August 27-31, 2023
FLORENCE - ITALY
16th International
Conference on
Wind Engineering

Investigation of atmospheric stability in Tokyo using observation data and analysis data by WRF

Ryuichiro Yoshie [1], Takumi Tachibana [2], Yingli Xuan [3]

[1] *Tokyo Polytechnic University, Kanagawa, Japan, yoshie@arch.t-kougei.ac.jp*
[2] *Wind Engineering Institute, Co, Ltd, Tokyo, Japan, tachibana@wei.co.jp*
[3] *Tokyo Polytechnic University, Kanagawa, Japan, y.xuan@arch.t-kougei.ac.jp*

SUMMARY
We investigated Bulk Richardson number (R_b) of real atmospheric conditions using wind speed and temperature observed at an altitude of about 200 m and ground surface temperature analyzed by WRF (Weather Research and Forecasting model). This clarified the range and occurrence frequency of R_b in real atmospheric conditions. It became clear that the range of R_b in the real atmospheric conditions was much wider than that in our previous wind tunnel experiment. We also investigated the correspondence between the R_b and the Pasquill atmospheric stability class used for environmental assessment of air pollution in Japan. The Pasquill stability and the R_b correspond well on average, but it is likely that the Pasquill stability is often inconsistent with the R_b. In addition, vertical profiles of mean wind speed obtained from Doppler Lidar observations were classified according to the atmospheric stability. It was found that the wind speed at low altitudes increases as atmospheric stability becomes unstable.

Keywords: bulk Richardson number, Pasquil stability class, vertical profile of mean wind speed

1. INTRODUCTION

Atmospheric stability has a large influence on pollutant dispersion in urban areas. We conducted gas dispersion experiment under various atmospheric stability in thermally stratified wind tunnel, and proposed *SER_C** (stability effect ratio of normalized pollutant concentration) (Hu and Yoshie, 2020). *SER_C** is the ratio of normalized pollutant concentration under non-neutral atmospheric stability condition to that under neutral condition. According to the experiment, *SER_C** increased as the Bulk Richardson number (R_b) increased, and it implied the *SER_C** could be expressed by the function of R_b. However, it is not clear to what extent the range of R_b that can be reproduced in the wind tunnel covers the range of real atmospheric conditions. Thus, we investigated Bulk Richardson number (R_b) of real atmospheric conditions using wind speed and temperature observed at about 200 m altitude and ground surface temperature analyzed by WRF.

2. PASQUILL STABILITY CLASS AND BULK RICHARDSON NUMBER

According to the Pasquill stability class (Table 1), seven main atmospheric stability classes are specified, A (very unstable), B (unstable), C (slightly unstable), D (neutral), E (slightly stable), F (stable), and G (very stable). The Pasquill stability class is used for environmental assessment for air pollution in Japan. On the other hand, the bulk Richardson number R_b is a dimensionless similarity parameter (pi number) that expresses the ratio of inertial force to buoyant force. The R_b is also used to express the atmospheric stability. The R_b is calculated by Eq. (1).

$$R_b = \frac{gH(\theta_H - \theta_G)}{\{\theta_a\, U_H^2\}} \tag{1}$$

Where g is acceleration of gravity [m/s^2], H is reference height [m], θ_H is representative potential temperature [K] and θ_G is ground surface temperature [K], θ_a is average of potential temperature below 200 m height [K]. For $R_b < 0$, the atmospheric stability is unstable, and $R_b > 0$, the atmospheric stability is stable. $R_b = 0$ represents a neutral condition.

Table 1. Pasquill stability class.

Surface wind speed at 10m above ground U [m/s]	Daytime Solar radiation T [kW/m^2]				Cloud cover	Night-time cloud cover	
	$T \geq 0.6$	$0.6 > T \geq 0.3$	$0.3 > T \geq 0.15$	$T < 0.15$	10	5-10	0-4
$U < 2$	A	A-B	B	D	D	G	G
$2 \leq U < 3$	A-B	B	C	D	D	E	E
$3 \leq U < 4$	B	B-C	C	D	D	D	D
$4 \leq U < 6$	C	C-D	D	D	D	D	D
$6 \leq U$	C	D	D	D	D	D	D

3. WRF ANALYSIS FOR GROUND SURFACE TEMPERATURE

In order to calculate R_b, ground surface temperature data θ_G is required. But since we had no observation data available, we decided to obtain ground surface temperature data through WRF calculation. The WRF analysis period is one year from May 2018 to April 2019. Fig**.** 2 compares the time series of near-surface air temperatures obtained by WRF and observation in August. The observation data is the hourly averaged air temperature at Tokyo Tower (point A in Figure 2, 4 m heigh). The temperature at 2m above the ground obtained by WRF is in good agreement with the observed data and reproduces the temporal change of temperature well. The ground surface temperature θ_G is also expected to be in good agreement.

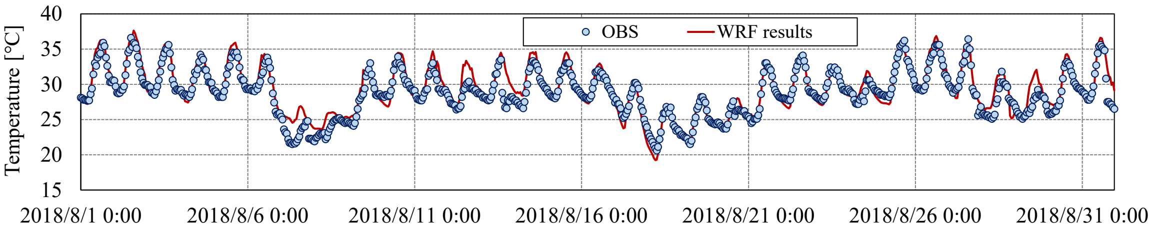


Figure 1. Time history of near-surface air temperature in August.

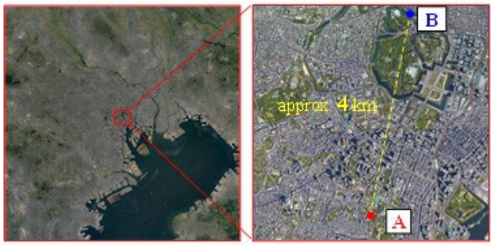


Figure 2. Observation points in central Tokyo. A: temperature, B: wind velocity

4. ANUAL FREQUENCY OF BULK RICHARDSON NUMBER

For the calculation of R_b, we used the temperature measured at Tokyo Tower (point A in Fig. 2, height 205 m) as the representative temperature θ_H. For the representative wind speed U_H, the wind speed at an altitude of 200 m measured by a Doppler lidar at point B was used. The ground surface temperature θ_G was evaluated by WRF analysis as previously described. Fig. 3 shows the annual occurrence frequency of the R_b. The R_b is distributed around -15~9 and occurs frequently on the unstable side. The range of R_b in the wind tunnel experiment (Hu and Yoshie, 2020) was -1.68~+1.94. The range of R_b in the wind tunnel experiments was found to be much narrower than in the real atmospheric conditions.

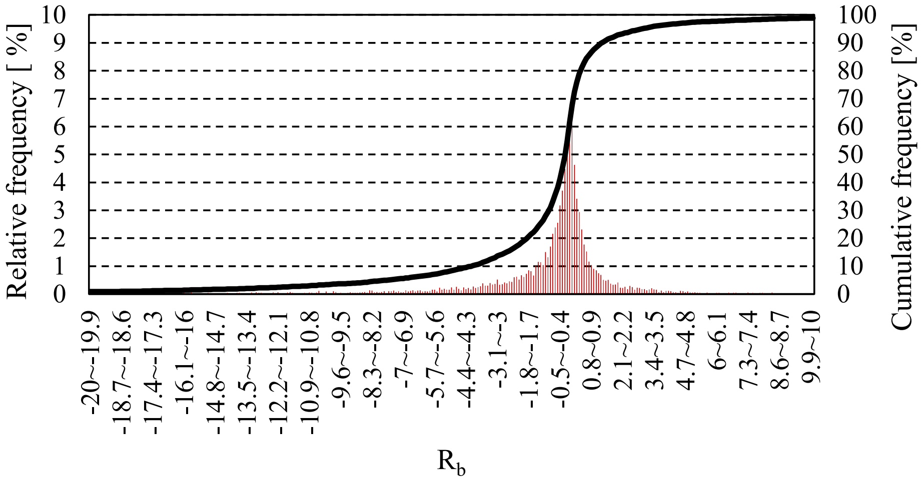


Figure 3. Annual occurrence frequency of bulk Richardson number (R_b).

5. COMPARISON BETWEEN PASQUILL STABILITY CLASS AND BULK RICHARDSON NUMBER

Fig. 3 shows relationship between Pasquill stability class and the R_b . The data was firstly classified by the Pasquill stability class. The average value and standard deviation of the R_b for each Pasquill stability class were then calculated. The circle and the error bar in Fig. 4 represent average value and standard deviation of the R_b respectively. For stability classes A, A-B, B, B-C, C and C-D, the average value of R_b is negative (unstable), and for E, F and G, the averaged value of R_b is positive (stable). The averaged value of R_b is almost 0 for stability class D, which means neutral. The Pasquill stability class captured the difference between unstable and stable atmospheric stabilities. However, the error bars are large when the Pasquill stability classes are A, A-B, B, D and G. Nakajima et al. (2020) investigated the relationship between Pasquill stability class and that from the Monin–Obukhov length using the observation data of upward turbulent heat flux and friction velocity measured by an ultrasonic anemometer in Tokyo. Our result (Fig. 4) is very similar to that of Nakajima et al.. From the above, the Pasquill stability class and the bulk Richardson number correspond well on average. However, the bulk Richardson numbers for "Very Unstable", "Unstable", "Neutral", and "Very Stable" vary widely. Therefore, it is likely that the Pasquill stability is often inconsistent with the bulk Richardson number.

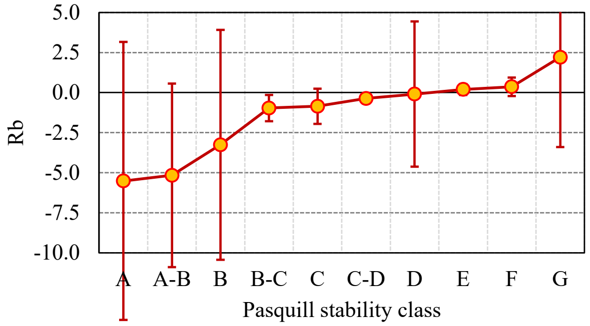
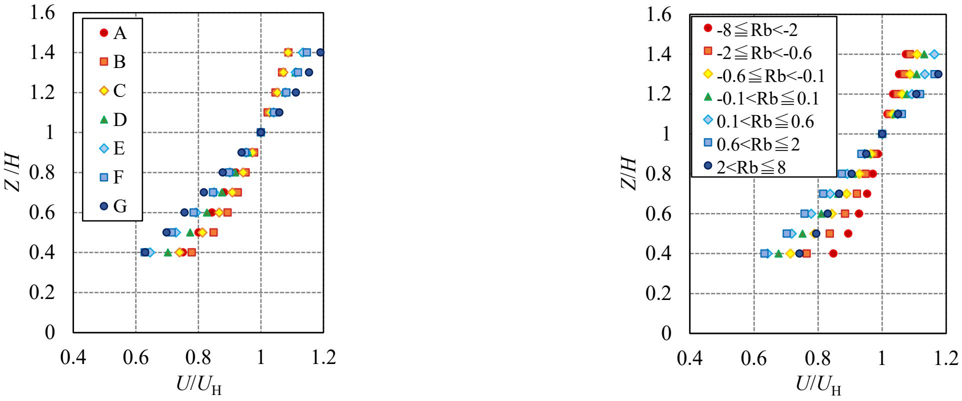


Figure 4. Relationship between Pasquill stability class and bulk Richardson number (R_b)

6. Vertical profiles of mean wind speed classified by atmospheric stability

Figure 5 shows the vertical profile of mean wind speed classified by atmospheric stability. It can be seen that when the atmospheric stability becomes unstable, the wind speed at lower part of boundary layer increases. This trend is more significant when classified by R_b than by Pasquill stability class.



(a) classified by Pasquill stability class

(b) classified by R_b

Figure 5. Vertical profiles of mean wind speed classified by atmospheric stability.

7. CONCLUSIONS

We investigated Bulk Richardson number (R_b) of real atmospheric conditions using wind speed and temperature observed at an altitude of about 200 m and ground surface temperature analyzed by WRF. This investigation revealed the followings: The range and frequency of occurrence of R_b under actual atmospheric conditions were clarified. The range of R_b in the previous wind tunnel experiment was much narrower than that in the real atmospheric conditions. The Pasquill stability and the R_b correspond well on average, but it is likely that the Pasquill stability is often inconsistent with the R_b. When the atmospheric stability becomes unstable, the wind speed at lower part of boundary layer increases.

REFERENCES

Hu, T. and Yoshie, R., 2020. Effect of atmospheric stability on air pollutant concentration and its generalization for real and idealized urban block models based on field observation data and wind tunnel experiments. Journal of Wind Engineering & Industrial Aerodynamics, 207 (2020) 104380.

Nakajima, K., Yamanaka, T., Ooka, R., Kikumoto, H., Sugawara, H., 2020. Observational assessment of applicability of Pasquill stability class in urban areas for detection of neutrally stratified wind profiles. Journal of Wind Engineering & Industrial Aerodynamics, 206 (2020) 104337.