Numerical investigation of the effect of river meander on the dynamics of the atmospheric boundary layer

M S Bobrov* and M Yu Hrebtov

Institute of Thermophysics of SB RAS, 630090, 1 Ac. Lavrentyev Ave., Novosibirsk, Russia

*E-mail: maximbobrov20@gmail.com

Abstract. We report on a numerical study of diurnal cycle in the atmospheric boundary layer above a meandering river. The topography and the river shape are taken from the satellite data near Krasnoyarsk (Russia). Convective patterns developing during the early morning and the daytime lead to the formation of horizontal circulation and the jet-like flow across the river at the point of maximum curvature of the meander. This effect may play an important role in the transport of atmospheric pollutants in urban environment. During the flow evolution, formation of some coherent large-scale vertices is observed. The observed pattern can appear in many similar conditions in nature.

1. Introduction

Rivers and lakes due to the high heat capacity of water can become a source of buoyancy and moisture at night. Nocturnal cooling rate of the surrounding ground is much higher than that of the water, which leads to a growing difference between the temperature of the ground and the surface of water. In the daytime water bodies are cooler then the surroundings thus exerting a local stabilizing effect on the atmospheric boundary layer above them. In addition, there can be a significant effect of the river flow [1], which leads to the formation of horizontal circulations near the river. For an idealized straight river in nocturnal conditions, an increase in the growth rate of the mixed layer was observed when taking into account the effect of the river flow. However, the effect of the river meander on the atmospheric boundary layer has not been sufficiently studied. The Yenisei River was chosen as an object of study because it has a great influence on the atmospheric boundary layer in the city of Krasnoyarsk (Russia). Free-convective flows from the river may significantly affect the scalars dispersion around the city of Krasnoyarsk. Investigation of such influence might help developing ways to improve the ecological situation. In this paper, a numerical study of the effect of the meandering part of the river Yenisei on the diurnal evolution of the atmospheric boundary layer in the vicinity of the city was carried out.

2. Computational methodology

The Large Eddy Simulation equations (1) – (3) in anelastic approximation were considered. The simulation parameters were mimicking air properties (kinematic viscosity $\nu = 1.6 \times 10^{-5}$ m$^2$/s and $Pr = 0.71$). The study was carried out using an open-source package for modeling of atmospheric flows MicroHH 1.0 (www.microhh.org) [2], with fourth-order accurate staggered schemes for spatial discretization and third order compact Runge-Kutta scheme in time. The local mixing length was taken into account in a subgrid model (6). The switch from stable to unstable model was calculated by the sign
of Monin-Obukhov length at each point of horizontal cross-section. The code was previously tested on several atmospheric cases [2] and shown to provide reasonable agreement with experimental data.

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\begin{align*}
\frac{\partial \bar{u}_i}{\partial t} + \frac{1}{\rho_0} \frac{\partial \rho_0 \bar{u}_i}{\partial x_j} &= \frac{1}{\rho_0} \frac{\partial \bar{p}'}{\partial x_j} + \delta_{ij} \beta g \bar{\theta} (1+0.61q_v - q_l) + \frac{1}{\rho_0} \frac{\partial \rho_0 \tau_{ij}}{\partial x_j} \\
\frac{\partial \bar{\phi}}{\partial t} + \frac{1}{\rho_0} \frac{\partial \rho_0 \bar{\phi}}{\partial x_j} &= \frac{1}{\rho_0} \frac{\partial \rho_0 \tau_{ij}}{\partial x_j} \\
\frac{\partial \rho_0 \bar{u}_i}{\partial x_j} &= 0 \\
\tau_{ij} &= -2\nu_{sgs} S_{ij} \\
\nu_{sgs} &= \lambda^2 S \left(1 - \frac{Ri}{0.3}\right)^{0.5} \\
\frac{1}{\lambda^2} &= \frac{1}{(\kappa z)^2} + \frac{1}{(c_s \Delta)^2}
\end{align*}
\]

In (1)-(6) overbar denotes LES filtering operation. Other notations are as follows: \( u \) – velocity, \( \phi \) – scalars, \( \beta \) – air thermal expansion coefficient (3.38 \( \times \) 10\(^{-3}\) K\(^{-1}\)), \( q_v \) – water vapor mixing ratio, \( q_l \) – liquid water mixing ratio, \( \rho_0 \) – reference density profile, \( S \) – local strain rate, \( Ri \) – local gradient Richardson number, \( \kappa \) – von Karman constant (0.4), and \( c_s \) – Smagorinsky constant (0.12).

The size of the computational domain (Fig.1 (left)) was \( 10 \times 10 \times 1 \) km (in the x, y, and z directions, respectively) with a grid of \( \sim 10^9 \) nodes. The conditions of stable stratification with inversion amplitude of 2\(^\circ\)C / km were set as the initial temperature profile. The velocity field in the river surface was obtained from additional two-dimensional simulations. The mean velocity in the river was set to be 1.5 m/s. The size of ground-adjacent grid cell was \( 5 \times 5 \times 0.5 \) m, which may be considered adequate based on the grid convergence study of atmospheric LES flows [3].

![Figure 1. The satellite image with marked computation domain boundary (left), and the used ground temperature variation profile (right)).](image)

3. Results and discussion

Simulation starts in the nocturnal conditions when the river temperature is 5\(^\circ\)C higher than its surroundings. The updraft starts to develop above the river surface locally lifting the inversion layer from the ground. Then the air starts spreading horizontally, creating low-altitude circulations around the river. Next, as the ground gradually heats up the flow pattern changes. Around the river the convective cells start to appear. The most prominent change appears above the maximum curvature point of the river meander. At this point the horizontal flow direction is changed, creating a jet-like formation in the
upper part of the mixed layer (Fig. 2). The air is transferred by this jet from one river bank to the other. In previous studies [1] it was found that the straight linear river flow intensifies locally the growth rate of the mixed layer due to the interaction of horizontal shear with buoyancy-induced vertical updrafts. In our case this effect is further intensified by the appearance of transverse jet-like flow described above. It can be seen (Fig. 2 bottom) that the difference in inversion height between different cross-sections of the flow may achieve up to 250m which is about 50% of the horizontally-averaged inversion height.

This jet effect leads to a difference between the inversion heights above two river banks, which is visible at the distances of several kilometers from the river. Because of the interaction with the opposite bank circulation the air in the jet is further accelerated upwards compensating the negative buoyancy effect from the inversion. The point of maximum altitude of the jet is located about 2 curvature radii (or 4 km) away from the point of maximum curvature of the river meander.
On the distributions of the longitudinal velocity component (Fig.3), it can be seen that the longitudinal component of the momentum, created due to the motion of the underlying surface, accumulates in a rather narrow layer at a certain height above the ground. This accumulated momentum can be a source of turbulence energy and might intensify the mixing. This effect appears due to the interaction of the river flow with a free-convective flow from the river. At the beginning of the simulation, this accumulation happens directly above the river, however, when an intense jet-like cross-river flow appears, this layer begins to shift in the direction of the jet flow, which is accompanied by the local growth of the mixed layer.

**Fig.4.** Vertical profiles temperature distribution at $x = 7500$ and $y = 2500$ m (left), $y = 5000$ m (center), $y = 7500$ m (right) respectively.

In the vertical temperature profiles, it is seen that in the daytime the inversion height in the center of the region (Fig.4 (center)) is about 200m higher than over the river (Fig.4 (left)), which indicates the intensity of the arising phenomena. Formed jet-like flow promotes the transfer of heat and moisture from the river to the periphery. This process continues until the temperature of the river is equal to the temperature of the surrounding air. At this moment, the horizontal temperature gradient disappears and the air circulation changes in such a way that the upward leaves the river and shifts toward the center of the region. Later, as the surface cools, the river again becomes the center of the upward flow. Further, under the appropriate conditions, this process may be repeated.

**Conclusion**

The jet formation effect, which is the most pronounced in the first part of the day, is accompanied by the appearance of large-scale vertical vortices at the sides of the jet. The observed vortices are clearly visible in the time-filtered velocity distribution (Fig. 5). The horizontal scale of the vortices is about 150 m and the circulation period is about 14 min. The vortex lifetime is ~1.5 hours. The maximum velocity in the vortex is located at its periphery which indicates the large size of vorticity core. The air moves upward at the vortex periphery and downward at the vortex center in accordance with temperature distribution which has lower values at the center.

In the case when there are several consequent meanders with alternating curvature signs the most stable vortices are formed at the points of zero curvature. These large vortices may accumulate significant amounts of energy and detach from the point of formation in the form of vortex pairs which can travel with self-induced velocity. Such an effect can play an important role in the heat and mass transfer processes of atmospheric boundary layer near the rivers.
Acknowledgements
This work was supported by the Russian Foundation of Basic Research (project № 19-45-543010).

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