Estimation of the vertical turbulent diffusivity from thoron profiles

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ABSTRACT

Field measurements of the vertical Tn profiles were carried out on the university campus. On comparison of the observed Tn profiles with those calculated by assuming $K = a + bz$, some discrepancies were found between them. Profiles of the vertical diffusivity K were estimated from observed Tn profiles. It was found that the estimated K profiles may be expressed well by an experimental formula; $K_{Tn}(z) = az^{\beta}$. Some discrepancies were found between the diffusivity K_{Tn} estimated from Tn profiles and the diffusivity K_M calculated from wind speed by assuming neutral stability. These discrepancies are discussed in relation to the stability of the atmosphere.

1. Introduction

^{222}Rn (radon, Rn) and ^{220}Rn (thoron, Tn) diffuse continuously from the ground surface to the atmosphere. These radioactive emanations are transported upwards by turbulent diffusion in the atmosphere. Therefore, there exist close relations between Rn and Tn concentrations and the turbulent diffusivity of the air.

There have been numerous researches into the relation between Rn and Tn concentrations and turbulent diffusivity of the air (K). The vertical distributions of Rn and Tn have been calculated by assuming various functional forms of K with respect to altitude (Hess & Schmidt 1918; Schmidt, 1926; Malakhov, 1959; Jacobi & André, 1963; H. Israël et al., 1967; Ikebe, 1970; Birot et al., 1970). On the contrary, Wilkening (1956) and Sisigina (1964) calculated the mean value of K between two altitudes from Rn measurements, assuming K to be constant. Recently Hosler (1969) and Lettau (1970) evaluated the mean value of K between two altitudes from Rn measurements under steady and non-steady state conditions, respectively. Reiter (1969) also estimated the mean value of K from RaB concentration. Hess (1955), Kawano (1957), and Yordanov (1970) also discussed the effect of turbulent diffusion upon the atmospheric electric phenomena. On the other hand, Jacobi (1965), G. W. Israël (1965), Crozier & Biles (1966) and H. Israël et al. (1967, 1968) studied the relation between atmospheric Tn concentrations and the turbulent diffusivity.

In the present paper, we report the evaluation of the vertical profiles of the turbulent diffusivity from observed Tn profiles.

2. Arrangements used for Tn measurements

Measurement of Tn concentration in the air is difficult owing to its short life, and direct measurements were impossible until several years ago. First Fontan et al. (1961, 1962) developed a method using an indirect method of enrichment. Recently, G. W. Israël et al. (1964, 1966) developed a new method using ionization chambers. In the present work, we used the method developed by Israël et al. Fig. 1 shows the arrangement used for the present work. Air was introduced into the chamber through a filter F_1 by a vacuum pump. Aerosols and ions in the air were ascertained to be completely removed by the filter.[1] The effective volume of the chamber is 30 litres, and 700 volts was applied to the chamber.

[1] A millipore filter (pore size: 8 μ) of 7 cm in diameter was used for F_1, and that (pore size 0.3 μ) of the same size was used for F_2.

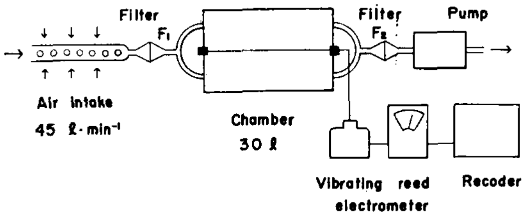

Fig. 1. Experimental arrangement used for measuring thoron concentration.

About 90 % of the saturation current was obtained by the voltage, which was clarified both by experiment (plateau curve) and by calculation (Jaffe's theory). Flow rate used was 45 l/min. The decreases of the inner pressure and the ionization current due to the air flow were ascertained to be less than 1 %.

Ionization current due to α particles formed on the decay of Tn and ThA atoms was measured with a vibrating-reed electrometer and recorded automatically. Tn gas emanated from the standard RdTh solution (^{228}Th, 1.65×10^{-6} Ci) distributed by N.B.S. was used for calibrating the ionization current, i. Calibration was as follows: ^{220}Rn was emanated from the ^{228}Th solution by bubbling of air at the flow rate of v cc/sec. After the air containing Tn (v cc/sec) was mixed with the fresh air introduced via a bypath at a flow rate of V-v cc/sec, they were introduced together into the chamber at the flow rate $V = 750$ cc/sec $= 45$ l/min. Fig. 2 shows the relation of $1/i$ vs. $1/v$. The linearity of the observed points was also obtained theoretically (Shimo et al., 1972). From the intersection of the straight line with y axis, we can obtain the ionization current i_0 which corresponds to that when all Tn produced in the solution was introduced into the chamber. On the other hand, Tn concentration at the entrance of the chamber, denoted by Q_0, is expressed by

$$Q_0 = \frac{N_0}{V} \cdot \frac{\lambda}{3.7 \cdot 10^{10}} \text{(Ci/cc)} \tag{1}$$

where λ is the decay constant of Tn (1.27×10^{-2} sec^{-1}) and N_0 is the production rate of Tn in the solution (6.07×10^4 sec^{-1}). Thus the ionization current $i_0 = 9.7 \times 10^{-10}$ Amp corresponds to $Q_0 = 2.78 \times 10^{-11}$ Ci/cc; i.e.

$$Q_0/i_0 = 0.029 \tag{2}$$

The relation between i_0 and Q_0 was also studied theoretically. We can calculate i_0 from the following relation

$$i_0 = 3.7 \cdot 10^{10} \cdot e \frac{E}{W} \bar{Q} V f \tag{3}$$

where

e electronic charge, 1.6×10^{-19} Coul.
E energy of α-rays $(6.28 + 6.78) \times 10^6$ eV
W W value of air, 35.5 eV
$\bar{Q}$ mean Tn concentration in the chamber, Ci/cc
V volume of the chamber, 3.0×10^4 cc
f correction factor

The following correction factor was evaluated.

$$f = f_1 \cdot f_2 \cdot f_3 \tag{4}$$

where f_1 is the factor which represents the decrease of the current due to the columnar recombination, f_2 represents the decrease of the current due to the wall effect of the chamber, and f_3 is the factor which corrects the difference between "ideal"[1] and "actual" state of air flow in the chamber. f_1, f_2, and f_3 were evaluated and found to be $f_1 = 0.90$, $f_2 = 0.89$, $f_3 = 0.89$ (Shimo et al., 1972). From formulae (3) and (4), we can calculate the relation between i_0 are Q_0. The result is expressed as

$$Q_0/i_0 = 0.027 \tag{5}$$

which agrees well with eq. (2) obtained by the calibration.

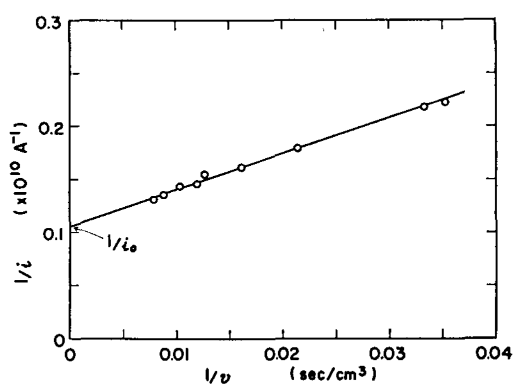

Fig. 2. The relation between $1/i$ and $1/v$.

[1] "Perfectly uniform flow" was assumed as the ideal flow. Then,

$$\bar{Q} = Q_0 \frac{v}{\lambda V} (1 - e^{-\lambda V/v}).$$

3. Measurements of ^{220}Rn profiles

Field measurements were conducted at two sites on the university campus; in the green belt where the ground surface is covered with lawn (lawn area, 61 m × 91 m) and on the bare soil (soil area, 61 m × 100 m). Measurements were made in the daytime from Aug. to Nov. 1968. Among the Tn profiles obtained during the measuring period, those which satisfy the following three conditions are chosen in the present work as some examples of Tn profiles: (1) wind direction; N ∼ NW, (2) fairly constant wind speed, and (3) dry ground surface. The measurements were made at the leeward (east) edge of each site.

Fig. 3 shows those Tn profiles measured above the lawn area. In the figure, measured points are classified into four groups according to the date of measurements. As is shown in the figure, four Tn profiles may be drawn according to the wind speed (u) at 1 m above the ground. The profiles seem to be fairly similar to those obtained by Crozier & Biles (1966).

Fig. 4 shows Tn profiles measured above the soil area. Measured points are also classified into four groups. In this case, e, f, and g, profiles do not differ so much from each other according to the wind speed as above the lawn area. This discrepancy seems to be explained by the difference of the exhalation rate between lawn and soil area. Namely, as will be described in the next section (Table 1), the exhalation rate (E_0) over the lawn area does not depend so much upon the wind speed, whereas that over the soil area depends largely upon the wind

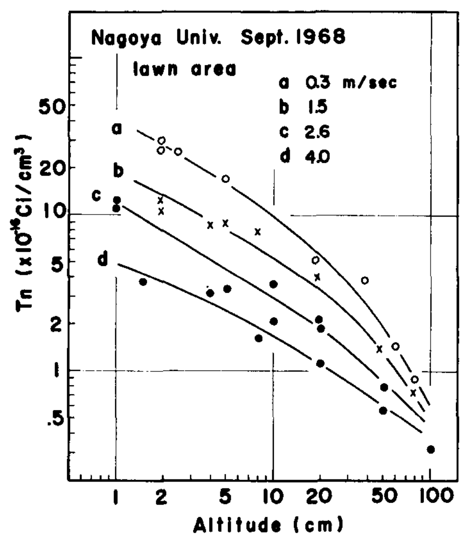

Fig. 3. Vertical profile of thoron concentration measured on the lawn area of the campus. (a) Sept. 3 (u = 0–0.5 m/sec); (b) Sept. 2 (0.7–2.0); (c) Sept. 6 (2.0–3.2); (d) Aug. 31 (3.2–6.0).

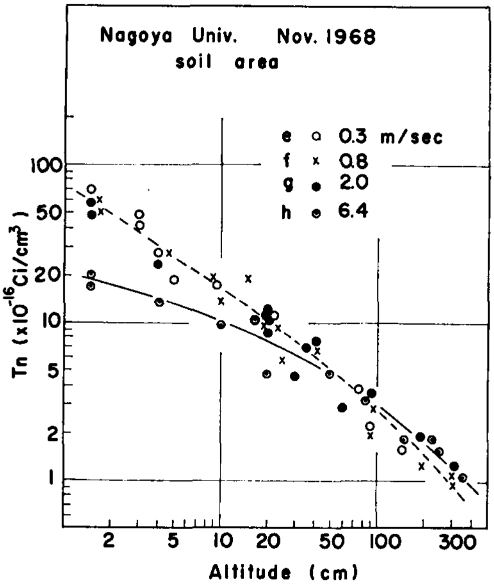

Fig. 4. Vertical profiles of thoron concentration measured on the naked ground of the campus. (e) Nov. 20 (u = 0–0.5 m/sec); (f) Nov. 19 (0.6–1.2); (g) Nov. 1 (1.5–3.1); (h) Nov. 28 (5–7.5).

Table 1. *Estimation of thoron exhalation rates*

Authors	Method	E_0(× 10^{-16} Ci/cm^2 sec)
Junge (1963)	Calculated from ^{232}Th	56
Crozier & Biles (1966)	Indirect	21
Israël et al. (1968)	Direct	7.4
Crozier (1969)	Direct	42 ± 14
Styra et al. (1970)		
dry soil area	Direct	33 ± 5
Guedalia et al. (1970)		
dry grass area	Direct	50 ± 20
Present author (1970)	Indirect	
Lawn area	(Sept., 1968)	9.2
	Indirect	
Soil area	(Nov., 1968)	
	0.3 m/sec	13
	0.8 m/sec	21
	2.0 m/sec	31
	6.4 m/sec	37

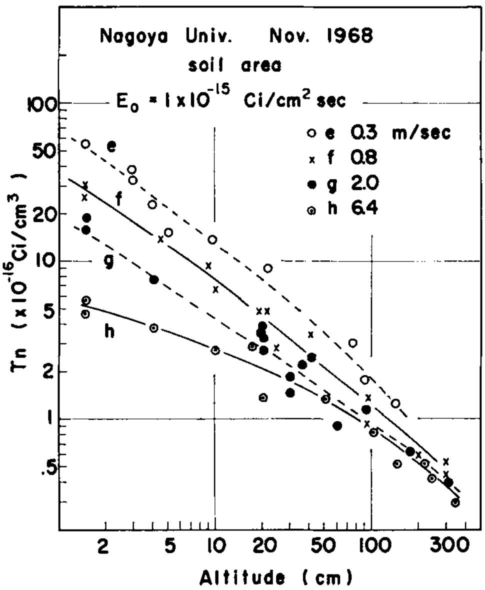

Fig. 5. Vertical thoron profiles for a constant exhalation rate ($E_0 = 1 \times 10^{-15}$ Ci/cm² sec) estimated from Fig. 4 by using E_0 values shown in Table 1.

speed. Fig. 5 shows Tn profiles above the soil area drawn from Fig. 4 by assuming a constant exhalation rate, $E_0 = 1 \times 10^{-15}$ Ci/cm²sec. Each measuring point shown in Fig. 4 is multiplied by E_{oc}/E_{ou} and is plotted in Fig. 5 where E_{oc} is 1×10^{-15} Ci/cm²sec and E_{ou} denotes the exhalation rate shown in Table 1. The profiles shown in Fig. 5 are rather similar to those above the lawn area. It should be noted that the Tn profiles shown in Figs. 3 and 4 are neither average profiles nor typical profiles. They are only some examples obtained on some particular days.

The vertical profiles of Tn at a constant exhalation rate can be obtained from the following differential equation:

$$\frac{\partial n}{\partial t} = \frac{\partial}{\partial z}\left(K\frac{\partial n}{\partial z}\right) - \lambda n \quad (6)$$

where

n concentration of Tn at altitude z (Ci/cm³)
K vertical turbulent diffusion coefficient (cm²/sec)
λ radioactive decay constant of Tn (sec⁻¹)

In the case of ^{222}Rn, in general, the steady-state condition does not exist (Phillip, 1959), whereas in the case of ^{220}Rn, the steady-state condition usually does exist. The equation may then be expressed as

$$\frac{d}{dz}\left(K\frac{dn}{dz}\right) - \lambda n = 0 \quad (7)$$

The diffusion coefficient K is quite variable with altitude. In the turbulent boundary layer near the ground surface, K is approximately expressed by the following linear law of z;

$$K = a + bz \quad (8)$$

where a is molecular diffusion coefficient (cm²/sec), and b is turbulent diffusion coefficient at a unit altitude (cm/sec). If we assume $K = a + bz$, the analytical solution of eq. (7) can be obtained (H. Israël et al., 1967; Ikebe, 1970):

$$n = E_0 K_0\left(\frac{2}{b}\sqrt{\lambda(a+bz)}\right) \Big/ \sqrt{\lambda a}\, K_1\left(\frac{2\sqrt{\lambda a}}{b}\right) \quad (9)$$

where K_0 is the modified Bessel function of the second kind of order zero, K_1 is that of first order, and E_0 is a constant exhalation rate of Tn.

The curves drawn in Fig. 6 among the plotted observed points are theoretical ones calculated from equation (9) for a constant exha-

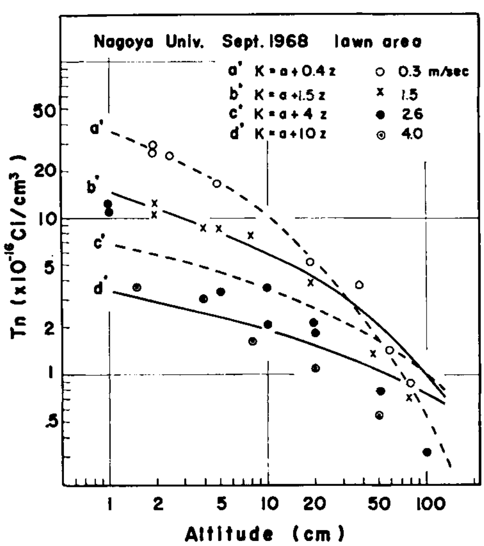

Fig. 6. Comparison of the observed points of thoron obtained on the lawn area with calculated thoron profiles by assuming $K = a + bz$.

lation rate. Although observed points for $\bar{u} = 0.3$ m/sec rather seem to agree with calculated profile for $K = a + 0.4z$, those for $\bar{u} = 2.6$ m/sec and 4.0 m/sec do not agree with calculated profiles. In the case of soil area, the discrepancies between observed points and calculated profiles by assuming $K = a + bz$ are more apparent. These discrepancies suggest that the diffusivity K in the atmosphere near the ground cannot be expressed strictly by $K = a + bz$. Therefore, in the following section we attempt to evaluate K profiles from observed Tn profiles.

4. Estimation of Tn exhalation rate

To evaluate K profiles from observed Tn profiles, we must evaluate Tn exhalation rate (E_0) at the observation sites. Recently methods for the direct measurement of Tn exhalation rates have been developed by several researchers (H. Israël et al., 1968; Crozier, 1969; Styra et al., 1970; Guedalia et al., 1970). However, it is as yet impossible to measure E_0 directly taking into consideration of the effect of the wind speed. In the present work, we estimate E_0 indirectly as described by Ikebe (1970).

Fig. 7 shows the correlations between Tn concentrations at 4 cm above the lawn and soil areas of the campus and the wind speed at 1 m above the ground. The relationship was found theoretically as follows: Under neutral conditions, the vertical distribution of mean wind speed near the ground surface is given by the logarithmic profile;

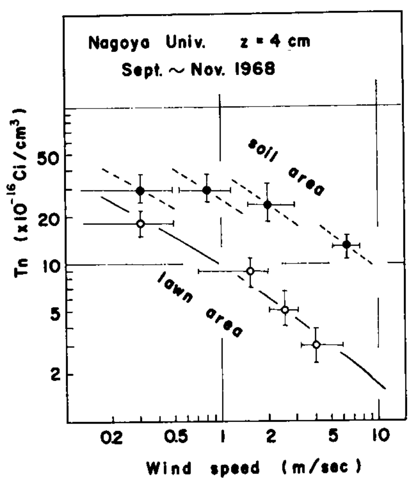

Fig. 7. Correlation between the thoron concentration ($z = 4$ cm) and wind speed ($z = 1$ m) obtained on the lawn and soil areas of the campus. (O, Mean value; I—I, width of dispersion.) The solid and dotted lines represent the theoretical relationships for $z_0 = 0.2$ and 0.04 cm, respectively.

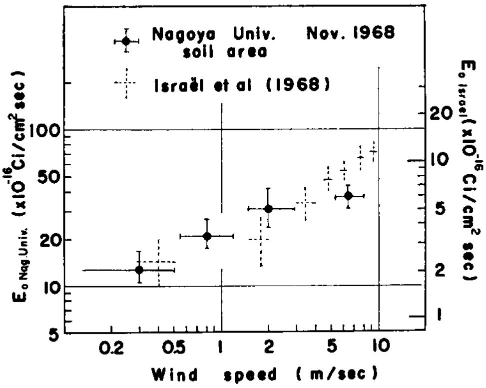

Fig. 8. Dependence of the exhalation rate on the soil area upon the wind speed. Data obtained by Israël et al. (1968) are also shown.

$$u(z) = \frac{u_*}{k} \ln \frac{z}{z_0} \tag{10}$$

where

$u(z)$ wind speed at altitude z (cm/sec)
k von Karman constant
u_* frictional velocity (cm/sec)
z_0 roughness length (cm)

Assuming the vertical turbulent diffusion coefficient of Tn, denoted by $K(z)$, to be equal to momentum eddy diffusion coefficient, we can express $K(z)$ as

$$K(z) = ku_*z \tag{11}$$

If $u(z_1)$ is given, we can estimate u_* from eq. (10). Comparing eqs. (8) and (11), we can put $b \cong ku_*$. Then we can estimate corresponding $n(z_2)$ from eq. (9). Thus the theoretical relationships between $u(z_1)$ and $n(z_2)$ were obtained for $z_1 = 100$ cm, $z_2 = 4$ cm, and $E_0 = 1$ atom/cm²sec (Ikebe, 1970). z_0 values were assumed to be $z_0 = 0.2$ cm (lawn area) and $z_0 = 0.04$ cm (soil area) (Deacon, 1949).

In Fig. 7, theoretical relationships are drawn by a solid line and four dotted lines. In each line, E_0 is taken as to fit observed points. The value of E_0 is summarized in Table 1.

The rather low exhalation rate of thoron

(9.2×10^{-16} Ci/cm²sec) on the lawn area seems to be due to the condition of the ground surface: i.e. Tn exhalation may be prevented by roots and leaves of the lawn. Above the naked ground, four different exhalation rates corresponding to four different wind speeds are evaluated, and exhalation rate increases with increasing wind speed. The relation between the exhalation rate and wind speed is shown in Fig. 8 together with the results obtained by H. Israël et al. (1968). The correlation obtained by the present work seems to agree fairly well with that by Israël et al.

5. Estimation of K profiles from Tn profiles

In the present work, K profiles are evaluated from observed Tn profiles as follows: Integrating the diffusion eq. (7) for steady state condition, we obtain

$$\left[K\frac{dn}{dz}\right]_{z_3}^{z} = \int_{z_3}^{z} \lambda n\, dz \qquad (12)$$

Then $K(z)$ may be given by

$$K(z) = \left\{K(z_3)\left(\frac{dn}{dz}\right)_{z_3} + \lambda\int_{z_3}^{z} n\, dz\right\} \Big/ \left(\frac{dn}{dz}\right)_z \qquad (13)$$

Now Tn flux E at altitude z may be given by

$$E = -K\frac{dn}{dz} \qquad (14)$$

Then

$$K(z) = \left\{-E(z_3) + \lambda\int_{z_3}^{z} n dz\right\} \Big/ \left(\frac{dn}{dz}\right)_z \qquad (15)$$

From observed Tn profiles, we can evaluate

$$(dn/dz)_z, \quad (dn/dz)_{z_3} \quad \text{and} \quad \int_{z_3}^{z} n\, dz.$$

In this work z_3 is taken as 3 cm, and $E(3)$ is estimated in each profiles as

$$\frac{E(3) - E(0)}{3} = -\lambda n(1.5) \qquad (16)$$

Then we can evaluate $K(z)$ from the formula (15).

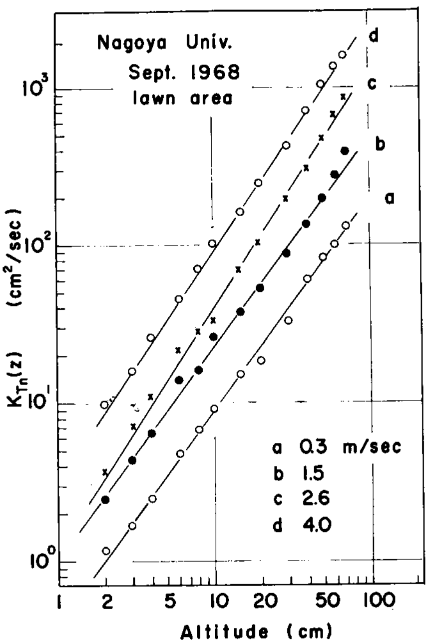

Fig. 9. Vertical K profiles on the lawn area estimated from thoron profiles shown in Fig. 3.

Fig. 9 shows the K profiles on the lawn area estimated from Tn profiles shown in Fig. 3 using eqs. (15) and (16). Fig. 10 shows those on the soil area from Fig. 5. As is shown in the

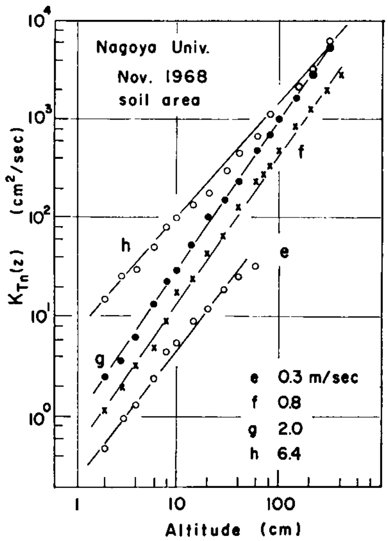

Fig. 10. Vertical K profiles on the soil area estimated from thoron profiles shown in Fig. 5.

figure, estimated K profiles somewhat differ from $K \simeq bz$. The estimated K profiles may be expressed well by an experimental formula

$$K(z) = \alpha z^{\beta} \tag{17}$$

The values of α and β are shown in Table 2. β takes the values from 1.2 to 1.5.

6. Discussions

Fig. 11 shows the relation between $K(70)$ and $u(100)$ obtained from Figs. 9 and 10. The dotted and solid line shows the relation calculated from the formula (11) for $z_0 = 0.2$ and 0.04 cm, respectively (Rossby relation). In general, estimated diffusivity from Tn profiles, denoted by $K_{\mathrm{Tn}}(z)$, take about 50 % larger value than those calculated from wind speed, denoted by $K_M(z)$. Although the interpretation of this discrepancy is rather difficult, the main causes for this discrepancy may be (1) departure of the atmospheric stability from neutral condition and (2) the error for evaluating Tn exhalation rates. As for Tn exhalation rates, "direct" and precise measurements are desirable in the future works. Concerning the stability of the air, the following discussion may be useful: According to the similarity theory developed by Monin & Obukov,

$$\frac{du}{dz} \equiv \frac{u_*}{ku}\varphi\left(\frac{z}{L}\right)$$

$$K_M \equiv \frac{ku_* z}{\varphi} \tag{18}$$

where L is the stability length and φ is a function expressed by the following KEYPS equation (Yamamoto, 1959);

$$\varphi^4 + \zeta\varphi^3 - 1 = 0 \tag{19}$$

$$\zeta = -\frac{\sigma z}{L} = \zeta_0 \frac{z}{z_0} \tag{20}$$

where σ is an empirical constant, and ζ_0 is dimensionless parameter defined by eq. (20). The stability parameter ζ_0 is positive in unstable conditions, negative in stable conditions, and zero in neutral conditions.

In the present work, we do not know the stability parameter ζ_0. But we can estimate the value of ζ_0 so that the calculated diffusivities K_M from eq. (18) may coincide with the estimated diffusivities K_{Tn} from Tn profiles. The procedures are as follows: According to the theory of Deacon (1949) and Shimanuki (1969), unstable and neutral stability corresponds to $\beta > 1$ and $\beta = 1$ respectively, where β is defined by eq. (17). Therefore considering the gradient β of $K_{\mathrm{Tn}} = \alpha z^{\beta}$ profiles we can probably assume that $\zeta_0 = +0.003$ for $a \sim g$ profiles and $\zeta_0 = 0$ for h profile. Yamamoto (1959) and Shimanuki (1969) calculated ku/u_* as a function of z/z_0 for various values of ζ_0. Then we can evaluate u_* from u (100) and ζ_0 for each profile. On the other hand, Yamamoto (1959) calculated φ as a function of ζ. Then we can estimate $\varphi(z)$ from assumed ζ_0 using eq. (20). From u_* and $\varphi(z)$, we can evaluate K_M by eq. (18). In Fig. 12, calculated value of K_M for each profile is shown in comparison with the value of K_{Tn}. As is shown in the figure, the descrepancies

Table 2. *$K(z) = \alpha z^{\beta}$ profiles estimated from thoron profiles*

Profile	Date	α	β
a	Sept. 3	0.40	1.35
b	Sept. 2	1.0	1.3
c	Sept. 6	1.1	1.5
d	Aug. 31	3.0	1.4
e	Nov. 20	0.23	1.4
f	Nov. 19	0.45	1.5
g	Nov. 1	1.0	1.5
h	Nov. 28	7.0	1.2

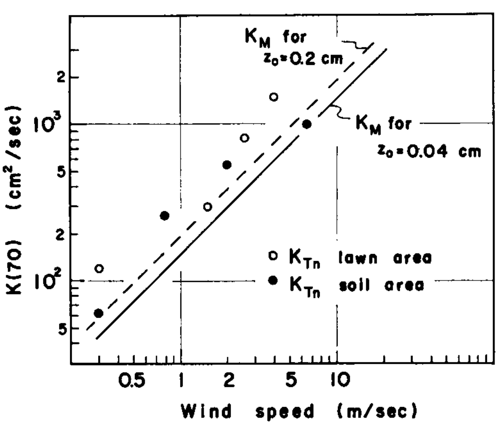

Fig. 11. Dependence of $K(70)$ upon the wind speed at 1 m above the ground.

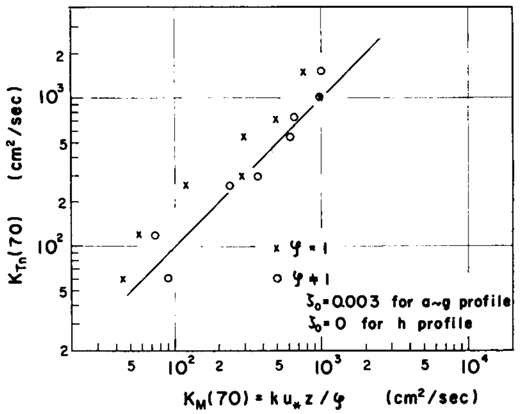

Fig. 12. Comparison of K_{Tn} (the diffusivity estimated from thoron profiles) with K_M (the diffusivity calculated from wind speed).

between K_{Tn} and K_M seem to be explained by considering the stability of the atmosphere.

7. Summary and concluding remarks

Field measurements of the vertical Tn profiles were carried out on the campus. Comparing the observed Tn profiles with those calculated by assuming $K = a + bz$, some discrepancies were found between them.

Comparing the theoretical relationship between Tn concentration and wind speed with the observed one, we evaluated exhalation rates of Tn. Although the exhalation rate on the lawn area seems to be constant with respect to wind speed, that on the soil area increases with increasing wind speed.

Estimations of K profiles from observed Tn profiles were made. It was found that the estimated K profiles may be expressed well by an experimental formula; $K(z) = \alpha z^{\beta}$. The discrepancies between the diffusivity K_{Tn} estimated from Tn profiles and that K_M calculated from the Rossby relation (10) were discussed from the view point of the stability of the atmosphere.

In the present paper, an homogeneous surface source of thoron is assumed and advection term is neglected. In the future works, evaluation of advection term should be made. In this work, Tn exhalation rates were estimated indirectly by assuming neutral stability of the atmosphere, which may cause some errors for evaluating K profiles from Tn profiles. In the future works, "direct" and precise measurements of Tn exhalation rates are desirable. It is also desirable that the meteorological variables which concern with the atmospheric stability such as wind speed profiles, temperature profiles, and heat flux are also measured simultaneously with Tn profiles and Tn exhalation rates.

In the present work, K profiles below several meters were evaluated from Tn profiles. Above several meters ^{222}Rn (radon) profiles seem to be useful for evaluating K profiles. In the future works ^{222}Rn profiles should be discussed in relation to the diffusivity and stability of the atmosphere.

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REFERENCES

Birot, A., Adrouger, B. & Fontan, J. 1970. Vertical distribution of radon 222 in the atmosphere and its use for study of exchange in the lower troposphere. *J. Geophys. Res. 75*, 2373–2383.

Crozier, W. D. & Biles, N. 1966. Measurements of radon 220 (thoron) in the atmosphere below 50 centimeters. *J. Geophys. Res. 71*, 4735–4741.

Crozier, W. D. 1969. Direct measurement of radon 220 (thoron) exhalation from the ground. *J. Geophys. Res. 74*, 4199–4205.

Deacon, E. L. 1949. Vertical diffusion in the lowest layers of the atmosphere. *Quart. J. Roy. Meteor. Soc. 75*, 89–103.

Fontan, J., Blanc, D., Bonnafous, M. & Bouville, A. 1961. Dosage du radon et du thoron contenus dans l'air atmosphérique, application à l'étude de l'équilibre radioactif entre ces gaz et leurs descendants. *Phys. Rad. 22*, 179A–181A.

Fontan, J., Blanc, D., Bonnafous, M. & Bouville, A. 1962. Une méthode de dosage direct du radon et thoron contenus dans l'atmosphère. *Nuovo Cimento*, Suppl. 23, Ser. 10, 132–143.

Guedalia, D., Laurent, J. L., Fontan, J., Blanc, D. & Druilhet, A. 1970. A study of Radon 220 emanation from soils. *J. Geophys. Res. 75*, 257–369.

Hess, V. F. & Schmidt, W. 1918. Über die Verteilung radioaktiver Gase in der freien Atmosphäre. *Physik. Zschr. 19*, 109–114.

Hess, V. F. 1955. The role of eddy diffusion in the distribution of ions in the atmosphere near the ground. *Nuovo Cimento 1*, 51–62.

Hosler, C. R. 1969. Vertical diffusivity from radon profiles. *J. Geophys. Res. 74*, 7018–7026.
Ikebe, Y. 1970. Variation of radon and thoron concentrations in relation to the wind speed. *J. Meteor. Soc. Japan. 48*, 461–468.
Israël, H. & Israel, G. W. 1966. A new method of continuous measurements of radon (Rn^{222}) and thoron (Rn^{220}) in the atmosphere. *Tellus 18*, 557–561.
Israël, H., Horbert, M. & de la Riva, C. 1967. The thoron content of the atmosphere and its relation to the exchange conditions. Final Tech. Rept., European Research Office, U.S. Army, Contract DA-91-591-EUC-3761.
Israël, H., Horbert, M. & de La Riva, C. 1968. Measurements of the thoron concentration of the lower atmosphere in relation to the exchange (Austausch) in this regon. Final Tech. Rept., European Research Office, U.S. Army Contract, DAJA 37-67-0-0593.
Israël, G. W. 1964. Neues Verfahren zur Direktmessung des atmosphärischen Thoron-Gehaltes. *Naturwissenschaften 51*, 134–135.
Israël, G. W. 1965. Thoron (Rn-220) measurements in the atmoshpere and their application in meteorology. *Tellus 17*, 383–388.
Jacobi, W. & Andre, K. 1963. The vertical distribution of radon-222, radon-220 and their decay products in the atmosphere. *J. Geophys. Res. 68*, 3799–3814.
Jacobi, W. 1965. The thoron-content of atmospheric air near the ground level. *Atomkern Energie 10*, 471–478.
Junge, C. E. 1963. *Air chemistry and radioactivity*. Academic Press, New York and London.
Kawano, M. 1957. The coefficient of eddy diffusivity estimated by the method of atmospheric electricity. *J. Meteor. Soc. Japan 35*, 29–32.
Lettau, H. 1970. Discussion of the paper by C. R. Hosler, "Vertical diffusivity from radon profiles". *J. Geophys. Res. 75*, 2849–2850.
Malakhov, S. G. 1959. Vertical distribution of radioactive emanation in the atmosphere. *Izvest. Acad. Nauk S.S.S.R. Ser. Geopfiz. 9*, 1344–1351.
Phillip, J. R. 1959. Atmospheric diffusion and natural radon. *J. Geophys. Res. 64*, 2468.
Reiter, R. 1969. On radioactive equilibrium in atmospheric aerosols at 700 and 1 800 m a.s.l., as influenced by particle size and vertical mixing activity. *Pure Appl. Geophys. 74*, 134–150.
Schmidt, W. 1926. Zur Verteilung radioaktiver Stoffe in der freien Luft. *Physik. Zschr. 27*, 371–378.
Shimanuki, A. 1969. Formulaton of vertical distributions of wind velocity and eddy diffusivity near the ground. *J. Meteor. Soc. Japan 37*, 292–297.
Shimo, M., Ikebe, Y. & Kawano, M. 1972. Measurement of the thoron concentration of the air near the ground. *Oyobutsuri*, to be published (in Japanese).
Sisigina, T. L. 1964. Vertical distribution of radon in the boundary layer of the atmosphere (0–300 m) in connection with changing meteorological conditions. *Izvest. Akad. Nauk S.S.S.R. Ser. Geofiz. 3*, 414–421.
Styra, B., Nedveckaite, T. N. & Senko, E. E. 1970. New methods of measuring thoron (radon 220) exhalation. *J. Geophys. Res. 75*, 3635–3638.
Sutton, O. G. 1953. *Micrometeorology*. McGraw-Hill, New York.
Wilkening, M. H. 1956. Variation of natural radioactivity in the atmosphere with altitude. *Trans. Amer. Geophy. Union. 37*, 177–180.
Yamamoto, G. 1959. Theory of turbulent transfer in non-neutral conditions. *J. Meteor. Soc. Japan 37*, 60–70.
Yordanov, D. 1970. On the stationary electric field in the air surface layer. *Pure Appl. Geophys. 79*, 85–91.

ОЦЕНКА КОЭФФИЦИЕНТА ВЕРТИКАЛЬНОЙ ТУРБУЛЕНТНОЙ ДИФФУЗИИ ПО ПРОФИЛЮ ТОРОНА

Полевые измерения вертикальных профилей концентрации *Tn* были проведены на территории университета. При сравнении наблюдавшихся профилей с вычисленными в предположении $K = a + bz$, были найдены некоторые различия между ними. Профили коэффициента вертикальной диффузии *K* были оценены из наблюдавшихся профилей *Tn*. Было найдено, что найденные таким образом профили *K* могут быть хорошо описаны экспериментальной формулой $K_{Tn}(z) = \alpha z\beta$. Были найдены некоторые различия между коэффициентом K_{Tn}, оцененным по профилям *Tn* и коэффициентом диффузии K_M, найденным по профилю ветра в предположении нейтральной устойчивости. Эти различия обсуждаются в их связи с устойчивостью атмосферы.