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# DISPERSION MODEL FOR LOW WIND AND ATMOSPHERIC CALM PART I: DESCRIPTION

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*Abstract.* A dispersion model is developed for low wind and atmospheric calm. The model takes into account both turbulent diffusion and advection along the wind direction in the case of low wind. It provides one option for calculating the concentration in low wind and two options for calm conditions, implements an algorithm for calculating the building effect, and uses the Briggs plume rise equations. The effect of wet deposition and radioactive decay is also considered.

*Key words*: atmospheric calm, low wind, ConDefa.

## 1. INTRODUCTION

The dispersion of pollutants in the atmosphere is mainly determined, on the one hand, by the mean flow of the atmospheric fluid that carries the pollutants along the dominant direction of the wind and, on the other hand, by the turbulent speed fluctuations that disperse the pollutants in all directions.

In the case of moderate or strong wind, the continuously emitted pollutants are forming a plume (pollutant cloud) along the wind direction, having the origin in the source. In this situation, the downwind advection dominates over diffusion, and the lateral and vertical distributions of the pollutant concentrations are of Gaussian type.

Low wind and calm are the atmospheric states most critical for the dispersion of pollutants because they are leading to the highest concentration values at the ground level. Low wind is the state in which wind speed is less than 2 m/s and the calm condition is the state of the atmosphere in which the wind speed is below device detection limit. In this paper, the wind speed in atmospheric calm was considered equal to zero. In low wind conditions, diffusion along the wind direction can have an important role in determining the concentration distribution and, in addition, pollutants cannot form a cone-shaped plume along the wind direction [1]. Thus, in case of low wind, the assumption that advection dominates over diffusion along the wind direction is no longer valid, the two physical processes having comparable contributions to the resulting concentration field. Low wind conditions frequently occur in all regions of the globe. Low wind speeds, coupled with thermal inversion conditions, are expected to occur in 30–40% of the time in most locations [2, 3].

There are dispersion models which estimate the atmospheric dispersion of radionuclides at different spatial scales, from the local scale [4, 5], at the regional scale [6] and the global one [7, 8], making use of different physical assumptions. Typical Gaussian models have a limitation of principle, namely, the concentration expression is obtained without taking into account the diffusion process along the wind direction, which at low speeds of the wind (below 2 m/s), becomes comparable or more important than the advection. This limitation determines an overestimation of pollutant concentration by the Gaussian models when they are applied in situations characterized by low wind.

The steady-state dispersion models based on the Gaussian approximation, *e.g.*, OML [9, 10], ADMS [11, 12], and AERMOD [13], do not contain algorithms for calculating pollutant concentrations for low wind and atmospheric calm; for example, in OML, for calm conditions, one considers the wind speed value to be equal to 0.5 m/s and a wind direction resulted from interpolation between the directions specific to the ends of the interval where there is calm state. ADMS as well does not consider atmospheric conditions with wind speeds less than 0.75 m/s.

To address these limitations, a special dispersion model, ConDefa (**Con**diții **Def**avorabile: unfavourable conditions, in Romanian) was developed that enables the estimation of the air concentrations of radioactive and stable pollutants, in low wind conditions (speed $< 2$ m/s) and atmospheric calm.

The evaluation of the ConDefa model is presented in the companion paper.

## 2. DESCRIPTION OF THE DISPERSION MODEL CONDEFA

ConDefa is a local scale dispersion model, with a GUI (Graphical User Interface), developed to estimate the concentrations of radioactive and stable pollutants in the atmosphere under low wind and calm conditions, for constant emission rates. The calculation options are identified with the following labels: *LW* for low wind, and *ACn* for atmospheric calm, option *n*, respectively.

### 2.1. CASE OF LOW WIND

For dispersion modelling in the case of low wind, the model employs a non-Gaussian distribution of the pollutant concentration field. The corresponding option for dispersion calculation is called *diffusion coefficients (LW)*.

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This option uses the solution of the advection-diffusion equation describing the concentration, $C$, for a continuous source of strength $q$, located at a point $(0,0,H)$, for a spatially homogeneous wind field and constant eddy diffusivities, obtained by the method of integral transforms [2]:

$$C(x,y,z,H) = \frac{q\mathrm{e}^{Ux/2K_x}}{4\pi(K_xK_yK_z)^{1/2}}\left\{\frac{\mathrm{e}^{-Uf/2K_x^{1/2}}}{f}+\frac{\mathrm{e}^{-Ug/2K_x^{1/2}}}{g}\right\} \tag{1}$$

where:

$$f=\left[\frac{x^2}{K_x}+\frac{y^2}{K_y}+\frac{(z+H)^2}{K_z}\right]^{1/2}$$

and

$$g=\left[\frac{x^2}{K_x}+\frac{y^2}{K_y}+\frac{(z-H)^2}{K_z}\right]^{1/2}.$$

$U$ is the mean wind speed and $K_i(i=x,y,z)$ are the constant eddy diffusivity along the coordinate axes with Ox-axis oriented along the mean wind. The diffusion coefficients are dependent on the atmospheric stability class which is determined by two schemes based on the vertical temperature gradient and wind speed. Thus, in the case of $K_z$, an average value of the coefficient was calculated for the mixing layer specific to each stability class [14–17]. The model assumes homogeneous turbulence in the horizontal plane, so $K_x=K_y(=\alpha K_{zm})$, where $1\leqslant\alpha\leqslant\alpha_m$ and $K_{zm}$ is the average value of $K_z$ for the mixing layer, obtained by supposing linear dependence up to the height of 100 m [14, 15] and a constant value up to the mixing height. The quantity $\alpha_m$ corresponds to the highest value of $K_x$ and $K_y$ and is set to 100 m$^2$ s$^{-1}$ [18].

### 2.2. CASE OF ATMOSPHERIC CALM

From a physical point of view, calm refers to the dynamical processes specific to stagnant weather conditions in which there still exists turbulence and diffusion different from the molecular one. In order to calculate the concentration in atmospheric calm, the ConDefa model provides two options: *variable $K_z$ (AC1)* and the *NRC model (AC2)*.

#### 2.2.1. Variable $K_z$ (AC1)

The calculation algorithm of pollutant concentration is based on a system of equations resulting from the numerical discretization of the diffusion equation with a source term of delta-function type, a height dependent vertical diffusion coefficient, and a removal term quantifying the wet deposition and radioactive decay. The associated equation system is solved by a calculation algorithm in 7 points by making use of the successive relaxation method with an iterative scheme [19]:

$$
\begin{aligned}
Q = -&\left[(K_{zm}+K_{zm+1})\frac{\Delta x\Delta y}{\Delta z}+K_{yIj+1M}\frac{\Delta x\Delta z}{\Delta y}\right.\\
&\left.+(K_{xi+1JM}+K_{xiJM})\frac{\Delta y\Delta z}{\Delta x}+(\lambda+\omega)\Delta x\Delta y\Delta z\right]C_{IJM}\\
&+K_{zm+1}\frac{\Delta x\Delta y}{\Delta z}C_{IJm+1}+K_{zm}\frac{\Delta x\Delta y}{\Delta z}C_{IJm-1}\\
&+K_{yIj+1M}\frac{\Delta x\Delta z}{\Delta y}C_{Ij+1M}+K_{yIjM}\frac{\Delta x\Delta z}{\Delta y}C_{Ij-1M}\\
&+K_{xi+1JM}\frac{\Delta y\Delta z}{\Delta x}C_{i+1JM}+K_{xiJM}\frac{\Delta y\Delta z}{\Delta x}C_{i-1JM}
\end{aligned}
\tag{2}
$$

where:

$$C_{IJM}=\frac{1}{\Delta x\Delta y\Delta z}\int_{x_i}^{x_{i+1}}\int_{y_j}^{y_{j+1}}\int_{z_m}^{z_{m+1}}C(x,y,z)\mathrm{d}x\mathrm{d}y\mathrm{d}z,$$

$$C_{IjM}=\frac{1}{\Delta x\Delta z}\int_{x_i}^{x_{i+1}}\int_{z_m}^{z_{m+1}}C(x,y_j,z)\mathrm{d}x\mathrm{d}z,$$

$$K_{(y,x)IjM}=K_{(y,x)}\left(\frac{x_i+x_{i+1}}{2},y_j,\frac{z_m+z_{m+1}}{2}\right),$$

$$K_{zm}=K_z(z_m),$$

$$Q=-q\delta_{mm_s}\delta_{jj_s}\delta_{ii_s}$$

$$\delta_{ll_s}=\begin{cases}1 & \text{if } l=l_s,\\ 0 & \text{if } l\neq l_s.\end{cases}$$

$Q$ is the pollutant source per unit volume, $\delta$ is the Kronecker symbol, $\lambda$ is the radioactive decay constant, and $\omega$ is the wet deposition coefficient. The grid in the modelling area is defined by the following structure of points: $x_{i+1}=x_i+\Delta x$, $y_{j+1}=y_j+\Delta y$, $z_{m+1}=z_m+\Delta z$. The method does not generate non-physical (negative) values for concentrations, including in their asymptotic variation domain [20, 21].

### 2.2.2. NRC model (AC2)

The method is based on the simplified scheme used by the NRC (The US Nuclear Regulatory Commission). In this option the concentration depends only on the stack height and the plume-rise; the parameters that describe the turbulence intensity (the square root of the mean square fluctuations of the wind speed components in the three directions) are considered constant and independent of atmospheric stability [22]. According to this model the pollutant concentration is computed by the formula:

$$C(x,y,z,H) = \frac{q\sigma_u}{(2\pi)^{2/3}\sigma_v\sigma_w r^2} \tag{3}$$

where

$$r^2 = x^2 + \left(\frac{\sigma_u}{\sigma_w}\right)^2 (H - z_r)^2,$$

$x$ is the distance from the stack to the receiver point considered to be on the plume center line $(y = 0)$ in the orthogonal plane on the stack axis, located at the receiver height, $z_r(z = H - z_r)$, and $\sigma_u$, $\sigma_v$, and $\sigma_w$ are the mean square fluctuations of the wind speed on the $O_x$, $O_y$ and $O_z$ directions. The height, $H$, is the sum between the physical height of the stack and the plume rise of the pollutant cloud (plume). In this approach, the parameters $\sigma_u$, $\sigma_v$, $\sigma_w$ do not depend on stability and they are independent of height, and have the values $\sigma_u = \sigma_v = 0.4$ m/s, $\sigma_w = 0.04$ m/s.

### 2.3. INPUT DATA

The input data required by the model are the following:

- grid parameters (number of grid points, the grid spacing [m]);
- meteorology: temperature gradient [°C/100 m], air temperature [°C], exponent for height dependence of $K_z$, wind speed [m/s], wind direction [degrees], height at which anemometer is located [m], coefficient for calculating $K_x$ and $K_y$ as function of $K_z$, the mixing height [m], schemes for determining the stability of the atmosphere [2, 23] based on vertical temperature gradient and wind speed, washout coefficient [1/s];
- pollutant source characteristics: emission rate [g/s or Bq/s], stack height [m], stack diameter [m], gas exit speed [m/s], gas temperature [°C] and radioactive constant [1/s];
- data for building effect calculation: building area [m$^2$] normal to the wind speed and roughness length [m];
- model output options: the height of receptors [m] and output file names.

The ConDefa GUI used to facilitate data input is shown in Figure 1.

The classification of atmospheric stability conditions employed is the Pasquill scheme: unstable atmosphere (classes A, B, C), neutral atmosphere (Class D) and stable atmosphere (classes E, F, G). As indicator of atmospheric stability, vertical temperature gradient of air is used [24].

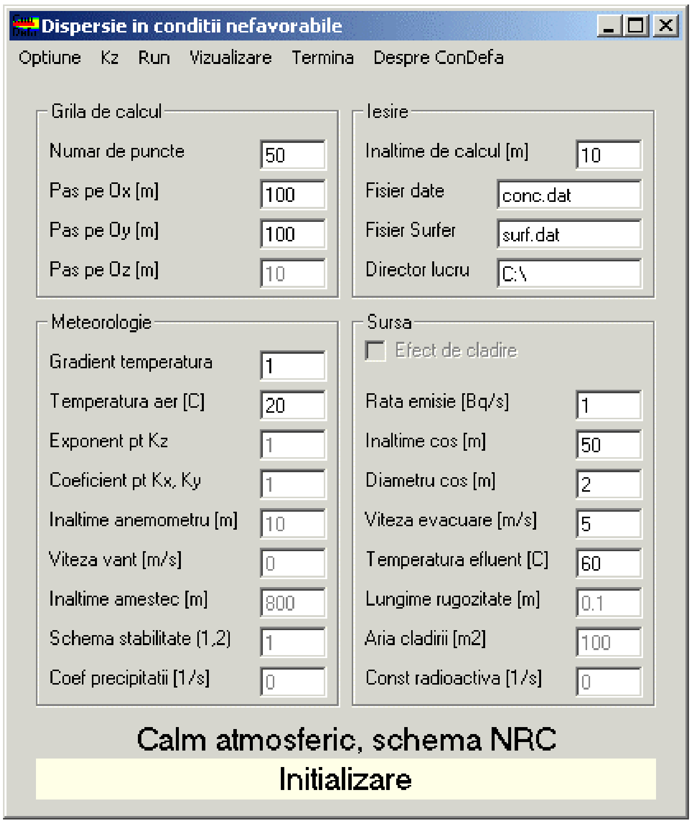


Fig. 1 – The ConDefa GUI.

For the plume rise calculation using Brigg's equations, the following physical data are needed: vertical exit velocity and temperature of the stack effluent, stack diameter and the meteorological data: wind speed at the anemometer height, vertical temperature gradient, and air temperature [22].

The option for building effect is not available for calm and low wind with the diffusion coefficient option; under conditions of atmospheric calm, the diffusion on the horizontal plane being homogeneous, the building influence is negligible [25, 26]. In other cases, the building effect will be calculate by making use of Ramsdell's procedure [25–27].

Simulation of the entrainment processes of radionuclides in the atmosphere through precipitation (wet deposition) and the loss through radioactive decay is performed by considering an exponential decrease of the source intensity. Washout coefficient values depend on the intensity and the type of precipitation (rain or snow) [22].

## 2.4. RESULTS

In this section there are presented examples of model output for low wind conditions in Figure 2, and for atmospheric calm in Figure 3. The runs were done for a point source with an emission rate of 1 Bq/s, gas exit speed of 5 m/s, stack height of 50 m, stack diameter of 2 m, and effluent temperature of 50°C. Ambient temperature was assumed to be 20°C, and the wind speed for the low wind case was 0.8 m/s.

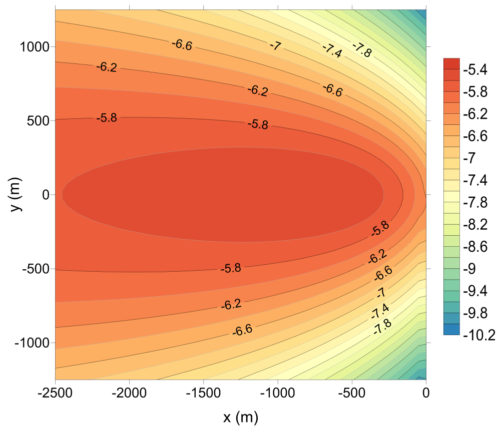


Fig. 2 – Ground level concentration field (decimal logarithm) for low wind conditions. Input parameters are described in the Results section.

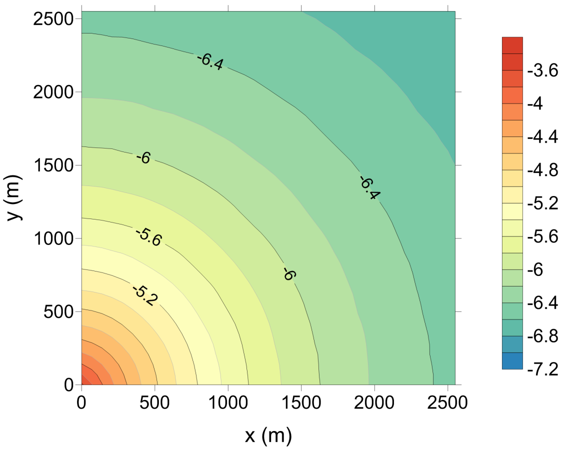


Fig. 3 – Ground level concentration field (decimal logarithm) for atmospheric calm. Input parameters are described in the Results section.

In case of low wind, the calculation of the pollutant concentration was performed for the stability class E (stable atmosphere) determined by the vertical temperature gradient equals to 1°C [24] and a vertical diffusion coefficient specific to this class, equals to 5 $m^2/s$, at the height of 100 m [16]. As far as atmospheric calm is concerned, the calculation has been made for the stability class was D (neutral atmosphere), characterized by the vertical temperature gradient equals to -1°C [24] and a vertical diffusion coefficient equals to 15 $m^2/s$ , at the height of 100 m [16]. As one may be seen from Figure 3, in case of atmospheric calm there is a uniform distribution of the concentration field and a build-up of this one around the source due to unfavourable dispersion conditions. The concentration distribution in the Figure 2 shows that in case of low wind this distribution is symmetric around the wind direction (in this case being 90 degrees).

## 3. CONCLUSIONS

In this paper, a dispersion model for low wind and calm conditions has been presented. The low wind and calm conditions are the most unfavourable for dispersion of pollutants in the atmosphere and are associated with high pollution episodes characterized by pollutant concentration values exceeding by far the limits imposed by regulations in order to protect the population and vegetation. Therefore, such a dispersion model can become a valuable management tool for facilities releasing in the atmosphere radioactive or stable pollutants that may have a negative impact on human health and the environment. The evaluation of the model is presented in the companion paper.

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