The main features of condensation nuclei distribution in the free atmosphere over the European territory of the USSR

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ABSTRACT

According to the numerous observations from airplanes the mean profiles of the condensation nuclei concentration up to the height of 6 km in different geographical points have been obtained and the regularity of their vertical distribution has been specified. It has been shown that the theoretical diffusion-coagulation formula (6) is in good agreement with the empirical data.

According to the relations obtained the total of the condensation nuclei content in the troposphere ($1.15 \cdot 10^{27}$ nuclei) has been estimated.

Basing on the data of stationary soundings and on a great number of additional horizontal flights the peculiarities of geographical condensation nuclei distribution in the lower troposphere over the European territory of the USSR have been cleared up.

The schematic maps of nuclei distribution at levels 2 and 3 km are given which are compared with the distribution of the atmospheric precipitation mineralization.

During the International Geophysical Years in the USSR observations of the condensation nuclei concentration in the atmosphere up to 6–6.5 km were organized at several stations of aircraft sounding. These observations went on during the next years so that up to now a large amount of data have been accumulated—more than 5000 soundings at different points—from which the distribution of condensation nuclei in the free atmosphere was studied.

For the aircraft observations an arrangement using Scholtz counter (ALEKSANDROV & PETRENTCHUK, 1959) was developed. In spite of the well-known imperfection of such types of counters they are irreplaceable when organizing network observations due to their simple construction and the possibility of using them under field conditions.

By means of the above counter and other similar instruments the countable concentration of small-size particles of aerosols is measured, as it is generally known. These particles become condensation nuclei at supersaturations created in the counter chambers, and in the atmosphere only a small number of them are active condensation nuclei which are often called "cloud condensation nuclei". In literature (FUKS, 1955; JUNGE, 1963; SIKSNA, 1961) suggestions were made concerning the more exact definition of terminology in this field, but the term "condensation nuclei" for a broad class of small particles of aerosols—in the range of $5 \cdot 10^{-7}$–10^{4} cm—which we also accept, is still widespread. The study of concentration of these particles scattered throughout the troposphere has a sufficiently general importance for physics of the atmosphere. In this connection the corresponding observations were organized, some results of which are given in the present report.

First of all let us dwell on the principal regularities of the vertical distribution of condensation nuclei. It is usually accepted that at the steady (average) distribution of condensation nuclei their vertical turbulent flow is balanced by gravitational sinking. Under these conditions the following formula is obtained for the vertical nuclei distribution.

$$N(z) = N_0 e^{-(w_n/K)z}, \tag{1}$$

where N the condensation nuclei concentration, w_n the mean rate of their sinking, K the turbulent coefficient accepted as a constant for the free atmosphere.

An empirical formula (WIGAND, 1919; ZAITSEV, 1948) of such kind was also obtained:

$$N = N_0 e^{-z/h}. \tag{1'}$$

However, the coefficient at z in formula (1) differs by 2–3 orders from the value of h derived from experimental data which fact shows inadequacy of theoretical prerequisites. On the other hand, empirical formula (1′) describes the vertical distribution of condensation nuclei in some small layers of the atmosphere and is unfit for the troposphere as a whole.

When solving the problem theoretically an equation of atmospheric contaminant transfer in general form should be considered

$$\frac{\partial N}{\partial t} = -\left(u\frac{\partial N}{\partial x} + w\frac{\partial N}{\partial z}\right) + \frac{\partial}{\partial z}K\frac{\partial N}{\partial z} - w_n\frac{\partial N}{\partial z} - \alpha N^2 - \Psi, \tag{2}$$

where w vertical component of air motion, w_n rate of gravitational sinking of condensation nuclei, α coagulation constant, ψ function of nuclei removal by rainout and other processes.

Having evaluated the order of terms in equation (2) we are convinced that for condensation nuclei the prevailing size of which is $r \sim 10^{-5}$–10^{-6} cm, the term $w_n\,\partial N/\partial z$ may be neglected and coagulation term αN^2 when $N \sim 10^3$–10^4 cannot be removed (α for condensation nuclei by a number of evaluations has an order of 10^{-9}–10^{-8} cm³/sec.).

It is difficult to say something definite of the function ψ; one may suppose that $\psi \sim \beta N$ but the coefficient β is unknown to us. Therefore, we do not take into account the function ψ for the present.

For stationary conditions, taking into account the evaluation of the equation (2) terms, we obtain the equation

$$K\frac{d^2N}{dz^2} - \alpha N^2 = 0. \tag{3}$$

In such a form the equation was solved in SELEZNEVA & YUDIN. (1960); for $N(z)$ after integration (3) the following dependence has been obtained:

$$N(z) = \frac{\sigma K}{\alpha}(z + C)^{-2}. \tag{4}$$

The integration constant C is determined from the condition $N = N_0$ at $z = 0$; therefore,

$$C = \left(\frac{\sigma K}{\alpha N_0}\right)^{\frac{1}{2}}. \tag{5}$$

The final form of formula (4) may be as follows:

$$N(z) = N_0\frac{C^2}{(z + C)^2}. \tag{6}$$

The numerical value of C is to be found by experimental data as the magnitudes of formula (5) are not known exactly. From formula (6) it follows that at $z = C$ the ratio $N/N_0 = \frac{1}{4}$. It should be noted that the values of C found by this condition from experimental data and estimated by formula (5) have the same order ($\sim 10^5$ cm).

The parameter C is a very significant characteristic of the vertical distribution of condensation nuclei. Thus, the greater the value of C is the greater is K, which corresponds to the more intensive vertical exhange in the atmosphere and to the slow decrease in the number of condensation nuclei with height; and vice versa small values of C indicate the weak exchange in the atmosphere and the rapid decrease in nuclei concentration.

Through this parameter a total quantity of condensation nuclei in an atmospheric column is determined,

$$\int_0^{z\to\infty} N(z)\,dz = N_0\frac{C^2}{z + C}\Bigg|_{z\to\infty}^{0} \to N_0C. \tag{7}$$

It is of interest to note that in an atmospheric layer from the earth's surface up to $z = C$ a half of all aerosol particles is contained,

$$\int_0^{z=C} N(z)\,dz = 0.5\,N_0C.$$

Let us compare all these theoretical conclusions with experimental data.

In Fig. 1 the mean distribution of condensation nuclei by the results of all soundings made in the USSR (as was indicated above, their number exceeds 5000) is given. The data are plotted in different coordinates:

1. $[N/N_1, z]$, 2. $[N/N_1 \cdot \varrho_1/\varrho, z]$,
3. $[\lg N/N_1, z]$, 4. $[\lg N/N_1, \lg(z + C)]$.

N_1 is a value at the first level $z_1 = 250$ m.

By curve (1) it is determined that $C = 900$ m. Using this value of C and formula (6) N/N_1 plotted as Δ in the figure have been calculated. The calculated values are in good agreement

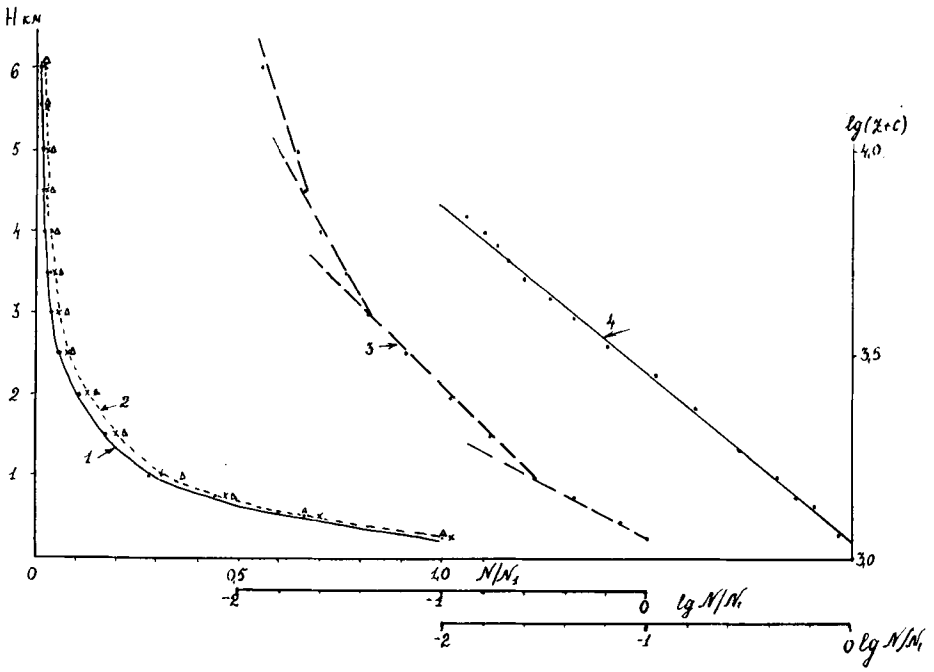

FIG. 1. The mean vertical distribution of condensation nuclei. 1. N/N_1 as function z; 2. $N/N_1\ \varrho_1/\varrho$ as function z, points Δ—N/N_1 calculated by formula (6) at value $C = 900$ m; 3. lg N/N_1, as function z; 4. lg N/N_1, as function lg $(z+C)$.

with curve (2) showing the change in the condensation nuclei concentration taking into account the change in air density $[N/N_1 \cdot \varrho_1/\varrho]$.

A good agreement of formula (6) with the average distribution of condensation nuclei is also confirmed by straight line (4). At the same time it is clearly seen by the character of curve (3) that a simple exponential formula does not describe the distribution of nuclei throughout the considered layer and may be accepted only for individual small layers of the atmosphere. It should be noted that this was also indicated by the first investigator of condensation nuclei in the free atmosphere, A. WIGAND (1919), but it was not taken into account in many later works.

In different points the vertical profile of condensation nuclei concentration differs from the mean distribution to some or other extent (Fig. 2). The peculiarities of nuclei distribution at each point are determined by physical and geographical conditions, large-scale circulation and local nuclei-production sources. In the lower 2 km layer local factors are strongly expressed. The highest values of concentration have been obtained near such large industrial centers as Moscow and Sverdlovsk.

Above two kilometers the aerosols concentration in the atmosphere is influenced by more general factors. Thus, in the middle troposphere (3–6 km) the higher concentrations of condensation nuclei have been obtained in the southern regions near Kiev and Volgograd. The slow decrease in the number of nuclei in these regions with height shows an intensive vertical exchange which leads to the increase in the aerosols concentration at the indicated heights.

Of great interest are the peculiarities of condensation nuclei distribution in the regions of Krasnoyarsk and Tashkent. In the boundary layer of the atmosphere the nuclei concentration is considerable—near Krasnoyarsk due to industrial pollution and in the arid regions of Central Asia (Tashkent) the general pollution of the atmosphere is high; however, in the middle troposphere the nuclei concentrations in these areas are less than in the points situated on the European Territory of the USSR. This

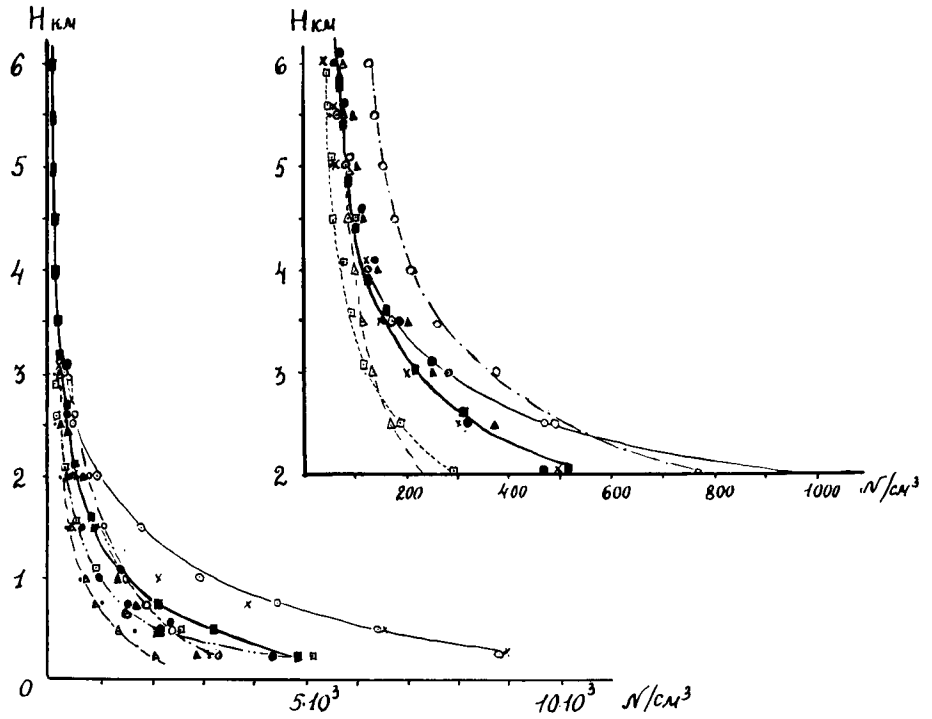

FIG. 2. The mean vertical distribution of condensation nuclei at different points. · Leningrad, ⊙ Moscow, △ Kazan, × Swerdlovsk, ▲ Volgograd, ○ Kiev, ● Tashkent, ⊡ Krasnoyorsk, ■ average.

decrease in aerosols concentration is noticeable from 1–2 km and particularly strongly expressed in the cold half-year. Using aerological data and general climatic characteristics shows that frequent temperature inversions, both night surface inversions and particularly winter anticyclonic ones, are determinant. Under the conditions of downward motions in winter anticyclones over inversions the air is very clear and dry; in such situations the nuclei concentration even at a height of 500 m is often less than 100/см³.

For these conditions in the basic equation the term $w\,\partial N/\partial z$ should be taken into account, where w is the rate of air downdraft, and the role of coagulation term is sharply decreased at a very low nuclei concentration. In such cases for some layer of atmosphere an exponential law of the decrease in the condensation nuclei concentration is likely to be true; however, the exponent will be more complicated as is shown by A. G. LAKTIONOV (1960).

The vertical distribution of condensation nuclei in the eastern areas is also influenced by the peculiarities of large-scale circulation—the considerable frequency of northern currents bringing air with low nuclei content from high latitudes.

Thus, a peculiar continental effect may be marked in the condensation nuclei distribution. When moving deep into the continent the content of condensation nuclei in the middle troposphere decreases owing to air downdrafts in anticyclones and due to high frequency of inversions in the boundary layer of the atmosphere. Even in summer season the increase in the number of condensation nuclei in the free atmosphere and the lifting of "continental dust top" are not seen when moving towards the east, as it was suggested in some investigations (JUNGE, 1951). Owing to the above factors the troposphere is refined of aerosol pollution probably to a greater extent than as a result of washout by rain.

Based on the results of soundings other characteristics of condensation nuclei distribution in the atmosphere were also studied; they are diurnal and annual changes at different heights,

the peculiarities of distribution in the boundary layer, the dependence of vertical distribution on the stratification of atmosphere and other meteorological factors. The horizontal inhomogeneities of nuclei concentration in the atmosphere and the most basic peculiarities of geographical distribution were also studied. The results of these investigations have partly been published in the Proceedings of Voeikov Main Geophysical Observatory (SELEZNEVA, 1962, 1963, and 1964) and partly prepared for publication. It is impossible to give all the results of these works in the present report.

Only the estimation of the condensation nuclei concentration in the surface layer will be cited below from the results of these works. Observations in individual points, as a rule, are greatly distorted by local influences and due to this fact are not representative. Using the theoretical relations by the data of nuclei distribution in the free atmosphere one may determine N_0 which is typical for a sounding region and not for an individual point. On the basis of the average distribution of condensation nuclei we obtain the value $\bar{N}_0 \simeq 6.5 \cdot 10^3$ (cm^{-3}) for the surface layer; for some regions the prevailing values are $4 \cdot 10^3$–$5 \cdot 10^3$ (cm^{-3}) and for northern areas $2 \cdot 10^3$–$3 \cdot 10^3$ (cm^{-3}). It should be noted that according to the data of surface observations, which have been generalized in the well-known monograph by LANDSBERG (1938), higher concentrations ($\sim 10^4$) are taken for intracontinental areas than the values given above. However, estimations of the concentration value which is typical for the surface layer, which have been made for different reasons by LETTAU (1939) and JUNGE (1963), are close to the values obtained by us. The values given by JUNGE (1963) in the same paper for the middle troposphere are also confirmed.

By the average value of $\bar{N}_0$ and mean value of parameter $C = 9 \cdot 10^4$ cm let us estimate the total number of condensation nuclei in the trophosphere column of the unit section over continents using equation (7).

$$N_0 C \simeq 6 \cdot 10^8 \text{ nuclei/cm}^2.$$

To evaluate the content of condensation nuclei in the whole troposphere the data over the surfaces of oceans are necessary. It is known that the nuclei concentration over seas and oceans is considerably less than over land

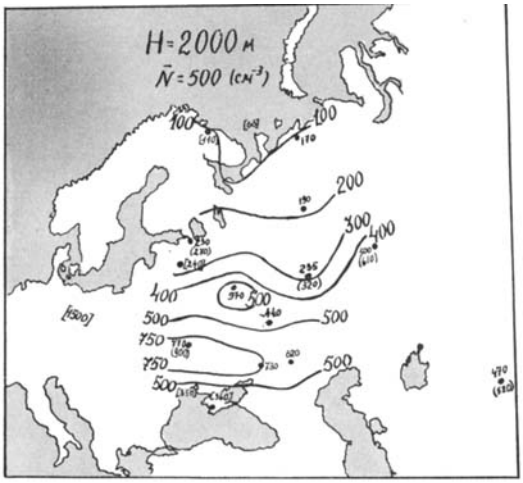

FIG. 3. Geographical distribution of concentration of condensation nuclei at the level 2000 m.

(LANDSBERG, 1938). In the layer near water far from shores the concentrations of 400–500 nuclei/cm^3 may be taken as a typical value. There is very little information on the vertical distribution of condensation nuclei over oceans. The workers of the Main Geophysical Observatory (BELYASHOVA, 1964, and others) made a number of soundings over the northern and Far East seas as well as over some intracontinental reservoirs.

The results of these observations show that in the lower atmosphere the number of nuclei decreases slowly with height over water surface; the inversion distribution of nuclei is often observed with maximum at a height of 300–500 m. The almost constant concentration of condensation nuclei up to some height may be explained, to our mind, by the influence of vertical exchange at the absence of influx (over freshwater reservoirs) or at the slight influx (over seas) from the underlying surface. The inversion distribution of nuclei is likely to appear due to absorption of aerosol particles by the water surface.

With the above peculiarities of condensation nuclei distribution over oceans the feature expressed by formula (6) cannot be applied to the whole layer over water beginning from the water surface. Gradual and very slow decrease in the nuclei number begins from 250–300 m and sometimes from 500 m; above this level the value C for ocean troposphere makes

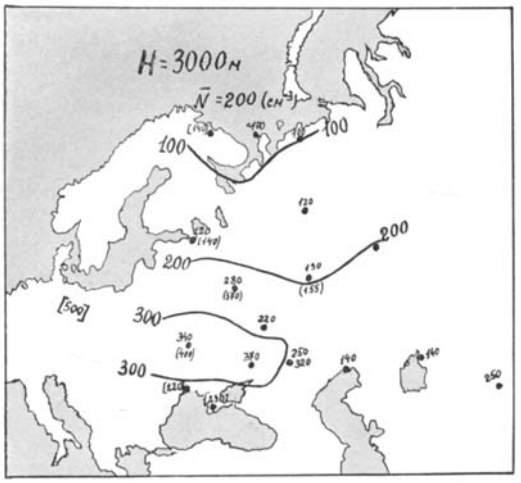

FIG. 4. Geographical distribution of concentration of condensation nuclei at the level 3000 m.

2000–2500 m. According to the given values over oceans $N_0C \simeq 10^8$ nuclei/cm³. Thus, on the average for the Earth taking into account the ratio of the surface of land and oceans is $N_0C = \frac{1}{4} \cdot 6 \cdot 10^8 + \frac{3}{4} \cdot 10^8 = 2.25 \cdot 10^8$ (cm^{-2}). Therefore, in the whole troposphere $2.25 \cdot 10^8 \cdot 5.1 \cdot 10^{18} \simeq 1.15 \cdot 10^{27}$ condensation nuclei are scattered.

In clonclusion we shall dwell briefly on the macro-geographical peculiarities of condensation nuclei distribution in the free atmosphere. For the space characteristics of nuclei distribution the data of stationary soundings are supplemented by observations in specially organized flights over different remote areas. By the results of all the observations one may present, in general outline, the change of condensation nuclei concentration in the free atmosphere on such a vast area as the European Territory of the USSR. Two scheme maps for the levels of 3000 m and 2000 m are given (Figs. 3 and 4). The condensation nuclei concentration increases from northern areas to southern ones; over the south of the territory under consideration a zone of the highest values of concentration is revealed, it covers industrial regions with the most dense population. Undoubtedly, pure geographical factors are also of great importance (vegetation zones, soil cover conditions, etc.) as well as meteorological factors—the intensity of vertical exchange etc. Below 2000 m a great inhomogeneity in the condensation nuclei distribution is due to industrial pollutions, as has been noted above.

The concentration of condensation nuclei at a level of 2000 m is changed from 100–150 (cm^{-3}) at the extreme north up to 750–1000 (cm^{-3}) in a maximum zone, at a level of 3000 m from 100 to 300–400 (cm^{-3}). Hence, one may estimate a latitudinal gradient of nuclei concentration: at a height of 3000 m $\partial N/\partial\varphi \simeq 15$ (nuclei cm^{-3}/1°L), at a height of 2000 m $\partial N/\partial\varphi \simeq 40$ (nuclei cm^{-3}/1°L); at lower levels the gradient increases to about 100 (nuclei cm^{-3}/1°L).

The geographical distribution of condensation nuclei is in good agreement with that of constituents in atmospheric precipitation. For comparison a map (Fig. 5) of the average mineralization of precipitation (the total amount of ions in mg/l.) is given from DROZDOVA, PETRENTCHUK, SELEZNEVA & SVISTOV, 1964. It is natural that the greatest contamination of atmosphere and precipitation is observed in the same regions. The study of atmospheric precipitation composition (DROZDOVA. PETRENTCHUK, SELEZNEVA & SVITOV, 1964) showed that an increase in mineralization at the south of ETU occurs due to continental components (sulphates and hydrocarbonates); in coastal regions chloride is a prevailing component of precipitation. The same change in the atmospheric precipitation composition on the continents has been obtained in other investigations (JUNGE, 1963). The atmospheric aerosols composition is likely to change in the same way.

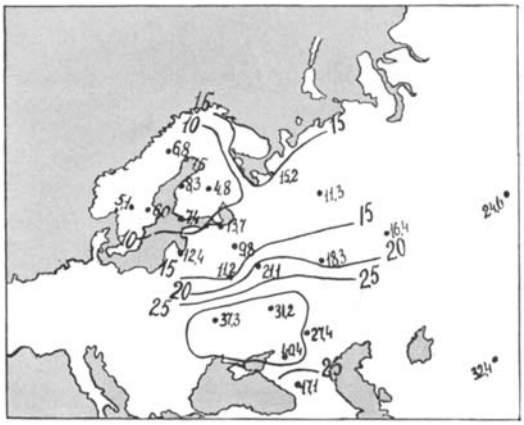

FIG. 5. Total amount of constituents of atmospheric precipitation over the European Territory of the USSR (mg/l).

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ОСНОВНЫЕ ОСОБЕННОСТИ РАСПРЕДЕЛЕНИЯ ЯДЕР КОНДЕНСАЦИИ В СВОБОДНОЙ АТМОСФЕРЕ НАД ЕВРОПЕЙСКОЙ ТЕРРИТОРИЕЙ СССР

По результатам многочисленных наблюдений с самолетов до высоты 6 км получены средние профили концентрации ядер конденсации в разных географических пунктах и уточнена закономерность их вертикального распределения. Показано, что теоретическая диффузионно-коагуляционная формула (6) хорошо согласуется с опытными данными.

По полученным соотношениям оценено общее содержание ядер конденсации в тропосфере ($\sim 1{,}15 \cdot 10^{27}$ ядер).

На основании данных стационарных зондирований и большого числа дополнительных горизонтальных полетов выяснены особенности географического распределения ядер конденсации в нижней половине тропосферы над Европейской территорией СССР. Приводятся схематические карты распределения ядер на уровнях 2 и 3 км, которые сравниваются с распределением минерализации атмосферных осадков.