Role of Görtler vortices on the turbulent mixing in a katabatic flow along a curved slope for stably stratified atmospheric boundary layer.

Application to real mountain slopes in the Alps.

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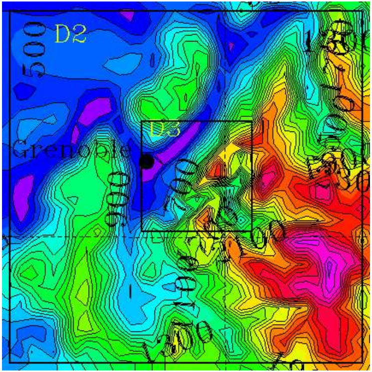
13 mai 2011.

- Geophysical flows along mountain orography
- Stably stratified Atmospheric Boundary Layers
- Katabatic flow / Turbulent mixing ?



Grenoble, in a **'Y'** valley surounded by 3 mountains :

- Alps (East)
- Chartreuse (North)
- Vercors (West)

27 december 2006
PM10 pollution
Stable Stratification
PhD Y Largeron 2010

State of the art I

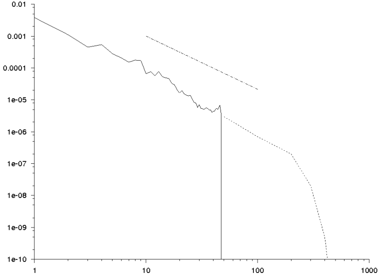
- Katabatic flow along a slope
  - Stably stratified ABL Nieuwstadt & Meeder 1996
  - Slope winds along valleys Doran & Horst 1983
  - Night-day Thermodynamic Cycle : surface radiative cooling Hoffmann, Muck & Bradshaw 1985
- Numerical fine description of Katabatic flows
  - Simple slope (LES) Skyllingstad 2003
  - Simple slope (DNS) Fedorovich et al. Acta Geoph. 2010
  - Real terrain & geostrophic forcing Cuxart et al. 2006

1 Introduction

- Meso-NH Model
  CNRM & LA Toulouse
  - Pseudo-incompressible Navier-Stokes equations
  - Anelastic approximation
  - Buoyancy effects
  - No Coriolis effects
  - Dry air (perfect gas)
  - LES : K_{SGS} equation & mixing length based eddy viscosity closure

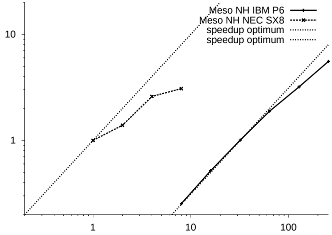
- Numerical Schemes :
  - Momentum eq. : centred O(4)
  - Θ & K_{SGS} eq. : centred positive definite O(2)
  - Pressure solver : Conjugate Residual method
  - Time advancement : Leap Frog O(2)

$E(k)$



LES DNS $k = \frac{\pi}{\Delta}$

CPU_{ref}/CPU



NEC SX8 IBM P6

Proc *nb*

DNS : $N = Re^{9/4}$

LES : $N = 5$ *Millions*

$Re = 10^5$

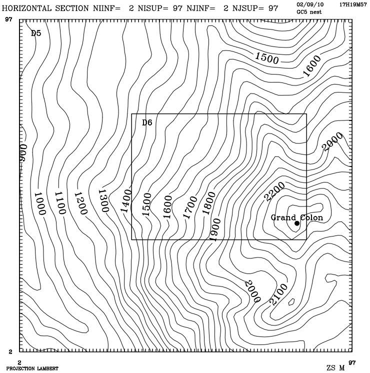
MPI : CPU Speed up

IBM P6 : 128 proc

- Numerical Resolution :
  - 2 embeded domains
  - $n_x \times n_y \times n_z = 150 \times 108 \times 150$
  - $L_x \times L_y \times L_z = 1.8km \times 1.3km \times 8km$
  - $\Delta z_{max} = 200\ m$
    $z_{min} = 2\ m$
  - $\Delta x = \Delta y = 12m$
  - $\Delta t = 0.1\ s$
- Initial Conditions : ECMWF 27 december 2006 at 12 :00
  - $N = 0.011\ s^{-1}$
- Ground Bound. Conditions coupling with SURFEX module

REAL CASE

$y\ (m)$



$x\ (m)$

(French Alps : Belledonne)

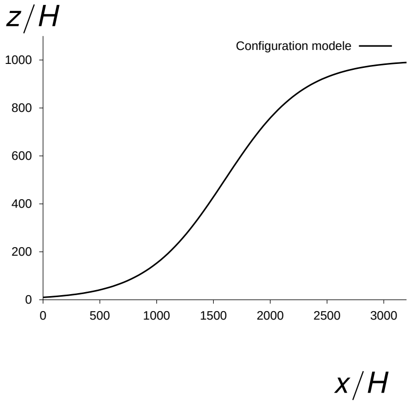
- Numerical Resolution :
  - 2 embeded domains
  - $n_x \times n_y \times n_z =$ $150 \times 108 \times 150$
  - $L_x \times L_y \times L_z =$ $1.8km \times 1.3km \times 8km$
  - $\Delta z_{max} = 200\ m$ $z_{min} = 2\ m$
  - $\Delta x = \Delta y = 12m$
  - $\Delta t = 0.1\ s$
- Initial Conditions : ECMWF 27 december 2006 at 12 :00
  - $N = 0.011\ s^{-1}$
- Ground Bound. Conditions coupling with SURFEX module

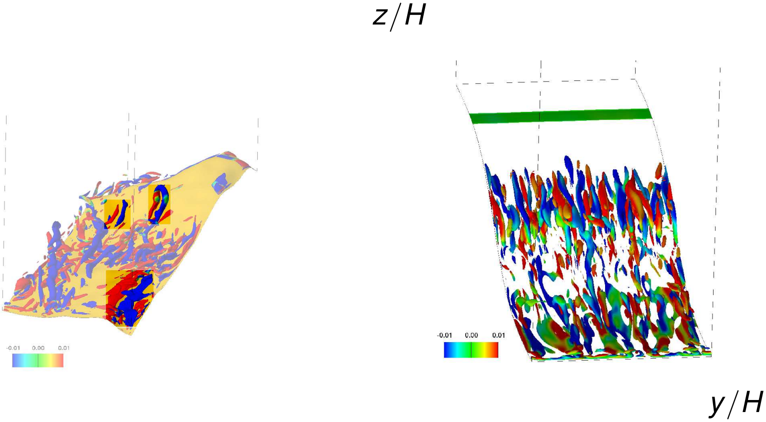
REAL CASE

Grand Colon (Grenoble)
Master M2 : S. Blein, 2010-11

- Numerical Resolution :
  - Hyperbolic Tangent Slope
  - $n_x \times n_y \times n_z = 128 \times 128 \times 300$
  - $L_x \times L_y \times L_z = 3.2km \times 1.3km \times 7km$
  - $\Delta z_{max} = 120\ m$
    $z_{min} = 1\ m$
  - $\Delta x = 25m, \Delta y = 10m$
  - $\Delta t = 0.05\ s$
- Initial Conditions : At Rest
  - $N = 0.013\ s^{-1}$
- Ground Bound. Conditions
  - $q_w = -30\ W/m^2$
  - Roughness $z_o = 0.35\ m$

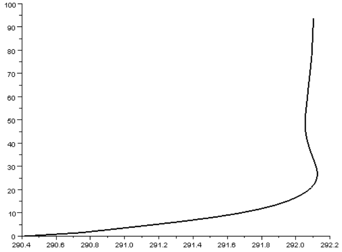
IDEAL CASE





- Isovalues of $Q = \frac{U_{max}^2}{H^2}$ colored by axial vorticity

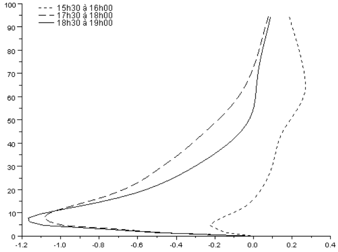
$z - z_o[m]$



$\langle\theta\rangle\ [K]$

potential temperature

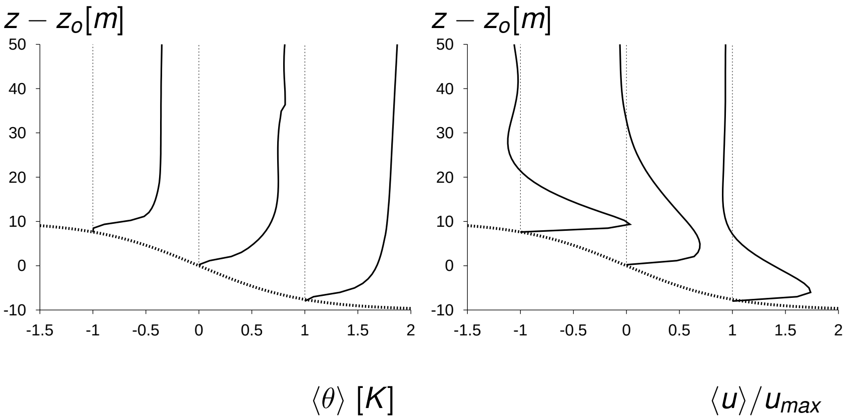
$z - z_o[m]$



$\langle u\rangle / u_{max}$

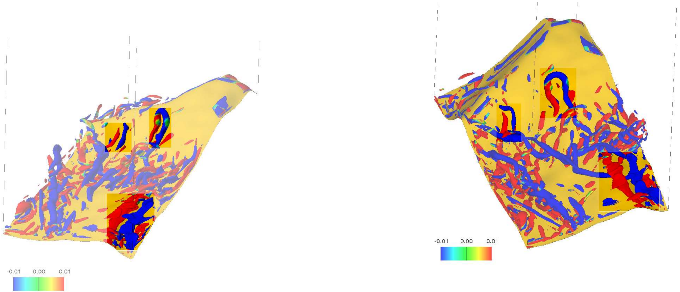
streamwise velocity

Realistic simulation along the alpine slope of the Grand Colon



potential temperature streamwise velocity

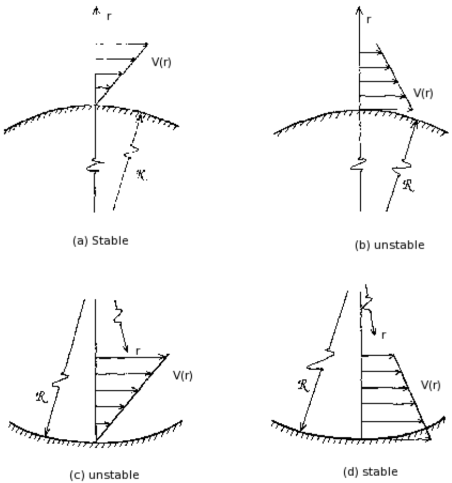
Idealised simulation on a model slope



High vertical resolution : $\Delta z = 2\ m$ at ground

- Isovalues of $Q = \frac{U_{max}^2}{H^2}$ colored by axial vorticity

Görtler vortices



- convex/concave curvature

'Görtler Vortices'
Illustrations of velocity distributions that lead to centrifugal instabilities

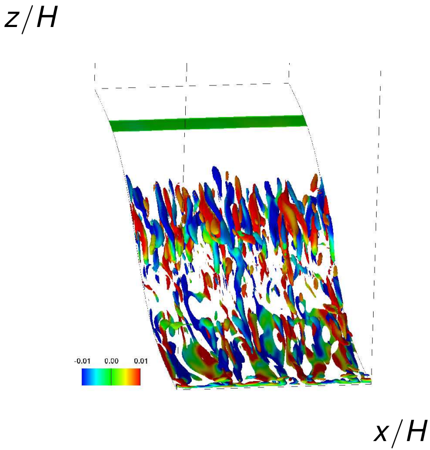
W. S. Saric, 1994
Annu. Rev. Fluid Mech.

- Isovalues of Q colored by axial vorticity :

$$Q = \frac{\bar{\omega}_{ij}^2 - \bar{S}_{ij}^2}{2} = \frac{U_{max}^2}{H^2}$$

Görtler vortices
$z \approx 30m$

high vertical resolution :
$\Delta z = 1\ m$ at ground

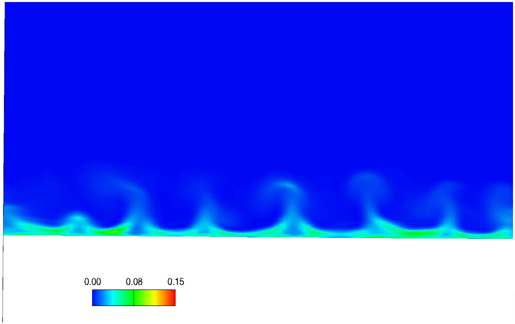


- TKE Slice
  in the ABL
  $z \approx 30m$

  Görtler vortices
  $\lambda_y \approx 200m$

  Turbulence level
  $Tu = 5\%$

z/H

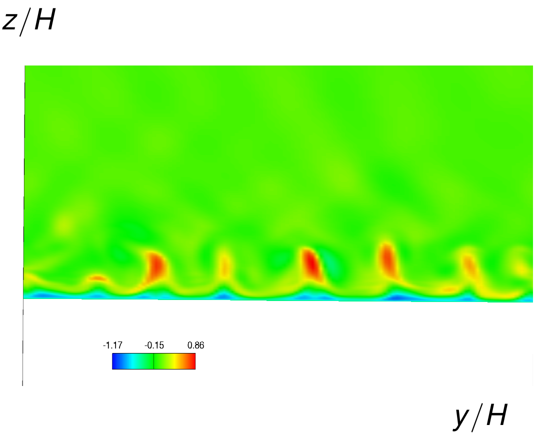


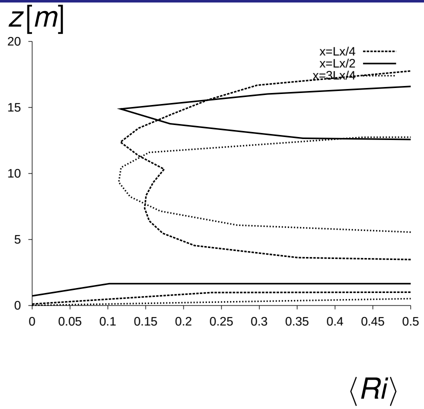
y/H

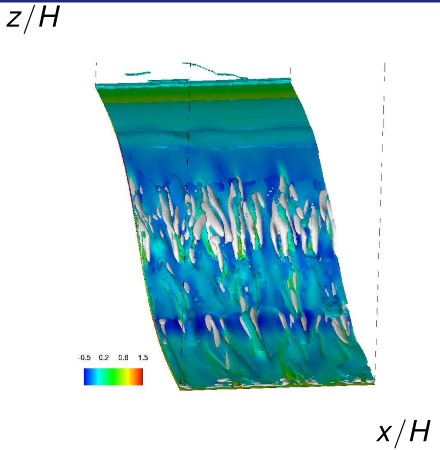
- W slice
  in the ABL
  $z \approx 30m$

  vertical mixing
  $\lambda_y \approx 200m$

  Max velocity
  $W_{max} \approx 1\ m/s$







Gradient Richardson number

- Isovalues of Q (grey scale)
- Isovalues of Ri $Ri_c = 0.25$

Conclusion

- Realistic Simulation of the stable ABL along alpine slopes
- High vertical resolution requirements
- Katabatic flow development near the ground surface
- Görtler instability and turbulent mixing

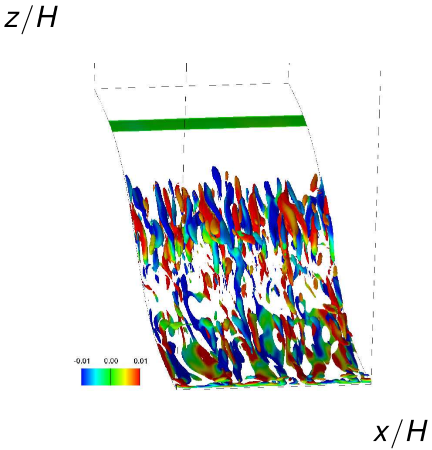
Outlook

- Precise analysis of the results (x,t)
- Half-ideal LES : real ground surface - ideal IC & BC
- Ground surface 1D modeling : vertical resolution
- Full realistic simulation with regional coupling (30 millions points)

We represent reality based on images we build out of it : We make images out of facts. Indeed, to represent reality, such images need to share the same structure and the same logical form with reality.

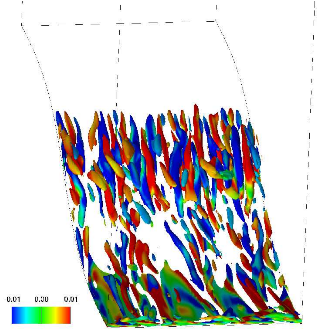
Ludwig Joseph Johann Wittgenstein, Tractatuslogico-philosophicus, Wienn, 1921

- Isovaleurs de Q colorées par la vorticité axiale :
  $Q = U_{max}^2 / H^2$
  rough ground surface



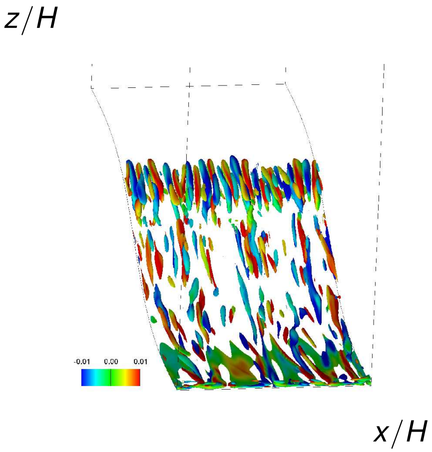
- Isovaleurs de Q colorées par la vorticité axiale : $Q = U_{max}^2/H^2$
  free-slip ground surface

z/H

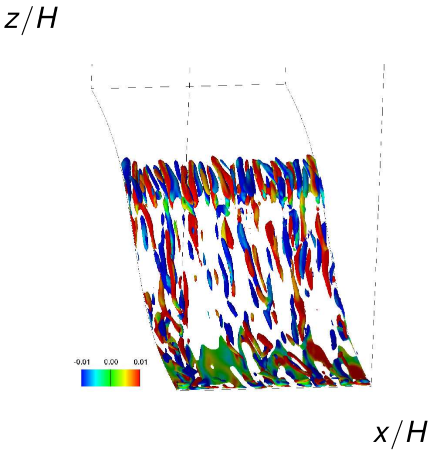


x/H

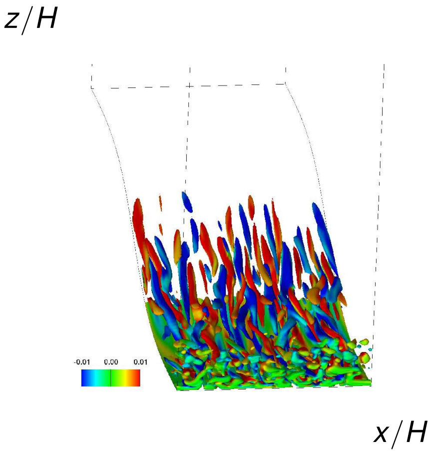
- Isovaleurs de Q colorées par la vorticité axiale :
  $Q = U_{max}^2/H^2$
  Surface cooling : $Q = -10 W/m^2$



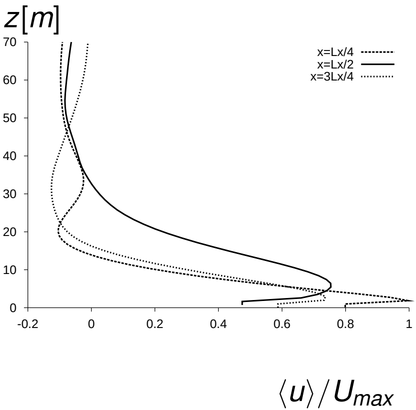
- Isovaleurs de Q colorées par la vorticité axiale : $Q = U^2_{max}/H^2$
  Stratification : $N = 0.20$

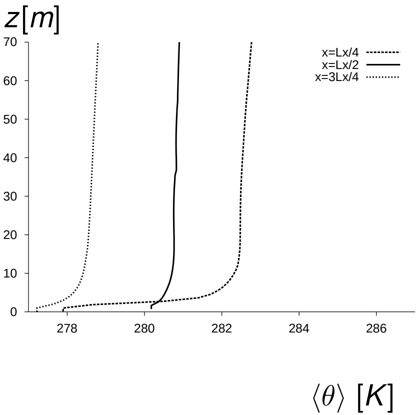


- Isovaleurs de Q colorées par la vorticité axiale :
  $Q = U_{max}^2 / H^2$
  Stratification : $N = 0.07$



Statistics



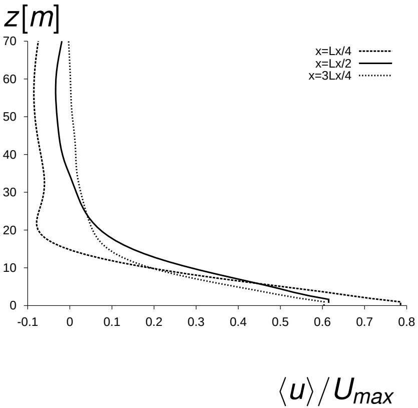


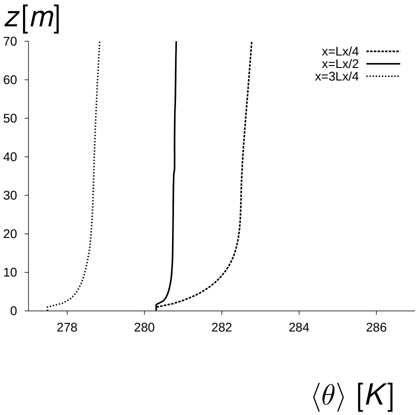
Streamwise velocity

BC : surface roughness

$U_{max} = 1.5 m/s$

Potential temperature





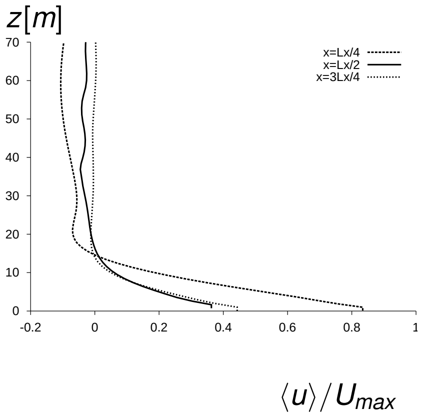
Streamwise velocity

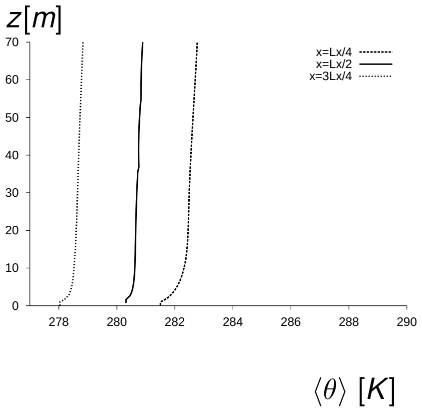
BC : surface roughness

$U_{max} = 2.7 m/s$

Potential temperature

Statistics





Streamwise velocity

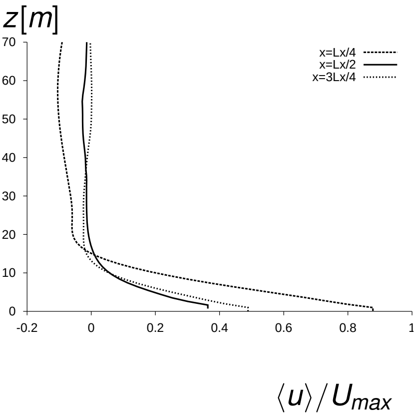
Surface cooling :

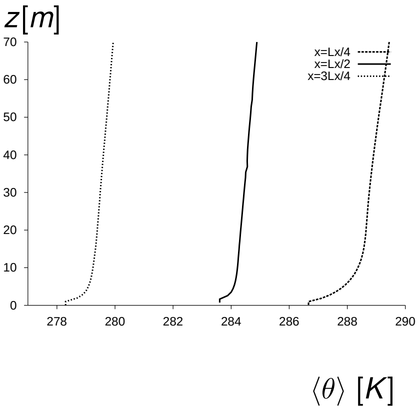
$Q = -10W/m^2$

$U_{max} = 1.6m/s$

Potential temperature

Statistics





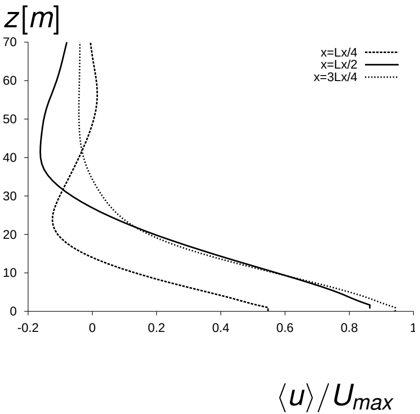
Streamwise velocity

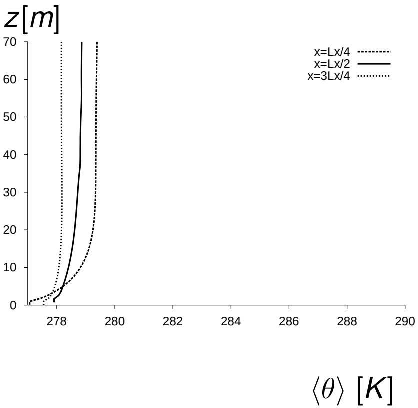
Stratification : $N = 0.20$

$U_{max} = 2.2m/s$

Potential temperature

Statistics





Streamwise velocity

Stratification : $N = 0.07$

$U_{max} = 4.0 m/s$

Potential temperature