KEYNOTE

ACTUAL PROBLEMS OF DEVELOPMENT OF AIR POLLUTION MODELLING AND ITS INFLUENCE ON THE ENVIRONMENT

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SUMMARY. The main directions of developing the atmospheric diffusion and air pollution modelling connected with its application are considered. The modelling is based on numerical integration of the turbulent diffusion equation together with the equation system which determines plume rise and the structure of atmospheric boundary layer including the spatial distribution of wind velocity and exchange coefficient. The solution and results of calculating of the concentration fields from different types of single and multiple industrial and motor transport sources are presented. Increasing the scale of dispersion acquired the improvement of the model which consisted in account of pollutants deposition due to their interaction with the underlying surface. The main results of the calculating methods have been confirmed on numerous experimental data and entered into official documents approved by the government services for obligatory use when designing and exploiting enterprises.

1. INTRODUCTION.

In recent years the methods of atmospheric diffusion modelling have acquired greater importance and a leading role in solving the problems of environmental protection, especially in urban and industrial areas. Air basins of these regions, where the most part of population is concentrated, are the important objects for application of the modelling results. Over urban territories numerous air pollution sources are distributed and their dimension have a tendency to increase. The impact of these sources on urban area and on city environs is also increasing. Therefore, the problem is to take into account not only different types of sources but also the increase of distances from them. The last, in its turn, is connected with accounting for a number of factors, which may be neglected when modelling local processes. These factors include the interaction of pollutants with the underlying surface and possible transformation of some pollutants.

The main directions of model development are connected also with application of the obtained results.

First of all, they are intended for establishing maximum permissible emissions for air quality standards and other criteria for toxic pollutants influence on the environment (soil, water, forest).

Solution of modern problems in some important cases requires accounting for physics and chemistry of investigated processes rather completely, as well as the increase of spatial scale of emission dispersion from their sources.

The problems of atmospheric diffusion and air pollution modelling are described in a number of books and conference proceedings (Pasquill 1974, Newstadt and Von Dop 1982, Hanna 1982 Renderson 1984, Stern 1985, Venkatram and Wyngaard 1988, Szepesi 1989, Kretzchmar et al. 1994 and others).

This presentation concerns mainly the investigations performed in the Main Geophysical Observatory (MGO) and aimed at accounting for some factors which are typical for urban and industrial areas. The investigations include modelling of pollutant distribution based on a solution of systems of equations describing the atmospheric diffusion under different meteorological and topographical conditions (Berlyand 1982, 1991a, 1994, Berlyand et.al. 1984, 1987a, b, 1990, 1992a).

The main principles of the proposed models have to do with integrating this system of the atmospheric diffusion equation and equations that determine the atmospheric boundary layer (ABL) structure including the spatial distribution of wind velocity and turbulent exchange coefficient.

Due to a great number of factors determining the turbulent diffusion and dispersion conditions for their modelling, numerical methods of solution of equations describing these processes, are widely used. Modern computer techniques allow more significant and universal results to be obtained compared with different modifications of the Gaussian models obtained on the empirical statistical base. However, the application of the numerical integration results often becomes difficult and does not allow clear identification of the nature of pollutant distribution or the determination of the role of separate factors.

In principle, generalization of numerical experimental data creates the same difficulties as treatment of observations. The difference mainly lies in the fact that in the former the initial data can be obtained in much greater amounts. Therefore, for heuristic aims an analytical solution of the problem with certain simplifications may be useful for speeding up and increasing the generalization efficiency of calculation results. Thus, for calculating air pollution in the surface layer it is suitable to use the solution of the turbulent diffusion equation for the case when the change of wind velocity and the exchange coefficient with height are determined by the power law. Such an analytical solution law was obtained by Berlyand (1963) and used to find an interpolation relation in the presented results of MGO.

2. THE INITIAL EQUATIONS AND PARAMETERS.

2.1 Atmospheric diffusion equation.

The initial equation of atmospheric turbulent diffusion in the Cartesian coordinate system is

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

where c is pollutant concentration, u and w are horizontal and vertical components of the motion velocity, k_z and k_y are horizontal and vertical components of the exchange coefficient; α is index of pollutant transformation; z=0 corresponds to the level of the underlying surface.

The second term in (1) disappears for gases and fine-particulated pollutants (for which w=0). If the unstationary term $\partial c/\partial t$ is added to (1), for practical purposes (in the accident case) the equation may be integrated over time t and become stationary again, but the concentrations c will be replaced by the dose $D = \int_0^t c\,dt$.

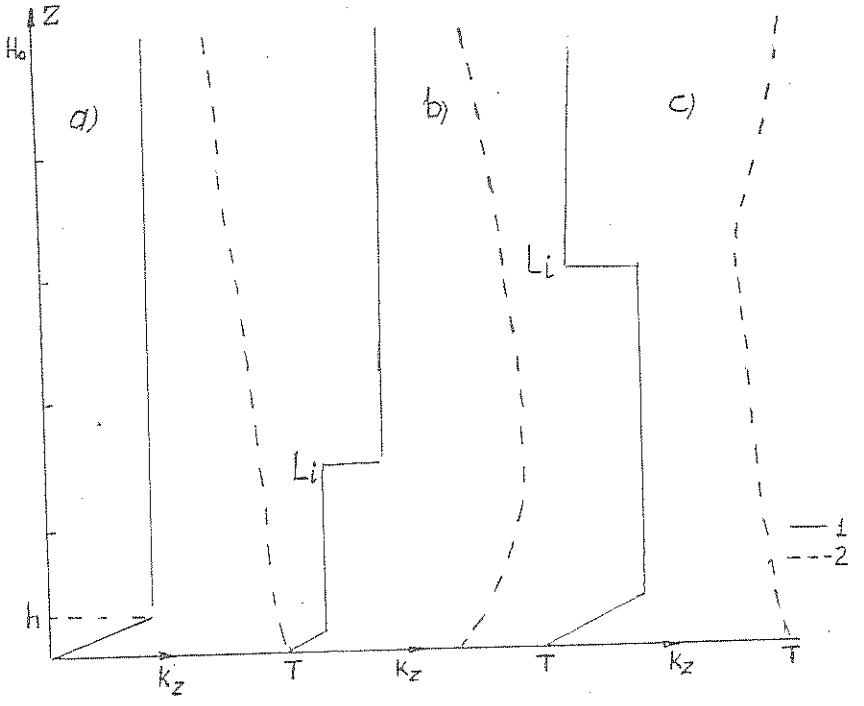

Fig. 1. Vertical profiles of exchange coefficient k_z at monotonous changing of temperature 1 with height z (a). ground inversion (b) and elevated inversion (c); 1 – k_z, 2 – T.

In the case of uneven terrain instead of x and z in (1) flow coordinates $\xi_1 \sim \varphi$ and $\xi_2 \sim \psi$ are used, where φ and ψ are real and imaginary parts of the function of conformal transformation of the flow domain to a half-plane.

The initial system of equations includes also equations determining the coefficients and parameters contained in (1) and the boundary conditions.

2.2 The plume rise.

Emissions from smoke stacks and other industrial sources always possess certain initial speed and often have temperature exceeding the ambient air. Therefore we account for initial rise of pollutant $_{\Delta}H$ or some effective height $H_e = H + {}_{\Delta}H$. The initial plume rise problem has been considered in many works. The main ones were published by Briggs (1969), Randerson (1984), Henderson-Sellers (1987). For determining $_{\Delta}H$ we used a system of equations of motion and heat transfer describing jet propagation in a shear flow (Berlyand, 1982).

$$u\frac{\partial w}{\partial x} + w\frac{\partial w}{\partial z} = \frac{\partial}{\partial z}k_z\frac{\partial w}{\partial z} + \frac{\partial}{\partial y}k_y\frac{\partial w}{\partial y} + \frac{g}{T_a}\vartheta \qquad (2a)$$

$$u\frac{\partial \vartheta}{\partial x} + w\frac{\partial \vartheta}{\partial z} = \frac{\partial}{\partial z}k_z\frac{\partial \vartheta}{\partial z} + \frac{\partial}{\partial y}k_y\frac{\partial \vartheta}{\partial y} \qquad (2b)$$

where ϑ is deviation of pollutant temperature from the ambient temperature T_a.

The field of vertical velocity w is determined by numerical solution of (2). Then the obtained values w are substituted into (1) for determining pollutant concentration c. As a result of comparison of the surface concentrations, yielded from the solution of this system, with those, obtained from one equation of diffusion (1), for a source of the fixed height H, the initial plume rise H is found in the form

$$\Delta H = \frac{w_0 R_0}{u}\left(3.75 + 0.17\,\frac{R_0 \Delta T}{u^2}\right) \qquad (3)$$

Here w_0 and $\Delta_0 T$ are initial emission velocity (m/s) and heat excess (in K), respectively and u is wind velocity (m/s) at the vane height (10m), R_0 is stack radius.

Such a method of determining $_{\Delta}H$ gives less errors than methods for determining H_e at the height where the plume axis becomes almost horizontal because the accuracy of estimation strongly depends on the acceptable degree of axis steepness.

2.3 ABL structure

For determining wind velocity and exchange coefficient k_z, a system of equations of motion and turbulent energy balance should be solved. For the ABL it is accepted that

$$\frac{d}{dz}k_z\frac{dw}{dz} = 2\omega_z\left(w - w_g\right) \qquad (4)$$

where $w = u + iv$ and u , v are wind velocity components along the X and Y axes, ω_z is vertical component of the angular speed of the Earth's rotation and w_g is geostrophic wind velocity.

The solution of the equation (4) and investigation of the boundary layer structure was also considered in a lot of papers and in many books (Laikhtman (1970)), Zilitinkevich (1970), Monin and Yaglom (1973), Stull (1989), Garatt (1992)). Many important and interesting results were obtained, however, the turbulence in the upper part of the ABL, whose vertical length is greater by an order than that of lower part of it, has been investigated much less than the surface layer (SL).

The essential limitations of the results are often connected with accepted assumptions concerning atmospheric turbulence sources. So it is supposed that above the given grounds area such a source is created only due to interaction of the atmosphere with the underlying surface. As a result it is assumed that $K_z \to 0$ on the upper boundary of the ABL, where this interaction disappears. In reality the ABL turbulence depends also on permanent mixture of the air volume under consideration with the ambient air (adjacent to the top and the sides), including mixing during advective transfer. The ABL model in Fig. 1 and described by formulas

$$k_z = k_1 h \text{ at } z \le h,\ k_z = k_h \text{ at } z > h \qquad (5)$$

where $k_h = k_1 h/z_1$ is average value of k_z over SL (z>h), seems to be more justified.

By definition, in the SL, the friction tension $\tau = k_z\frac{du}{dz}$ and heat flow $P = k_z\frac{d\vartheta}{dz}$ are approximately constant. Using these properties and the general solution of (4) it is possible to obtain the approximation that at $z < h$

$$\mu = \mu_1\frac{\ell n z/z_0}{\ell n z_1/z_0} \qquad (6)$$

and

$$h = 0.05\,\frac{K_1}{\omega_z} \qquad (7)$$

From the conditions $w = w_g$ it can be shown determine that the height of the upper boundary of ABL $H_0 \approx 10h$ and from the solution of the turbulence energy equation – that in the layer $(h < z < H_0)$

$$k_h = k_{h0}\left(1 - r\,\bar{R}_i\right)^{1/2} \qquad (8)$$

Here k_{ho} is k_n under neutral conditions, R_1 is the Richardson number obtained by averaging the temperature gradient

$\overline{\frac{du}{dz}}$ and $\left(\overline{\frac{du}{dz}}\right)^2$ over the layer $(h < z < H_0)$.

To find the value k_1 from (8), a successive iteration process is used, assuming in the first approximation on the right hand side of (8) the value $k_n = k_{ho}$, corresponding to neutral stratification.

Such calculations show that when the temperature in ABL decreases monotonically (i.e. under neutral and unstable stratification H_0=1–2km and h=100–200 m. Under ground inversions at night even in the cases when they are rather developed the monotonic rise of temperature with height is restricted to hundreds or tens of metres. In this cases H_0 is of order one hundred or tens of metres and k_n is much less than under neutral and unstable conditions. Therefore it follows that up to larger heights the exchange coefficient decreases considerably from day-time to night-time not only near the ground but also at high levels. In reality, considering the ABL structure, the example during the diurnal course in the layer above the surface inversion the intense turbulence with the value k_h close to neutral conditions k_{ho} can be preserved. This layer, determined by Stull (1992) as a residual layer, is hardly investigated at all. At the same time an interest in it should arise in modern investigations of atmospheric diffusion for cases of high and powerful sources, when emissions from them are spreading up to heights of 1 km and more. For this purpose as shown in Fig. 1b,c, besides two layers (z<(H) and (h<z(L_1), a third layer $\left(z > L_1\right)$ should be introduced, when the upper boundary of the inversion is $z=L_1$.

The third layer in ABL is introduced also when within ABL (at $Z<H_o$) there is an elevated inversion above the unstable and neutral layer (Fig. 1c). The solution of the three-layer problem is performed similarly using (8) separately for the layers (h,L_1) and (L_1, H_o).

3. REGULATORY MODELLING OF AIR POLLUTION.

3.1 Air pollution from industrial sources.

Within the framework of the above mentioned works (Berlyand, 1982, Berlyand et.al., 1987a) based on atmospheric diffusion modelling, it was obtained that short-term (20-30 min) surface concentrations from a single and a group of closely located N sources, with account for the initial plume rise, may be determined by the formula.

$$C = C_m r S_1\left(x/Px_M\right) S_2(|y|/x) \qquad (9)$$

where C_m is the maximum concentration c at the distance $x = x_M$ along the downwind directed axis x (where y=0) and at the critical wind velocity $u = u_M$ at the vane height of 10m.

$$C_M = \frac{AMF\, m n}{H^2}\eta \sqrt[3]{\frac{N}{V\Delta T}} \qquad \text{or}$$

$$C_M = \frac{AMF\, m'}{H^{4/3}}\eta \quad (\text{when } \Delta T \approx 0) \qquad (10)$$

Here M and V are the total mass and volume of pollutants emitted per time unit from sources with height H, orifice radius R_o, velocity of gas escape M_o, gas overheating $-\Delta T$; A=0.3 (λ/φ_o), u_1=2m/s is defined by the characteristics of vertical (λ) and horizontal (φ_o) exchange where k_1 and u_1 are the values of the exchange coefficient k_z and wind velocity u at the height z_1=1m, φ_o is dispersion of wind direction fluctuations for the time interval 20-30 min, for which the concentrations are estimated; coefficient F is defined by the pollutant deposition velocity (for light pollutants and gases F=1, for dust F=1, 5-3); coefficient η determines the influence of the relief, for flat terrain $\eta = 1$; in case of the rough terrain η depends on the ratio of the vertical and horizontal lengths of the terrain obstacle, as well as the source location (Berlyand et al (1987a)). The tables and graphs for determining η are presented. For complex terrain with the height difference h_o when H/h_o (0.5) and the steepness of slopes about 10–15°, η=2–4. With the increase of H/h_o the η decrease and η=1–2 when H/h_o=3–5. Under the same height difference and the terrain slope the influence of a hollow is more than that of a ridge. The correction factor of building effect is also similar introduced (Berlyand et al, 1987b).

For practical use the functions, r, p, s_1, s_2 are presented in graphs and analytical form. For example the functions r, p are shown in Fig. 2 and expression s_1 (ξ) for ($1<\xi<8$) is

$$S_1(\xi) = \frac{1.13}{1 + 0.13\,\xi^2} \qquad (11)$$

while

$$S_2\,(|y|/x) = e^{\left(\frac{-y^2}{2\sigma_y^2}\right)} \qquad (12)$$

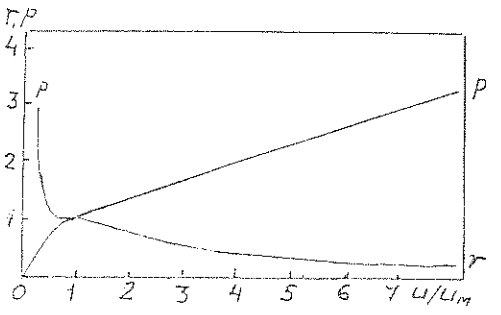

Figure 2. Functions $r = r\ (u/u_M)$ and $p=p(u/u_M)$

The formulae (9) and (10) are for calculating the concentration field from a cluster of sources on the basis of the superposition principle.

From the forms of the functions r, p and s_1 it can be seen that when $u>u_M$ with increasing u the value r is decreasing, but the value of p is increasing. The values s_1 grow correspondingly. Therefore at the distance $x\neq x_M$ at certain $u\neq u_M$, which is found from the condition $\partial c/\partial u=0$, the concentration reaches some maximum $C = c_{MX}$ that is less than c_M.

From general considerations, it follows that at $x/x_M>1$ and at rather large x_1 when the value x is increasing, the value U_{mx} is decreasing. The determination of U_{mx} is considered in more detail by Berlyand et. al (1977).

Now let us consider the relation between c_M and the stability index, λ. With the increase of λ the value c_M increases, but the value x_M on the contrary decreases, hence the values s_1 are also decreasing. So at the given $x>x_M$ it is possible to obtain from the equation $\partial c/\partial\lambda=0$ that at some values $\lambda=\lambda m$ the maximum value $c=c_{M\lambda}$ is reached. In this case $c_{m\lambda} < c_M$ and λ_M less than λ, that corresponds to c_M at $x=x_M$. With increase of x the values λ decreases.

Thus at rather large distances from a source the maximum concentration increases with the decrease of wind velocity u and stability index λ. By this it can be explained why in cities, when summarising "plume tails" from many sources, the largest concentrations are observed at

inversion and weak wind, close to calm. However the maximum value c_M (10) is reached in unstable conditions.

The values of concentrations (9), (10) are obtained for conditions where exchange coefficient k_z increases with height according to (5) and wind velocity u is changing with z approximately according to logarithmic low (6). It corresponds to comparatively frequently observed (normal) meteorological conditions. Besides these, anomalous dangerous weather conditions (elevated inversion, calm, fog and other) are treated separately. They happen rather infrequently and should be forecast and taken into consideration practically in 1-2 percent of the cases (Berlyand 1991b, Manual of air pollution forecasting, 1993).

3.2 Air pollution due to motor transport.

Emissions due to motor vehicles in city streets and highways may be represented in the form of line sources while those from a whole town or its districts with a branching motor transport net are treated as an area source.

The essential feature of car emissions is that the initial plume rise, which is characteristic of the most industrial sources and which essentially depends on wind velocity, is not typical for them. The height of these emissions does not practically depend on wind velocity at all. In general, a highway may be regarded as a volume source of height $h_c \simeq 2$m, covering the highway area. The important feature of such a line volume source is the dependence of concentration on the angle β between wind direction and the source line. The maximum concentration is reached at $\beta=0$, when the wind blows along the source. With increase in β, the distance from the source at which maximum concentrations are reached increases. For the case when $\beta=\pi/2$ (that is, when the wind blows perpendicularly to the highway), on the basis of numerical integration of the system of atmospheric diffusion equations, according to (Berlyand et al. 1990, 1992a) the concentration c, at distance x from a highway of width d_o, is determined by the formula :

$$c = \frac{1.24\ M}{\lambda u\ d_o \theta(x - d_o)} \left[f(x) - f(x - d_o) \right] \qquad (13)$$

where

$$f(x) = \ell n \left(\lambda x + \sqrt{h_c^2 + \lambda^2 x^2} \right)$$

Here M is the mass emission rate from unit length of the highway, $\theta(x - d_o)$ – the unit step function.

In Fig. 3 the computed concentrations of CO under unfavourable meteorological conditions from main roadways on area of 18x22 km in St. Petersburg are shown.

The important feature of emissions due to motor transport is that some of their main components, nitrogen oxides and hydrocarbons, in the atmosphere are subjected to photochemical transformation with very toxic oxidants, such as ozone, forming. To model these processes Berlyand et al (1992a) presented a numerical solution of, the atmospheric diffusion equations and a system of equations of photochemical reaction, which were used by Hoffert et al (1975). They obtained results for the ozone concentration changing with increasing distance x from a highway in daytime in summer under cloudless conditions as shown in Fig. 4.

Fig. 3. Maximal concentration of CO (mg/m^2) under unfavourable meteorological conditions from the main roadways and highways in the area of 19≠22 km^3 in St. Petersburg.

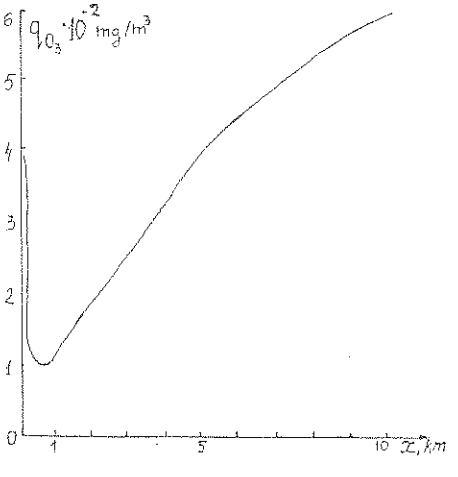

Fig. 4. Dependence of ozone concentration q on distance from a highway in a cloudless day in summer.

4. MEAN ANNUAL AND SEASONAL CONCENTRATION.

Mean annual and seasonal concentrations are determined on the basis of the results for short-time concentrations estimated with allowance for probability density $P(\varphi, u, \lambda)$ of wind direction φ and velocity u as well as stability index λ for the time interval under consideration. On the basis of statistical analysis of the observational data according to Berlyand et al. (1984) $P(\varphi, u, \lambda) = P(\varphi)p'(u)\,p''(\lambda)$ where $P(\varphi)$ is probability of wind direction with angle (φ) determined by the wind rose, and $p'(u)$, $p''(\lambda)$ are probability densities for u and λ. Hence in the general case the concentration c averaged for a long period is determined in the form.

$$\bar{C} = P(\varphi) \iint_{u,\lambda} c(u,\lambda)\; P'(u)P''(\lambda)\, du d\lambda \qquad (14)$$

Here

$$P'(u) = 2\frac{\sigma_2 - \sigma_1 + u\sigma_1}{\sigma_1\sigma_2^2}\; e^{-\left[\frac{\sigma_1 - \sigma_1 + u\sigma_1}{\sigma_1\sigma_2}\right]^2} \qquad \text{for } u > 1 \text{ m/s}$$

Where σ_1 and σ_2 can be defined directly by the mean value u and variation coefficient v_u of wind velocity in the considered region. For the considered averaging period the values u and v_u are available in climate reference books both for single season and years as a whole. For example, for Rudny station in Northern Kazakhstan the average annual values are σ_1=2.2, σ_2=4.0. In the case of u<1m/s (practically, it is calm in the surface layer) in the expression for P'(u) it is enough to accept the mean velocity $\bar{u}$ – 0.5 m/s and to use instead of p'(u) the frequency of calms F'(u) where P'(u)=dF'/du. For the function p'(u) the gamma-function is used

$$P''(\lambda) = \frac{u\alpha^u}{\lambda^{u+1}}\; e^{-\left(\frac{\alpha}{\lambda}\right)^u} \qquad (15)$$

Within the range of the observed values of α and u, the expression (15) approaches the δ –function.

Therefore $P''(\lambda)$ can be approximated by the corresponding δ– function. Substituting in (14), C from (9) at y=0 we obtain that

$$\bar{C} = B_i\, P_i(\varphi)\, C_M\, \phi_i \qquad (16)$$

where

$$\phi_i = r\left(\frac{0.5}{u_M}\right) S_1\left[\frac{b_i x}{p(0.5/u_M)x_M}\right] F'\left(uK\left|\frac{M}{s}\right.\right) + \int_1^{u^*} r\left(\frac{u}{u_M}\right) S_1\left[\frac{b_{ix}}{p(u/u_M)x_M}\right] P'(u)du$$

Where B_i and b_i are constants defined by the coefficient A and the average value of λ is determined in accordance with (10) which are different for each i–th seasonal periods u^* is a considerably high wind velocity observed in the considered region in less than 5 percent of the cases.

For determining the mean annual concentrations from (16) it follows :

$$\bar{C} = \frac{1}{4}\sum_{i=1}^{4} B_i(\phi)P_i(\varphi)C_M\phi_i \qquad (17)$$

For appropriate calculations Berlyand et al. (1984) proposed the use of the correlative dependence of mean annual concentration.

$$\bar{C} = a_1 P(\varphi) r \frac{0.5\bar{u}}{u_M} S_1\left[\frac{X}{1.3p(a_2 u/u_M)X_m}\right] \qquad (18)$$

where a_1 and a_2 are constants, $\bar{u}$ is mean annual wind velocity. Function r, p, and s_1 are the same as in (9) for short-time concentration.

5. POLLUTION DEPOSITION AND INTERACTION WITH UNDERLYING SURFACE.

When modelling local processes of air pollution, pollutant reflection from the underlying surface (z = 0) is usually assumed as a boundary condition. The interaction between pollutant and surface produces a flow $p = K\frac{dc}{dx}\Big|_{z=0}$ to the underlying surface and is defined as dry deposition of pollutants with deposition velocity v_d. It is assumed that

$$K\frac{dc}{dz}\Big|_{z=0} = V_d C \qquad (19)$$

The value of V_d is mostly obtained from the ratio P/C which is determined from the observed data at different heights within the interval from several to dozens meters. It is assumed also that P maintains a constant value, and (19) is taken as a boundary condition. Such an approach is justified if the initial equations of atmospheric diffusion relate to heights above the levels of constant P. In other cases it can lead to not very accurate results. Therefore in dispersion modelling it is expedient to account for the influence of dry deposition in concentration in the surface layer by the dependence on x of the total pollutants flow to the underlying surface

$$\Pi = \int_0^x \int_{-\infty}^{\infty} P(x,y)\, dxdy \qquad \text{, where } P(x,y) = V_d C$$

According to (9) and (12) it follows that

$$\Pi = \sqrt{2\pi}\,\varphi_o \int_0^x x\, P(x)_x \quad , \text{where } P(x) = V_d C\big|_{y=0}$$

It obtain the expression for P(x) and Π (x) as well as for concentration C the following iteration process is used. For the first iteration it is assumed that $c = c^{(1)}$, where from (9)

$$C^{(1)} = C_M\, r\, S_1\, (x/Px_M) \tag{20}$$

This coincides with the formula which is obtained for the condition of pollutant reflection from the underlying surface. Then $P^{(1)}=v_d C^{(1)}$ and

$$\Pi^{(1)} = ME \int_0^\xi \xi\, S_1\,(\xi)\, d\xi$$

where

$$E = \sqrt{2\pi}\; v_d\, \varphi_o \frac{C_M}{M} (Px_M)^2 \,, \xi = X/px_M \tag{21}$$

and we determine the coefficient $\chi^{(1)} = \dfrac{M - \Pi^{(1)}}{M}$

According to the i-th iteration

$$C^{(i)} = C^{(i)}\, \chi^{(i-1)} \qquad , \chi^{(i-1)} = \frac{M - \Pi^{(i-1)}}{M}$$

$$\Pi^{(i)} = ME \int_o^\xi \xi\, S_1(\xi)\, \chi^{(i-1)}\, d\xi$$

In practice it is enough to carry out about 5-10 iterations and then we get for $\Pi=\Pi^{(1)}$ approximately

$$\Pi = 1 - e^{-\gamma E\sqrt{\xi}} \tag{22}$$

From the results of calculation it also follows that even when V_d is rather large, to the distance $x=x_M$, $\chi=1$.

The correction for C is important only for comparatively large distance x at ξ , when it is determined by the coefficient E (21). These results allow us to increase the scale of the considered model up to several hundred kilometres and to use it more widely for estimation of air pollution and its deposition flow onto the underlying surface. The calculation of mean- annual and mean-seasonal values of pollutants flow, Π, is fulfilled similarly as far as concentration (14) using p'(u) and p''(λ) which are the same functions as for the concentration C. Similarly, the values of $\bar{c}$ and $p = \overline{v_d C}$ are obtained by taking into account the deposition effect.

It should be noted that a part of emissions emitted into the atmosphere in cities is washed out onto the underlying surface with precipitation; this also increases the toxic load on the environment.

The total flow Π(x) due to washing out with precipitation of pollutants from sources of emission rate M, up to the distance x is determined, (Berlyand, 1991a) by:

$$\Pi = M\left(1 - e^{-\gamma_1 x/u}\right) \tag{23}$$

where γ_1 is a parameter that is determined from the structure and intensity of precipitation.

6. VERIFICATION OF MODELLING RESULTS

The results of modelling are confirmed on vast experimental data of more than 40 expeditions organized by MGO in different climatic zones and regions with different types of sources (Berlyand 1982, 1991ab). In regions of heat, power stations with stacks from 20-30m up to 300m in height, the distributions of concentrations of SO_2, NO_x and ash up to the distances of 20-30 km were determined. Near large aluminium plants, the dispersion of fluoride emissions exhausted through line skylights on roofs of the factory buildings stretching 600-700 m length, were investigated. The expeditions were conducted in the vicinity of chemical enterprises in city environments and others. During these expeditions, together with measuring pollutants concentrations and their emissions, characteristics of meteorological conditions were determined. To verify the theory, the most complete sets of experimental data made abroad were also used. In general the agreement between the results of modelling and observations was satisfactory. As an example, the data for heat power stations with stacks of different height is given in Fig. 5.

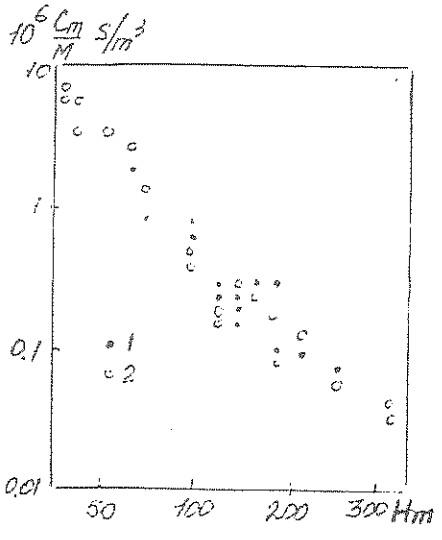

Fig. 5 Comparison of calculation (1) and experimental data on the ratio of SO_2 maximum concentration to emission rate (c_M/M) for power plants with stack heights H.

In MGO work, attention was also paid to experimental investigation of air pollution from motor transport under unfavourable meterological conditions (Burenin et al 1979, Berlyand et al. 1992b). To verify the calculations the data of the trace experiment in Detroit (USA) (Cadle et al, 1976) were used as well. The data obtained confirm the theoretically established dependence of concentration on distance from the highway, wind velocity, wind direction and etc. As an example of the comparison of calculated and observed data in summer daytime for the region of Donetsk city and on the data of the Detroit trace experiment, both for the angle between wind velocity and highway $\beta = 45°$, the values of normalized (per unit emissions rate) the concentration $\tilde{c} = c/M$ as depending on wind velocity μ are shown in Table 1.

Table 1

Comparison of computered and measured values $\tilde{c}$ of normalized (per unit emission rate) concentration CO.

Name of experiment	Distance from a highway	Data	Wind velocity μ (m/s)				
	x(m)		0.5	1.	2.	3.	4.
		exp.	0.22	0.18	0.13	0.09	0.06
Donetsk	50	comp.	0.22	0.19	0.14	0.11	0.10
		exp.		0.22	0.19	0.14	0.09
Detroit	15	comp.		0.26	0.23	0.18	0.14

7. THE PRACTICAL APPLICATION OF MODELLING.

The confirmation of model results by much experimental data allows their practical application and the development of regulatory standard documents. An important example is the Methodics (1987) model for air pollution calculation, which has been approved on the governmental level. Its application is obligatory when implementing air protection measures and estimating air pollution.

The calculations for unfavourable weather conditions mentioned above are used to plan better atmospheric protection measures for the long term. For the periods of anomalous dangers, meteorological conditions which are usually short, it is recommended to forecast them and take measures for temporary reduction of emissions, when they happen. For this purpose the Manual of forecasting air pollution (1993) is used.

The models for the cases of accidental emissions are being developed separately, Methodics (1991). One of their main features are emissions unstationary in time. Therefore instead of concentration C at dose D, which is mentioned above, its integral, meaned over time, is introduced. The Manual (1993) and Methodics (1991) are approved on government level and are for obligatory use.

The Methodics (1987) was widely used for establishing maximum permissible emissions (MPE).

By definition, MPE are established for every source in such a way that emissions from it and from neighbouring multiple sources in towns or residential areas should not create a surface concentration C exceeding the maximum permissible concentrations (MPC). If these air quality conditions are fulfilled for short-term (20-30 min) concentrations, then they will be fulfilled mostly for mean annual concentrations too. Therefore, calculations are performed mainly for short-term concentrations.

To establish MPE for sources located in an urban area it requires performing concentration calculations practically for all clusters of sources in it. In this connection in recent years calculations of concentration fields from multiple sources for the most important single ingredients have been performed in more than 500 towns of Russia and the former USSR. They have made use of the Methodics of calculation (1987) on the base of which 15 computer programs were developed. These programs allow us to account for thousands of sources typical for cities and provide calculations of concentrations of grid points with estimation of corresponding values of critical wind velocity and direction and so on.

When modelling air pollution in urban areas, the smallest sources may be neglected. Some groups of small sources are united into area and line sources. According to (Berlyand et al. 1987a, Methodics 1987) the sources for which $M/MPC(\varphi)$ may be not accounted for. Here M is total emission rate (in g/s) and $\varphi=0.01$, when their mean source heights $H>10$m or $\varphi=0.1$, when $H < 10$m. Some criteria for uniting small similar sources are proposed; they include their minimum distances to the nearest points of the grid, distances between neighbouring sources and so on.

As an example of the above mentioned calculations of air pollution in cities connected with establishing MPE, a field of maximum short-term concentrations under unfavourable meteorological conditions for the Russian city of Pskov with more than thousands sources are shown in Fig. 6.

Fig. 3 shown above may be considered as another example of such calculation, in which the concentration field of CO from a roadway net over a big area in St. Petersburg is presented. This calculation was performed by Burenin and Volkodaeva (194) using the same computer program that was used in Fig. 6.

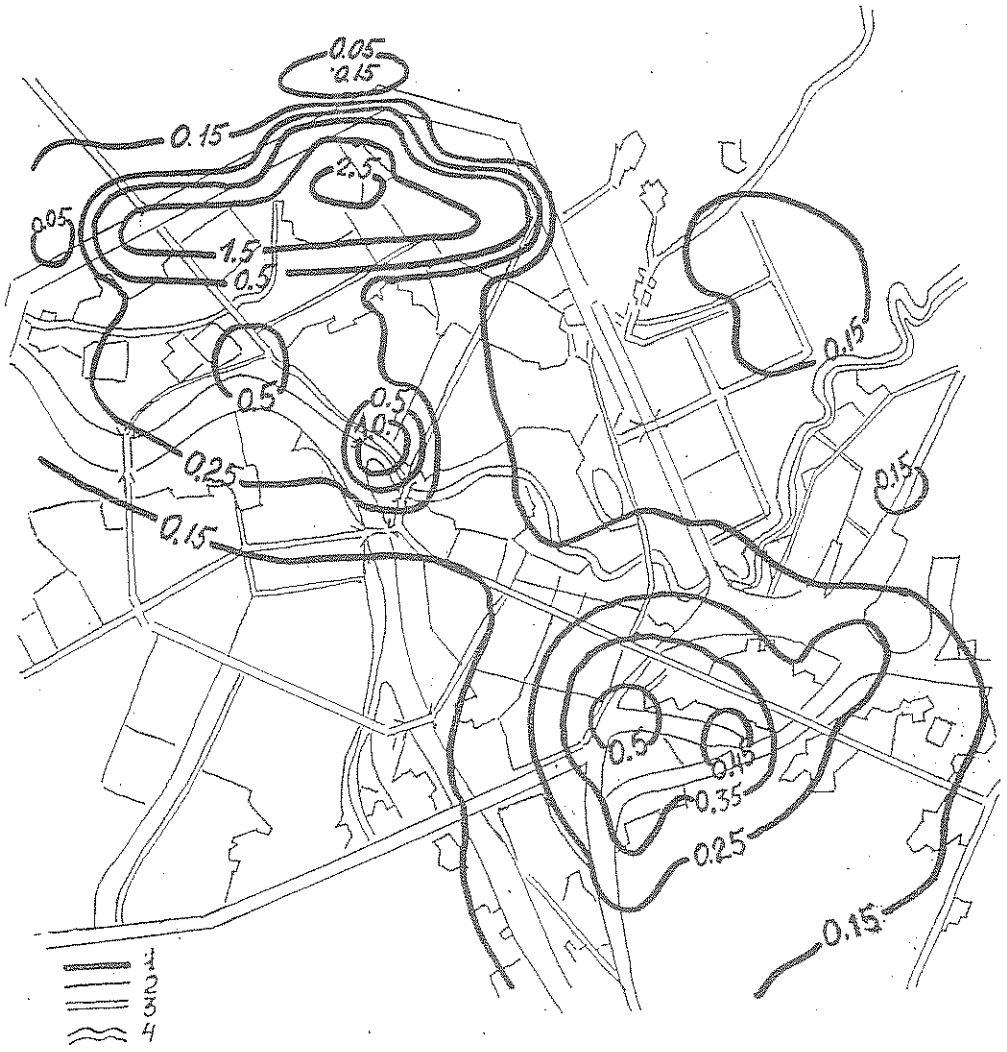

Fig. 6. Maximum concentration of SO_2 (mg/m^3) under unfavourable meteorological conditions in the city of Pskov. 1-isolines of concentrations, 2-3 streets, 3-highways, 4-river.

The account for pollutant flow onto the underlying surface allows us to arrive at a new approach to establishing MPE. At present they are determined by the condition that the maximum concentration C=MPC, from which, according to (10), it follows, in particular, that C is increasing up to zero when $H \to \infty$. It gives the possibility to increase MPE unlimitedly due to the increase in the emission height. If, in addition to this, the dependence (10) and the condition $\Pi = \Pi cr$ from (23) are accounted for, then the obtained value of MPE will not depend on the emission height.

8. CONCLUSION.

The results of the considered problems confirm the wide possibilities of modern methods of atmospheric diffusion and air pollution modelling at present. They play an important role in the evaluation of air quality and pollution influence on the environment, especially for solving practical problems of atmospheric protection, such as establishing maximum permissible emissions from industrial and motor vehicle sources.

REFERENCE

Berlyand M.E. On turbulent diffusion theory. Trudy GGO (Proc. MGO), N138, 31-38, 1963.

Berlyand M.E. Moderne probleme der atmospherishen diffusion und der ferschmutzung der atmosphare, Akad. Ver lag. Berlin, 436s, 1982.

Berlyand M.E. Problems of industrial air pollution modelling considering Soviet experience. Air pollution modelling and its application VIII, Plenum Press, New York, 16-26, 1991a.

Berlyand M.E. Prediction and regulation of air pollution. Kluwer Acad. Publ., Dordrecht, 312pp. 1991b.

Berlyand M.E. The main principles of atmospheric diffusion modelling for regulatory purposes using Russian experience. Operational short-range atmospheric dispersion models for environmental impact assessment in Europe. V.1., VITO, Mol, 149-158, 1994.

Berlyand M.E., Genikhevich E.L., Zashikhin M.N., Onikul R.I., The estimation of critical value of

wind velocity for high sources. Trudy GGO (Proc. MGO) N 387, 13-22, 1977.

Berlyand M.E., Genikhovich E.L., Chicherin S.S. Theoretical basis and calculation of technique for mean years pollutant concentration field from industrial sources. Trudy GGO (Proc. MGO), N 479, 3-16, 1984.

Berlyand M.E., Genikhovich E.L., Onikul R.I., Gracheva I.G., Filatova E.N., Khurshudyan L.G., On improving air pollution calculations method. Trudy GGO, N 511, 24-37, 1987a.

Berlyand M.E., Genikhovich E.L., Gracheva I.G., Zashikhin M.N., Kulic A.S., Chicherin S.S., Taking into account building when calculating air pollution. Trudy GGO, N511, 24-37, 1987b.

Berlyand M.E., Genikhovich E.L., Onikul R.I., Modelling of pollution of atmosphere by emissions from low and cold sources. Meteorology and Hydrology N5, 5-17, 1990.

Berlyand M.E., Genikhovich E.L., Ziv A.D., Onikul R.L., Tsyro S.G., Atmospheric diffusion modeling as a foundation of investigation of air pollution due to motor vehicles for practical applications. Proc. Sov. Americ. Symp. on mobile sources of air pollution. V.1, St. Petersburg, 87-104, 1992a.

Berlyand M.E., Burenin S.N., Genikhovich E.L., Onikul R.I., Panfilova G.A., Tsyro S.G., Experimental investigation of atmospheric pollution due to motor vehicles. Proc. Sov. Americ. Symp. on mobile source of air pollution. V.I., St. Petersburg, 105-121, 1992b.

Briggs G., Plume rise. US Atomic Energy Commission, Div. of Techn. Information, 81pp., 1969.

Burenin N.S., Onikul R.I., Solomatina I.I., On estimation of emission from motor vehicles into the atmosphere and pollution near roadways. Trudy GGO, N436, 102-110, 1979.

Burenin N.S., Volkodaeya M.V., To estimation of motor vehicles impacts on the atmosphere of St. Petersburg. Problems on protection of the atmosphere from pollution. MGO Inform. Bul. N 1, 1994.

Garratt G.R., The atmospheric boundary layer. Cambridge University Press, 316pp., 1992.

Hederson-Sellers B., Modeling of plume rise and dispersion - The University of Salford model : USPR. Springer-Ferlag. Berlin, 114pp., 1987.

Cadle S.R., Chock D.P., Hause J.M. Monson P.B. Results of General Motor sulfate dispersion experiment. Environ. Sc. Dep. General Motors Res. Lab., Waren, Michigan 48090, CNR 2107, EV-26a, 1976.

Hoffert M.I., Hoydysh W.G., Hammed S., Lebedeff S.A., Laboratory simulation of photochemically reacting atmospheric boundary layers : a feasibility. Atmos. Environ. V. 9, N1, 33-48, 1975.

Manual of air pollution forecasting, Berlyand M.E. and Sprkin L.R. (eds.). St. Petersburg, Gidrometeoizdat, 1993.

Methodics of calculating concentration of pollutants contained in industrial emissions into the atmospheric air.

Berlyand M.E. et. al (eds). Leningrad, Gidrometeoizdat, 100pp., 1987.

Methodics for forecasting the scale of contamination with poison substances under accident on chemically dangerous installations and during transportation, St. Petersburg. Gidrometeoizdat, 1991.

Newwstadt F. and van Dop. H. (eds). Atmospheric turbulence and air pollution modelling. D. Reidel P.C., Dordrecht, 358pp., 1982.

Pasquill F. Atmospheric diffusion. 2nd ed. J. Wiley, New York, 429pp., 1974.

Renderson D (ed), Atmospheric science and power production, Tech. Inf. Cont. US Dep. of Energy, 850pp., 1984.

Stern A. et.al., Fundamentals of air pollution, Acad. Press, 450pp., 1985.

Szepesi D.S. Compendium of regulatory air quality simulation models, Acad. Kindo, Budapest, 516p., 1989.

Venkatram A. and Wyngaard J.C. (eds). Lectures on air pollution modeling. AMS. Boston, 390pp., 1988.