Numerical investigation of the influence of river flow on the atmospheric boundary layer under stably stratified conditions

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Abstract. We report on Large Eddy Simulation of a stably stratified atmospheric boundary layer with a simplified river flow at the bottom boundary. The shear generated by the friction of water surface leads to creation of the air flow in a thin layer above water surface. Stratification prevents vertical motion due to negative buoyancy effects, and the flow expands in horizontal direction. This leads to accumulation of kinetic energy of the flow in a narrow layer near the surface (about 10 meters), where the air velocity may reach about a half of the velocity of the river surface. In case of strong inversion magnitude (20°C/km) the effect of formation of large-scale vortices was found for such configuration. These vortices significantly intensify heat and mass transfer in horizontal direction. The formation of these vortices is attributed to the process of inverse spectral transfer of turbulent energy, possible because of a quasi-two-dimensional structure of the flow.

1. Introduction
The stable temperature stratification inherent to the night atmospheric boundary layer is known for its strong influence on turbulent flows. One of the consequences of stratification is the transition from isotropic to strongly anisotropic turbulence. In this case the amplitude of turbulent fluctuations is suppressed along the vertical direction due to negative buoyancy. As a result of such suppression, flows under these conditions often acquire a complex structure, with the formation of jets at certain altitudes. In addition, the stratification may lead to separation of the flow in the horizontal plane into zones with strongly varying turbulence intensity and laminar spots and may increase intermittency in the flow [1].

Also, due to buoyancy effects in the stratified atmosphere, internal waves moving in the horizontal direction can develop with a significant effect on the long-wave part of the spectrum [2]. Anisotropic structure of a stratified atmosphere can lead to the appearance of quasi-two-dimensional features in the flow. In the presence of an energy source for horizontal velocity fluctuations (e.g. net horizontal shear) the effects of inverse spectral energy transfer may appear with the growth of large-scale vortex structures. In atmospheric conditions a river flow under the nocturnal conditions may serve as such a source of horizontal shear.

To test this hypothesis we conducted a series of LES simulations of an idealized river under the stably stratified atmospheric conditions. The results show a presence of large-scale vortices and an inverse energy cascade.
2. Computational details
The low-pass filtered Navier-Stokes and heat transport equations were solved numerically in a Large Eddy Simulation framework with Boussinesq approximation for buoyancy effects. The kinematic viscosity of air was set to be $1.5 \times 10^{-5}$ m$^2$/s and Pr = 0.71. LES studies were carried out using the open-source package for modeling of atmospheric flows MicroHH 1.0 (www.microhh.org) [3], using fourth-order accurate schemes in space and the third order in time. The subgrid model takes into account the local scale of stratification (mixing length). The switch from stable to unstable model is determined by the sign of Monin-Obukhov length at the point. The code was previously extensively tested in application to atmospheric flows, showing good agreement with experimental results [3].

The computational domain had dimensions of $1000 \times 1000 \times 100$ m, with a grid of 136 million nodes. The near wall grid cell size was $0.8 \times 0.8 \times 0.1$ m. The width of the river was 50 m. On the lateral boundaries of the computational domain periodic conditions were set, and at the upper boundary the free-slip condition was set. To obtain realistic velocity fields in the river, we developed a code for solving the depth-averaged Reynolds equations (with a standard $k$-$\varepsilon$ model) for a given river bed depth profile. The average value of the river depth used in simulations was 10 meters and the average velocity was 2 m/s. The computed velocity profile is shown in figure 1.

Simulations were carried out for several different intensities of stratification. The vertical component of temperature gradient (the inversion strength) in different simulations varied from 20 to 3ºC/km. These values are in the range of realistically observable near-ground inversions in the nocturnal atmospheric boundary layer.

3. Results and discussion
The horizontal velocity distributions in vertical cross-sections for different inversion strengths are shown in figure 2. It is evident, that for higher strengths of the inversion the height of the layer where the air motion exists is lower. At the same time the horizontal spreading of the motion is intensified for stronger inversions.

Stronger inversions lead to higher values of friction-induced momentum (longitudinal velocity) in the near-surface layer. For the highest considered inversion strength the value of longitudinal velocity in the air is close to the half of the maximum velocity of the river surface.

The structure of the flow consists of several horizontal layers one above the other with opposite signs of transverse components of horizontal velocity. This is due to the interaction of the flow, expanding in the horizontal direction, with the inversion layer, where, due to friction, the Kelvin-Helmholtz type instabilities occur leading to the formation of longitudinal (with respect to the river) vorticity and a secondary layer of motion with horizontal velocities of opposite sign. This process may be repeated several times with a magnitude decaying with altitude.
Figure 2. Velocity field. Longitudinal ((a), (b), (c)) and transverse ((d), (e), (f)) velocity components distribution in vertical cross-section. For $dT/dz = 20^\circ C/km$ ((c), (f)); $11^\circ C/km$ ((b), (e)); $3^\circ C/km$ ((a), (d)).

From the horizontal distribution of velocity and vertical vorticity (figure 3, left) it is seen that some concentrated vortices are forming with a vertical direction of vorticity. These vortices form near the ground surface at altitudes below 10 m. The vortices at the opposite banks of the river have opposite signs of vorticity. The evolution of these vortices leads to their horizontal spreading and entrainment of the background turbulence with the same sign of vertical vorticity. The vortices grow and eventually start to affect the longitudinal velocity distribution leading to changes in its direction. As seen from figure 2 the transverse velocity component magnitude is much smaller than the longitudinal velocity. This means that the transverse spreading of the momentum or humidity is much weaker than the longitudinal one. So the effect of the vortices significantly (about one order of magnitude) intensifies the transverse horizontal mixing intensity due to changes in the flow direction.

The observed behavior with the formation of large vortices takes place only for the strongest considered inversion strength ($20^\circ C/km$). For weaker inversions the large concentrated vortices do not form.

To further investigate into the origin of the vortex formation we calculate the spectral flux of turbulent energy $\Pi$ [4, 5] for several different horizontal scales in the cross-section where the maximum intensity of the vortices is observed (7 m above ground). The spectral energy flux is determined in the following way:

$$\Pi = \overline{S_y \tau_{ij}}; \quad \tau_{ij} = \overline{u_i u_j} - \overline{u_i} \overline{u_j},$$

where $S_y$ is a strain-rate tensor, and the overbar defines a spatial low-pass filtering operator at the specific lengthscale. The negative values of $\Pi$ correspond to the energy transfer from small scales of turbulent motion to the larger ones.

It can be seen (figure 3, right) that above the river (i.e. in the central part of the plot) there are regions with a strong negative spectral flux of turbulence energy. That means that the mechanism of vortex formation is closely related to the inverse energy cascade well-known for a two-dimensional turbulence. In our case, the thermal stratification suppresses vertical motion of the air, so the horizontal velocity fluctuations, originating from the shear at the river banks, are interacting mainly with each other, and very rarely with vertical velocity fluctuations. Such interactions, with a lack of
vortex stretching, lead to a transfer of energy toward the larger scales of the flow (i.e. the formation of large vortices).

4. Conclusion
The paper shows that the river flow has a significant influence on the night atmospheric boundary layer, and also affects the transport of aerosols. At the same time, the emerging large-scale vortices, accumulating turbulent energy in a narrow horizontal layer at low altitudes, expand the influence of the river on the area of about 10 river widths in horizontal direction. The large vortices, emerging from the horizontal shear at the river surface because of the inverse spectral transfer of turbulent energy, induce strong oscillations to the direction of air flow. This leads to a significant increase in the horizontal mixing. These effects may play an important role in the transport of humidity or pollutant concentration in an urban environment in the presence of a fast river running through the city.

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References
[1] Riley J J 2011 Boundary-Layer Meteorology 139(2) 241–59
[2] Riley J J, Lindborg E 2008 Journal of the Atmospheric Sciences 65(7) 2416–24
[3] Heerwaarden C C et al 2017 Geoscientific Model Development 10(8) 3145–65
[4] Chen S, Ecke, R E, Eyink G L, Rivera M, Wan M and Xiao Z 2006 Physical Review Letters 96(8) 084502
[5] Eyink G L, Aluie H 2009 Physics of Fluids 21(11) 115107