Simulation and modeling of the turbulent katabatic flow along a slope for stably stratified atmospheric boundary layer.

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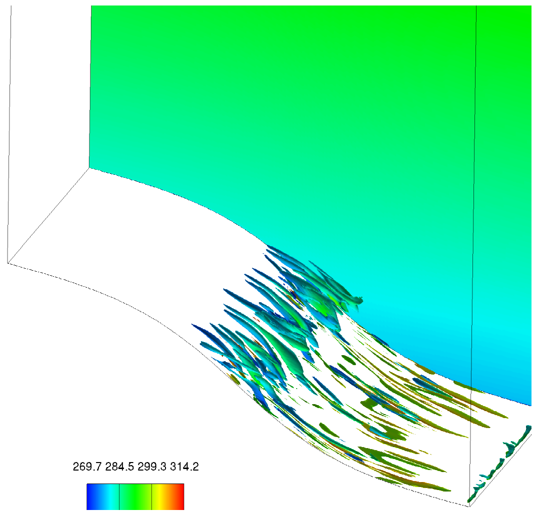


(a) Q criterion

Figure 1: Isovalues of the Q criterion (a) ang kinetic energy (b) colored by the streamwise velocity during transition to turbulence in the external shear layer of the ABL (zoom) for the case R0Q3N13.

The behaviour of the Atmospheric Boundary layer (ABL) along alpine valleys is strongly dependent on the day-night thermodynamic cycle and might impact meteorology and air pollution prediction [12]. At night, the ABL is stably stratified and the radiative cooling of the surface yields the development of a katabatic flow (Doran and Horst 1983, Doran et al. 1990, Monti et al. 2002). This flow consists of a downslope wall-jet which has the structure of both wall turbulence in the inner-layer zone and shear layer turbulence in the outer-layer zone and enhances a relative mixing eventhough stable stratification is considered (Baines 2005, Ahlman et al. 2007). Many analytical models based on the so-called Prandtl model (1942) have been and are still derived for katabatic flow (Shapiro and Fedorovich 2007) but a full 3D description of such flow by mean of Large Eddy Simulation of turbulence (LES) has not yet been achieved, except recently on relatively simple slopes (Skyllingstad 2003, Smith and Skyllingstad 2005) or including geostrophic wind forcing (Cuxart et al. 2006, Cuxart and Jimenez 2006). The main reason why such configuration has received only few attention is due to the huge amount of computational resources necessary to describe toogether all the scales from the synoptic scales to the ABL surface scales at realistic high Reynolds number. [10, 13, 7, 11, 1, 14, 6, 8]. The vertical resolution of the computational grid was necessarily refined to reach about a few meters close to the surface and properly capture the extrema of the downslope jet and the mean external shear and RMS maximum obtained in the first 20 meters of the ABL. Such LES has never been performed on more complex slope and this is the purpose of the present study to accurately describe the ABL on a hyperbolic tangent slope with stable stratification.

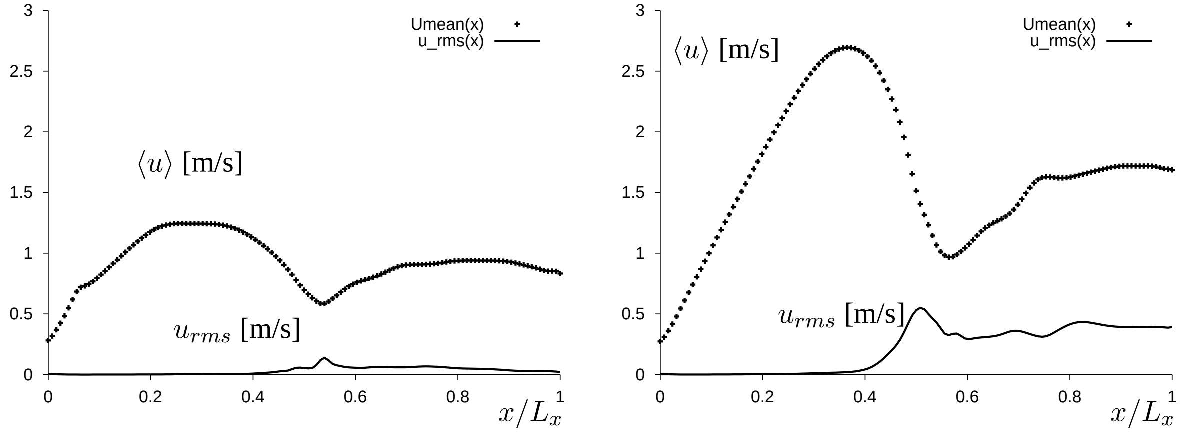
The numerical code used, Meso-NH, has been developed in CNRM/Meteo-France and Laboratoire d'Aérologie Toulouse, and consists of an anelastic non-hydrostatic model solving the pseudo-incompressible Navier-Stokes equations with a Boussinesq approximation [2]. Since ABL are highly turbulent flows, LES is considered with an extra transport equation for the sub-grid scale kinetic energy in complement to momentum and potential temperature equations, coupled with mixing length closure for the determination of the turbulent stresses. Numerical discretisation is performed with 4^{th} order centred scheme for the momentum equation, 2^{nd} order centred positive definite scheme for the temperature and kinetic energy equations, and the pressure solver consists of a Conjugate Residual method. The numerical domain of simulation consists of a large 3D domain of height L_z, length L_x and width L_y on the top of a 2D hyperbolic tangent slope of height H and maximum angle α_{max}, to represent a simple model of alpine slope (Table 1). About 5 million grid points are necessary to afford a relatively precise description of the flow in the vicinity of the surface, with a special refinement in the vertical direction to capture the wall-jet developing along the slope. The time step of the simulation is about $\Delta t = 0.05s$ that is to say $1.4s$ CPU on 8 processors (MPI) of the Nec Sx-8 french high-performance computer (IDRIS).

$L_x\ (m)$	$L_y\ (m)$	$L_z\ (m)$	$n_x \times n_y \times n_z$	Δx	Δy	Δz_{surf}	Δz_{top}	$H\ (m)$	α_{max}
$3,200$	$1,280$	$7,250$	$128 \times 128 \times 300$	$25\ m$	$10\ m$	$1\ m$	$120\ m$	$1,000$	35.5^o

Table 1: parameter of the numerical study

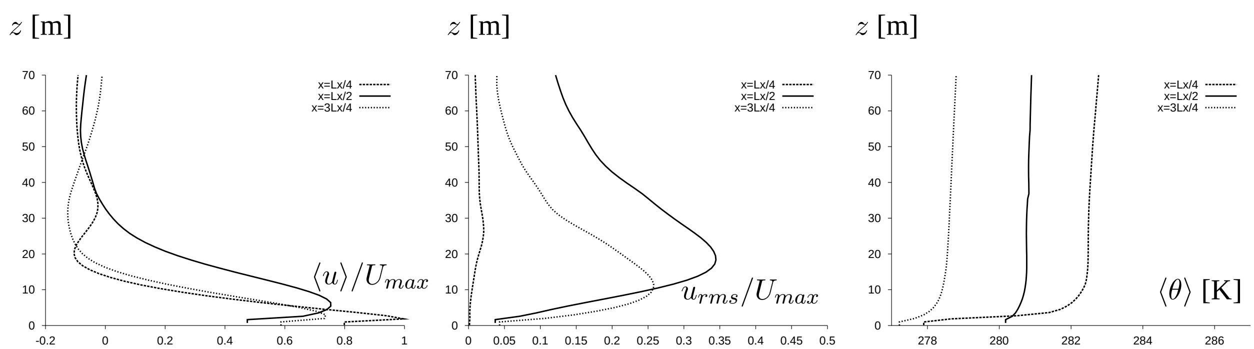
The setting of initial and boundary conditions is crucial for the simulation of stable ABL. Initial conditions consist of air at rest following a stable temperature profile with a constant Brunt-Väisälä frequency $N = 0.013$ (other values of N from 0.007 to 0.020 will be considered as well). Periodicity is considered in the spanwise L_y direction of the domain. Open Orlanski type boundary conditions are applied in the slope L_x direction of the ABL, with a constant phase velocity of $c = 10\ m/s$ of the order of magnitude of the gravity waves expected to spread in such configuration. On the top of the domain, non-reflective boundary conditions are considered. At the surface, the minimum vertical mesh size $\Delta z_{surf} = 1\ m$ is of the order of the boundary layer thickness. At the surface two sets of boundary conditions have been considered, first a rough surface condition with a roughness lengthscale $z_o = 3.5\ cm$ (case R0Q3N13), second an ideal case with slip conditions inducing a zero surface shear stress $\tau_w = 0$ (case U0Q3N13). As a first order surface model for the ABL we apply a constant negative surface heat flux $q_w = -30\ W/m^2$ [14] which acts as a source term for the katabatic flow.

The direct effect of surface cooling ($q_w \leq 0.$) on the stably stratified fluid initially at rest is to generate a katabatic downslope flow along the bottom surface (figs. 1, 3 and 4) due to gravity effect. After a transient, the flow reaches a maximum streamwise velocity of about $\langle u \rangle = 1$ to 3 m/s at about $x = 0.4L_x$ (fig. 2), determined at a vertical position of $z = 1$ to 2 m (the ABL thickness). A strong mean shear is observed in the external part of the ABL all along the slope (figs. 3 and 4) which forms a shear layer with a thickness of about 10 to 20 m. Transition to turbulence occures in the shear layer zone (fig. 1) and turbulent structures develop along the slope, are stretched and advected further downstream. The surface temperature difference of the downslope-jet is about -2K to -4K with respect to the initial temperature (figs. 3 and 4), all this being consistent with existing literature on katabatic flows [14, 9]. The gradient Richardson number which provides a measure of whether the external ABL shear flow will yield transition to turbulence is about to reach values above the critical number $Ri_{cr} = 0.2$ (Nieuwstadt and Duynkerke 1995). In this context, it is particularly interesting to analyse how turbulent structures borned out of the external shear layer instability (Kelvin Helmholtz vorticies) will be stretched in the streamwise direction and enhance streamwise vortices and increase local mixing as shown on figure 1. This property is of direct interest for scalar mixing and must be accurately described to allow for air quality prediction [5, 3, 4]. The effect of the two sets of



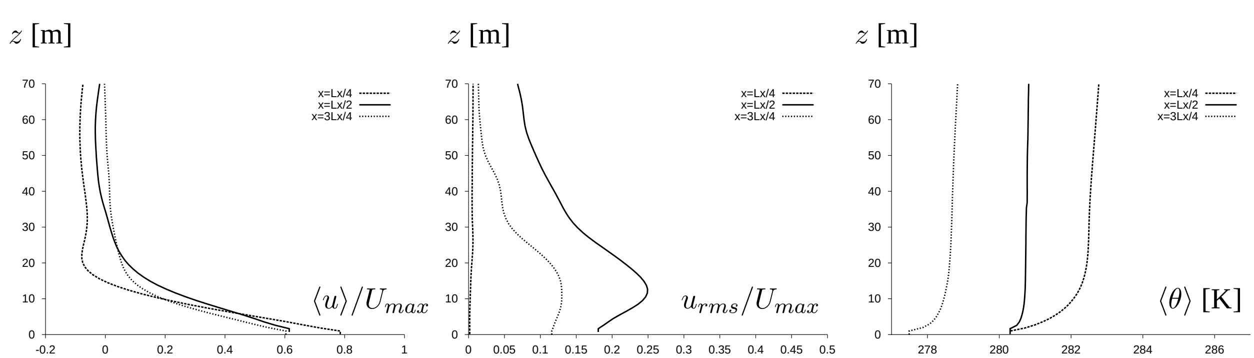
(a) $r_o = 0.35\ m$, $u_\tau \neq 0$, $t = 01H39M$ (b) $N = 0.013$, $u_\tau = 0$, $t = 02H52M$

Figure 2: Mean and RMS streamwise velocity evolution along the TH slope for $z = 1\ m$. Reference case R0Q3N13 : $N = 0.013$, $r_o = 0.035\ m$, $Q_w = -30\ W/m^2$ (a). and case U0Q3N13 : $N = 0.013$, $u_\tau = 0$, $Q_w = -30\ W/m^2$ (b).



(a) Mean streamwise velocity (b) RMS streamwise velocity (c) Mean potential temperature

Figure 3: Mean streamwise velocity profiles (a), RMS streamwise velocity profiles (b) and Mean potential temperature profiles (c) at 3 stations along the TH slope, $x_1 = L_x/4$, $x_2 = L_x/2$ and $x_3 = 3L_x/4$. Reference case R0Q3N13 at $t = 1h39min$: $N = 0.013$, $r_o = 0.35m$, $Q_w = -30\ W/m^2$.



(a) Mean streamwise velocity (b) RMS streamwise velocity (c) Mean potential temperature

Figure 4: Mean streamwise velocity profiles (a), RMS streamwise velocity profiles (b) and Mean potential temperature profiles (c) at 3 stations along the TH slope, $x_1 = L_x/4$, $x_2 = L_x/2$ and $x_3 = 3L_x/4$. Reference case U0Q3N13 at $t = 2h52min$: $N = 0.013$, $u_\tau = 0$, $Q_w = -30\ W/m^2$.

boundary conditions presently considered (no slip and free slip) is quantitatively very strong (all figures) and points out the importance of designing very accurate surface models and surface boundary conditions for ABL prediction especially when stable ABL is involved.

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