Large Eddy Simulation of katabatic flow along a slope model.

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Résumé :

La modélisation de la turbulence est un élément essentiel de la prédiction de la qualité l'air en vallée alpine, en particulier en situation stablement stratifiée. Des SGE à haute résolution sont effectuées avec le code de calcul Meso-NH. On évalue l'effet des conditions aux limites, refroidissement et rugosité en paroi, sur le comportement turbulent de l'écoulement catabatique généré le long d'une pente modèle. La prise en compte du transport et du mélange de scalaire est envisagée.

Abstract :

Turbulence modeling is a main ingredient in air quality predicition for alpine valleys, especially when stably stratified situations are involved. Highly resolved LES are performed with the Meso-NH numerical code. The effect of boundary conditions in term of surface cooling and surface roughness is considered and the impact on the turbulent structure of the katabatic flow developed on a slope model is quantified. Scalar transport and mixing will be analysed as well.

Mots clefs : **LES, katabatic flow, stably stratified atmospheric boundary layer**

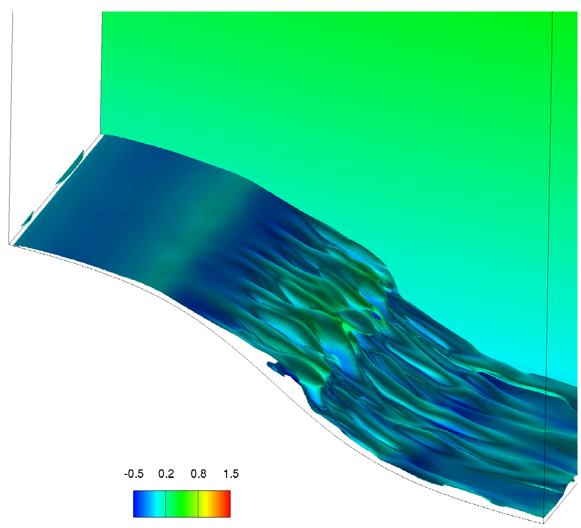

FIG. 1 – Isovalues of the Q criterion $Q = 10^{-5}s^{-2}$ (a) and turbulent kinetic energy $K = 0.15m^2/s^2$ (b) colored by the streamwise velocity ($t = 0h30min$) in the external shear layer of the ABL (zoom R0Q3N13).

1 Introduction

The behaviour of the Atmospheric Boundary Layer (ABL) along alpine valleys such as around Grenoble France is strongly dependent on the day-night thermodynamic cycle and might impact meteorology and air pollution prediction [1]. At night, the ABL is stably stratified and the radiative cooling of the surface yields the development of a katabatic flow [2, 3, 4]. 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 even though stable stratification is considered [5]. Many analytical models based on the so-called Prandtl model (1942) have been and are still derived for katabatic flow [6] 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 [7] or including geostrophic wind forcing [8, 9]. The main reason why such configuration has received only little attention is due to the huge amount of computational resources necessary to describe together all the scales from the synoptic scales to the ABL surface scales at realistic high Reynolds

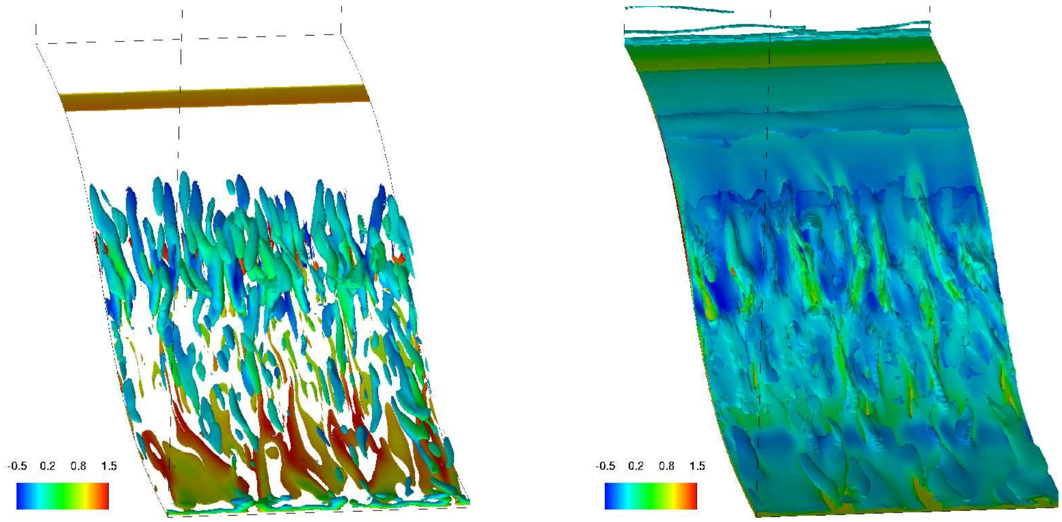

FIG. 2 – Isovalues of the Q criterion $Q = 10^{-5}s^{-2}$ (a) and Richardson number $Ri = 0.2$ (b) colored by the streamwise velocity in the fully turbulent regime ($t = 3h02$) in the external shear layer of the ABL (R0Q3N13).

number. [10, 11, 12, 13, 14, 7, 15, 16]. 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 representative of natural terrain flattering at the bottom and this is the purpose of the present study to accurately describe the ABL on a hyperbolic tangent (TH) slope with stable stratification.

2 Flow configuration and numerical aspects

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 an anelastic approximation introduced by Duran in 1989 [17, 18]. 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

TAB. 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 $N = 0.013$. 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 an advection velocity set to $u_x(N_x) + c$, $u_x(N_x)$ being the streamwise velocity at the boundary and $c = 10\ m/s$ a phase velocity 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 free slip conditions inducing a zero surface shear stress $\tau_w = 0$ (case U0Q3N13). The boundary condition at the ground surface for the thermal field is a constant negative heat flux $q_w = -30\ W/m^2$ [7] which acts as a source term for the katabatic flow.

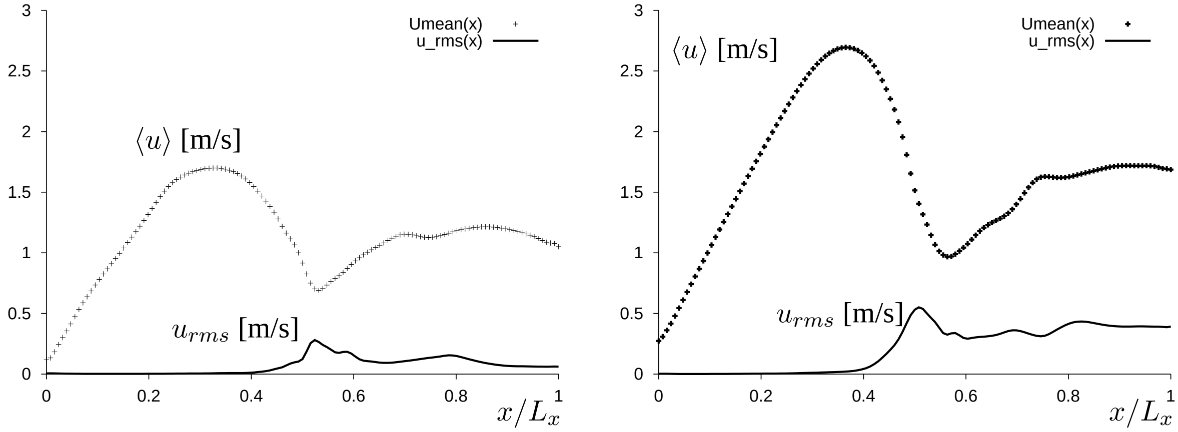

FIG. 3 – Mean and RMS streamwise velocity evolution along the TH slope for a constant height z near the surface. Reference case R0Q3N13 : $z = 3\ m$, $N = 0.013$, $r_o = 0.035\ m$, $Q_w = -30\ W/m^2$ (a). and case U0Q3N13 :$z = 1\ m$, $N = 0.013$, $u_\tau = 0$, $Q_w = -30\ W/m^2$ (b).

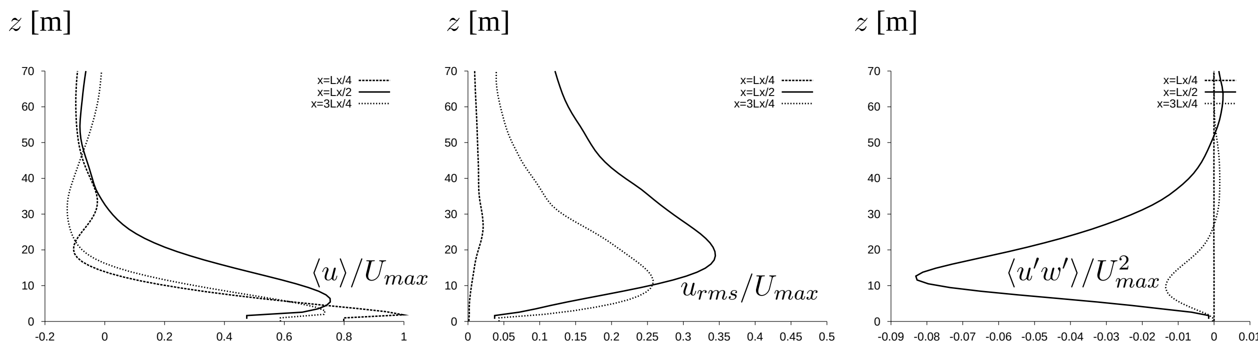

FIG. 4 – Mean streamwise velocity profiles (a), RMS streamwise velocity profiles (b) and Turbulent stresses profiles (c) at 3 stations along the TH slope, dashed line $x_1 = L_x/4$, solid line $x_2 = L_x/2$ and dotted line $x_3 = 3L_x/4$. Reference case R0Q3N13 at $t = 3h02min$: $N = 0.013$, $r_o = 0.35m$, $Q_w = -30\ W/m^2$.

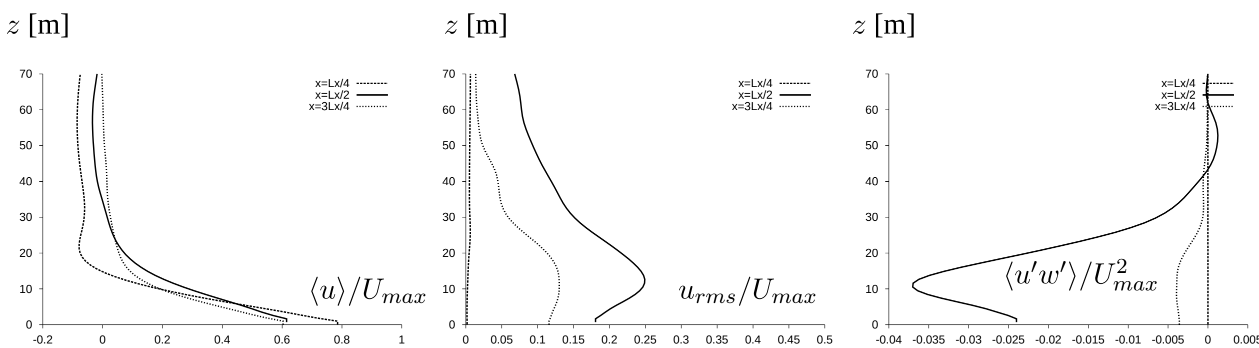

FIG. 5 – Mean streamwise velocity profiles (a), RMS streamwise velocity profiles (b) and Turbulent stresses profiles (c) at 3 stations along the TH slope, dashed line $x_1 = L_x/4$, solid line $x_2 = L_x/2$ and dotted line $x_3 = 3L_x/4$. Reference case U0Q3N13 at $t = 3h48min$: $N = 0.013$, $u_\tau = 0$, $Q_w = -30\ W/m^2$.

3 Description and analysis of the results

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, 2, 4 and 5) due to gravity effect. After a transient of about $30\ min$, the flow reaches a maximum streamwise velocity of about $\langle u \rangle = 1$ to 3 m/s at about $x = 0.4 L_x$ (fig. 3), determined at a vertical position of $z = 1$ to 3 m (the ABL thickness). For the no slip boundary condition case (R0Q3N13) the resulting friction velocity is $u_\tau = 0.47 m/s$ for $x = L_x/2$ and the first resolved point at the surface corresponds to a wall unit of about $z^+ = 31,000$. This clearly shows the need of increasing the vertical resolution to properly solve the internal shear layer of the ABL. A strong mean shear is observed in the external part of the ABL all along the slope (figs. 4 and 5) which forms a shear layer with a thickness of about 10 to 20 m. Transition to turbulence occurs in the shear layer zone (figs. 1 and 2) and turbulent structures develop along the slope, are stretched in the streamwise direction. Consequently velocity RMS (figs. 4b and 4b) and velocity turbulent stresses (figs. 5c and 5c) reach important levels in the external shear layer region. The surface temperature difference of the downslope-jet is about -2K to -4K with respect to the initial temperature (figs. 6a and 7a), all this being consistent with existing literature on katabatic flows [7, 9]. The resulting RMS temperature (figs. 6b and 7b) and turbulent heat fluxes (figs. 6c and 7c) show the important mixing property occuring in the present shear zone. 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 $Ri_{cr} = 0.2$. In this context, it is particularly interesting to analyse how turbulent structures developed from 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 figures 1 and 2. This property is of direct interest for scalar mixing and must be accurately described to allow for air quality prediction [19, 20, 21].

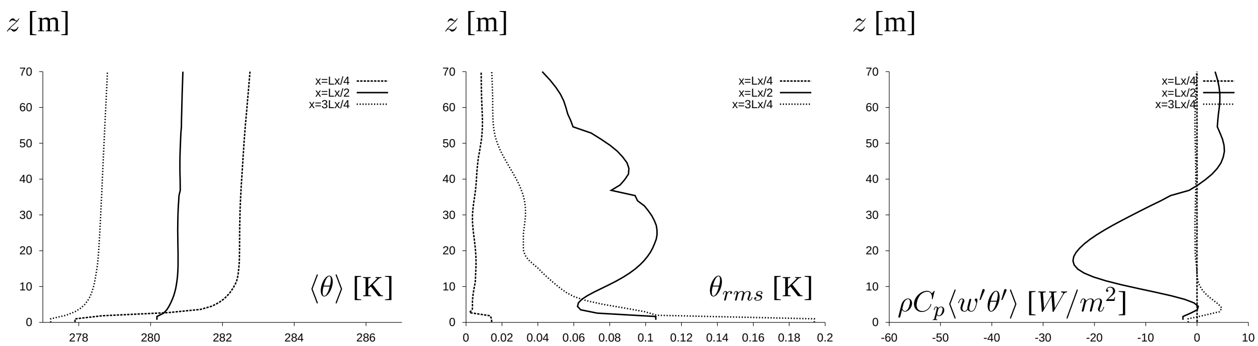

FIG. 6 – Mean potential temperature profiles (a) RMS potential temperature profiles (b) and Turbulent heat flux profiles (c) at 3 stations along the TH slope, dashed line $x_1 = L_x/4$, solid line $x_2 = L_x/2$ and dotted line $x_3 = 3L_x/4$. Reference case R0Q3N13 at $t = 3h02min$: $N = 0.013$, $r_o = 0.35m$, $Q_w = -30\ W/m^2$.

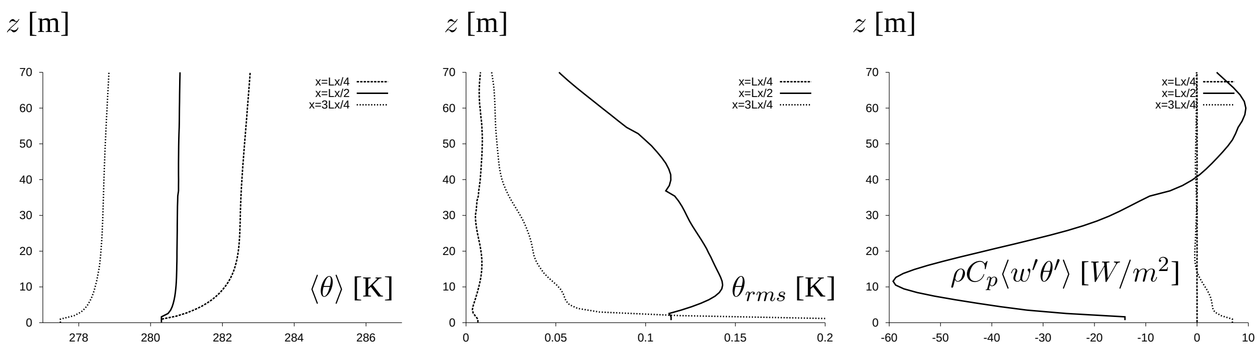

FIG. 7 – Mean potential temperature profiles (a) RMS potential temperature profiles (b) and Turbulent heat flux profiles (c) at 3 stations along the TH slope, dashed line $x_1 = L_x/4$, solid line $x_2 = L_x/2$ and dotted line $x_3 = 3L_x/4$. Reference case U0Q3N13 at $t = 3h48min$: $N = 0.013$, $u_\tau = 0$, $Q_w = -30\ W/m^2$.

4 Conclusion

LES of the turbulent katabatic flow along a simple TH slope has been performed with a special focus on the external shear layer which develops in the region close to the ground surface. The effect of two sets of boundary conditions presently considered (no slip and free slip) is quantitatively very strong and points out the importance of designing very accurate surface models and surface boundary conditions for ABL prediction especially when stable ABL is involved. Turbulent structures develop in the region close to the surface where the Richardson number is lower than the critical value $Ri = 0.2$ and their impact on scalar transport and mixing efficiency will be further discussed in the final contribution.

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