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Parameterization of Turbulent Mixing in the Western Equatorial Pacific
— Preliminary Observation —

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Abstract

The Richardson number dependence of vertical eddy diffusion coefficients in the western Equatorial Pacific Ocean was examined on the basis of a Microstructure Profiler (MSP) observations during the cruise of Natsushima (JAPACS-1989). The Richardson number was estimated by using the mean shear of velocity profile measured by an Acoustic Doppler Current Profiler (ADCP) with the vertical interval of 15 meters within one two hours of the each MSP cast. The raw data plot of the vertical eddy coefficient shows a large scatter with increasing tendency below $R_i=0.5$. The relation between the mean vertical eddy coefficient K_ρ and the Richardson number R_i, averaged over every 0.025 in the R_i, supports the model of Pacanowski and Philander (1981) in the range of $R_i>0.5$, but coincides with the result of Peter et al. (1988) in the range of $R_i<0.5$.

1. Introduction

The eastward flowing Equatorial Undercurrent plugged within the layer of thermocline is an important feature of the Equatorial Current system. The current firstly discovered by Cromwell in 1952 has typical width of about 300 km, thickness of about 100 m, and a pair of high shear zone just above and below the Undercurrent core. The vertical turbulent mixing of momentum and heat is one of major control terms for the Undercurrent dynamics.

The small-scale mixing processes may have also significant contributions to the large-scale dynamics in the equatorial region. The first observation of temperature and salinity microstructure in the region of the Atlantic Equatorial Undercurrent was made by Gregg (1976). Similar microstructure measurements in the same region were made by Crawford and Osborn (1979).

A new method for measuring turbulent velocity shear by using an airfoil probe has been developed by Osborn and Crawford (1980), Gargett and Osborn (1979) and Crawford and Osborn (1981). The method was applied for measurements of the rate of turbulent kinetic energy dissipation ε in the equatorial region. Crawford and Osborn (1981) measured the rate of turbulent dissipation in the eastern Pacific equatorial region (150°W, 3°N) during the cruise of the Candian Survey Ship Parizeau in 1979, and found that the averaged rate of dissipation clearly increases near the Equator. Crawford (1982) discussed about the result of the estimate of turbulent eddy viscosity and diffusivity using the rate of dissipation and large-scale shear and obtained the estimated vertical eddy viscosity of order of 0.001 m^2/s.

As a part of Tropic Heat Program, turbulence and shear were sampled intensively from the R/V Thompson between 3°N and 2.5°S at 140°W during mid November and early December 1984 (Peters et al., 1988). They discussed the vertical structure of the shear, stratification, and turbulence in the equatorial region, and parameterized the vertical eddy coefficient using the same Richardson number R_i as used for numerical modeling by Pacanowski and Philander (1981). They found that the eddy coefficient was low at high R_i, and gradually increased as R_i decreased until they rose dramatically near $R_i=1/4$.

Another intensive measurement on the mixing in the Pacific equatorial surface layer and thermocline was carried out during observation period of Tropic Heat I on the R/V Wecoma (Moum et al., 1989). They estimated the mean shear from ADCP data averaged vertically over 24 m to obtain the relations between ε and R_i. Their averaged ε gives the critical Richardson number of $R_{ic}=0.7\pm0.05$. However, Moum et al. stated that there is no sign of a functional dependence of ε on R_i.

In this paper, we describe K_ρ-R_i correlation of the preliminary observation of microstructure taken during January 24 and February 10, 1989 from the R/V Natsushima between 5°N and 5°S at from 175°W to 160°E. The instrument used in the observation is the microstructure profiler (MSP) developed by Kanari (1991). The MSP, a 0.8 m long free-fall vehicle, samples microscale velocity shear, temperature and conductivity gradients. The velocity shear is sensed by an airfoil shear probe at the lower end of MSP. The probe can resolve shears with vertical wavelengths between 0.01 and 1.0 m. Six-channel signals — shear, temperature, conductivity, temperature gradient, conductivity gradient, and pressure — are sampled with every 0.01 sec. interval and recorded on the self-contained IC-memory, which is read out after recovery of the instrument. The details of the instrument are discussed by Kanari (1991). This is the first observation of the microstructure in the western equatorial region, where the mixed layer is considerable thicker than in the eastern equatorial region. After a brief description on observation in section 2, correlation among the vertical profiles of the rate of energy dissipation, stratification, and ADCP shear are shown in section 3. The scatter plot of the estimated eddy coefficients as a function of R_i is presented in section 4.

2. Observation

Microstructure measurements were carried out during the cruise of JAPACS-89 by the R/V Natsushima along the ships track as shown in Fig. 1. The microstructure measurements were made at the seven stations from MSP1 to MSP7. The three of seven stations are located on the equator and the others are off equator of 3～5°N and 3～5°S. These stations are located in the western Pacific equatorial region from 175°W to 160°E.

Additional shear estimates of mean flow near each station were made using the ship board Acoustic Doppler Current Profiler (ADCP), which measures the current profile at a vertical interval of 15 meters. The ADCP shear was estimated from the ADCP velocity profile. The details of locations and time of MSP cast are listed in Table 1.

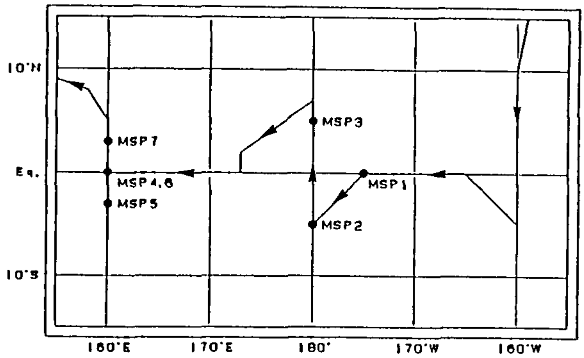

Fig. 1. The ship track of the JAPACS-89. The filled circles mark the location of MSP stations.

Table 1. The locations and the time of MSP observations in GMT and local mean time.

STN.	LOCATION	TIME (GMT)	TIME (LOCAL)
MSP 1	0°01′N 175°00′W	89-01-24 03:31	89-01-23 15:51
MSP 2	5°00′S 180°00′W	89-01-25 17:00	89-01-25 05:00
MSP 3	5°00′N 180°00′W	89-01-28 22:56	89-01-29 10:56
MSP 4	0°00′N 160°00′E	89-02-06 02:03	89-02-07 12:43
MSP 5	3°00′S 159°59′E	89-02-07 23:52	89-02-08 10:32
MSP 6	0°00′N 159°54′E	89-02-09 03:33	89-02-09 14:13
MSP 7	3°03′N 159°58′E	89-02-10 00:40	89-02-10 11:20

3. Correlation between mean field and turbulent dissipation

3.1 Mean current field

The typical current profiles measured by the ADCP at the stations, MSP3, MSP5, and MSP6 are shown in Fig. 2. In the profile at MSP6 (Fig. 2(b)) on the equator, the Equatorial Undercurrent can be found at the depths between 160 m and 280 m. The core velocity of about 60 cm/s at the depth of 200 m is rather typical in the western Pacific region. At the northern station MSP3 (Fig. 2(a)), there is no notable flow in contrast with the thick strong South Equatorial Currents flowing to WSW as seen in MSP5 (Fig. 2(c)).

The core velocity of the Undercurrent at the station of MSP1 (the profile is not shown here) is also as low as at MSP6, though the maximum velocity appears at 180 m.

3.2 Stratification profiles and dissipations

Figure 3 shows an example of the stratification conditions and dissipation profile at MSP6. The main thermocline in this region extends from the depths of 180 m to 260 m, and it almost coincides with the layer of the Equatorial Undercurrent as seen in Fig. 3(d).

The temperature profile reveals a typical mixed layer and thermocline structure with small inversions, while the salinity profile has considerable fine-scale fluctuations without any mixed layer structure. However, as seen in the stable density profile, the salinity profile is well compensated by temperature.

The microscale velocity shear (Fig. 3(b)) shows an almost constant variance in the mixed layer, but it drastically decreases in the thermocline. The rate of dissipation was estimated for every 3 m bins of the shear data. The resultant profile with logarithmic scale is given in Fig. 3(c). As seen in Fig. 3(c), the rate

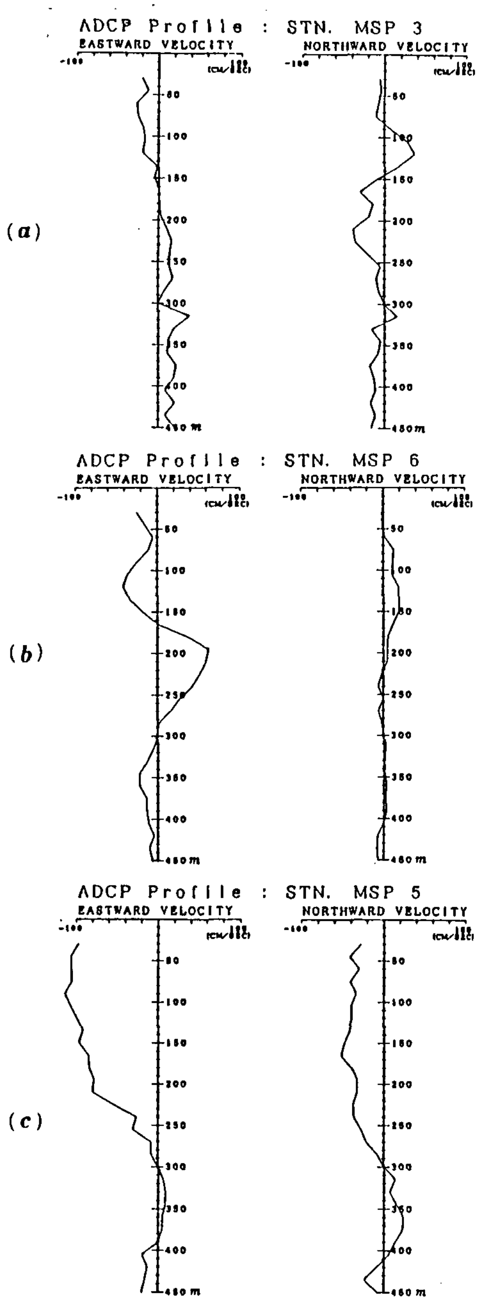

Fig. 2. The vertical profiles of velocity components at the stations of MSP3 (a), MSP6 (b) and MSP5 (c) on the basis of the ADCP data taken at every 15 m interval.

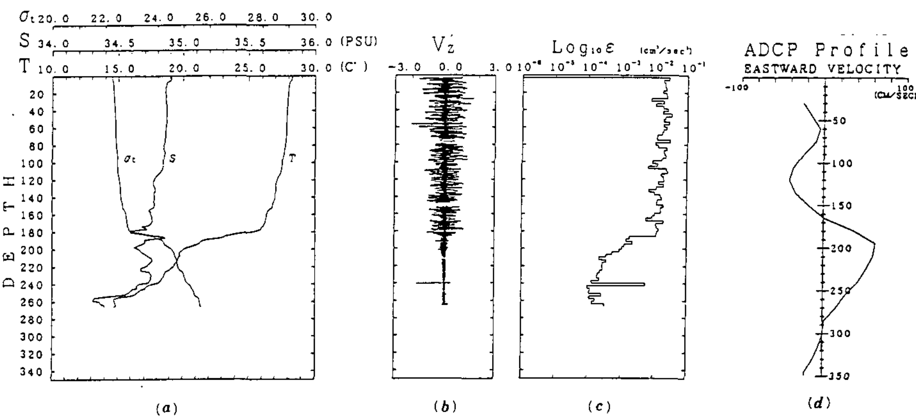

Fig. 3. Graphical correlation between stratification condition (a) and the microscale shear profile (b) at MSP6. The estimated rate of dissipation averaged in every 3 m bins (c) drastically decreases in the layer of the Under Current demonstrated in the ADCP profile (d).

of dissipation in the mixed layer at the station shows an almost constant value of about 2×10^{-2} (cm^2/s^3), and it decreases in the thermocline to the minimum level of about 10^{-4} (cm^2/s^3). A local high in the dissipation profile at the layer around 240 m may be reflection by wobbling of the instrument.

In comparison with the velocity profile, the rate of dissipation drops to the below of the Undercurrent core. Such a feature is slightly different from those by Peters et al. (1988) and also by Moum et al. (1989) in which the minimum of dissipation almost coincides to just the depth of the core. In the present case, the decreasing rate of dissipation is almost constant within the mixed layer at the station MSP6. Such a feature is seen in the profile at MSP4 taken three days before the MSP6 (both the same location). The profiles of dissipation rate at MSP2, MSP3, MSP5 and MSP7 off the equator are slightly different from those on the equator as shown in Fig. 4. The top left and right show the vertical profiles of dissipation rate at MSP7 (3°N) and at MSP3 (5°N) respectively. Both log $\varepsilon(z)$ profiles show a linear decrease from near surface to thermocline base. There is no distinct minimum even in the thermocline. The bottom left and right show the profiles at MSP5 (3°S) and MSP2 (5°S) respectively. These profiles also show the same feature as those at the station MSP3 and MSP7.

The dissipation profilers at the stations on the equator and the stations off the equator presented by Crawford (1982) also show a similar tendency as described above (Fig. 5 in Crawford's paper).

At the stations off the equator, the source of turbulence mainly comes from

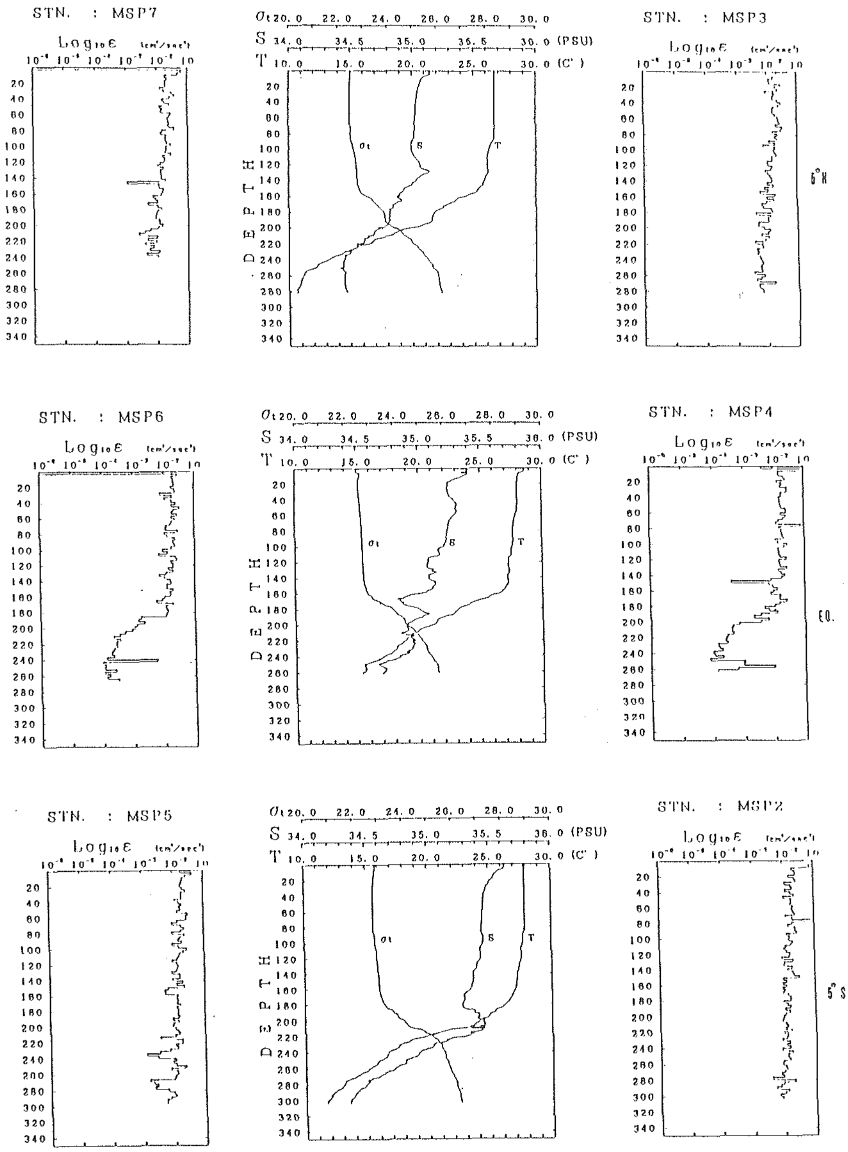

Fig. 4. The vertical profiles of the estimated rate of dissipation ε at each station compared with the representative stratification profiles at MSP3 (5°N), MSP4 (equator), and MSP2 (5°S). The profiles of dissipation rate on the equator (middle panel) show a sudden decrease below the mixed layer, while the profiles off the equator (top and bottom panels) show a gradual decrease from surface to the thermocline.

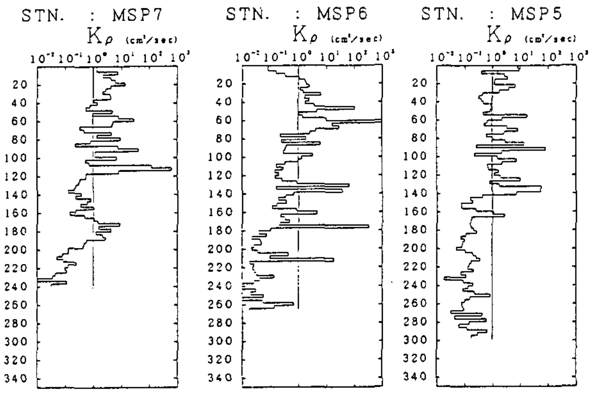

Fig. 5. Examples of the estimated K_ρ profiles at MSP5, MSP6 and MSP7.

surface, while on the equator the strong shear layer on the upper side of the undercurrent core is another source of turbulence. Such a difference in the turbulent source distribution would cause a local difference in dissipation profiles. Moum et al. (1989) have described that the core of the Equatorial Undercurrent coincides with both the pycnocline and the salinity maximum at 105 to 120 m depth. As seen in Fig. 4, however, there is no clear maximum in salinity profile, but the core of the Equatorial Undercurrent coincides with the local minimum of salinity at the depth of 200 m. Peters et al. (1988) reported that in contrast to the shear zones above and below, no events of high ε occurred in the undercurrent core, and mixing was not active in the core because the value of ε was almost always lower than the transition dissipation rate $\varepsilon_{tr}=20\nu N^2$, where ν is the kinematic viscosity, N the stability frequency. The transition dissipation rate ε_{tr} is a measure of turbulant 'activity', below which mixing no longer sustains the negative buoyancy flux necessary for a net increase in potential energy. In our measurement, the squared stability frequency N^2 in the thermocline is about 3×10^{-4} (1/s²), and this yields the transition of $20\nu N^2=6\times10^{-5}$ (cm²/s³), which shows that the minimum dissipation rate (1×10^{-4} cm²/s³) in the thermocline is larger than the transition, and the result suggests that the turbulence in the layer of the Undercurrent would be slightly active.

4. Parameterization of $K\rho$

Parameterization of eddy coefficients as a function of the Richardson number for the equatorial models have presented by Pacanowski and Philander (1981). They expressed the eddy coefficients K_m and K_h for momentum and heat respectively, as a functuion of Richardson number. Another parameterization was presented by Peters et al. (1988) using the microstructure data taken at the Pacific equatorial region. The result by Peters et al. (1988) shows a steep increase in the range below $R_i \sim 1/2$, while the coefficients by Pacanowski and Philander (1981) have a gradual increase over the whole range of Richardson number.

Similar approach has done by Moum et al. (1989) using the similar microstructure data sets. They examined the ε-R_i relation, and found that the dissipation rate drastically increases in the range of $R_i < 0.7$.

4.1 Estimate of the eddy coefficients

With the assumption that the stratification is dominated by temperature, an approximation of $K_h = K_\rho$ could be allowed, where K_ρ is the vertical eddy diffusivity of mass. The K_ρ can be estimated from a simplified equation of turbulent energy budget (Osborn, 1980) as

$$K_\rho = \gamma_m \ \varepsilon / N^2 \qquad (1)$$

where N is the stability frequency, γ_m is the mixing efficiency coefficient related with the flux Richardson number R_f. Moum et al. (1989) suggesting the value of γ_m ranges between 0.12 and 0.48, and they used an intermediate value of 0.2 to estimate the turbulent heat fluxes.

In the present estimate, we used the value of γ_m estimated from temperature microstructure and dissipation rate in each bin. The estimate of K_ρ was made for every 3 m vertical bins. Some examples of the estimated K_ρ profile are shown in Fig. 5. The middle panel shows the profile at the equator, and the left and right panels at 3°N and at 3°S, respectively. In each panel, the value of $K_\rho = 1.0\ \text{cm}^2/\text{s}$ is shown by a vertical line. The value of eddy coefficient K_ρ roughly takes a canonical value of $1.0\ \text{cm}^2/\text{s}$ in the mixed layer, and about one order lower value in the thermocline. A large fluctuation in the K_ρ profile may be due to reflection of widely scattered γ_m.

4.2 Mean shear in R_i estimate

In estimating R_i, the averaging scale of mean shear may be an important factor. It is not well understood what averaging scale is the best for the shear estimate in the evaluation of R_i. Moum et al. (1989) used the ADCP shear vertically averaged over 24 m. They noted that the averaging scale is much larger than scales of most turbulent eddies. Peters et al. (1988) also used the ADCP profiles of the depth bins of 6.4 m.

In the present estimate, we used the ADCP shear which was estimated by numerical differentiation of the ADCP profile taken with the vertical intervals of 15 m.

4.3 K_ρ-R_i relation

The scatterplot of the estimated vertical eddy diffusivity K_ρ is given as a

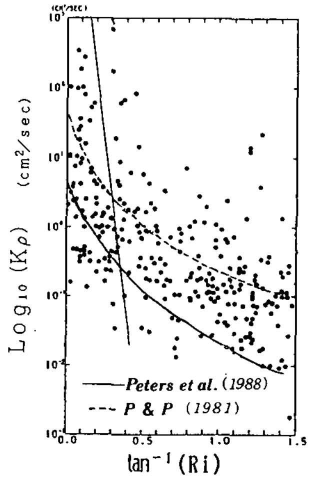

Fig. 6. The scatterplot of the estimated vertical eddy diffusivity K_ρ versus $\tan^{-1}(R_i)$. In the figure, the dashed curve shows the model of Pacanowski and Philander (1981), and the two solid lines by Peters et al. (1988).

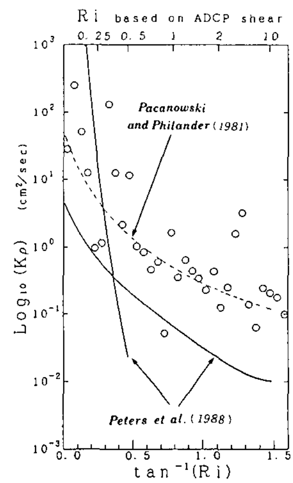

Fig. 7. The sectionally averaged K_ρ-R_i relation. The dashed curve and the two solid lines are the same as in Fig. 6.

function of $\tan^{-1}(R_i)$ in Fig. 6. In this figure, the dashed curve shows the K_h of Pacanowski and Philander's parameterization, and the two solid lines show the revised version by Peters et al. (1988). The R_i in Fig. 6 is based on the ADCP shear. The scatterplot in Fig. 6 seems to show an intermediate value between the Pacanowski and Philander (1981) and the Peters et al. (1988) over the whole range of $\tan^{-1}(R_i)$. Figure 7 shows the result of K_ρ dependence on the sectionary averaged Richardson number R_i over every 0.025 intervals of R_i. However, the averaged points in Fig. 7 (open circles) coincide with the model of Pacanowski and Philander (1981), and the increasing rate of K_ρ with decreasing R_i in the range of $R_i < 0.5$ coincides with the result of Peters et al. (1988).

5. Conclusion

As a preliminary research on the turbulent mixing in the Western Equatorial Pacific Ocean, we examined a several sets of microstructure data taken at the sites along the western equatorial region during the JAPACS cruise. The results are summarized in the below.

(1) The rate of turbulent kinetic energy dissipation on the equator is an almost constant value of about 2×10^{-2} cm^2/s^3, but it sharply drops to 7×10^{-5} cm^2/s^3 on the equator. The rate of dissipation at off the equator (3°～5°N and 3°～5°S) shows a linear decrease in log-scale from surface to the base of thermocline.

(2) The raw data scatterplot of vertical eddy diffusivity of mass correlated with the Richardson number R_i seems to show that the K_ρ value is slightly higher than that of Peters et al. (1988) but lower than that of the Pacanowski and Philander's model. However, the sectionally averaged K_ρ-R_i relation supports the model of Pacanowski and Philander (1981), in the range of $R_i > 0.5$, while it coincides with the result of Peters et al. (1988) in the range of $R_i < 0.5$.

The observation and the results in the present paper are the preliminary and tentative one. For establishing reliable parameterization of the equatorial turbulence, we need to accumulate more data with shorter time interval of profiling over various weather conditions. We are now preparing an instrument of new version to measure profiles with a shorter time interval. More qualified discussions will be done using the data from more intensified observations with the new version in near future.

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