# Adaptation of Pressure Based CFD Solvers for Mesoscale Atmospheric Problems

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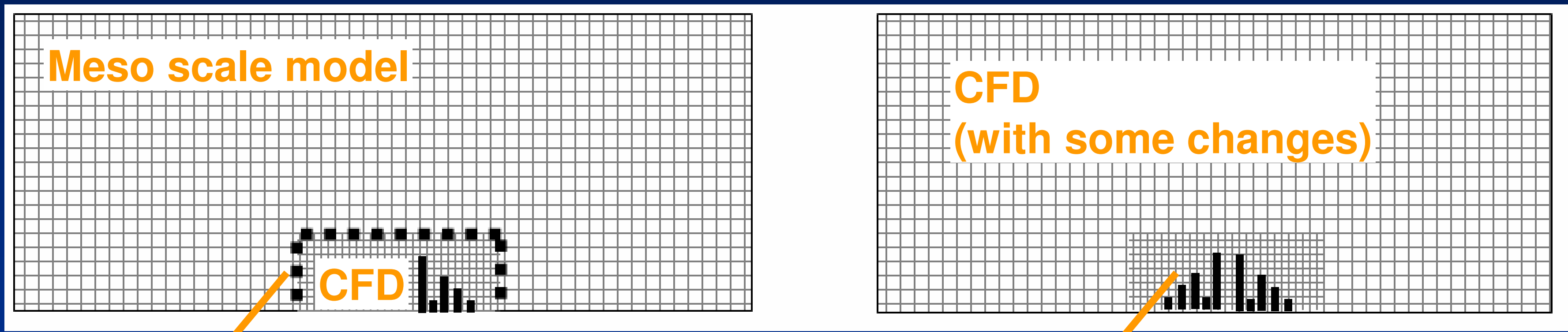
# Advantages of a CFD based model




model conversion interface

grid refinement

- The bidirectional interface is a source of numerical errors eg. it can cause partial reflection.

**Gravity waves ??**

**Thermal convection (UHIC) ??**

- Better geometrical description
- More general turbulence models
- Easy customization
- Advanced pre- and post processing

# Methodology

Incompressible CFD model (FLUENT)
+ transformation system
+ customized source terms

# Mathematical description

$$\tilde{\rho} = \rho_0 - \rho_0\,\beta\left(\tilde{T} - T_0\right)$$

$$\nabla \cdot \tilde{\mathbf{v}} = 0$$

$$\frac{\partial}{\partial t}\left(\rho_0 \tilde{\mathbf{v}}\right) + \nabla \cdot \left(\rho_0\, \tilde{\mathbf{v}} \otimes \tilde{\mathbf{v}}\right) = -\nabla \tilde{p} + \nabla \cdot \boldsymbol{\tau} + \left(\tilde{\rho} - \rho_0\right)\mathbf{g} + \mathbf{F}$$

$$\frac{\partial}{\partial t}\left(\rho_0 c_p \tilde{T}\right) + \nabla \cdot \left(\tilde{\mathbf{v}}\, \rho_0\, c_p \tilde{T}\right) = \nabla \cdot \left(K_t \nabla \tilde{T}\right) + S_T$$

$$\frac{\partial}{\partial t}\left(\rho_0\, k\right) + \nabla \cdot \left(\rho_0\, \tilde{\mathbf{v}}\, k\right) = \nabla \cdot \left(\frac{\mu_t}{\sigma_k} \nabla k\right) + G_k + G_b - \rho_0\, \varepsilon + S_k$$

$$\frac{\partial}{\partial t}\left(\rho_0\, \varepsilon\right) + \nabla \cdot \left(\rho_0\, \tilde{\mathbf{v}}\, \varepsilon\right) = \nabla \cdot \left(\frac{\mu_t}{\sigma_\varepsilon} \nabla \varepsilon\right) + \rho_0\, C_1\, S\, \varepsilon - \rho_0\, C_2 \frac{\varepsilon^2}{k + \sqrt{\nu\, \varepsilon}} + C_{1\varepsilon} \frac{\varepsilon}{k} C_{3\varepsilon} G_b + S_\varepsilon$$

Customized volume sources

Transformed variables $\tilde{\rho}, \tilde{T}, \tilde{p}, \tilde{\mathbf{v}}, \tilde{z}$

# Transformation expressions

$$T = \tilde{T} - T_0 + \bar{T}$$

$$p = \frac{\bar{\rho}}{\rho_0} \cdot \tilde{p} + \bar{p} = e^{-\zeta z} \cdot \tilde{p} + \bar{p}$$

$$\rho = \tilde{\rho} - \rho_0 + \bar{\rho}$$

$$z = -\frac{1}{\zeta} \mathrm{Ln}\left(1 - \zeta \, \tilde{z}\right)$$

$$w = \frac{\rho_0}{\bar{\rho}} \tilde{w} = \tilde{w} \, e^{\zeta z}$$

# Equilibrium profiles

## for proper elimination of the hydrostatic pressure gradients

$$\bar{T} = T_0 - \gamma z$$

$$\bar{p} = p_0 \left( \frac{T_0 - \gamma z}{T_0} \right)^{\frac{g}{R\gamma}}$$

$$\bar{\rho} = \rho_0 \, e^{-\zeta z}$$

$$T_0 = 288.15\,\mathrm{K}$$

$$p_0 = 1.01325 \cdot 10^5\ \mathrm{Pa}$$

$$\rho_0 = 1.225\,\mathrm{kg/m^3}$$

$$\gamma = 0.65\,^\circ\mathrm{C}/100\,\mathrm{m}$$

$$g/(R\gamma) = 5.2553$$

$$\zeta = 10^{-4}\ \mathrm{m^{-1}}$$

Standard ISA profile (up to 11km)

Approximate profile

Error bound is within 0.4% below 4000 m.

# Summary of source terms

In momentum equation:

$$S_u = \rho_0 f v - \rho_0 \ell\, \tilde{w}\, J$$

$$S_v = -\rho_0 f u$$

$$S_w = \rho_0 \left(J^2 - 1\right)\left(\ell\, u\, J^{-1} + \beta\left(\tilde{T} - T_0\right) g\right) + \rho_0\, \ell\, u\, J^{-1} + \zeta\; J \left(\tilde{p} - \rho_0 \tilde{w}^2\right)$$

In the energy equation:

$$S_T = J\, S_\Theta - \rho_0\, c_p\, \tilde{w}\left(\Gamma - \gamma\right) J$$

In the transport equation of turbulent kinetic energy

$$S_k = -\beta\, g\, \frac{\mu_t}{Pr_t}\left(\Gamma - \gamma\right)$$

In turbulent dissipation equation:

$$S_\varepsilon = -C_{1\varepsilon}\, C_{3\varepsilon}\, \frac{\varepsilon}{k}\, \beta\, g\, \frac{\mu_t}{Pr_t}\left(\Gamma - \gamma\right)$$

**Stratification + adiabatic heating** →

$$\Gamma - \gamma = 0.33 \frac{°\mathrm{C}}{100\,\mathrm{m}}$$

**Coriolis force** →

$$\ell = 2\,\Omega \cos\phi$$

$$f = 2\,\Omega \sin\phi$$

**Compressiblilty** →

$$J = \left(1 - \zeta \tilde{z}\right)^{-1}$$

# Related publications


[1] **Kristóf G, Rácz N, Balogh M: Adaptation of Pressure Based CFD Solvers for Mesoscale Atmospheric Problems, *Boundary-Layer Meteorol, 2008.***

[2] **N.Rácz, G.Kristóf, T.Weidinger, M.Balogh**: Simulation of gravity waves and model validation to laboratory experiments, *CD, Urban Air Quality Conf. Cyprus, 2007.*

[3] **G.Kristóf, N.Rácz, M.Balogh**: Adaptation of pressure based CFD solvers to urban heat island convection problems, *CD, Urban Air Quality Conf. Cyprus, 2007.*

[4] **G.Kristóf, N.Rácz, Tamás Bányai, Norbert Rácz:** Development of computational model for urban heat island convection using general purpose CFD solver, *ICUC6, 6-th Int.Conf.on Urban Climate, Göteborg, pp. 822-825., 2006.*

[5] **G. Kristóf, T. Weidinger, T. Bányai, N. Rácz, T.Gál, J.Unger**: A városi hősziget által generált konvekció modellezése általános célú áramlástani szoftverrel - példaként egy szegedi alkalmazással, *III. Magyar Földrajzi Konferencia, Budapest, 2006.*, Bp, CD

[6] **Kristóf G., Rácz N., Bányai T., Gál T., Unger J., Weidinger T.:** A városi hősziget által generált konvekció modellezése általános célú áramlástani szoftverrel– összehasonlítás kisminta kísérletekkel *A 32. Meteorológiai Tudományos Napok előadásai. Országos Meteorológiai Szolgálat, Bp.,* **2006**

[7] **Dr. Lajos T., Dr. Kristóf G., Dr. Goricsán I., Rácz N.:** Városklíma vizsgálatok a BME Áramlástan Tanszékén, hősziget numerikus szimulációja *VAHAVA projekt (A globális klímaváltozás: hazai hatások és válaszok) zárókonferenciája Bp. CD,* **2006**

[8] **Rácz N. és Kristóf G.**: Hősziget cirkuláció kisminta méréseinek összehasonlítása saját fejlesztésű LES modellel *Egyetemi Meteorológiai Füzetek No. 20 ELTE Meteorológiai Tanszék, Bp. 173-176,* **2006.**

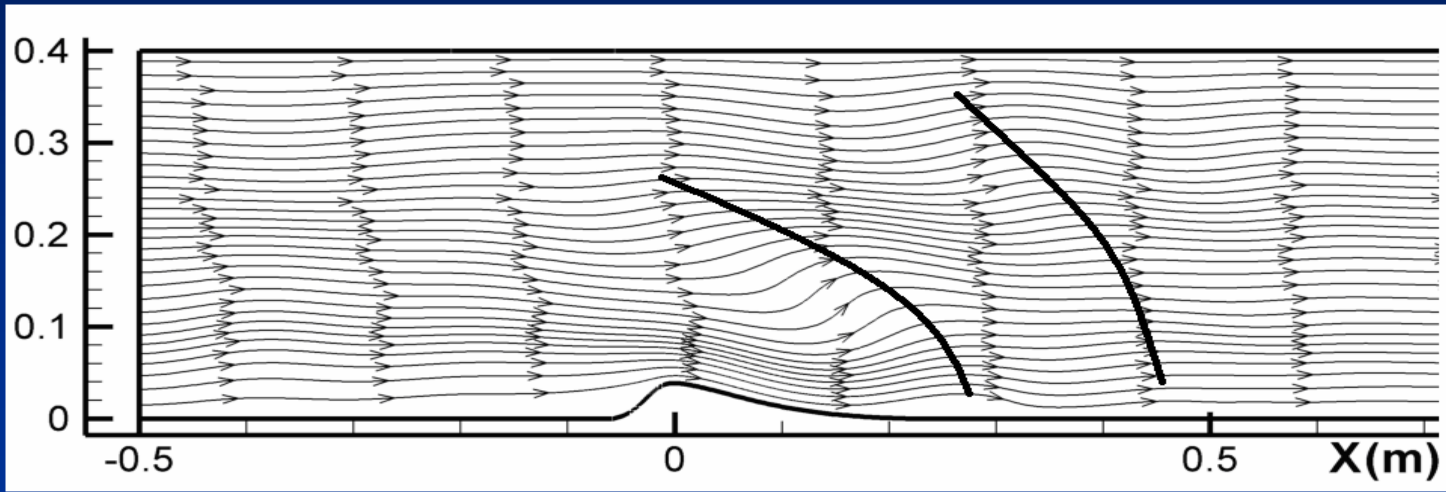
[9] **M. Balogh, G. Kristóf**:Automated Grid Generation for Atmospheric Dispersion Simulations*, pp.1-6., MICROCAD konferencia, Miskolc, 2007.*

# Model validation

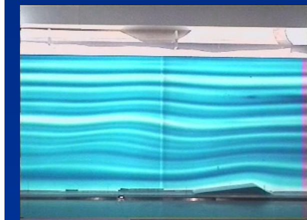
1. analytical solutions
2. laboratory experiments
3. a standard test case
4. a full scale event

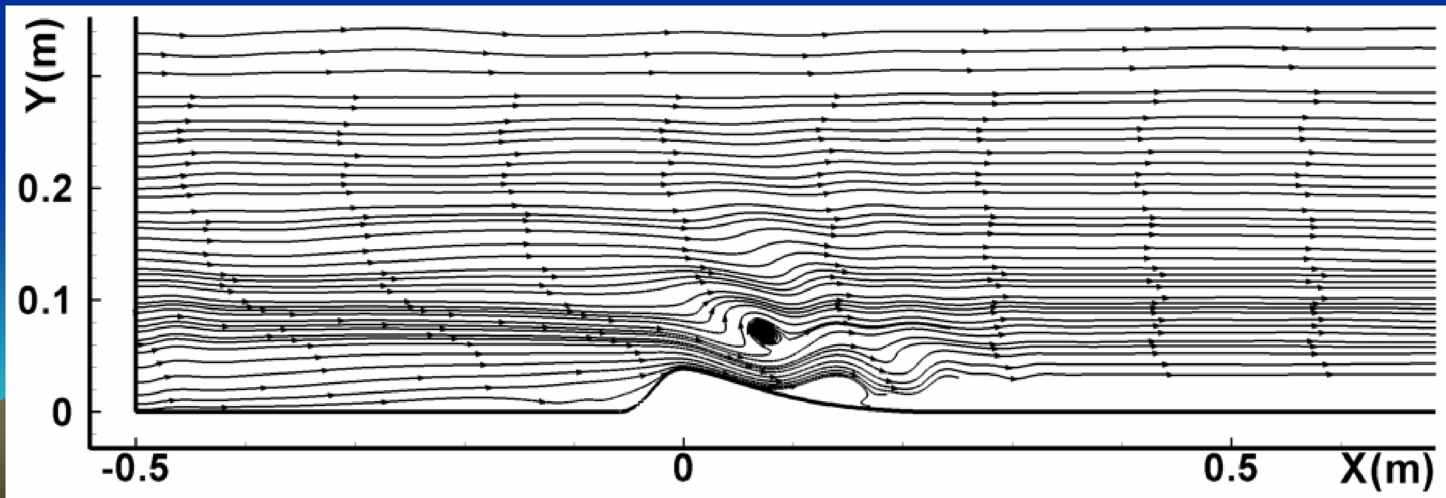
# Gravity waves

Gyüre, B. and Jánosi, I.M., 2003. Stratified flow over asymmetric and double bell-shaped obstacles. *Dynamics of Atmospheres and Oceans 37*, 155-170.

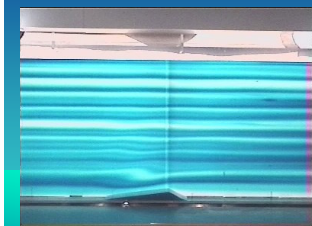



U/Nh = 1.4






U/Nh = 0.3

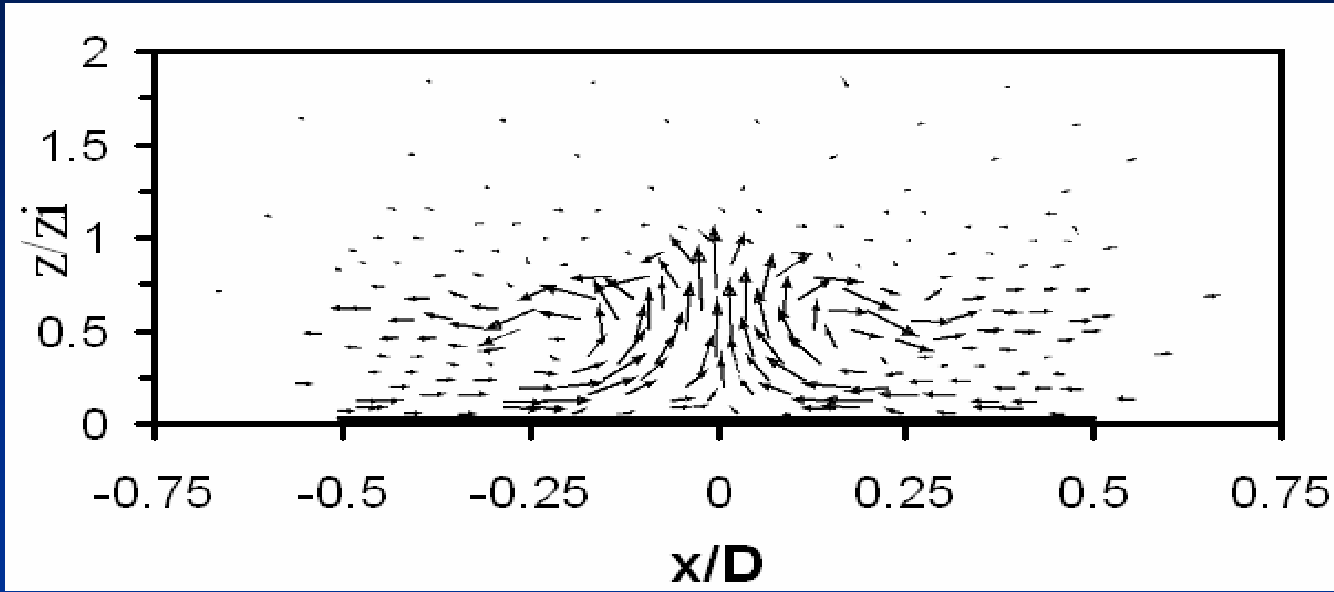


# Thermal convection (UHIC)

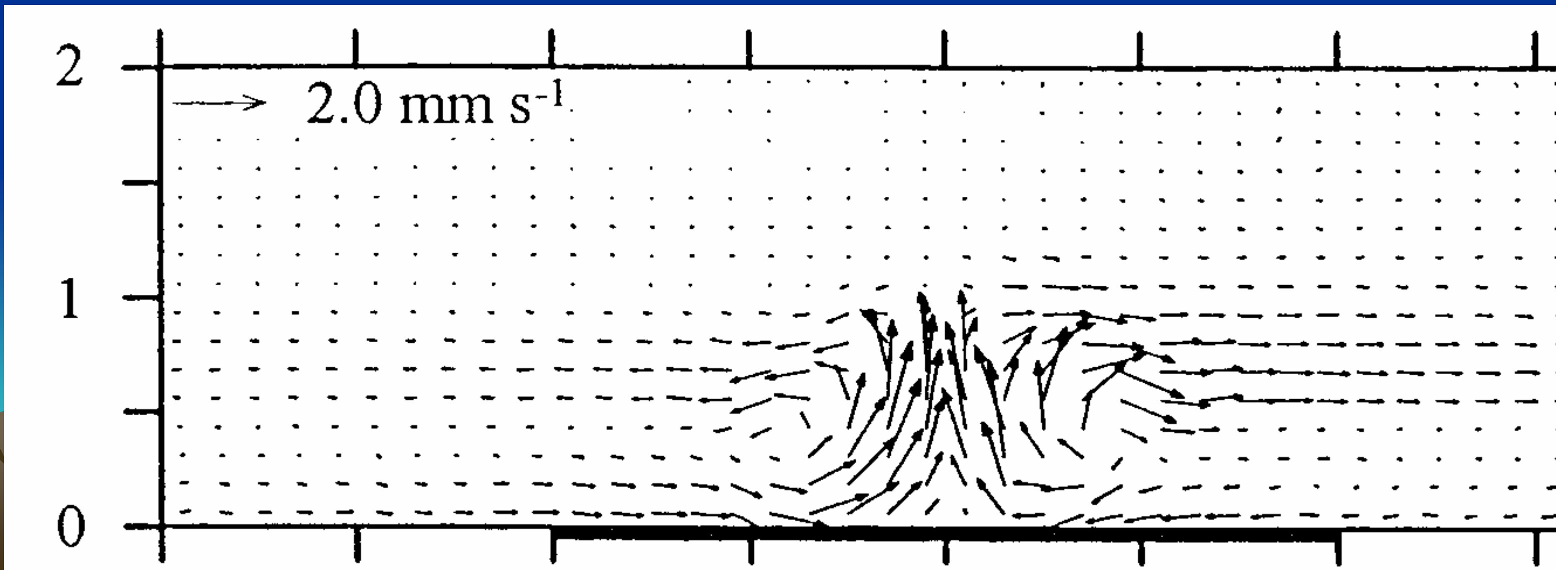
A.Cenedese, P.Monti: Interaction between an Inland Urban Heat Island and a Sea-Breeze Flow: A Laboratory Study, 2003.

CFD results

T(z) profiles are also in line with the measured data.

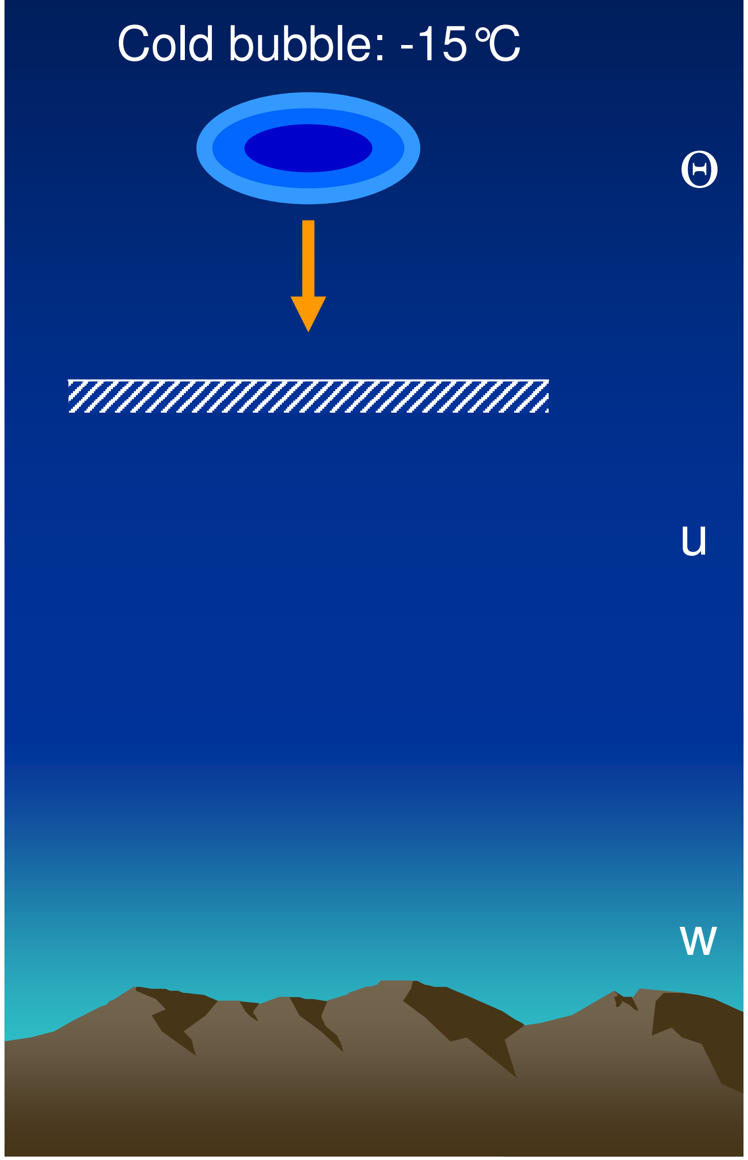


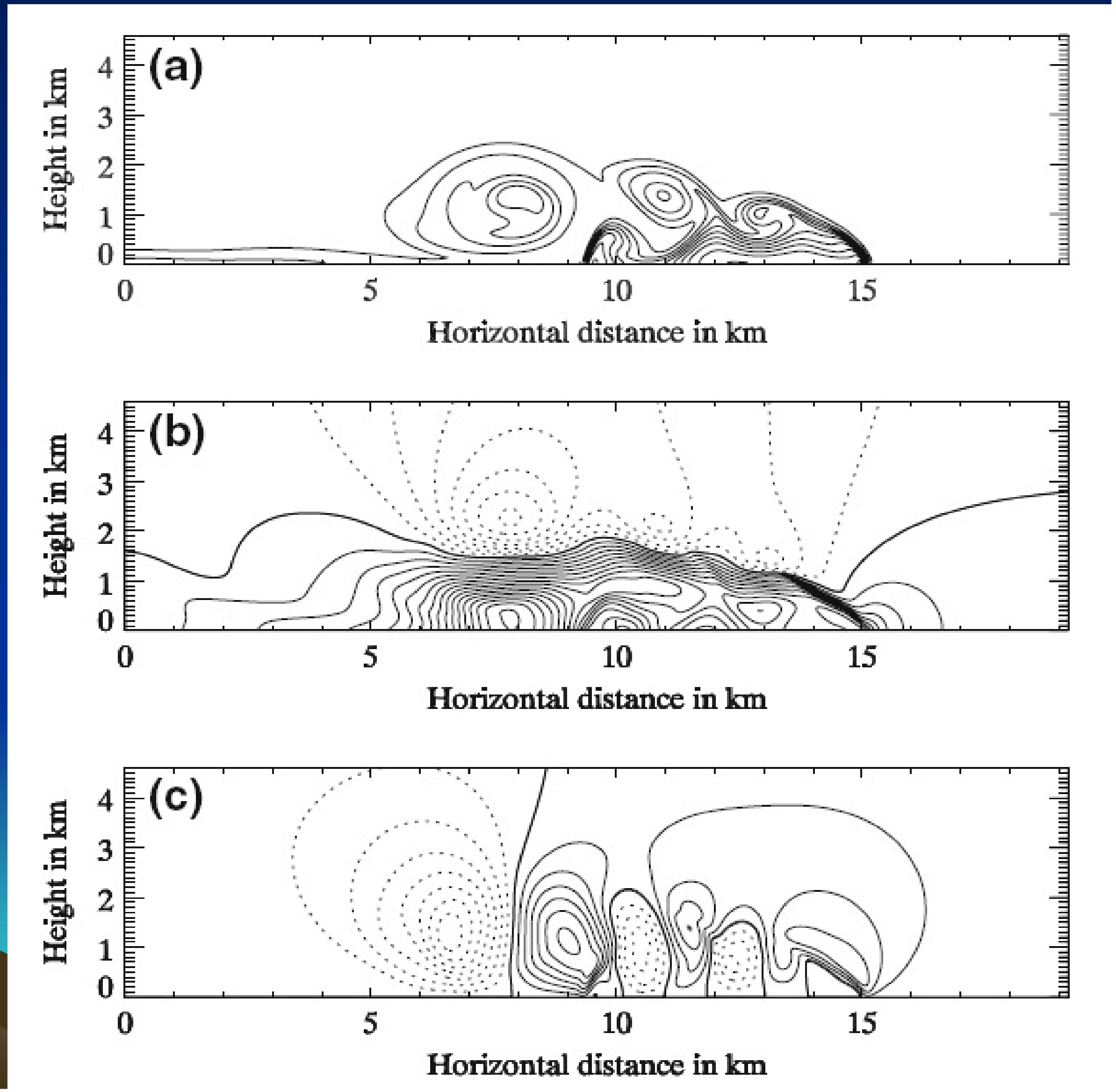

PIV results (Cenedese & Monti 2003)



# Down-burst test case

Straka et al.1990, Reinert 2007



# Results

Compressible version | Simplified (incompressible)

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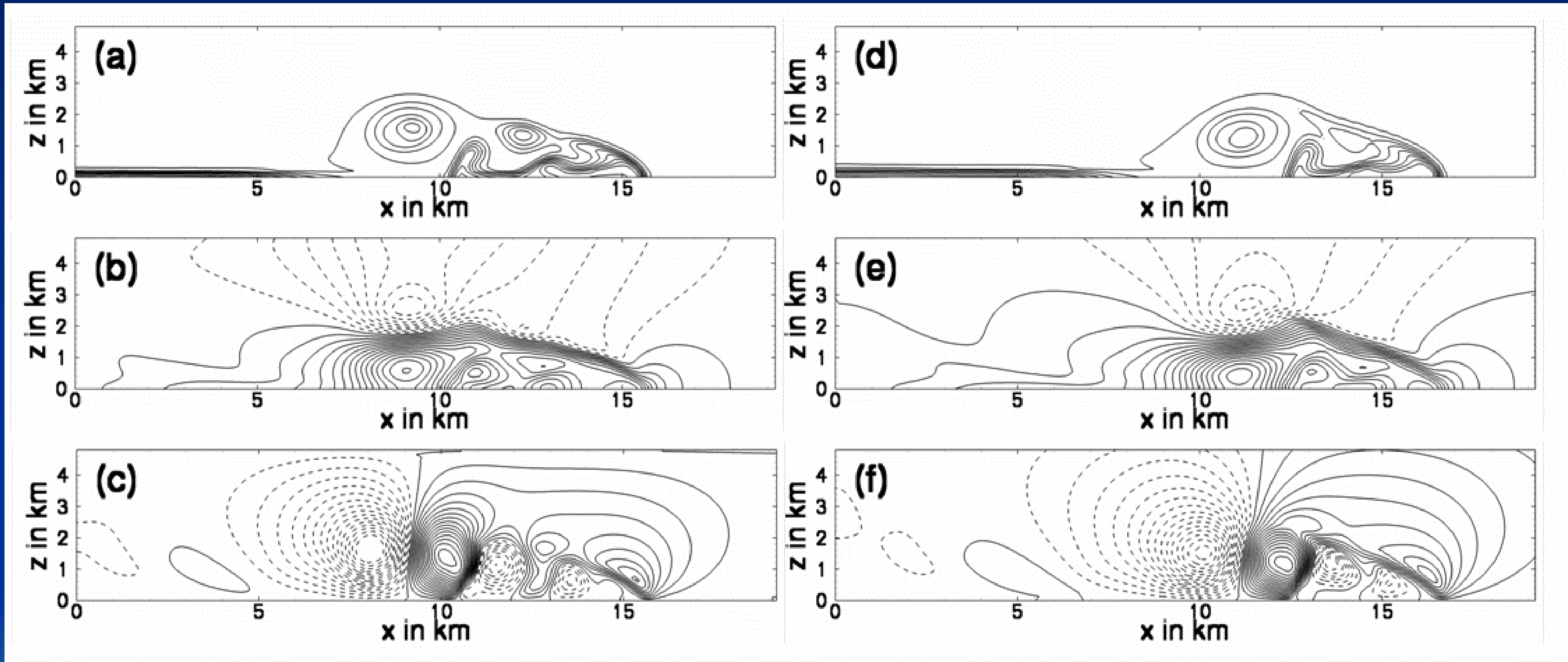
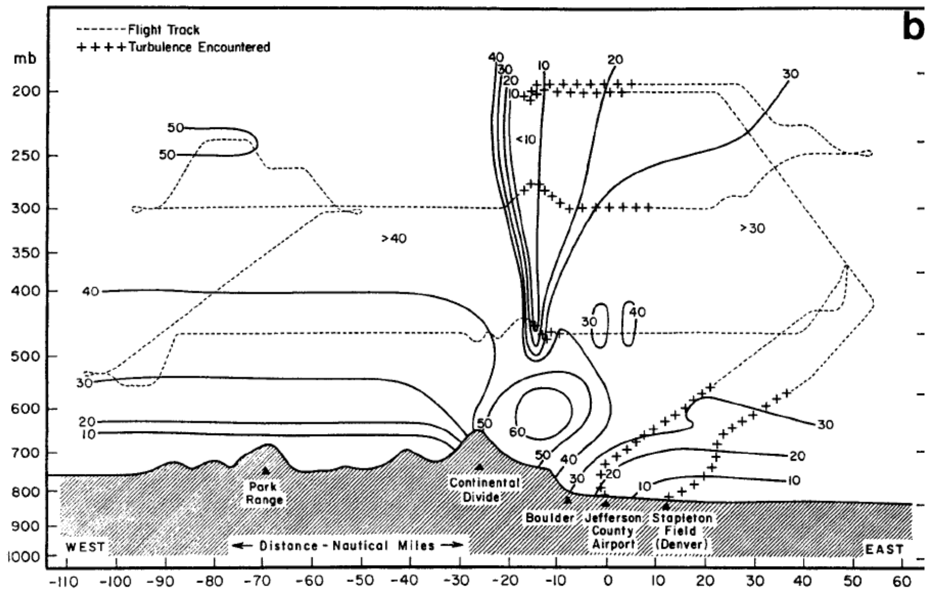


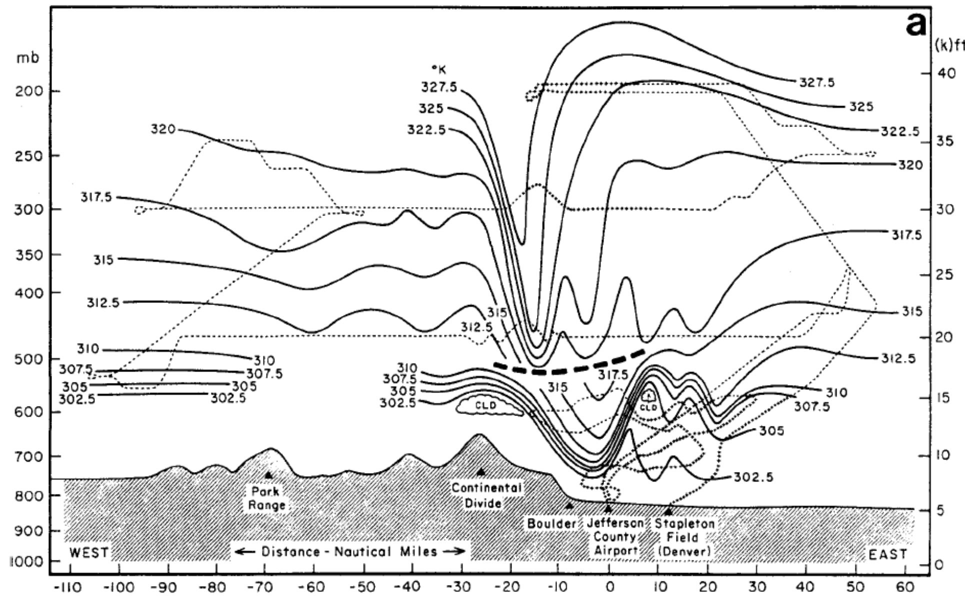
# Down-slope windstorm

Boulder 1972 jan.

Measured velocity field

Measured potential temperature




# Results

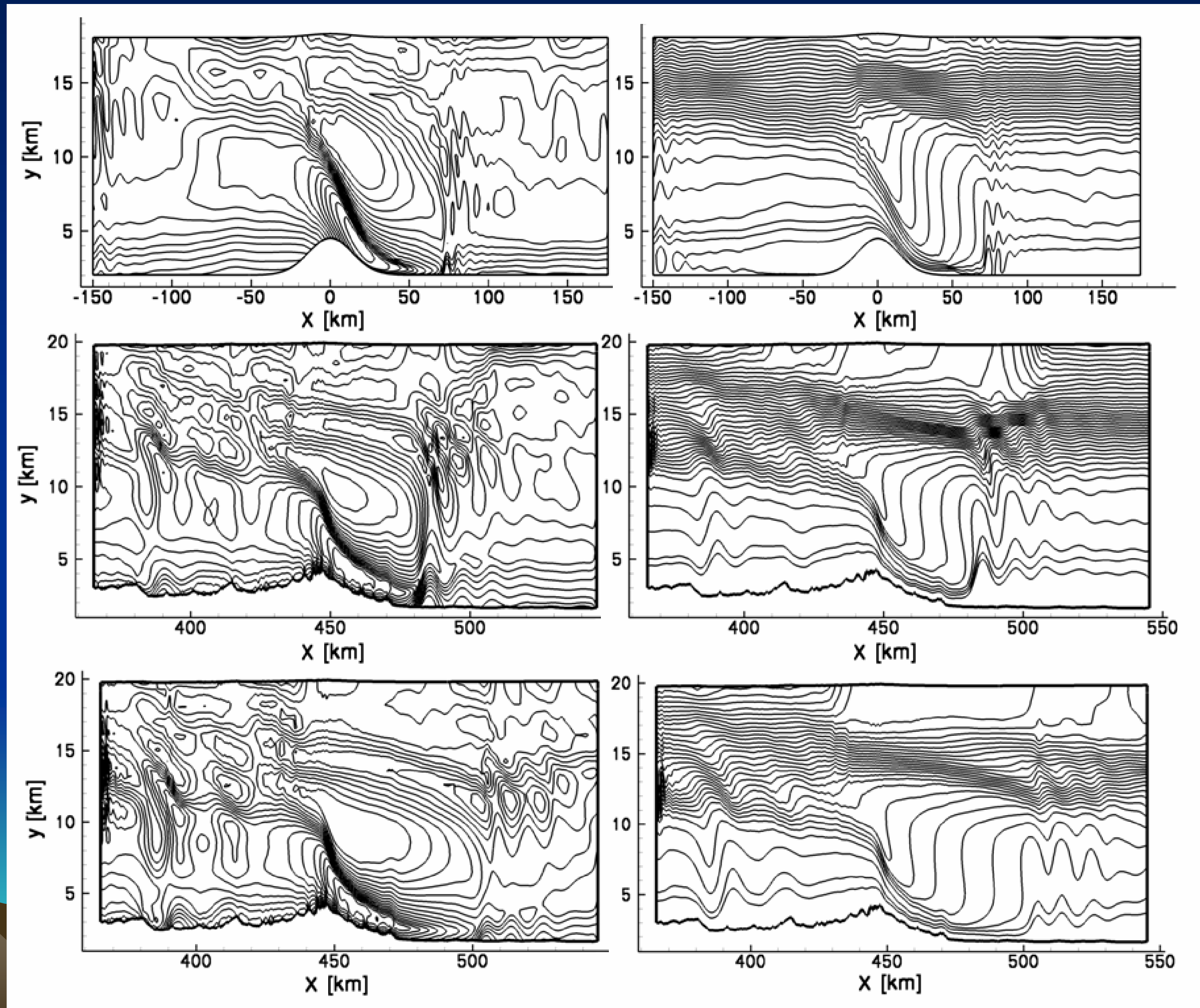
Velocity field

Potential temperature

For idealized topography:

For realistic topography:

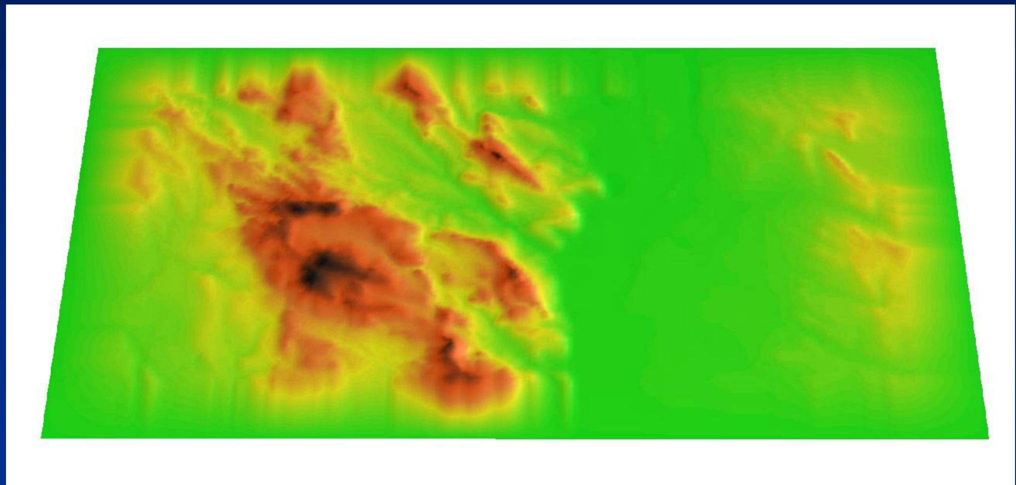
After a longer period of time:



# Two application examples

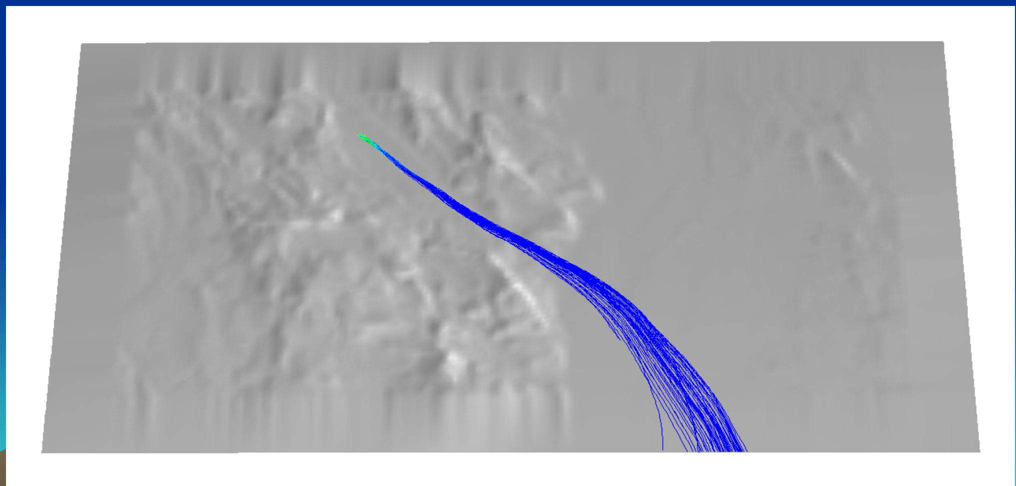
- Dispersion of pollutants
- Analyses of instabilities

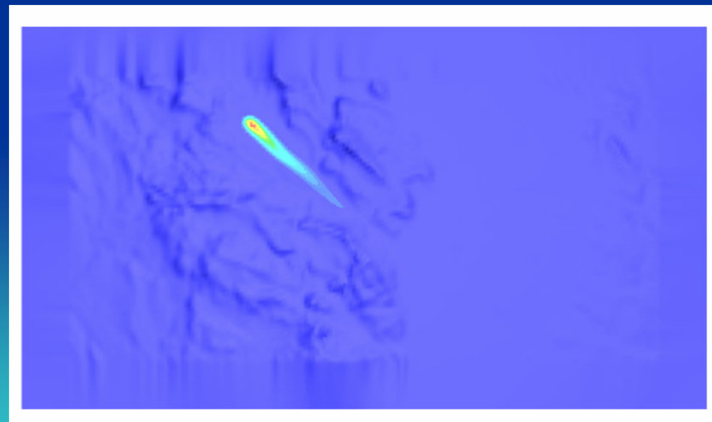
# Meso scale atmospheric dispersion



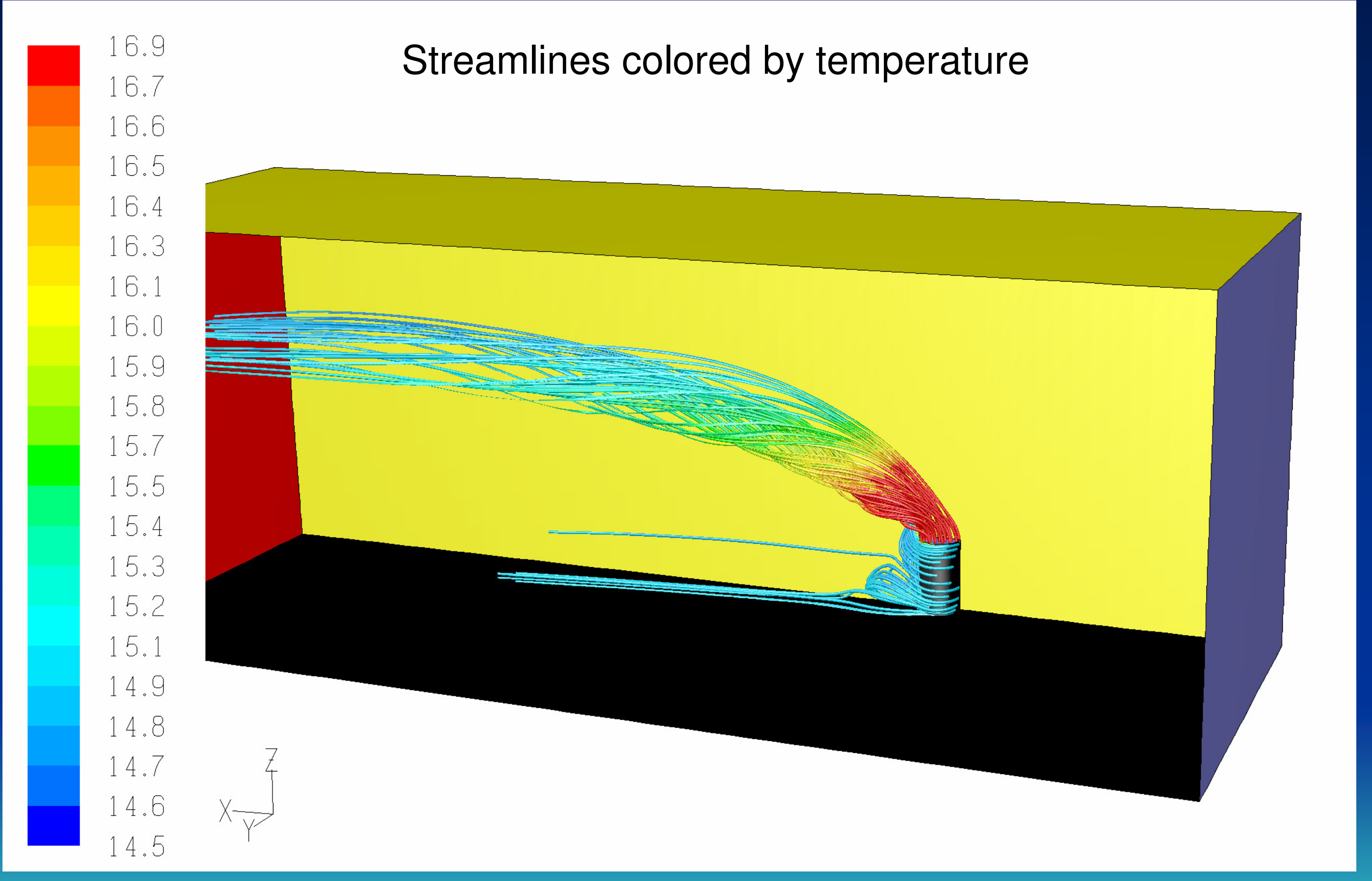
Orography of Pilis mountain

Evolution of surface concentration





# Micro-scale atmospheric dispersion



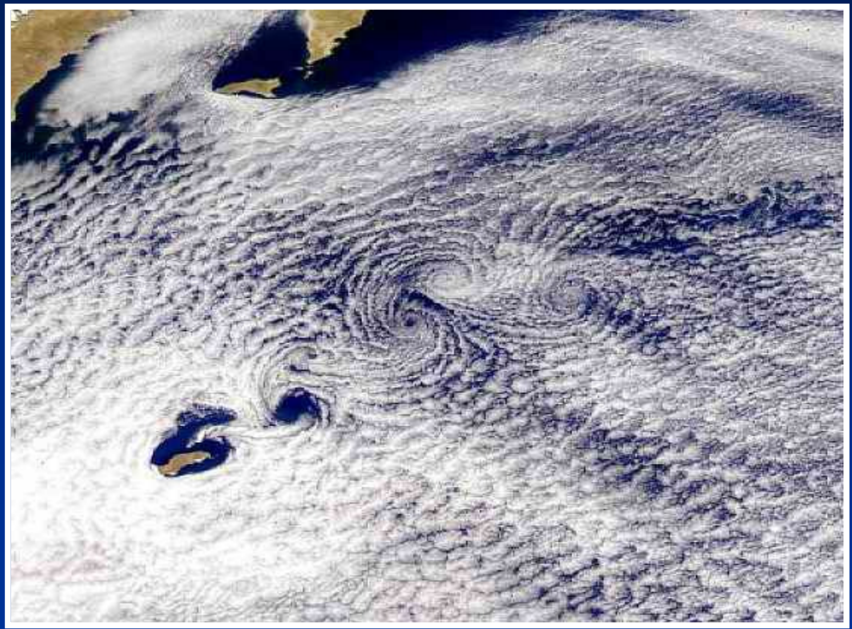

Chimney height 180 m

Standard (stable) temperature profile

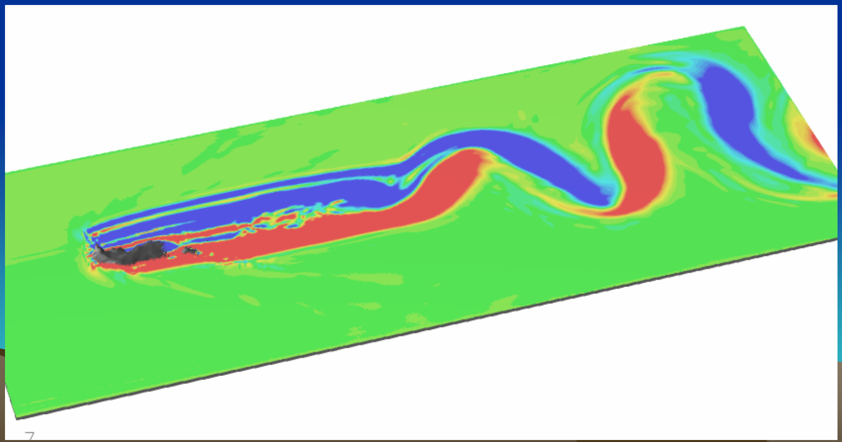
Wind speed: 3m/s

Injection velocity: 5 m/s

# Von Kármán vortices behind a volcanic island



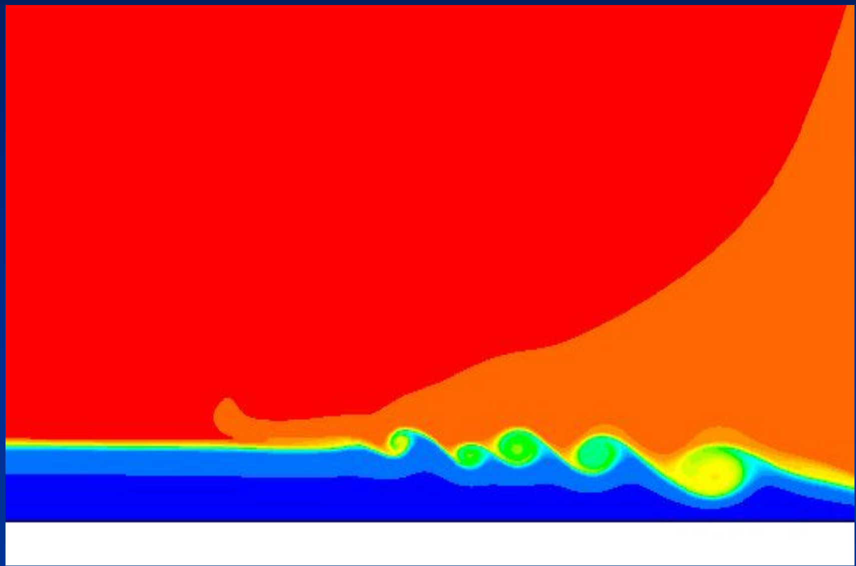
Satellite image about Guadalupe island



First CFD results

# Investigation of instabilities

Kelvin-Helmholtz instability



Comp. domain: 25 km x 5.5 km
Temperature difference 20 ℃

Cloud formation:

# Conclusions

- An easy to implement method has been developed for taking into account:
  - stratification effects,
  - adiabatic heat,
  - Coriolis force,
  - compressibility.
- The model has been validated against:
  - some analytic solutions,
  - laboratory experiments,
  - reference calculations,
  - in field measurements.
- Further effort is necessary for including:
  - moisture transport and phase changes,
  - porous drag models,
  - radiation heat transfer,
  - surface energy balance.
- Foreseeable applications:
  - local convections (e.g. UHIC, see breeze, valley breeze),
  - dispersion of pollutants (e.g. due to traffic, industry, chemical vapors),
  - meteorological research (e.g. gravity waves, cloud formation),
  - assessment of the wind power potential,
  - simulation of catastrophes (e.g. large fires, volcanism).