A numerical study of the vertical dispersion in a stable boundar layer

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Abstract

Turbulent diffusivity expressions obtained from local similarity theory and statistical diffusion theory are used to simulate two different times evolution of a stable boundary layer The model shows the asymmetry in the diffusive process to area source of contaminants relative to ground height

1. Introduction

Investigations of pollutant transport and dispersion in the atmosphere are an important factor for protection of air quality In order to calculate the spatial distribution of pollutant concentrations, we need an atmospheric dispersion model The classical approach to introduce the part played by atmospheric dynamics on pollutants transfer is to examine the so-called transport diffusion equation The turbulent diffusion terms in this equation are often closed w the aid of the gradient -transfer hypothesis which relate the turbulent fluxes with the mean quantities by a K diffusivity i e first-order closure These diffusivities are not constant like the kinematic viscosity but may vary in space and time Hence the aforementioned scheme closes the set of equations only to a certain degree the K diffusivities still have to be determined

The emphasis on this article is to use an eddy diffusivity derived from the Local Similarity Theory and the Statistical Diffusion Theory (Degrazia and Moraes 1992) to analyse the dispersion from an area source into an Stable Bounda Layer (SBL) of thickness h It is a simulated dispersion from area source near the ground and near the top of the boundary layer for two different times evolution of one SBL

2. Turbulent diffusion coefficients in the stable boundary layer

In order to deal with the local character of the stratified turbulence it is first assumed that the appropriate scales for turbulent fluxes should depend on local values of the Reynolds stresses $\tau(z)$, the vertical turbulent heat flux $\overline{w\theta}(z$ and the local Monin-Obukhov lenght Λ, defined respectively by

$$\frac{\tau}{\tau_0} = (1 - z/h)^{\alpha_1}; \qquad (1)$$

$$\frac{\overline{w\theta}}{\left(\overline{w\theta}\right)_0} = (1 - z/h)^{\alpha_2}; \qquad (2)$$

$$\frac{\Lambda}{L} = (1 - z/h)^{(3\alpha_1/2 - \alpha_2)}; \qquad (3)$$

where $\tau_0 = u_*^2$ is the surface stress, h is the height of the SBL, z is the height above the ground, L is the Monin-Obukhov lenght, and α_1 and α_2 are constants to be determined by fitting the model to experimental data This hypothesis is applicable in stable regimes, over homogeneous terrain where turbulence can be treated as continuous and not dominated by gravity waves

In the case for large diffusion times $(t \to \infty)$ Degrazia and Moraes (1992) have shown that the diffusion coefficien can be expressed as

$$K_{\alpha\alpha} = \frac{1}{4}\left[\sigma_i^2 \beta_i S_i(0)\right]; \qquad i = u, v, w; \qquad \alpha = x, y, z; \qquad (4)$$

where σ_i^2 denotes the turbulent velocity variances, β_i is defined as ratio of the Lagrangian to the Eulerian time-sc and $S_i(0)$ represents the behaviour of the turbulent energy spectra near the origin The form for K_{zz}, as given by gives a correct parametrization for the vertical flux of momentum and heat, and is of importance in modelling area source dispersion on an idealised SBL final equation for the vertical turbulent transport coefficient, as given by Degrazia and Moraes, is of the form

$$K_{zz} = \frac{0.33(1 - z/h)^{\alpha_1}(z/h)}{1 + 3.7(z/h)(h/\Lambda)} \qquad (5)$$

The model

present model used to simulate the vertical dispersion of contaminants released by an area source located in an SBL is described by equation

$$\frac{\partial \bar{c}}{\partial t} = \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial \bar{c}}{\partial z}\right), \qquad 0 < z < h; \qquad (6)$$

which the initial and boundary conditions should satisfy

$$\bar{c}(z,t) = Q\delta(z - h_s), \qquad \text{at } t = 0, \qquad (7)$$

$$K_{zz}\frac{\partial \bar{c}}{\partial z} = 0, \qquad \text{at } z = 0 \text{ and } z = h \qquad (8)$$

In the above system $\bar{c}$ denotes the mean concentration of contaminants, Q is the source strength, $\delta(z - h_s)$ is the Dirac's delta function, and h_s is the height of the area source

Results and discussion

Explicit results obtained from the diffusion numerical model discussed in section 3 are presented here. The turbulent diffusion was analised in two different times evolution of the nocturnal boundary layer. The first one simulated the diffusion just after the sunset when evolutionary nonstationary processes were present and it was assumed $(\alpha_1 = 2, \alpha_2 = 3)$ as indicated by the Minnesota experiments (Sorbjan 1986). The second one simulated the diffusion in a fully turbulent stable layer and it was assumed $(\alpha_1 = 3/2, \alpha_2 = 1)$ as indicated by Cabauw experiments (Nieuwstadt, 1984a).

In both cases the following parameters were used

- Monin-Obukhov length (L): $116m$;
- source strenght (Q): $400 g/m^2$;
- height of the SBL (h): $400m$;
- friction velocity (u_*): $0.31 m/s$

The time step used was $\Delta t = 10 sec$ and the vertical domain is solved with $N_z = h/\Delta z = 50$ levels (for the unrefined grid).

Figure-1 displays the time evolution of the vertical profile of material concentration, when the area source is located at $12.5m$ above the gound. The letters M and C represent the simulation with the α's Minnesota and Cabauw values respectively. It also shows that the shape of concentration change in time with a regular pattern and the boundary layer is filled from bottom to top. Such result should be interpreted in the light of the gradual decrease of turbulence to zero near the top of the boundary layer. As can be seen from this figure, the simulation done with the α - Minnesota values presents a more affective vertical mixing than the one abtained with the α - Cabauw values. As a consequence the vertical distribution of concentration becomes, at larges times, more homogeneous in the first case than in the second one.

Vertical concentration profiles for a source area located at $300m$ above the ground and for several times are presented in Figure-2. As can be seen from figure 2-C the height of maximum concentration is located, at all times approximately at same height of the source. The downward diffusion, in this case, is not very effective. When the α-Minnesota values are used, the diffusion at ground direction is slow, but due to the magnitude of the diffusion coefficients, the vertical profiles present, at large times, a homogeneous shape.

The diffusion of contaminants released at the upper part of the SBL are controlled by small eddies, where the gradient $d\sigma_w^2/dz \rightarrow 0$. These eddies create a quasi-homogeneous turbulent field, and the particles of contaminants remain during a long time at elevated heights without perceiving the non-homogeneous and dispersive turbulent field present at lower layers.

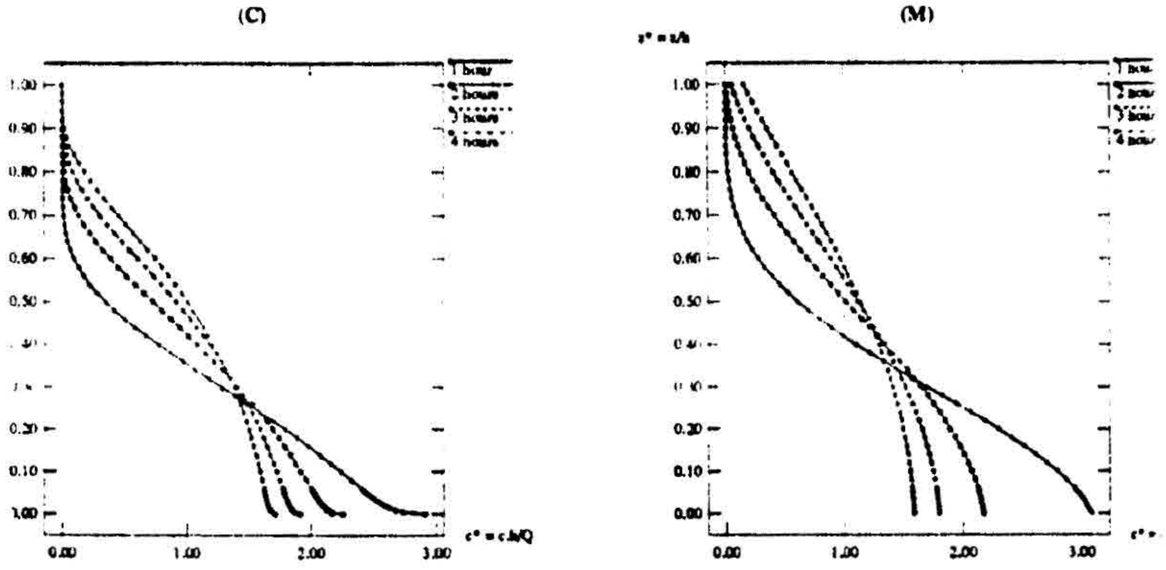

Figura 1 Vertical profile of the concentration for area source locate at 12.5 m above the ground

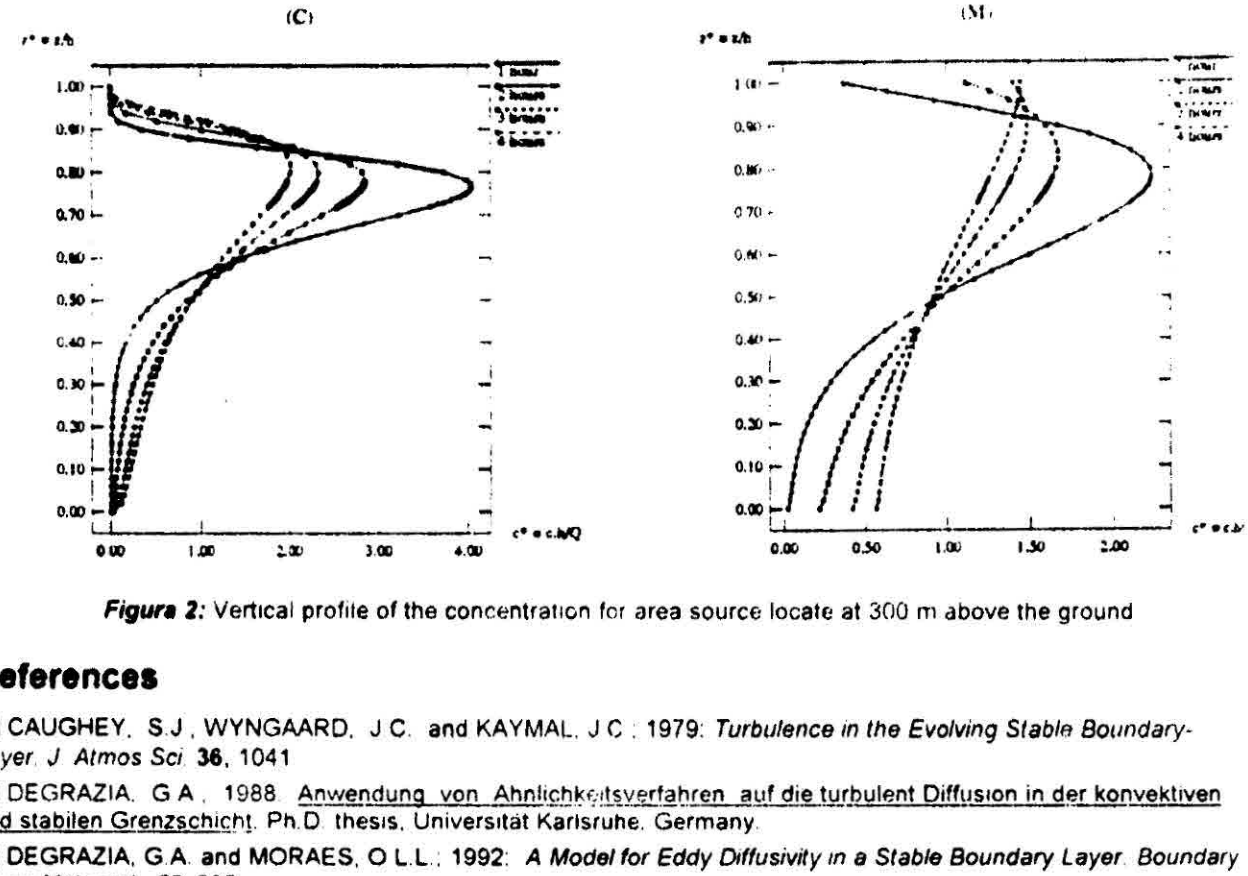

Figura 2: Vertical profile of the concentration for area source locate at 300 m above the ground

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