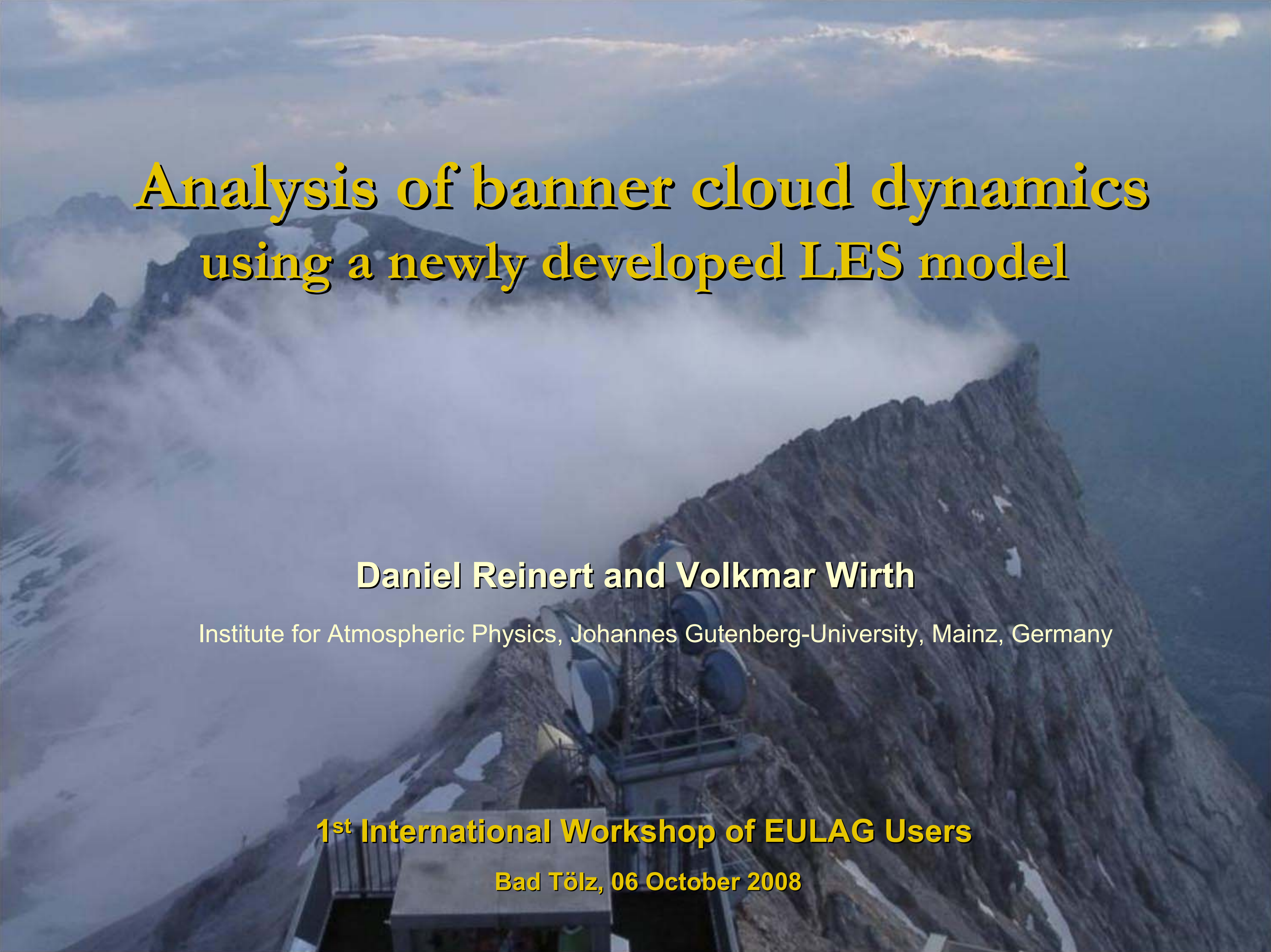

Analysis of banner cloud dynamics using a newly developed LES model

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Outline

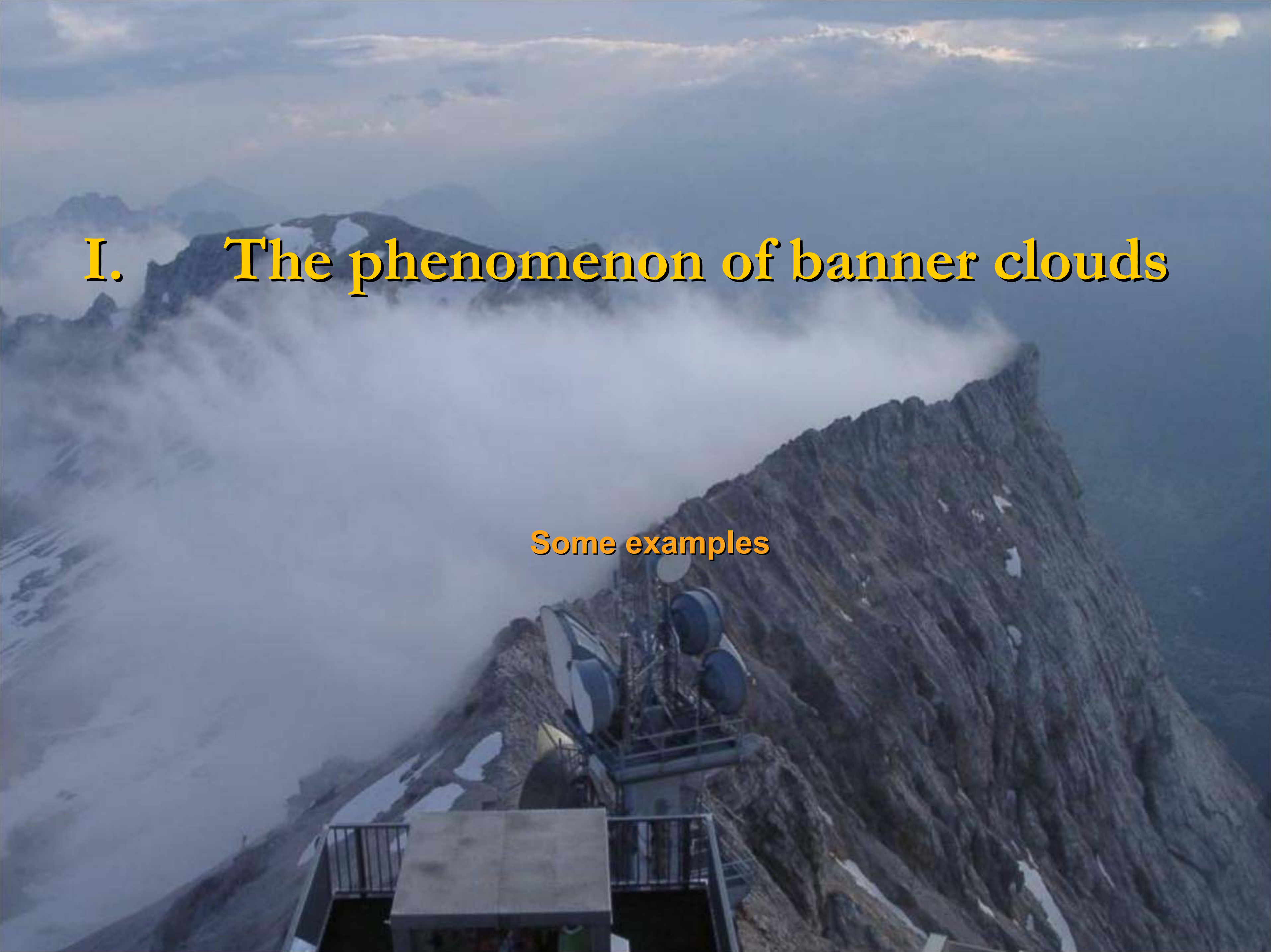
I. The phenomenon of banner clouds
- Some examples
- Existing theories of banner cloud formation

II. The applied LES model
- Some model specifics (complex orography, turbulent inflow)
- Model setup

III. Numerical simulation of banner clouds
- Dominant mechanism of formation
- Relative importance of dynamics versus thermodynamics

IV. Summary and conclusions

I. The phenomenon of banner clouds



Some examples

Examples

Banner clouds occur when sufficiently moist air flows across steep (often pyramidal shaped) mountain peaks or quasi 2D ridges.

Matterhorn (Swiss Alps)

27.08.2005 Duration: 19:07 – 20:20 UTC

Zugspitze (Bavarian Alps)

Characteristics:

- cloud is confined to the immediate lee
- windward side remains cloud-free

Postulated mechanism of formation (I)

1. Mixing of two air masses with distinct properties (temperature, humidity)
   ➔ Banner cloud = Mixing fog ? (Humphreys, 1964)

2. Adiabatic expansion in a region of accelerated flow at the mountain's tip, based on the Bernoulli-effect (Beer, 1974)

Simple scaling analysis

$$\Delta T \approx 0.2\,\mathrm{K} \longleftarrow \Delta p \approx 2\,\mathrm{hPa} \xleftarrow{\text{Bernoulli}} \Delta u \approx 14\,\mathrm{ms}^{-1}$$

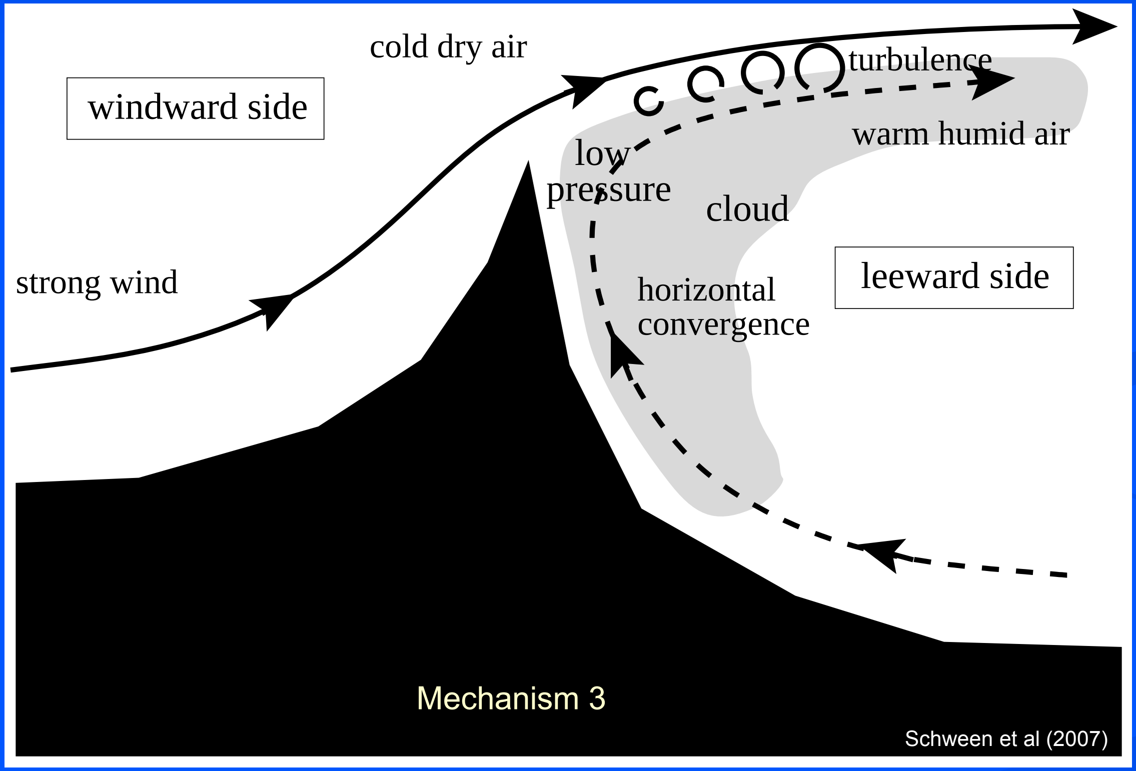
➔ Pressure reduction due to Bernoulli can not be more than a few hPa
   ➔ local cooling can not be more than a few tenths of a degree

➔ It is unlikely that the pressure decrease itself causes leeside condensation

Same cooling results form dry adiabatic lifting of only **$\Delta z \approx 20$m !**

Postulated mechanism of formation (II)

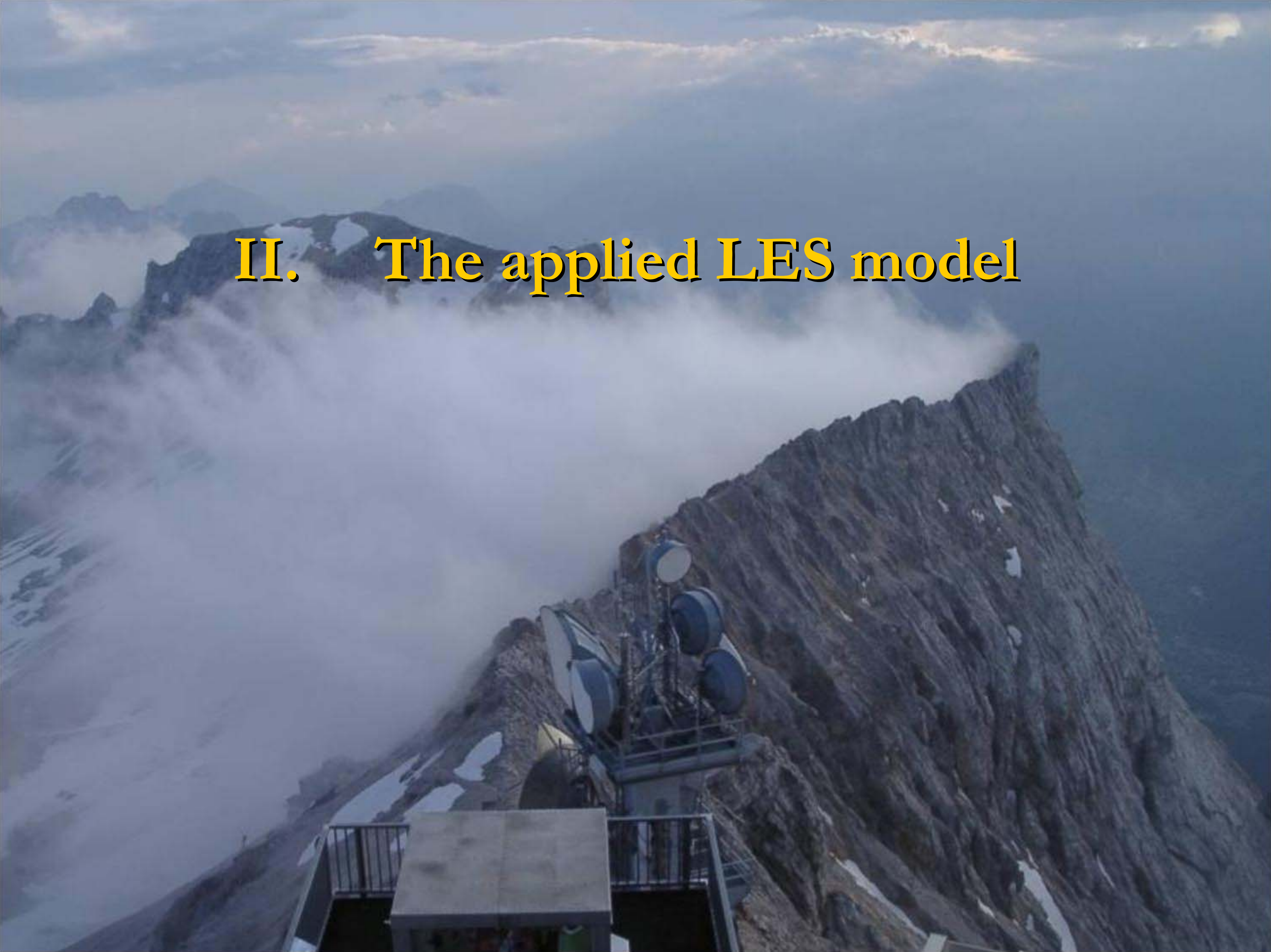
3. **Favoured mechanism:** Banner clouds as visible result of forced upwelling in the upward branch of a lee vortex (Glickman, 2000)



Objectives:

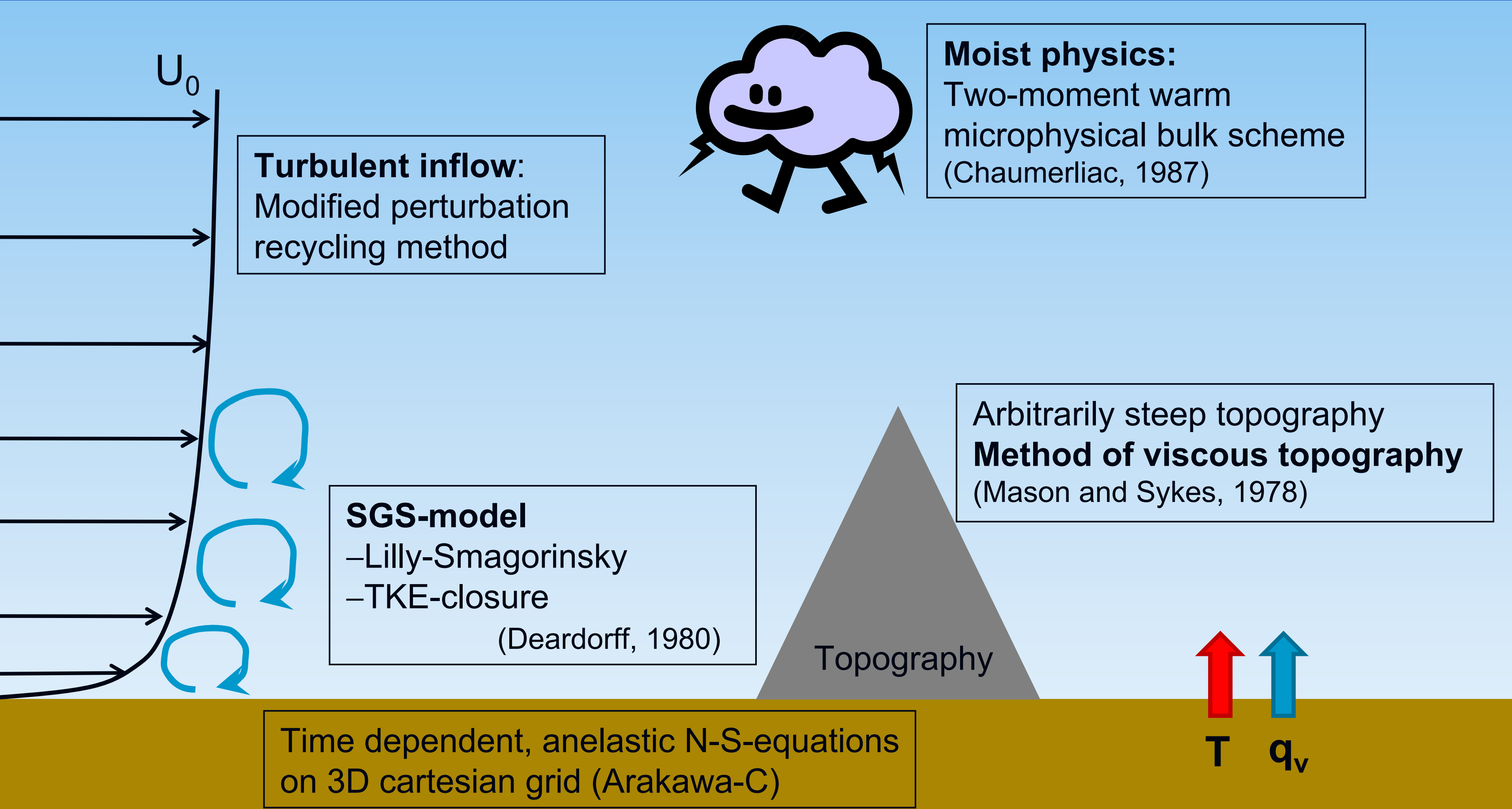
- Verification of postulated mechanism 3 using LES
- Clarify necessity of inhomogeneous conditions (temperature, humidity)
- Relative importance of thermodynamics for reinforcement and maintenance

II. The applied LES model

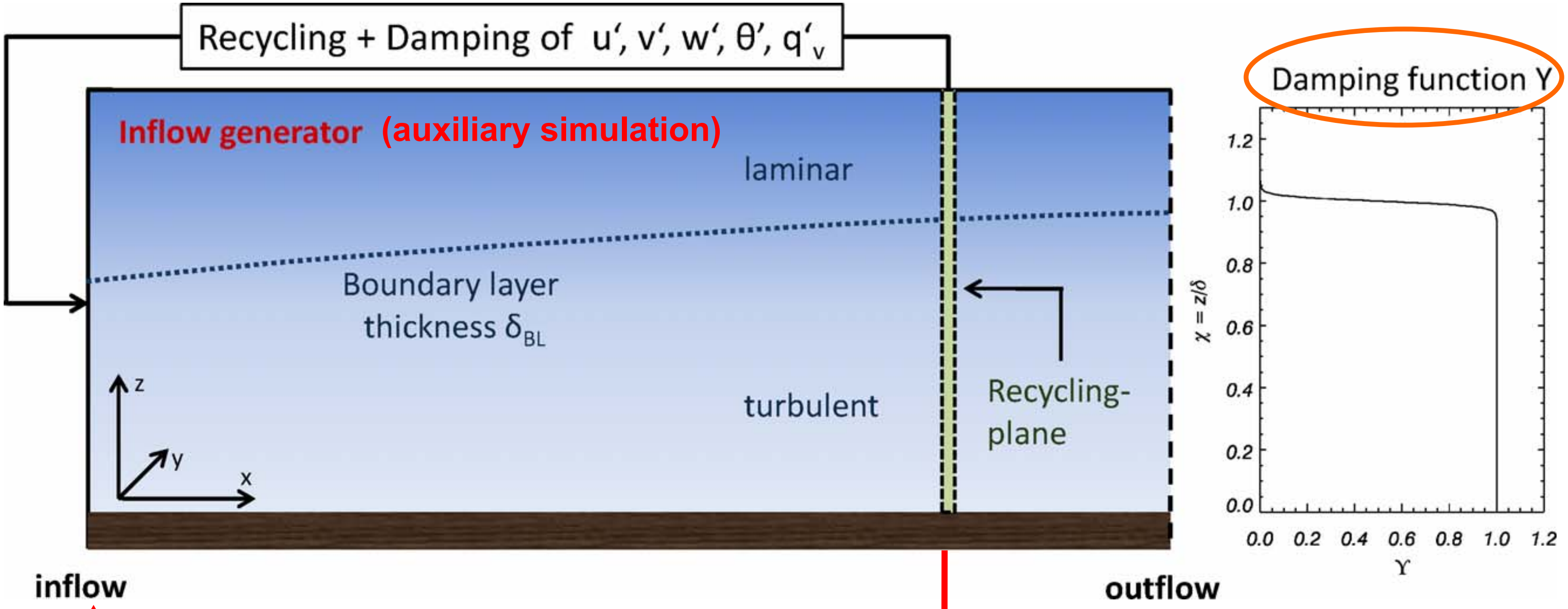


The applied LES model

- Developed during banner cloud project (Reinert et al, 2007); based on a former mesoscale (RANS) model



Turbulent inflow

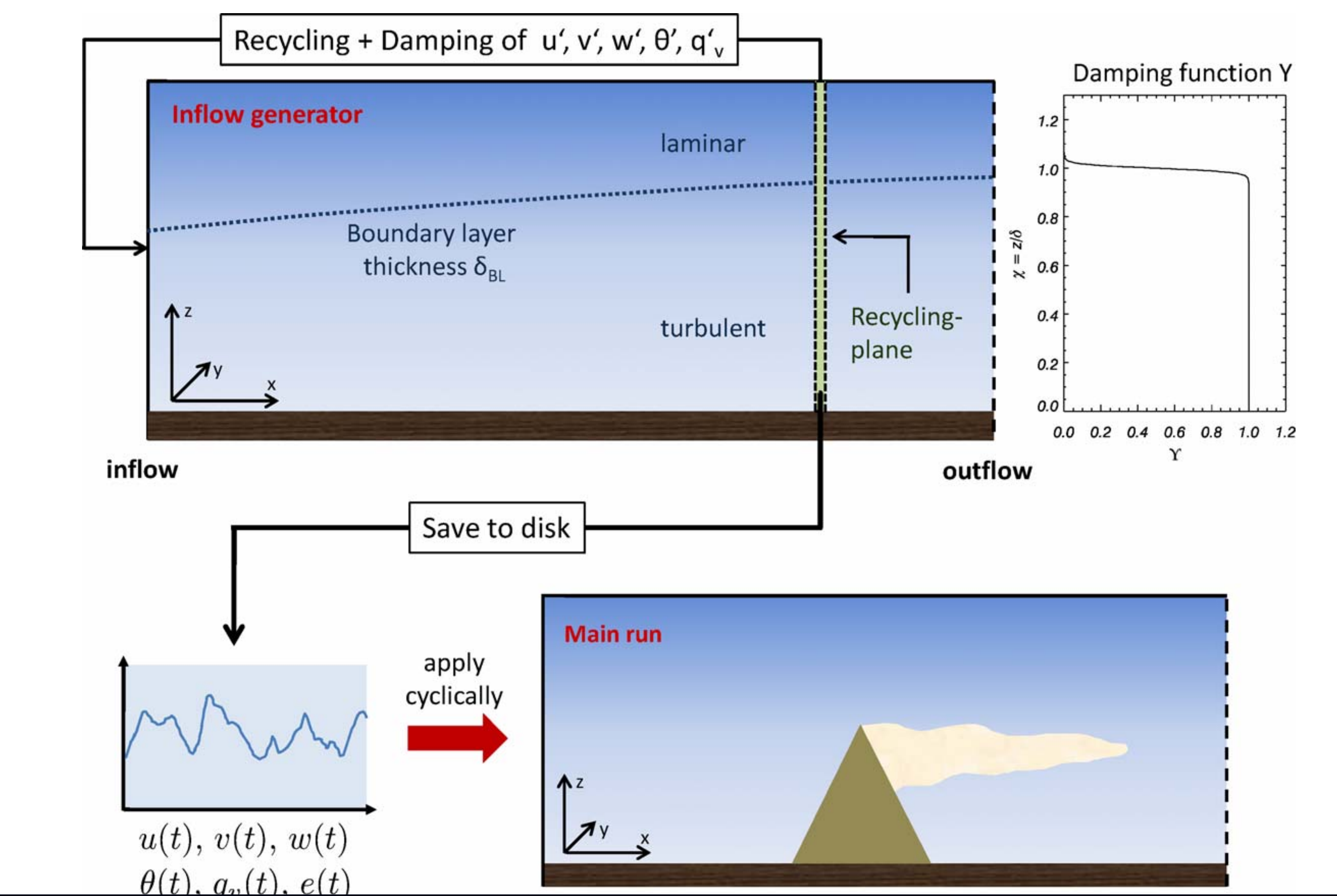


$$\Phi_{in}(y,z,t) = <\Phi_{in}>(z) + \Upsilon(\chi)\,\Phi'_{rec}(y,z,t)$$

$$\Phi'_{rec}(y,z,t) = \Phi_{rec}(y,z,t) - <\Phi_{rec}>(z)$$

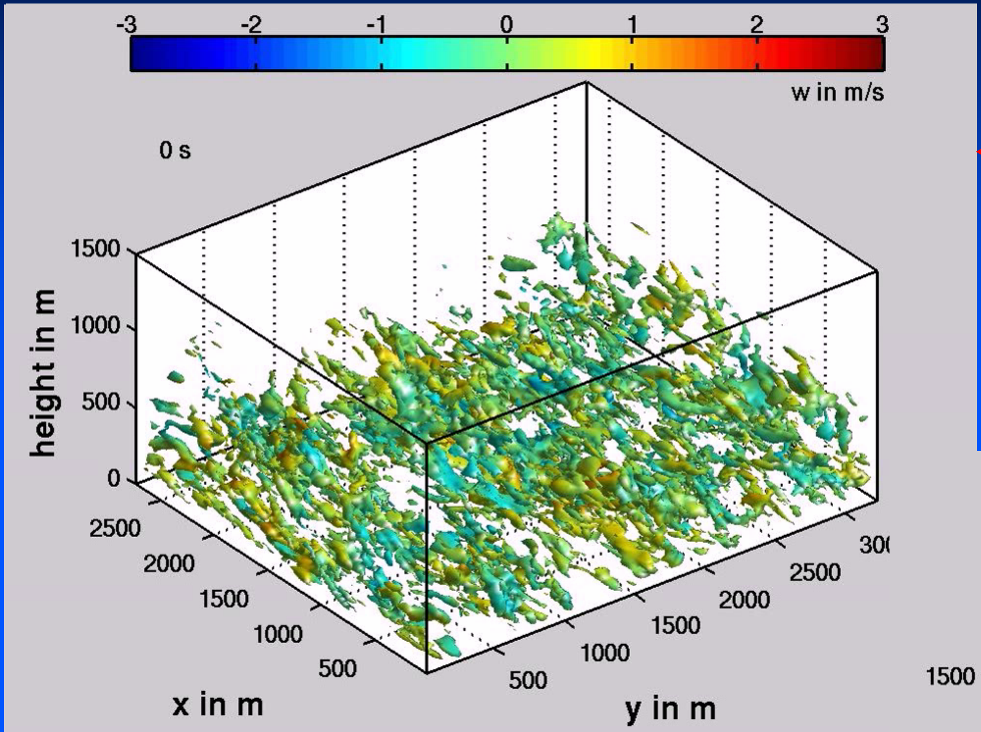
$$with \quad \Phi = u,\ v,\ w,\ \theta,\ q_v$$

Turbulent inflow

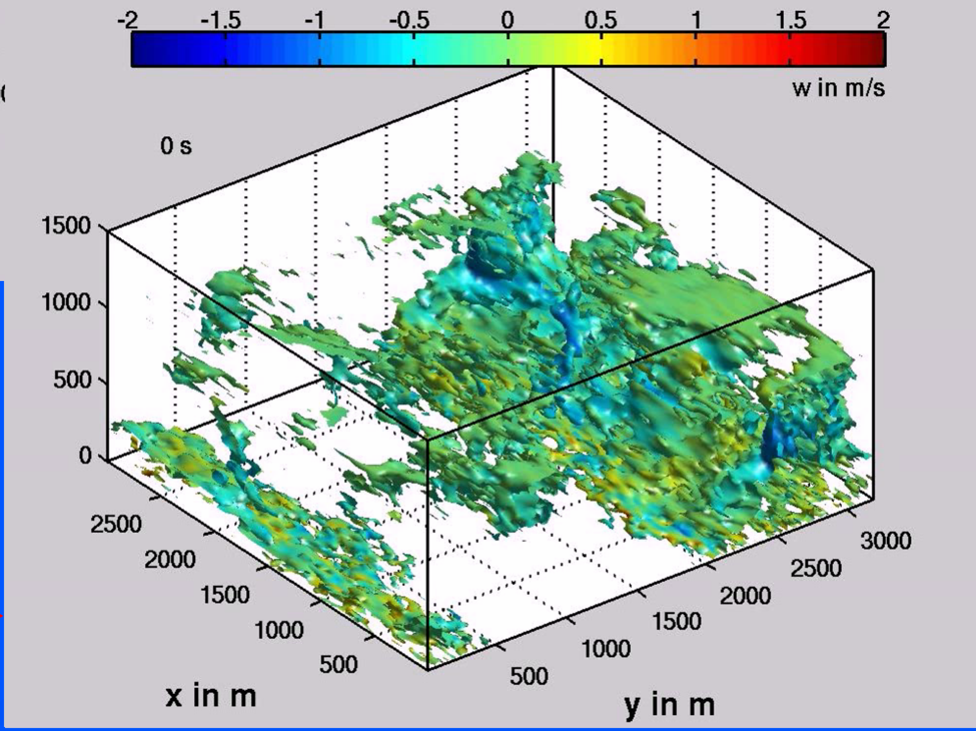


➔ Model consistent turbulence for u, v, w, q_v, θ

Qualitative example of generated turbulence



- **Coherent structures** visualized by Q-criterion (Jeong and Hussain, 1995)
- Isosurface coloured with vertical velocity

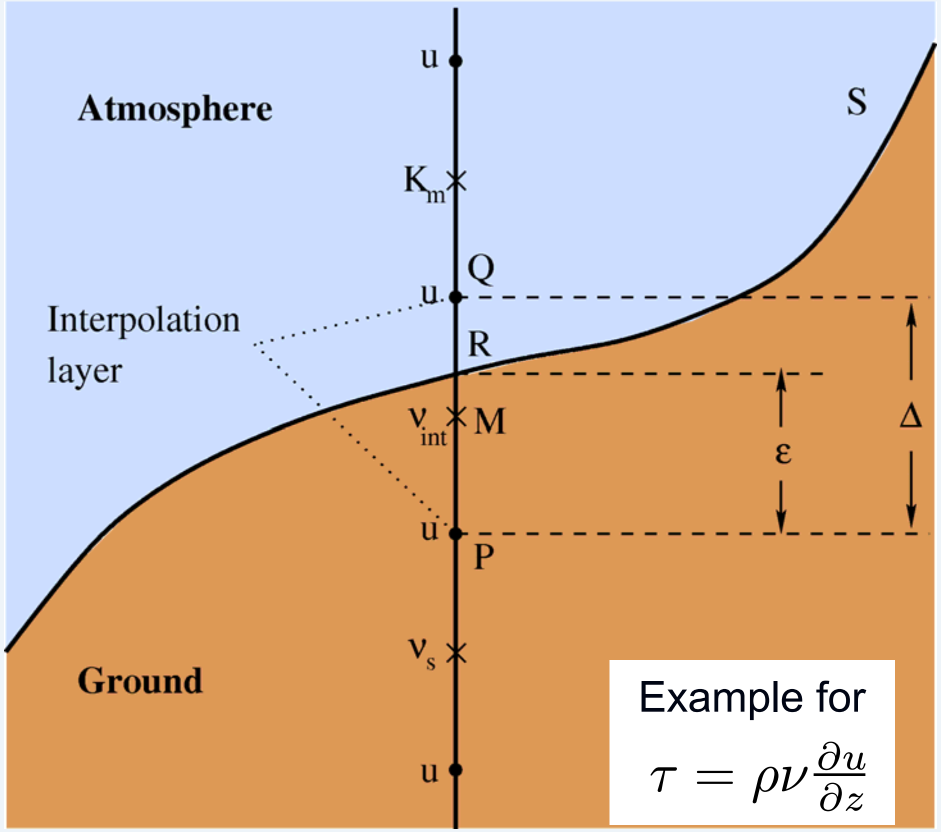


- Isosurface of **relative humidity** (rh=65%)
- Isosurface coloured with vertical velocity

Method of viscous topography (Mason and Sykes, 1978)

- Treatment of air and topography as two fluids with vastly different viscosities
- Modification of viscous stresses within grid cells intersected by orography
  - Application of a modified, interpolated viscosity / exchange coefficient

➔ Accounts for exact position of orography; refinement of stepwise approx.



Example for $\tau = \rho\nu\frac{\partial u}{\partial z}$

Model discretization:

$$\rho\nu\frac{\partial u}{\partial z} \rightarrow \rho\nu_{int}\frac{u_Q - u_P}{\Delta}$$

Goal:
choose ν_{int} such that flux calculated by the model equals flux assuming u=0 ms^{-1} at point R

Assumption:
constant fluxes within interpolation layer.

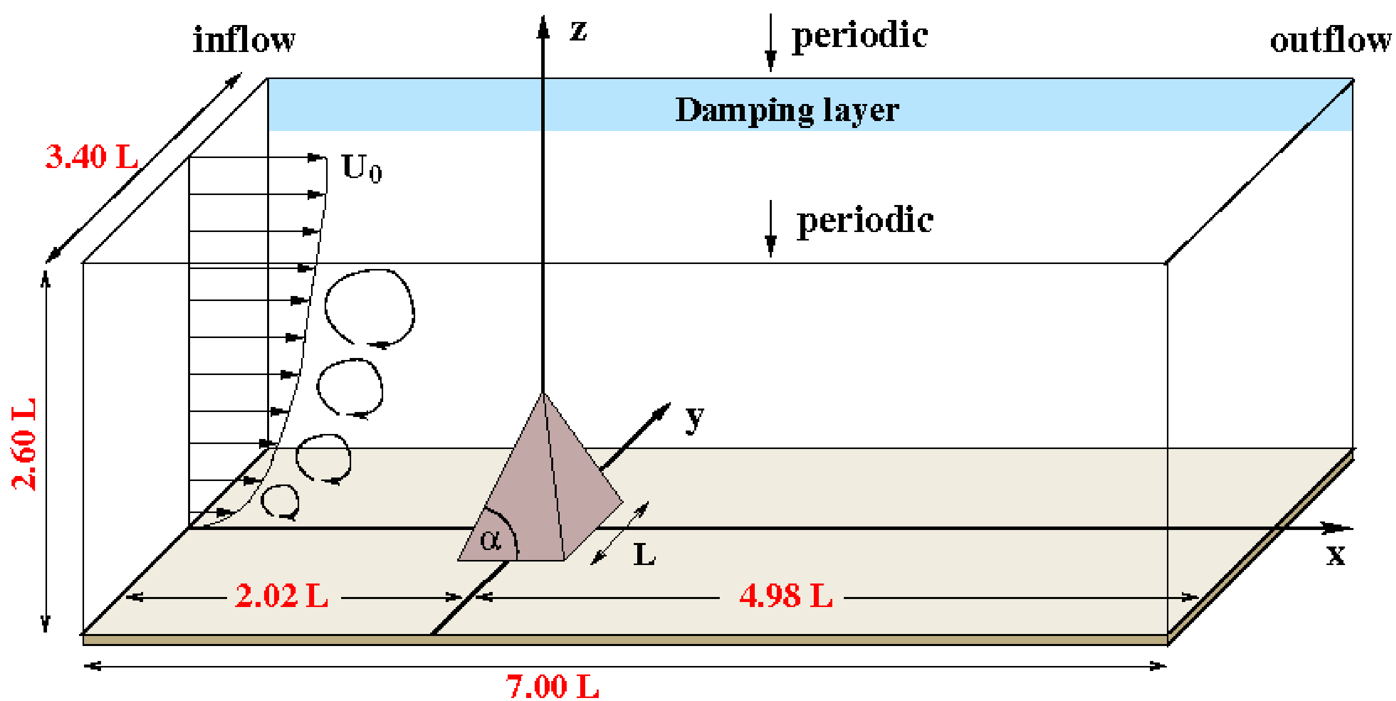
$$\rho K_m\frac{u_Q - u_R}{\Delta - \epsilon} = \rho\nu_{int}\frac{u_Q - u_P}{\Delta}$$

$$\rightarrow \quad \nu_{int} = K_m\frac{\Delta}{\Delta - \epsilon}$$

Model setup

- Numerical simulation of flow around idealized pyramidal-shaped obstacle
- Simulations were conducted on wind tunnel scale and atmospheric scale

Here: **Simulations on atmospheric scale will be shown.**



H = 1000 m
L = 930 m
α = 65°

Δx = 25m
Δy = 25m

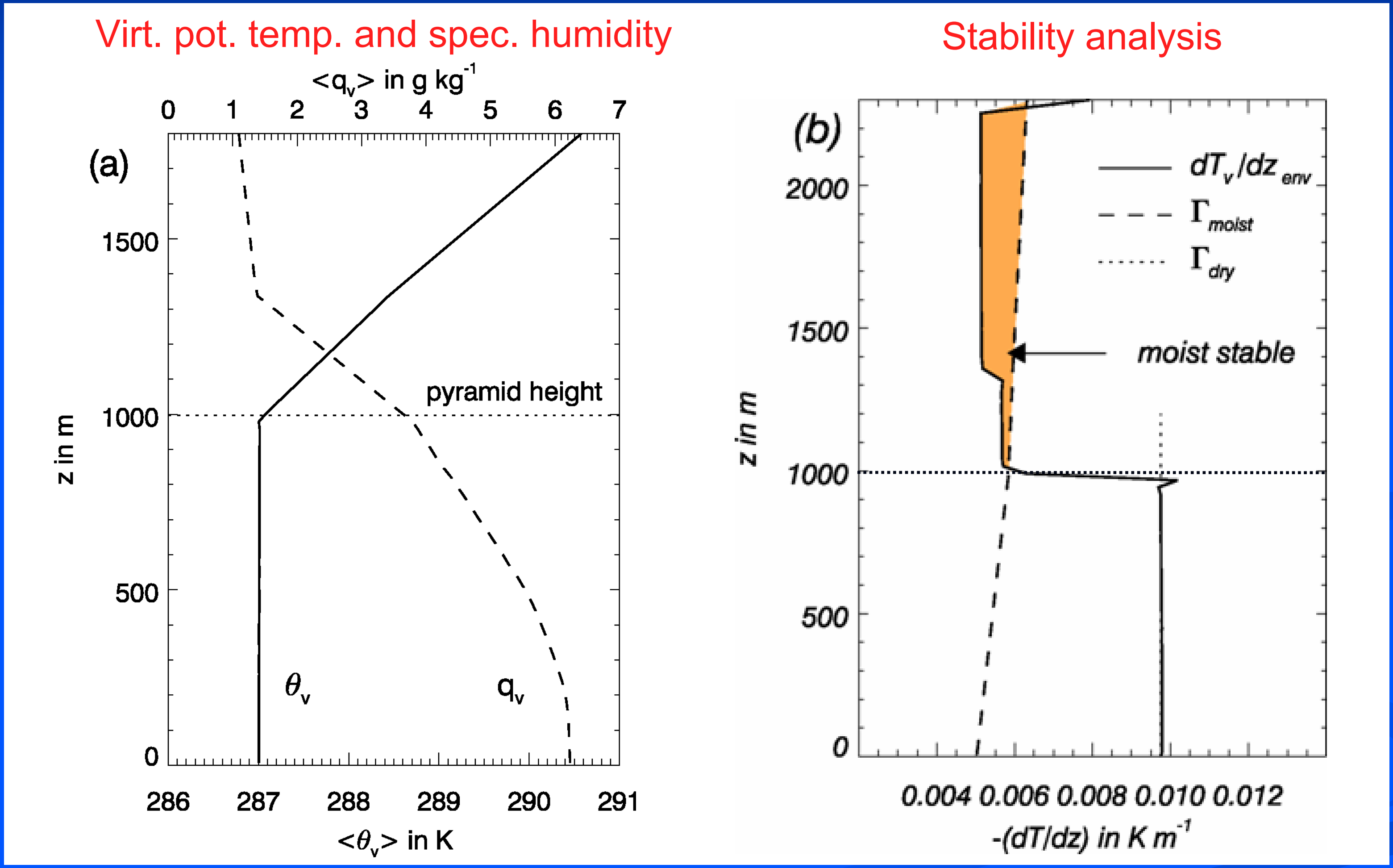
Re= 5.6 × 10^8

U_0= 9 ms^{-1}

- Turbulent inflow with logarithmic velocity profile
- 260(x) × 126(y) × 64(z) grid cells

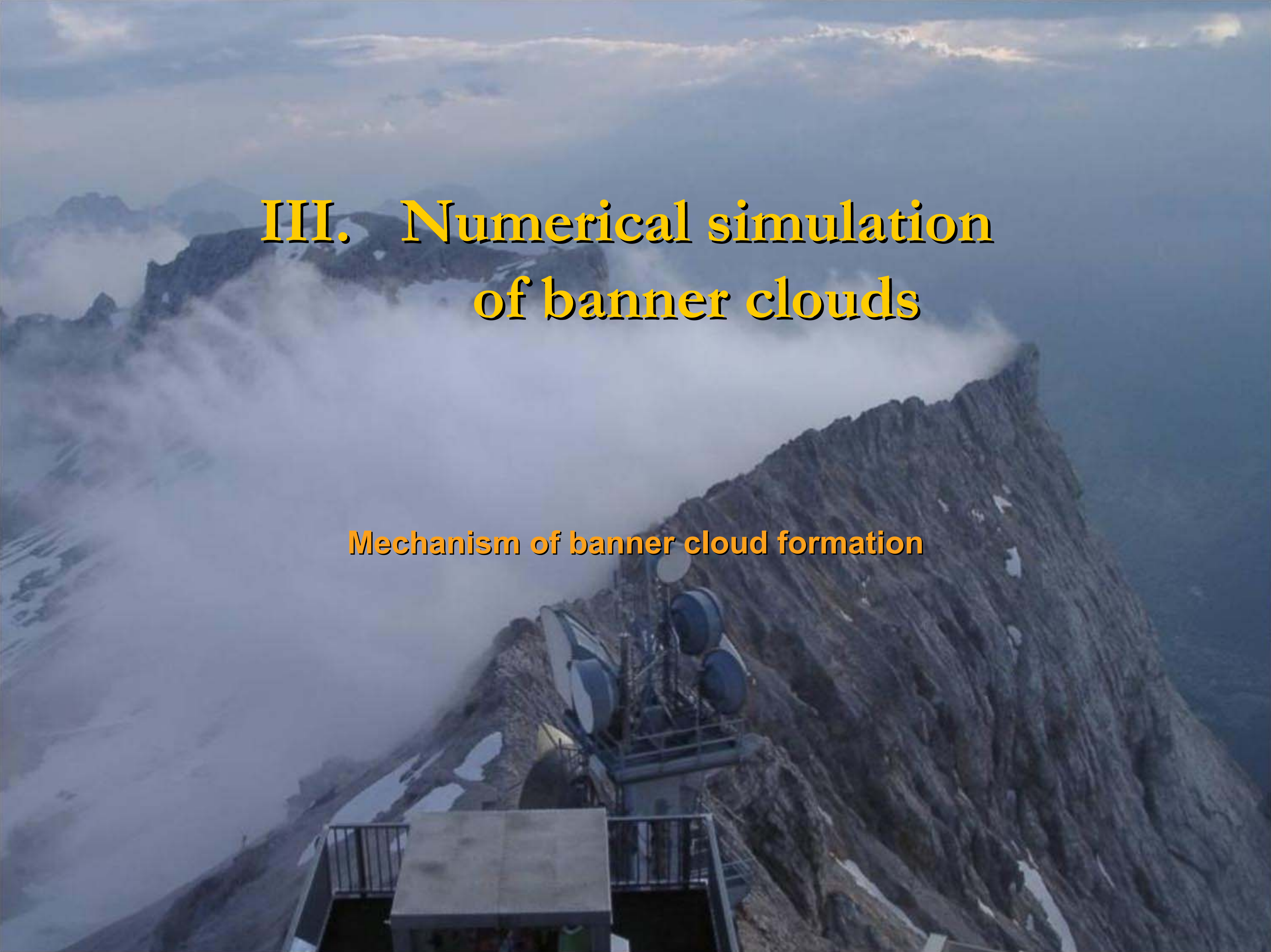
Thermodynamic situation

Idealised profiles motivated by measurements at Mount Zugspitze



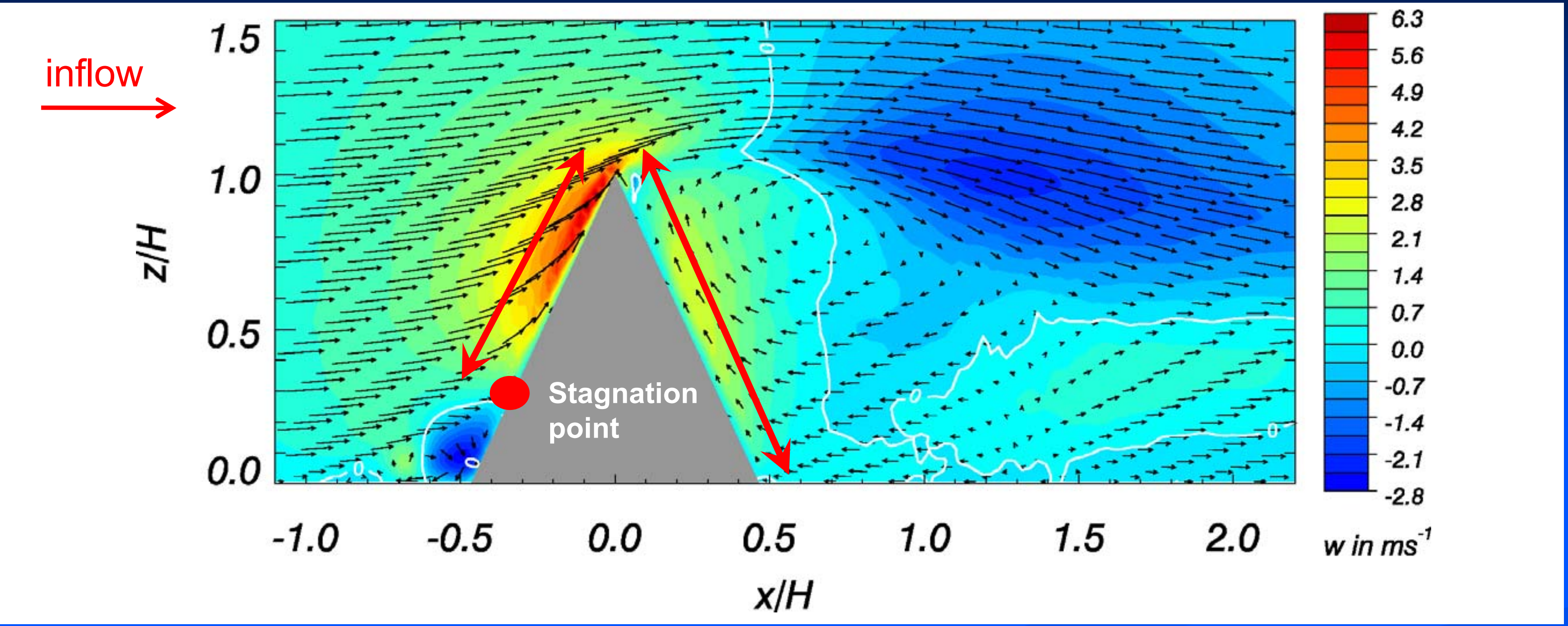
- Lifting cond. level **below** pyramid tip for large parts of boundary layer depth

III. Numerical simulation of banner clouds



Mechanism of banner cloud formation

Wind vectors of time mean flow



- Significant upwelling in the lee
- Highly asymmetric flow field regarding windward versus leeward side
- Upwelling region has larger vertical extent in the lee

Results support postulated mechanism 3

But !

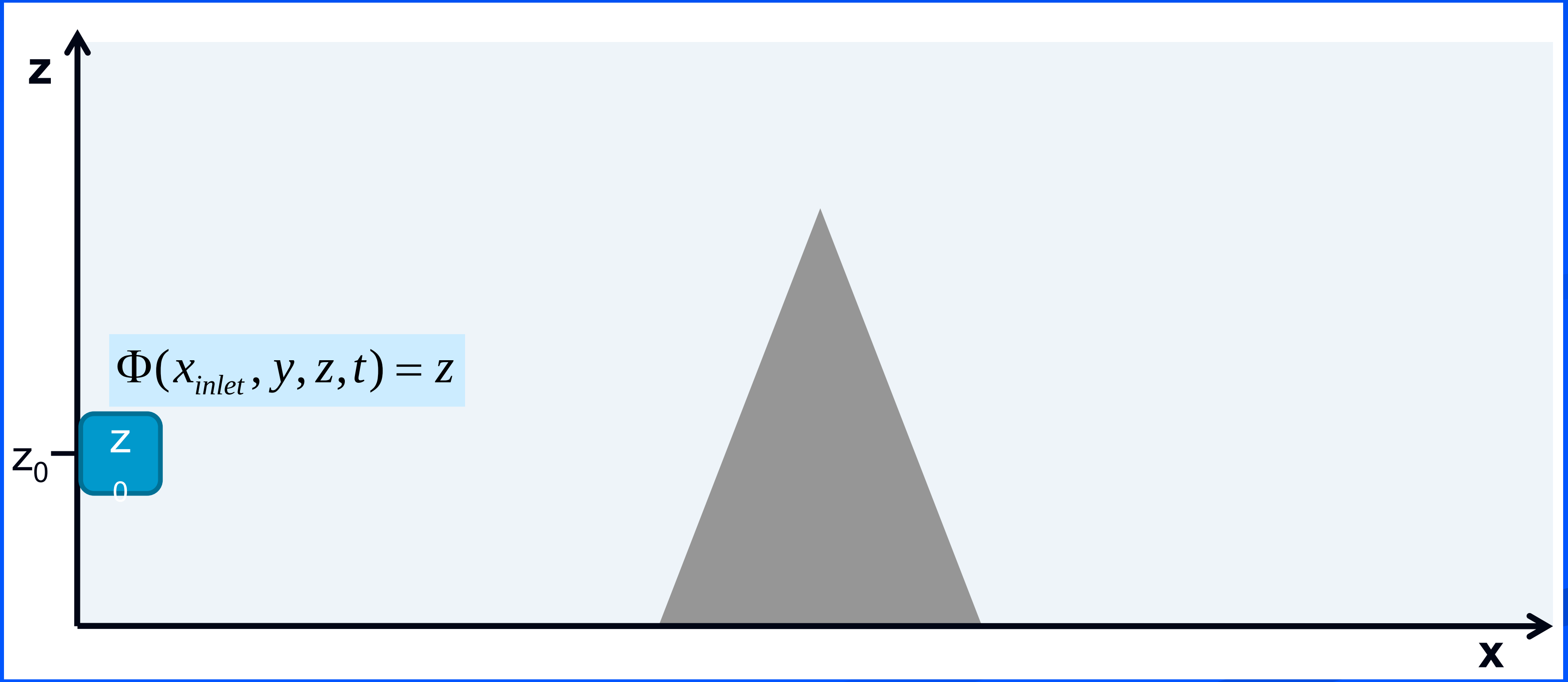
Does mechanism also work for horizontally homogeneous conditions ?

Lagrangian information about vertical displacement on lws and wws necessary

Initialization of passive tracer

- Advection of passive tracer Φ, satisfying $\frac{D\Phi}{Dt} = 0$

⇒ information about mean vertical displacement Δz of air masses on windward versus leeward side.



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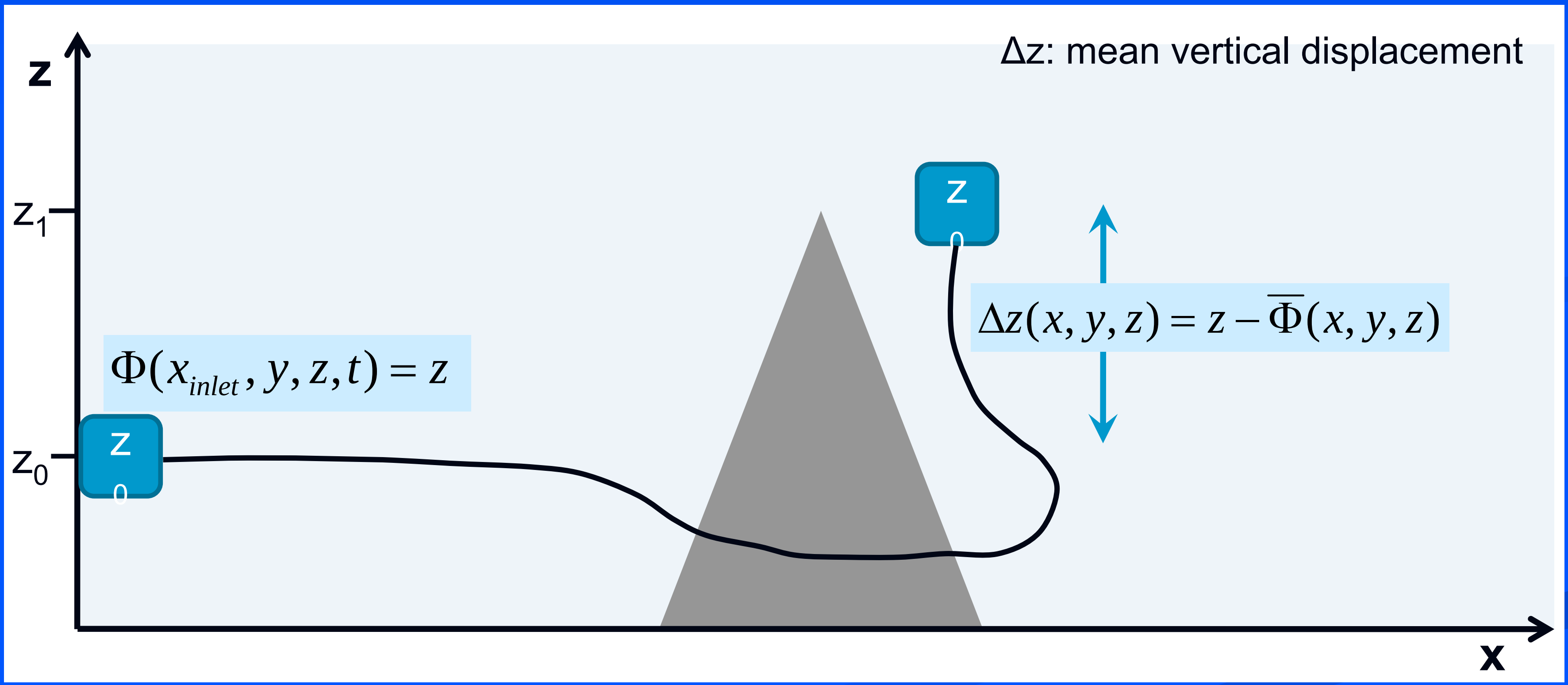
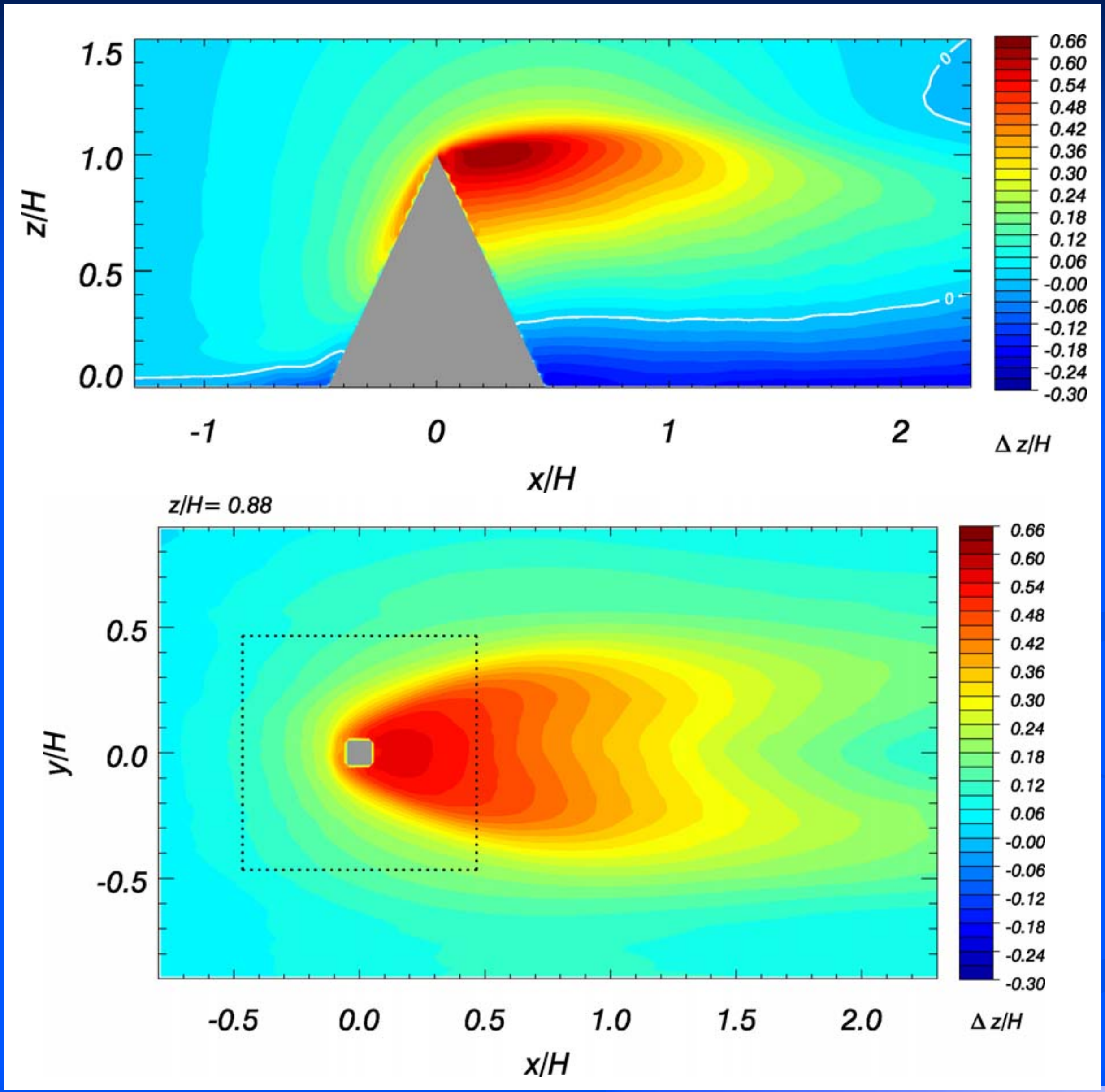


Time averaged vertical displacement Δz of passive tracer



- Highly asymmetric
- largest positive Δz in the immediate lee

⇓

No necessity for additional leeward moisture sources or distinct air masses

- Magnitude of asymmetry is a measure for the probability of banner cloud formation

Overall: strong structural similarity with real banner cloud.

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Simulation with moisture physics switched on

Objectives:
- Simulation of realistically shaped banner cloud
- Substantiate results/conclusions drawn from the former (dry) runs

Setup:
- no additional (leeward) moisture sources
- no distinct air masses
- no radiation effects

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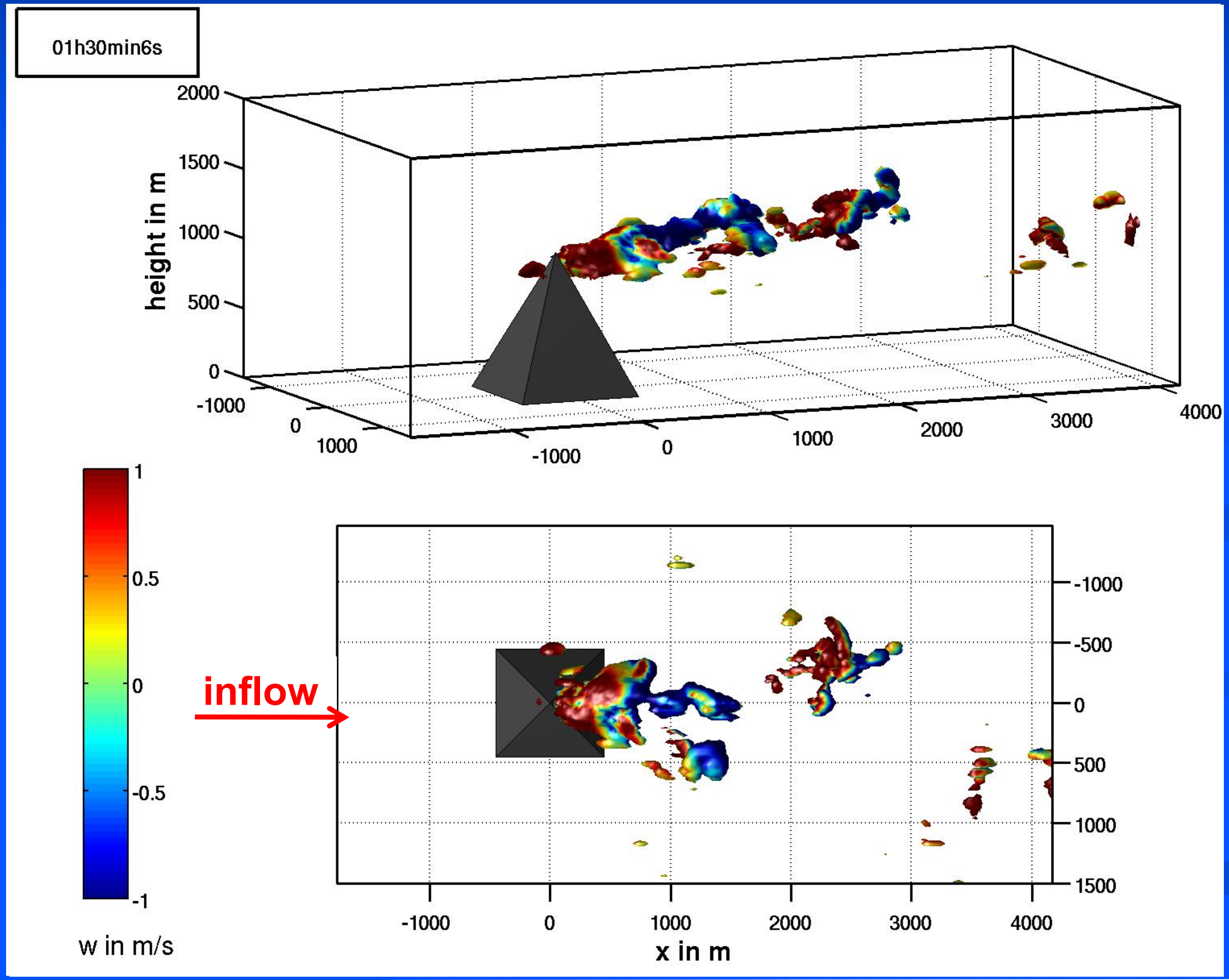

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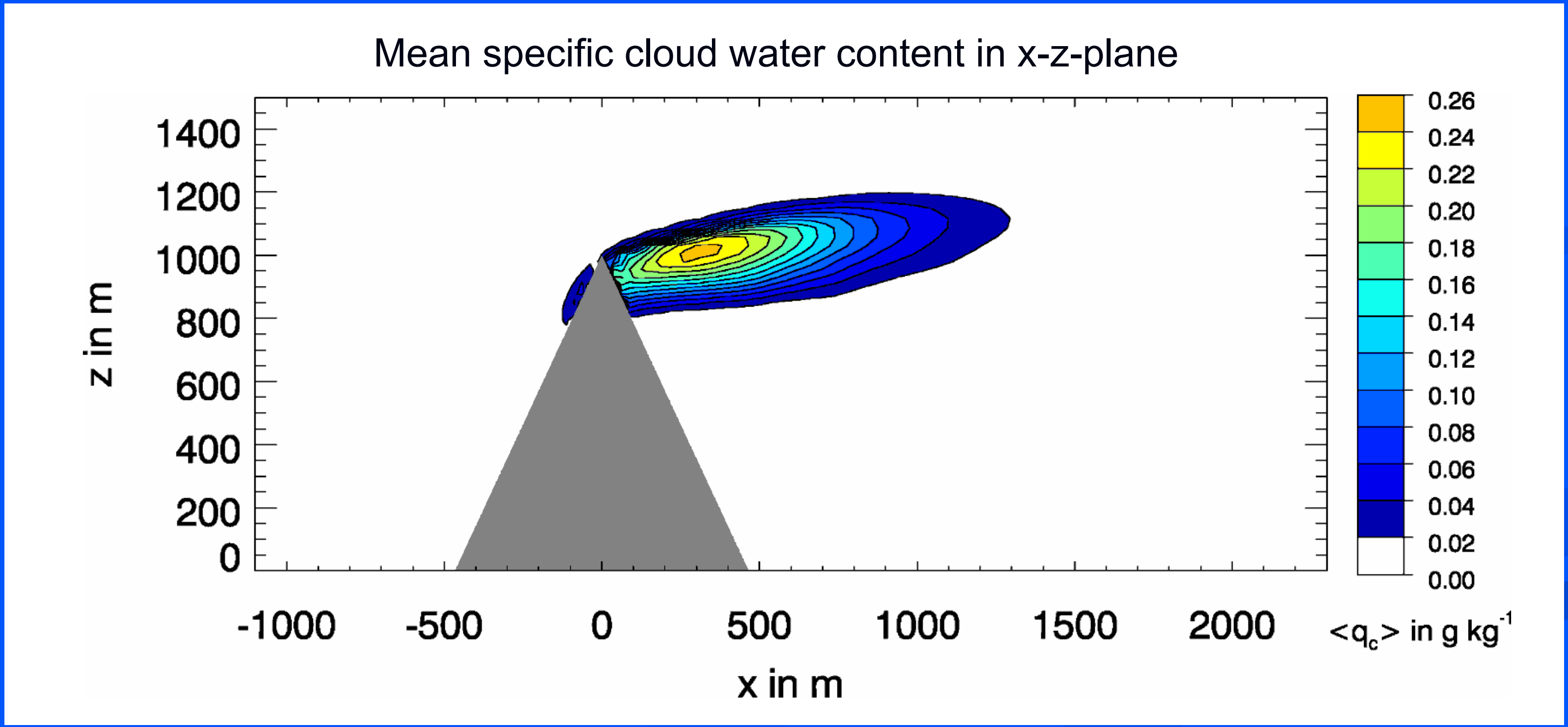

Impact of moisture physics

One could think of the following impacts:

- Impact on mean flow:
  - Potential to reinforce/sustain the upward branch of the leeward vortex
  - ⇒ Help to sustain banner clouds during episodes with weak dynamical forcing
- Impact on leeward turbulence:
  - Banner clouds give rise to a destabilization of the lee which may increase leeward turbulence

Results for one investigated thermodynamic situation:

- Moisture physics do not significantly impact the upward branch of the leeward vortex.
- Moisture physics give rise to a moderate increase of leeward turbulence.

Summary and conclusions

The numerical simulations revealed

- Banner cloud formation downwind of pyramidal shaped mountains can be explained through:
  - Forced upwelling in the upward branch of a leeward vortex

- Flow field is highly asymmetric regarding the Lagrangian vertical displacement

  ⇒ Banner clouds can form under horizontally homogeneous conditions

  ⇒ No need for additional features like:
  - leeward moisture sources
  - distinct air masses
  - radiation effects

- Theories based on mixing fog or Bernoulli-Effect are not necessary in order to explain banner cloud formation.

- Moisture physics probably of secondary importance for banner cloud dynamics

Thank you for your attention

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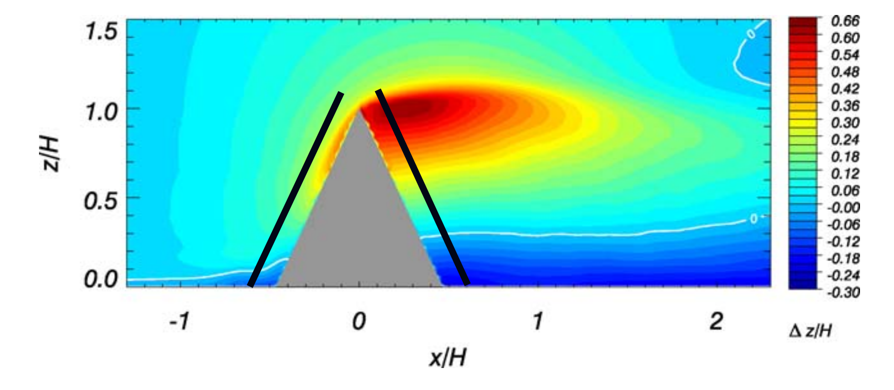
Meteorological conditions for banner cloud formation

- Whether a banner cloud forms or not is determined by both the **thermodynamical situation** (T(z), $q_v(z)$ upstream) **and** the **dynamical situation** (flow field induced by mountain)
- Thermodynamical situation (T(z), $q_v(z)$) and dynamical situation must match

Following schematic:

- Characterization of thermodynamical situation: Vertical profile of LCL derived from inflow dataset
- Characterization of dynamical situation: Vertical profiles of tracer displacement



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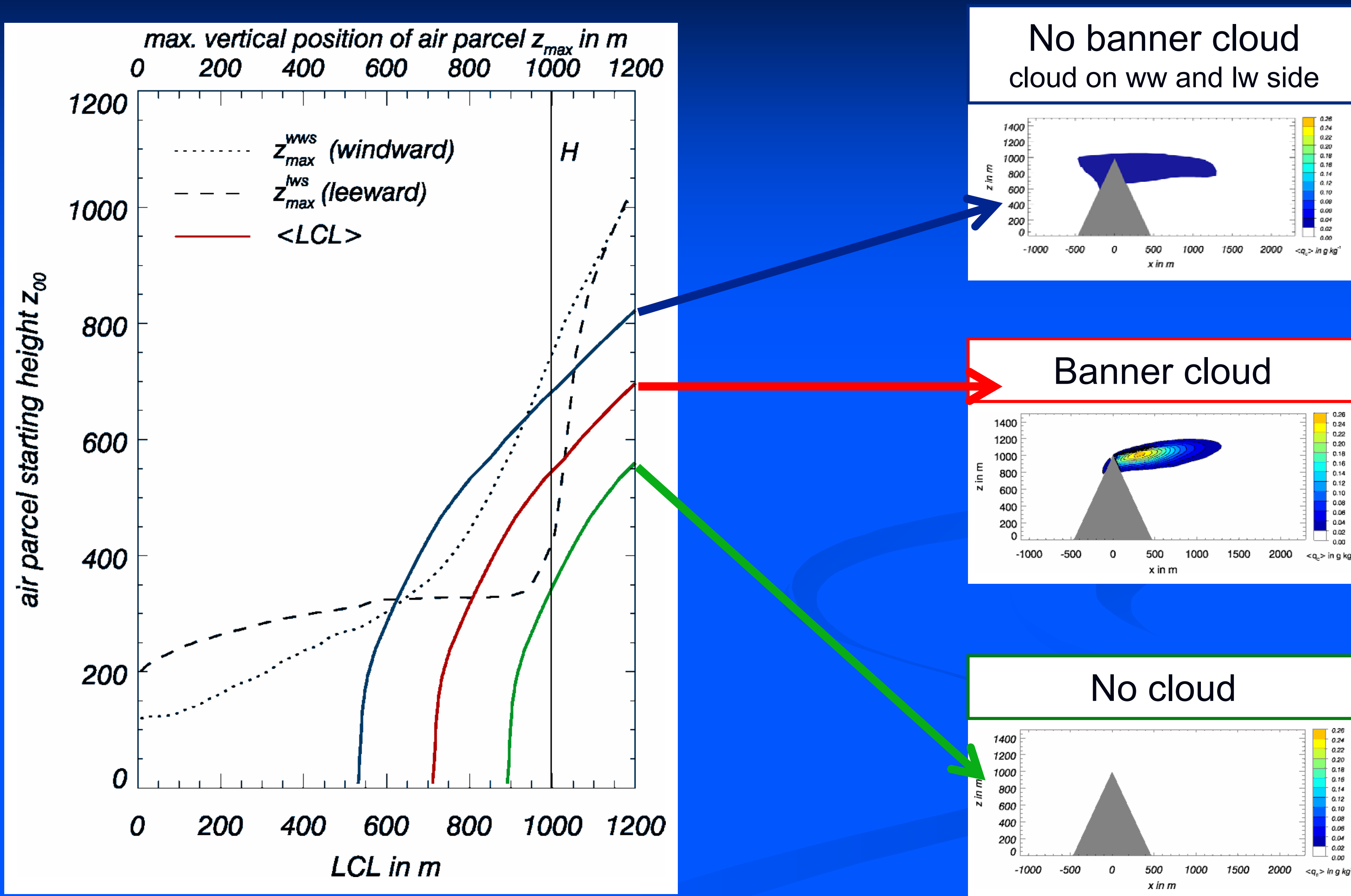
Meteorological conditions for banner cloud formation



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