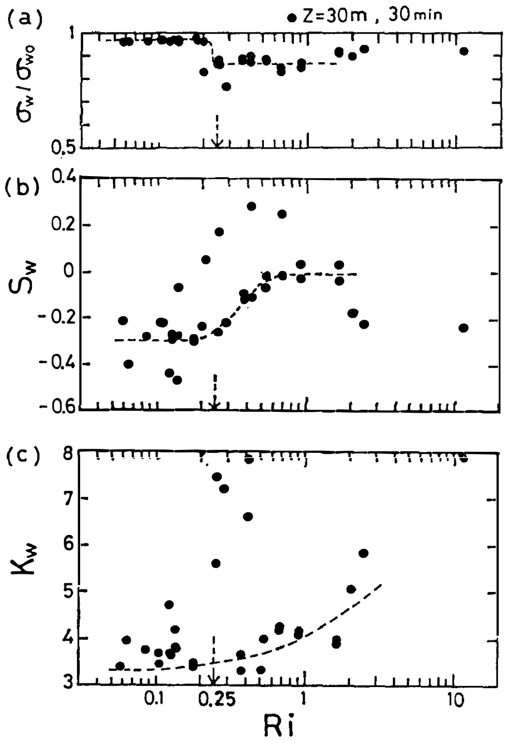

Fig. 6. (*a*) *Relation between Ri and the ratio of filtered σ_w to σ_{wo} calculated from raw data of the w component at 30 m.* (*b*) *Filtered S_w as a function of Ri.* (*c*) *Filtered K_w as a function of Ri. Dashed lines in* (*a*), (*b*) *and* (*c*) *are eye-fits to the data of σ_w/σ_{wo}, S_w and K_w, respectively.*

stability has been indicated by many workers. According to this result, we can conclude that the effect of the wave on K_w is much smaller than on S_w. Instead of this fact, it is inferred that intermittent turbulence may greatly affect the values of K_w.

4. Concluding Remarks

Characteristics of the vertical wind velocity found near the critical gradient Richardson number are mainly as follows:

1) Intermittent turbulence for w components at 3 and 30 m appears in the strong stable range of Ri=0.2–0.4.

2) In a wide range of Ri larger than 0.2, wave-like motion with two groups of periods are remarkable. That is, the periods of about 10 s and about 20 s.

3) After filtering through a 0.05 Hz high-pass filter, σ_w and S_w indicate a rapid change and K_w little change in the vicinity of Ri=0.25.

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