Emanated products as a probe of atmospheric transport

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ABSTRACT

Atmospheric transport of radon, thoron and their decay products is analysed in the light of the Richardson diffusion theory, replacing the length scale by a time scale. It is shown that the mean operation involved in the usual procedure of parameterisation of eddy diffusion must be related to the isotopic mean life, and its relation to spectra of atmospheric turbulence. There are cases where the conventional parameterisation of eddy diffusion is inconsistent and contradictory. For example the case of the thoron distribution which generally must be treated by Richardson formalism.

The conventional methods are shown to be reasonable for interpretation of radon^{222} and Pb^{212} profiles, provided this is done carefully. It is shown that the vertical transport due to the mean wind cannot be neglected, as sometimes it is a dominant factor. A criterion for estimating the relative importance of advection and eddy diffusion is derived. Application of this criterion establish that in the free atmosphere radon transport is generally dominated by advection. This result is demonstrated by semi-uniform numerical model.

For a practical application it seemed that the radon could be a promising tool for the study of the large scale (synoptic) vertical wind and of divergent regimes.

Introduction

Going over the literature one can notice that while the measurements of emanated products are relatively simple and reliable, applications of these measurements for the study of atmospheric transport are inconclusive.

Thus Israel (1966) has found a seven-fold difference between the eddy viscosity derived from the wind profile and eddy diffusivity obtained from the thoron profile. In the free atmosphere Shapouskas (1965) did not find any correlation between the diffusivity of radon and atmospheric stability. Also there is a reason to suspect that the vertical eddy diffusion obtained by Kirichenko (1964) reflected the synoptic regime and not necesarily eddy diffusion or convective currents.

Taylor (1959), Bolin (1962) and others clarified the limitation of the eddy diffusion parameters known as the "K approximation" by refering to Richardson's theory.

Applying the separation principle of Richardson to the dispersion of emanated clouds the conditions for the validity of the K approximation are defined and the inconsistency between eddy viscosity and thoron diffusivity is explained. This is done in sections 1 and 2.

The scale analysis in section 3 points out that radon concentration is sensitive to the synoptic regimes rather than to eddy diffusion. This result is demonstrated by a numerical model in section 4.

Emanated clouds in the light of Richardson separation principle

(a) *General review*

The transport of the matter forming a cloud in the atmosphere is a complex process controlled by both diffusion and advection. It was realised by Richardson (1926), that the mode of transport is related to the size of the transported cloud and its relation to the scale of atmospheric eddies. When atmospheric conditions are given, the transport should be related to the characteristics of cloud distribution.

Those characteristics were defined by Richardson (1926, 1952) as the autocorrelation q^* of the concentration of matter in the cloud, i.e.:

$$q^*(l) \equiv \int_{\infty}^{\infty} q(x)^* q(x+l)\,dx \Big/ \left[\int_{\infty}^{\infty} q(x)\,dx\right]^2 \quad (1)$$

Table 1

Rn^{222}	Po^{218}	Pb^{214}	Bi^{214}	Po^{214} (long lived isotopes)
3.8 d	3 min	27 min	19 min	164 μsec
				Tl^{208}
				3 min
Rn^{220}	Po^{216}	Pb^{212}	Bi^{212}	Po^{208} (stable)
54 sec	.1 sec	10.6 hr	1 hr	.3 μsec

(ι) was defined as the separation parameter. From the definition it is noticed that when ι exceeds the cloud size $q^*(\iota) = 0$.

The diffusion equation was then introduced on the ι, q^* coordinate as follows:

$$\frac{\partial q^*}{\partial t} = \frac{\partial}{\partial l}\left(F(l)\frac{\partial q^*}{\partial l}\right) \qquad (2)$$

Thus Richardson discusses "an atmosphere in which the diffusivity is independent of position, but depends on separation" (p. 722). In the following we shall refer to that statement as the "separation principle" due to Richardson.

For the sake of application, Richardson simplified the equation by assuming that the diffusivity $F(\iota)$ is dominated by the largest ι values, i.e. those which are equivalent to the size of the cloud. The diffusivity is then dependent on the size of the cloud. As Obokov (1964) puts it: "In the problem of turbulent diffusion the cloud itself plays the role of 'spectral instrument'. The vortices belonging to the scale considerably larger that the diameter ι, only transport the cloud as a whole without changing its size. With the growth of the cloud the increasing range of the spectrum of turbulence affects the relative motion of particles, i.e. diffusion, which causes the effective coefficient of diffusion to grow progressively."

Thus the diffusion rate of a given cloud depends on interaction with addies of size similar to its own. One of the consequences of this is that a single cloud cannot recognize the stochastic nature of these eddies because of insufficient statistics. To be statistically meaningful the diffusivity should be related to an ensemble of clouds, and not to a single one. The separation principle requires that clouds of different sizes should be grouped in different ensembles. The diffusivity of any cloud should then be related to the diffusivity of an ensemble mean of clouds of similar size or age.

Clouds of emanated products seem to be a promising tool for the study of the nature of such ensembles.

For a given source and atmospheric conditions there is a definite relationship between the time after injection to the atmosphere (age) and the expected size of a given cloud. The separation principle then can be related to the age of the cloud as well as to its size.

(b) *The characteristics of emanated clouds*

Radon (Rn^{222}) and thoron (Rn^{220}) emanate from the ground into the atmosphere. Both have short live decay products into which they disintegrate while in the atmosphere.
In Table 1 only three nuclides are of interest for the following study because they are distributed almost independently of one another (Jacobi & Andre 1963).

The emanated clouds have different characteristics and their age and size must be carefully defined.

These clouds are the results of a continuous flux of radon or thoron into the atmosphere which is balanced by radioactive decay. As the scavenging of radon isotopes is negligable the atmospheric mean lifes of radon and thoron coincides with their isotopic mean life. This is approximately true also for Pb^{212} in dry conditions (Gat & Assaf, 1968). Thus atmospheric mean life of emanated clouds will be approximated by $Tm = 1/\lambda$ where λ is the isotopic decay constant.

Tm can be defined as the age of the emanated clouds, and will be refered to as the scale in relation to which atmospheric transport processes have to be gauged.

The size of a cloud is usually defined as the characteristic length over which the mean concentration of matter is decreased by $1/e$. Such a definition can be ambiguous as two different operations for obtaining a mean concentration are possible: measuring a momentary distribution of the material in the cloud, over a period which is small compared to Tm (i.e. in

one of its phase) gives a "phase mean". An "ensemble mean" averages the concentrations over a period much longer than Tm. It is the peculiar property of unstable materials generally and of emanated clouds particularly that this operation depends on the matter studied. Averaging, for example, concentrations of Pb^{212} and of thoron over one hour will give a "phase mean" in the former case, but a measure of the mean concentration of an ensemble of clouds whose age is 75 sec (Tm of thoron) in the latter case. As the Richardson theory relates the diffusivity to an ensemble of clouds of different sizes or ages, the ensemble mean of emanated clouds provides a natural measure of such ensemble. The separation principle requires that the diffusivity should be related to the ensemble mean of emanated clouds and predict that in general the diffusivity derived from the various nuclides will be different.

A generally valid approach for describing the transport of emanated clouds would be the introduction of a measured ensemble-mean concentration profile into equation (1) to obtain $q(\iota)$, and then solve Richardson's equation (2) for $F(\iota)$. This will be done in a different context.

Until now the diffusivity of emanated clouds was interpreted as being independent of the separation. In the following we shall discuss the validity of such calculation in the light of the separation principle.

The validity and the limitations of the K approximation

(a) *General conditions for validity*

There are indications (Van der Hoven, 1957) that the eddy activity in the atmosphere is not uniform but is concentrated in two regions of the frequency spectrum. A region of turbulent eddies with mean life of a min. or so and the synoptic scale eddies with 4 day mean life. However, some activity appears also with characteristic life time of 12 hr. Between the small scale activity of several minutes mean life and that of several hours, there is a gap in which the amplitude of the horizontal wind is very small indeed.

In the case where such a gap exists (and only then) the dispersion rate of a given cloud is not necessarily a critical function of its separation or age. All clouds whose age is greater than about 20 min but less than 5 hours will then be dispersed by the same scale of eddies irrespective of their age (or size).

Thus when there is a gap in the eddy activity and the cloud is old compared with the eddies involved in the diffusion the diffusivity can be treated as independent of the separation.

The usual approach was then to introduce the eddy diffusion parameters through "K approximation" into the transport equations. The transport equation can be written as (Bolin 1962)

$$\frac{\partial q}{\partial t} + \mathbf{V}\nabla q + \frac{\nabla}{\bar{\varrho}}\overline{(\varrho v'' q'')} + \lambda q + P(r, t) = 0 \qquad (3)$$

In deriving this equation one uses the continuity equation:

$$\frac{\partial \varrho}{\partial t} + \nabla(\varrho \mathbf{V}) = 0 \qquad (4)$$

Where

q weighed mean concentration of the diffused materials,
λ decay constant,
P rate of scavenging of the concerned radionuclide,
ϱ air density,
X'' deviation of the parameter concerned (X) from the weighted mean,
$\mathbf{V}$ weighed mean velocity.

For radon and thoron $P = 0$. In the absence of precipitation and above 200 m. $P = 0$ also for Pb^{212}.

The K approximation is introduced by looking on the eddies as small diffusion elements. The eddy diffusion flux is treated in an analogous fashion to the molecular diffusion flux: e.g.

$$\overline{\varrho q'' u''} = -\bar{\varrho} K_x \frac{\partial q}{\partial x} \quad \overline{\varrho q'' v''} = -\bar{\varrho} K_y \frac{\partial q}{\partial y} \quad \overline{\varrho q'' w''} = -\bar{\varrho} K_z \frac{\partial q}{\partial z} \qquad (5)$$

It is usually assumed that the K values are similar in magnitude to the eddy viscosity, and that they are independent of the diffused material. H. Lettau (1951) put it like this (in our conventions). "In order to separate the properties of the wind from the properties of the

q distribution, a radious vector $\mathbf{l}'$ is introduced which is assumed to be independent of the particular q that is:

$$q'' = \mathbf{l}' \nabla q \tag{6}$$

The K values are defined then as:

$$K_x = \overline{U'' l_x'} \quad K_y = \overline{V'' l_y'} \quad K_z = \overline{W'' l_z'} \tag{7}$$

In the light of Richardson principle it is obvious that the K approximation can be applied only if the diffused cloud is much bigger and older than the eddies involved in its diffusion. Only then can the analogy to molecular diffusion be justified as the mixing length l, is much smaller than the size of the cloud and can be taken as independent of the cloud dimension, or the separation.

(b) *The validity of the K approximation for emanated clouds*

The size and the age of the emanated clouds depend upon their isotopic mean life.

When the mean life of a given radioisotope is not long relative to the eddies involved in the K approximation, the diffusivity will be a function of the particular q. This contradicts the assumption that $\mathbf{l}'$ and therefore, K are independent of the given q.

Many workers failed to recognize that the K approximation is limited to eddies which are short lived relative to isotopic mean life. Thus they wrongly apply the K approximation for describing transport of the short lived thoron (Tm = 70 sec).

In fact when the eddies are larger and of greater age than the emanated clouds, they function as advective elements rather than dispersives. The eddy flux will be then proportional to the mean concentration rather than its gradient.

As an illustration let us investigate the contribution of long lived eddies to the transport of thoron. Assuming we are at a height of 50 m over a uniform plan source of thoron and can measure its instantaneous concentration. This concentration will be close to zero, until a long lived eddy will blow upward. Then the thoron concentration will increase and if the eddy is long lived, the concentration can reach a steady state value given by the solution of the equation $W(\partial q/\partial z) + \lambda q = 0$, i.e. $q = q_0\, e^{-(\lambda/W)z}$, where W is vertical velocity. When the wind changes direction the concentration will decrease rapidly to zero. This process will be repeated after a while with variation in the duration and the amplitude. It is clear that at large enough heights only very selective state of atmospheric turbulence will contribute to the thoron transport. Assuming we have taken a long time measurements of the thoron profile at this height, our profile will be a measure of this selective states, in which the thoron concentration does exist. When such a profile is interpreted with the aid of the K approximation: i.e.

$$K_a \frac{\partial^2 q}{\partial z^2} - \lambda q = 0 \text{ whose solutions } q = q_0\, e^{\sqrt{\lambda/Ka}\, z}$$

The apparent K would be $Ka = (W^2/\lambda)$ which is a function of the nuclide mean life. Thus the seven-fold difference between the K values derived from the thoron profiles and the eddy viscosity derived from the wind profile (Israel, 1966) is not "outstanding", but the wind 1966) is not "outstanding", but is to be expected from Richardson separation principle. Similarly the thoron profiles calculated by Jacobi & Andre (1963) cannot be correlated in a simple manner with the measured profiles.

(c) *Atmospheric eddies as transport elements of emanated clouds*

As a general rule we can differentiate the spectra distribution of eddy activity for three classes, namely, advectives, dispersives and intermediate eddies. Advectives are eddies which are long lived relative to Tm. Dispersives are eddies which are short lived relative to Tm. Intermediate eddies are those whose period is comparable with Tm.

The role of atmospheric clouds as spectral instruments is in essence a discrimination between advective to dispersive eddies. The discrimination level which was related by Richardson to the size of the cloud can be related to Tm the mean life of the emanated clouds.

When there is a gap in the spectral distribution of atmospheric eddies the discrimination level Tm can be before, inside or beyond, the gap. In each of these cases the diffusivity should be treated differently. When Tm is small the short lived turbulence functions as intermediate eddies. The eddy transport cannot be approximated as dispersives nor as advectives. The

diffusivity will be a function of separation and it cannot be simplified. It should be related to the ensemble mean using Richardson's equation (2). This is the case of the thoron transport discussed above.

When Tm is inside the gap, the distinction between advective and dispersive eddies can be made meaningful. In that case the diffusivity can be treated as independent of the separation, and correlated with (5). Ensemble mean or phase mean concentration can be used.

The longest lived nuclide considered is the Rn^{222} (Tm = 150 hr), Its mean life is beyond the gap that is in the region of the synoptic activity.

The synoptic systems are in this case, intermediate eddies. The ensemble mean depends on the separation, and must be interpreted according to (2). The phase mean can be estimated by the diffusion equation (3, 4), in which advection is due to the mean wind.

For any application of an ensemble mean an essential problem is to define when and where it is possible to use the diffusion equation, that is to neglect the transport by the intermediate eddies. For an uniform distribution and for the same amplitude of eddy activity, advectives will be more effective as transport elements than the intermediate eddies. If we had a criterion for the relative importance of advection to the eddy diffusion, we could establish an upper limit to the transport by the intermediate eddies.

Furhtermore, since the amplitude of the turbulence eddies is ten times greater than that of the synoptic vertical wind, many authors tend to neglect the advection of emanated clouds. This assumption sometimes produced a large error in the interpretation of radon or Pb^{212} profiles. In the following we shall work out a criterion for the relative importance of advection and diffusion in the transport. We shall assume that there is a gap in the eddy activity and the mean life of emanated clouds is long relatively to the eddies involved in the K approximation.

The mean wind is either the mean wind in the period of the phase mean ot the mean amplitude of the advectives when the concentration is an ensemble mean.

The intermediate eddies are either neglected in relation to the ensemble mean, or included in the mean wind in relation to the phase concentration.

Three dimensional scaling analysis

In the following we shall concentrate on the distribution of emanated clouds above 200 m. At this height the thoron concentration vanish and we are left with only two independent concentration profiles, namely Rn^{222} and Pb^{212}. The spatial distribution of radon and Pb^{212} depends upon the source distribution as well as on meteorological conditions. Over the continents the source distribution depends upon the geographical regions (Pearson & Johnes, 1966). The oceans emanate a small amount of radon (Broecker, 1967), which is very small in comparison to the emanation over the continents.

As the source distribution is not uniform, we expect horizontal gradients which will cause horizontal transport of these nuclides. Thus the transport of long lived emanation products is essentially a three dimensional phenomenon, and it should be treated as such.

In order to study the characteristics of the atmosphere as a transport medium of radon and Pb^{212} we shall assume a steady state. In fact near the ground the radon concentration changes in a 24 hours cycle but the amplitude of this cycle reduces abruptly above 100 m or so (Servant, 1966). In any case this is a natural assumption to use in a scale analysis since the variation in the concentration will oscillate around the steady state.

Assuming the mean wind blows in the x direction and with the limitations mentioned above the diffusion equation becomes:

$$\frac{K_x}{\lambda}\frac{\partial^2 q}{\partial x^2} + \frac{K_y}{\lambda}\frac{\partial^2 q}{\partial y^2} + \frac{K_z}{\lambda}\frac{\partial^2 q}{\partial z^2} - \frac{U}{\lambda}\frac{\partial q}{\partial x} - \frac{W}{\lambda}\frac{\partial q}{\partial z} - q = 0 \tag{8}$$

By separation of variable we have:

$$\frac{K_z}{\lambda\zeta}\frac{\partial^2 \zeta}{\partial z^2} - \frac{W}{\lambda\zeta}\frac{\partial \zeta}{\partial z} = 1 - A_h \tag{9}$$

$$\frac{K_x}{\lambda\xi}\frac{\partial^2 \xi}{\partial X^2} - \frac{U}{\lambda\xi}\frac{\partial \xi}{\partial x} = A_h - B$$

$$\frac{K_y}{\lambda\eta}\frac{\partial^2 \eta}{\partial y^2} = B$$

Finally we get:

$$q = q_0 e^{-x/Hx} e^{-y/Hy} e^{-z/Hz}, \tag{10}$$

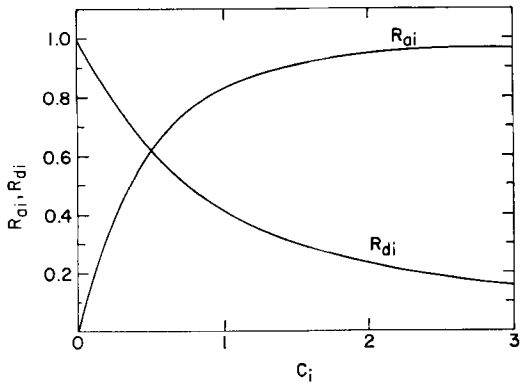

Fig. 1. The variations of the scaling parameters for diffusion R_{di} and advection R_{ai} with C_i $i = X, Z$.

where $$Hy = \sqrt{\frac{Ky}{\lambda B}}$$

$$Hx = -2Kx/(U - (U^2 + 4U^{*2})^{\frac{1}{2}})$$

$$Hz = -2Kz/(W - (W^2 + 4W^{*2})^{\frac{1}{2}})$$

are the characteristic length,

and $U^{*2} = \lambda K_x(A_h - B)$, $W^{*2} = \lambda K_z(1 - A_h)$

In deriving this solution we assumed a "regular condition". The regular conditions require that the steady state is achieved when the decay is balanced by positive transport from each direction and the concentration diminishes with increasing of x, y or z.

Mathematically we ignored the solution with positive exponents and demand that $0 < B < A_h < 1$. When $A_h = 1$ the decay is balanced by horizontal transport and the vertical transport diminishes. For $A_h = 0$ the decay is balanced by vertical transport and the horizontal transport diminishes.

Similarly B measures the relative importance of the transport in the y direction.

We shall define four characteristic lengths in the x and z directions. $H_{dx} = K_x/U^*$, $H_{dz} = K_z/W^*$ which gives the characteristic length when the transport is diffusion controlled, i.e. $U = W = 0$, and $H_{ax} = U_x/(A_h - B)\lambda$, $H_{az} = W/(1 - A_w)\lambda$ which are the characteristic lengths of concentration gradient when the transport is advection controlled, i.e. $K_x = K_z = 0$.

We shall weigh the diffusion in the transport by the ratios

$$R_{di} = \frac{Hd_i}{H_i} \; (i = x, z)$$ and the advection by $$R_{ai} = \frac{H_{ai}}{H_i}$$

Using the non dimensional parameter $c_x = U/2U^*$ $c_z = W/2W^*$ we derived the following relations

$$R_{di} = (C_i^2 + 1)^{\frac{1}{2}} - C_i; \; Ra_i = 2C_i Rd_i \; (i = x, z)$$

According to Fig. 1 we can see that when $C_i < 0.1$, $R_{di} > 0.9$, and the transport can be approximated by diffusion only. When $C_i = 1/2$, $R_{di} = R_{ai}$, the diffusion and advection play an equal part in the transport. When $C_i > 1.5$ $R_{ai} > 0.9$ and the transport is approximately advection controlled.

For computing the characteristics of the transport in the free atmosphere we assume $A_h = 1/2$ and $B = 0$, that is the vertical and horizontal transport are equally important and the horizontal transport is in the x direction alone. (This assumption will be justified later on.)

The distribution characteristics of Pb^{212} and radon in the free atmosphere as predicted by our scale analysis given in Tables 2 and 3.

Our scaling analysis brought us to the following conclusions. The horizontal transport of radon and Pb^{212} is, as expected, due to the synoptic scale wind, the eddy diffusion can be neglected (in fact even $Kx = 10^{10}$ cm²/sec results

Table 2. *Horizontal characteristics*

	Kx[a] (cm²/sec)	U (cm/sec)	Cx	Hx (km)
Rn^{222}	10^6	10^3	500	10^4
Pb^{212}	10^6	10^3	172	1100

Table 3. *Vertical characteristics*

	Kz[a] (cm²/sec)	W (cm/sec)	Cz	Hz (km)
Rn^{222}	5×10^4	+1	2.3	10
		−1	2.3	0.5
Pb^{212}	5×10^4	+1	0.77	1.5
		−1	−0.77	0.37

[a] It should be noticed that as our phase mean operate over an hour or so the K_i is due to the turbulence range of the spectra.

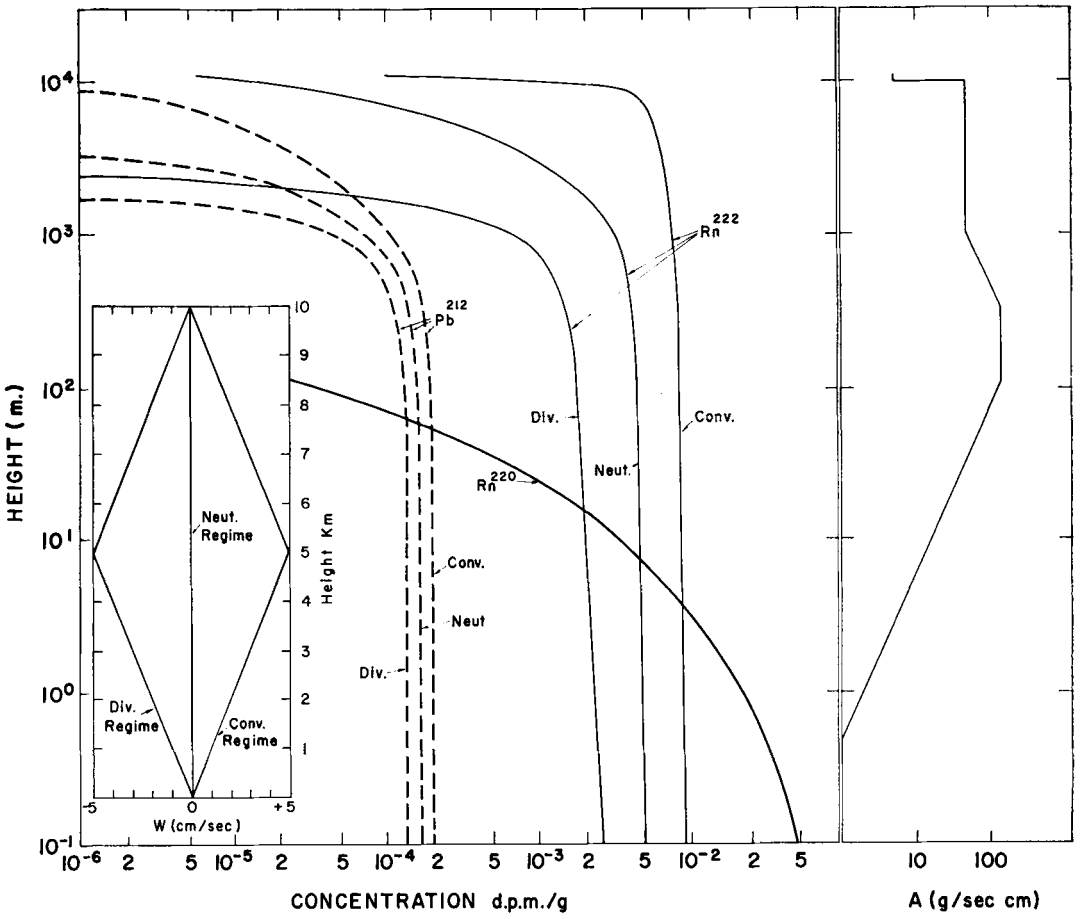

Fig. 2. The concentration of Rn^{222} and Pb^{212} as function of height for a different synoptic regimes.

with $Cx = 10$ and still diffusion can be neglected). Thus our assumption that $B = 0$ is satisfied.

In the vertical the K approximation is valid near the ground for Pb^{212} and Rn^{222}. Nevertheless in the free atmosphere the large scale vertical wind dominates in the transport of radon and it is at least as important as eddy diffusion in the transport of Pn^{212}. As the mean vertical wind estimated to be up to ± 10 cm/sec (Danielsen, 1966) we can conclude that radon profiles can be used as a sensitive measure for the large scale vertical motion. This will be illustrated in the following numerical model.

Semi uniform numerical model

As a result of our scaling analysis the steady state diffusion equation might be written as:

$$\frac{1}{\varrho}\frac{\partial}{\partial z}\left(Az\frac{\partial q}{\partial z}\right) - U\frac{\partial q}{\partial z} - V\frac{\partial q}{\partial y} - W\frac{\partial q}{\partial z} - \lambda q = 0; \qquad (A_z = \varrho K_z) \qquad (11)$$

We have seen before that the characteristic height of radon is 10 km for $W = +1$ cm/sec, and 0.5 km for $W = -1$ cm/sec. A positive (negative) vertical velocity is accompanied by a large horizontal convergent (divergent) regime. Assuming a meteorological system is over a region where the exhalation rate is more or less uniform (Pearson & Johnes, 1966), at the center of a convergent regime (cyclon) radon and Pb^{212} will be concentrated due to horizontal convergence and transported upward. The magnitude of horizontal convergence (divergence) is estimated to be 10^{-5} sec^{-1} (Landers, 1955; Danielsen, 1966) which is five times the rate

of decay for radon. We expect to find maximum concentrations of radon, and possibly of Pb^{212}, at the centre of a convergent regime. For a similar reason we expect a minimum concentration of radon and Pn^{212} at the centre of divergent regime. Thus in the free atmosphere we expect to find extremes of horizontal concentration profile at the centre of meteorological systems. In that case the diffusion equation becomes ($dq/dz = dq/dy = 0$).

$$\frac{1}{\varrho}\frac{\partial}{\partial z}\left(A_z\frac{\partial q}{\partial x}\right) - W\frac{\partial q}{\partial z} - \lambda q = 0 \qquad (12)$$

The horizontal coordinates are introduced implicitly in the above equation through the continuity equation.

The A_z profiles (Fig. 2) for our numerical model was extrapolated from Lettau analysis of Leipzig wind profile taken by Mildner (Lettau, 1950). The air density was changed according to standard atmosphere. The upper limit of our atmosphere was taken at 12 km where the boundary condition was $q = 0$.

In this troposphere (up to 10 km) calculations were done for three meteorological regimes (Fig. 2).

A neutral regime in which no convergence and no divergence exists and the transport is due to eddy diffusion alone ($W = 0$).

A convergent regime: This regime is characterised by a constant convergence up to 5 km and then a constant divergence up to 10 km.

A divergent regime (anticyclonic): In this regime the vertical wind is negative but its magnitude is the same as in the cyclonic regime at each level.

As boundary conditions on the surface we put arbitrarly, $Kdq/dz = 1$ for radon and thoron. For Pb^{212} we assumed that no flux exists near the surface, i.e. $dq/dz = 0$ (Gat & Assaf, 1968).

The results of the computation are given in Fig. 2, the sensitivity of radon concentration profiles to the divergent regime is very pronounced. Between 1 to 2 km height, where the vertical velocity exceeds 1 cm/sec, radon concentration decreases by four orders of magnitude in divergent regime, and is almost uniform all over the troposphere in convergent regime.

This result might be compared with the transport model given by Jacobi & Andre (1963). They assumed that the transport of radon is due to eddy diffusion, and computed the radon profiles for a different K profile. When the K profile was changed by a factor of 100, the corresponding changes in radon profile was much less than we get for the same K and different synoptic regime. Thus one cannot expect to measure the K_z profile in the free atmosphere by radon profiles. When one tries to interpret radon profile by neglecting a dominate factor such as convergent and large scale vertical winds one might receive apparent K_z values up to 10^8 cm²/sec (Kirichenko, 1964). As was expected from our scaling analysis Pb^{212} is less sensitive to the divergent regime (Fig. 2). Nevertheless one cannot ignore the large scale effect on Pb^{212} profile.

It should be noticed that our model gives only a qualitative picture. The assumptions of steady state and semiuniformity is very strong. It would be desirable to introduce the radon and Pb^{212} into experiments on the general circulation of the atmosphere. Only then one can follow the expected spatial and time characteristics of radon and Pb^{212}.

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ПРОДУКТЫ РАДИОАКТИВНОГО РАСПАДА КАК ИНДИКАТОРЫ ПРОЦЕССОВ ПЕРЕНОСА В АТМОСФЕРЕ

Атмосферный перенос радона, торона и продуктов их распада анализируется в свете ричардсоновской теории диффузии, причем пространственный масштаб заменяется временным. Показано, что операция осреднения, входящая в обычную процедуру параметризации турбулентной диффузии, должна быть связана со временем средней жизни изотопа и со спектром атмосферной турбулентности. Имеются случаи, когда обычная параметризация противоречива и несостоятельна, как например, в случае распределения торона, который в общем случае должен рассматриваться с привлечением формализма Ричардсона. Показано, что обычные методы при тщательном их использовании дают разумные результаты при интерпретации профилей радона — 222 и свинца — 212. Показано, что вертикальный перенос средним ветром не должен оставаться неучтенным, поскольку иногда он является доминирующим фактором. Выводится критерий для оценки относительной важности адвекции и турбулентной диффузии. Использование этого критерия дает, что в свободной атмосфере в переносе радона основную роль играет адвекция. Этот результат демонстрируется полуоднородной численной моделью.

С точки зрения практических приложений представляется, что радон мог бы служить полезным индикатором для изучения крупномасштабных (синоптических) вариаций вертикальной компоненты ветра и дивергентных режимов.