A Combined Numerical and Laboratory Study of Dispersion from a Point Source in the Atmospheric Convective Boundary Layer with Wind Shear

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INTRODUCTION

The paper present results from a combined numerical and laboratory study of gaseous pollutant dispersion in a horizontally evolving, sheared convective boundary layer (CBL) driven by bottom buoyancy forcing. Such type of CBL, which consists of convectively mixed layer capped by interfacial (or inversion) layer with sharp density gradients, is commonly observed in the atmosphere when a stably or neutrally stratified air mass is advected over a heated underlying surface.

The absolute majority of known field, numerical, and laboratory studies of gaseous dispersion in the CBL have been conducted under conditions (or assumptions) of horizontal (quasi-)homogeneity of the CBL flow, see e.g. Willis and Deardorff [1]-[3], [6], [9]; Lamb [4]; Deardorff and Willis [5], [7]; Deardorff [8]; Eberhard *et al*. [10]; Mason [11]; Henn and Sykes [12]; Nieuwstadt [13], [16]; Hibberd and Luhar [14], and Weil *et al*. [15]. This CBL type is usually called the nonsteady CBL. For a long time, properties of turbulent transport in the horizontally evolving CBL have been much less investigated compared to the nonsteady CBL. Only few laboratory studies of the plume dispersion in the sheared CBL have been conducted in thermally stratified wind tunnels, see review by Meroney [17]. A tracer diffusion in a CBL with weak wind shear was studied by Sada [18], who used the thermally stratified wind tunnel of Komae Research Laboratory, Japan. However, in the aforementioned wind tunnel studies, the experimentally obtained parameters of dispersion were not systematically analyzed in conjunction with properties of turbulence in the simulated CBL, and effects of flow shear on the tracer diffusion in the CBL were not particularly investigated.

Experiments of Fedorovich *et. al*. [18] and Kaiser and Fedorovich [19] in the thermally stratified wind tunnel of the University of Karlsruhe (UniKa), Germany, have shown that wind shears can essentially modify the CBL turbulence dynamics and parameters of turbulent transport across the capping inversion. In the subsequent study of Fedorovich and Thäter [20], properties of gaseous plume dispersion in the quasi-stationary, horizontally developing CBL with wind shear have been investigated and analyzed in conjunction with observed characteristics of turbulence in the wind tunnel CBL.

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In the present study, these wind tunnel experiments have been complemented by numerical large eddy simulations (LES) of gaseous tracer dispersion in the sheared CBL. We will show comparisons of laboratory and numerical results and then, based on their joint analysis, discuss particular features of turbulent diffusion in the horizontally evolving CBL with wind shear.

METHODS OF INVESTIGATION

In order to simulate dispersion of a gaseous tracer represented by its concentration *c*, a new simulation block was added to the LES code for the horizontally evolving CBL. This code with the subgrid kinetic energy turbulence closure is presented in Fedorovich *et al*. [21]. The corresponding concentration balance equation was taken in the form:

$$\frac{\partial \overline{c}}{\partial t}+\frac{\partial(\overline{u}_i\cdot\overline{c})}{\partial x_i}=\frac{\partial}{\partial x_i}\left[\mu_c\frac{\partial \overline{c}}{\partial x_i}-(\overline{cu_i}-\overline{c}\cdot\overline{u}_i)\right]+S_c\,,$$

where i=1, 2, 3; t stands for the time, $x_i=(x,y,z)$ are the right-hand Cartesian coordinates, $\overline{u}_i=(\overline{u},\overline{v},\overline{w})$ are the resolved-scale components of the velocity vector, $\overline{c}$ is the resolved-scale concentration of the tracer, S_c is the source term, and μ_c is the molecular diffusivity of the tracer. The overbar signifies the grid-cell volume average. The quantities $F_{si}=\overline{cu_i}-\overline{c}\cdot\overline{u}_i$ are the components of the subgrid concentration flux, respectively, which are parameterized as $F_{si}=-K_c(\partial\overline{c}/\partial x_i)$. The value of subgrid turbulent diffusivity K_c is assumed to be equal to the subgrid thermal diffusivity. The latter quantity is parameterized through the product of subgrid length scale and square root of the subgrid turbulence kinetic energy as described in [21].

Zero-gradient boundary conditions are employed for $\overline{c}$ at the walls of simulation domain (the wind tunnel test section), and the radiation condition is applied at the outlet. In the grid cell containing the source, the source term has the form: $S_c=Q_s/\Delta^3$, where Q_s is the source strength (volume of emitted tracer per unit time), and $\Delta^3=\Delta x\Delta y\Delta z$ is the grid-cell volume. In all other grid cells of the simulation domain, the value of S_c is set equal to 0.

Laboratory part of the study has been conducted in the closed-circuit thermally stratified wind tunnel of UniKa with controlled velocity and temperature profiles at the test section inlet [18]. The considered diffusion experiments have been performed with nonbuoyant source. The mixture of tracer gas (SF_6) with air has been emitted from a pipe outlet mounted at different elevations inside the simulated CBL and above it. The source was placed in the central vertical plane of the tunnel, at 3.32-m distance from the test section inlet, that is approximately at the downwind edge of the CBL transition zone discussed in [21]. Concentration measurements have been carried out by standard technique using electron detector method.

RESULTS

We first consider results of laboratory and numerical simulation of dispersion in the CBL flow over relatively smooth underlying surface and in the absence of elevated wind shear. This flow configuration has been specified as basic flow case (BFC) in the studies of Fedorovich *et al.* [19] and [22].

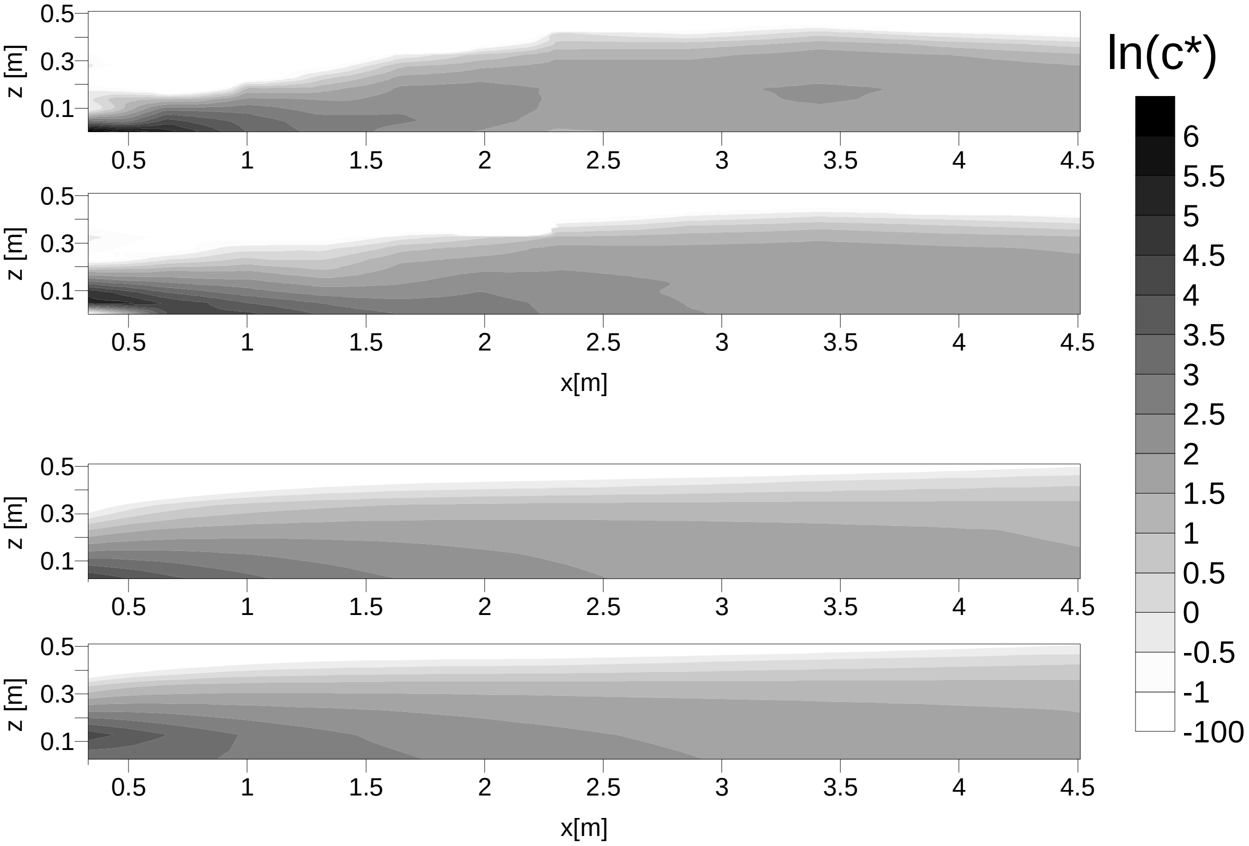
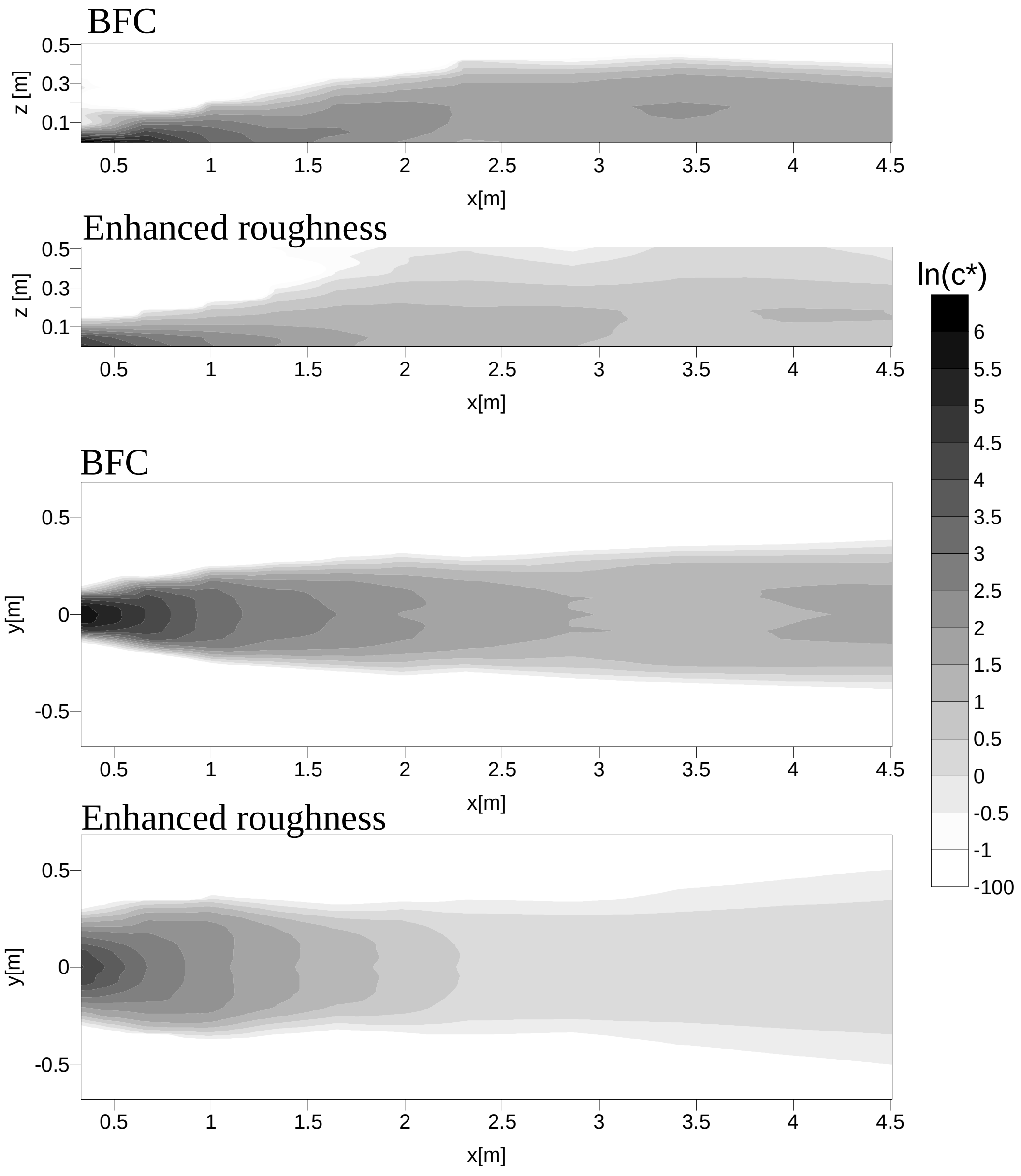


Figure 1. Longitudinal distributions of mean concentration in the basic configuration of the wind tunnel flow (BFC) for two source elevations: z_s=0m (ground source) and z_s=0.1m (elevated source). Two upper plots show the wind tunnel data and two lower ones – the LES results. The origin of the x ordinate is at the source location. The capping inversion height (the CBL depth) at x=0 is approximately 0.3m.

Results of comparison between the wind tunnel and LES concentration data for this flow regime and ground source of pollutant (z_s =0) are presented in Fig. 1. Shown concentration patterns refer to the central vertical plane of the tunnel. Concentration values in the plots are normalized as $c_* = c\cdot L^2\cdot U/Q_s$, where L=1m, U=1m·s^{-1}. The overall agreement between the measured and computed concentration distributions is not bad. However, some particular features of the plume behavior in the CBL (for instance, the fast rise of its centerline in the case of ground source, see discussion below) are not reproduced by the LES. This is presumably due to insufficient spatial resolution in the conducted numerical simulations.

Willis and Deardorff [2] have apparently been the first to demonstrate in their laboratory water tank that the average centerline of the plume released from a ground source rises fast inside the CBL. This finding manifests the specific character of dispersion in the CBL associated with the skewed vertical velocity field in the flow driven by the surface buoyancy forcing. On the other hand, it is known [4] that the average centerline of the plume released from an elevated source in the CBL descends quickly downwind of the source. Concentration distributions retrieved from the wind tunnel experiments with the BFC demonstrate these effects rather clearly, see Fig. 1.


BFC

Enhanced roughness

BFC

Enhanced roughness

Figure 2. Comparison of concentration patterns from the wind tunnel CBL for the case with smaller surface roughness (BFC) and for the case with an order of magnitude larger roughness. Two upper plots show mean c distributions over the longitudinal central plane and two lower plots correspond to the ground level. Coordinates of the source: x_s=0m, y_s=0m, and z_s=0m. The capping inversion height (the CBL depth) at x=0 is approximately 0.3m.

We now consider the new simulation data regarding the influence of surface roughness on the gaseous dispersion in the horizontally evolving CBL. In the traditional laboratory experiments on dispersion in the shear free CBL, this effect is not accounted for, as well as contribution to the dispersion of turbulence generated in the regions of CBL with significant wind shear, *e.g.* in its lower portion adjacent to the surface. Dispersion experiments of Fedorovich and Thäter [21] with comparatively small aerodynamic roughness (of the order of 0.0001m) have already indicated that surface shear has a pronounced influence on the longitudinal variations of mean concentration close to the surface. The comparison with water tank data of Willis and Deardorff [2] have revealed smaller horizontal concentration gradients in the lower portion of wind tunnel CBL affected by surface shear.

In the simulations of CBL above aerodynamically rough surface, the roughness has been increased by approximately one order of magnitude. Taking into account scaling proportions between the simulated CBL and its atmospheric prototype, in the atmospheric CBL the increased roughness length would have the value of the order of several meters. This value corresponds to the typical roughness range for the urban underlying surfaces.

Fedorovich *et al*. [23] found that flow disturbances induced by such enhanced surface roughness considerably affect the turbulence regime over the significant portion of the CBL. Both horizontal and vertical velocity variances are notably enlarged in this case compared to the BFC, and velocity variances are characterized by larger longitudinal variability. Profiles of CBL turbulence statistics from the wind tunnel model and LES point to a higher CBL growth rate over the rougher underlying surface.

Concentration distributions in the CBL flows above the surfaces with two different roughness lengths are demonstrated in Fig. 2. Location and properties of ground sources in both cases are the same. The comparison of presented mean concentration patterns clearly indicates that properties of the plume dispersion in the CBL over the rough surface substantially differ from the ones observed in the case with the smother surface. Spreading of the tracer material in both lateral and vertical directions is considerably larger over the rough surface, whilst the absolute concentration levels at the equal distances from the source are several times smaller. Due to stronger and more uniform mixing in the lower portion of the CBL, the plume rise with distance over the rough surface is detained and not as pronounced as in the smoother surface case.

SUMMARY

Generally good agreement has been observed between results of wind tunnel modeling and LES of gaseous plume dispersion in the horizontally evolving CBL. Increase of the surface roughness by an order of magnitude has been found to substantially modify dispersion pattern of the tracer leading to its faster spreading associated with smaller local concentrations.

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