Simplified theoretical notion of contaminant removal by precipitation from the atmosphere

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ABSTRACT

Processes of contaminant washout and rainout from the atmosphere by precipitation are considered. Formulas of decreasing contaminant concentration in precipitation and in the air as a function of duration of precipitation are deduced. Coefficients of contaminant washout (below the cloud) and rainout (in the cloud layer of the atmosphere) for gases and aerosols are determined from comparison of theoretical curves with experimental data. Rainout of almost all the gases of the atmosphere is, at least, a factor of 10 less than that of aerosols.

In nature there are some constantly acting factors leading to continuous flow of gaseous and aerosol contaminants into the atmosphere. Hence the special importance of processes resulting in self-scavenging of the atmosphere from these contaminants. The main mechanism of removing contaminants from the atmosphere is their washout and rainout. Greenfield (1957) proposed the theory of washout and rainout of aerosol contaminants from the atmosphere. He suggested that the capture of dust particles by drops takes place under the influence of inertia forces in the subcloud layer of the atmosphere and under the influence of diffusion forces in the cloud. Greenfield gave calculated curves of dependence of dust particle capture by drops on the size of particles and drops. But lack of knowledge of particle capture mechanisms led to imperfection of calculations. As an example can be noted the fact of neglecting the effect of drop and particle electrical charges and the role of convective diffusion mechanism. Research carried out at the present time, for example, experiments on washout of ambrosia pollen (Gatz, Dingle, 1963) showed that Greenfield's theoretical scheme of washout needs to be corrected. The method of calculation of gas rainout from the atmosphere suggested by Chamberlain (1960) which was based upon Ranz & Marshall's work (1952) has also some essential simplifications. But the main drawback of the existing methods of calculation is the following. When using them, it is necessary not only to have a clear idea of capture mechanisms but also to know some parameters which are difficult to measure: size and charge distribution of drops and particles, their velocities, turbulent regime of the atmosphere, etc. In this connection it can be noted that in practice the size spectrum of particles removed by precipitation (washed and/or rained out) is nearly always unknown. Therefore, at present for the purposes of predicting self-scavenging effects more adequate is the method of integral estimations of contaminant washout or rainout parameters from the atmosphere in which the mechanism of particle capture by drops is not concretized. The process of particle capture by drops can be described by Smolukhovsky's coagulation equation in the extended form -see below, equation (2). Parameters characterizing washout or rainout of a given contaminant are determined experimentally from the dependence of contaminant concentration in precipitation on duration of precipitation. They can be used in the future to predict washout and rainout effects. Let us consider in general the process of contaminant washout and rainout from the atmosphere.

As it is known, the capture of contaminant by precipitation elements takes place in the cloud mass and in the subcloud (below-cloud) layer of the atmosphere. In the process of rainfall the contaminant concentration in the rain water evidently will not remain constant. Two main reasons which lead to gradual decrease of

contaminant concentration in precipitation can be given here. The first reason is continuous dilution of contaminated water supply contained in the cloud with pure water entering the cloud in the form of condensed vapour. It is known that the supply of water both in stratonimbus and cumulonimbus is not large in comparison to the amount of precipitation falling from them (Mamina, Fedorov, 1957; Muchnick, 1961). Water falling out of the cloud is replenished by continuous influx of water vapour and its condensation in the cloud. As a certain time is required for capture of contaminants by fresh water droplets, continuous dilution of contaminated water with pure water will occur during precipitation, and the concentration of contaminants in precipitation will decrease with time. The second cause of decreasing the contaminant concentration in precipitation is gradual exhaustion of contaminated matter in cloud because of its continuous capture by cloud drops. It is possible to say the same about the subcloud layer of the atmosphere where exhaustion of contaminant supply occurs due to the capture by falling rain drops. The process of continuous replenishment with masses of contaminated matter which are introduced by air flows superimposes the process of contaminant exhaustion in the cloud and subcloud air. Therefore we observe the resulting effect caused by superimposing simultaneous processes of exhaustion and replenishment of contaminants.

Considering upflow velocities and the life time of drops in various types of clouds it is not difficult to show that in cumulonimbus in middle latitudes updrafts are so powerful and precipitation is so fast that decrease of contaminant concentration in precipitation is practically due only to dilution effect, and concentration in the air when it is raining remains on about one and the same level (Makhon'ko, 1964*a*). To understand the essence of the process let us suppose for simplicity that the considered cloud is homogeneous, the drops and washed particles are monodispersed (uniformly dispersed) and the water balance during precipitation is not upset which is, to all appearances, true for rather a long time until destruction of the cloud. If I is the intensity of precipitation and t is the time, then It is the amount of moisture which will be continuously removed from the cloud during rain, and just the same quantity must continuously go into the cloud in the form of condensed vapour. Let us denote the contaminant concentration in the cloud water by C_1 and the concentration of cloud drops by N_0 and the average volume by V_0. During precipitation lasting dt the amount of contaminant $N_0 V_0 dC_1$ will be removed from a unit cloud volume. On the other hand, this value can be presented as a product of the amount of water removed from this volume Idt/H_0 (H_0 = thickness of cloud) and the instantaneous value of contaminant concentration C_1. Equating these expressions and integrating we obtain:

$$C_1 = C_0 \exp\left(-\frac{It}{H_0 V_0 N_0}\right) \tag{1}$$

where C_0-contaminant concentration in the cloud water directly before the beginning of precipitation. Thus, the dilution effect leads to the exponential decrease with time of contaminant concentration in the water of cumulonimbus.

In nimbostratus forming as a result of slow uplift of air mass over large areas the effect of exhaustion of contaminant supply in the air at the initial stage of precipitation will play the main role. But at later stages of the process one cannot neglect air mass flux into the cloud. Thus, contaminant concentration in the cloud air q changes with time under the influence of two processes: capture of contaminant by cloud drops and the divergence of contaminant flow (Makhon'ko, 1964*b*).

Describing the process of particle capture by cloud drops wiht the help of a coagulation constant K, and taking into account divergence of contaminant flux $\overline{qv}$, it is possible to write the following expression for change of contaminant concentration in the air with time:

$$\frac{\partial q}{\partial t} = -KN_0 q + \operatorname{div}(\overline{qv}) \tag{2}$$

During rain, contaminant is continuously being removed out of the cloud by falling drops. Partial replenishment of this loss occurs due to continuous capture of contaminant particles by cloud drops. For simplicity let us assume that immediately after the capture contaminant is directly removed out of the cloud with a rain drop. Now, contaminant flux out of the cloud can be presented as a product of contaminant

concentration in cloud water C_1 and the intensity of precipitation I. On the other hand, this flux of contaminant appears as a result of the decrease of contaminant concentration in the cloud air with time. This occurs because of the process of contaminant capture by cloud drops; that is, for a cloud thickness H_0 the flux will be $H_0 K N_0 q$. Equating these expressions and solving the equation relative C_1 we have:

$$C_1 = \frac{H_0}{I} K N_0 q \tag{3}$$

where q-solution of the equation (2). This solution can be obtained very simply, if modified (2) in the following way. Consider within a cloud an air column with a unit base and height equal to cloud thickness H_0. If the mean velocity of air flow through the column base is v_z, the product $q_0 v_z$ will equal the contaminant flow into this volume. Air flow penetrating into the cloud apparently spreads, thus promoting the growth of a cloud system in a horizontal direction. Outflow of contaminant through the side surface of our volume usually equals $q H_0 \cdot 2(v_x + v_y)$. Inflow and outflow differences divided by the volume of our column of air give the expression for divergence of flow. Using the equation of continuity of flow $v_z = H_0 \cdot 2(v_x + v_y)$, the expression of divergence can be written as $(q_0 - q) v_z / H_0$. Now the equation (2) will have the following solution:

$$\frac{q}{q_0} = \frac{v}{H_0 N_0 K + v} + \frac{H_0 N_0 K}{H_0 N_0 K + v} \times \exp\left[-\left(K N_0 + \frac{v}{H_0} \right)(\tau + t) \right] \tag{4}$$

Time integration was carried out here from 0 to $\tau + t$, where τ is the duration of coagulation processes in the cloud until the beginning of precipitation at the observation place, and t is the duration of precipitation at this place. In (4) index z of v is omitted for compactness. Substituting (4) into (3) we obtain the expression for contaminant concentration in the water of the nimbostratus. This expression shows that after rain begins the contaminant concentration in water decreases, but with a lapse of time it tends to a constant limit, which is due to the establishment of a dynamic equilibrium: the amount of contaminant outflow becomes equal to that of the contaminant flow into the cloud with upflows of air. The amount of contaminant in precipitation collected at the earth's surface consists of contaminant captured by drops in the cloud and of that captured from the subcloud layer of the atmosphere when drops are falling. Let us determine the second term. As earlier, when deducing the formula (3), let us present the contaminant flow into the earth's surface which appeared due to washout in the subcloud layer, as a product of contaminant concentration C_2 and the intensity of rain I. This flow appears as a result of decreasing contaminant concentration dq/dt in the subcloud layer of the air, the height of which is H. That is, it can be presented as $H(dq/dt)$. From the equality of these flows it follows

$$C_2 = \frac{H}{I} \cdot \frac{dq}{dt} \tag{5}$$

The velocity of decreasing contaminant concentration in the air during rain is proportional to the value of this concentration (Makhon'ko, K. P., 1963):

$$\frac{dq}{dt} = -\sigma q \tag{6}$$

where σ is the coefficient of contaminant washout in the subcloud layer of the atmosphere. The solution of (6) will be

$$q = q_0 \exp(-\sigma t) \tag{7}$$

where q_0 contaminant concentration in the air until the beginning of rain. Substituting (7) into (5) we obtain:

$$C_2 = \frac{H}{I} \sigma q_0 \exp(-\sigma t) \tag{8}$$

Combining now formulas (8) and (1) and also (8) and (3) and taking into account (4) the final expression for contaminant concentration in the atmospheric precipitation can be written:

$$C = \alpha + \beta e^{-\sigma_0 t} + \gamma e^{-\sigma t} \tag{9}$$

where $\gamma = (H/I) \cdot \sigma q_0$ always takes place. For nimbostratus

$$\alpha = \frac{vH_0KN_0}{I(H_0KN_0+v)}, \quad \beta = \frac{(H_0KN_0)^2}{I(H_0KN_0+v)} \cdot$$

$$\times \exp\left[-\left(KN_0+\frac{v}{H_0}\right)\tau\right], \quad \sigma_0 = KN_0+\frac{v}{H_0}$$

for cumulonimbus

$$\alpha \approx 0, \quad \beta = C_0, \quad \sigma_0 = \frac{I}{H_0N_0V_0}$$

In practice, the contaminant concentration is more often measured in the diurnal sample of precipitation, and it is the whole amount of precipitation that is measured and not its intensity and duration. In this case it is useful to modify the formula (9) in such a way that it should express the dependence of mean diurnal integral value of contaminant concentration on the diurnal amount of precipitation $h = It$. It is not difficult to obtain this dependence by integration (9). It has the following form:

$$\bar{C} = \alpha + \frac{\beta'}{h}(1-e^{-\sigma_0'h}) + \frac{\gamma'}{h}(1-e^{-\sigma'h}) \qquad (10)$$

where $\gamma' = Hq_0$, $\sigma' = \sigma/I$; for nimbostratus

$$\beta' = \left(\frac{H_0KN_0}{H_0KN_0+v}\right)^2 \cdot H_0 \exp\left[-\left(KN_0+\frac{v}{H_0}\right)\tau\right],$$

$$\sigma_0' = \frac{\sigma_0}{I}$$

for cumulonimbus

$$\beta' = C_0H_0N_0V_0, \quad \sigma_0' = \frac{I}{H_0N_0V_0}$$

As intensity of rain I and contaminant concentration in the air before the beginning of precipitation q_0 are determined from the experiment, parameter γ is easily expressed through σ, and γ' becomes known if to take into account that the height of the lower boundary of cloudiness can be assumed, on the average, as $H = 1$ km with enough degree of certainty. Having obtained the experimental dependence of contaminant concentration in precipitation on its duration it is not difficult to receive parameters α, β, σ_0 and σ in the formula (9) from the graphical analysis of this curve. Graphical analysis is possible due to the fact that in the initial period of rain the last addend in (9) almost does not influence the slope of the curve and at the later stages of the process, on the contrary, it is possible to neglect the second addend in (9). When receiving the experimental dependence of mean diurnal contaminant concentration in precipitation on its diurnal amount for determination of parameters it is convenient to use the cumulative curve in the form $\bar{C}h = f(h)$, where $\bar{C}$ is given by the formula (10).

The experience showed that determination of the coefficient of contaminant washout from the subcloud layer of the atmosphere is made very inaccurately by this method, because for nearly all the possible atmospheric contaminants the value of σ is too small and the corresponding part of the curve $\ln C = \varphi(t)$, from which σ is determined, has too small slope. Therefore it is much easier to determine σ from dependence of contaminant concentration in the surface layer of the air on duration (or amount) of precipitation. This dependence is described by the formula (7).

Parameter σ_0 characterizes the velocity of the contaminant rainout process in the cloud. In middle latitudes the greatest part of precipitation falls from nimbostratus. For this case it is useful to calculate from the value σ_0 the effective value of constant of contaminant particle coagulation with cloud drops, K. Here we assumed the average value of cloud drop concentration $N_0 = 300$ cm^{-3} and thickness of cloudiness $H_0 = 4$ km. It must be pointed out that the second term in the expression for σ_0 was always an order lower than the first one, therefore the magnitude of H_0 almost does not affect the results of determination of coagulation constant K.

In Table 1 are given results of the determination of parameters of contaminant washout and rainout from the atmosphere from experimental curves shown in Fig. 1. This table gives the place where precipitation was sampled, the time when precipitation occurred and the type of contaminant washed out. To make the picture more complete, data on gas and atmospheric dust removal by precipitation were supplemented with some information on removal of fission products and radon daughter decay products by precipitation from the atmosphere which is available elsewhere (Table 1, items 6–8). In Fig. 1 curves which are drawn by a thick line are calculated according to the for-

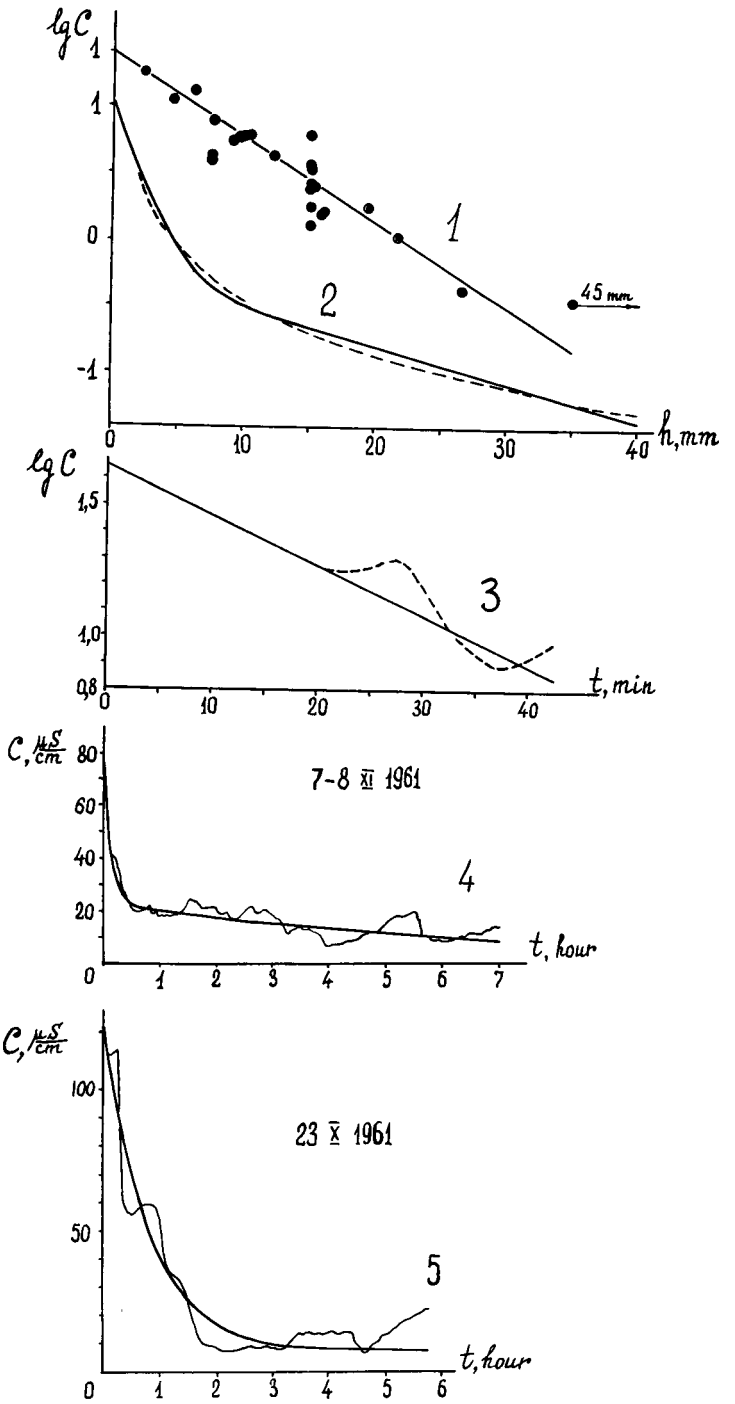

Fig. 1. Contaminant concentration in the atmospheric precipitation vs. amount or duration of precipitation: *1*, radon; *2*, SO_4, NH_4, Cl, NO_3; *3*, atmospheric dust; *4*, *5*, dissolved inorganic contaminant.

Table 1. *Washout and rainout parameters determined from*

No. of items	Measurement site	Period of measurements	Type of contaminant	β
1	India (Calcutta)	VI–VIII.1964	Radon	$4.17 \cdot 10^{-10}$c/l
2	—	—	SO_4, NH_4, Cl, NO_3	182 rel. un
3	India (Bombay)	VI, VIII.1958	Atmospheric dust	44.7 mg/l
4	GFR (Frankfurt (Main))	XI.1961	Dissolved inorganic contaminant	63 μ S/cm
5	GFR (Frankfurt (Main))	X.1961	Dissolved inorganic contaminant	134 μ S/cm
6	Belgium	I–XII.1959	Fission products	$24 \cdot 10^5$
7	USSR	VI–VIII.1960	Fission products	$1.34 \cdot 10^5$
8	USSR	1960; 1963	Radon decay products	—

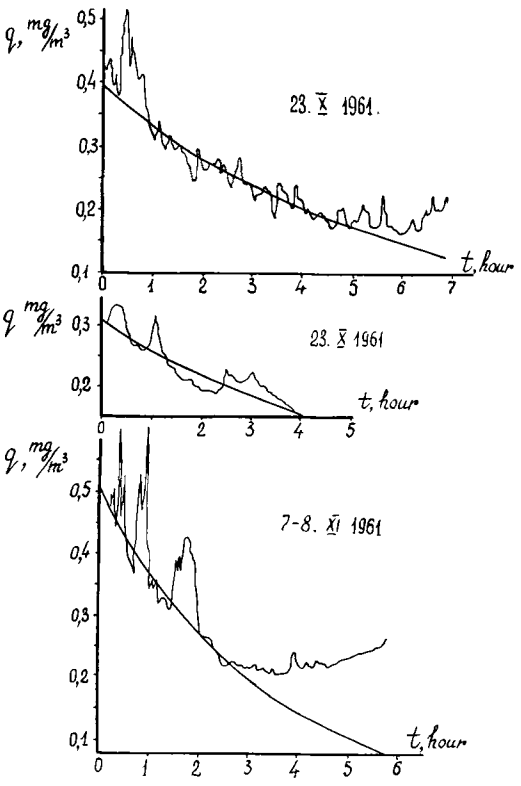

Fig. 2. Sulfur dioxide concentration in the air vs. duration of rain.

mula (10) using parameters given in Table 1. It is seen that there is rather good agreement between calculated curves and experimental data. In the first two cases when determining σ_0 from dependence of contaminant concentration on the amount of precipitation it was assumed that typical value $I = 1$ mm/hr. Considering the data from the Table 1 first of all it is seen that the coefficient of contaminant rainout from the cloud is $\sigma_0 \sim 10^{-4} - 10^{-3}$ sec^{-1}. Rainout velocity of radon, noble gas, from the cloud is 1–2 orders less than that of the aerosol contaminant. The effective value of the coagulation constant of aerosol particles with cloud drops is, on the average, of the order of $K \sim 10^{-6}$ cm^3/sec. Variations of K values are within the range of $(6 - 74) \cdot 10^{-7}$ cm^3/sec but the magnitude of these variations is, to all appearances, not connected with the type of rained out contaminant.

The coefficient of contaminant washout from the subcloud layer of the atmosphere was determined from the dependence of contaminant concentration in the subcloud layer of the atmosphere on the duration of precipitation.

The corresponding experimental curves for sulfur dioxide taken from Georgii's work (Georgii, 1963) are given in Fig. 2. Curves calculated from the formula (7) are drawn by a thick line. Some narrow peaks of sulfur dioxide concentration which are far beyond the limits of regularity are explained, perhaps, by the fact that measurements were carried out in the industrial region where sharp fluctuations of SO_2 concentration are natural and are due to the drift of smoke plumes. In two cases increase of contaminant concentration coincided with the growth of precipitation intensity. The author explains these peaks by destruction of shower cells and by the appearance of air masses from above to the earth's surface as a result of

measurements of contaminant concentration in precipitation

γ	α	σ_0, 10^{-4} sec^{-1}	σ, 10^{-5} sec^{-1}	K, 10^{-7} cm^3/sec	References
—	—	0.4	—	1	Banerji, Chatterjee
11 rel. un.	—	2	2	6	Kalkstein *et al.*
—	—	7	—	24	Shirvaikar *et al.*
23 μ S/cm	—	22	4	74	Georgii
—	8.6 μ S/cm	4	—	12	Georgii
$\alpha+\gamma=0.2\cdot10^5$		20	—	70	Makhon'ko, Dmitrieva
$0.2\cdot10^5$	$1.0\cdot10^5$	2	$\lesssim1$	6	Makhon'ko, 1964 b
—	—	10[a]	—	30[a]	Styra *et al.*

[a] It is determined from the vertical profile of radon decay product concentration in the cloud air. The data are recalculated by us for the concentration of cloud drops $N_0 = 300$ cm^{-3}.

increasing turbulence of the atmosphere. Perhaps, in reality, this effect does take place but the existence of other peaks of contaminant concentration which are not accompanied by the growth of precipitation intensity cannot be explained in this way. Therefore the supposition about the effect of smoke plumes seems more natural in a number of cases. Deviation of the experimental curve from the calculated one observed at the end of the upper curve and especially well-marked at the end of the lower one should be possibly explained by the effect of sulfur dioxide advection.

The results of our measurements of atmospheric dust concentration during precipitation are shown in Fig. 3. Our measurements were carried out by the optical method. The interval of time over which the concentration was averaged was 2 min 37 sec for the cases shown in this figure. As before, the calculated curve is drawn by a thick line. Agreement between experimental and calculated data for atmospheric dust, just as for sulfur dioxide, should be acknowledged satisfactory in spite of the fluctuations of contaminant concentration which are rather large in some cases.

The results of determinations of washout coefficient σ from the curves (Figs. 2 and 3) are tabulated (Table 2). Given in this Table, for comparison, are data taken from literature on washout coefficients of fission products, hot particles formed during nuclear explosions and radon decay products (Table 2, items 10–13). From Table 2 it follows that the coefficient of contaminant washout from the subcloud layer of the atmosphere is of the order of $\sigma \sim 10^{-5}$ –

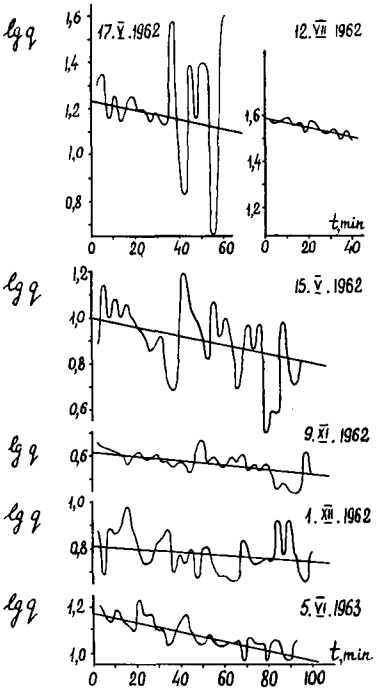

Fig. 3. Atmospheric dust concentration in the air vs. duration of rain.

10^{-4} sec^{-1}. Comparison of data from Tables 1 and 2 allows us to conclude that $\sigma_0 \sim 10\,\sigma$; that is, removal of contaminant from the atmosphere takes place mainly in the cloud. Considering the data in this table it should be said that washout coefficients of sulfur dioxide and aerosol contaminants from the subcloud layer of the atmosphere are about the same irrespective of

Table 2. *Washout coefficient determined from measurements of contaminant concentration in the surface layer of the atmosphere during precipitation*

No. of items	Measurement site	Period of measurements	Type of contaminant	σ, 10^{-5} sec^{-1}	References
1	GFR (Frankfurt (Main))	XI.1961	Sulfur dioxide	4.6	Georgii
2	GFR (Frankfurt (Main))	X.1961	Sulfur dioxide	8.8	Georgii
3	GFR (Frankfurt (Main))	X.1961	Sulfur dioxide	4.6	Georgii
4	USSR (Moscow region)	V.1962	Atmospheric dust	8.2	Our measurements
5	USSR (Moscow region)	V.1962	Atmospheric dust	8.3	Our measurements
6	USSR (Moscow region)	VII.1962	Atmospheric dust	7.8	Our measurements
7	USSR (Moscow region)	XI.1962	Atmospheric dust	4.8	Our measurements
8	USSR (Moscow region)	XII.1962	Atmospheric dust	2.9	Our measurements
9	USSR (Moscow region)	VI.1963	Atmospheric dust	8.0	Our measurements
10	USSR (Moscow region)	IX–XII.1961–62	Fission products	4	Makhon'ko *et al.*
11	USSR (Moscow region)	I–VIII.1961–62	Fission products	$\lesssim 0.5$	Makhon'ko *et al.*
12	USSR (Moscow region)	IX–XII.1961–62	Hot particles	8	Makhon'ko, Malakhov
13	USSR (Caucasus)	1956; 1957	Radon decay products	4[a]	Malakhov, Solodikhina

[a] It is determined from the radon decay product concentration in rain water, collected at two various altitudes in the mountains.

the type of contaminant. The exception from a number of approximately equal σ values is the washout coefficient of aged fission products, which is about an order lower than the value of σ for the periods of nuclear weapon tests. Returning to Table 1 it should be noted that the value of σ_0 for aged fission products (1960) is also an order lower than that for comparatively fresh fission products (1959). Thus, aged fission products are generally less removed by precipitation than the fresh ones, washout and rainout velocity of which is nearer to the velocity of removing other kinds of contaminants from the atmosphere. It is especially clearly seen for σ, less clear but, on the average, rather well for σ_0.

The weak dependence of velocity of aerosol contaminant removal by precipitation from the atmosphere on its kind can be explained in the following way.

Dust appearing in the atmosphere is of the most various origin. Mainly it is soil dust, but sufficient contribution is made by industrial, organic, cosmic and volcanic dust and also by dust of sea origin, etc. Every kind of dust, when originating, has its own characteristic particle size spectrum. But existing in the atmosphere dust gradually "ages": larger size fractions precipitate on the earth's surface and smaller ones intensively coagulate. The process of "aging" leads to approximate levelling of particle size spectrums for all the kinds of dust. It should be taken into account that the coagulation process includes not only the acts of attachement of dust particles of one kind but also cross-coagulation of dust particles of various origin. As a result, very small particles which form when radon decays in the atmosphere and when fission processes during nuclear explosions take place, appear sorbed by larger particles of the atmospheric non-radioactive dust. Thus, size spectra of dust particles of various origin appear to be approximately similar with the lapse of time. This leads to similar intensities of processes of their removal by precipitation from the atmosphere. Naturally, in some particular cases removal by precipitation of just formed, not yet "aged" dust can be observed. This causes great scatter of obtained values of removal parameters σ_0 and σ. Thus, "age" of washed out dust influences washout and rainout intensity, which conceals the effect of particle origin, and, on the average, leads to more or less stable values of σ_0 and σ parameters.

Observations of fission product removal by precipitation from the atmosphere allow us to make a conclusion about the character of

changes occurring in the particle size spectrum when the process of dust "aging" is very long, lasting many months. As follows from Tables 1 and 2 atmospheric dust labelled by fission products of test series of nuclear explosions is removed by precipitation much better during the period of explosions than in a year or in half a year afterwards. It happens so because in such long processes of aging not only coagulation and sedimentation but also removal by precipitation takes place. As it is known the extreme parts of particle size spectrum, being approximately larger than 1 μ and less than 0.1 μ, are more intensely removed by precipitation, and the parts of size spectrum 0.1–1 μ are removed even less. With the lapse of time atmospheric dust, as a result of washout and rainout becomes deficient in fractions which are easily removed, and the removal by precipitation of atmospheric dust as a whole becomes less. Particle size spectrum is gradually transformed at the expense of decrease of the largest and the smallest particle amount.

Now let us compare the intensity of removing gaseous and aerosol contaminants by precipitation from the atmosphere. Two cases were considered above: the rainout of radon, noble gas, and washout of highly active sulfur dioxide. While in the cloud radon was rained out by about one or two orders less than dust and in the subcloud layer of the atmosphere it is almost not washed out at all, and sulfur dioxide had the same value of washout coefficient σ as aerosols.

The above is obvious because sulfur dioxide actively reacts with atmospheric moisture and forms sulfurous acid and radon does not react at all. As it is known, volumetric solubility (absorption) of radon in water at 0°C is 0.51 and of sulfur dioxide is 79.8. When all the gases of the Earth's atmosphere are written in the order decreasing solubility we obtain the following sequence: $CO_2 > N_2O > Rn > O_3 > Xe > Kr > He > CH_4 > NO > Ar > O_2 > CO > N_2 > H_2 > Ne$, where the solubilities diminish from 1.71 to 0.012. Thus, nearly all the gases which are found in the atmosphere are removed from it less than radon. That is, the rate at which gases are removed by precipitation from the atmosphere is at least a factor of 10 less than that of aerosols. This conclusion, of course, can be considered as preliminary, because rainout of radon was determined by us from the data of only one work in which results received in one concrete geographical point are given. Under other conditions rainout of radon will probably be somewhat different. For example, in the work by Karol & Malakhov (1962) it is shown that radon concentration in precipitation is an order lower than in the case considered by us that points to even less radon removal by precipitation.

Conclusions

1. Use of integral parameters characterizing washout and rainout of contaminants from the atmosphere by precipitation allows us to determine them easily experimentally and, further, to apply them for the purpose of prediction of average washout and rainout picture.

2. Washout coefficient of atmospheric aerosols in the subcloud layer of the atmosphere is of the order of $\sigma \sim 10^{-5} - 10^{-4}$ sec^{-1}, and in the cloud $-\sigma_0 \sim 10^{-4} - 10^{-3}$ sec^{-1}; that is, removal of contaminants by precipitation mainly occurs in the cloud.

3. The rate of removal by precipitation of the principal gases of the Earth's atmosphere is at least a factor of 10 less than that of aerosols.

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УПРОЩЕННЫЕ ТЕОРЕТИЧЕСКИЕ ПРЕДСТАВЛЕНИЯ ОБ УДАЛЕНИИ ЗАГРЯЗНЕНИЙ ИЗ АТМОСФЕРЫ ОСАДКАМИ

Рассматриваются процессы вымывания примеси осадками из подоблачного слоя атмосферы и в облачном слое. Выводятся формулы убывания концентрации примеси в осадках и в воздухе в зависимости от продолжительности осадков. Из сравнения теоретических кривых с экспериментальными данными определяются коэффициенты вымывания примеси в облаке и в подоблачном слое атмосферы для газов и аэрозолей. Вымывание в облаке почти всех газов, входящих в состав атмосферы, происходит не менее, чем на порядок, хуже вымывания атмосферной пыли.