

# Turbulent transport across a sheared inversion at the convective boundary layer top

E. Fedorovich<sup>1,2</sup> and J. Thäter<sup>2</sup>

<sup>1</sup>School of Meteorology, University of Oklahoma  
100 East Boyd, Norman OK 73019, USA

<sup>2</sup>Institute for Hydromechanics, University of Karlsruhe  
Kaiserstrasse 12, 76128 Karlsruhe, GERMANY

Contact e-mail: fedorovich@ou.edu

## 1 Introduction

Two principal forcing mechanisms determine turbulence regime in the atmospheric convective boundary layer (CBL) driven by buoyant heat transfer from the warm underlying surface. The main of them is associated with turbulence production by buoyancy forces, and the secondary one is the turbulence generation due to the surface wind shears and shears across the density interface at the CBL top (the elevated shears). Density interface in the atmospheric CBL is marked by sharp temperature gradients and usually referred to as the capping inversion layer (or simply the capping inversion). Interaction of the CBL with the free atmosphere aloft is characterized by the entrainment of heat through the capping inversion layer down into the convectively mixed core of the CBL. The entrainment, which is the essential mechanism of the CBL deepening, is primarily caused by convective updrafts (thermals) that rise from the heated surface and penetrate into stably stratified fluid above the CBL.

Experimental and model studies of CBL conducted during the last several decades were mainly focused on the turbulence structure and entrainment dynamics in the case of pure buoyantly driven CBL (the so-called shear-free CBL) and on the role of surface wind shear in the CBL turbulence production. The effects of elevated wind shear on the turbulent transport across the capping inversion and on the CBL evolution have not been sufficiently studied so far.

In this paper we show results of numerical simulation of the CBL with sheared capping inversion and present new wind tunnel model data on the dispersion in the atmospheric CBL with elevated shear. We also discuss a possible physical mechanism of the directional effect of shear on the turbulent exchange at the CBL top.

## 2 Simulation Results

For the numerical part of our study, a modified version of large eddy simulation (LES) code by Nieuwstadt and Brost [3] has been employed. The original code was designed for simulating the turbulence regime of a temporally evolving, horizontally homogeneous atmospheric CBL in a rectangular domain with periodic lateral boundary conditions. The code was modified in order to match requirements of simulating quasi-stationary, horizontally inhomogeneous CBL.

As the reference case for the present study, the CBL with shear-free upper interface has been used. This CBL case was comprehensively studied in the stratified wind tunnel of the University of Karlsruhe (UniKa). It has been also simulated numerically, using the aforementioned LES code, and a fairly good agreement has been found between the numerical and experimental results. The configuration of flow at the tunnel inlet in the reference case is as follows: the lower portion of the flow with a uniform temperature is separated from the stably stratified flow aloft by a temperature jump; above the jump, the temperature is growing linearly with height; the flow velocity has value 1 m/s everywhere. The bottom heat flux is kept constant over the entire wind tunnel floor area.

Two CBL cases with velocity shears across the capping inversion layer have been investigated. In the case with positive elevated shear (PS), the flow velocity was kept 1 m/s below the temperature jump (inversion) and increased in the jump-like way to 1.5 m/s above the inversion. In the case of negative elevated shear (NS), the mean velocity was 1 m/s below the inversion and reduced to 0.5 m/s above it. The remaining flow parameters in the both test cases were same as in the reference case.

With present operating ranges of the UniKa wind tunnel, the NS case cannot be reproduced there. For the PS case, the wind tunnel study of Fedorovich and Kaiser [1] has shown that positive elevated shear obstructs the entrainment and vertical turbulent transport across the inversion. As a first guess, this effect could be explained by the so-called shear sheltering of turbulence (Hunt and Durbin [2]). Our recent wind tunnel experiments on gaseous tracer dispersion in the CBL with sheared inversion have provided additional evidence concerning suppression of the vertical diffusion at the CBL top in the PS case.

From the comparison of concentration patterns presented in Figure 1 one can see how elevated positive shear inhibits the diffusion of tracer at the CBL top in addition to the blockage of diffusion by stable stratification inside the inversion layer. The resulting concentration values in the upper portion of the CBL with sheared capping inversion (PS) are thus noticeably smaller than in the CBL with shear-free upper interface (RC). Numerical simulation of the PS case has provided additional data on turbulence statistics at the CBL top. These statistics have been found in fair quantitative agreement with their counterparts obtained in the wind tunnel model.

Turbulence regime in the CBL with negative shear across the inversion (the NS case) was also investigated numerically. This investigation yielded rather

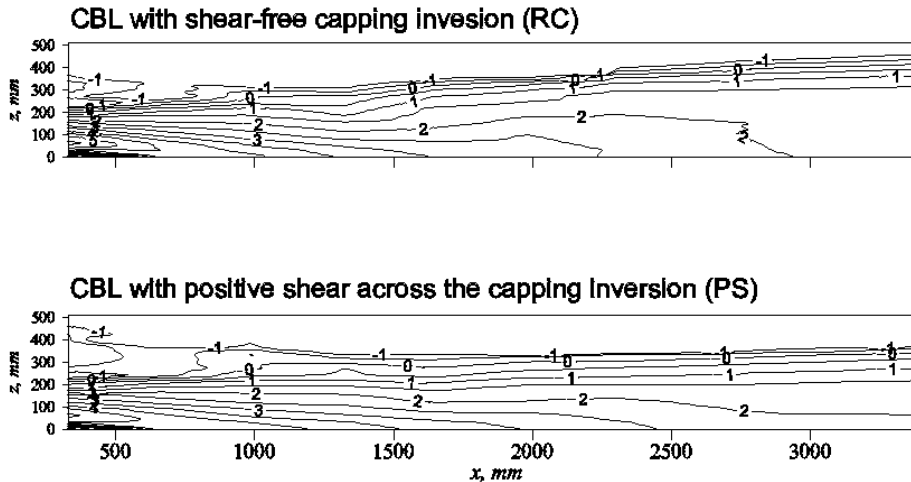


Figure 1: Distribution of logarithm of normalized concentration along the CBL in the RC and PS cases. The source elevation is 100mm.

surprising result. It turned out that damping of thermals in the inversion layer with negative shear is weakened compared to the case of the CBL with shear-free inversion (RC) and as a result the entrainment and the CBL growth are activated in the NS case. In other words, the effect of negative elevated shear on the CBL evolution appeared to be opposite to that of positive elevated shear.

This opposite effect of positive and negative elevated shear on the CBL development is clearly seen in the vertical distribution of the temperature variance presented in Figure 2. In the PS case (left plot), the maximum values of temperature variance observed at the capping inversion level are shifted downwards with respect to the corresponding RC extrema. In the NS case (right plot), they are shifted upwards. At the same time, the magnitudes of temperature variance inside the inversion layer are not significantly altered in the PS and NS cases compared to the reference shear-free case.

### 3 Discussion and Conclusions

The effect of elevated shear on the turbulent exchange across the CBL turned out to be dependent on the shear sign. We found in particular that the effect of negative elevated shear on the CBL growth is opposite to that of the positive shear. This is not consistent with shear sheltering theories we know. Our study suggests that with positive elevated shear, the thermals that penetrate into the sheared inversion are vertically squashed by the stable stratification and stretched downwind by the higher-momentum flow in the inversion layer.

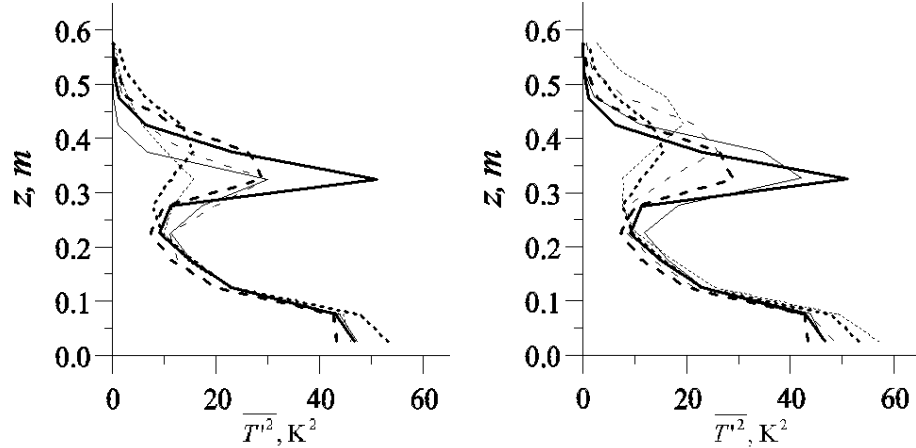


Figure 2: Temperature variance profiles in the evolving CBL at three subsequent locations along the simulation domain (wind tunnel test section):  $x=3.98\text{m}$  (solid lines),  $x=5.63\text{m}$  (dashed lines), and  $x=7.28\text{m}$  (dotted lines) for the PS case (left plot, thin lines) and for the NS case (right plot, thin lines). The reference case (RC) profiles at the same locations are shown in both plots by heavy lines.

This leads to the localization of vertical motion within a comparatively shallow zone and, consequently, to the reduction of vertical turbulent exchange across the inversion layer. With negative elevated shear, the squashed penetrating thermals encounter a lateral blockage by the lower-momentum flow that brakes their horizontal transport. Such blockage induces local pressure gradients that redistribute energy from the horizontal velocity component to the vertical one. The enhanced vertical motions intensify the turbulent exchange across the inversion and lead to the faster CBL growth.

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## References

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