AICE SURVEY OF USSR AIR POLLUTION LITERATURE, VOLUME I. ATMOSPHERIC AND METEOROLOGICAL ASPECTS OF AIR POLLUTION

M. Y. Nuttonson

American Institute of Crop Ecology
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A collection of USSR studies of atmospheric and meteorological aspect of air pollution. Some of the papers deal with the emission of noxious pollutants emitted to the atmosphere in high concentration or near ground level and with exposure of these pollutants to the continuous mixing, diffusion, stirring and dilution that takes place in the atmosphere as a result of air turbulence. Other aspects discussed are; the intensity and structure of air turbulence in relation to temperature and wind, the direction frequencies and intensities of wind, and, the effect of rain on air pollution levels and the state of diffusion under other various meteorological factors that modify the behavior and distribution of air pollutants or affect the natural cleansing capacity of the atmosphere.

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AICE* SURVEY OF USSR AIR POLLUTION LITERATURE

Volume I

ATMOSPHERIC AND METEOROLOGICAL ASPECTS OF AIR POLLUTION

Edited By

M. Y. Nuttonson

The material presented here is part of a survey of
USSR literature on air pollution
conducted by the
Air Pollution Section
AMERICAN INSTITUTE OF CROP ECOLOGY

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***AMERICAN INSTITUTE OF CROP ECOLOGY**
809 DALE DRIVE
SILVER SPRING, MARYLAND 20910

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PREFACE

The behavior of atmospheric contaminants, notably gases and fine particles discharged into the air, is similar to that of the air masses near the surface of the earth -- the distribution of the contaminants being influenced by atmospheric stability, wind, precipitation, and topographic features of a given area or region. The most outstanding and dominant characteristic of the atmosphere is its unceasing change, a change resulting from variations of temperature, wind, and precipitation. These meteorological conditions vary widely as a function of latitude, season, and topography. Seasonal as well as diurnal temperature gradients, horizontal and vertical, affect the speed of the wind flow. Generally, the greater the wind velocity the more rapid is the dispersion of pollutants in the atmosphere. In continental areas the temperature gradients and the consequent wind flow increase during the winter season and during the daytime periods, the latter being usually subject to more turbulent winds of higher velocity than those that prevail during night hours that are typically characterized by low-level stability with a minimum dispersal and dilution of the pollutants.

Some of the papers of this volume deal with various noxious pollutants emitted to the atmosphere in high concentration at or near ground level and with the exposure of these pollutants to the continuous mixing, diffusion, stirring, and dilution that take place between regions of the atmosphere as a result of air turbulence. A number of papers deal with the intensity and structure of air turbulence in relation to temperature and wind, which form the background of atmospheric diffusion and stirring. Other papers deal with the direction frequencies and intensities of wind, which differ markedly for stable and unstable conditions of atmosphere; with the extremely slow diffusion through an inversion; and with the general climatology of atmospheric turbulence, diffusion, and the dispersions of air pollutants in different parts of the country and during different seasons of the year. The effect of rain on air pollution levels and the state of diffusion under fog conditions as well as a number of other meteorological factors that modify the behavior and distribution of air pollutants or affect the natural cleansing capacity of the atmosphere are also discussed.

In the first paper in this volume it is pointed out that the studies of atmospheric diffusion and air pollution constitute a new and rapidly developing area of meteorological sciences; that determination and analysis of the complex set of meteorological factors causing the processes of atmospheric diffusion are being extensively developed in conjunction with theoretical and experimental studies of the pattern of propagation of contaminants in the atmosphere; that these methods of study find application in the solution of a great many scientific and practical problems; and that investigations of atmospheric diffusion are of essential importance in determining the effectiveness and improvement of aerosol methods of treatment of agricultural crops by means of ground and airplane generators, and in the development of methods by which atmospheric processes are actively affected.

It is hoped that the papers selected for presentation in this volume will permit an assessment of some of the USSR studies of atmospheric and meteorological aspects of air pollution. As the editor of this volume I wish to thank my co-workers in the Air Pollution Section of the Institute for their valuable assistance. Special thanks are due to Adam Peiperl, who as one of the principal translators carried much of the load of this project.

M. Y. Nuttonson

Silver Spring, Maryland
September 1969

CHIEF PROBLEMS OF ATMOSPHERIC DIFFUSION AND AIR POLLUTION

M. E. Berlyand (Doctor of Physico-mathematical Sciences)

From Trudy, Glavnaya Geofiz. Observat. im. A. I. Voeykova, No. 218, p. 295-308 (1967).

Studies of atmospheric diffusion and air pollution constitute a new and rapidly developing area of meteorological sciences.

At the present time, methods both of theoretical and experimental study of the patterns of propagation of contaminants in the atmosphere and those of determination and analysis of the complex set of meteorological factors causing the processes of atmospheric diffusion are being extensively developed.

These methods find applications in the solution of a great many scientific and practical problems. Such problems include primarily studies of atmospheric contamination by noxious discharges from various types of sources, including smokestacks and flues, various explosions and ground works, automobile transport, etc., and associated problems of forecasting and control of the degree of contamination of the air reservoir. Consideration should be given to the study of both local contaminations and planetary propagation of contaminants of artificial and natural origin, and also to the determination of changes in the chemical composition of air, precipitation, and clouds.

Investigations of atmospheric diffusion are of essential importance in determining the effectiveness and improvement of aerosol methods of treatment of agricultural crops by means of ground and airplane generators, and in the development of methods by which atmospheric processes are actively affected, particularly in the prevention of first autumn frosts, involving dispersal of fogs and clouds.

Of major importance is the solution of so-called reverse problems, whereby the parameters of atmospheric diffusion are used to establish certain meteorological characteristics, primarily the components of the austausch coefficient, etc. These characteristics, as well as methods of atmospheric diffusion already developed, can be used for studying many natural processes, particularly heat and humidity exchange. Such are the problems involved in the study of the meteorological regime of small water reservoirs and in the theory of many meteorological instruments, including various types of evaporimeters, thermal anemometers, and radiation flow meters.

A common base connected with the study of the mechanism of atmospheric diffusion underlies the solution of these problems. It is now widely recognized that the processes of transport of the contaminant in the atmosphere are primarily determined by the laws of turbulent mixing. This common character is manifested most clearly in the construction of theoretical models of the phenomena, based on the solution of the equation of turbulent diffusion under corresponding regional conditions. In all cases, it is necessary to know the turbulence characteristics and the distribution of the meteorological elements determining the mechanism of atmospheric exchange.

To a considerable extent, the development of work on turbulent diffusion and atmospheric turbulence has proceeded in two parallel directions. The above-mentioned problems stimulated the development of research on atmospheric diffusion, and the latter promoted the study of turbulent exchange in the atmosphere, particularly in the ground layer of air.

To date, numerous published papers have been devoted to these questions. We shall consider only those papers which shed some light on certain basic problems of atmospheric diffusion and air contamination as studied at the Main Geophysical Observatory. This is justified not only by the fact that the present collection of papers is devoted to problems of development of meteorological investigations of the MGO 50 years after the Great October Socialist Revolution, but also by the fact that it was the MGO that began the investigations of atmospheric diffusion in our country, which had a considerable influence on the development of these problems in other institutes.

The works of A. A. Fridman and L. V. Keller on problems of atmospheric turbulence were already of fundamental importance for further studies of atmospheric diffusion. They formulated hypotheses which apply to substances obeying the laws of turbulent mixing.

In the 1920's-30's, the opinion developed that in many cases, the transport of heat, moisture and momentum in the ground layer of air can actually be treated as the transport of a passive contaminant. Their changes in the atmosphere are essentially described by the same differential equations. Therefore, studies of the theory of distribution of atmospheric elements in the vicinity of the underlying surface, the selection and validation of the model for the austausch coefficient, etc., have been of great importance.

B. I. Izvekov (39) elaborated a simple theoretical mechanism for the change of the ground moisture of air in the course of 24 hours. A. A. Dorodnits (24) constructed a model of daily variation of temperature, assuming that the vertical component of the austausch coefficient k_z, usually called the austausch coefficient, increases exponentially with height z. A theoretical mechanism of the change of wind with height in the presence of a linear increase of k_z with height was worked out by E. N. Blinova and I. A. Kibel' (33). A further development of this mechanism was made by M. I. Yudin and M. E. Shvets (54), who proposed a model for the dependence of k_z on z with a "break." This model, which consisted in a linear growth of k_z to a certain height h and in the preservation of a constant value of k_z at $z \geqslant h$, has simplified the solution of a great many problems. It is still being used successfully in many investigations, particularly for describing the process of diffusion from different types of sources.

The relationship between theoretical problems of atmospheric diffusion of a contaminant and heat and moisture exchange in the ground layer of air is directly manifested in the solution of the corresponding problems as well. Thus, the Green functions obtained by solving differential equations of heat and moisture exchange constitute the distribution functions of the diffusing substance from sources for certain boundary conditions. In this connection, we should indicate a series of later investigations in the area of transformation of air masses, local changes of the temperature and humidity of air, etc., carried out by M. E. Berlyand (8, 9), D. L. Laikhtman (41, 44), M. E. Shvets (52), and others.

It was important to establish the form and type of equations describing atmospheric diffusion. By analogy with molecular diffusion processes, parabolic-type equations of thermal conductivity frequently referred to as Fick's equations, were used for this purpose. However, there were a number of objections to this procedure. They followed from the known empirical results of L. Richardson, which were subsequently interpreted theoretically by A. N. Kolmogorov and A. M. Obukhov, according to whom the mixing coefficient in the atmosphere may depend on the scale of vortices.

One of the first pieces of evidence that Fick's equation could be used to describe diffusion processes in the atmosphere on the basis of probability considerations was given by L. V. Keller (33). This problem was developed further in original investigations by M. I. Yudin (56, 57, 59). Analyzing the process of atmospheric diffusion, Yudin suggested that the dispersion of particles relative to the moving center be separated out, and the role of the Lagrange effect be thus evaluated. In addition, he used his method of "physical averaging" in a statistical description of turbulent fields and identified a series of essential features of turbulent transport of a contaminant in the atmosphere. On this basis, he examined Richardson's conclusions on the dependence of the austausch coefficient on the scale of vortices and indicated the possibilities of describing processes of atmospheric diffusion by means of Fick's equation. Certain Lagrange characteristics of turbulence pertaining to problems of atmospheric diffusion were later examined by E. K. Byutner (21).

The problem of describing atmospheric diffusion was also studied by E. S. Lyapin (46), who showed the possibilities of using a system of hyperbolic equations for this purpose. The results obtained made it possible to evaluate the limits of applicability of Fick's equation and to refine the description of contaminant diffusion in certain cases, particularly at the boundaries of the cloud of contaminant, when consideration of the finite velocity of its propagation is essential.

Even in the early foreign studies, two approaches to the theoretical investigations of propagation of the contaminant in the ground layer of air were indicated. One of them was retained in the study of Roberts, who obtained a solution of the equation of turbulent diffusion with constant coefficients. The other, developed by Settin, consisted in the use of formulas for determining concentrations of the contaminant from a source, formulas obtained from statistical considerations.

In the work of the MGO, based to a certain extent on the above-indicated investigations, the route of solving the equations of turbulent diffusion with variable coefficients was chosen. This approach is more universal, and permits one to study problems with sources of different types and different characteristics of the media and boundary conditions. It enables one to use parameters of turbulent austausch used in problems of heat and mositure exchange. This prompted studies aimed at determining the coeffficient of turbulent austausch. They included the earliest studies involving construction of models for determining the austausch coefficient; studies of the distribution of atmospheric elements when allowing for the stability in the ground layer of air, which were carried out by M. I. Budyko (15) and D. L. Laikhtman (40); the study of E. S. Lyapin (46), aimed at developing a kinematic method of determination of the austausch coefficient on the basis of measurements of fluctuations of wind velocity; and also the development of these investigations and the determination of the austausch coefficient at higher levels in the subsequent works of A. S. Dubov (36), S. N. Zilitinkevich, D. L. Laikhtman (38, 44), and others.

Of central importance for the solution of problems of atmospheric diffusion are determinations of not only the vertical component of the austausch coefficient but also its horizontal component.

One of the chief problems in the study of processes of dispersion of the contaminant from different sources is to obtain solutions of the corresponding equations by considering both the vertical and the horizontal components of the austausch coefficient.

Important studies along these lines were made by Laikhtman. In particular, he obtained a solution of the equation of turbulent diffusion for sources of different kinds for an exponential law of change of k_z with height z, and values of the wind velocity and of the horizontal component of the austausch coefficient k_y constant with the height (cf., for example, the survey of A. S. Monin, published in the collection "Uspekhi Fizicheskikh Nauk," vol. 67, no. 1, 1959).

We obtained (5, 12) values of k_y from observations of the outline of a smoke cloud and proposed a model for the change of the horizontal component of the austausch coefficient k_y with the height, according to which k_y changes in proportion to the wind velocity u. On the basis of this model, in our study of 1946 (given in [12]), a solution was obtained for the equation of turbulent diffusion of a suspended contaminant whose coefficients u, k_z, and k_y are expressed by exponential functions of the height z. Also formulated were initial conditions for a high altitude source taking the influence of wind velocity into consideration and using the delta function for this purpose; the possibility of neglecting the influence of diffusion along the direction of the wind was noted. L. S. Gandin and R. E. Soloveichik (28) obtained with the same model, for the components of austausch coefficient and wind velocity, a solution of the equation of diffusion of a heavy contaminant from a high altitude source in the ground layer of air. They also examined (29, 31) certain theoretical problems of propagation of radioactive emanation at the earth's surface by solving the equation of transport of contaminant decaying with time.

L. R. Arrago and M. E. Shvets (3, 4) undertook the first attempts at a numerical study of turbulent dispersal of a contaminant from a linear source. At close distances from the source, they used a known analytical solution with simplified conditions as the initial condition for the numerical solution of the problem.

The general study of the distribution of a contaminant is directly related to the above-mentioned solutions of the reverse problems for determining turbulent characteristics of the atmosphere.

Important results along these lines were obtained by Yudin (55, 57, 58). He obtained a solution for the equation describing the process of turbulent diffusion of a heavy contaminant, and performed a physico-statistical analysis of this process. On this basis, a method was proposed for determining the austausch coefficient from data of experiments with dispersal of falling particles in the ground layer of air; it was also found that both the parameters of dispersal of the contaminant and the austausch coefficient thus obtained depended substantially on the fall velocity of the particles. Yudin was the first to consider the characteristics of dispersal of a known conservative (heavy) contaminant. The results he obtained are also of major importance for the solution of direct problems of atmospheric diffusion of falling particles.

In a study of the influence of thermal stratification on turbulent austausch, M. I. Budyko (15, 17) obtained a criterion for the formation of convection in the ground layer of air. He gave this criterion the interesting interpretation as an indicator of instability of propagation of the smoke cloud under convective conditions, related to the "detachment" of the cloud from the earth's surface. Experiments set up by Budyko and Lyapin (16) confirmed these results.

Some methods of determination of the vertical component of the austausch coefficient from data obtained by observing the distribution of the concentration of smoke from a ground source were discussed by Lyapin (45).

In the reference cited (5), the horizontal component of the austausch coefficient was determined from the outline of a smoke cloud. In a subsequent study (11), we carried out a general study aimed at determining the horizontal and vertical components of the turbulence coefficient from the outline of a smoke plume from industrial smokestacks.

Among the first applications of the results of studies of atmospheric diffusion were the investigations made at the MGO for the purpose of controlling first autumn frosts by the methods of smudging and open heating. We carried out (6, 7, 9, 10) a theoretical analysis and evaluation of the thermal effect of a smokescreen and open heating on plantations and orchards during the period of the first autumn frost. The results of the analysis permitted the establishment of a direct relationship between the increase of the temperature of air in the smoke and the concentration of the smoke, and also the weight of the vertical column of smoke particles attenuating the long-wavelength radiation of the earth. The theory of open heating (7) was based on a solution of the equation of turbulent diffusion from thermal sources for an exponential law of increase of the wind velocity and components of the austausch coefficient with the height, the horizontal component being assumed proportional to the wind velocity. Use of this solution made it possible to determine the temperature field for isolated heat sources produced by heaters or by brick fuel, and also to determine the total thermal effect from a system of sources located between the plants being heated. As a result, the degree of rise of air temperature at various heights was determined as a function of the consumption of protective agents and weather conditions, and a system of practical recommendations for taking measures designed to protect the plants from first autumn frosts was also worked out.

Another application of the results of the completed investigations pertains to the calculation of the dispersal of fogs achieved by raising the temperature of air in the creation of thermal sources (M. E. Berlyand) and as a result of the propagation of hygroscopic particles (M. I. Budyko).

Allowing for the influence of horizontal austausch, L. S. Gandin and R. E. Soloveichik (27, 30) developed the theory of evaporation from confined water reservoirs. They obtained a solution of the corresponding equation of turbulent diffusion of moisture in the ground layer of air with the condition that the concentration of water vapor on the evaporating surface be a known function of the coordinates. Analysis of the solutions showed that the influence of horizontal austausch on the distribution of moisture near the ground and on the magnitude of the evaporation may sometimes be substantial, especially when the size of the evaporating surface is small.

The works of G. Kh. Tseitin (50, 51) have also been devoted to the calculation and analysis of the influence of horizontal austausch in the direction perpendicular to the direction of the wind on the transport of moisture from the evaporating band. In his studies, working formulas were derived and calculations were made for a number of examples under certain simplifying conditions. In particular, Tseitin evaluated the so-called coefficient of reduction for converting the readings of evaporimeters to values of evaporation under natural conditions.

In a certain sense, among the applications of studies of turbulant diffusion of heat and moisture one can also include a wider group of studies of the transformation of air masses under the influence of the underlying surface, which was begun at the MGO by I. A. Kibel' and N. R. Malkin. However, a discussion of these studies is beyond the scope of this paper. Therefore, we shall confine ourselves to references to surveys of the corresponding investigations (9, 44) and note only some as supplements to the above-indicated papers.

A comprehensive cycle of studies of the transformation of an air stream above water reservoirs was carried out by M. P. Timofeev (49). They proposed methods of determination of evaporation from water reservoirs, and in cooperation with T. V. Kirillova and T. A. Ogneva, studied the characteristics of the meteorological regime above water reservoirs and in their vicinity. D. L. Laikhtman and M. I. Yudin studied the solution of equations of heat and moisture exchange in a moving air stream under steady conditions and discussed the application of the solution to the evaluation of the effectiveness of irrigation (18, 42, 43). The study of N. I. Yakovleva (60) is closely related to this work.

Our studies, summed up in ref. (9), discuss the problems of the theory of unsteady and steady transformation of moving and of relatively stagnant air masses. On the basis of these studies, the conditions of transition from one type of transformation to the other were examined, and methods were developed for taking the transformation into account in forecasting changes of the temperature and humidity of the ground layer of the atmosphere. Of essential importance are studies of the experimental verification of these methods and a synoptic-aerological analysis of the transformation conditions, carried out by M. V. Zavarina (37) and later at the Central Forecasting Institute by A. A. Bachurina.

The stationary transformation of an air stream, turbulent austausch and vertical currents being considered, was studied by L. R. Arrago (2). Of major importance for carrying out many of the indicated studies and also for the purpose of investigating the characteristics of transformation under certain conditions were the approximate methods of solution of boundary layer problems worked out by M. E. Shvets (52, 53). The studies of M. E. Berlyand and R. I. Onikul (13, 47) were devoted to the development of a theory of heat and moisture exchange in a moving air stream above a highly irregular underlying surface, using as an example the formation of river fogs, and to the use of numerical methods of solution for this purpose.

Another interesting application of the methods of atmospheric diffusion has recently been developed in the study of M. I. Budyko and L. S. Gandin (19, 20). They are studying the theoretical problems of propagation of carbon dioxide above the plant cover for the purpose of exploring the effects of photosynthesis and possibly evaluating the productivity of the biomass.

Important results in a series of applied studies of atmospheric diffusion and related problems were also obtained by V. A. Gaevskii, N. P. Rusin, M. S. Sternzat, and others.

Starting in the middle 1950's, the work of the MGO in the area of atmospheric diffusion was further expended, first at the Geophysical Institute of the USSR Academy of Sciences, then at its daughter institutions, the Institute of Atmospheric Physics and the Institute of Applied Geophysics (studies by A. S. Monin, A. M. Obukhov, A. I, Denisov, I. L. Karol', O. S. Berlyand, A. Ya. Pressman, V. N. Petrov, E. N. Teverovskii, N. L. Byzova, and others), and toward the end of the 1950's and the beginning of the 1960's, at the Leningrad Hydrometeorological Institute (studies by D. L. Laikhtman, L. G. Kachurin, F. A. Gisina, Ya. S. Rabinovich, and others).

The problem of investigations of atmospheric diffusion has lately assumed a special urgency and has attracted major attention. At the present rate of development of industry and power engineering, the amount of noxious substances discharged into the atmosphere is increasing rapidly. The protective measures employed are proving insufficiently effective.

It is assumed that the discharges of noxious substances by chemical, metallurgical, and other industrial plants will increase in the near future, in spite of the purification steps being taken. This situation makes it necessary to develop indirect methods of decreasing the concentration of noxious substances near the ground; these methods consist primarily in increasing the height of the discharging source and using the effect of dispersal of the contaminant in the air. Hence derives the importance of an effective consideration of weather conditions, when designing and operating industrial plants, for the purpose of decreasing the harmful contamination of the ground layer of air.

Attempts to utilize the results of earlier studies of atmospheric diffusion for this purpose, including the known formulas of Setton, should undoubtedly be evaluated positively. However, even the first episodic measurements of contaminant concentrations showed that the data obtained by calculation and by experiment differed severalfold, particularly in the case of powerful sources.

Thus, practice has revealed new requirements for studies of atmospheric diffusion. It is necessary to study the characteristics of turbulent mixing at higher levels above the underlying surface and the conditions of dispersal of the contaminant from sources to greater distances than in previous studies. The meteorological factors should be taken into account more fully and more rigorously. It is not enough, as was done earlier, to confine oneself solely to data on the wind velocity and air temperature near the ground. In calculating the dispersal of discharges from high sources, it is necessary to develop a theory of turbulent diffusion in a layer of air with a thickness of several hundred meters, allowing for possible changes of temperature, wind, and austausch coefficient. Also required is a switch from conditions of a level area, to which the previous studies usually pertain, to actual topographical forms and the development of methods of observations and characterization of the contamination of the atmosphere over large areas, etc.

In this connection, several years ago special studies were undertaken within the system of Gidrometsluzhba (Hydrometeorological Service). A section for the study of atmospheric diffusion and atmospheric contamination, which carried out a broad spectrum of theoretical and experimental work, was created at the MGO. The chief results of this research are described below (14, 22-26).

The theoretical studies made by M. E. Berlyand, E. L. Genikhovich, V. K. Dem'yanovich, R. I. Onikul and others were based on the solution of the equation of atmospheric diffusion from high altitude sources. The coefficients of the given equation are generally functions of the coordinates, and the type of the functions may be complex if one studies an atmospheric boundary layer several hundred meters thick, particularly in the presence of elevated temperature inversions, under hilly ground conditions, etc. This required the development of numerical methods of integration and calculation by means of computers.

In the solution of the problem, consideration was given to the variability of the direction of the wind with time, and corresponding averaging was made for the time to which the concentration referred. This permitted a more accurate evaluation of the horizontal dispersal of the contaminant and the determination of the concentration values averaged for different time intervals.

Also taken into consideration was the increase of the effective height of the source of the discharge, caused by the initial velocity of the ascent and overheating of the new gases. Since the initial ascent of the contaminant is a function of the wind velocity, the dependence of the concentration near the ground on the wind velocity assumes a complex character. There is a certain unsafe wind velocity u_M at which the highest value of the maximum of the concentration near the ground q_M is reached.

On the basis of the solution of the problem obtained, working formulas and schemes were derived for determining the concentration q_M. They included the dependence of q_M on the amount of noxious contaminant and on the volume of flue gases discharged per unit time, height of the smokestacks and their number, velocity at which the flue gases are carried off, difference in the temperature of the gases discharged from the smokestacks and the temperature of the surrounding air, and also precipitation velocity of the contaminant. The formulas contain a coefficient determining the influence of vertical and horizontal mixing in the atmosphere. Its value is established as a function of the characteristics of the vertical distribution of air temperature for conditions under which the maximum value of the concentration above ground is reached for the unsafe wind velocity. The value of this coefficient proves to be different for different climatic zones. It is greater for southern and wooded regions, where an intense vertical turbulent exchange takes place.

Working formulas were obtained for comparatively frequent unfavorable conditions. They are characterized by the fact that the temperature falls off with the height, and the wind velocity changes approximately in accordance with the logarithmic law. At the same time, the degree of turbulent austausch is considerable, and an intensive transport of contaminant from high altitude sources to the ground layer of air takes place. The theoretical studies that were carried out showed that the concentrations above ground may reach still higher values in the presence of elevated inversion layers with an attenuated turbulence, which inhibit the upward transport of the contaminant. From the results of the calculations it follows that in cases where the layer with attenuated turbulence is located directly above the source, the maximum of the concentration of light contaminant is sometimes more than doubled. In cases where such a layer is located at a height of 100-200 m above the source, the increase in concentration is substantially smaller.

The presence of elevated inversions may cause a substantial effect in cold discharges as a result of restriction of their initial volume. In these cases, the importance of the unsafe velocity decreases, and the concentrations near the ground in the presence of a weak wind increase markedly.

In certain cases, substantial deviations in the vertical profile of the wind from the logarithmic distribution, suitable mainly for average conditions, are possible. The calculations that were performed show that the presence of still layers at the underlying surface leads to a concentration rise, which is greater the thicker these layers.

Specially arranged gradient observations in the ground layer (V. P. Gracheva, G. P. Rastorgueva) and aerological studies (P. A. Vorontsov, I. V. Vasil'chenko) in the region of powerful sources of discharge of noxious contaminants were of great importance in this research.

In the presence of terrain irregularities or of complex topography, movements of air arise, which may lead to substantial changes of the contaminant. The use of modern methods of theoretical investigation of atmospheric diffusion, including computers, has provided an approach to these difficult problems as well. To date, calculations have been made for various areas with relatively slight topographical irregularities. It was found that under these conditions, the maximum of contaminant concentration near the ground was found to be generally higher than above level ground. This is sometimes noted even when the smokestacks are located on high ground, but in the vicinity of the leeward slope, where the wind velocity decreases sharply and downward flows are generated. Analysis has shown that in the case of gentle topographic features, the air stream flows around the latter and hence, a slight increase of concentration takes place. The influence of rolling topography on the distribution of concentration is manifested in places where the wind velocity changes substantially at a fixed height. In this connection, it was useful to utilize the studies made earlier at the MGO by I. A. Gol'tsberg (32), S. A. Sapozhnikova (48) and others on the microclimatic survey of an area, and also a similar study in a region of electric power stations, recently made by I. I. Solomatina, et al.

At the present time, these studies are being carried on at the MGO in two directions. Numerical studies of the equations of motion describing the structure of an air stream in the presence of rolling topography are being made. In cooperation with laboratories of the Leningrad Shipbuilding Institute and of Moscow State University, experimental studies are being conducted in a wind tunnel with models of rolling topography. The experiments are performed under close to self-simulating conditions, making it possible to avoid certain difficulties of simulation of atmospheric processes. The first stage produced data on the vertical wind profile in different parts of the topography as a function of the angle of slope of the underlying surface relative to the horizon, height differential, etc.

Numerical methods of solving the equations of atmospheric diffusion are also currently being used for studying distortions in the field of distribution of the contaminant, caused by water reservoirs and usually produced in the vicinity of large power and industrial facilities, and for analysis of the influence of fogs on the contamination of the ground layer of air, etc.

In order to check the theory and obtain the necessary parameters, a number of large expeditions were organized in 1961-1965 into regions of the Shchekinskaya, Cherepetskaya and Moldavskaya electric power stations, where the highest smokestacks in the USSR have been erected. In these studies, the Moscow Scientific Research Institute of Hygiene measured the concentration of ash and sulfur gas at distances of 15-20 km from the stacks, while the Southern Branch of the ORGRES Combine and the All-Union Power Engineering Institute determined the extent of discharge of ash and sulfur gas into the atmosphere and the entrainment velocity and temperatures of the flue gases. The MGO made measurements of the vertical distribution of temperature and wind, and also certain other characteristics making it possible to obtain additional data on turbulent austausch to a height of several hundred meters. Observations on the ground were made with telescopic masts 17 m high, and at higher levels by means of a captive balloon, light airplanes, and helicopters. In addition, systematic ground photographs of the smoke plume were taken, and the parameters of the plume were determined, particularly its width at various distances from the airplane or helicopter. It should be pointed out that, to our knowledge, this is one of the most complete studies of this type made thus far in the world.

The results obtained led to an optimistic estimate of the degree of contamination of the atmosphere in regions of powerful industrial sources. Their comparison with calculated data showed a completely satisfactory agreement. Agreement was observed between theoretical conclusions and data of special experiments carried out at the Institute of Applied Geophysics (IAG), involving dispersal of particles discharged from different heights by a 300-meter meteorological mast.

The theoretical results were also confirmed by less detailed observations made by the Moscow Institute of Hygiene in previous years and by public health studies recently performed in the vicinity of a number of electric power stations located in the central European USSR, the Ukraine and the Urals, in Belorussia, Latvia, Estonia, Siberia and Kazakhstan, and in addition, in the vicinity of some metallurgical plants.

On this basis, the MGO in cooperation with the IAG and the Moscow Institute of Hygiene worked out a "tentative method of calculation of dispersal of discharges from smokestacks of electric power stations in the atmosphere" (24, 26). The method has been widely applied in the design of electric power stations in the USSR and in certain other countries, and has been translated into many foreign languages. It has now been used to work out an improved method and to compile recommendations for calculating the dispersal in the atmosphere of dust and sulfur gas discharged from powerful industrial sources. These recommendations are being distributed among a large group of plants in the metallurgical, chemical, petroleum, and other branches of industry.

Certain limitations involved in the method of calculation are due to the fact that it does not extend to cases of cold discharges. In this connection, special studies have been planned at the MGO. The first experimental studies were made in the region of the Neva chemical plant, whose stacks discharge nitrogen oxides at relatively low temperatures. Expeditionary investigations have begun in regions of artificial fiber plants for the purpose of studying the propagation of cold discharges of hydrogen sulfide and carbon disulfide.

Recently, extensive research, aimed at studying the contamination of the atmosphere in the cities of the USSR, has begun at the MGO. Data of observations made for many years at sanitary-epidemiological stations (SES) and recently initiated measurements of the concentration of noxious substances over a network of hydrometeorological stations have been analyzed and processed. Despite the inhomogeneity and insufficiency of these data, they are as a whole of considerable interest and have made it possible to reach certain conclusions, particularly in regard to the patterns of change of maximum concentrations, etc. They served as the basis for a compilation of the first surveys of the state of contamination of the atmosphere on the territory of the USSR.

An interesting synoptic-climaticological analysis of experimental data was carried out by L. R. Son'kin and E. Yu. Bezuglaya. Deserving of attention are certain conclusions on the geographical distribution of dust of organic and inorganic composition which were obtained by N. N. Aleksandrov. They were based on a method of observation of dust by a network of stations. We should also note a series of other studies made by N. N. Aleksandrov, B. B. Goroshko, and others, aimed at improving methods of dust sampling and also certain techniques of analysis of radioactive fallout described in (1, 22, 24). We should also note the theoretical studies recently carried out by M. E. Berlyand, E. L. Genikhovich, and G. E. Maslova on the relationship between the concentration of aerosols in the ground layer of air and their flow on a horizontal plane table. They should permit a considerable expansion of the use of the experimental data on dust observations which were obtained at stations with the aid of plane tables and filtering ventilating units.

Investigations of atmospheric contaminations are being substantially expanded. Under a coordinated program by SES and weather stations, measurements of concentrations of noxious substances and meteorological and aerological observations have now been made for about two years at eight large industrial centers.

Systematic observations are being made on the territory of the country to determine the change of the chemical composition of precipitation. Analysis of the latter, made by V. M. Drozdova, O. P. Petrenchuk, P. F. Svistov and E. S. Selezneva (35), permitted an evaluation of the amount of chlorides, sulfur, and certain other elements falling out in the precipitation in various parts of the USSR. At two sections of the station (in the Don Basin and near Leningrad), observations are now being made on precipitation in order to determine the degree of its contamination by discharges from industrial plants.

In the 1950's, the Hydrometeorological Service organized regular observations of concentrations of noxious ingredients simultaneously at several points located in areas with the highest contamination of the ground layer of air. To carry out such observations, the MGO is preparing recommendations for the use and improvement of known methods of determination of the concentration of noxious substances, and has proposed a project for equipping automobiles and special cabins, which have already been installed in many cities, for the observations.

The installation of automatic recording gas analyzers and also recorders of the direction of wind velocity and certain atmospheric elements should assume a primary importance. These devices will make it possible to carry out a continuous control of the degree of contamination of the atmosphere, will detect cases of highest concentrations of noxious contaminants, and will analyze the causes of their appearance.

The Design Office of Automation in cooperation with the MGO has now developed the first automatic recorder of sulfur gas in the USSR.

At the MGO, a special expedition was organized, whose composition includes a separate division under the Novosibirsk branch of the NIIAK for the systematic investigation of air contamination in industrial cities; this expedition has already begun studies in ten large cities of the Ukraine, Urals, and Siberia.

We shall not dwell on certain other problems indicated at the beginning of the paper, since they have been studied less. Nevertheless, these problems have also been the subject of a number of interesting treatments, and their role will undoubtedly grow with time.

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THE STRUCTURE OF AN AIRSTREAM AS A FACTOR IN THE TRANSPORT OF PRODUCTS OF ATMOSPHERIC POLLUTION

P. A. Vorontsov

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Using materials of the latest expeditions of the GGO [tr. note, Main Geophysical Observatory (MGO)] , the present paper gives an analysis of the structure of the boundary layer of the atmosphere in September 1965 in the region of the Moldavian GRES [tr. note, State Regional Electric Power Plant (SREPP)] , in October 1964, in the region of the Cherepet' GRES [tr. note, SREPP], and offers a comparison for March 1964 in the region of the Shchekino GRES [tr. note, SREPP] .

The studies were made by means of ascents on a captive aerostat carrying the following instruments:

1) An instrument recording the horizontal (u') and vertical (w') components of gustiness and wind velocity u at levels of 2, 100, 200 and 300 m;

2) A meteorograph recording the temperature and humidity of air, atmospheric pressure, wind velocity and horizontal component of fluctuations of the wind velocity at levels of 2, 15, 50, 100, 150, 200, 300, 400 and 500 m, averaged over 5 min.

The studies were also made by using airplane and helicopter sounding.

The airplane usually carried an electrometeorograph which recorded on the photographic film of an oscillograph the atmospheric pressure, temperature and humidity of air, overloads on the airplane, and also temperature fluctuations.

We shall give a brief description of the meteorological conditions in the regions of the work of the expeditions.

In the region of the Shchekino SREPP from 16 to 26 March 1964, a cloudiness of the lower layer up to 10 points was observed, from 28 March the cloudiness of the upper layer was 10 points with marked temperature fluctuations in the 8 hour observations from -5.2° to -0.9° C. and fluctuations of humidity from 70 to 96%. On the average, the temperature of air for 2:00 P.M. was about 0° C.

In the region of the Cherepet' SREPP, from 8 to 10 October 1964 the weather was slightly cloudy, from 13 to 30 October a continuous cloudiness of the lower layer predominated, frequently with drizzle and with fogs in the morning. The mean monthly temperature for 2:00 P.M. was about 10° C.

In the region of the Moldavian SREPP, from 1 to 6 September 1965 slightly cloudy weather predominated, from 8 to 12 September the cloudiness of the upper layer was 8-9 points, and from 14 September to the end of the expedition, stable anticyclonic weather with cloudiness of cumulus forms of 2-4 points was observed. The wind was weak in the morning and its velocity was 4-6 m/sec during the day. The temperature at 2:00 P.M. was about 24° C.

Structure of the Air Stream

We shall consider the characteristics of distribution of the following structural elements of an air stream in the lower layers of the atmosphere: τ_u - periods of fluctuations of the horizontal component, sec; σ_u and σ_w - mean square values of fluctuations u' and w', m/sec, or of their kinetic energy; $\frac{\sigma u}{u}$ and $\frac{\sigma w}{u}$ - intensities of kinetic energy of fluctuations u' and w'; l_u and l_w average dimensions of eddy formations, m; $\frac{\sigma w}{\sigma u}$ - isotropy index of the atmosphere.

The errors of aerostatic and airplane sounding have been discussed in detail in ref. (3) and will not be considered here. We shall note that in aerostatic sounding, the measured dimensions of the horizontal component of the eddy l_u, although not equal, are commensurate with the true characteristic dimensions of the eddies, whereas the vertical dimensions l_w reflect only the displacement of the eddy relative to the stationary instrument along the vertical during passage of the eddy at the velocity of the wind. Therefore, the values l_w may be somewhat lower than the true dimensions of the eddies in the vertical plane; values of l_w characterize the approximate mixing length of the eddy. It should be noted that all the characteristics of the structure of an airstream are distinguished by considerable fluctuations of their average values in time and space, and that these fluctuations usually increase with increasing thermal instability. This is particularly apparent in horizontal airplane sounding, when segments with different structures of the underlying surface intersect rapidly.

These characteristics of the structure of an air stream were discussed in ref. (1, 2) and also will not be considered here. Below we shall use quantities characterizing the wind structure, averaged over time and space.

Let us now discuss the structure of an air stream based on data of aerostatic sounding. In view of the fact that the ascents were made only in the daytime and their number was unevenly distributed over the hours of observation, we shall subsequently consider only the values of the separate elements of wind structure averaged for the day (Table 1).

The tables given below include only those observations in which fluctuations of the vertical and horizontal components of the wind velocity ≥ 0.1 m/sec were noted.

In Table 1, all of the data for each point are divided, except the Cherepet' SREPP, into two groups:

a) ascents with $u' \geq 0.1$ m/sec;

b) ascents with $u' \geq 0.6$ m/sec.

Thus, ascents with an intense turbulence were separated out. It should be noted that in the region of the Cherepet' SREPP, in 40 ascents of the instrument with recording the wind structure, gustiness was absent in 67% of all cases, and gusts were recorded in only 33%. Correspondingly, in the region of the Moldavian SREPP, of 61 ascents, gustiness was absent in only 15% of the cases, and in 85% well-developed wind gusts were observed.

Table 1 lists mean square values $\sqrt{\bar{u}'^2} = \sigma_u$ and correspondingly, $\sqrt{\bar{w}'^2} = \sigma_w$. All the other designations are standard.

The dsitribution of turbulent energy with the height in the boundary layer depends on the inhomogeneities in the structure of the underlying surface and on the thermodynamic stratification of the atmosphere. Points of observations on the Moldavian and Shchekino SREPP, were located on an open platform, and those of the Cherepet' SREPP, on a small clearing surrounded by a high forest.

Table 1

Mean Values of the Structural Elements of the Air Stream in the 2-300 m layer

H m	u m/sec	$\gamma_{0,100}$ m	σ_u m/sec	$\sigma_{u\,max}$ m/sec	σ_w m/sec	τ sec	l_u m	l_w m	$\frac{\sigma_u}{u}$	$\frac{\sigma_w}{u}$	$\frac{\sigma_w}{\sigma_u}$	k m²/sec	Number of cases
Moldavian SREPP: Sep. 1965 t° = 23.8; u' ≥ 0.1 m/sec; Ri = 0.6													
2	3,5	—	0,53	1,38	0,30	—	—	—	—	—	—	—	40
100	5,0	1,8	0,90	1,78	0,56	40	200	74	0,18	0,12	0,62	36	45
200	5,5	1,0	0,93	2,15	0,58	47	256	94	0,17	0,11	0,63	48	40
300	5,9	0,9	0,99	1,97	0,67	48	283	76	0,17	0,11	0,68	37	40
Moldavian SREPP; Sep. 1965; u' ≥ 0.6 m/sec; Ri = - 0.8													
2	4,0	—	0,64	1,37	0,34	—	—	—	—	—	—	—	30
100	5,3	1,7	0,95	2,15	0,59	46	295	70	0,18	0,11	0,62	39	32
200	5,9	0,9	1,00	1,83	0,65	44	260	78	0,17	0,11	0,65	53	30
300	6,4	1,0	1,06	1,98	0,69	46	280	76	0,17	0,11	0,66	43	30
Cherepet' SREPP; Oct. 1964; u' ≥ 0.1 m/sec; t° = 10.4; Ri = 0.1													
2	1,9	—	—	—	—	—	—	—	—	—	—	—	12
100	6,9	0,8	1,46	2,76	0,88	50	345	75	0,21	0,13	0,60	52	10
200	10,2	0,4	1,27	1,70	0,54	43	440	98	0,10	0,05	0,56	42	10
300	12,2	0,5	1,16	1,97	0,44	50	610	92	0,09	0,04	0,38	36	6
Shchekino SREPP; March 1965; u' ≥ 0.1 m/sec; t° = - 0.2; Ri = 0.8													
2	4,5	—	0,75	1,62	0,24	33	—	—	0,17	0,05	0,32	—	28
100	6,2	0,9	0,83	1,66	0,34	38	237	48	0,13	0,06	0,41	13	37
200	6,7	0,5	0,77	1,44	0,32	37	248	51	0,11	0,05	0,40	13	33
Shchekino SREPP: March 1965: u' ≥ 0.6 m/sec; Ri = 0.5													
2	5,1	—	0,92	1,64	0,30	30	—	—	0,18	0,06	0,33	—	—
100	6,9	0,9	1,18	1,68	0,41	37	255	43	0,17	0,06	0,35	14	21
200	7,2	0,7	1,07	1,45	0,39	36	257	48	0,15	0,05	0,37	15	21

The thermodynamic stratification was determined by Richardson's number Ri, calculated for the 2-300 m layer. It is apparent that during observations at the Moldavian SREPP, the magnitude of Ri corresponded to unstable stratification, at the Cherepet' SREPP it was close to an indifferent equilibrium, and at the Shchekino SREPP, a stable thermodynamic stratification was observed. Table 1 shows average values of air temperature at the 2 m level for 2:00 P.M. The values of wind velocity u m/sec and vertical temperature gradient γ°/100 m were obtained as averages from all the observations of the given group.

Subsequently, observations in the region of the Moldavian SREPP will be referred to conditions of an unstable state with $\gamma \gtrsim \gamma_a$ and Ri $\lessapprox 0$, data for the region of the Cherepet' SREPP, to indifferent stratification with $\gamma \simeq 0.5$-0.8 and Ri $\simeq 0$, and finally, observations at the Shchekino SREPP, to a stable state with Ri $\simeq$ 0.4-0.5. In the presence of unstable stratification, the turbulent energy of both the longitudinal and vertical components increases with the height, and for both σ_w and σ_u the maximum in the 100-300 m layer was noted at a level of 300 m.

The ratios $\frac{\sigma u}{u}$ and $\frac{\sigma w}{w}$, which characterize the intensity of the turbulent energy of both components, remain practically constant in the entire 100-300 m. layer. The parameter $\frac{\sigma w}{\sigma u}$, which indicates the anisotropy of atmospheric eddies, also reaches a maximum of 0.66-0.68 at a level of 300 m in the presence of unstable stratification. It should be noted that this parameter is remote from the values of the corresponding isotropies, when the ratio $\frac{\sigma w}{\sigma u} = 1$.

At the Moldavian SREPP, relatively high wind velocities with a well-developed gustiness were generally observed, and for this reason there were practically no large differences in the absolute values of the individual components σ_u and σ_w and other elements of the first and second groups (u' $\gtrsim$ 0.1 m/sec and u' $\gtrsim$ 0.6 m/sec).

According to observations at the Cherepet' SREPP, in an indifferent equilibrium, the maximum of σ_u and σ_w was observed at a level of 100 m; above it, these quantities decreased, particularly σ_w. Here one should note an increase in stability with the height; for the 200-300 m layer, Ri = 0.45. Under these conditions, the parameter $\frac{\sigma w}{\sigma u}$ decreases from the 100 m level primarily because of a decrease of the vertical component. The intensity of turbulent energy $\frac{\sigma u}{\bar{u}}$ and $\frac{\sigma w}{\bar{u}}$ above 100 m also decreases rapidly. Because cases with u' $\gtrsim$ 0.1 m/sec were processed, the average values $\bar{u}$ obtained for the Cherepet' SREPP and listed in Table 1 are slightly high. For all the observations, the average wind velocities at 100 m were u = 4.9, at 200 m 5.3, and at 300 m 5.8 m/sec.

In a stable equilibrium (Shchekino SREPP), low values of the vertical component σ_w and a comparatively slow decrease of σ_u are observed. For the given stratification, the anisotropy of the atmosphere increases even more, and the value of the ratio $\frac{\sigma w}{\sigma u}$ is only 0.35-0.41.

The periods of fluctuations $\mathcal{T}_u$ change over relatively narrow limits for different stratifications from 50 to 30 sec, i.e., from 0.02 to 0.033 cps.

The horizontal component of the eddy, calculated from the formula $l_u = \mathcal{T}_u = u$, gives its most characteristic dimensions. As we know, in the boundary layer the dimensions of atmospheric eddies should range approximately from 10^2 to 10^3. According to the author's data, the values of l_u range from 250-600 m, they increase somewhat with the height and vary not so much with the stratification as with the wind velocity; as u increases, so does l_u.

The vertical component of the mixing length of the eddy l_w depends on the thermal stratification more than l_u does; at Ri = from -0.6 to -0.8, it amounts to 70-95 m, reaching a maximum at a height of 200 m, and the turbulence coefficient k also decreases somewhat with the height. As the stability increases (at Ri = 0.5), the absolute values of l_w decrease by almost one-half, but their maximum always corresponds to a level close to 200 m.

In the first approximation, the maximum gusts are twice as high as their mean values, although this is due in part to the method of treatment adopted by the author.

If average values of the parameter $\frac{\sigma_w}{\sigma_u}$ are taken in the 100-300 m layer, the following relationship of these parameters with Ri is obtained (Table 2).

Table 2

Dependence of Parameter $\frac{\sigma_w}{\sigma_u}$ on Ri in the 100-300 m Layer.

Ri	—0,8 — 0,6	0,1	0,5
$\frac{\sigma_w}{\sigma_u}$	0,65	0,51	0,35

The relationship obtained between the stratification of the atmosphere and the anisotropy of the eddies is quite satisfactory; as the stability increases, the vertical component rapidly decreases.

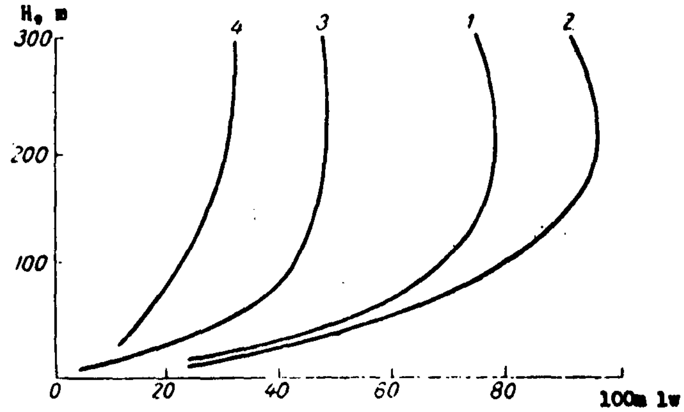

FIG. 1 Determination of l_w in the 0-3000 m layer. 1- Moldavian SREPP, 2 - Cherepet' SREPP, 3 - Shohekino SREPP, 4 - after Lettau.

In the first approximation, for the range of u from 5 to 12 m/sec, the dependence of the horizontal component of the eddy on the wind velocity may be expressed as $l_u = 40$ u. Values of the mixing length of the eddy l_w in the 0-300 m layer for certain points are given in Fig. 1. In the unstable state, a marked increase of l_w is observed. For comparison, this figure also gives the data of Lettau (4), which are generally close to the data of the Shchekino SREPP at Ri = 0.5-0.8.

The frequencies of σ_u and σ_w are given for the three points considered (Table 3).

The frequency of σ_u in the 0.7-1.3 m/sec range is: at the Moldavian SREPP at 100 m - 58%, at 200 m - 54% and at 300 m - 44%; at the Cherepet' SREPP at 100 m - 6%, at 200 m - 12% and at 300 m - 6%; at the Shchekino SREPP, 38% and 51% respectively. The frequencies of σ_w in the 0.4-0.7 m/sec range, at the Moldavian SREPP for the 100-300 m layer amount to 44-54%, for the Cherepet' SREPP, 10-28% and for the Shchekino SREPP, 28-44%.

During ascents of the aerostat meteorograph, the longitudinal component of fluctuations of wind velocities σ_u was recorded to a height of 500 m at a number of levels.

Table 3

Frequency of Mean Values of σ_u and σ_w in per cent in the 100-300 m Layer.

SREPP	H м	Gradations of σ u and σ_w, m/sec										Number of cases
		0,0 0,1	0,1 0,4	0,4 0,7	0,7 1,0	1,0 1,3	1,3 1,6	1,6 1,9	1,9 2,2	2,2 2,5	2,5	
					σ_u							
Moldavian	100	10	7	9	40	18	7	7	2	—	—	57
	200	19	4	19	35	19	6	2	—	—	—	57
	300	15	5	20	24	20	10	—	7	—	—	39
Cherepet'	100	72	3	6	—	6	3	—	8	—	—	36
	200	72	3	11	6	6	—	3	—	—	—	36
	300	84	—	3	6	—	—	3	3	—	—	34
Shchekino	100	17	3	19	19	19	19	3	—	—	—	36
	200	17	6	17	20	31	8	—	—	—	—	35
					σ_w							
Moldavian	100	9	20	51	18	2	—	—	—	—	—	45
	200	14	19	54	6	6	—	—	—	—	—	48
	300	15	29	44	9	3	—	—	—	—	—	34
Cherepet'	100	45	—	18	35	5	5	—	—	—	—	20
	200	60	12	28	—	—	—	—	—	—	—	25
	300	72	12	16	—	—	—	—	—	—	—	26
Shchekino	100	4	48	48								32
	200	30	42	28								38

Table 4

Mean values of σ_u and $\frac{\sigma_u}{\bar{u}}$, Moldavian SREPP.

Time	Height, m								Number of ascents
	25	50	100	150	200	300	400	500	
	σ_u m/sec								
8	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	12
10	0,6	0,5	0,5	0,4	0,4	0,1	0,3	0,0	14
12	1,0	0,8	0,6	0,6	0,5	0,3	0,3	0,1	18
14	1,0	1,0	0,8	0,8	0,5	0,4	0,4	0,3	19
16	0,6	0,6	0,4	0,4	0,4	0,1	0,1	0,1	9
18	0,5	0,3	0,3	0,3	0,1	0,1	0,1	0,0	4
	$\frac{\sigma_u}{u}$								
8	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	—
10	0,21	0,16	0,14	0,10	0,09	0,02	0,05	0,0	—
12	0,23	0,16	0,12	0,11	0,09	0,05	0,05	0,02	—
14	0,21	0,20	0,15	0,15	0,09	0,07	0,07	0,05	—
16	0,13	0,11	0,07	0,07	0,07	0,02	0,02	0,02	—
18	0,14	0,07	0,06	0,06	0,02	0,02	0,02	—	—

Table 4 gives mean values of σ_u and $\frac{\sigma_u}{\bar{u}}$ for all the ascents in the region of the Moldavian SREPP, independently of whether wind gusts were observed or not, i. e., for $u' \geqslant 0.1$ m/sec. Of interest in this case is the daily variation of σ_u and $\frac{\sigma_u}{\bar{u}}$ in the layer up to 500 m. The maximum of these quantities as given by average data is observed in the lower layers (20-50 m) and decreases with the height everywhere. At the 400-500 m level, the gustiness of the wind weakens markedly, and only during daytime hours σ_u = 0.3-0.4 m/sec, and $\frac{u}{u} \approx$ 0.02-0.05. In the morning, the gustiness of the wind is reduced. Similar data on the daily variation of the Cherepet' SREPP are given in Table 5. Here the quantities σ_u and $\frac{\sigma_u}{u}$ have a generally similar course with a maximum at the bottom and a decrease with increasing height. The absolute values of σ_u are much higher than at the Moldavian SREPP. Particularly large values of σ_u and $\frac{\sigma_u}{u}$ were noted at a height of 25 m, corresponding to the level of the tops of the trees surrounding the clearing on which the ascents were carried out. At night, the gustiness of the wind was pronounced.

(See Table 5 on Following Page)

Table 5

Mean Values of σ_u and $\frac{\sigma_u}{\bar{u}}$, Cherepet' SREPP

Time	Height, m								Number of ascents
	25	50	100	150	200	300	400	500	
					σ_u m/sec				
8	0,9	1,1	0,8	0,6	0,5	0,0	0,0	0,0	12
10	1,7	1,5	0,8	0,8	0,6	0,0	0,0	0,0	7
12	0,9	0,9	0,8	0,8	0,9	0,9	0,6	0,5	6
14	1,9	1,6	1,4	1,1	1,0	0,7	0,8	0,5	10
16	2,4	2,1	1,7	1,5	1,4	1,0	0,5	—	4
18	2,2	2,2	1,1	1,0	0,9	—	—	—	4
20	1,1	0,9	0,6	0,6	0,9	0,6	0,5	—	3
2	0,9	0,9	1,0	0,8	0,8	0,2	0,2	0,2	6
4	1,6	1,2	1,5	0,8	0,6	0,5	0,1	0,0	6
6	1,6	1,4	1,0	0,8	0,5	0,2	0,1	0,0	6
					$\frac{\sigma_u}{\bar{u}}$				
8	0,3	0,3	0,2	0,1	0,1	0,0	0,0	0,0	
10	0,5	0,4	0,2	0,1	0,1	0,0	0,0	0,0	
12	0,2	0,2	0,2	0,2	0,2	0,2	0,1	0,1	
14	0,5	0,3	0,3	0,2	0,2	—	—	—	
16	0,6	0,4	0,3	0,2	0,2	0,1	0,1	—	
18	0,5	0,4	0,2	0,1	0,1	—	—	—	
20	0,4	0,3	0,1	0,1	0,2	0,1	0,1	—	
2	0,2	0,2	0,1	0,1	0,1	0,0	—	—	
4	0,4	0,2	0,2	0,1	0,1	0,1	0,0	—	
6	0,4	0,2	0,1	0,1	0,1	0,0	0,0	—	

Turbulence Coefficient

Turbulent mixing is one of the basic factors in the transport of atmospheric impurities. The values of the turbulence coefficient, which can be used to characterize mixing, depend on the vertical temperature gradients γ and wind velocity β, properties of the underlying surface, parameters of the free atmosphere, and other conditions. In practice, it may be considered that the magnitude and profile of the turbulence coefficient k_z are chiefly determined by the values of β and γ and their vertical distributions; more exactly, all these three quantities are interrelated. Subsequently, we shall analyze only the values of the turbulence coefficient along the vertical, and the coefficient will be designated by K.

For data of aerostatic sounding, the calculation was made by using E. S. Lyapin's formula

$$K = \frac{\overline{w'^2}\, t_w\, \bar{u}}{2u'}, \qquad (1)$$

where w' and u' are in m/sec, τ_w is the time of conservation of w' of the same sign in sec, and u is the wind velocity at the given level.

In the calculation, K was averaged over a five minute interval.

Based on results of airplane sounding for recording overloads, the calculations of K were made by using A. S. Dubov's formula (5) with correction for the frequency of fluctuations proposed by M. A. German (6)

$$K = \frac{\overline{w'^2} \; t v_a}{2} \; ; \qquad (2)$$

$$W' = \frac{b_\omega |\Delta n|}{\Delta \eta} \; , \qquad (3)$$

where v_a is the air velocity of the airplane; η is the correction factor allowing for the frequency of fluctuations; b_ω is a transmission function relating the overloads of the airplane in fractions Δn with the magnitude of the vertical component of the wind velocity; Δ is a correction for density.

The quantity K, like any other quantity characterizing the structure of an air stream, has a fluctuational character, but subsequently we shall use only its averaged values.

Fig. 2 shows the profile of K based on data of Table 1 in the layer up to 300 m as an average of two groups of σ_u. In the presence of unstable stratification, K has a maximum of $\simeq$ 50 m^2/sec at a height of 200 m, and decreases toward the 300 m level. In the presence of indifferent stratification (Cherepet' SREPP), the absolute values are practically the same, but the maximum is located at a height of 100 m with a decrease above this level. The conservation of high K values is apparently due to high wind velocities in this case.

In the presence of stable stratification (Shchekino SREPP), a considerable decrease of absolute values K $\simeq$ 13-14 m^2/sec is observed with nearly constant values in the 100-200 m layer.

The relationship obtained between K and the wind velocity was quite interesting (Table 6).

At low wind velocities, the values of K are relatively low and reach maximum values at wind velocities of 6-8 m/sec; at u $\geqslant$ 8 m/sec the values of K decrease. This dependence is apparently related to the corresponding variation of γ °/100, which at high wind velocities begins to decrease, and the value of K decreases correspondingly. Hence, in the 2-100 m layer for the region of the Moldavian SREPP, the optimum conditions for an intense vertical austausch corresponded to wind velocities of 6-8 m/sec. For higher levels, the K values were calculated from data of airplane sounding in the summer of 1963 in the region of the Shchekino SREPP.

Table 6

Mean Values of K and l_w from Gradations of the Wind Velocity in the 2-100 m Layer. Moldavian SREPP

u m/sec	2—4	4—6	6—8	8—10
K	49	71	97	53
l_w	17,3	32,2	50,5	36,5
Number of cases	5	16	7	2

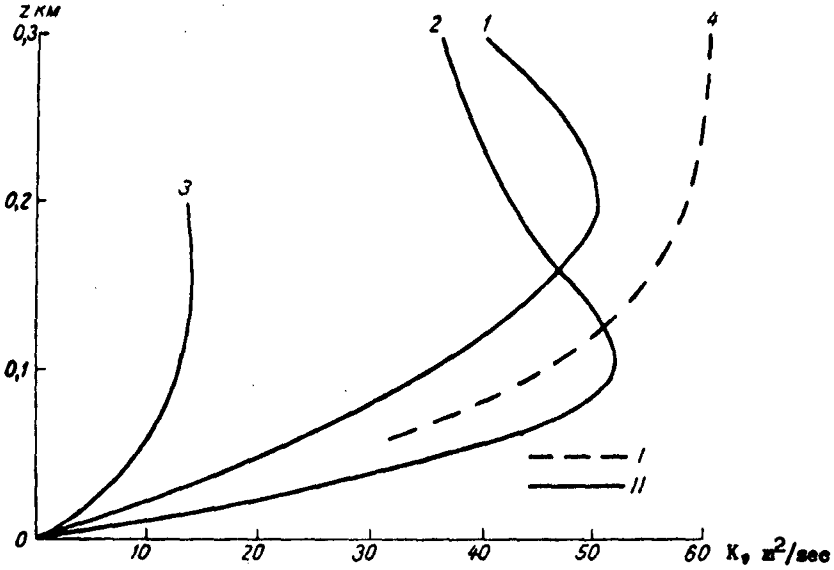

Fig. 2. Profiles of K in the 0-300 m layer, short-period profiles (I) and Long-period profiles (II).
1 - Moldavian SREPP; 2 - Charempet' SREPP; 3 - Shchekino SREPP, March 1965; 4 - Shchekino SREPP, August 1963, airplane.

Table 7

Mean Values of K, w' and l_u From Data of Airplane Sounding. Shchekino SREPP, August 1963.

Height, m																					Number of cases
150			200			300			400			500			750			1000			
K	w'	l_u	K	w'	l_u	K	w'	l_u	K	w'	l_u	K	w'	l_u	K	w'	l_u	K	w'	l_u	
52	1,3	91	58	1,6	97	64	1,2	96	70	1,4	103	61	1,3	95	63	1,5	106	57	1,2	119	14

According to the data of Table 7, the maximum values of K in August 1963 were located at a level of 400 m, a decrease of K was observed above this level, and starting at 500 m, the values of K were nearly constant. The vertical fluctuation w' reached the first maximum at a height of 200 m and a second maximum at 750 m. The profiles of K and w' in the 150-1000 m layer are given in Fig. 3. The characteristic size of the atmospheric eddies generally increased somewhat with the height, reaching their first maximum at the 400 m level and second maximum at 1000 m.

The frequency of the basic characteristics of the air stream according to layers is shown in Table 8.

Therefore, it may be stated that in the presence of unstable stratification (Moldavian SREPP), the turbulent energy of both the longitudinal component l_u and vertical component l_w increases with the height, reaching a maximum above 300 m. The intensity of the turbulent energy of both components remains constant in the entire 300 m layer. The parameter $\frac{\sigma_w}{\sigma_u}$, as an indicator of the degree of anisotropy of atmospheric eddies, reaches a maximum at a height of 300 m and amounts to 0.66-0.68.

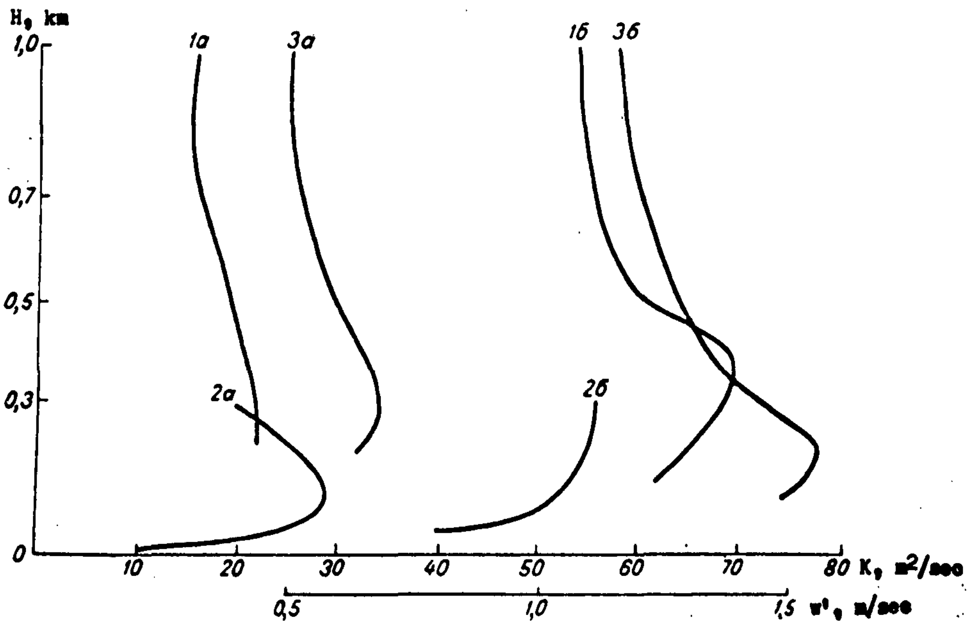

Fig. 3. Profiles of K (1, 2) and w (1, 3), Shchekino SREPP. 1a - airplane, 1962; 1b - airplane, 1963; 2a - aerostat, 1962; 2b - aerostat, 1963; 3a - airplane, 1962; 3b - airplane, 1963.

In an indifferent equilibrium (Cherepet' SREPP), maxima of σ_u and σ_w were observed at a level of 100 m, and decreased above this level. Because of the closed location of the area from which the aerostat ascended, there occurred a particularly rapid increase of these values to the level of 100 m; all the other characteristics of the structure of the air stream also underwent a marked decrease to the same level.

In a stable equilibrium, small values of σ_w were observed. Under the given conditions, the anisotropy of the atmospheric eddies increased even more, and the ratio $\frac{\sigma_w}{\sigma_u}$ was only 0.35-0.41. The magnitude of the mixing length of the eddy l_w depends on the thermal stratification, amounting to 70-95 m at Ri = -0.8, and as the stability increases, l_w is cut by almost one-half, but its maximum always coincides with the 200 m level. The horizontal size of the eddies l_u depends more on the wind velocity, and for the range of u from 5 to 12 m/sec, the relation $l_u = 40\,\overline{u}$ is fulfilled.

Table 8

Basic Characteristics of the Air Stream in the 150-200 m, 300-500 m and 750-100 m Lavers. Airplane Sounding in the Region of the Shohekino SREPP, August 1963.

Characteristic	150—200 m									Number of cases	300—500 m				
Gradation of k	30 40	41 50	51 60	61 70	71 80	81 90	91 100	101 110	111 120		30 40	41 50	51 60	61 70	71 80
Frequency of k, %	11	24	25	11	7	4	14	4	—	28	14	16	16	16	16
Gradation of w'	0,1 0,3	0,3 0,5	0,7 0,9	0,9 1,1	1,1 1,3	1,3 1,5	1,5 2,0	>2,0			0,1 03	0,3 05	05 07	07 09	09 11
Frequency of w, %	—	—	25	18	7	11	25	14		28	—	—	5	19	20
Gradation of lu	70	71 80	81 90	91 100	101 110	111 120	>121					71 80	81 90	91 100	101 110
Frequency of lu, %	4	—	43	18	28	7				28		8	15	42	25

Characteristic	300—500 m				Number of cases	750—1000 m									Number of cases
Gradation of k	81 90	91 100	101 110	111 120		30 40	41 50	51 60	61 70	71 80	81 90	91 100	101 110	111 120	
Frequency of k, %	11	9	2	—	44	16	15	23	15	15	4	8	—	4	26
Gradation of w'	11 13	1,3 1,5	1,5 2,0	>2,0		0,1 0,3	03 05	05 07	07 09	09 11	1 13	113 15	1,5 2,0	>2,0	
Frequency of w, %	12	15	27	2	41	—	4	—	11	19	19	31	4	12	26
Gradation of lu	111 120	>121					71 80	81 90	91 100	101 110	111 120	>121			
Frequency of lu, %	5	6			40		4	8	40	24	12	12			25

The magnitude of turbulent energy σ_u and its intensity $\frac{\sigma_u}{u}$ have a well-defined daily variation with a maximum during midday hours (Moldavian SREPP).

The turbulence coefficient at Ri = -0.8 has maximum values $\simeq$ 50 m^2/sec at the 200 m level, and for indifferent Ri = 0.0 the maximum of K will be at a height of 100 m. In the presence of stable stratification of the atmosphere, the absolute values of K = 13-15 m^2/sec undergo little change in the 100-200 m layer.

For the Moldavian SREPP, the optimum conditions of intense vertical austausch occurred at wind velocities of 6-8 m/sec. According to the data of airplane sounding, in August 1963 the maximum of K was at 400, and starting at 500 m its magnitude was practically constant.

Experience in calculating the components of the equation of turbulent energy balance is based upon data of aerostatic sounding. The process of generation of transport and dissipation of turbulent energy may be followed by analyzing the equation of turbulent energy balance, which, without taking the terms of horizontal diffusion and advection into account, is of the form

$$\frac{dE}{dt} = K\beta^2 - K_t \frac{g(\gamma_e - \gamma_o)}{T} + \frac{\partial}{\partial z} K \frac{\partial E}{\partial z} - \varepsilon , \qquad (4)$$

where

$$E = \tfrac{1}{2} (\sigma_u^2 + \sigma_v^2 + \sigma_w^2). \qquad (5)$$

Here E is the kinetic energy of turbulent fluctuations of wind velocity along axes x, y and z, referred to the unit mass.

We shall subsequently assume that

$$\sigma_u = \sigma_v ,$$

then

$$E = \sigma_u^2 + \frac{\sigma_w^2}{2} . \qquad (6)$$

In equation (4) $K\beta^2$ = B is the work of turbulent friction of the moving stream (dynamic factor);

$$K_t \frac{g(\gamma_e - \gamma_o)}{T} = A$$

is the inflow-outflow of energy due to work done against the buoyant forces (power of convection); ε – is the dissipation rate of turbulence energy; according to ref. (7) we shall assume that

$$\varepsilon = a \frac{E}{K} , \qquad (7)$$

where a is a constant factor equal to 0.046; K and K_t are the coefficients of turbulence of viscosity and thermal diffusivity; $K = K_t$.

Remaining symbols: β - vertical gradient of wind velocity at 100 m; T - average temperature of layer; g - acceleration due to gravity; γ_e and γ_o - equilibrium and observed vertical gradients of air temperature referred to the 100 m layer;

$$\frac{\partial}{\partial z} K \frac{\partial E}{\partial z} = D \qquad (A)$$

where D is the magnitude of diffusion of turbulence energy.

In accordance with ref. (8), D will be calculated from the formula

$$D = \frac{\partial}{\partial z} K \frac{\partial E}{\partial z} \bigg|_i =$$

$$= \frac{(K_{i+1} + K_i) E_{i+1} - (K_{i+1} + 2K_i + K_{i-1}) E_i + (K_i + K_{i-1}) E_{i-1}}{2 \Delta z^2} . \qquad (8)$$

Near the earth's surface, the values of E and K were taken to be equal to zero. The values of D in observations at levels of 100, 200 and 300 m could be calculated only at heights of 100 and 200 m.

The ratio $\frac{dE}{dt}$ gives the inflow-outflow of kinetic energy between two segments of time in a given layer; when $\frac{dE}{dt} > 0$, kinetic energy is gained, and when $\frac{dE}{dt} < 0$, it is expended.

This term was not calculated by the author.

According to ref. (9), we shall assume that $\gamma_e = 0.6°/100$ m.

The values of K m^2/sec were determined from Lyapin's formula.

The quantity $K\beta^2$ always has a plus sign: the energy is gained as a result of friction of moving air masses; the quantity ε, which is the dissipation of turbulent energy, always has a minus sign; the energy of total motion is expended and converted into thermal energy.

In the expression

$$A = -K \frac{g(\gamma_e - \gamma_o)}{T}$$

the sign will be determined by the relationship of γ_e to γ_o.

In accordance with the author's assumption that $\gamma_e = 0.6$, when $\gamma_o > 0.6°$/100 m, A will be positive, and when $\gamma_o < 0.6°$/100 m, it will be negative; when $\gamma_o = 0.6°$/100 m, A = 0.

The diffusion flow is given by the expression

$$D = \frac{\partial}{\partial z} K \frac{\partial E}{\partial z} . \qquad (B)$$

At positive values, D is directed downward, and at negative values, upward.

Since the turbulence coefficient K enters into all of the terms of equation (4), it is necessary to note certain aspects of its calculation:

1) The initial sensitivity of the receiver u' was 2-2.5 m/sec, and for this reason the values of K at winds of less than 2.5 m/sec were not used in the calculation;

2) At u and u' = 0, the turbulence coefficient, according to Lyapin's formula, becomes zero or infinity. Therefore, cases with u' $\geqslant$ 0.1 m/sec and u $\geqslant$ 2.5 m/sec are considered below;

3) The time of conservation of vertical fluctuations of the same sign is determined by the spectrum of the eddies.

In calculating K, "long-period" fluctuations with τ_w = 20-50 sec were taken. In this case, the value of K changed from a few units to a few tens of m^2/sec in the 300-meter layer.

The literature does not contain any data on direct measurements of components of the balance of turbulent energy in the boundary layer with its quantitative characteristics. We can only mention the study of Panofsky (10), which gives an estimate of the main terms of equation (1) based on data of measurements at levels of 233, 46 and 91 m on the Brookhaven tower. Panofsky established that up to a height of 91 m, all the energy fluxes are positive, i. e., directed upward, and increase with height. It was assumed that the energy flux varied linearly with the height, and was equal to zero on the ground. Comparison of the numerical values of $\frac{\partial u}{\partial z}$ (1 - Ri) and $\frac{\partial (Ew)}{\partial z}$ showed that the major part of the turbulent energy formed in the 100 m layer in the presence of unstable stratification is carried upward. At high values of Ri, only a small part of the energy formed is propagated upward.

Some data on the distribution of certain components of the balance of turbulent energy are given in the papers of V. N. Ivanov and Z. I. Volkovitskaya (11) and in the author's paper (12).

The starting data for the author's calculations were the results of ascents of an instrument recording the structure of the air stream, using a captive aerostat, in the region of the Cherepet' SREPP in October 1964, Shchekino SREPP in March 1965 and Moldavian SREPP in September 1965.

In view of the fact that the ascents of the instruments were made every two hours, but only in the daytime, and that their number was unevenly distributed in time, it was necessary to bring them together in a single group without considering the time.

Tables 9 and 10 given here include only those observations in which fluctuations of the horizontal component of the wind velocity u' $\geqslant$ 0.1 m/sec were observed.

All of the data for the Moldavian SREPP were divided according to heights of 100, 200 and 300 m into two groups:

a) ascent at u' $\geqslant$ 0.1 m/sec,

b) ascents at u' $\geqslant$ 0.6 m/sec.

Tables 9 and 10 give the initial data and values of the components of the balance of turbulent energy.

Table 10 gives a column with values of Σ, which are given by

$$\sum = K\beta^2 + A + D - \varepsilon. \qquad (C)$$

The term $\frac{dE}{dt}$ from equation (4) does not appear here. In an accurate calculation of all the terms of the equation of the turbulent energy balance, $\Sigma = 0$. In the present paper, the author did not attempt to give an analysis of the complete equation (4) for a certain period, but only to consider the characteristics of the distribution of its various terms in the layer up to 300 m. The main source of penetration of turbulent energy into the atmosphere, particularly during the cold period, is the energy of average motion of the stream due to friction, characterized by the term $B = K\beta^2$. The maximum values of term B will be in the vicinity of the earth's surface, but they are relatively high at a height of 100 m as well. We should note the characteristics of the distribution of this quantity in the region of the Cherepet' SREPP. The platform from which the aerostat ascended was located in a forest, and for this reason a rapid increase of the wind velocity was observed, particularly in the lowest 100 m at β = 5 m/sec for 100 m; in the 100-200 m layer β = 3.3 m/sec. These characteristics of the orography of the point of ascent are obviously a purely local distribution of the quantity $K\beta^2$.

In the summertime, according to data of observations at the Moldavian SREPP, $B < A$ in the entire 300 m layer, i. e., the contribution of the convection energy to the balance is greater than the contribution of the energy of average motion.

Table 9

Average Values of $\bar{E}$ m^2/sec^2, β m/sec x 100 m^{-1}, K m^2/sec and γ°/100 m.

H m	E	β	K	γ	E	β	K	γ
	Moldavian SREPP, u' = 0.1 m/sec				Moldavian SREPP, u' = 0.6 m/sec			
100	0,97	1,5	36	1,8	1,07	1,3	39	1,7
200	1,04	0,5	48	1,0	1,21	0,6	53	0,9
300	1,20	0,4	37	0,9	1,36	0,5	43	1,0
	Cherepet' SREPP				Shchekino SREPP			
100	2,51	5,0	52	0,8	0,74	1,7	13	0,9
200	1,77	3,3	42	0,4	0,64	0,5	13	0,5
300	1,45	2,0	36	0,5	—	—	—	—

Table 10

Components of Balance of Turbulent Energy

H m	Kβ²	A	D	—ε	Σ	Kβ²	A	D	—ε	Σ
	Moldavian SREPP, u' = 0.1 m/sec					**Moldavian SREPP, u' = 0.6 m/sec**				
100	81	143	—15	26	222	66	142	—14	14	180
200	12	62	3	10	67	19	52	1	13	59
300	6	37	—	18	—	11	57	—	20	—
	Cherepet SREPP					**Shchekino SREPP**				
100	1300	35	—90	56	1180	38	14	—5	42	5
200	456	—28	22	34	416	3	—5	—	32	—
300	145	—12	—	27	—	—	—	—	—	—

It is interesting to follow the change of B with the height. This is given in the following table, where values of $K\beta^2$ at the 100-m level are taken as 100%.

Moldavian SREPP			Cherepet SREPP	Shchekino SREPP
H m	u' ⩾ 0,1 m/sec	u' ⩾ 0,6 m/sec		
100	100	100	100	100
200	15	29	35	8
300	7	17	11	—

(D)

In this case, there takes place a relatively rapid 20-to 8-fold attenuation of friction intensity with the height to a level of 300 m, and as the energy of turbulant motion E rises, the friction intensity decreases, for example, at the Moldavian SREPP at $u' \geq 0.6$ m/sec and at the Cherepet' SREPP. In the practical conditions of our experiment, beginning at the 0.5 km level, B was close to zero. The energy of convective motions, expressed by the term

$$A = -K \frac{g}{T} (\gamma_e - \gamma_o) ,$$

is primarily determined by the relationship of γ_e to γ_o. At large values of γ_o, this takes place in daytime hours of the summer, the contribution of the convection energy is considerable, and hence $A > B$, as is obvious from observations at the Moldavian SREPP. During the cold period of the year, A is small and frequently negative, as is the case beginning with the 200 m level in the regions of the Cherepet' and Shchekino SREPP's.

The diffusion transport of turbulent energy in the lowest 100 m layer always has a minus sign, i. e., the stream is directed from the earth toward the upper layers; starting at the 200 m level, it changes sign, and this corresponds to the direction of diffusion transport from the upper layers toward the ground.

Of great interest is the dissipation of turbulent energy ϵ. Usually, the magnitude of dissipation has a maximum at the earth's surface and decreases with the height in the presence of stable stratification, something that is amply illustrated by the data of the Cherepet' SREPP and partially by those of the Shchekino SREPP.

According to observations in the region of the Moldavian SREPP, there occasionally occurs a certain increase of ϵ at the 300 m level, this being obviously due to the instability, and hence, the growth of the total kinetic energy E at this height. The contribution of each component into the balance of turbulent energy is given in Table 11, where the arithmetic sum of all the components is taken as 100%, and the value of each term has been calculated at the 100 and 200 m levels.

Table 11

Contribution of the Component into the Balance of Turbulent Energy (%)

H m	B	A	D	ϵ	B	A	D	ϵ
	Moldavian SREPP, $u' \geq 0.1$ m/sec				Moldavian SREPP, $u' \geq 0.6$ m/sec			
100	31	54	5	10	28	60	6	6
200	14	71	4	11	22	61	2	15
	Cherepet' SREPP				Shchekino SREPP			
100	88	2	6	4	38	14	5	43
200	85	5	4	6	—	—	—	—

During the warm period of the year, in an unstable state, the greatest contribution is made by the convection energy, and its fraction increases at the 200 m level. The energy of friction makes a maximum contribution during the cold period of the year under conditions of broken terrain or in the presence of a stable state of the atmosphere.

Data of the Cherepet' SREPP reflect the characteristics of only the platform on which the ascent of the captive aerostat took place.

The data cited constitute a first attempt to utilize the results of aerostatic sounding for energy calculations. Subsequently it will be necessary to validate the accuracy of the calculation of the separate components of the turbulent energy balance and to perform calculations of their daily variations.

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ANALYSIS OF AEROLOGICAL CONDITIONS OF ATMOSPHERIC POLLUTION IN CERTAIN REGIONS OF THE EUROPEAN TERRITORY OF THE USSR (ETU).

V. I. Selitskaya

From Trudy, Glavnaya Geofiz. Observat. im. A. I. Voeykova, No. 207, p. 188-201, (1968).

In order to study the aerological conditions of atmospheric pollution associated with the operation of many state regional electric power plants (SREPP) located in various regions of the European territory of the USSR, special meteorological observations are conducted in the lowest 500-meter layer. The present paper gives results of treatment of the observational data obtained.

We shall first cite some characteristics of the structure of the atmosphere, based on data of aerostatic sounding at the Moldavian SREPP.

The sounding was carried out in daylight (from 8:00 A. M. to 6:00 P. M.) up to a height of 500 m (sometimes up to 200 m). At even hours a meteorograph was sent up to 500 m to record the temperature, pressure, air humidity, average wind velocity and horizontal component of wind velocity fluctuations with 5 minute plateaus at standard heights; and, at odd hours, a meteorograph was sent up to record the average wind velocity and fluctuations with the horizontal and vertical components of the wind velocity at 100, 200 and 300 m levels. Average values of air temperatures are given in Table 1 of the Appendix. A rapid growth of air temperature took place from 8:00 A. M. to 2:00 P.M. in the entire 2-500 m layer.

The amplitude of air temperature from 8:00 A. M. to 6:00 P. M. decreased rapidly with the height, dropping from 11.2° at the 2 m level to 3.8° C. at 200 m and 2.3° C. at 500 m. The chief decrease of amplitude was observed up to a height of 200 m, and there was little change in amplitude above this level. Correspondingly, the greatest changes of vertical temperature gradients were observed in the lowest 100 meter layer.

At 10:00 A. M., ground inversions were still taking place. The average thickness of the inversion layer at 8:00 A. M. was 230 m (Table 1) with a 7.2° C. rise in temperature (average value), and in some cases with a 9.4° C. rise. The average vertical gradient of air temperature at that time was -3.0° C. at 100 m. By 10:00 A. M., the average height of the upper boundary of the inversion was about 140 m, and its magnitude was -1.7° C. (in some cases -3.7° C.) with a vertical temperature gradient of -1.6° C. at 100 m.

Positive gradients occurred between 10:00 A. M. and 11:00 A. M., and a superadiabatic gradient was observed at 12:00 Noon in the 100 m layer; above, the γ's were close to 1°. This gradient remained until 6:00 P. M.

Height, Intensity and Capacity of Various Ground Inversions.

Date	ΔH м	$t_1°$	$t_2°$	$Δt°$	γ	Date	ΔH м	$t_1°$	$t_2°$	$Δt°$	γ
7 - 8 A. M.						10 A. M.					
5/Sep	200	16,6	21,6	5,0	—2,50	5/Sep	200	21,8	23,8	2,0	—1,0
6/Sep	200	15,0	22,6	7,6	—3,80	10/Sep	180	18,7	22,4	3,7	—2,05
19/Sep	190	10,8	14,2	3,4	—1,78	19/Sep	50	16,6	17,2	0,6	—1,20
19/Sep	100	11,8	14,7	2,9	—2,90	-	—	—	—	—	—
20/Sep	260	8,6	16,4	7,8	—3,00	-	—	—	—	—	—
20/Sep	175	10,0	16,0	6,0	—3,40	-	—	—	—	—	—
23/Sep	130	11,8	16,0	4,2	—3,20	23/Sep	110	17,3	17,8	0,5	—1,00
24/Sep	400	9,2	18,6	9,4	—3,50	-	—	—	—	—	—
-	400	10,4	18,6	8,2	—3,00	24/Sep	200	17,5	19,2	1,7	—0,85
Average	230	—	—	7,2	—3,00	Average	140	—	—	1,7	—1,60

An elevated inversion was observed only on 2 September at 8:00 A. M. in the presence of fog. The height of its lower boundary was 50 m, and of its upper boundary, 200 m.

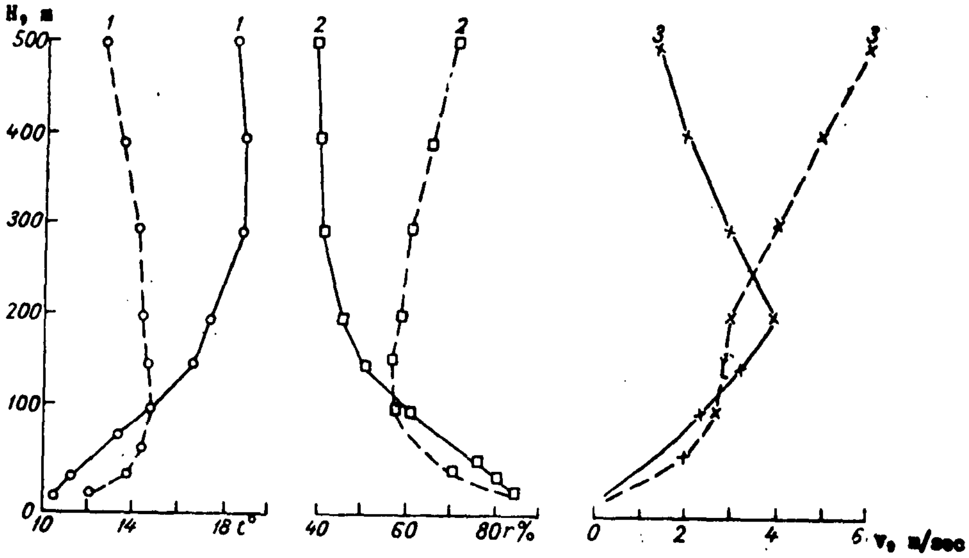

Fig. 1. Profiles of air temperature (1), relative humidity (2) and average wind velocity (3) on various days with inversions.

Fig. 1 shows the distribution of temperature t, relative humidity r and average wind velocity v over individual inversions, when the height of the inversion was above (24 Sept. -- solid line) and below the smokestack level (19 Sept. -- dashed line). The presence of ground inversion of air temperature, and of layers with an attenuated wind, hence, with a decreased turbulent austausch leads to a slowing down of the transport of contaminants both vertically and horizontally, something that occurred on 24 Sept.

In the second case (19 Sept.), the inversion was below the height of the smokestacks. In ref. (1) it is shown that a ground inversion whose lower boundary approximately coincides with the smokestack level or runs below it, has no effect whatsoever on the form of the smoke spread, and the transport conditions are determined by data of the vertical temperature gradient and wind velocity in the layer above the inversion.

By using the classification of profiles of air temperature and wind velocity given in ref. (2), one can establish a relationship between them from data of aerostatic sounding in the region of the Moldavian SREPP (Table 2).

Table 2

Frequency of Types of Wind Profiles as a Function of Types of Stratification

Type of Stratification	Type of Wind Profile						Number of cases
	Ia	Iб	IIa	IIб	IIIa	IIIб	
I	—	18	1	—	1	2	22
II	—	8	1	—	—	1	10
III	3	7	4	—	—	2	16
IV	—	—	—	—	—	—	—
V	1	—	—	—	2	—	3
VI	2	—	—	2	12	—	16
Number of Cases	6	33	6	2	15	5	67

Unstable stratification (types I and II) is characterized by wind profile type Ib (increase of wind velocity in the lowest 25-50 m layer and approximate constancy of the velocity up to 500 m).

For conditions with ground and elevated inversions (types V, VI), the predominant wind profile is 3a (presence of maximum of wind velocity or marked discontinuity due to the inversion layer within the 500 m layer).

Table 3

Frequency of Temperature Profiles from Data in the Region of the Moldavian SREPP.

Type of Stratification	Time, hours						Frequency, %
	7	8	10	12	14	16	
I	0	0	0	7	8	7	33
II	0	0	0	4	5	1	15
III	0	0	4	5	5	0	21
IV	0	0	0	0	0	0	—
V	0	1	1	0	0	0	3
VI	3	8	8	0	0	0	28
Number of cases	3	9	13	16	18	8	

The frequency of any given type of stratification according to the time of day is shown in Table 3. It is evident from these data that profiles with unstable stratification (types I and II) are characteristic from 12:00 Noon to 4:00 P.M. They comprise 48% of the total number of observations. In the morning (from 7:00 A. M. to 10:00 A. M.), 31% are made up of inversion types of stratification, whereas type III (state of equilibrium) was observed in 21% of the cases of all ascents.

Fig. 2 shows average wind profiles for various temperature stratifications in the 2-500 m layer, observed in the region of the Moldavian SREPP.

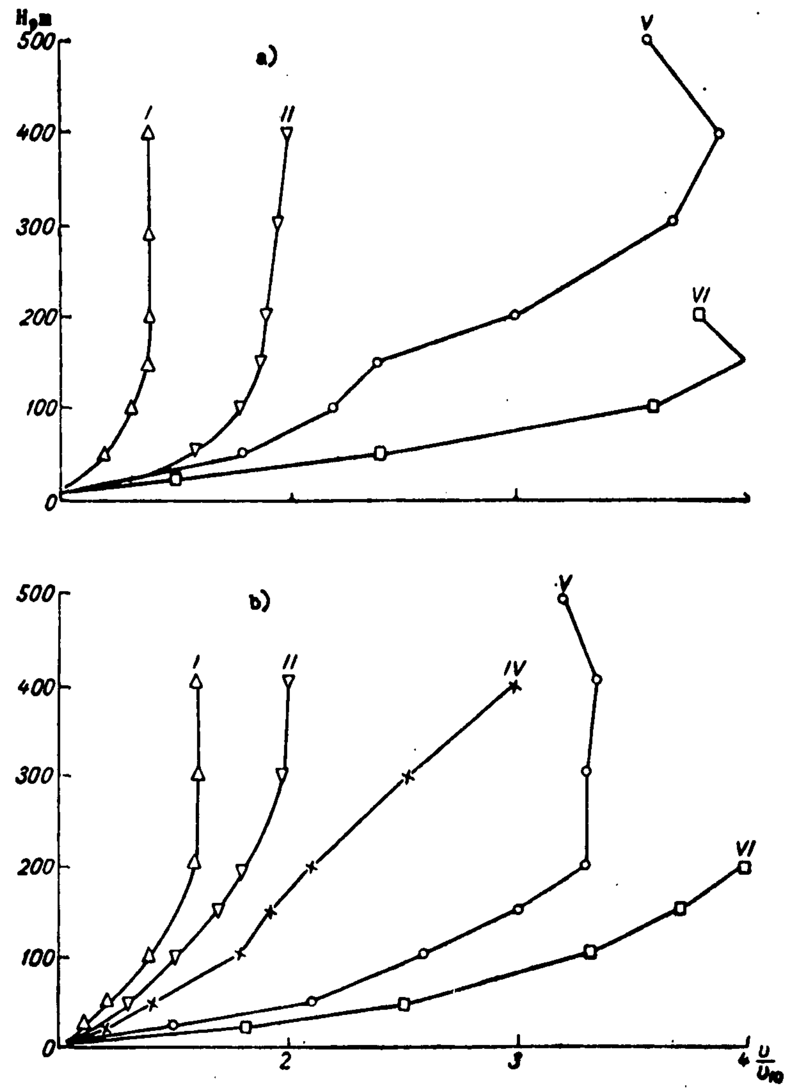

Fig. 2. Average Wind Profiles at Various Temperature Stratifications.
a) Moldavian SREPP, b) Cherepetskaya SREPP

For the unstable type of stratification (type I), above 150 m, the wind velocity is nearly constant with the height. The more stable the stratification at the lower levels (100-150 m), the greater the wind shift. Thus, profiles V and VI have inversion gradients at the bottom and stable gradients at the top. However, profile VI has a more stable stratification in the entire layer, and the wind shift of almost 50% at the 150 m level is greater when compared with profile V.

The distribution of the relative and specific air humidity in the region of the Moldavian SREPP is shown in Tables 3 and 4 of the Appendix.

The relative humidity maximum occurs at 8:00 A. M. in the 2-100 m layer, and the minimum in the entire 2-500 m layer, on midday hours (2:00 A. M. - 4:00 A. M.). The variation of the relative humidity is the reverse of the variation of air temperature. The amplitude of the relative humidity is maximum near the earth's surface, 48%, and the minimum humidity is 19% at the 500 m level.

In the variation of the specific humidity, the latter increases until 10:00 A. M., while the minimum of the specific humidity occurs at 4:00 P. M. in the entire 2-500 m layer. The decrease of the specific humidity from 10:00 A. M. to 4:00 P. M. amounts to 1.8 g/kg near the ground and 1.1 g/kg at 500 m; up to a height of 100 m, it takes place rapidly, and further changes are relatively slight.

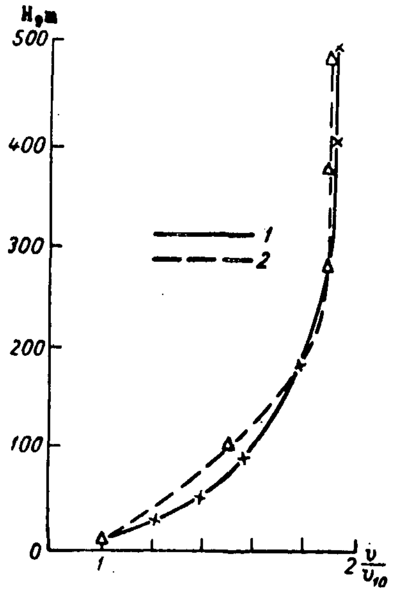

Fig. 3. Ratio v/v_{10} based on aerostatic and pilot balloon observations, Moldavian SREPP.

1 - aerostatic observations,
2 - pilot balloon observations.

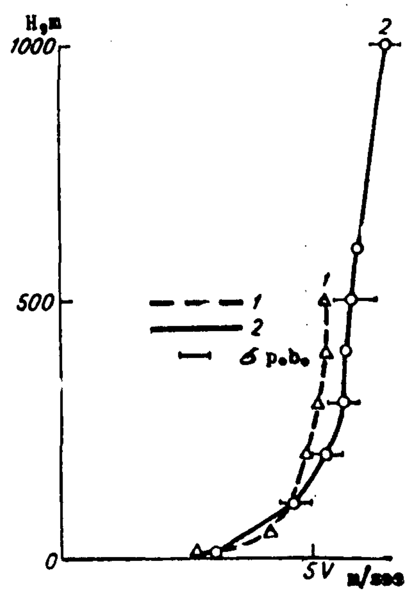

Fig. 4. Wind velocity based on aerostatic and pilot balloon observations and σ p.b.

1 - aerostatic observations,
2 - pilot balloon observations.

An average wind velocity was also obtained from data of aerostatic sounding (Table 5 of Appendix). The wind velocity values are low (3-5 m/sec) and change little with the height. The presence of a rapid increase of wind velocity from the earth's surface to the 100-150 m level is characteristic only of the lower layer. The wind velocity near the ground increases until 2:00 P. M., then decreases.

At high levels, however, its values undergo little change from 12:00 Noon to 6:00 P. M.

The value of $\frac{v_z}{v_0}$ up to the 500 m level was 1.3-1.5 in the daytime hours (Table 4). Fig. 3 shows the ratio of $\frac{v_z}{v_0}$ based on aerostatic and pilot balloon observations. The variation of the horizontal components of the wind velocity can also be followed rather well (Table 5). At 8:00 A. M., an even stream of air was observed in the inversion layer, but from 10:00 A. M. on, a certain fluctuation of the wind velocity was already developing. By noontime, this fluctuation was maximum over the entire height, and then the magnitude of the fluctuations decreased.

Table 4

The Ratio $\frac{v_z}{v_{\pm 0}}$

Time, hr.	Height, km										
	0,1	0,2	0,3	0,4	0,5	0,1	0,2	0,3	0,4	0,5	1,0
	Aerostat					Pilot balloon					
8	4,1	5,6	6,7	7,0	7,2	2,9	6,0	7,2	7,3	7,1	7,1
10	1,7	2,0	2,3	2,3	2,4	1,4	1,8	2,4	2,4	2,6	2,8
12	1,3	1,4	1,4	1,4	1,5	1,4	1,4	1,5	1,6	1,7	1,6
14	1,3	1,3	1,3	1,3	1,3	1,2	1,3	1,4	1,5	1,5	1,7
16	1,4	1,7	1,9	1,9	1,9	1,5	1,6	1,5	1,4	1,6	1,8

Table 5

Average Values of Fluctuations of Horizontal Component of Wind.

Time, hour	Height, m							
	25	50	100	150	200	300	400	500
8	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
10	0,5	0,4	0,4	0,3	0,3	0,1	0,2	0,0
12	0,8	0,6	0,5	0,5	0,4	0,2	0,2	0,1
14	0,8	0,8	0,6	0,6	0,4	0,3	0,3	0,2
16	0,5	0,5	0,3	0,3	0,3	0,1	0,1	0,1
18	0,4	0,2	0,2	0,1	0,1	0,1	0,0	0,0

In addition to aerostatic observations, pilot ballon observations were also taken. Average values of the wind velocity obtained from aerostatic and pilot balloon observations are given in Fig. 4. On the average, the data of these two methods are in good mutual agreement. The discrepancy at 500 m was $\pm$0.5 m/sec.

However, larger discrepancies were also observed on certain days. The mean square error of the wind velocity with respect to heights for double pilot balloon observations was ±0.2 - ±0.4 m/sec.

Observations in the region of the Cherepet' SREPP were conducted in October 1964 to a height of 200-500 m (depending on the weather conditions). Average values of air temperature are given in the Appendix (Table 1). Starting at 8:00 A.M., a rise of air temperature took place, and the maximum in the 2-200 m layer occurred at 2:00 P. M. The daily amplitude of air temperature at a height of 2 m was 6.3° C. and at a height of 200 m, approximately 2.3° C.

The magnitude of the vertical temperature gradient is one of the characteristic features of the temperature regime of the lowest atmospheric layer. Table 2 of the Appendix gives average values of vertical temperature gradients relative to the periods of observation. The maximum of γ° up to a height of 150 m occurred at 2:00 P. M. Positive gradients in this layer were noted from 10:00 A. M. to 6:00 P. M. Temperature inversions were observed during the remaining time of the day. As is evident from Table 6, both surface and elevated inversion were observed.

Table 6

Average Height of Boundaries, Intensity Δ t° and Capacity Δ H m of Ground and Elevated Inversions in the Region of the Cherepet' SREPP.

Time, hr.	Start		End		Δt°	Δ H m	Number of cases
	H_1 m	t_1°	H_2 m	t_2°	$(t_2 - t_1)$	$(H_2 - H_1)$	
20	0	6,0	60	6,4	0,4	60	1
2	0 (175[1])	2,9 (4,5)	120 (380)	7,3 (7,4)	4,4 (2,9)	120 (205)	2 (3)
4	0 (160)	2,8 (8,3)	290 (330)	7,4 (10,6)	4,6 (3,3)	220 (170)	3 (2)
6	0 (200)	2,0 (7,9)	270 (360)	7,0 (10,5)	5,0 (2,6)	270 (160)	3 (2)
8	0 (100)	3,8 (8,6)	175 (260)	8,5 (10,1)	4,7 (1,5)	175 (160)	4 (2)
10	0 (80)	9,9 (7,3)	220 (240)	10,9 (8,0)	1,0 (0,7)	220 (160)	1 (2)
12	(220)	(9,6)	(510)	(13,1)	(3,5)	(290)	(1)
14	(280)	(11,6)	(500)	(12,1)	(0,5)	(220)	(1)

[1] Data for elevated inversions are given in parentheses.

The upper boundary of ground inversions was located at heights from 70 to 460 m. On the average, a ground inversion reached its highest capacity by 4:00 - 6:00 A. M. The lower boundary of elevated inversion was located at heights of 50-300 m, and the upper boundary, from 150 m and above 510 m.

Data on the distribution of the relative and specific humidity of air are shown in Tables 3 and 4 of the Appendix. Maximum values of the relative humidity were observed near the ground at 8:00 A. M., by 2:00 P. M. the humidity had decreased to 20%, and beyond that it was seen to increase. The change in height was maximum at 8:00 A. M. and amounted to 12% at 200 m.

The specific humidity in the entire layer beginning at the ground increased slightly starting at 8:00 A. M. Its decrease with height occurred rapidly up to a height of 50-100 m.

Average values of the wind velocity are given in Table 5 of the Appendix, but this material is insufficient for characterizing daily variations of the wind velocity.

It may be stated that near the earth's surface during the day (2:00 P. M.), a faint maximum of the wind velocity was observed, and a minimum was noted during night hours (8:00 P. M. - 2:00 A. M.). From a height of 50 m, however, the wind velocity had a faint reverse cycle; a minimum was observed there in daytime hours, and a maximum in nighttime hours.

In the region of the Shchekino SREPP, observations were made from 15 March to 2 April 1965 from 8:00 A. M. to 5:00 P. M. up to a height to 200-300 m. During this period, weather with heavy and continuous clouds predominated, with the following air temperature fluctuations: at 8:00 A. M. from -5.2 to -0.9°, humidity from 78 to 96%; at 2:00 P. M., the temperature varied from -2.0 to 2.0; and the humidity from 73 to 94%. For analyzing and detecting certain particular features of the main meteorological elements, the data obtained were subdivided into the periods of 8:00 A. M., 10:00 A. M., 12:00 Noon, 2:00 P. M. and 4:00 P.M.

We shall consider the variation of air temperature (Table 1 of Appendix). A rise of air temperature in the 2-200 m layer took place after 4:00 P. M., and its amplitude was 2.0° at the 2 m level and approximately 1.9° C. at a height of 200 m. The curves of the daily temperature variation up to 100 m were almost parallel. To characterize the change of air temperature with the height, Table 2 of the Appendix gives average values of the vertical temperature gradient γ °/100 m. Values of the vertical temperature gradient are very changeable, particularly in the lower layers, where the influence of the thermal behavior of the underlying surface is manifested. In midday hours in the layer up to 50 m, superadiabatic gradient values of 1.2°-1.6° C./100 m were observed, and on some days the values of γ ° exceeded 4.0° C./100 m.

At 4:00 P. M. the gradient began to decrease, remaining superadiabatic in the layer up to 50 m. In the 100-200 m layer the gradient was equal to an average of 0.70° C./100 m.

Table 7

Average Gradients in the 0-200 m Layer From Data of Shchekino SREPP and Dolgoprudnaya Station of the Moscow Region.

Shchekino SREPP (March 1965)					Dolgoprudnaya Station (spring)				
	layer, m					layer, m			
time, hours	0—50	50—100	0—100	100—200	time, hours	0—50	50—100	0—100	100—200
08	0,98	0,85	0,92	0,63	7	0,98	0,62	0,80	0,28
10	1,20	0,83	0,90	0,79	10	2,32	0,80	1,56	0,68
12	1,23	0,94	1,13	0,62	13	1,45	1,00	1,22	0,93
14	1,58	0,91	1,22	0,67	14	1,80	0,95	1,38	0,88
16	1,25	0,86	1,14	0,57	—	—	—	—	—

Table 7 shows temperature gradients obtained from March 1965 in the region of the Shchekino SREPP; for comparison, we shall cite the same values for Dolgoprudnaya station for the spring period (3).

It is apparent that the average values of the gradients in these regions are in good mutual agreement.

Changes of the relative (r%) and specific (q g/kg) humidity of air are given in Tables 3 and 4 of the Appendix. At 8:00 A. M. near the ground, maximum humidity values were obtained, by 12:00 Noon, the humidity decreased insignificantly, then rose slightly; the relative humidity may be considered to be practically constant during this period.

Changes of the specific humidity were very slight along the height; they amounted to approximately 0.4 g/kg in the 2-200 m layer. In examining the average wind velocity values (Table 5 of Appendix), it should be noted that in March 1965, ascents of an aerostat with a volume of 39 m^3 were made which permitted the study of the wind only in the interval up to 8 m/sec near the ground and 12 m/sec at higher levels. At greater wind velocities, no aerostat ascents were carried out.

The data cited show that the average wind velocity in the 2-200 m layer changed little with the height. It increased somewhat faster in the bottom 100-meter layer, and above this level the increase in velocity was slower. At the earth's surface and along the height, the wind velocity by 12:00 Noon was slightly less than in the morning. The difference in velocities did not exceed 0.4 m/sec at almost any level.

Data of aerostatic sounding are in agreement with those of Dolgoprudnaya station for the spring period (Table 8).

Table 8

Region	Height, m					
	2 (12)	50	100	150	200	300
Shchekino SREPP, March	4,7	6,0	6,3	6,4	6,5	7,3
Dolgoprudnaya station, spring	2,3	4,9	6,0	6,3	6,5	7,1

The divergence in the data for heights of 12 m and 50 m may be explained by the influence of the regional topography, which markedly alters the wind velocity even at a short distance, and by the remoteness of the points of observation from each other.

The average wind velocity was also measured by a gustiness meteorograph. The average wind velocity values obtained by two meteorographs are close to each other (Table 9).

Table 9

time, hours	Height, m: 3	100	200	3	100	200
	Main meteorograph			Gustiness meteorograph		
10	4,5	6,4	6,5	4,3	6,1	6,6
12	4,3	5,8	6,2	4,3	6,0	6,8
14	5,1	6,6	6,8	4,7	6,1	6,7
16	5,2	6,0	6,9	5,0	6,5	6,2

Aerological studies of the lowest atmospheric layer up to 500 m were made in the region of the Shchekino SREPP and earlier (1962 and 1963). Some results of these observations were published in ref. (4, 6). Data on the distribution of temperature and wind velocity during the spring period of observations are listed in Table 10.

Table 10

Average Values of t° and v m/sec During Periods of Studies of Expeditions of the Main Geophysical Observatory at the Shchekino SREPP.

Weather	Element	Height, m: 2	25	50	100	150	200	300	400	n
March 1962										
Slightly cloudy	t	−1,2	−1,6	−1,8	−2,0	−2,2	−2,5	−3,0	−3,8	28
	v	4,1	4,9	5,1	5,3	5,4	5,6	5,7	5,7	
Cloudy	t	−0,2	−0,7	−1,0	−1,5	−1,9	−2,3	−3,1	−3,6	8
	v	5,0	5,7	6,0	6,2	6,2	6,2	6,5	6,9	
March 1963										
Slightly cloudy	t	−15,1	−15,1	−14,8	−14,2	−13,9	−14,8	−14,8	−15,4	23
	v	3,5	4,1	4,7	5,2	5,5	5,6	5,7	5,9	
Cloudy	t	−10,1	−10,6	−10,8	−11,0	−11,3	−11,3	−11,3	−11,2	9
	v	6,3	7,6	8,0	8,2	8,5	9,1	9,6	10,6	
March 1965										
Cloudy	t	−1,0	−1,3	−1,6	−1,9	−2,2	−2,5	—	—	50
	v	4,7	5,6	6,0	6,3	6,4	6,5	—	—	

As was noted above, a heavy and continuous cloudiness was observed chiefly in March 1965. Anticyclonic weather with low air temperatures predominated in March 1963, and high air temperatures, a frequent change of weather types and a heavy cloudiness predominated in March 1962. For this reason, all of the data were divided into two groups, for cloudy and slightly cloudy weather. Cloudy days were considered to be those with a cloudiness of the lower cloud layer of 6-10 points or with a cloudiness of the middle layer of 8-10 points. All the other days were considered to be slightly cloudy.

In March 1965, the number of cloudy days was 94%, in March 1963, 28%, and in March 1962, 22%. Therefore, Table 8 lists data for only cloudy weather for March 1965.

Average air temperatures and average velocities on days with cloudy weather for March 1965 and 1963 are close to the absolute values at all heights. The temperature divergence on the ground is 0.8° C., and at a height of 200 m, only 0.2° C., and the average wind velocity of these heights diverges by 0.3 m/sec. The value of the temperature and wind velocity for March 1963 differs sharply from these data.

The difference of surface temperatures (March 1965 and 1963) is 9.1° C. and at a height of 200 m, 11.4° C. The average wind velocity for all heights in March 1963 was greater than 1.6-2.6 m/sec.

In conclusion, it may be noted that the given characteristics of the lowest layer (500 m) during the period of study of the expeditions indicate a significant daily variability of all the meteorological elements.

In further studies, the number of ascents during the night should be increased, in order to make it possible to carry out more detailed investigations of the capacity and intensity of the inversion layers, which create unsafe conditions for pollution of the lowest layer.

APPENDIX

Table 1

Average Values of Air Temperature.

Time, hours	Height, m									Number ascents
	2	25	50	100	150	200	300	400	500	
Moldavian SREPP										
8	12,6	13,8	14,6	15,9	16,8	17,1	17,3	16,7	16,1	12
10	18,8	19,0	19,1	19,0	18,7	18,5	18,1	17,5	16,7	14
12	22,2	21,3	20,8	20,4	20,0	19,6	18,8	18,0	17,2	18
14	23,8	22,7	22,3	21,8	21,3	20,9	20,0	19,2	18,4	19
16	23,8	22,6	22,2	21,6	21,1	20,6	19,8	19,0	18,3	9
18	19,1	18,6	18,2	17,7	17,4	17,0	16,4	15,6	—	4
Cherepet' SREPP										
8	6,1	6,1	6,1	6,4	6,6	6,4	—	—	—	7
10	7,4	7,1	6,8	6,6	6,6	6,5	—	—	—	7
12	9,7	9,2	8,8	8,3	7,9	7,6	—	—	—	6
14	10,4	9,8	9,5	8,9	8,4	8,0	7,2	6,6	—	10
16	9,2	8,8	8,5	8,2	7,7	7,2	6,3	5,8	—	4
18	8,5	8,4	8,1	7,7	7,5	7,0	6,3	5,7	—	4
20	7,7	7,9	7,5	7,3	7,4	7,1	6,4	5,6	—	3
02	4,9	5,2	5,6	5,8	5,8	5,7	6,3	5,9	—	6
04	4,5	4,6	4,9	5,3	5,5	5,7	5,8	6,3	—	6
06	4,1	4,4	4,6	5,2	5,6	5,7	5,8	6,6	—	6
Shchekino SREPP										
8	—2,2	2,4	—2,7	—3,1	—3,5	—3,7	—	—	—	11
10	—1,4	—1,7	—1,9	—2,4	—2,8	—3,2				10
12	—1,0	—1,4	—1,7	—2,1	—2,5	—2,8				12
14	—0,2	—0,7	—1,0	—1,4	—1,8	—2,1				10
16	0,2	—0,2	—0,5	—0,9	—1,4	—1,8				8

Table 2

Average Values of Vertical Temperature Gradient.

Time, hours	Height, m							
	25	50	100	150	200	300	400	500
Moldavian SREPP								
8	—4,90	—3,40	—2,46	—1,65	0,71	0,02	0,54	0,33
10	—0,97	—0,14	—0,24	0,54	0,44	0,78	0,64	0,72
12	3,31	1,55	1,11	0,83	0,73	0,76	0,80	0,78
14	4,06	1,51	1,01	0,98	0,86	0,89	0,87	0,78
16	4,57	1,77	1,24	0,89	0,94	0,94	0,80	0,77
18	1,80	1,50	1,10	1,00	0,82	0,90	0,80	—

Time, hours	Height, m							
	25	50	100	150	200	300	400	500
Cherepet' SREPP								
8	0,00	—0,90	—0,95	—0,62	0,09	—	—	—
10	1,31	1,09	0,51	0,03	0,24	—	—	—
12	2,13	1,33	0,97	0,87	0,63	—	—	—
14	2,20	1,40	1,06	1,06	0,80	0,73	0,66	—
16	1,50	1,10	0,75	0,85	0,95	0,90	0,80	—
18	0,70	0,90	0,90	0,60	0,70	0,68	0,31	—
20	—0,80	0,13	0,49	0,40	0,60	0,73	0,83	—
02	—1,27	—1,33	—0,57	0,07	0,25	—0,53	—0,32	—
04	—0,53	—1,06	—0,73	—0,37	—0,57	—0,27	0,03	—
06	—0,87	—1,07	—1,10	—0,48	—0,12	—0,13	0,04	—
Shchekino SREPP								
8	0,98	0,98	0,85	0,67	0,58			
10	1,20	1,04	0,92	0,82	0,78			
12	1,40	1,07	0,93	0,67	0,76			
14	1,96	1,04	0,91	0,76	0,60			
16	1,83	1,03	0,86	0,91	0,71			

Table 3

Average Values of the Relative Humidity of Air.

Time, hours	Height, m								
	2	25	50	100	150	200	300	400	500
Moldavian SREPP									
8	88	80	74	68	61	58	54	50	50
10	68	63	62	60	60	59	60	61	64
12	51	50	51	51	52	53	53	55	54
14	41	41	42	43	42	43	44	45	47
16	40	41	43	43	44	44	44	44	45
18	52	53	54	55	57	57	58	60	—
Cherepet' SREPP									
8	92	91	90	88	85	80	—	—	—
10	86	86	87	88	86	85	—	—	—
12	74	74	75	76	76	76	—	—	—
14	72	72	73	74	76	76	75	77	—
16	82	84	84	85	87	89	89	89	—
18	85	85	86	87	88	88	89	90	—
20	88	86	85	84	84	85	87	88	—
02	87	85	82	80	78	78	70	70	—
04	89	88	86	83	83	78	75	70	—
06	91	91	89	86	83	81	73	71	—

Time, hours	Height, m								
	2	25	50	100	150	200	300	400	500
					Shchekino SREPP				
8	86	85	84	84	84	85	—	—	—
10	83	80	80	81	82	84	—	—	—
12	80	82	82	83	83	82	—	—	—
14	82	81	81	83	84	85	—	—	—
16	82	81	81	82	82	83	—	—	—

Table 4

Average Values of the Specific Humidity of Air

Time, hours	Height, m								
	2	25	50	100	150	200	300	400	500
					Moldavian SREPP				
8	8,2	8,2	8,2	7,8	7,6	7,2	6,9	6,9	6,8
10	9,1	8,5	8,4	8,1	7,9	7,8	7,6	7,5	7,4
12	8,2	7,8	7,7	7,6	7,5	7,5	7,5	7,5	7,2
14	7,5	7,2	7,2	7,0	6,9	6,9	6,9	6,9	6,3
16	7,3	7,1	7,1	7,0	6,9	6,8	6,6	6,3	6,5
18	7,6	7,5	7,5	7,6	7,5	7,0	6,7	6,7	—
					Cherepet' SREPP				
8	5,4	5,3	5,3	5,3	5,2	4,9	—	—	—
10	5,5	5,5	5,4	5,4	5,3	5,2	—	—	—
12	5,6	5,4	5,4	5,3	5,2	5,1	—	—	—
14	5,7	5,5	5,4	5,4	5,4	5,3	5,1	5,0	—
16	5,9	6,0	6,0	6,0	6,0	6,0	5,8	5,6	—
18	6,1	6,0	5,9	5,9	5,9	5,8	5,6	5,5	—
20	6,0	5,9	5,8	5,8	5,8	5,7	5,6	5,4	—
02	4,8	4,8	4,7	4,6	4,5	4,3	4,2	4,0	—
04	4,8	4,8	4,7	4,7	4,6	4,5	4,5	4,0	—
06	4,8	4,8	4,9	4,7	4,7	4,6	4,3	4,1	—
					Shchkino SREPP				
8	2,7	2,6	2,6	2,6	2,5	2,4	—	—	—
10	2,8	2,7	2,6	2,6	2,6	2,6	—	—	—
12	2,9	2,8	2,8	2,8	2,7	2,7	—	—	—
14	3,0	2,9	2,8	2,8	2,7	2,7	—	—	—
16	2,9	2,8	2,7	2,7	2,6	2,6	—	—	—

Table 5

Average Values of Wind Velocity,

Time, hours	Height, m								
	2	25	50	100	150	200	300	400	500
Moldavian SREPP									
8	0,6	1,0	1,9	2,7	3,0	3,3	4,0	4,3	4,6
10	2,3	2,8	3,2	3,7	4,1	4,4	5,1	5,5	5,6
12	3,6	4,4	4,9	5,0	5,3	5,3	5,5	5,6	5,7
14	4,0	4,7	5,0	5,3	5,4	5,5	5,5	5,6	5,6
16	3,7	4,8	5,3	5,6	5,5	5,4	5,2	5,1	5,0
18	2,5	3,6	4,3	4,9	5,3	5,8	6,4	6,6	—
Cherepet' SREPP									
8	1,4	3,2	3,9	5,3	5,8	5,9	—	—	—
10	1,1	3,3	4,2	5,0	5,6	6,0	—	—	—
12	1,1	4,0	4,5	4,9	5,3	5,8	—	—	—
14	2,1	3,9	4,6	4,9	5,2	5,3	5,8	6,2	—
16	1,8	4,9	5,5	6,5	7,2	7,7	8,0	8,2	—
18	1,9	4,1	4,9	6,7	7,2	7,9	8,5	8,8	—
20	0,6	2,8	3,4	4,6	5,4	6,1	6,6	7,4	—
02	0,8	4,2	5,8	7,2	8,4	9,0	9,3	9,5	—
04	1,2	3,9	5,1	6,6	7,6	8,3	9,4	10,1	—
06	1,2	4,2	6,0	7,1	8,2	8,7	9,8	10,7	—
Shchekino SREPP									
8	4,7	5,3	5,8	6,0	6,1	6,4	—	—	—
10	4,5	5,7	6,1	6,4	6,5	6,5	—	—	—
12	4,3	5,2	5,6	5,8	5,9	6,2	—	—	—
14	5,1	5,7	6,2	6,6	6,8	6,8	—	—	—
16	5,2	6,0	6,6	6,9	6,9	6,9	—	—	—

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SOME CHARACTERISTICS OF THE PROPAGATION OF NOXIOUS POLLUTANTS FROM HIGH SOURCES AS A FUNCTION OF SYNOPTIC-METEOROLOGICAL FACTORS

B. B. Goroshko

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At the present time, the meteorological aspect of the problem of preventing air pollution caused by industrial enterprises and transport is of major importance. Particular attention should be given to the study of pollution of the atmosphere by high-capacity industrial and power sources, when noxious substances may spread to great distances in large concentrations. For example, the smoke spread from large State Regional Power Stations (SRPS) with stack heights above 100 m has been observed at distances of over 20-30 km under certain meteorological conditions.

One of the essential conditions for the study of the influence of meteorological elements on the magnitude of ground-level concentrations of noxious substances discharged from smokestacks is the necessity of obtaining systematic and reliable data on air pollution with a simultaneous measurement of a broad group of meteorological parameters determining the dispersal of impurities in the atmosphere. In this connection, major expeditionary studies were carried out in the region of the Shchekino SRPS. They were conducted for many years in various seasons and under different meteorological conditions by the Main Geophysical Observatory im. A. I. Voeikov, by the Moscow Scientific Research Institute of Hygiene im. F. F. Erisman and by the southern division of the State Trust for the Organization and Efficiency of Electric Power Plants.

A number of papers (1, 2, 4, 5, 6) on the completed work have already been published, which discuss the problem of pollution of the atmosphere by thermal power stations; a theoretical treatment has been given, and comparison of theoretical calculations with experimental data is made.

The present paper is devoted to a synoptic-meteorological study of results of the observations.

In order to analyze the effect of baric formations on the degree of pollution of the atmosphere by sulfur gas in the region of the SRPS, synoptic charts for the periods of selection of air samples were studied. The following gradations were thus established: anticyclonic formations, including anticyclones and crests; cyclonic formations--cyclones and troughs; intermediate baric field between the cyclones and anticyclones for a rectilinear position of the isobars or a diffuse baric field. In Table 1, which gives the number of cases with corresponding formations, it is apparent that the samples were taken most frequently in anticyclonic weather. It has been shown theoretically (1, 2) that in the case of dispersal from high sources, an increase in ground level concentrations takes place in the presence of unstable stratification and reinforcement of turbulent austausch. This is in good agreement with results obtained by processing factual material and comparing with meteorological data.

Table 1

Baric formation			Total cases
anticyclonic	cyclonic	intermediate	
53	48	45	146

The material was treated in accordance with a method proposed by M. E. Berlyand, given in ref. (6). Illustrated are figures representing data on the concentration of sulfur gas as a function of changes of meteorological elements and characteristics of turbulence in various gradations, taking into account the synoptic conditions, time of day, etc.

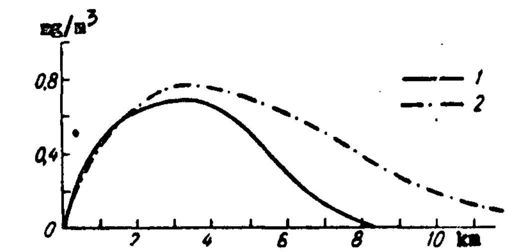

FIG. 1 Distribution of concentration of sulfur gas in February-March of 1962-1963.
1 – during cyclone conditions, 2 – during anticyclone conditions.

Fig. 1 shows a graph of the distribution of concentrations of sulfur gas from SRPS stacks in February-March 1962-1963 in a cyclone and anticyclone. The curve running through the maximum concentrations observed in anticyclonic weather differs little from the one for cyclonic conditions. A similar picture is observed in the intermediate baric field. This is due to the fact that the daily variation and distribution of the meteorological elements determining the dispersal of contaminants coincide or compensate one another in the various baric formations. Therefore, the degree of pollution should not be discussed solely on the basis of the synoptic situation or without considering the specific distribution of the various meteorological elements and their influence on the distribution of contaminants.

In order to elucidate the influence of the daily variation of meteorological elements on the dispersal of noxious substances during the period of experimental studies at the Shchekino SRPS, the selection of sulfur gas samples was made along a grazing graph, i. e., two days a week, in the morning, daytime, and evening. All the data for the observation period 1962/63 were initially divided into three groups. The first group included data obtained on days with anticyclonic isobars, the second group included cyclonic isobars, and the third, the intermediate baric field. All three groups were then divided according to the time of sampling: morning period from 5:00 A.M. to 9:00 A. M., daytime period from 9:00 A.M. to 4:00 P.M., and evening period from 4:00 P.M. to 7:00 P.M.

It was found that the largest number of cases of selection of concentrations under the smoke spread coincided with the intermediate baric field in the daytime.

Unfortunately, there were very few cases in the evening, and there was a complete lack of morning periods for the anticyclonic and cyclonic bend of isobars. This is due to the fact that a fog or low cloud cover is frequently observed in the morning, and it was impossible to determine the direction of the smoke spread from the SRPS.

Fig. 2 shows the distribution of sulfur gas concentrations as a function of the distances to the source in the intermediate baric field at different times of the day. The curves running through the maximum concentrations differ markedly from morning to daytime and from daytime to evening. It is apparent from the available data that the lowest surface concentrations of sulfur gas are observed in the morning in the intermediate baric field and reach maximum values at a distance of 3-4 km from the source (up to 0.9 mg/m^3). Concentrations near the maximum permissible standard (MPC) and above are encountered at distances of 1.5-5.5 km.

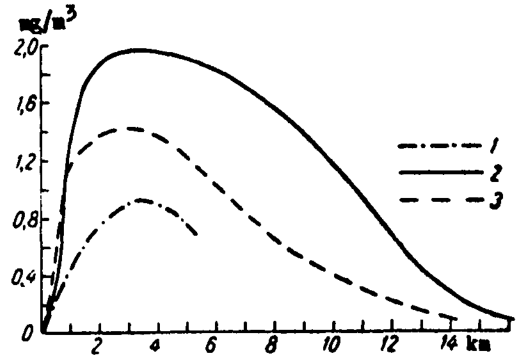

FIG. 2 Distribution of concentrations of sulfur gas in intermediate baric field at different times of day.
1 - morning, 2 - day, 3 - evening.

The curve running through the maximum concentrations in the daytime differs substantially from the morning curve, its maximum is smoother, and the highest concentrations range from 2 to 5 km. The concentrations increase rapidly with the distance from the source (the curve rises steeply upward) and, having reached a maximum, decrease slowly, spreading to large distances. Concentrations above MPC during the day occur from 1 to 13 km, i.e., in this case the zone of high concentrations broadens appreciably, and large areas are subjected to its action; the maximum increases to 1.9 mg/m^3.

The curve of concentration distribution in the evening time is similar to the one for daytime, but in this case the maximum concentrations decrease at all distances from the source, and its maximum exceeds the concentration maximum in the morning period by a factor of only 1.5. The zone where concentrations above MPC occur decreases, and is located at a distance of 1 to 9 km.

Therefore, it may be concluded that the most unfavorable conditions in the intermediate baric field arise in the daytime, when the concentrations increase substantially, and the pollution zone expands considerably. In the evening, the concentrations decrease again.

Graphs of the distribution of maximum concentrations in anticyclonal weather in the daytime and evening were plotted in similar fashion. In general, curves for daytime and particularly evening periods in the intermediate baric field and in the anticyclone were similar. This is because of the fact that the daily variation of the number of meteorological elements in these baric formations is similar, and hence, the conditions of propagation of noxious substances are also similar.

We shall now consider the distribution of concentrations in cyclonic formations. The corresponding graphs indicate that the maximum concentrations differ slightly from the values in the intermediate and anticyclonal baric fields. The daytime concentrations also increase rapidly with the distance from the source, reach a maximum, and, in contrast to previous cases, decrease much more slowly, i.e., they can be observed at large distances in cyclonic fields of considerable magnitude. This may be explained by an increase of the wind velocities in cyclones.

The graph obtained for evening conditions in a cyclone is different from the preceding ones. Here, maximum concentrations are given that are fairly close to the corresponding values in the intermediate and anticyclonic baric fields, but the position of the maximum is shifted to the right, i. e., to large distances from the stacks. There takes place a smooth increase of concentrations with the distance to the maximum, and the same kind of smooth decrease to larger distances. This may also be because of a reinforcement of the influence of the wind velocity on the transport of impurities. Hence, the greater the heating and the more developed the instability, the closer to the source can one expect the maximum concentrations to be located.

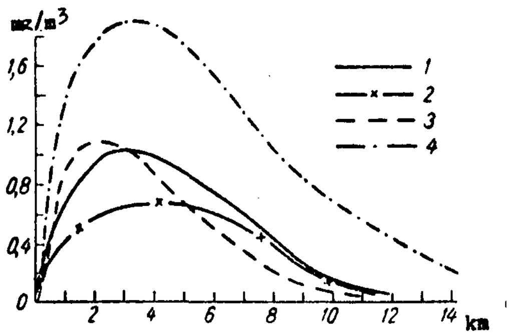

FIG. 3 Change in the concentrations of sulfur gas as a function of the temperature distribution.

1-for summer conditions at $\Delta t \leq 0$ in the 0.5-2.0 m layer, 2-for winter conditions at $\Delta t \leq 0$ in the 0.5-2.0 m layer, 3-for winter conditions at $\Delta t > 0$ 0.5-2.0 m layer, 4-for summer conditions at $\Delta t > 0$ in the 0.5-2.0 m layer.

Having examined the influence of large-sized baric formations on the propagation of noxious substances from SRPS stacks, we shall now consider the analysis of the influence of individual meteorological elements on the magnitude of surface concentrations from the same source.

It was noted above that the magnitude of concentrations undergoes a considerable change from morning to daytime conditions and from daytime to evening conditions. It is natural to postulate that, in this case, the greatest influence on this change is exerted by the daily variation of the temperature gradient and of the wind velocity. Therefore, we shall first consider the influence of the change in the temperature gradient on the magnitude of surface concentrations.

In ref. (2), a substantial influence of the vertical distribution of temperature and wind velocity on the propagation of contaminants was theoretically demonstrated. The author discussed factual material on the influence of the temperature change with the height on the magnitude of the surface concentration of a light contaminant (sulfur gas).

Fig. 3 shows the change of concentrations as a function of the distance from the stacks when the temperature difference in the 0.5-2 m layer, based on data of gradient observations, was equal to or less than zero, and for cases where this difference was above zero. The figure shows curves for winter-spring and summer-fall conditions. It is apparent from these curves that, in any seasons, the temperature gradient has a great influence on the distribution of pollutants near the ground. The establishment of an isothermal or inversion distribution of temperature even in the lowest two-meter atmospheric layer leads to a substantial decrease of the surface concentrations of sulfur gas. Concentrations above MPC at $\Delta t \leq 0$ in winter occur in a zone ranging from 1.5 to 7 km from the source, and in summer from 1 to 6 km. The maximum then shifts from 4 to 2 km. Thus, from winter to summer there takes place a shift of the maximum toward the source, while the width of the zone with concentrations above MPC remains the same.

If one considers graphs for summer and winter at $\Delta t > 0$, it is apparent that the maximum in the general case is observed at a distance of approximately 3 km from the source; concentrations above MPC in winter can be found from 1 to 7.5 km and in summer from 1 to 11 km, i. e., the zone of influence of the source expands by a factor of 1.5 from winter to summer. In addition, during warm periods of the year, the ground concentrations are higher than in winter.

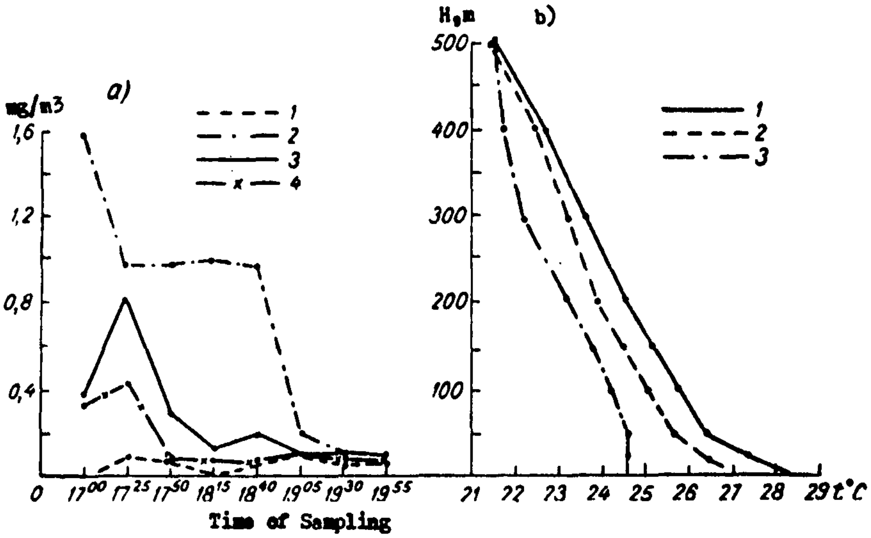

FIG. 4 Distribution of sulfur gas concentrations with distance (a) and distribution of temperature with height (b).

a) 1-1 km, 2-2 km, 3-4 km, 4-10 km; b) 1- at 3:50 P.M., 2- at 5:40 P.M., 3-at 7:20 P.M.

On the basis of the above, one can speak of the great influence of the temperature distribution on surface concentrations. Isothermy and inversion lead to an attenuation of turbulent diffusion and transport of pollutants from upper layers. This is apparent from Fig. 4, which shows an example of the distribution of sulfur gas concentrations at distances of 1, 2, 4 and 10 km on August 9, 1962, and also gives the temperature profiles based on data of aerostatic sounding in this region.

On that day, the samples were taken in the evening from 5:00 P.M. to 8:00 P.M., and 70 samples were taken at four distances from the source. Two to three samples were taken simultaneously at all distances, and of these, the maximum concentration at each distance was taken at a given time.

Comparing the concentrations and the distribution of temperature with the height, we see that during the initial period of sampling, at 3:50 P.M. and 5:40 P.M., the atmosphere was stratified unstably. At the same time, maximum concentrations were observed, particularly at a distance of 2 km. At 5:50 P.M., at distances of 4 and 10 km, a sharp decrease of concentrations took place, and the temperature difference at that time in the 0.5-2 m layer was close to zero.

When the aerostat rose at 7:20 P.M., isothermy was recorded in the 0-50 m layer, and at that time the concentrations at all distances were minimal.

The author selected cases in which the temperature gradient in the 0-100 m layer was equal to or less than zero. The maximum concentration values are shown in Table 2, from which it is apparent that the maximum possible concentrations are much lower than when the temperature decreases with the height.

Table 2

Distance from source, km....	0.5	1.0	2.0	3.0	4.0	5.0	6.0	10.0
Maximum concentrations of sulfur gas, mg/m^3......	0.7	0.37	0.22	0.08	0.20	0.07	0.06	0.11

From Figs. 3 and 4 and from Table 2 it is apparent that one of the basic factors affecting the magnitude of surface concentrations of light pollutants is the temperature gradient in the lowest layer. The establishment of isothermy or inversion in the lowest layer leads to substantial changes of the concentrations toward a decrease of its magnitude. Here the author confines himself to an examination of the influence of the temperature gradient on the diffusion of noxious pollutants only in the layer up to the height of the source; however, even these data show the great influence that the forecasting of the temperature profile has on the preparation of the forecast of pollution from high sources of high capacity.

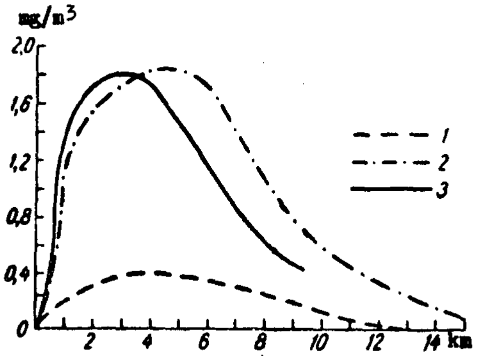

FIG. 5. Distribution of sulfur gas concentrations at various wind velocities. 1) 0-2 m/sec, 2) 3-6 m/sec, 3) 6 m/sec.

Fig. 5 gives an idea of the dependence of the surface concentrations on the wind velocity at a height of 2 m. The following gradations of wind velocity were used in the treatment of the data: 0-2.0; 3.0-6.0, and above 6.0 m/sec.

The curves of the graphs show that the minimum surface concentrations are observed at wind velocities up to 2 m/sec, and that there is no sharply defined maximum. The concentrations do not exceed the MPS and are one-fourth the value at a wind velocity of over 2 m/sec. As the wind velocity increases, there is a simultaneous increase of the surface concentrations of sulfur gas, reaching a maximum value of 1.8 mg/m^3 for the 3.0-6.0 m/sec gradation.

As the wind velocity increases further, the maximum changes little in absolute value, but it shifts in distance toward the source.

This is explained by the fact that at a wind velocity of 6 m/sec and higher, the effective height of ascent of the smoke plume is moderate and the plume is almost horizontal, and, as a result of turbulence, sulfur gas is rapidly transported into the ground layer in the vicinity of the source, where the maximum concentrations are observed.

The author examined the dependence of the surface concentration on the change of the turbulence coefficient, which was calculated from the formula of M. I. Budyko from data of gradient observation (3, 6)

$$k_1 = \frac{0{,}14 u_1}{\ln \frac{1}{z_0}} \left(1 + \frac{\Delta T}{u_1^2} \frac{\ln^2 \frac{1}{z_0}}{\ln \frac{z_3}{z_2}} \right),$$

where u_1 is the wind velocity at a height of 1 m, z_0 is the roughness of the underlying surface under equilibrium conditions, and z_3 and z_2 are the heights of observations of air temperature in the 0.5-2 m layer.

The data obtained for the turbulence coefficient were distributed into three gradations: 0-0.10, 0.11-0.20, and 0.21-0.3 m^2/sec.

Graphs similar to the preceding ones were plotted for these gradations. They show that the magnitude of the concentration in the lowest atmospheric layer depends substantially on the turbulence coefficient: the higher k_1, the lower the sulfur gas concentrations. If k_1 = 0.2-0.3 m^2/sec, maximum concentrations q_m = 1.5 mg/m^3 were noted, and the distance at which the concentrations exceed MPC ranged from 1 to 10 km; then at k_1 = 0.1-0.2 m^2/sec, q_m = 1.2 mg/m^3 and the distance was 1-5 km; and at k_1 = 0-0.1 m^2/sec., q_m = 0.5 mg/m^3 at a distance of about 2 kilometers from the source.

Thus, as the austausch coefficient increases, an increase of the surface concentrations is observed, and the distances at which concentrations above MPC can be found change considerably.

These data indicate the influence exerted by the turbulence coefficient on the dispersal of light contaminants in the atmosphere and on the magnitude of surface concentrations. The significant decrease of concentrations at low values of k_1 near the ground is explained by the fact that most of the dispersal of the contaminant takes place at a comparatively great height.

The low values of the turbulence coefficient under winter conditions can also explain the fact that lower concentrations than during other seasons are obtained in repeated samplings for sulfur gas in the zone of the smoke spread of the Shchekino SRPS near the ground.

Considering that for any latitudes in all seasons there is, in the lowest layer, a distinct manifestation of the daily and annual variation of the turbulence coefficient characterized by high values in the daytime hours and during warm periods of the year, the results obtained can be used for evaluating the influence of meteorological conditions on the contamination of the lowest atmospheric layer.

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SOME RESULTS OF SYNOPTIC-CLIMATOLOGICAL ANALYSIS OF AIR POLLUTION IN CITIES

L. R. Son'kin

From Trudy, Glavnaya Geofiz. Observat. im. A. I. Voeykova, No. 207, p. 56 64, (1968).

The problem of air pollution in cities sets before meteorologists a whole series of tasks, including those aimed at studying the influence of climatic factors on air contamination and its forecasting. It is well known that for the same discharges, the contamination of air in the lowest layer may vary considerably depending on the meteorological conditions. For this reason, in cities having discharges of approximately the same character but located in different climatic conditions, a substantially different degree of air contamination may arise. Knowledge of the nature of the influence of climatic conditions on the degree of contamination of city air is required for solving the problem of atmospheric purity. Such data must be taken into account in the planning and construction of new cities and industrial centers and also of new industrial plants in existing cities.

The forecasting of contamination is also of great significance in the efforts designed to maintain the purity of air. It is particularly necessary during periods of extensive contamination of air in cities, when the health of many thousands of people is jeopardized. In this case, effective measures to decrease the degree of contamination of the atmosphere should be taken in accordance with the forecast.

The solution of these two problems would not present any fundamental difficulties if the problem of influence of meteorological conditions on air contamination in cities was fully understood. At the present time, the process of air contamination by various sources under different meteorological conditions is understood in its general features (1, 2, 3). In an industrial city, the problem is complicated by the presence of a large amount of most diverse discharges: cold and hot, low and high, organized and disorganized. Random discharges frequently occur. The prolonged action of a large number of sources in a city leads to a qualitatively new effect in air contamination, i. e., the creation of a background concentration of contaminants (9, 12, 18). Among other phenomena connected with the characteristics of contamination of city air, a heat island and the creation of local air circulation directed toward the center of the city should be mentioned (17).

Along with a general complication of the problem, there arises the possibility of simplifying the analysis of the influence of meteorological conditions on the contamination of city air. In the city, the influence of various sources on the creation of the contaminant concentration in air is evened out. In this case it may be expected that fluctuations of the concentration of the contaminants will be determined more by the weather conditions than by changes in the discharges of the various industrial plants. Therefore, in the first approximation, the characteristics of contamination of air by various sources located in the city may be neglected, and the concentrations of contaminants at stationary points should be directly correlated with the meteorological characteristics. Such treatment sheds light on the extremely important problem of the influence of meteorological conditions on air contamination in real cities.

At a later stage, in order to solve the problem completely, it is necessary also to consider the character of the discharges of noxious contaminants in the city.

It has been pointed out in many studies that the most unsafe conditions for the contamination of city air are weak winds and the stability of the atmosphere. This has been utilized by American researchers as the basis for forecasting air contamination in cities (10, 11, 13, 15, etc.). It is known at the same time that in industrial cities there is a large amount of high, hot discharges; an unsafe contamination of the lowest layer of air in such discharges takes place essentially under opposite meteorological conditions (1, 2, 3). If one also considers the above-mentioned additional effects in the mechanism of contamination of city air, it becomes clear that the problem still requires a thorough study.

At the present time, data have been collected at the Main Geophysical Observatory on the contamination of air with noxious contaminants in many of the country's cities. This has been achieved largely thanks to units of the Sanitation and Epidemiology service, which have supplied us with observational data. At the same time, it has been possible to utilize the initial data obtained by the network of stations of the Hydro-meteorological Service.

However, analysis of this material involves major difficulties because of its heterogeneity and the lack of a definite system for conducting the observations. If one adds to this the considerable variability of the characteristic being studied plus constant changes in the amount of contaminants discharged, the difficulties of the analysis of individual cases becomes understandable. To elucidate the basic regularities, it is advisable to carry out a statistical treatment of the mass of data. Of particular importance in this regard is the synoptic-climatological analysis of data on air contamination in cities.

Annual Variation of Contamination of City Air

Data on the annual variation of air contamination in cities may be used in planning the operating conditions of industrial plants.

In addition, analysis of the annual variation of atmospheric contamination is of interest from a climatological point of view, since the annual variation of atmospheric contamination should be largely determined by seasonal characteristics of the development of meteorological processes.

The annual variation of air contamination in cities is determined by at least three factors: 1) change of the amount of discharges in the course of the year, 2) seasonal characteristics of the development of atmospheric processes, 3) nature of the discharges, i. e., relative proportions of high and low, cold, and overheated discharges. The second and third factors are interrelated, since, as was indicated above, the influence of meteorological conditions on the contamination of the atmosphere depends on the nature of the discharges. Analysis of factual data for the annual variation of air contamination makes it possible to identify the role of these factors to some extent.

In the first place, it was interesting to determine whether a heavier contamination of the city atmosphere takes place during the warm or cold half of the year. The periods, April-September and October-March, were taken as the warm and cold halves of the year, respectively. Such data for certain ingredients and in different cities were plotted on maps, one of which (for dust) is shown in Fig. 1.

It is apparent from the figure that with some exceptions, in all regions of the country, the heaviest contamination of the city atmosphere with dust is observed during the warm half of the year.

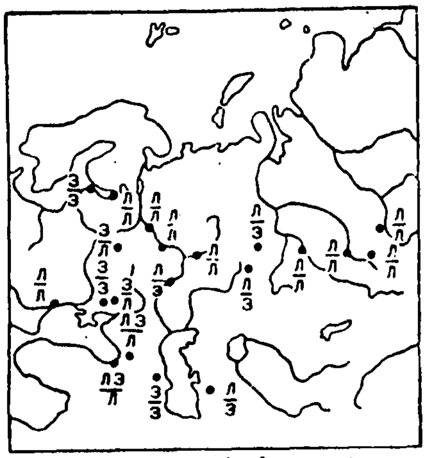

Fig. 1. Characteristics of atmospheric contamination with dust in the course of a year.

Russian	English
" Л "	" S "
" З "	" W "

S (summer) - high dust content during warm period as compared to cold period, W (winter) - dust content during cold period as compared to warm period according to data on frequency of concentrations above MPC (in the numerator) and maximum concentrations (in the denominator).

No such clear-cut relationship was found for other contaminants. However, it may be positively stated that the existing point of view of a winter maximum of air contamination due to maximum fuel combustion is not confirmed in many cases. This may be due to the influence of climatic conditions on atmospheric contamination.

The analysis showed the presence of common features in the characteristics of the annual variation of contamination of air by various noxious impurities in cities located in certain geographical regions. Several regions with approximately the same characteristics of annual variation have been shown to exist on the territory of the Soviet Union (Fig. 2). It was found that above most of the European part of the Soviet Union, two maxima in the annual variation of air contamination are observed during the intermediate seasons, the values of the spring maximum being in most cases higher than those of the fall maximum. On the territory of Western Siberia, Kazakhstan, and part of Central Asia, a summer maximum of air contamination was observed, and a winter maximum was noted in Eastern Siberia. In the southernmost regions of the country there is a tendency for a maximum air contamination to arise in the annual variation both during the intermediate seasons and in winter.

The above-mentioned characteristics of the annual variation of air contamination on the territory of the USSR are linked in their general features with the nature of the atmospheric processes. In Eastern Siberia, the winter maximum of air contamination is related to the existence of the Siberian anticyclone during that time of the year. The emergence of developed winter cyclones periodically removes contaminants from cities of the European territory of the USSR (ETU). Figure 3 shows the annual variation of the number od days per month with anticyclonic circulation above the ETU (region 4, after L. A. Vitel's), based on data for 1961-64 (4), where two anticyclonicity maxima appear during the intermediate seasons with greater values of the spring maximum, which generally correspond to the annual variation of air contamination.

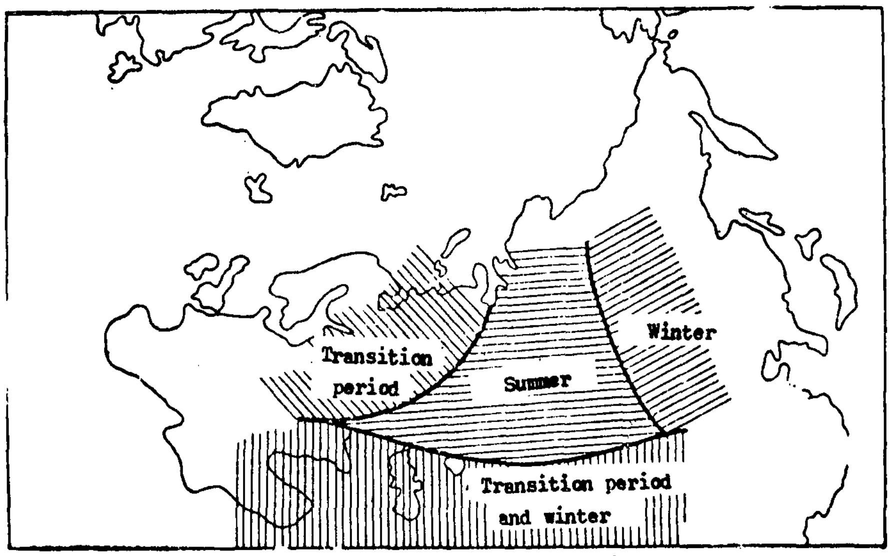

Fig. 2. Geographical distribution of characteristics of annual variation of air contamination indicating seasons during which the maximum air contamination is observed in the annual variation.

The summer maximum of contaminant concentrations of air in cities of Western Siberia and Kazakhstan is apparently connected with the high turbulent austausch in these regions, resulting in a considerable contamination of air by high discharges of large-capacity industrial plants.

Thus, despite considerable changes in the amount of discharges in the course of the year, analysis of the massive material has shown the presence of a relationship between the contamination of the atmosphere and the frequency of anticyclonic fields in the annual variation.

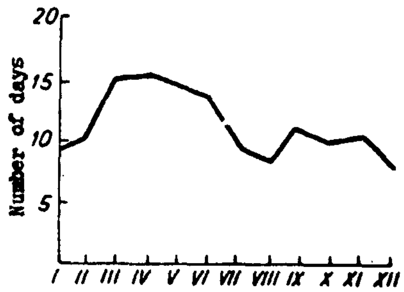

Fig. 3. Annual variation of the number of days with anticyclonic circulation above the center and north of ETU.

Synoptic Conditionality of Air Contamination in Cities

Analysis of the synoptic conditionality of air contamination is of great interest because in principle, the synoptic situation reflects the entire variety of processes occurring in the atmosphere. Weather maps of the northern hemisphere have been published (7), and therefore the synoptic analysis of air contamination of any city does not require any additional selection of material.

On the other hand, an objective physical evaluation of situations in the presence of their appreciable variability presents major difficulties. For this reason, at this stage of the investigation it is inadvisable to consider the relationship between air contamination and daily meteorological situations. The synoptic conditionality of air contamination manifests itself in two ways:

1. From data of all stationary points of the city, days with the most contaminated and relatively pure air are selected, and the synoptic situations which are then observed are examined. Also examined are the synoptic situations observed for the maximum values of the contaminant concentration (for a month, a season, etc.).

2. Clearly defined and long-lasting (no less than 3 days) synoptic situations are selected and the associated air contamination is described.

Thus, in order to find the functions being sought, the extreme, most clearly manifested cases of air contamination and corresponding synoptic situations are subjected to analysis. This method is being widely and successfully employed in synoptic-climatological investigations (6, etc.).

As in earlier research (8, etc.), the following synoptic situations were selected: anticyclone -- ac, cyclone -- C, intermediate field -- I, low-gradient field -- L. The most diversified situation is I, which includes cases where transfer of air between cyclonic and anticyclonic formations was observed above the region under consideration. Consequently, it is necessary to subdivide the given situation further. This was done as a function of the direction of the transfer. In a more detailed analysis, situation I may also be subdivided as a function of the curvature of the isobars in the following manner: I -- for rectilinear isobars, IAC -- for anticyclonic curvature of isobars, IC -- for their cyclonic curvature. This subdivision is used in the present paper. It was also found desirable among cyclonic situations to select the situation of a weak cyclone -- C_W, since for a weak cyclone the conditions of air contamination differ substantially from those in a developed cyclone.

Analysis of these observations showed that periods of time occur when at most or even all stationary points of the city a consistent growth of contaminant concentration is observed. This phenomenon is also known from the literature, and manifests itself most distinctly in smogs (9, 12, etc.). In many cases, all these stationary points of the city were also found to register low contaminant concentrations. This supports the point of view of the establishment of a background concentration in the city.

To analyze the synoptic conditionality of the contamination of city air, use was made of relatively complete data of observations in one of the industrial cities of the Urals. Daily samples of air for the analysis of dust and sulfur gas were taken almost every day at three stationary points. It is obvious that for this investigation, daily values of the contaminant concentration with averaging of their random fluctuations have a distinct advantage over single values. Observations for the 1961-1964 period were examined. Relatively strict criteria were set for the selection of days with contaminated and those with clean air. Days with contaminated air corresponded to cases where more than half of the observations per day showed concentrations above MPC, and days with clean air corresponded to cases where all the samples showed concentrations of no more than ½ MPC. It was required that no fewer than four daily samples out of six be taken during a day (at three points for dust and sulfur gas). When the indicated points were used, of the total number of days with data on air contamination, 243 days were taken with contaminated air and 134 days with clean air, and also the synoptic situations in which these cases were observed were analyzed. The frequency of the synoptic situations in each of the two groups of days was calculated separately for the cold and hot half-years (Table 1). In the case under consideration, depending upon the direction of the transport, it was found convenient to analyze two situations with an intermediate field: one of them includes cases of transport of air from north and east; and the other, from west and south. This subdivision was made in accordance with the relative positions of the main industrial plants and stationary points.

Table 1

Frequency (%) of Synoptic Situations on Days with Clean and Contaminated Air

Half-year	Days	Synoptic Situations					
		AC	$I_{n,e}$	$I_{s,w}$	C	C_w	L
Cold	With pure air	9	3	69	15	2	2
	With contaminated air	54	23	9	2	3	9
	With absolute maximum per month	42	27	11	6	6	8
Warm	With pure air	0	3	55	28	4	10
	With contaminated air	38	27	7	2	7	19
	With absolute maximum per month	22	27	15	2	10	24

Notation of synoptic situations: AC - anticyclone, $I_{n,e}$ - intermediate field with northern and eastern transport of air, $I_{s,w}$ - intermediate field with southern and western transport of air, C - cyclone, C_w weak cyclone, L - low gradient field.

Analysis of the table shows that substantially different synoptic situations are observed on days with clean and on those with contaminated air. On days with contaminated air, chiefly anticyclones are observed, and also situations $I_{n,e}$, and on days with clean air -- situations $I_{s,w}$ and cyclones. The nature of the relationship under consideration is clearly manifested when one compares the frequency of the different situations on days with the opposite state of air contamination. Situations $I_{s,w}$ and C are observed much more frequently on days with clean air than situations AC on days with contaminated air; $I_{n,e}$ and L -- vice versa. It is characteristic that in the presence of a weak cyclone (associated with weak winds, the lack of precipitation, growth of pressure), days with contaminated air are observed more frequently than those with clean air.

A more detailed analysis of data on air contamination in intermediate fields showed that, other things being equal, a greater air contamination is associated with the anticyclonic bend of isobars (IAC) and a lesser air contamination is associated with the cyclonic bend (IC) than with rectilinear isobars (I).

Table 1 also lists data on the frequency of synoptic situations on days with absolute maximum values of the contaminant concentration per month. For each month, two values were considered, for dust and for sulfur gas. As is evident from Table 1, at the maximum contaminant concentrations, the same synoptic situations prevailed as in cases of general contamination of city air. This conclusion means that the same causes are usually attributed to the absolute maximum concentrations of contaminants at individual points and to the air contamination above the entire city. It is characteristic that in 71% of the cases, the maximum monthly concentrations of contaminants coincide with periods of general contamination of the air above the city.

Periods of prolonged presence of clearly defined synoptic situations were then selected, and the frequency of concentrations above MPC during these periods was analyzed. It was found that the results of the computations could be illustrated graphically (Fig. 4), although not rigorously, since the situations cannot be expressed quantitatively. However, the situations can be arranged according to the indicator of their similarity by starting with a stationary anticyclone and ending with a developed cyclone. Intermediate fields with the cyclonic bend of the isobars are not included in the graph because of the small number of cases of their stable existence. In Fig. 4 it is apparent that the highest dust content during the cold as well as the warm half of the year is observed in stationary anticyclones (SAC). Contamination of air by sulfur gas in anticyclones is also substantial, but the highest frequency of concentration above MPC takes place in this case in the presence of intermediate fields with a northern and eastern transport ($I_{n,e}$ and $IAC_{n,e}$). The lowest air contamination was found in developed cyclones and in intermediate fields with western and southern transport.

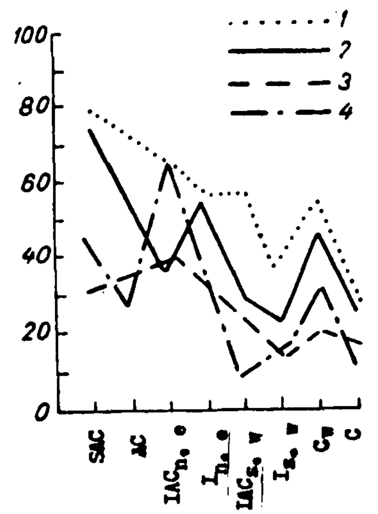

Fig. 4. Frequency of concentration above MPC for stable synoptic situations.

1 - dust in summer, 2 - dust in winter, 3 - sulfur gas in summer, 4 - sulfur gas in winter.

In general, a tendency was shown toward a decrease of contamination from $IAC_{m,e}$ to $I_{n,e}$ and from $IAC_{s,w}$ to $I_{s,w}$ (see Fig. 4). A secondary maximum of air contamination for weak cyclones which showed up consistently on all four curves was characteristic. It should be noted that an examination of data on the contamination of the air of other cities also showed the presence of cases of heavy contamination in cyclonic fields. Apparently, the purification of air in cyclones is chiefly due to precipitation and strong winds. In the absence of these phenomena (in weak cyclones, in diffuse cyclonic fields), cyclones are more unsafe for air contamination than intermediate fields. This may be termed the secondary effect of air contamination in cyclones.

Thus, the analysis of synoptic situations for extreme values of contaminant concentrations in air and the characteristics of air contamination in clearly defined synoptic situations have led to consistent results.

The data given in the present paper indicate the same synoptic conditioning of air contamination in cities during winter and summer. This means that a great influence on the degree of air contamination is exerted by those characteristics of synoptic processes which are the same in the course of the entire year. For stationary anticyclones, which are associated with the heaviest air contamination, the following signs are common to all seasons: weak winds and absence of directed transport in the bottom layer, 3-5 km thick, absence of precipitation, downward motions, inversion of compression at a height of 1-2 km. It is evident that the main cause of the substantial air contamination in industrial cities is the absence of horizontal outflow of contaminants. The accumulation of a large amount of contaminants above a city in an unsteady process leads to a considerable contamination of air in the lowest layer. This is promoted by downward motions and by inversion at a height of 1-2 km, which hinder vertical mixing.

The relationship between monthly characteristics of air contamination (frequency of concentrations above MPC in specific months) and monthly pressure anomalies was analyzed. Fig. 5 shows the corresponding correlation graph, where a direct relationship is observed between air contamination and monthly pressure anomalies (Δ P). The coefficient of linear correlation $r = 0.54 \pm 0.12$. The

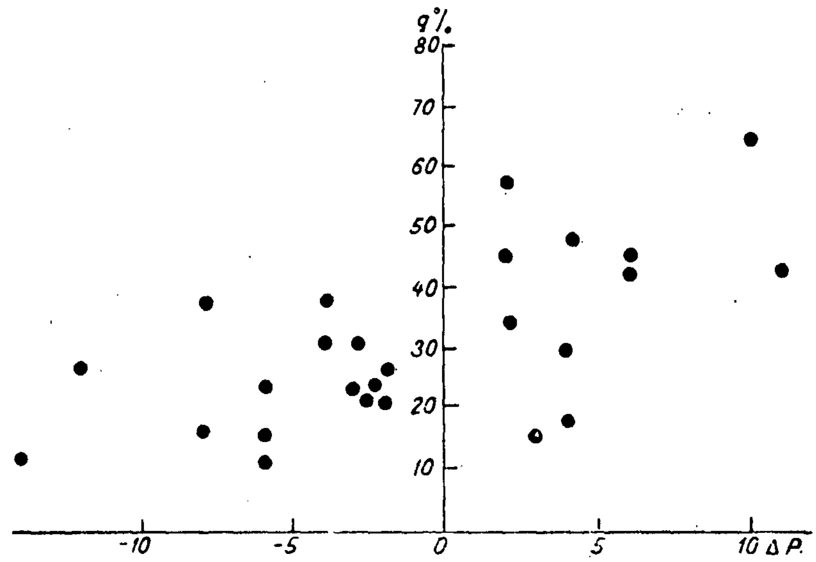

Fig. 5. Frequency of contaminant concentrations above MPC in the course of a month as a function of monthly pressure anomalies.

same correlation coefficients were calculated for two cities at the center of the ETU. They were also found to be positive, but with a lesser closeness of the relationship ($r = 0.49$ and 0.21). Here, relatively clean air is almost always observed at negative values of Δ P. Months with contaminated air are associated in most cases with high positive values of Δ P. Of the 15 months with high values of the frequency of concentrations above MPC, 11 occurred at $\Delta P > 2$ mb. However, the remaining four months were observed at considerable negative ΔP values (-2, -1, -4, -7 mb). This may be due to the secondary effect of air contamination in cyclonic fields.

The results obtained shed some light on the problem of influence of meteorological conditions on air contamination in cities. Further development of this research will give a more detailed picture of the mechanism of the process considered, and will make it possible to arrive at some practical recommendations for taking meteorological conditions into account in efforts aimed at achieving purity of the atmosphere.

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PROCESSING AND ANALYSIS OF OBSERVATIONS

OF AIR POLLUTION IN CITIES

L. R. Son'kin and D. V. Chalikov

From Trudy, Glavnaya Geofiz. Observat. im. A. I. Voeykova, No. 207, p. 51-55, (1968).

The analysis of observations of the concentration of noxious contaminants in cities may be useful for determining the influence of meteorological conditions on the contamination of city air and for understanding the physical mechanism of this phenomenon. In this connection, research of this type was recently begun at the Main Geophysical Observatory. The present paper gives results of an analysis of data on the air contamination of the cities of Moscow and Leningrad in 1961-1964, based on observations of sanitation and epidemiology stations. The meteorological characteristics were obtained from observations of hydrometeorological stations. In all, use was made of about 7,000 observations of the concentration of dust and sulfur gas in air, of which about 2,000 pertain to Leningrad and about 5,000 to Moscow.

A special program was set up on the "Ural-4" computer for processing the data. A large quantity of different variants were checked during a relatively short time because of the rapid action of the computer.

The most suitable method for establishing the statistical relationships between contamination and the determining meteorological factors is multiple-correlation type statistical analysis. However, such analysis is ineffective for a large number of predictors. Therefore, it is necessary to carry out preliminary research on the selection of the main determining factors that are responsible for most of the dispersion of the concentration of contaminating ingredients.

To this end, a program for the "Ural-4" computer was written, which made it possible to calculate the frequency of ingredient concentrations above a certain value, and also the average ingredient concentrations for arbitrary conditions of the meteorological parameters. A large quantity of the material introduced into the computer required the use of an external memory, i. e., two magnetic drums with a total capacity of about 64,00 entries. The calculation of a single variant required 3-4 minutes of computer time.

The difficulties of the analysis of observations of contaminant concentrations in air lay in their great disconnectedness and inhomogeneity. Nevertheless, some results of the calculations are of definite interest. In principle, a meteorological analysis of the observations of air contamination would be desirable at each point, consideration being given to the nature of the contamination. However, in the present paper, because of the inadequate quantity and quality of the material, principal attention has been given to the meteorological analysis of all the data of the observations, independently of the part of the city where they were made. A combined analysis was performed for observations carried out at 13 stationary points of the city of Leningrad and also 7 stationary points of the city of Moscow, and an attempt was made to find some of the most general relationships between the meteorological characteristics and the air contamination in cities. Curves giving the distribution of the frequency of the dust and sulfur gas concentration for Moscow and Leningrad were obtained first (Fig. 1). It is evident from the figure, for example, that the frequency of contaminant concentration above the maximum permissible value (MPC) of 0.5 mg/m^3 is 8% for dust and 10% for sulfur gas in Moscow; in Leningrad, 18% for dust and 19% for sulfur gas; above 1.0 mg/m^3 (2 MPC), respectively 2, 3, 4, and 5%.

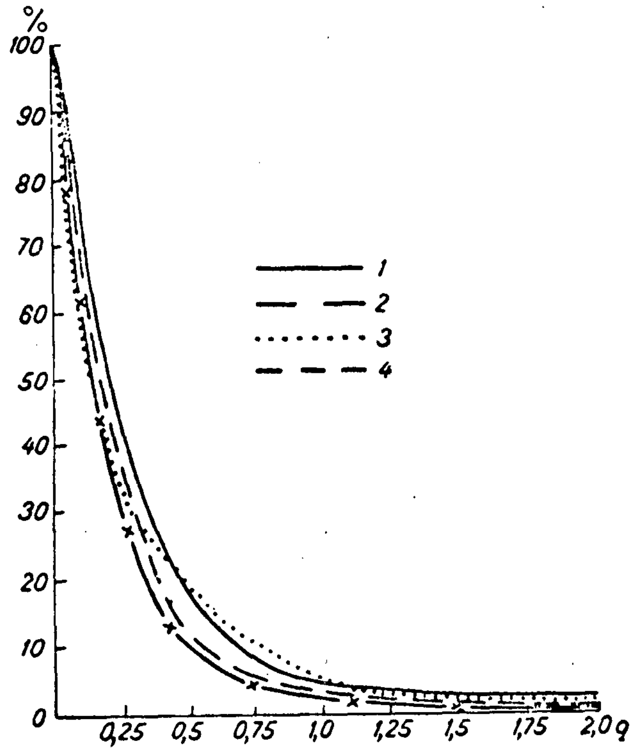

FIG. 1 Curves of distribution of frequency of contaminant concentrations above MPC.

1 - dust in Leningrad, 2 - dust in Moscow, 3 - sulfur gas in Leningrad, 4 - sulfur gas in Moscow

A calculation of the annual variation of the contaminant concentration in Leningrad and Moscow showed a tendency toward a high contamination of air during spring and fall. An explanation of possible reasons for this annual variation is given in other papers (2, etc.). It is essential to note the parallel annual variation of two characteristics of air contamination, which were considered: the frequency of the concentration above MPC (g), % and average concentration values, mg/m^3.

The weak relationship between the concentration of contaminants in air and the direction of the wind in Leningrad was noted earlier. In Moscow, a different picture is observed in this respect; the relationship between air contamination and the wind direction in the region of the individual stationary points was found to be rather close. The difference of g for different wind directions exceeds 20%, and of q_{av}, 0.3 mg/m^3.

Analysis of the change of the concentration of contaminants as a function of wind velocity, based on data for both Leningrad and Moscow (Fig. 2), generally confirmed the effect noted earlier (2); the first miximum is observed during calm owing to low discharges and to the background concentration; and the second, at a wind velocity of 4-6 m/sec, apparently owing to high discharges. A whole series of calculations was made in the analysis of the indicated relationship. The dependence of air contamination on the wind velocity was analyzed during various seasons and also with the stipulation that at the time of the sampling and during the preceding 5 hours there had been no precipitation, which, obviously, would remove the contaminants from the air. In summer, the second maximum (at a velocity of 5-6 m/sec) is more pronounced than the first; whereas in winter, the first maximum is more predominant. According to data on sulfur gas, as compared to dust, the second maximum is more pronounced and the first maximum, less. If one eliminates cases with precipitation during the preceding 5 hours ($\Upsilon > 5$ hours), these relationships are more distinct (Fig. 2).

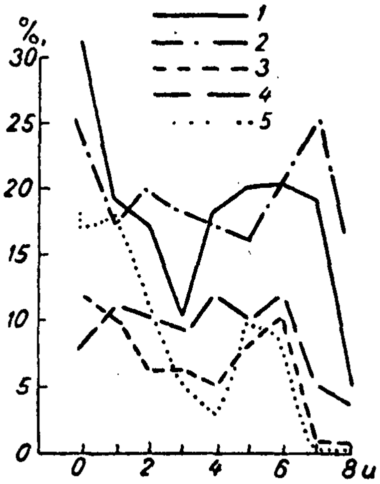

FIG. 2 Frequency of contaminant concentrations above PMC (g) in percent as a function of wind velocity.

1 - dust in Leningrad, 2, sulfur gas in Leningrad, 3 - dust in Moscow, 4 - sulfur gas in Moscow, 5 - dust in Moscow in winter during time interval between end of precipitation and start of sampling - $\Upsilon > 5$ hours.

The effect of removal of dust and sulfur gas from air by precipitation has been noted in a number of studies (1, 3, 6, etc.). In the present paper and in an earlier study (2), consideration is given to the dependence of air contamination on the time between the end of precipitation and the start of sampling (Υ).

Some results of the calculations are given in Table 1.

It is apparent from the table that in Leningrad, several hours after the end of precipitation, the air is much cleaner than average. The manifestation of this effect in Leningrad is shown more convincingly in ref. (2). In Moscow such a phenomenon is also observed, but it is les manifest, particularly on the basis of data on the dust concentration in the air. Thus, the level of air contamination in Moscow is restored faster after precipitation, when compared with Leningrad. This conclusion, and also earlier calculations of the characteristics of air contamination as a function of the wind direction permit one to postulate differences in the nature of the phenomenon in Moscow and Leningrad. In Leningrad, a comparatively high background contamination of the atmosphere above the city takes place. For this reason, the dependence of the contaminant concentration on the wind velocity is not clearly manifested, and for several hours after the precipitation the air is substantially cleaner than average. In Moscow, the background contamination of air is apparently slight. Various sources of contamination operate against a background of a relatively clean atmosphere. If, as was done by M. Wetherley (8), the concentration of contaminant in the city is divided into local and background concentrations, it will be noted that the contribution of the local factor is considerable in Moscow. That is why a close relationship was found in this case between the concentration of contaminants and the wind direction. It is also evident that the contamination of air by specific sources is relatively independent of past precipitation.

Table 1

Contamination of city air as a function of time between end of precipitation and start of sampling (τ).

City	Intervals of values hours	Dust		Sulfur gas	
		g%	qav. mg/m^3	g%	qav. mg/m^3
Moscow	≤5	9	0,25	16	0,29
	>5	20	0,34	21	0,32
Leningrad	≤5	8	0,20	9	0,20
	>5	8	0,25	13	0,32

A whole series of variants taking into consideration the contamination of air as a function of various meteorological characteristics was checked by means of a "Ural-4" computer. Part of the computations did not yield any results. This applies primarily to aerological characteristics of the atmosphere. The above appears to be closely related to the great complexity of the mechanism of air contamination in cities, with different influences of meteorological conditions on the formation of contaminant concentrations in the lowest layer of air from various sources and with certain other causes.

According to the data of observations made in Leningrad, it was possible to analyze the characteristics of air contamination as a function of the austausch coefficient at the level of 1 m-k_1. The values of k_1 were calculated from gradient observations of the Koltushi station. All the cases were subdivided into two groups according to the values of k_1, and the results are given in Table 2.

Table 2

Contamination of air in Leningrad as a function of k_1.

k_1 m^2/sec	Dust		Sulfur gas	
	g%	qav. mg/m^3	g%	qav. mg/m^3
≤0,20	16	0,31	19	0,30
>0,20	25	0,43	21	0,34

From Table 2 it is apparent that at high k_1 values in the Leningrad region, air contamination is high in the city.

In the first variant, data on synoptic situations were put on punched cards. Preliminary computations confirmed the hypothesis, known from the literature, on the high contamination of air in anticyclones (2). However, later it was found that a synoptic analysis of data on the contaminant concentration does not always produce a sufficient effect. In view of the marked variability of the synoptic location, in many cases the recorded synoptic situation may contain no information on the actual processes occurring in the atmosphere. In this connection, clearly manifested synoptic situations that have existed for a long time are of greatest interest. In the first place, it was found of interest to examine the contamination of air in stationary anticyclones, which are linked with the most unsafe conditions (4, 5, 9).

In Table 3, these data, expressed in deviations from average values, are given for Leningrad and Moscow. Results of the computations are represented separately for the cold and warm parts of the city.

Table 3

Deviation from Average Frequency of Contaminant Concentration MPC in Stationary Anticyclones (%).

City	Dust		Sulfur gas	
	cold period	warm period	cold period	warm period
Moscow	+7	+1	+18	—2
Leningrad . . .	+21	+13	+13	—1

It is apparent from the table that during the cold part of the year, the contamination of air in stationary anticyclones is substantially higher than average. During the warm part of the year, this effect manifests itself only for dust, in Leningrad, and does not manifest itself at all in Moscow. In order to check how real this dependence is, the frequency of contaminant concentrations above MPC in stationary anticyclones in Sverdlovsk and Magnitogorsk was examined. The air contamination in these cities in stationary anticyclones was also found to be much higher than average in summer. The impression is created that in summer, high contaminant concentrations in stationary anticyclones are characteristic of cities with a rapid industrial development, where the process involved in the contamination of air occupies a considerable layer of air. In relatively clean cities, the establishment of a stationary anticyclone in summer does not result in high contaminant concentrations.

During the cold part of the year, a high contamination of city air in stationary anticyclones is apparently a general rule.

In conclusion, it may be noted that the initial results indicate the advisability of continuing this work, using a large quantity of observations of the concentration of contaminants in many cities of the country. When sufficient material becomes available, analysis of observations at individual stationary points, taking into account the character of air contamination, will be of great interest.

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THE THEORY OF ATMOSPHERIC DIFFUSION UNDER FOG CONDITIONS

M. E. Berlyand, R. I. Onikul and G. V Ryabova

From Trudy, Glavnaya Geofiz. Observat. im. A. I. Voeykova, No. 207, p. 3-13, (1968).

An effective protection of an air reservoir from contamination with harmful industrial waste requires the development of studies of the mechanisms of atmospheric diffusion in various weather situations. Of particular importance are studies of "hazardous" weather conditions, when high concentrations of contaminant can be observed in the ground layer of air. Consideration of these mechanisms in the design and operation of industrial plants permits a standardization of the industrial waste for the purpose of avoiding intolerable concentrations of noxious substances in the atmosphere, even in the presence of an unfavorable combination of the meteorological factors determining the distribution of contaminants.

Analysis of cases of heavy air contamination shows that some of them correspond to periods of lasting fogs. The harmful effect of smoke and gas contaminants associated with fogs is observed more distinctly than under other weather conditions, their unpleasant presence is felt more keenly, and the presence of contaminants in fogs causes an additional decrease of visibility, etc. The opposite effect is also noted, i. e., the presence of smoke promotes the condensation of atmospheric moisture. Thus, a mutually reinforcing effect of smokes and fogs takes place. A special term, "smog," made up of the beginning and end of the two words smoke and fog, has come into widespread use for describing the smoke-fog condition. The presence of fogs and their variety, smogs, is held responsible for many periods of high morbidity and mortality rates in many cities and industrial areas of Great Britain, the U.S.A., Belgium, and other countries.

Nevertheless, the conditions of air contamination associated with fogs and the nature of the direct action of fogs on the diffusion of impurities have been little studied. The available experimental data have been very scarce, and inadequately classified and analyzed. This is due in part to the difficulty of sampling for the purpose of comparing cases with and without fogs, other similar weather conditions being the same. The influence of fogs on the content of contaminants in air is very complex in character. On the one hand, fogs are frequently associated with specific conditions of distribution of weather constituents promoting an increase in the concentration of contaminants near the ground. Some theoretical estimates in this area, made by F. A. Gisina (9), pertain chiefly to the evaluation of the contamination of the ground layer of air under certain conditions of distribution of the intensity of the vertical component of turbulent austausch. On the other hand, in the presence of fogs, the qualitative composition of atmospheric impurities and the toxic nature of their interaction change. They are partially absorbed by droplets of water, thus occasionally causing the formation of new substances, while the concentration of contaminant in air decreases. The nature of the interaction of gases and certain aerosols, especially hygroscopic ones, varies. On hygroscopic particles, the condensation of moisture and formation of fog may start at a relative humidity below 100%; the microphysical characteristics of a fog are affected by the quantity and properties of the condensation nuclei. The deposition of moisture on aerosols increases their size and the rate of gravitational displacement toward the earth's surface.

Considering the complexity of the processes taking place, it becomes particularly important to develop the theoretical aspects of atmospheric contamination in the presence of fogs, using computers for the calculations. It then becomes necessary to consider as fully and rigorously as possible such characteristics as the size of the zone occupied by the fog, the water content, the temperature stratification, etc. Since experimental data on these characteristics are scarce at the present time, for some types of fogs it is desirable to make use of completed theoretical studies. This paper presents evaluations, obtained in this manner, of the influence of river fogs (the theory of which has been developed in ref. [6, 7, 11]) on the propagation of gaseous contaminants.

The study of the diffusion of contaminants in the presence of river fogs is of special interest. River fogs forming in winter in the valleys of nonfreezing rivers, for example Angara River in the region of the major industrial city of Irkutsk, not only cause substantial and lasting impairments of visibility, which interfere with flights along many important air routes, but may also promote air contamination. The paper also discusses certain characteristics of the diffusion of a contaminant in the presence of radiation fogs.

A steady process of turbulent diffusion of a gaseous contaminant under fog conditions is approximately described by the following differential equation:

$$u \frac{\partial q}{\partial x} = \frac{\partial}{\partial z} k_z \frac{\partial q}{\partial z} + \frac{\partial}{\partial y} k_y \frac{\partial q}{\partial y} - \alpha q. \qquad (1)$$

Here axis x is directed along the mean wind, axis y is perpendicular to it in the horizontal plane, axis z is directed vertically upward, q is the concentration of contaminant at a comparatively large distance from the fog droplets, u is the wind velocity, k_z and k_y are respectively the vertical and horizontal components of the coefficient of turbulent austausch, and a characterizes the relative degree of absorption of the contaminant by water droplets of the fog.

The influence of the fog is determined by the last term on the right side of equation (1), which characterizes the outflow of the contaminant as a result of its absorption by the fog droplets. This component should play no part outside the fog, i.e., coefficient a is equal to zero outside the fog.

The boundary conditions in the given problem are formulated as in the general case of propagation of the contaminant from high-altitude sources at x = 0

$$q = \frac{Q}{u} \delta (z - H) \delta (y), \qquad (2)$$

where H is the height of the source, Q is the power of the source, and δ (y) is the delta function.

On the underlying surface, the boundary conditions differ, depending on its character.

In considering river fogs on the water surface it is assumed at at $z = 0$

$$q = 0, \tag{3^a}$$

and on the surface of dry land at $z = 0$

$$k_z \frac{\partial q}{\partial z} = 0. \tag{3^b}$$

In the case of radiation fogs, boundary condition (3^b) is also employed.

It is also assumed that at a sufficiently large distance from the source, concentration q tends to zero.

The last term of equation (1), describing the outflow of the contaminant in the fog, may be expressed by the formula

$$\alpha q = \int_0^\infty P(r) N(r) dr, \tag{4}$$

where P(r) is the amount of contaminant absrobed by a fog droplet of radius r per unit time, and N(r) is the size distribution function of the droplets. The quantity P(r) is usually determined by studying the interaction of the contaminant with the fog droplets. These points are discussed in the survey of A. G. Zimin (10) and other sources.

In the immediate vicinity of the droplet surface, a boundary layer is created in which the contaminant concentration (it will be designated c) is less than q, since on the surface of the water droplet, c is equal to zero as a result of absorption of the contaminant.

In the steady state, the distribution of concentration c may be determined approximately, as was done, for example, by A. G. Zimin (10), by solving the equation of molecular diffusion in spherical coordinates.

$$\frac{\partial}{\partial \rho} \rho^2 \frac{\partial c}{\partial \rho} = 0, \tag{A}$$

where ρ is the radius vector; using as the boundary conditions the equality $c = 0$ on the surface of the droplet (at $\rho = r$) and $c \to q$ at a sufficient distance from the droplet (when $\rho \to \infty$). This solution is of the form $c \to q\ (1 - \frac{r}{\rho})$, whence we immediately find the flow of contaminant toward the surface of the droplet

$$P(r) = -\nu \frac{\partial c}{\partial \rho}\Big|_{\rho=r} 4\pi r^2 = 4\pi \nu q r, \tag{5}$$

where ν is the coefficient of molecular diffusion of the contaminant in air.

The size distribution function of the fog droplets may, according to A. Kh. Khrgian and I. P. Mazin (13), be approximated by the following relation

$$N(r) = ar^2 e^{-br}, \tag{6}$$

$$a = \frac{\left(\frac{5}{2}\right)^6 \Delta}{\pi \rho_k r_m^6}; \quad b = \frac{5}{r_m}.$$

where Δ is the water content of the fog; r_m is the radius of the drops corresponding to the maximum of the distribution functions; $\rho_k = 1\ g/cm^3$ is the density of water.

Substituting (5) and (6) into (4) and integrating, we get

$$\alpha = 0{,}6\nu \frac{\Delta}{\rho_k r_m^2}. \tag{7}$$

From the formula obtained it follows that the absorption of the contaminant by fog droplets, other things being equal, increases with rising water content of the fog Δ or with decreasing drop size r_m.

Thus, the problem consists in solving equation (1) for boundary conditions (2) and (3), taking expressing (7) for a into consideration. In general, the coefficients of the original equation are complex functions of the coordinates; this applies primarily to the vertical coordinate z. In the case of a river fog, the dependence of k_z on the horizontal coordinate x assumes a considerable importance. At different distances from the winward bank, there are substantial differences in the values of the water content of the fog Δ and in its vertical distribution a, and hence in coefficient a. The vertical temperature gradients change markedly with the distance x, giving rise to a complex field of the vertical components of the austausch coefficient. The change in the values of these quantities was studied in ref. (6,7).

In the present paper, the solution of the formulated problem was carried out on the basis of numerical methods developed earlier in ref. (2-6) for transport processes in the boundary layer of the atmosphere. The use of the relation proposed by M. E. Berlyand for the proportionality of the horizontal component of the austausch coefficient and wind velocity $k_y = k_0 u$ (1) made it possible to carry out the substitution of variables

$$q = q' \frac{e^{-\frac{y^2}{4k_0 x}}}{2\sqrt{\pi k_0 x}} \tag{8}$$

and reduce the three-dimensional system of equations and boundary conditions (1)-(3) to a two-dimensional system analogous to the system describing the distribution of a contaminant from a linear source. The value of s, proportional to concentration q on the axis of a smoke plume standardized for the source emission rate, was calculated on a "Ural-4" computer on the basis of differential factoring:

$$s = \frac{2\sqrt{\pi k_0}}{Q} 10^{12} q \,|_{y=0}. \tag{9}$$

The wind velocity was assumed to increase as the log of the height

$$u = u_1 \frac{\ln \frac{z}{z_0}}{\ln \frac{z_1}{z_0}}, \tag{B}$$

where u_1 is the wind velocity at height z_1, and z_o is the roughness of the underlying surface.

On the basis of the numerical solution, some characteristics of the diffusion of the contaminant in the presence of river fogs and radiation fogs were investigated.

In the study of contaminant diffusion in the presence of river fogs, use was made of the distribution of fog moisture content above the river and the bank necessary for calculating coefficient a; this distribution was calculated theoretically by using the method given in ref. (7). Results of a theoretical evaluation of the intensity of vertical turbulent austausch above the river were also used.

As an example, Fig. 1 shows the results of a calculation of the austausch coefficient above the river and fog water content, corresponding to the following initial assumptions: width of river 700 m, temperature of water surface 0°, temperature and relative humidity in the equilibrium-stratified stream of air flowing over the river, -20° and 90% respectively, wind velocity at a height of 1 m, 0.5 m/sec. The left side of Fig. 1a shows the profile of the austausch coefficient k^o on the windward bank, and on the right side, isolines have been plotted for the ratio of the austausch coefficient above the river k' to the austausch coefficient k^o at the same height. It is evident from this figure that the austausch coefficient above the river increases substantially in some boundary layer. Isolines of the fog water content Δ g/m^3, characterizing the change of the height and fog water content in space, have been plotted in plane zox of Fig. 1 b.

The calculations were made for different source heights and under different weather conditions, including both the presence and absence of fog. The effect of contaminant absorption by the fog droplets was evaluated from the difference in the distribution of contaminant concentrations in these cases. In addition, to analyze the part played by the main operating factors, the influence of some of these factors was artificially excluded in the calculations. Thus, for example, the effect of reinforcement of turbulent austausch above the river, absorption of contaminant by the water surface of the river, etc., were excluded.

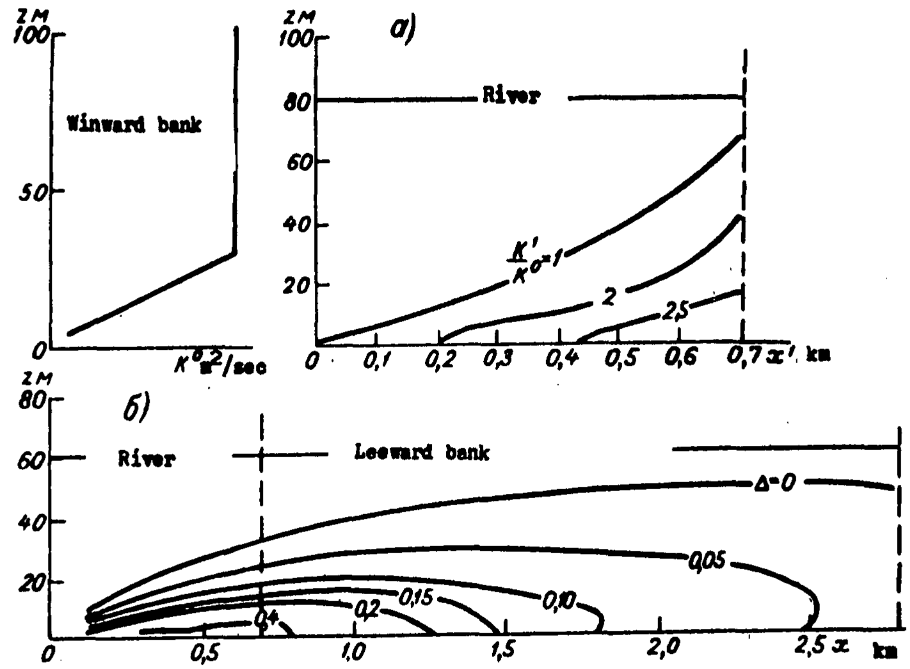

Fig. 1.

The calculations showed that river fog conditions are characterized by the absorption of a considerable portion of the contaminant by fog droplets above the river and near the bank, where the highest values of the fog water content were observed; almost no contaminant in the gaseous state is left at any height in the fog layer, and this effect decreases on the windward bank with increasing distance from the river and decreasing water content. It is also noted that in this case, when the source of contaminant is located above the fog layer, a decrease of concentration is observed not only inside the fog, but also above it. This may be due to the fact that because of the heavy absorption of the contaminant by the fog droplets in the bottom layers, the intensity of the diffusion flow of the contaminant, directed downward, is enhanced.

As an example, Table 1 gives results of a calculation of the concentrations of gaseous contaminant from a source 80 m high, located on the windward bank 1 km from the river, for river fog conditions, for which the distribution of water content and austausch coefficient are shown in Fig. 1. The drop radius r_m, corresponding to the maximum of the distribution function, was taken as 2μ. The table gives values of s at heights of 2, 50 and 80 m above the river at distances of 200 and 700 m from the edge of the windward bank and on the leeward bank at distances of 500 and 1000 m from its edge. For each height, the top row gives values of s calculated without considering the absorption of the contaminant by the fog droplets ($a = 0$), and the bottom row also gives values of s, but calculated by taking this factor into account ($a \neq 0$).

Table 1

Height, m	Distance from windward bank, m		Distance from leeward bank, m	
	200	700	500	1000
2	140 $7\cdot10^{-2}$	230 10^{-8}	300 3,4	330 11
50	790 56	640 53	550 51	480 50
80	1200 630	840 180	650 110	530 80

It follows from this table that in the fog, the concentration of the contaminant in air decreases sharply owing to its dissolution in the droplets. Although, as is evident from Fig. 1, the 50 and 80 m levels are located above the fog, even at these levels the concentration substantially decreases. Thus, the presence of the fog is responsible for the fact that its droplets concentrate not only the contaminant which would be located near the underlying surface in the absence of the fog, but also a considerable portion of the contaminant from the superjacent and in this case the most contaminated layers. Thus, the fog droplets may be said to accumulate the contaminant from a highly extended layer, thus substantially increasing the total contamination of air in the vicinity of the underlying surface.

Conclusions regarding the influence of fog on the atmospheric diffusion of contaminants were reached on the basis of an analysis of Table 1 (and other data), based on a comparison of calculations made by neglecting the capture of the contaminant by the fog droplets and by taking it into account. It is of interest to elucidate the role of various factors in the formation of the concentrations.

Fig. 2 shows curves of the distance dependence of the concentration S at a height of 2 m above the underlying surface for different variants of the calculation at a = 0. In the first variant (curve 1) it was assumed that above the river there is no reinforcement of turbulence and no absorption of the contaminant by the underlying surface. The second variant (curve 2) differs from the first only in the fact that the absorption of the contaminant by the water surface of the river is taken into account. Comparison of these curves indicates that if the intensity of turbulent austausch above the river is the same as above the bank, the absorption of contaminant by the water surface slightly decreases the concentration of contaminant above the river, but even in the vicinity of the water surface this effect is slight, and the decrease does not exceed 30%. Beyond the river, curves 1 and 2 come together rapidly. Curve 3 was calculated by considering the increase of the austausch coefficient above the river, but neglecting the absorption of the contaminant by the fog droplets and by the river surface. Comparison of curve 3 with curve 1 shows that if an increase of the austausch coefficient such as takes place above the river were observed above dry land, the maximum contaminant concentration would be approximately doubled, and the distance at which the maximum concentration is observed at the underlying surface would be closer to the source. However, as is evident from a comparison of curve 3 with curve 4, in the calculation of which the effect of absorption of the contaminant by the river surface was also considered, this is not observed because the effect of reinforcement of turbulent austausch is offset by the increasing absorption of the contaminant on the underlying surface.

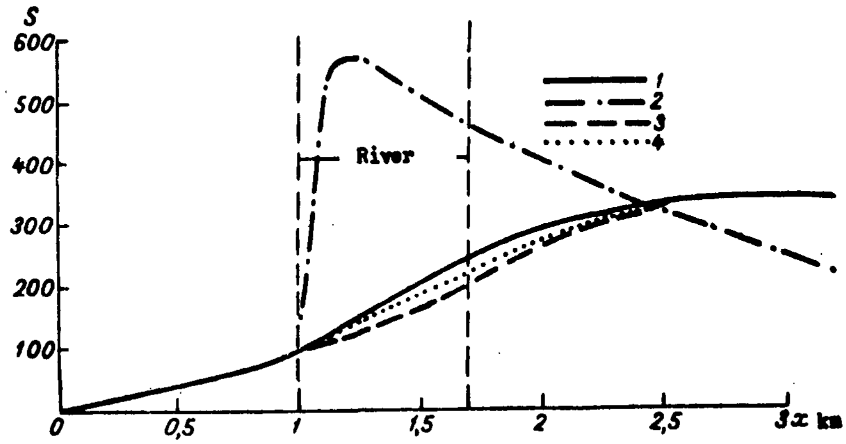

Fig. 2.

A similar technique may be used in studying the turbulent diffusion of contaminant in the case of the presence of radiation fog above a homogeneous underlying surface. One of the interesting characteristics of the structure of the boundary layer of the atmosphere in the presence of developed radiation fogs is an elevated temperature inversion, which frequently arises on their upper boundary. In particular, reference may be made to the experimental data of P. A. Vorontsov (8) and other studies, which cited cases where in the presence of fog, a layer of elevated temperature inversion was located at heights of 100-300 m, whereas below this layer, an equilibrium stratification was present in the fog layer.

It is well known that in the presence of elevated temperature inversions, the chance of contamination of the ground layer of air increases. Theoretical studies of the influence of elevated temperature inversions on atmospheric diffusion have been made in ref. (2-5), but did not consider the turbulence of fogs. In the present paper, the same pattern of vertical distribution of the austausch coefficient was employed as in these studies. In particular, k was assumed to increase linearly with the height in the ground layer of air, then to remain constant down to the lower boundary of the inversion, and to decrease rapidly to very low values in the inversion layer. In regard to the water content of the fog Δ , it was assumed to be constant throughout the fog layer to simplify the problem.

The calculations were made for a number of source heights under different weather conditions; as in the case of river fogs, the presence of the fog was found to have a substantial effect on the propagation of the contaminant in the atmosphere.

Let us consider the important features of dispersion of the contaminant in the presence of an elevated inversion located directly above the source, the absorption of the contaminant by water droplets being initially neglected. These calculations were used for two purposes. First, for the given type of fogs, elevated inversions result from their existence, and it was of interest to make a quantitative estimate of the associated concentration change. Secondly, and most importantly, as in the case of river fogs, the direct influence of absorption of the contaminant by the fog droplets can be evaluated by comparing calculations made both by neglecting and by considering this effect.

Table 2 gives, for different levels, the ratio of the contaminant concentrations in the presence of an elevated temperature inversion above the source to the concentrations in its absence. It was noted at $a = 0$; the height of the source located at the lower inversion boundary was 100 m; the wind velocity $u_1 = 2$ m/sec. It is known (2, 3) that in the absence of inversion in the vicinity of the source, the maximum concentrations are observed at $z = H$, and above and below the concentrations decrease in approximately symmetrical fashion; with increasing distance from the source, the vertical concentration gradients decrease, and the line of maximum concentrations gradually approaches the underlying surface.

Table 2

Height, m	Distance from source, m				
	1000	2000	3000	4000	5000
2	1,14	1,26	1,36	1,45	1,53
50	1,23	1,41	1,52	1,60	1,68
100	1,59	1,77	1,88	2,02	2,16
115	0,80	1,32	1,60	1,85	2,10

The presence of an elevated inversion above the source causes an asymmetry of the vertical distribution of the concentration at close distances, due to a sharp increase in the contamination of air in the subinversion layer, where the bulk of the contaminant is concentrated. At a sufficiently large horizontal distance from the source, the contaminant gradually penetrates into the lower part of the inversion, which also becomes contaminated.

Table 3 gives the ratio of the contaminant concentration in air, allowing for absorption of the contaminant by droplets of the fog, to the concentrations in its absence for the same conditions and levels as in Table 2. The height of the fog was taken as 100 m, the water content Δ was 0.2 g/m^3, and the droplet radius was $r_m = 5\mu$.

The calculations showed that in the case under consideration, a decrease in the contaminant concentration is observed at all levels, and decontamination takes place in the elevated inversion layer, in which, as was indicated above, part of the contaminant becomes concentrated at large distances from the source in the

Table 3

Height, m	Distance from source, m				
	1000	2000	3000	4000	5000
2	0,16	0,06	0,02	0,01	0,00
50	0,30	0,12	0,05	0,01	0,00
100	0,53	0,27	0,13	0,01	0,01
115	0,80	0,59	0,41	0,08	0,01

absence of fog. This confirms the conclusion, reached earlier on the basis of calculations of the influence of river fogs on the diffusion of contaminants from high altitude sources, on the "accumulation" by the fog of contaminants from superjacent layers, resulting in an increase of the total concentration at levels located in the fog and in a decrease of the concentration of gaseous contaminant above the fog. The presence of a fog under the inversion prevents the contaminant from penetrating into the inversion layer, even at large distances from the source, and causes it to penetrate almost completely into the water droplets, which change into a solution of noxious substances. As another example, we shall describe the results of calculations under the same weather conditions, but at a source height H = 150 m. In this case, the source was located inside the inversion layer at a distance of 50 m from its lower boundary. Because of the weak turbulence at such heights, the contaminant disperses slowly and moves above the fog in the form of a concentrated plume. Only a small amount of contaminant reaches the ground, the concentrations are low, and reach a maximum at large distances from the source. The presence of a weak turbulence layer between the source and the fog hinders any appreciable accumulation of the contaminant from superjacent layers, although, as in the cases discussed above, the bulk of the contaminant that has entered the fog dissolves in its droplets.

Of major interest is the study of the influence of a fog on the diffusion of sulfur gas, which is one of the most common noxious contaminants present in the atmosphere. As was pointed out above, if the total contamination in air and water droplets is considered, a contamination in the fog frequently increases substantially as compared to the case where no fog is present, most of the contaminant passing into the fog droplets. Dissolution of sulfur gas in the fog droplets causes the formation of an aerosol of sulfuric acid. The latter has a higher toxicity than sulfur gas, and its presence in the atmosphere considerably increases the corrosion of metal objects, etc. Moreover, sulfur gas dissolved in fog droplets oxidizes to sulfuric anhydride much faster than does sulfur gas in the gaseous state. This is due to the fact that the fog droplets usually contain certain trace elements having catalytic properties, and in their presence the oxidation is more rapid. In view of the fact that sulfuric anhydride reacting with water form sulfuric acid, for the sake of simplicity we may refer to the partial oxidation of sulfur gas in the atmosphere to sulfuric acid. This mechanism of formation of sulfuric acid in fog droplets is characteristic of the so-called "sulfuric acid-sulfate" smogs of Great Britain, Belgium and some other countries. The paper of R. E. Waller (15) gives a survey of a large number of studies devoted to the investigation of the sulfuric acid content of town air. It was found that sulfuric acid droplets in air were detected in appreciable amounts only in the presence of fogs. A rapid oxidation of sulfur gas to sulfuric acid in London smog was pointed out by Ellis (13).

In the Los Angeles smogs, an acceleration of the oxidation of sulfur gas to sulfuric acid takes place during the day in photochemical reactions occurring under the influence of solar radiation. According to the data of Moyer (14), the strongest oxidation is observed in the presence of a weak wind, a temperature inversion at moderate heights, and a large amount of oxidants; in this case, up to 20% of the sulfur present in sulfur gas discharged into the atmosphere oxidizes to sulfuric acid. The relative amount of oxidizing sulfur gas decreases as its concentration rises.

Attention should be given to the increase in the weight concentration of harmful contaminants, taking place as a result of the reaction of sulfur dioxide and trioxide with water and formation of sulfurous and sulfuric acids respectively. Thus, for example, the oxidation of 1 g of sulfur dioxide molecular weight 64) yields approximately 1.5 g of sulfuric acid (molecular weight 98).

We have mentioned above a number of factors that might substantially increase the contamination of the atmosphere in the presence of a fog and their toxicity for the case of a single source. In the case of several sources located along some line or scattered over an area, in the presence of an elevated temperature inversion, which is frequently associated with fogs, additional causes of increased contamination of the ground layer of air may appear. Under such conditions, as shown by theoretical calculations (2), there is a substantial increase of the distance at which the maximum concentration is observed, and a decrease of the concentration with the distance after its maximum takes place very slowly. As a result, there is an increase in the influence of the mutual superposition of the concentration fields from the several sources, and a more homogeneous contamination in the industrial area is produced than under convective conditions. In addition, even if the concentrations from an individual source are relatively low, the total contamination may be very significant.

A definite part in the contamination of ground layers of air may be played by the precipitation of large fog droplets, in which the dissolved contaminant is transported from superjacent layers, which are frequently highly contaminated, to the underlying surface; thus, for example, Waller (15) points out that in London in the presence of heavy fogs, drizzle whose droplets contain substantial concentrations of sulfuric acid precipitates on the underlying surface. He named this effect the "acid rain."

The results obtained have shown that the methods of study employed permit one to elucidate a number of major aspects of the propagation of contaminants in the presence of a fog. However, this problem is very complex and requires further study.

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GEOGRAPHIC DISTRIBUTION OF THE TURBULENCE COEFFICIENT IN THE LOWEST ATMOSPHERIC LAYER IN DAYTIME IN SUMMER

V. P. Gracheva

From Trudy, Glavnaya Geofiz. Observat. im. A. I. Voeykova, No. 207, p. 164-169, (1968)

Turbulent exchange in the lowest layer of air is one of the essential meteorological factors causing dispersal of industrial discharges in the atmosphere. To calculate the surface concentrations of noxious industrial discharges from smokestacks, it is important to know the characteristics of turbulent mixing in various climatic zones of the USSR at different times of the year and day. It is well known that unfavorable meteorological conditions promoting the generation of high concentrations of contaminant from high smokestacks in the lowest layer of air arise from extensive turbulent exchange. According to literature data on the manual and daily variation of the vertical component of the turbulence coefficient in the lowest layer of air under different climatic conditions([1-4] etc.),the turbulence usually takes on the highest values in summer and during noon hours.

In this connection, the present paper discusses the turbulent mixing intensity characteristic over the territory of the USSR in the lowest layer of air in July for the 12:00 noon to 1:00 P. M. period.

The initial material used were data on heat balance observations by a network of meteorological stations, including measurements of wind velocity, temperature and air humidity at two heights (0.5 and 2.0 m), and also measurements of the temperature and humidity of the soil, radiation balance, and cloud cover.

The heat balance observations are usually carried out on primary instrument platforms or air weather stations of the Civil Air Fleet, located if possible in open level areas in different physico-geographical regions of the USSR. Observational data from 92 heat balance stations for the period 1954-1966 were analyzed. Unfortunately, many of the observations obtained were heterogeneous because the work at the various stations began in different years during this period. The number of stations which carried out the observations can be evaluated from Fig. 1. If the total number of stations is divided into groups according to the number of years of observations at these stations (from one to 12 years) in July in hours, then there will be 17, 12, 15, 8, 8, 6, 3, 7, 6, 5, 3 and 2 stations in each group respectively. Hence, at approximately 70% of all the stations the observations were carried out in the course of three or more years.

The distribution of stations over the territory of the USSR is also irregular. More than half are located on the European territory of the USSR (ETU), 18 in Kazakhstan and Central Asia, and approximately the same number on the huge territory of Siberia and the Far East, chiefly in the southern parts. In the northern parts of West and East Siberia there are only 4 stations, three of which have been opened in the last few years. The same may be said for the northeastern part of the ETU.

In selecting the method of calculation of the vertical component of the turbulence coefficient at a height of 1 m in the lowest layer of air, the main criteria were the presence of original observational data and the simplicity of the method of calculation. During the indicated period, the most frequent conditions of the state of the atmosphere were unstable. For calculating the turbulence coefficient under these conditions, it was considered possible to use the method of determination of K_1 given in a handbook on gradient observations (5) and currently recommended as the chief method for the network of heat balance stations. According to this method, the turbulence coefficient was determined for the 1:00 P.M. period every day of the month of July with the exception of days when no observational data were available. After determining its daily values, mean monthly July values were obtained for the individual years, then an average value for the series of available years. The mean monthly values of the turbulence coefficient obtained for each station for 1:00 P. M. in July, the average for the series of years and the period of averaging are given in Table 1. Asterisks denote stations currently shut down because they are not representative for the heat balance observations (the conditions of homogeneity of the underlying surface were disturbed, houses were constructed near the platform, trees grew, etc.). The required condition of quasi-stability of the lowest layer of air is not met at these stations. Stations conducting observations in accordance with the program of joint studies by sanitation epidemiological stations and hydrometeorological stations are underlined.

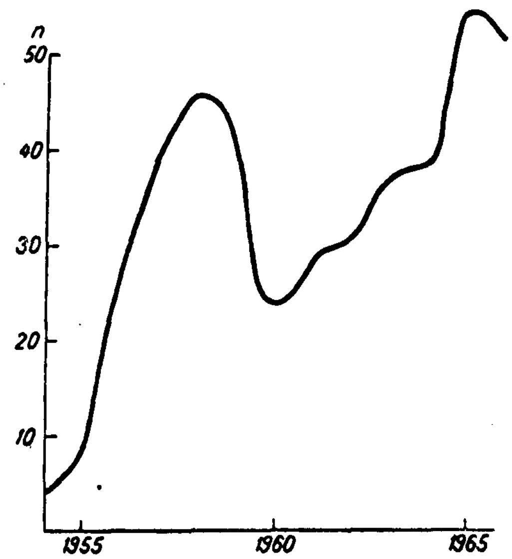

Fig. 1. The number of stations (n), conducting observations at 1:00 P.M. in July in different years.

In order to evaluate the influence of the inhomogeneity of the series in the averaging for the period under consideration, and the influence of disturbances of the homogeneity of the underlying surface at stations marked with asterisks in the table, graphs of the distribution of July values of the turbulence coefficient were plotted for a series of individual years (1958, 1959, 1963, 1964) on the basis of all the stations, and also a map was plotted from average values of K_1 for the available series of years, calculated only from data of representative stations. Analysis of these data showed that the exclusion of K_1 values at nonrepresentative stations (marked with asterisks) did not change the basic pattern of this distribution, and that the mean monthly values for each individual year are in fairly good agreement with values at neighboring stations obtained for the series of years. On all the maps,

Table 1

Average Values of Turbulence Coefficient at a Height of 1 m for the 1:00 P. M. Period in July

Name of Station	K_1 m^2/sec	Period of Observations
Khibiny	0,149	1959, 1963—1966
Petrozavodsk	0,164	1962—1966
Arkhangel'sk	0,130	1964—1966
Kotkino	0,152	1965—1966
Kargopol'	0,125	1964—1966
Ust'-Vym	0,178	1965—1966
Tallin	0,142	1965—1966
Priozersk*	0,144	1956—1958
Voyeykovo	0,142	1954—1958, 1966
Nikolayevskoye	0,162	1955—1964, 1966
Tiyrikoyya	0,140	1956—1957, 1960—1966
Riga	0,136	1955—1966
Kaunas*	0,119	1956
Pinsk	0,138	1963—1966
Smolensk	0,146	1956—1965
Toropets	0,132	1959—1964
Torzhok	0,148	1956—1966
Rozhnovskiy mys*	0,148	1956—1958, 1960—1962
Kostroma	0,134	1956—1958, 1960—1965
Gor'kiy*	0,140	1956, 1958—1959
S. I. Nebol'sin Station	0,131	1955—1966
Pavelets	0,154	1956—1966
Nikitskiy sad	0,150	1966
Voronezh*	0,161	1957—1959
Nizhnedevitskiy*	0,153	1958—1959
Ushakovo*	0,150	1957—1959
Konotop	0,131	1957—1959
Borispol'-Kiev	0,168	1954, 1958—1959, 1961—66
Poltava	0,167	1958—1959, 1961—1966
Derkul*	0,204	1956—1957
Kam. Step'	0,162	1957—1959, 1961, 1963—1966
Beregovo	0,129	1957—1959, 1962—1966
Kishinev*	0,146	1956—1959
Bolgrad*	0,120	1957—1959
Askaniya-Nova	0,190	1956—1959, 1961—1965
Verkhniy Anadol'*	0,171	1957—1959
Gigant	0,143	1958—1966
Volzhskiy*	0,197	1958—1961
Saratov*	0,201	1956
Kubyshev	0,150	1955—1963, 1966
Yelshanka*	0,229	1955—1958, 1960
Astrakhan'	0,174	1958—1959, 1963—1966
Port Shevchenko	0,177	1959—1964, 1966
Artem Island	0,205	1957—1966
Yershov	0,185	1966
Churuk	0,189	1965—1966
Nakhichevan'	0,149	1965
Tbilisi*	0,136	1956—1958
Telavi	0,138	1958, 1962—1966
Yerevan*	0,120	1956—1958
Nolinsk	0,149	1957—1963, 1965
Kushnarenkovo	0,151	1963—1966
Vysokaya Dubrava*	0,107	1954—1959, 1965
Chardzhou	0,126	1963—1966
Beki-Bent	0,190	1958—1966
Ak-Molla	0,175	1961, 1963—1966
Tamdy	0,242	1958—1966
Termez	0,146	1964—1966

Table 1 (Continued)

Name of Station	K_1 m²/sec	Period of Observations
Fergana	0,118	1964—1966
Dushanbe	0,125	1959—1966
Umbet*	0,175	1957—1959
Aydarly	0,192	1962—1963, 1965
Alma-Ata*	0,122	1956—1959
Frunze	0,157	1954—1956, 1958—1959, 1964—1966
Tvan'-Shan'*	0,162	1957—1958
Rudnyy	0,181	1962—1966
Omsk*	0,156	1955
Tselinograd	0,224	1961, 1963—1966
Zhanna-Semey*	0,153	1957—1960
Ogurtsovo	0,176	1961—1963, 1965—1966
Kopashevo*	0,170	1957—1958
Solyanka	0,164	1957—1966
Khkasskaya	0,156	1956—1959, 1965—1966
Kyzyl	0,133	1965—1966
Khomutovo	0,149	1963—1966
Turukhansk	0,156	1965—1966
Tura	0,116	1965
Skovorodino	0,131	1962—1966
Tolstovka	0,152	1965
Khabarovsk*	0,135	1959
Sad-gorod*	0,122	1957
Yakutsk	0,148	1957—1962, 1964—1965
Okhotsk*	0,203	1957
Bol'shoy Shantar*	0,282	1956
Kalmykovo	0,201	1958—1963, 1966
Primorskaya	0,200	1965—1966
Magnitogorsk	0,190	1965
Berezniki	0,160	1965
Irkutsk	0,116	1965
Chita	0,178	1965—1966
Mangut	0,165	1966
Verkhoyansk	0,165	1966

approximately the same arrangement of regions with maximum and minimum turbulent austausch is observed. From one year to the next, only a slight shift of these regions to one side or the other is noted. Thus, the inhomogeneity of the series in the averaging and the values of K_1 at nonrepresentative stations have only a slight effect on the distribution of the intensity of turbulent austausch over the territory of the USSR. Therefore, in the analysis we shall use a scheme plotted from average data on the magnitude of turbulent austausch in the lowest layer of air for the 1 P. M. period in July at all stations for the entire series of years available at each station, as shown in Fig. 2, (see following map).

Analysis of this map shows that the highest values of the turbulence coefficient in the lowest layer of air (0.20-0.24 m^2/sec) at midday in July are noted in the deserts of Central Asia and Kazakhstan, regions of the lower Volga River, and in southern Ukraine.

The central regions of the ETU and certain western regions, with the exception of the coast of the Gulfs of Riga and Finland, are characterized by comparatively moderate values of turbulent austausch (0.12-0.15 m^2/sec). When compared

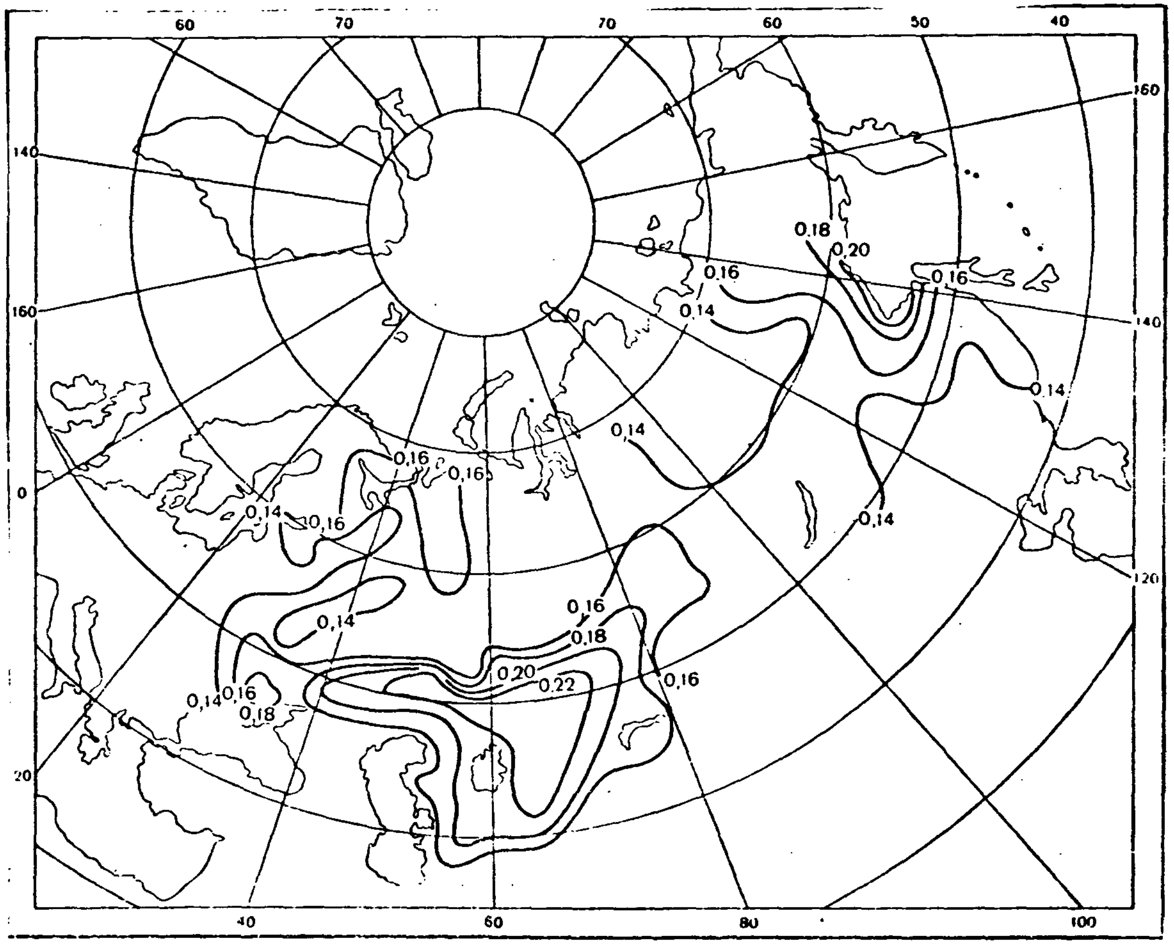

Fig. 2. Distribution of values of the turbulence coefficient at a height of 1 m over the territory of the USSR. July, 1:00 P. M.

with the central part, a certain increase of turbulent mixing (0.14-0.18 m^2/sec) is observed in the northwest and northeast of the ETU. A somewhat attenuated turbulent austausch (0.12-0.14 m^2/sec) is observed in the foothills of Tyan'-shan', Altay and Sayan, and also in the Far East, with the exception of the shore of Okhotskoye Sea, where the turbulent austausch is considerable (0.20 m^2/sec) because of strong winds in July. Data on the turbulent conditions in the Far East are tentative, since values of the turbulent coefficient in this region were obtained from data for only one to two years of observation.

Values of the turbulence coefficient calculated for different geographic regions are in agreement with the magnitude of the radiation balance and with the state of humidity of the soil, and also with the frequency of probability of wind of different velocities. Thus, in the deserts of Central Asia, Kazakhstan and the lower Volga River and in the south of the ETU, in addition to large values of the radiation balance and to a slight humidity of the soil, there is also noted a maximum of frequency of strong winds in July. Conversely, in the central and western regions of the ETU, a maximum in the frequency of weak winds together with a substantial humidity of the soil, which decreases the vertical temperature gradient, causes low values of the turbulence coefficient. The substantial frequency of strong winds in the northwest of the ETU and weak winds in the southeastern regions of Central Asia and in the south of western Siberia may be explained respectively by a reinforced and by an attenuated turbulent austausch in these regions. The same may be observed in other physico-geographical conditions as well.

Material on data of gradient observations collected on the network of heat balance stations will later aid in explaining the characteristics of the distribution of the turbulence coefficient in the lowest layer of air over the territory of the USSR in different seasons and days of the year.

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INVERSIONS OF LOWER TROPOSPHERE AND THEIR INFLUENCE ON THE AIR POLLUTION OF THE CITY OF MOSCOW

E. Yu. Bezuglaya

From Trudy, Glavnaya Geofiz. Observat. im. A. I. Voeykova, No. 207, p. 202-206, (1968).

The presence of elevated inversions limits the layer of air in which mixing takes place, and thus promotes an increase in the concentration of noxious contaminants in air in the presence of steady sources of discharges (1, 7).

A study of the influence of different meteorological conditions on the distribution of concentrations of noxious substances in air has shown that the wind velocity and degree of stability of air in the lower troposphere play an essential role (8, 9). It is noted that particularly unsafe conditions of accumulation of pollution arise in the presence of ground and elevated inversions, which decrease the thickness of the layer of mixing of contaminants (6,7).

In this connection, it was of interest to study the distribution of inversion layers in the lower troposphere, and to calculate their frequency and location at different levels in an annual cycle.

Observational results of airplane soundings above Moscow (Vnukovo station) for the period 1953-1957 were used for this purpose. Data of airplane ascents for 4:00 A. M. and 4:00 P. M. were used to extract values of the height of the upper boundary of ground inversions and also of the lower and upper boundaries of elevated inversions. Isothermy layers were also included in the estimates.

If more than two inversion layers were noted during the ascent, the estimates included characteristics of only the ground inversion and of the lowest layer of the elevated inversion.

The number of observations used in the present paper are listed in Table 1 for day and night ascents separately.

Table 1

Numbers of Observations

Time of observations	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Night	151	115	142	142	148	145	150	150	127	138	134	147
Day	142	126	140	140	148	146	150	150	129	146	135	140

Table 2 lists the frequencies of ground inversions based on the total number of observations for day and night ascents separately, and also the frequencies of ground inversions in stationary anticyclones.

Table 2

Annual Course of the Frequency of Ground Inversions Above Moscow, %.

Period and characteristics of observations	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
At night												
for entire period	40	58	48	59	70	82	74	78	60	41	32	36
in stationary anticyclones	38	83	62	60	72	100	83	93	83	71	53	78
During the day												
for entire period	30	17	15	7	5	7	2	2	2	11	21	32
in stationary anticyclones	43	21	18	13	—	—	—	—	—	67	50	87

As is evident from Table 2, the frequency of diurnal ground inversions for the entire period in December and January amounts to 30-32% and decreases to 2% during the period July-September.

The frequency of nocturnal ground inversions is somewhat greater and has the opposite annual variation. The maximum of ground inversions (70-82%) is observed from May to August, and the minimum (32-40%) in winter. A similar annual variation was obtained for Moscow in an analysis of the temperature profiles in the lowest 500-meter layer (2).

Of greatest interest, however, is the analysis of the annual variation of the frequency and height of the base of elevated inversions (Table 3).

Table 3

Annual Course of the Frequency of Inversions of Free Atmosphere (%) at Various Heights

Time and characteristic of observations	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
At night												
for entire period	90	98	89	82	73	67	66	71	83	90	88	90
in stationary anticyclones	95	100	95	93	100	71	59	79	87	100	87	67
with base in layer												
0.1-1 km	67	51	57	42	26	16	22	22	25	30	54	61
1-2 km	26	41	36	34	30	40	24	21	39	50	32	34
2-3 km	4	5	4	18	28	15	27	35	27	14	10	4
3-4 km	3	3	3	6	16	29	27	22	9	6	4	1
During the day												
for entire period	92	96	93	81	78	68	67	67	73	86	89	96
during stationary anticyclones	81	100	94	87	86	71	77	72	82	100	93	100
with base in layer												
0.1-1 km	69	74	43	15	6	6	4	2	12	28	46	65
1-2 km	22	20	46	47	36	30	24	33	48	49	47	30
2-3 km	8	6	8	27	37	42	46	36	34	18	6	3
3-4 km	1	—	3	11	21	22	26	29	6	5	1	2

As is evident from Table 3, elevated inversions above Moscow occur very frequently. From September to April, their frequency both at night and during the day amounts to 82-98%, and in summer decreases to 66-70% (June-August).

In winter, over 90% of all the elevated inversions both during the day and at night have the lower boundary in the layer up to 2 km. In summer, the frequency of inversions forming at higher levels increases, and in June - August the frequency of inversions with a base above 3 km increases to 22-29%.

The frequency data show a great stability of the position of the layer of elevated inversions during the winter.

Fig. 1 shows the annual variation of the position of the layer of ground and elevated inversions based on data of the entire period (1) and in stationary anticyclones (2). As is evident from the figure, the average height of ground inversions undergoes little change in the course of the year; only a slight increase in height (up to 0.5-0.6 km) is observed during the period from December to February in both diurnal and nocturnal observations.

According to ref. (6, 7), as the mixing layer decreases to 1.0-1.5 km, favorable conditions arise for the accumulation of pollution.

Analysis of air contamination in Moscow also shows a definite role of elevated inversions during the winter period. During the winter, there is observed a gradual increase of contaminants with a maximum in April and a sharp decrease of the sulfur gas concentration in the summer months, when the height of elevated inversions increases considerably.

A number of studies (4, 5, 8, 9) have noted a major influence of stationary anticyclones, giving rise to conditions of air stagnation that promote the accumulation of noxious contaminants in air.

In order to explain the manner in which the structure of the lower troposphere changes under conditions of stationary anticyclones, average values of ground inversions, their frequency, and the frequency and average height of elevated inversions were calculated for the period 1962-1964 for days when a stationary anticyclone was located above Moscow (the anticyclone was considered stationary if it remained above Moscow for over four days). At a height of the isobaric surface of 500 m, such an anticyclone is manifested by a heat crest.

It is evident from Table 2 that the frequency of ground inversions in stationary anticyclones in winter is greater than the frequency based on data of observations for any synoptic situations. In summer, their frequency in the stationary anticyclone at night is also higher, and ground inversions are not observed in a stationary anticyclone during the day.

The frequency of elevated inversions (see Table 3) is greater in stationary anticyclones during most of the year. Only in December and January does their frequency decrease, something that can be explained by the fusion of ground and elevated inversions as the power of ground inversions increases.

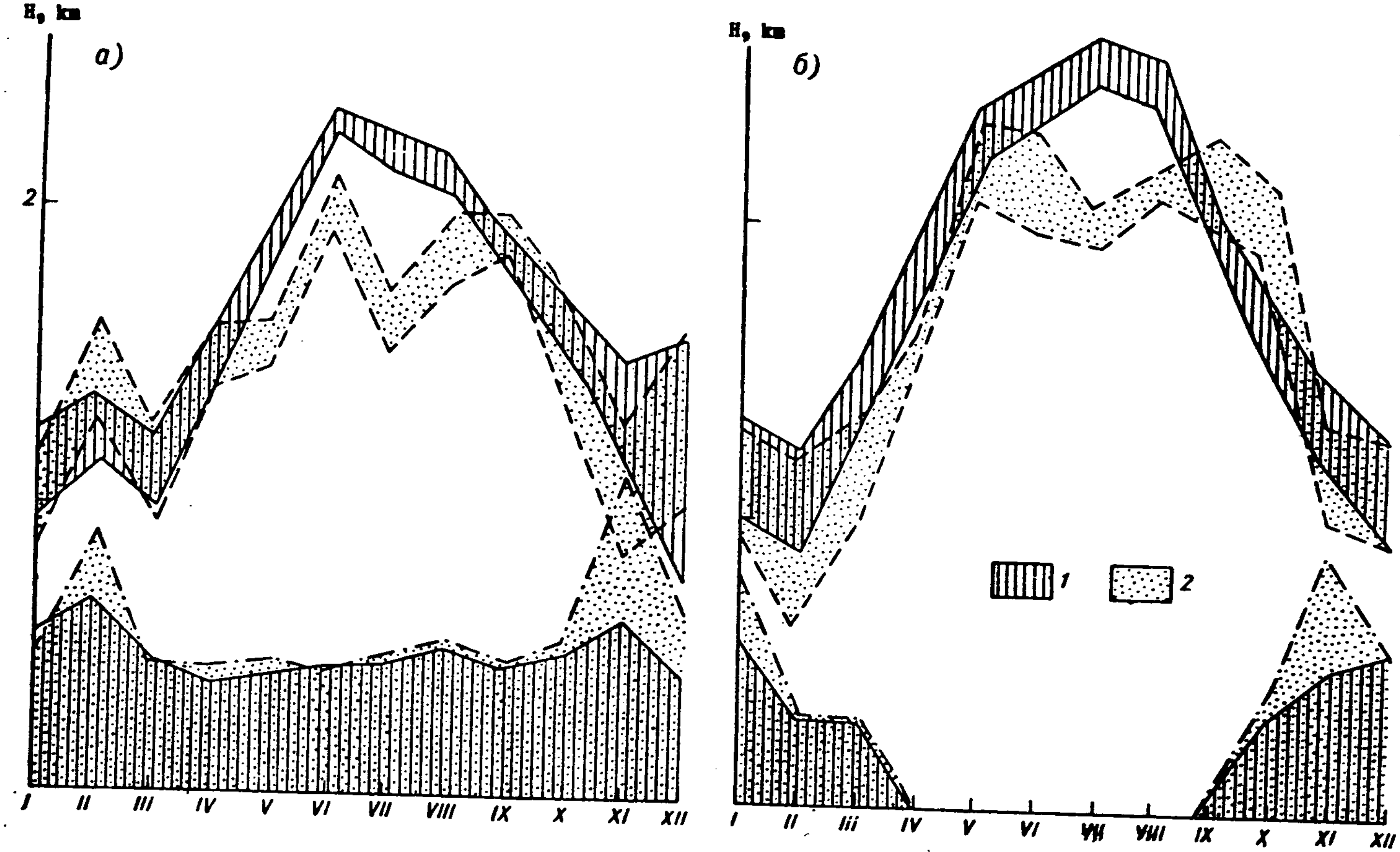

Fig. 1. Annual course of nocturnal (a) and diurnal (b) inversion layers.

As in the case of the entire period of observations, in stationary anticyclones the height of the lower boundary of the intercepting inversion layer increases from winter to summer. However, as is evident from Fig. 1, during most of the year the layer of elevated inversions in a stationary anticyclone is located somewhat lower than its average position for the entire period: in winter, at a level of 0.7-0.9 km and, in summer, at a height of 1.6-2.0 km. The greater frequency of ground inversions in a stationary anticyclone and the decrease of elevated inversions result in a decrease of the layer of mixing over Moscow to 0.2-0.3 km in winter.

Comparison of data for the concentration of sulfur gas in stationary anticyclones and under average conditions in the air of Moscow in winter shows a rise in the concentration of the contaminant in stationary anticyclones. A particularly marked increase of sulfur gas concentration is observed in April. For this reason, the maximum content of noxious contaminants in the air in an annual cycle, observed in spring, cannot be attributed solely to the increase in the frequency of anticyclones during this period. Obviously, an important part is played by the thermal structure of the lower troposphere and by its change in spring.

The great stability of the layer of elevated inversions during the year and its influence on the change of the ground concentration of contaminants in city air indicates the necessity of a further study of inversions, their changes in the annual and daily cycle, and also above various geographical regions.

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RESULTS OF EXPERIMENTAL STUDIES OF ATMOSPHERIC POLLUTION IN THE REGION OF THE MOLDAVIAN GRES [STATE REGIONAL ELECTRIC POWER PLANT (SREPP)]

R. S. Gil'denskiol'd, B. B. Goroshko, G. A. Panfilova and B. V. Rikhter

From Trudy, Glavnaya Geofiz. Observat. im. A. I. Voeykova, No. 207, p. 65-68, (1968).

The A. A. Voeikov Main Geophysical Observatory in cooperation with the F. F. Erisman Moscow Scientific Research Institute of Hygiene and the southern division of ORGRES [Tr. note: the State Trust for the Organization and Efficiency of Electric Power Plants (STOEEPP)] in August-September 1965 conducted studies of the dispersal of sulfur gas and ash from the stack of the Moldavian GRES [Tr. note: SREPP].

During the period of the study, the Main Geophysical Observatory conducted a large group of the following meteorological and aerological studies: gradient observations of wind velocity, temperature and air humidity to a height of 17 m; actinometric observations of all the components of heat balance, temperature and soil humidity; aerological observations consisting of aerostatic and airplane sounding of the atmosphere, and pilot balloon observations. The method and program of the observations are described in ref. (1, 3, 5).

The F. F. Erisman Moscow Institute of Hygiene conducted measurements of the concentrations of sulfur gas and ash in the zone of influence of the smoke plume from the SREPP at various distances from the source.

The southern division of the STOEEPP measured the following parameters characterizing the discharges: total volume of gases discharged from the stacks; temperature of the effluent gases (behind ash-trapping units); amount of ash discharged and its fractional composition.

The main purpose of these studies in the region of the Moldavian SREPP was to check on high stacks (H = 180 m, D = 6 m) the experimental data of the "Tentative Method for Calculating the Dispersal of Discharges (Ash and Sulfur Gas) in the Atmosphere from Smokestacks of Electric Power Stations" (4), in the verification of which use was made earlier of data on the pollution of the atmosphere in the vicinity of electric power stations with stacks of 40-150 m. In addition, the influence of specific meteorological conditions of the region of the Moldavian SREPP, located in the southern part of the territory of the USSR, was investigated. Such studies were first carried out in the region of the SREPP with the so-called wet method of ash trapping, which causes a lowering of the temperature of the effluent gases and their wetting.

The discharge of sulfur gas is determined by calculation in accordance with a method using the amount of fuel consumed, its sulfur content, etc.

The samples were taken in the daytime for 3-4 hours, along a grazing graph

[Ed. note: hymograph] under a visually determined axis of the smoke plume at a distance of 0.5 to 10 km. Measurements of sulfur gas concentrations were made simultaneously at three to four distances from the source at approximately 5 points at each distance by means of suction tanks and automobile aspirators. Measurements of the ash concentrations were made with two automobile aspirators at three to four points at two to three distances. The duration of each sampling was 20 min.

All the data obtained were processed according to a method proposed by M. E. Berlyand (6). Graphs of the concentrations of noxious contaminants versus wind velocity at the height of the wind vane were plotted separately for each distance. On each graph, an enveloping line was drawn which bounded the majority of the points. Table 1 lists concentrations of sulfur gas (mg/m^3) taken from the enveloping lines for each distance at different wind velocities.

Table 1

x, km	Number of cases	U, m/sec			
		2	3	4	6
1	44	0,08	0,09	0,09	0,07
2	48	0,18	0,18	0,18	0,16
3	73	0,23	0,22	0,20	0,16
4	25	0,22	0,27	0,20	0,10
5—6	105	0,17	0,20	0,15	0,11
8—9	56	0,08	0,08	0,07	0,06

From the above table it is apparent that the maximum sulfur gas concentrations were around 0.3 mg/m^3. A zone of high sulfur gas content was observed at distances of 3-4 km, i. e., in the zone of 10-40 H at wind velocities of 2-3 m/sec at the height of the wind vane.

From [4], one can calculate the maximum sulfur gas concentration for the entire period of observations and the unsafe wind velocity at which the maximum concentrations were calculated from the following formulas:

$$C_{M SO_2} = \frac{A M_{SO_2} F m}{H^2} \sqrt[3]{\frac{N}{V \Delta T}}; \qquad (1)$$

$$u_M = 0{,}65 \sqrt[3]{\frac{V \Delta T}{NH}}, \qquad (2)$$

where A is a coefficient dependent on the temperature stratification, in this case equal to 160; M_{SO_2} is the total discharge of sulfur gas; H is the stack height; F and M are dimensionless coefficients; N is the number of stacks; V is the volume of effluent contaminants; Δ T is the difference between the temperature of the effluent gases T_g and that of the surrounding air T_a.

From the data of these studies it was found that C_{SO_2} = 0.26 mg/m^3 and U_M = 2.5 m/sec; this is in good agreement with the experimental data.

Table 2 gives the theoretical changes of the concentrations of sulfur gas at various distances from the source at different wind velocities, in a manner analogous to Table 1.

Comparison of the data of calculation and experiment should be considered satisfactory in this case.

Analysis of measured ash concentrations showed that for simultaneous sampling at several points, markedly different values were obtained. The spread of these values is due to the fact that the air contained large amounts of natural soil dust, particularly in cases where harvesting work was being carried out in the vicinity of the points of sampling. After an examination of the samples under the microscope, they were found to contain a large amount of organic particles. Therefore, the maximum concentrations of the dust cannot be due solely to discharges from stacks of the SREPP.

Table 2

x, km	U, m/sec			
	2	3	4	6
1	0,02	0,06	0,06	0,05
2	0,14	0,21	0,20	0,14
3	0,22	0,24	0,22	0,15
4	0,24	0,22	0,21	0,14
5—6	0,23	0,21	0,18	0,12
8—9	0,18	0,15	0,12	0,08

Simultaneously with meteorological observations and sampling of air, the smoke plume was photographed in the daytime. Photographs taken every 15-20 min. were used to determine the height of the smoke plume above the stack, ΔH, Graphs were plotted for the dependence of the ascent of the smoke plume on the wind velocity at the height of the wind vane and at the height of the stack. The highest ascents of smoke were observed in the presence of a weak wind and amounted to about 400 m. Values of the wind velocity at the height of the source were taken from the aerological observations performed (7). Only those cases were selected in which the photographing of the smoke plume and the determination of the wind velocity at the height of the stack were carried out simultaneously. In all, about 70 such cases were found. For each, the mean square deviation ΔH for different gradations of the wind velocity was calculated. Fig. 1 represents a plot of the average values of ΔH and their mean square deviations, based on experimental data, as a function of the wind velocity at the height of the source. Comparison was made of ascents of the smoke plume obtained from photographs and calculated from the formula obtained in ref. (2)

$$\Delta H = \frac{1,5 w_0 R_0}{u}\left(2,5 + \frac{3,3 g R_0 \Delta T}{T_s u^2}\right), \quad (3)$$

where w_0 is the average velocity of discharge of the flue gases, R_0 is the stack radius and U is the wind velocity at the height of the wind vane.

From the wind velocity at the level of the wind vane one can switch to the wind velocity at the level of the source u_0. Therefore, in the calculations, the wind velocity at the height of the wind vane is replaced in the formula by the wind velocity at the height of the stack by introducing a suitable coefficient. The theoretical curve is given in the figure, from which it is apparent that the agreement between the experimental and theoretical data is also satisfactory. There is a slight discrepancy at low wind velocities, but it should be kept in mind that few data were available for velocities below 2 m/sec.

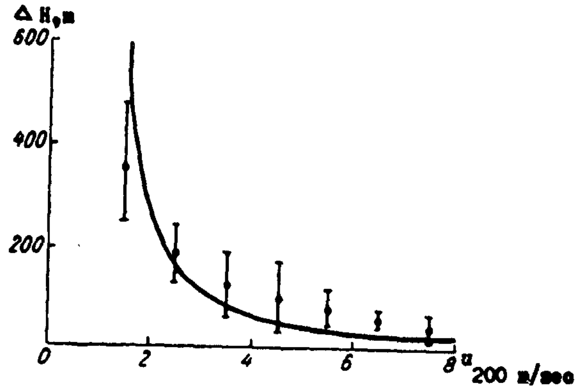

Fig. 1. Ascents of smoke plume versus wind velocity at height of source.

Analysis of the experimental material and its comparison with the results of calculations using formulas show a satisfactory agreement.

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THE SETTLING OF AN AEROSOL INTRODUCED INTO THE ATMOSPHERE IN THE FORM OF A VERTICAL TURBULENT CURRENT

V. F. Dunskiy

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In the theory of convective diffusion of an aerosol from a point or linear source, usually only the output of the source is taken into consideration; its other properties (the initial kinetic and thermal energies, etc., imparted to the aerosol) are not touched on by theory.

In the majority of cases, such a simplification is permissible. However, in solving certain technical problems connected with a high-power current source, this simplification creates great misrepresentations and deprives the results of practical value.

In solving similar problems, it is expedient to utilize the semiempirical theory of turbulent currents [1]. An investigation of the trajectory of thermal currents in the surface layer of the atmosphere, conducted using this theory, can serve as an example [2].

Certain elements of this theory can be used in solving the present problem of the settling of an aerosol from a vertical current.

In the fine-droplet spraying of farm crops using a ground generator that makes a stream of roughly dispersed aerosol (air with droplets suspended in it), the effective working width can be increased substantially by directing the stream upward. Simultaneously, the stream raises the droplets to a certain height from which they settle over a considerably wider zone than when the stream is directed horizontally. The height to which the droplets are carried is decreased with increased wind velocity; because of this, the effect of wind velocity on the spread of drops over the treated zone is decreased; i. e., the dependency of the results of treatment on meteorological conditions is decreased. These advantages have been a stimulus for carrying out a number of experimental works (see [3] , for example) that basically confirm the advantages of this method.

The height to which the droplets are carried is determined by the form of the current in the wind carrying it. The form of the axis of the air stream flowing in a cross current from a round nozzle can be determined by the following empirical equation proposed by Shandorov [4]:

$$\frac{x}{2R_0} = \frac{q_{01}}{q_{02}}\left(\frac{z}{2R_0}\right)^{2,55} + \frac{z}{2R_0}\left(1 + \frac{q_{01}}{q_{02}}\right)\operatorname{ctg}\alpha_0, \quad (1)$$

where x, z are the coordinates of points of the stream axis (the z axis is directed upward, the origin of the coordinates is placed in the center of the output cross-section of the nozzle; the x axis is in the direction of the driving stream); R_0 and a_0 are the radius of the nozzle and the angle between the direction of the nozzle axis and the direction of the driving stream:

$$q_{01}=\frac{\rho_1 u^2}{2}, \quad q_{02}=\frac{\rho_2 v_0^2}{2}$$

are the high-speed pressures in the dirving stream and in the output cross-section of the nozzle, respectively.

The equation is accurate in a variability range of $q_{0\,2}/q_{0\,1}$ from 2 to 22 and of a_0 from 45° to 90°.

Yu. V. Ivanov [5] derived a different empirical equation that is accurate in the interval $2<q_{02}/q_{01}<1000$, $60°<\alpha_0<120°$,

$$\frac{x}{2R_0}=\left(\frac{q_{01}}{q_{02}}\right)^{1,3}\left(\frac{z}{2R_0}\right)^3+\frac{z}{2R_0}\operatorname{ctg}\alpha_0. \quad (2)$$

The theoretical solution of the problem of [1] is well-known and satisfactorily complies with equations (1) and (2).

The precise correspondence between empirical equations (1) and (2), derived through modeling, and the process that interested the authors would have occurred in conditions of geometric similarity and equality of the corresponding criteria of similarity. This condition was not observed. However, deviations from geometric similarity have a secondary characteristic, but differences in the Reynolds criterion (at Re > 20000), even in the degree of turbulence of an accompanying or drive stream, do not greatly affect the current's structure ([1], p. 575). Therefore, it can be assumed that equations (1) and (2) are roughly applicable to the investigated outflow of a vertical turbulent drop-air stream into the atmosphere under conditions that hinder spraying (inversion, isotherms, weak convection).

According to equations (1) and (2), the ordinate of spray trajectory z grows without limitation with an increase in distance from nozzle x. However, with the stream's increase its average velocity v quickly decreases (the result of intensive interspersion with surrounding air and the maintenance of constant momentum), and for a certain value z = ΔH the vertical component v_z of average stream velocity nears in value the vertical component u_z^1 of the average pulsation velocity of a driving stream, after which the difference between the jet and the driving stream practically disappears. It can be shown that the equality $v_z = u_z^1$ roughly corresponds to the inclination of the stream tg a $\cong$ 0.2, from which the formula

$$\Delta H=2{,}58R_0\left(\frac{v_0}{u}\right)^{1,3}. \quad (3)$$

for the height to which the stream rises (i. e., the rise of the particles above the generator nozzle) is derived by equation (2).

The corresponding $\Delta_x = 1.66\Delta H$. As long as the width of the zone the droplets settle on exceeds H by a factor of 10(see below), Δx can be disregarded in calculations.

When the rate of gravitational settling of particles $w \gg u_z^1$ (i. e., for the coarser aerosol fractions), the height of particle rise can prove to be less than calculated by equation (3); such particles fall from the stream in the immediate vicinity of the generator. With proper generator construction and correct selection of operating conditions, these particles comprise a miniscule fraction of the sprayed substance.

After the effective height of the source $H = H_1 + \Delta H$ (H_1 is the height of the initial stream cross-section above the ground) is determined, the theory of atmospheric diffusion can be used for a calculation of the additive's settling to the ground. The task is formulated as follows: a continuous point source (i)* of the settling additives moves at height H at a constant velocity v_n [Usually written v_c in English; left here for typographic convenience. - - Trans.] perpendicular to the wind and follows path l for time T. The solution of an equation of nonstationary diffusion in corresponding originating and marginal conditions is sought.

With the problem prepared in this manner, the solution is complicated and the derivation of simple calculated formulas is most difficult; further simplifications are desired.

It is assumed that the existing simplifications are possible without loss of solution precision if it is limited to the determination of the area of additive precipitation on the ground. The nonstationary process has been investigated: the localized values of additive concentration c (x, y, z, τ) in the ground layer of atmosphere change with time. However, the cumulative

values $\int_0^\infty c(x, y, z, \tau)\, d\tau = \varphi(x, y, z)$, derived by summation

of the instantaneous values of c at every point and determining the area of additive settling on the ground, form a stationary field (independent of time). In solving the given problem, as with the majority of problems connected with the precipitation of a solid additive from the surface layer of air on a ground surface, the authors were mostly interested in the area of additive coverage, i. e., the cumulative and not the instantaneous values of concentration. Therefore, the nonstationary problem of additive precipitation from an instantaneous, continuous, moving source can be reduced to a stationary problem of additive precipitation from an equivalent (ii)* continuous, secured source.

That such a simplification for the simplest case of an instantaneous point source is acceptable and, in particular, that, from the point of view of the precipitation produced this can be replaced by an equally effective continuous point source, has been demonstrated.

Let there be a function $G_1 f(x, y, z, \tau - t)$ that determines the concentration field c for an instantaneous point source with output G_1 kg., operating at moment $\tau = t$. The area of additive settling on the ground formed by this source with

*For explanation of (i) and (ii) see end of this paper.

gravitational settling of particles w is,

$$g_1 = G_1 w \int_t^{\infty} f(x,\ y,\ z_0\ \tau - \ )\, d\tau,$$

or after conversion of the variable under the integral $\tau = \theta + t$ and of the corresponding change in the integration limits

$$g_1 = G_1 w \int_0^{\infty} f(x,\ y,\ z_0,\ \theta)\, d\theta. \tag{4}$$

The continous point source with output G_2 kg./sec. is now approached.

Using the principle of superposition, it will be examined as the aggregate of an ever increasing number of elementary, instantaneous point sources with output $G_2 d\tau$, subsequently operating in an ever increasing period of time τ. The concentration field dc formed by each source at the moment $\tau = t$ is

$$dc = G_2 d\tau f(x,\ y,\ z,\ t - \tau).$$

The total additive concentration, formed by the aggregation of elemental sources at moment $\tau = t$,

$$c = G_2 \int_{-\infty}^{t} f(x,\ y,\ z,\ t - \tau)\, d\tau = G_2 \int_{t}^{-\infty} f(x,\ y,\ z,\ t - \tau)\, d(-\tau),$$

or after the conversion of the variable under the integral, $\tau = t - \theta$, and the corresponding change of integration limits

$$c = G_2 \int_0^{\infty} f(x,\ y,\ z,\ \theta)\, d\theta.$$

The area of precipitation, formed after one second by the accumulation of elementary sources and corresponding to the continuous source examined,

$$g_2 = cw = G_2 w \int_0^{\infty} f(x,\ y,\ z_0,\ \theta)\, d\theta. \tag{5}$$

For identical additive expenditures (i. e., when G_1 [kg.] = G_2 [kg./sec.]), expressions (4) and (5) are identical, and $g_1 = g_2$; equivalency is demonstrated.

In an analogous manner, the equivalency (in the given sense) of both instantaneous and continuous linear sources of infinite length, instantaneous and continuous linear sources of finite length, etc., can be demonstrated. The equivalency of sources applicable to this problem, especially those following path l for T time, and that of continuous linear source of length l also can be demonstrated. When neglected by limiting effects, the latter can be approximated by the source of infinite length.

As the result of introduced simplifications, the problem is reduced to the solution of an equation of stationary diffusion

$$u(z)\frac{\partial c(x,z)}{\partial x} - w\frac{\partial c(x,z)}{\partial z} = \frac{\partial}{\partial z}\left[K(z)\frac{\partial c(x,z)}{\partial z}\right] \tag{6}$$

applicable to the settling of a roughly dispersed aerosol on a growing plot of ground, i. e., by taking into consideration not only gravitational but inertia precipitation. As shown in [6], in this case the limiting factor on the upper limit of the growing plot z=h is

$$\frac{\partial c(x,h)}{\partial z} = aC(x,h), \tag{7}$$

where

$$a = \frac{h\alpha\beta u(h) + w(h\beta_r - 1 + \xi)}{K(h)}, \tag{8}$$

$\xi = \frac{c(x\,0)}{c(x\,h)}$; a is the coefficient of particle retention by plants; β is the specific area of plant projection at the surface, normal $\bar{u}$; β_r is the specific area of the horizontal plant projection; and K is the coefficient of convective diffusion.

The source specification is

$$c(0,z) = \frac{G}{u(H)}\delta(z-H),$$

where δ is the symbol of the delta function; G is the output of the continuous linear source, kg./m./sec.

The infinity specification is

$$c \to 0 \quad \text{when} \quad \sqrt{x^2+z^2} \to \infty.$$

The solution for this problem when

$$K(z) = kz, \quad u(z) = u_1 z^n$$

(which corresponds to an isotherm), is given in [6], u_* is the "flow rate", z_0 is the coefficient of roughness. Together with the precise solution, there is a rough formula for area of additive precipitation on the ground

$$g_0 = \frac{\xi w c_0(x,0)}{\alpha\beta h u(h)/w + \xi}, \tag{9}$$

where

$$c_0(x,0) = \frac{G(1+q)}{Hu(H)}\frac{\exp(-A/x)}{\Gamma(1-p)}\left(\frac{x}{A}\right)^{p-1}, \tag{10}$$

This is the solution of Rounds [7] when z = 0 for the same problem, but without taking into consideration inertia precipitation; along with condition (7), the condition is adopted

$$K(z)\frac{\partial c(x,z)}{\partial z} \to 0 \quad \text{when} \quad z \to 0.$$

Here Γ is the gamma-function symbol,

$$A = \frac{Hu(H)}{0{,}4(1+q^2)u_*}, \quad p = \frac{w}{4u_*(1+q)},$$

u_* is the "flow rate."

A comparison of calculated results by formulas (9) and (10) with experimental data will be given.

An experimental investigation of aerosol precipitation from a vertical, turbulent stream formed by a moving generator was conducted at Krasnodar Kray and the Armenian SSR [8], and in the Kustanay Oblast [3]. The tests [8] were conducted with EAU-1 and AG-L6 aerosol generators furnished with a Venturi directional adapter; the liquid was atomized by a rapid stream of air in a narrow-gage nozzle. The output and capacity of the jets in these two generators were approximately identical. In tests [3], the OPS-30, a considerably more powerful generator equipped with a directional nozzle having large through-flow sections, was used. The long range vertical stream formed by this generator provided a coverage of up to 200 m. in width.

In tests, a generator installed on a two-wheeled trailer or on the platform of a motor vehicle worked perpendicular to the wind at a rate of 4 to 6 km./hr. On the ground, parallel to the wind, ditches and glasses for measuring the amount of liquid settling to earth under the plants and the size of precipitated droplets were spread out.

At first the glasses were covered by a layer of zinc stearate or silicon to provide a constant contact angle (coefficient of spreading) for drops of different sizes. Glasses with droplets were observed under microscope; the drops with their splash were counted and measured into classes of sizes taking into consideration the examined area of the glass. Preliminary tests showed that the effect of vapors of drops of nonvolatile liquids (transformer and solar oils) could be disregarded.

In comparisons with theory, the generator of a poly-dispersed aerosol was considered as the accumulation of several sources of a monodispersed aerosol (of fractions with a narrow range of drop sizes) moving independently of one another; the settling of each fraction was analyzed individually.

The dispersion of the aerosol in the stream upon exiting from the generator was determined using a cascade impactor with a slotted closing device. The output of the source, corresponding to i aerosol, was assumed equal to $G_i = Gh_i$, where h_i is the relative weight of fraction i on leaving the generator.

During each test, gradient measurements of the mean wind velocity u and air temperature t at heights of 0.5 and 2 m. were made. The coefficient of roughness z_0 was determined by the results of gradient measurings in isotherms.

The tests were made on level plains covered by sparse grass 5 to 15 cm in height (lowland, virgin soil).

Table 1

Test Number	Time of start of test	Test Site	Generator	Liquid	Height of nozzle open end off ground, m.	Radius of nozzle open end, m	Velocity of aerosol emanation, m./sec.	Outlay of liquid Kg./min.	Wind Velocity m./sec. 0,5	Wind Velocity m./sec. 2,0	Difference in air temperature $t_{0.5} - t_{2.0}$
1	6 42	Krasnodar Kray	EAU-1 with directional nozzle	Transformer oil	1,70	0,04	32	3,26	2,3	3,0	—0,07
2	6 12	"	"	"	1,70	0,04	32	3,21	2,3	3,0	+0,1
3	6 12	"	"	"	1,70	0,04	32	3,02	2,2	2,9	+0,06
4	14 16	"	"	"	1,70	0,04	32	3,16	2,2	2,9	+0,12
5	16 10	Armenian SSR	AG-L6 with directional nozzle	Solar Oil	1,80	0,022	73	3,05	4,5	6,3	+1,9
6	16 38	"	"	"	1,80	0,022	73	3,15	5,1	7,0	+2,1
7	19 47	"	"	"	1,80	0,022	73	2,98	4,3	5,7	+0,5
8	19 05	Kustany oblast	OPS-30 with directional nozzle (twofold treatment)	"	2,8	0,1	41	13,5	3,4	4,5	—0,04

Table 2

Fraction d = 90 to 122 μ

Test Number	ξ^1	w m/sec.	h^1 м	$\alpha\beta h^1$	$u(h)$ m/sec.	G gm/sec.	ζ	H м	z_0 м	u^1 m/sec	φ	u (H) m/sec.
1, 2, 3, 4	1,0	0,214	0,05	0,0015	1,5	69,5	0,144	3,80	0,0052	0,199	0,176	3,3
5, 6, 7	1,0	0,214	0,05	0,0015	2,8	61	0,248	3,07	0,0043	0,42	0,213	6,7
8	1,0	0,214	0,08	0,006	2,8	257	0,310	6,60	0,0066	0,30	0,150	5,4

[1] (see [6])

In order to decrease the effect of fluctuations in the area of aerosol settling g, for comparison it is expedient to use the average results of several tests conducted in approximately identical meteorological conditions, or during a twofold treatment when fluctuation is less. These test conditions are presented in Table 1.

For comparisons, the average values of settling area g_0 of individual fractions of an aerosol for each group of tests were selected, and the values of parameters given in Table 2 were used in calculations.

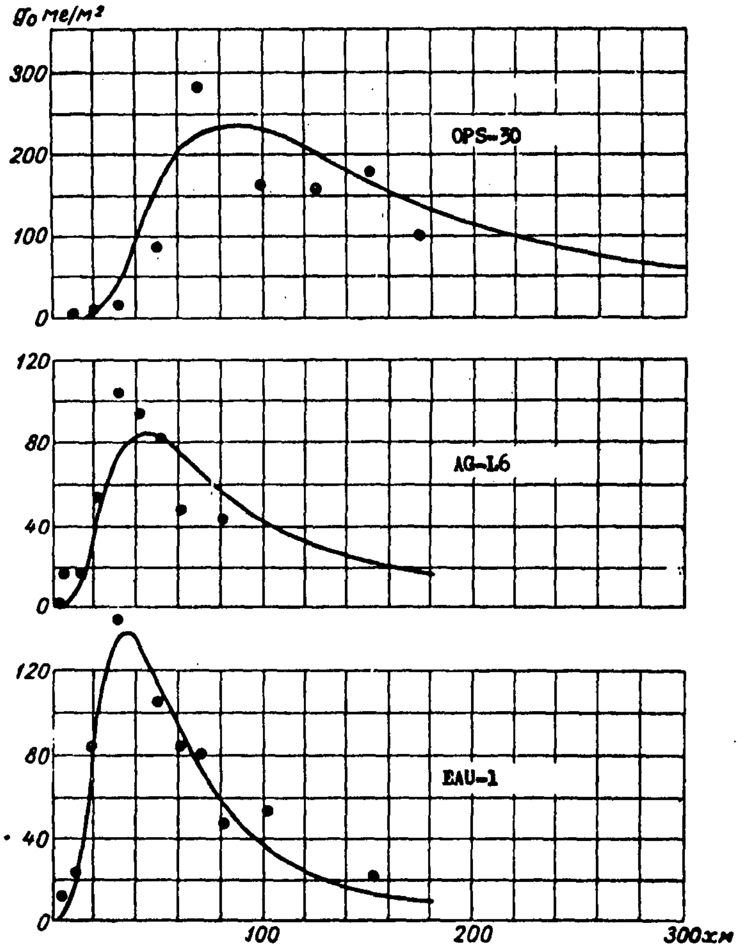

Fig. 1. Calculated and measured values of density of g_0 drops of a diameter 8-114 mc at a flow of aerosol, directed upward.

It is not hard to ascertain that in view of the small values of $a\beta h$, the denominator in the right section of formula (9) is close to one (i. e., in the given conditions [low, sparse grass, 100-micron drops] inertial settling plays a secondary role).

In Figure 1, the results of calculations (unbroken lines) and tests (dots) for one of the aerosol fractions in three different generators are compared. Agreement between measured and calculated values of g_0 is satisfactory. Analogous results have been obtained for other fractions also.

In this manner, the adopted method (using the theory of convective diffusion with the inclusion of the theory of turbulent currents) gives results that satisfactorily agree with test data, and leads to formulas applicable for approximate practical calculations.

(i) The element of an aerosol stream at height H can be roughly examined as a point source, since the sizes of the stream cross-section at this height are small in comparison with H.

(ii) In the sense of generated precipitations.

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CALCULATION OF DISPERSAL OF PRECIPITATING CONTAMINANT FROM A LINEAR SOURCE IN THE BOUNDARY LAYER OF THE ATMOSPHERE

V. F. Dunskiy, I. S. Nezdyurova and R. I. Onikul

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Each year, industrial plants and electric power stations discharge millions of tons of dust and ash into the atmosphere, and agricultural aviation disperses mineral fertilizers, herbicides, insecticides, etc., over tens of millions of acres. In this connection, the study of the characteristics of atmospheric diffusion of a precipitating aerosol is of great practical importance. Consideration of the rate of atmospheric diffusion as a function of meteorological conditions permits an efficient organization of a set of steps designed to insure the purity of air in the lowest layer of the atmosphere, and in particular, makes it possible to select the height of stacks and cleaning units and to carry out aircraft spraying in the most economic manner.

In view of the complexity of the process of atmospheric diffusion and of the large number of factors that affect it, the calculation of the concentration or density of precipitation on the underlying surface from the characteristics of the initial discharge and meteorological parameters should be carried out on the basis of a solution of the equation of turbulent diffusion. Comparison of the calculations and experiments refines the parameters of atmospheric diffusion and the scope of applicability of the theory, errors are discovered, and possibilities of generalizing the results to other climatic conditions are evaluated.

The solution of the equation of turbulent diffusion of a precipitating contaminant by analytical methods taking into consideration the actual variations of the austausch coefficient and wind velocity with the height involves considerable difficulties. In this connection, a few years ago, the Main Geophysical Observatory (4, 5) conducted studies on the numerical solution of this equation with computers for a wind changing as the log of the height, and for a model with a discontinuity for the vertical component of the coefficient of turbulent diffusion. Tables were complied for concentrations of the contaminant near the ground as a function of the height of the source, distance from the latter, and rate of precipitation of the contaminant; and formulas were obtained for conversion of these tables to various wind velocities and austausch coefficients.

On the basis of the numerical solution, calculations were made for the contamination of the air reservoir by ash from smokestacks of thermal power plants; they were confirmed by experimental data taken for various climatic conditions, with a wide variation of the height, diameter and number of stacks, rate of discharge and temperature of the stack gases and other parameters of the discharge (3,9). Experiments on the dispersal of a polydisperse precipitating contaminant, carried out by using a 300-meter meteorological mast, were processed on the same basis (1). The agreement of the calculations with the observations proved satisfactory, and data were obtained on the dependence of both the coefficient of turbulent diffusion and the contaminant concentrations near the ground on the height of the source, wind velocity, stratification of the atmosphere and fall velocity of the aerosol (6).

In (3-6), a method for using the numerical solution is presented for the case of a monodisperse contaminant. We shall discuss it here as it applies to the calculation of the precipitation on an underlying surface of a polydisperse contaminant dispersed uniformly over a segment of length L by an airplane flying at velocity v at right angles to the direction of the wind.

The calculation is based on the use of the principle of superposition, whereby the aerosol is subdivided into n fractions, for each of which the capacity of the source is known. The size of the particles in each fraction changes over a relatively narrow range, and this is used to find the precipitation velocity sufficiently characteristic of each fraction from the average diameter of the particles by means of the Stokes formula. The diffusion of each fraction is assumed to occur independently, i. e., the coalescence, evaporation and fine subdivision of the aerosol particles do not play any appreciable part in the experimental conditions. The concentration of the polydisperse aerosol at any point in space is treated as the sum of the concentrations of all the fractions.

We shall use a coordinate system whose origin is located on the underlying surface under the center of the source (lines of spraying of the aerosol), axis x being directed along the wind and axis y being parallel to the source.

The complete precipitation of the aerosol on a unit area of underlying surface q_p is calculated as the sum of the precipitations of the separate fractions

$$q_p = \sum_{i=1}^{n} q_{ip}. \qquad (1)$$

The amount of aerosol of fraction q_{ip} precipitating on a unit area of the underlying surface is calculated from the formula

$$q_{ip} = c_{Lip|z=0} t w_i. \qquad (2)$$

Here $C_{Lip}|_{z=0}$ is the concentration on the underlying surface of the aerosol fraction i from a source of length L; t is the time during which the source is acting

$$t = \frac{L}{v} \qquad (3)$$

W_i is the fall velocity of fraction i of the aerosol,

$$c_{Lip|z=0} = c_{ip|z=0} K(x, y), \qquad (4)$$

$C_{ip}|_{z=0}$ is the ground concentration of fraction i of an aerosol from a linear source of infinite length located at the same height and having the same capacity Q_i ($\frac{g}{m\ sec}$) as the linear source of finite length under consideration; K (x, y) is a correction factor allowing for the finiteness of the length of the source.

$$K(x,\ y)=\frac{1}{2}\left[\operatorname{erf}\left(\frac{2y+L}{4\sqrt{k_0x}}\right)-\operatorname{erf}\left(\frac{2y-L}{4\sqrt{k_0x}}\right)\right]. \tag{5}$$

The expression for K (x, y) was found by M. E. Berlyand with the assumption of similarity of the vertical distributions of the coefficient of horizontal turbulent diffusion and of the wind velocity $k_y = k_0u$ (2). This formula was obtained for a gaseous contaminant, but it also applies to a precipitating contaminant.

Taking (2-4) into consideration, one can write

$$q_{ip}=c_{ip|z=0}\frac{L}{v}w_iK(x,\ y). \tag{6}$$

The quantity C_{ip} is determined from the solution of the equation

$$u\frac{\partial c_{ip}}{\partial x}-w_i\frac{\partial c_{ip}}{\partial z}=\frac{\partial}{\partial z}k_z\frac{\partial c_{ip}}{\partial z} \tag{7}$$

with the following boundary conditions:

For x = 0 $\qquad c_{ip}=\frac{Q_i}{u}\delta(z-H);$ $\qquad$ (A)

For z = 0 $\qquad k_z\frac{\partial c_{ip}}{\partial z}=0;$ $\qquad$ (B)

For $z \to \infty$ $\qquad q\to 0.$ $\qquad$ (C)

Ref. (5) gives tables of a numerical solution of (7) with

$$u=u_1\frac{\ln\frac{z}{z_0}}{\ln\frac{z_1}{z_0}}; \tag{8}$$

$$k_z=\begin{cases}\nu+k_1z & \text{при}\quad 0\leqslant z\leqslant h\\ \nu+k_1h & \text{при}\quad z\geqslant h\end{cases} \tag{9}$$

Here k_1 and u_1 are the vertical component of the coefficient of turbulent diffusion and the wind velocity at unit height z_1 respectively, v is the coefficient of molecular diffusion for air, z_0 is the roughness of the underlying surface, and h is the height of the lowest layer of air.

In ref. (5), two tables (for h = 50 m and h = 100 m) at different values of the source heights H, distances x and fall velocities w_i give the quantity s, related in the CGS system to the quantities $C_{ip}|_{z=0}$ necessary for the calculation by the following formula:

$$s = \frac{c_{ip|z=0} \cdot 10^{12}}{\sqrt{x}\, Q_i}. \qquad (10)$$

Considering G_i, the total amount of fraction i of the aerosol discharged during the experiment

$$G_i = Q_i \frac{L}{v} \qquad (11)$$

and substituting (10) into (6), we obtain

$$q_{ip} = G_i s \sqrt{x}\, w_i K(x, y) \cdot 10^{-4}. \qquad (12)$$

In the calculations, G_i is taken in g/m, x in m, w_i in m/sec; the quantity s is taken directly in the units in which it is given in the tables of (5); in this case, the quantity q_{ip} is obtained in g/m^2.

The indicated tables were calculated for $u_1 = u_1^{(1)} = 4$ m/sec, $k_1 = k_1^{(1)} =$ 0.2 m/sec and $z_0 = 0.01$ m. We shall designate the quantity s given in the tables as $s^{(1)}$. If it is necessary to determine $s^{(2)}$ at $u_1^{(2)} \neq u_1^{(1)}$ and $k_1^{(2)} \neq k_1^{(1)}$, the following working formula will be used for a linear source

$$s^{(2)}(x, w_i) = A s^{(1)}(x', w_i'), \qquad (13)$$

where

$$\left.\begin{aligned} A &= \left[\frac{u_1^{(1)}}{u_1^{(2)}}\right]^{\frac{3}{2}} \left[\frac{k_1^{(2)}}{k_1^{(1)}}\right]^{\frac{1}{2}}; \\ x' &= \frac{k_1^{(2)}}{k_1^{(1)}} \frac{u_1^{(1)}}{u_1^{(2)}} x; \\ w_i' &= \frac{k_1^{(1)}}{k_1^{(2)}} w_i. \end{aligned}\right\} \qquad (D)$$

According to formula (13), $s^{(2)}$ is found from tables calculated for the same H, h and z_0. To this end, the value of $s^{(1)}$ at distance $x = x'$ for $w_i = w_i'$ is determined. The value obtained is multiplied by A.

Data on experiments carried out in June-July 1960-1961 were published in ref. (8). In these experiments, using an AN-2 airplane on which an Avia sprayer [Ed. note "for aerosol spraying"] was mounted, a linear source of finite length approximately perpendicular to the wind was created at heights of 100 to 600 m. The flight velocity v was 170 km/hr, and the source length L varied from 8 to 16 km. The airplane sprayed a water-glycerine mixture. The principal method of measurement of the amount of aerosol deposited on the underlying surface consisted in a microscopic analysis, made after the experiment, of glass plates laid out on the experimental field in rows parallel to the line of flight. The distance between plates in the same row was 500 m, and the length of the row was close to the length of the source. The distance between neighboring rows in some of the experiments was 500 m, and in the remaining ones, 1000 m. The aerosol was considered to consist of 7 to 8 fractions. Each fraction was considered to be approximately monodisperse, and from the average particle size, using the Stokes formula, the mean fall velocity w_i, which varied from 0.01 to 1 m/sec, was calculated for each fraction.

A method of determination of the capacity of the source G_i for each fraction was developed in special experiments. In the microscopic analysis of the glass plates, the number of droplets of different sizes was counted, and after conversion to the number per unit area, the density of deposition of each fraction q_{ie} was determined.

If the above-mentioned superposition principle is used, each experiment with a polydisperse aerosol (flight) may be treated as several combined experiments with different monodisperse aerosols under the same meteorological conditions.

At one point on the edge of the experimental field, the vertical distribution of temperature and wind velocity was determined by means of an aerostat and pilot balloons. On the basis of these observations, the parameter characterizing the stratification of the atmosphere was calculated for each flight:

$$\alpha = -\frac{\Delta T_{100-1.6}}{\Delta u_{100-1.6}}, \qquad (14)$$

where $\Delta T_{100-1.6}$ and $\Delta u_{100-1.6}$ are, respectively, the differences of temperature and wind velocity at heights of 100 and 1.6 m averaged over the time of the experiment. The necessity of averaging was due to the fact that the experiments were conducted in the morning (5-6 A. M. or evening (6-8 P.M.), so that there were marked changes in the meteorological conditions.

In all, data for 12 of the most qualitative experiments are given, divided into the following two groups according to the values of parameter α: A $(-0.3 < \alpha < +0.1)$ and B $(+0.3 < \alpha < +0.5)$.

M. I. Yudin (10) showed the necessity of carrying out experiments that make it possible to make separate studies of the atmospheric diffusion of particles with different fall velocities. The above-described studies apparently constitute one of the first attempts to gather such experimental material, which is suitable, in particular, for studying the dependence of the vertical coefficient of turbulent diffusion on the fall velocities of the aerosol. Use of data on the dispersal of an aerosol from a linear source permits the study of this effect in a comparatively pure form, since the influence of turbulent diffusion in the direction of axis y is excluded in this case.

Processing and analysis of the experiments were carried out on the basis of the above-described method of utilizing the results of a numerical solution of the equation of turbulent diffusion. In view of the fact that ref. (8) gives only the value of wind velocity u averaged over the layer from the underlying surface to the source and over the time of the experiment, the value of the calculated velocity $u_1^{(2)}$ was determined from the formula

$$u_1^{(2)} = \frac{\bar{u} \ln \frac{z_1}{z_0}}{\ln \frac{H}{z_0} - 1}. \qquad (15)$$

For $u_1^{(2)}$, given by formula (15), and $z_0 = 0.01$ m, for which the numerical solution of the equation of turbulent diffusion was carried out, the mean value of the wind in the layer from z_0 to H is also equal to $\bar{u}$.

In ref. (8), for leveling purposes, values are given for the precipitation of the aerosol on the underlying surface, averaged over the entire sampling line, which was parallel to the source. Calculations made with formula (5) showed that for the source length and sampling lines employed, considering that k_0 is of the order of 1 m, one can compare the calculation with observations at K (x, y) = 1 with an accuracy sufficient for practical purposes.

The available tables of numerical solution of the equation of turbulent diffusion, partially published in ref. (5), proved to be sufficient for processing the data of 8 flights: 1, 2, 3, 4, 5, 6, 6, 9 and 11, using the numbering given in ref. (8). For four of them, the flight altitude was 100; for three, 200; and for one, 400 m. Use of the superposition principle made it possible to process independently each fraction of each flight, i. e., essentially, 56 experiments were analyzed. The results showed that in ten of them, the arrangement of the plates on the ground did not permit the determination of the maximum precipitation of a given fraction on the underlying surface. For the lightest fractions, this was due to the lack of measurements at large distances from the source, and for heavy fractions, at short distances. Therefore, 46 experiments were found to be suitable for processing.

We shall use the following designations: q_{mie} and x_{mie} -- experimentally determined values of the maximum precipitation of a given fraction of aerosol on the underlying surface and distance from the source to the line where the maximum precipitation was observed; q_{mic} and x_{mic} -- corresponding values obtained by calculation. At the first stage of processing for each experiment, the solution of the reverse problem was used to obtain the optimum k_1 independently from the following relation:

$$\left| \frac{q_{mic}}{q_{mie}} - 1 \right| = \min, \qquad (16)$$

provided that

$$0.8 \leqslant \frac{x_{mic}}{x_{mie}} \leqslant 1.2. \qquad (17)$$

In 8 out of 46 cases it was found that $\frac{q_{mic}}{q_{mie}}$ for the same value of k_1 does not fall within the 0.5-2 range; these cases were excluded from further analysis, since apparently the aerosol deposits had been measured with substantial errors.

In all, 38 values of k_1 were determined; for six experiments of the first, second and ninth flights; five experiments of the fourth and seventh flights; four experiments of the third flight; and three experiments of the fourth and eleventh flights. From these data, the average value of the austausch coefficient k_{1av} was determined for each flight.

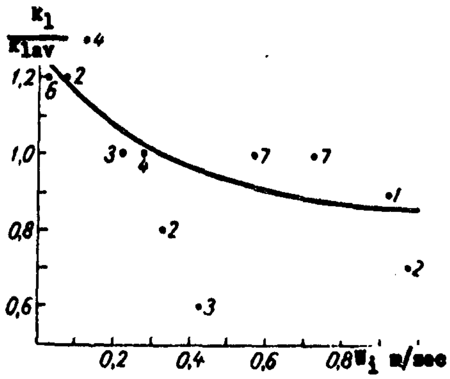

Fig. 1.

Fig. 1 shows the dependence of $\frac{k_1}{k_{1av}}$ on the fall velocity w_i. Normalization of k_1 values to their average value from several experiments pertaining to the same meteorological conditions made it possible to plot the data of all 38 experiments on one graph. The entire range of change of w_i was broken up into intervals 0.05 m/sec each, the graph shows the average value of $\frac{k_1}{k_{1av}}$ for each interval, and indicates the number of cases in the given interval.

The figure shows a certain dependence of the austausch coefficient on the size of the aerosol particles, which is possibly determined by the influence of the effect theoretically predicted by M. I. Yudin (10). Studies in this direction should be continued by processing a substantially larger volume of observations, so that it will be possible to reduce the influence of errors inherent in the experiment and theory.

Under the experimental conditions employed, the influence of this effect was comparatively slight, and apparently, at the present time, we can confine ourselves in practical calculations to certain average values of the coefficients of turbulent diffusion. Let us consider this question in more detail. The solid lines of Figs. 2 and 3 characterize the frequency of errors of the numerical calculation in the determination of k_1 according to conditions (16) and (17); in the majority of cases, the agreement was found to be satisfactory both in the magnitude of maximum precipitations and in the distances at which they are observed. In approximately 80% of the cases, the error in the calculation of q_{mic} does not exceed 0.3 q_{mie}. The errors in the calculation of x_{mic} are also small, but the shape of the graph of the frequency of different $\frac{x_{mic}}{x_{mie}}$ values indicates that the results from which Fig. 1 was plotted are not free from systematic errors.

In Fig. 2 and 3, the dashed lines show the frequency of errors for the case where a constant value of k_1 equal to k_{1av} was taken in the calculation for all the experiments of a single flight. On the average, the errors in the calculation of the magnitude of maximum precipitations were found to change insignificantly. Errors in the determination of distances at which the maximum precipitations were observed increased somewhat more markedly, but the shape of the error distribution became more reliable. Therefore, considering that the dependence of the austausch coefficient on the fall velocity of the aerosol has been insufficiently studied, it is possible to carry out the calculations at constant k_1. This is confirmed by Fig. 4, on which for the sixth flight at $k_1 = k_{1av}$, a comparison was made of the calculated (solid lines) and measured (dashed lines) precipitations on the underlying surface of a height source H = 200 m, average wind velocity in the layer from the ground to the source u = 4 m/sec, coefficient of turbulent diffusion in the boundary layer of the atmosphere k = 14h = 25 m^2/sec. For all the fractions except one, the agreement may be considered satisfactory.

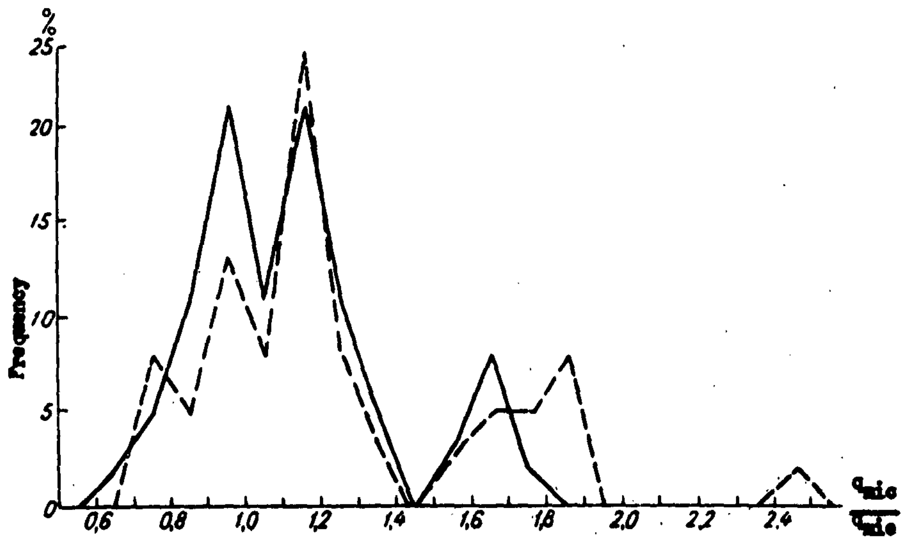

Fig. 2.

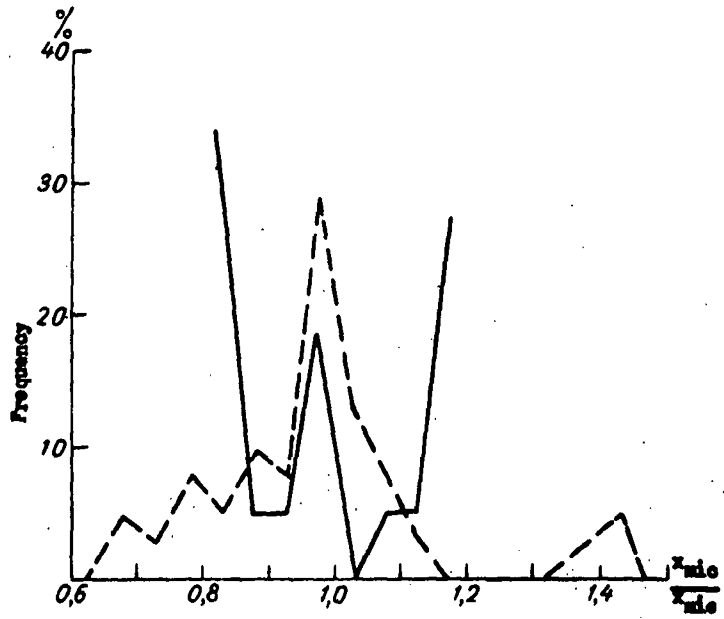

Fig. 3.

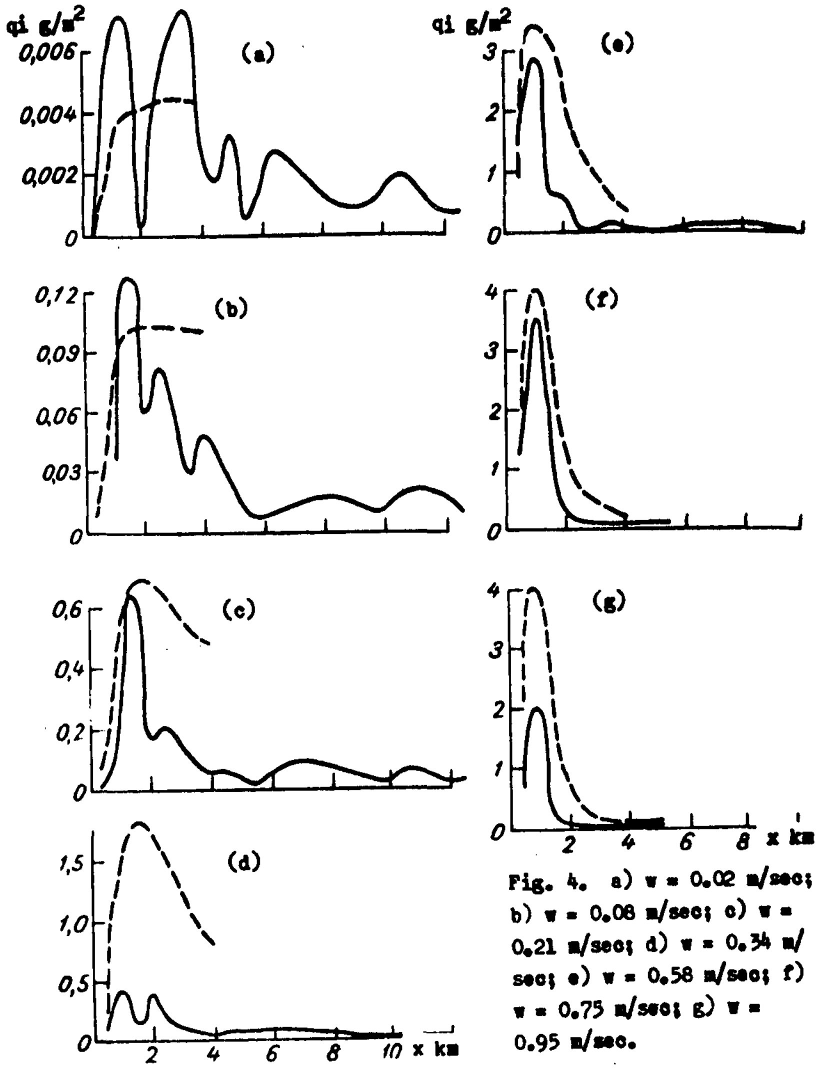

Fig. 4. a) w = 0.02 m/sec; b) w = 0.08 m/sec; c) w = 0.21 m/sec; d) w = 0.34 m/sec; e) w = 0.58 m/sec; f) w = 0.75 m/sec; g) w = 0.95 m/sec.

It follows from this figure that for the heaviest fractions at a frequency of sampling lines of 0.5 km and even more so at 1 km, considerable errors may occur in the determination of the magnitude and position of the maximum precipitations of the aerosol on the underlying surface. This accounts in particular for the undesirability of striving for an accurate agreement between the calculation and experiment and a very high accuracy of the numerical solution of the equation of turbulent diffusion, since the latter involves a considerable investment of equipment and computer time.

We shall compare x_{mic} with $x_0 = \frac{H\bar{u}}{w_i}$, which characterizes the distance at which all of the contaminant would precipitate at fall velocity w_i, if the influence of turbulent diffusion is excluded. The dependence of $\frac{x_{mic}}{x_0}$ on w_i based on the data of all 38 cases is given in Fig. 5.

It is apparent from the figure that as the rate of turbulent austausch increases, the distance from the source to the line on which the maximum precipitation is observed decreases. For a stable stratification, as w_i increased, x_{mic} rapidly approached x_0. Under such conditions, the values of q_{mic} and the width of the band where the dispersal of the contaminant takes place depend primarily on k_1; therefore, in determining k_1, a decisive part is played by the agreement between q_{mic} and q_{mie}. In the presence of strong turbulence, over the entire range of w_i considered (0.01-1 m/sec), the maximum precipitation of the contaminant was observed at distances substantially less than x_0. The figure also shows that in determining k_1, the agreement between x_{mic} and x_{mie} plays the most decisive part in light fractions.

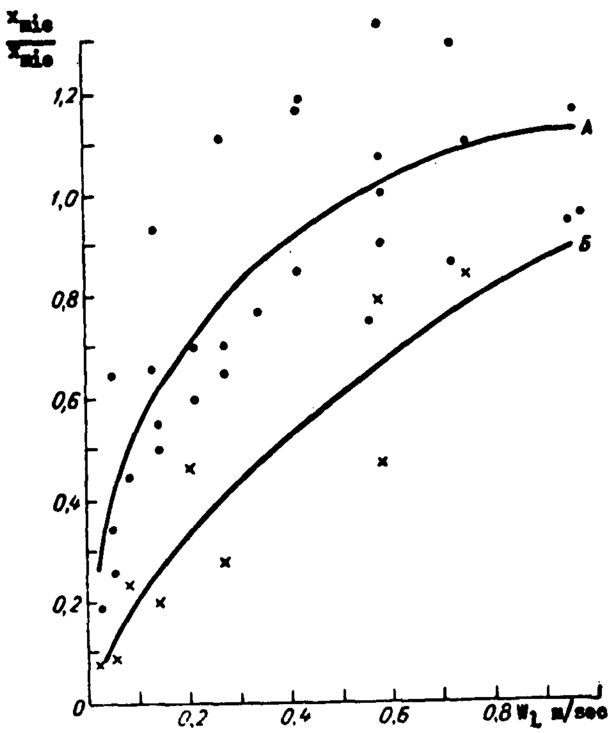

Fig. 5.

It was indicated above that all the experiments were divided into two groups, A and B, depending upon parameter α, which characterizes the stability of the atmosphere. The calculations showed that for experiments of group A, conducted in the presence of a more stable stratification, the average value of the coefficient of turbulent diffusion at source level H, equal to $k_{1av}H$, ranged from 2 to 20 m^2/sec, and in the presence of unstable stratification (group B), from 25 to 40 m^2/sec.

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