Modelling of air pollution transport over a patchwork of surface features

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ABSTRACT

The numerical model of pollution transport over a nonhomogeneous earth surface is presented. The model is based on the semi-empirical theory of the atmospheric boundary layer (ABL). Pollution transport is described by the turbulent diffusion equation. In this equation vertical profiles of diffusivity and wind speed are modified under the influence of the temperature and roughness discontinuity between different surfaces. Such modification of the ABL parameters is interpreted as an internal boundary layer (IBL). Computed results for two typical examples are given, namely formation of a convective IBL in a coastal area and a stable IBL under land-water transition.

INTRODUCTION

The transport processes of air pollution over a nonhomogeneous earth surface differ considerably from ones over a homogeneous area and this difference is mainly connected with sharp changes in surface temperature and roughness. Such transition leads to a noticeable modification of atmospheric boundary layer parameters near the earth surface that may be interpreted as an internal boundary layer (IBL). Over a patchwork surface several inserted IBLs could be formed. A most important and interesting example of this process is formation of the thermal internal boundary layer (TIBL) in coastal areas which often have great population density combined with high concentration of industrial installations. In these regions a typical situation is the phenomena of fumigation which is intensive mixing of pollution plumes throughout the growing convective IBL. It may result in a considerable increase of ground-level pollutant concentrations.

Starting with the model of Lyons and Cole [5] the investigation of the TIBL structure and its influence on pollution diffusion has received a lot of attention (e.g. Raynor et al. [9], Venkatram [14], Van Dop et al. [13], Misra [6], Deardorff and Willis [1], Hanna [2]). Most of the published models
compute the IBL height from the following equation

\[ H_{\text{TIBL}} = Ax^b \]  

where \( x \) is distance from a shoreline and an empirical constant \( b \) usually of the order of 0.5. Coefficient \( A \) varies within more wide limits, e.g. Hsu [3] used \( A = 1.91 \), Misra and Onlock [7] obtained \( A \) in the range of 2.71 to 5.61. Under using such models diffusion processes are described by the Gaussian formula and additional hypotheses about the mixing processes within the TIBL (Stunder et al. [12]). Based on analysis of dispersion data, Weil and Brower [15], Stunder and SethuRaman [11] concluded that the standard dispersion models cannot simulate coastal diffusion processes.

THE NUMERICAL MODEL OF THE IBL

The problem of the atmospheric boundary layer transformation over a nonhomogeneous earth surface is examined. After air flow transition to an area with another surface temperature and roughness vertical profiles of diffusivity, temperature and wind could be changed in magnitude and redistributed in height. Modification of boundary layer parameters primarily starts near the earth surface and spreads up during the flow movement over this area. It is such changes of the vertical profiles that may be interpreted as formation of an internal boundary layer or several inserted layers with different temperature stratifications and rates of turbulent diffusion (over adjacent next region). Clearly it leads to another pattern of the pollutant plume dispersion as compared with plume transport over a homogeneous surface.

Modelling of an air flow movement is based on the semi-empirical theory (K-theory) of the atmospheric boundary layer (ABL) by Monin and Obukhov [8] and Laykhtman [4]. The model represents a system of equations for the ABL over areas with varying temperature and roughness. Transport of pollution emitted from industrial sources (i.e. smoke stacks) is described by the turbulent diffusion equation where the wind profile and vertical diffusivity are solutions of the ABL equations. In such a way it isn’t necessary to use any additional concepts and hypotheses such as the TIBL height, uniform mixing of the pollution inside of TIBL and so on.

The system of equations and boundary conditions for two adjacent areas can be written as

\[
\frac{\delta u}{\delta x} + \frac{\delta u}{\delta y} + \frac{\delta u}{\delta z} - \left( \frac{\delta}{\delta z} K_z \right) = f(v-v_g) = 0
\]

(2)

\[
\frac{\delta v}{\delta x} + \frac{\delta v}{\delta y} + \frac{\delta v}{\delta z} + f(u-u_g) = 0
\]

(3)
\[
\frac{\partial \varepsilon}{\partial t} + u \frac{\partial \varepsilon}{\partial x} + v \frac{\partial \varepsilon}{\partial y} = K_z \left[ \left( \frac{\partial}{\partial x} \right)^2 + \left( \frac{\partial}{\partial y} \right)^2 \right] \frac{\partial \varepsilon}{\partial z} + \frac{\delta}{\delta z} \left( -a_t K_z \left( \frac{\partial T}{\partial z} + \gamma_a \right) \right) - b_c \frac{\varepsilon^2}{K_z} \tag{4}
\]

\[K_z = 1 \varepsilon^{0.5} \tag{5}\]

\[l = -2kb_c^{0.25} \frac{\phi}{(\delta \phi/\delta z)} \tag{6}\]

\[\phi = \left( \frac{\partial}{\partial z} \right)^2 + \left( \frac{\partial}{\partial y} \right)^2 \frac{g \delta T}{T} \tag{7}\]

\[
\frac{\partial \varepsilon}{\partial t} + u \frac{\partial \varepsilon}{\partial x} + v \frac{\partial \varepsilon}{\partial y} = ( - \frac{\partial}{\partial z} K_z ) \frac{\partial \varepsilon}{\partial z} \tag{8}\]

\[
\frac{\partial \varepsilon}{\partial t} + u \frac{\partial \varepsilon}{\partial x} + v \frac{\partial \varepsilon}{\partial y} = ( - \frac{\partial}{\partial z} K_z ) + w_{pl} \frac{\partial \varepsilon}{\partial z} \tag{9}\]

\[
x=0 \quad u=u_1(z); v=v_1(z); \varepsilon=\varepsilon_1(z); T=T_1(z); c=(Q/\mu_{st})\delta(z-H_{st}) \tag{10}\]

\[
z=z_{01,2} \quad u=0; v=0; \varepsilon=b_{c}\varepsilon^{0.5}u_{*1,2}; T=T_{1,2}; \delta z = 0 \tag{11}\]

\[
z=H_{BL} \quad u=u_g; v=v_g; \varepsilon=0; T=T_{H}; c=0 \tag{12}\]

where the \((x,y,z)\) axes are the Cartesian coordinate system (the \(x\)-axis is aligned perpendicular to the borderline); \(u\), \(v\), \(u_g\) and \(v_g\) are the components of the wind and geostrophic wind accordingly; \(K_z\) is the vertical diffusivity, \(\varepsilon\) is the kinetic energy of turbulent pulsations; \(l\) is the scale of turbulence; \(T\) and \(T_{01,2}\) are the air and surface temperatures; \(w_{pl}\) is the plume rise velocity; \(z_{01,2}\) are the aerodynamic roughnesses; \(H_{BL}\) is the boundary layer height; \(v_*1,2\) are the friction velocities; \(H_{st}\) is the smoke stack height; \(Q\) is pollutant emission from a smoke stack; \(\delta(z-H_{st})\) is the Dirac delta-function (the source locates at the border between two areas); \(f\) and \(k\) are the Coriolis parameter and von Karman constant; \(\gamma_a\) is the dry adiabatic lapse rate of 9.8 K/km; \(a_c\), \(a_t\), \(b_c\) are empirical constants. Pollutant concentration \(C(x,y,z)\) is given by form \(C = F(y)c(x,z)\) where \(F(y)\) is the standard Gaussian function.

Initially Equations (2) through (7) are solving for the first semi-infinite surface. Then obtained vertical profiles of the
boundary layer parameters are used as the boundary conditions for the second area with other roughness and temperature, and Equations (2) through (9) are computed for a common case. For several different areas this procedure is repeated in the same way, i.e. transformed boundary parameters at the end of a previous area are the boundary conditions for a next region. Before numerical processing the equations are converted to a nondimensional form. Dimensional scales and particulars of the reverse conversion to dimensional variables are described by Lykhtman [4].

RESULTS OF CALCULATIONS

The main parameter determined the pollution dispersion is the vertical turbulent diffusivity $K_z$. Namely its transformation, such as increase, decrease or vertical redistribution, determines the scenario of the plume diffusion. In particular, under daytime onshore wind the abrupt increase of surface temperature and roughness usually leads to the TIBL formation and fumigation process.

Two typical situations have been analysed. In the first case the stably stratified air flow passes from a sea surface to a land surface (a coastal area is examined). Land-sea temperature difference is 20 K (summer). In the second example the neutrally stratified flow passes from land to cooler water (e.g. a great lake). In this case water-land temperature difference is -20 K. Predicted vertical diffusivity profiles for different downwind distances from a borderline are given in Figures 1 and 2. As it has been expected, under a onshore air flow turbulence increases by a factor of 40 and its maximum displaces up from 30 m to 200 m. The TIBL is formed and its depth grows that is seen from Figure 1. Basing on diffusivity profiles one can introduce conception of the TIBL height defining it as a height where diffusivity returns to its background values. In particular, Stunder and SethuRaman [10] presented some results of aircraft measurements from the Brookhaven experiment during onshore wind. Observed values and computed by the present model TIBL heights are in a good qualitative agreement with each other.

In the second case the negative temperature difference leads to formation a stable IBL and meaningful decrease of turbulent intensity.

For the same cases dispersion of plume released from a 100m smoke stack located near a borderline is computed. In Figure 3 and 4 ground-level concentrations for $Q = 1 \text{ kg/s}$ are given. For comparison, concentrations under plume transfer over a homogeneous surface (1-st surface) are also shown. It is seen that there is a considerable increasing of concentration in case of the stable onshore flow i.e. fumigation takes place (Figure 3). Under a land-water transition the stable IBL serves as a barrier for vertical dispersion of plume material decreasing the ground-level concentrations (Figure 4). Thus an extensive cool water surface assists to longer pollution transport.
Figure 1: Vertical diffusivity over coastal area (wind speed 4.5 m/s).
- □ x=0; + x=1km; ◊ x=3km; △ x=5km; × x=7km

Figure 2: Vertical diffusivity over water surface (wind speed 4.5 m/s).
- □ x=0; + x=1km; ◊ x=3km; △ x=5km; × x=7km
Figure 3: Ground-level pollution concentration ($\mu g/m^3$) under stably stratified air flow.
- square: sea-land transition; +: homogeneous (sea) surface

Figure 4: Ground-level pollution concentration ($\mu g/m^3$) under neutrally stratified air flow.
- square: land-water transition; +: homogeneous (land) surface
CONCLUSIONS

The present IBL model is more physically grounded and more universally applicable. In the framework of this model, a patchwork of surface features as coastal areas, great lakes, farms, forests etc. may be simulated.

Pollution transport from industrial sources is also simulated on the K-theory base without using of any additional hypotheses about plume mixing within the IBL.

ACKNOWLEDGMENT

The author expresses his gratitude to Dr. I. Seter and Dr. A. Manes for helpful discussions.

REFERENCES

