Evidence of Göttler vortices in katabatic jet along a convexly curved slope.

Christophe Brun and Sébastien Bien
LEGI, Grenoble, France

Abstract
Large Eddy Simulation of katabatic flow along a convexly curved slope is performed. A special focus is given on the outer-layer shear of the katabatic jet. Both a statistical quantitative analysis and a qualitative description of vortical structures are used to describe the present turbulent flow. It is shown that Göttler vortices oriented in the streamwise downslope direction and with a vertical mushroom shape develop in the shear layer. They play a specific role with respect to local turbulent mixing in the ground surface boundary layer. Such curved slope constitutes a realistic model for alpine orography. We provide a novel procedure based on local turbulence anisotropy to track Göttler vortices for in situ measurements.

Meso-NH Model: CNRM & LA Toulouse France
- Pseudo-incompressible Navier-Stokes equations
- Anelastic approximation
- Buoyancy effects (gravity)
- No Coriolis effects
- Dry air (perfect gas)
- LES: eddy model & mixing length closure
- Grid vertical refinement near the ground surface
- 5 3D grid points on 128 MPI proc. of IBM-SP6
- Initial conditions: air at rest with a constant $\nabla T = \frac{\Delta T}{\Delta z}$
- Ground surface cooling $H_u > 0$

Resolution/Boundary conditions

$\frac{\Delta x}{x} = \frac{\Delta y}{y} = \frac{\Delta z}{z} =$

200, 250, 300, 125, 100, 50
(1) in the domain $H_u (m)$

Q criterion $Q = \left( \frac{\nabla u}{\nabla T} \right)^2$

Statistical Results

temp. deficit
downslope velocity
Turbulent Kinetic Energy

$\langle u^2 \rangle = \frac{1}{2} \left( \frac{\partial V}{\partial x} \right)^2$

Prandtl Model

Analytical solution for the Prandtl model:

$u_{\infty}(z) = U_{\infty} \sin(z/L_0) e^{-z/L_0}$

$u_0(z) = -u_{\infty}(z/L_0) e^{-z/L_0}$

Three characteristic scales $L_0$, $v_0$, and $u_0$ have to be prescribed from the boundary and ambient conditions. For heat flux boundary conditions, replacing viscous by turbulent quantities, and assuming mixing coefficients $K_m$ and $K_v$ constant along z, one gets

$L_0 = \frac{1}{P_v^{1/4}} \frac{2}{K_v^{1/4}} \frac{K_m}{v}$

$V_0 = \frac{1}{P_v^{1/4}} \frac{1}{K_v^{1/4}} \frac{K_m}{v}$

$\theta_0 = \frac{1}{P_v^{1/4}} \frac{1}{K_v^{1/4}} \frac{K_m}{v}$

where $\theta_0 = \frac{K_m}{v}$ is the heat flux at the ground surface.

Heat flux and turbulent kinetic energy budget:

$K_m = \theta_0 \rho c_p \frac{\partial T}{\partial z}$

$\theta_0 = \frac{1}{P_v^{1/4}} \frac{1}{K_v^{1/4}} \frac{K_m}{v}$

$\theta_0 = \frac{1}{P_v^{1/4}} \frac{1}{K_v^{1/4}} \frac{K_m}{v}$

$\theta_0 = \frac{1}{P_v^{1/4}} \frac{1}{K_v^{1/4}} \frac{K_m}{v}$

Prandtl model with constant diffusion:

$x = 1.45 m, 0.15 m, 0.05 m, 0.04 m, 0.03 m, 0.02 m, 0.01 m, 0.005 m, 0.004 m, 0.003 m, 0.002 m, 0.001 m$

$x = 1.5 m, 0.5 m, 0 m, -0.5 m, -1.0 m, -1.5 m, -2.0 m, -2.5 m, -3.0 m$

Numerical Model

Meso-NH Model: CNRM & LA Toulouse France
- Pseudo-incompressible Navier-Stokes equations
- Anelastic approximation
- Buoyancy effects (gravity)
- No Coriolis effects
- Dry air (perfect gas)
- LES: eddy model & mixing length closure
- Grid vertical refinement near the ground surface
- 5 3D grid points on 128 MPI proc. of IBM-SP6
- Initial conditions: air at rest with a constant $\nabla T = \frac{\Delta T}{\Delta z}$
- Ground surface cooling $H_u > 0$

Anisotropy Invariant Map

Anisotropy tensor:

$a_1 = \langle u \rangle / \langle \nabla T \rangle$

$a_2 = \langle w \rangle / \langle \nabla T \rangle$

$a_3 = \langle z \rangle / \langle \nabla T \rangle$

Second and third invariants:

$b_2 = \frac{1}{2} a_1^2 - a_2$

$b_3 = \frac{1}{3} a_1^3 - a_2 a_1$

Axisymmetry parameter:

$X_\sigma(z) = 2 \sqrt{a_1} / \left( b_2 \right)^{1/3}$

TKE Budget

Turbulent Kinetic Energy

$TKE = \left( \langle u^2 \rangle + \langle v^2 \rangle + \langle w^2 \rangle \right)$

Horizontal and vertical production

$P_h = -\langle u \frac{\partial u}{\partial x} \rangle - \langle u \frac{\partial u}{\partial y} \rangle - \langle u \frac{\partial u}{\partial z} \rangle$

$P_v = -\langle v \frac{\partial v}{\partial x} \rangle - \langle v \frac{\partial v}{\partial y} \rangle - \langle v \frac{\partial v}{\partial z} \rangle$

Horizontal Advection

$Adv_h = -\langle u \frac{\partial u}{\partial x} \rangle - \langle u \frac{\partial u}{\partial y} \rangle - \langle u \frac{\partial u}{\partial z} \rangle$

$Adv_v = -\langle v \frac{\partial v}{\partial x} \rangle - \langle v \frac{\partial v}{\partial y} \rangle - \langle v \frac{\partial v}{\partial z} \rangle$

References