Scaling laws for the heterogeneously heated free convective boundary layer

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COLA/LSM Workshop, 5 December 2013

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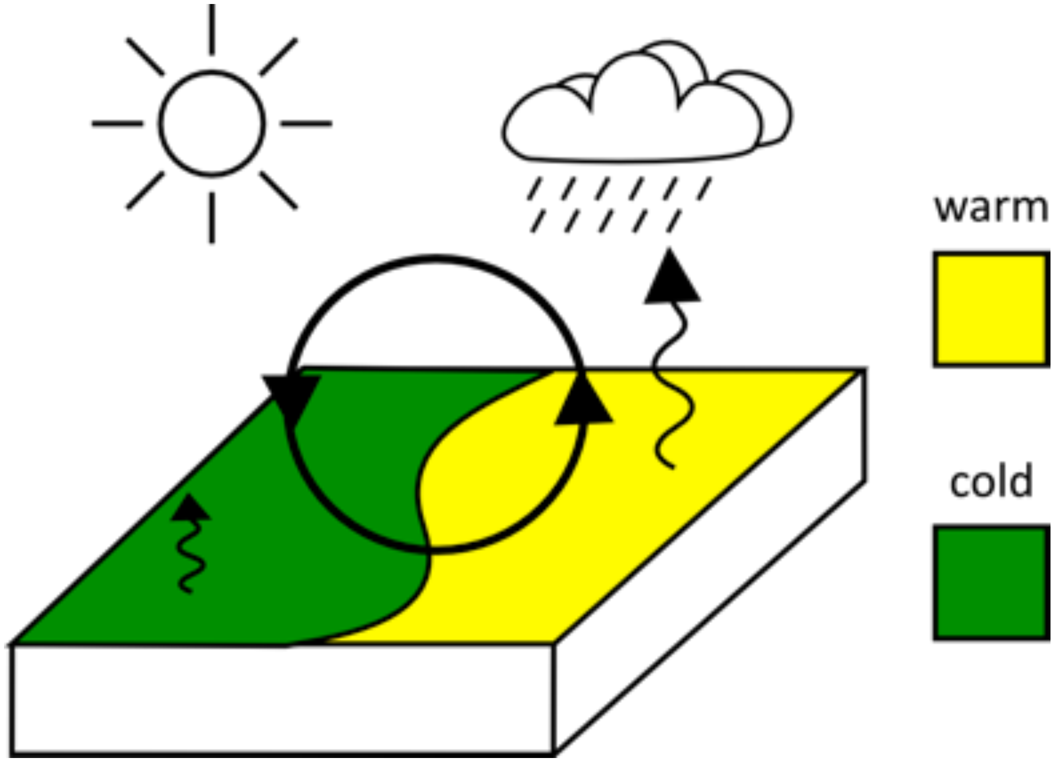
Motivation: a meteorological problem

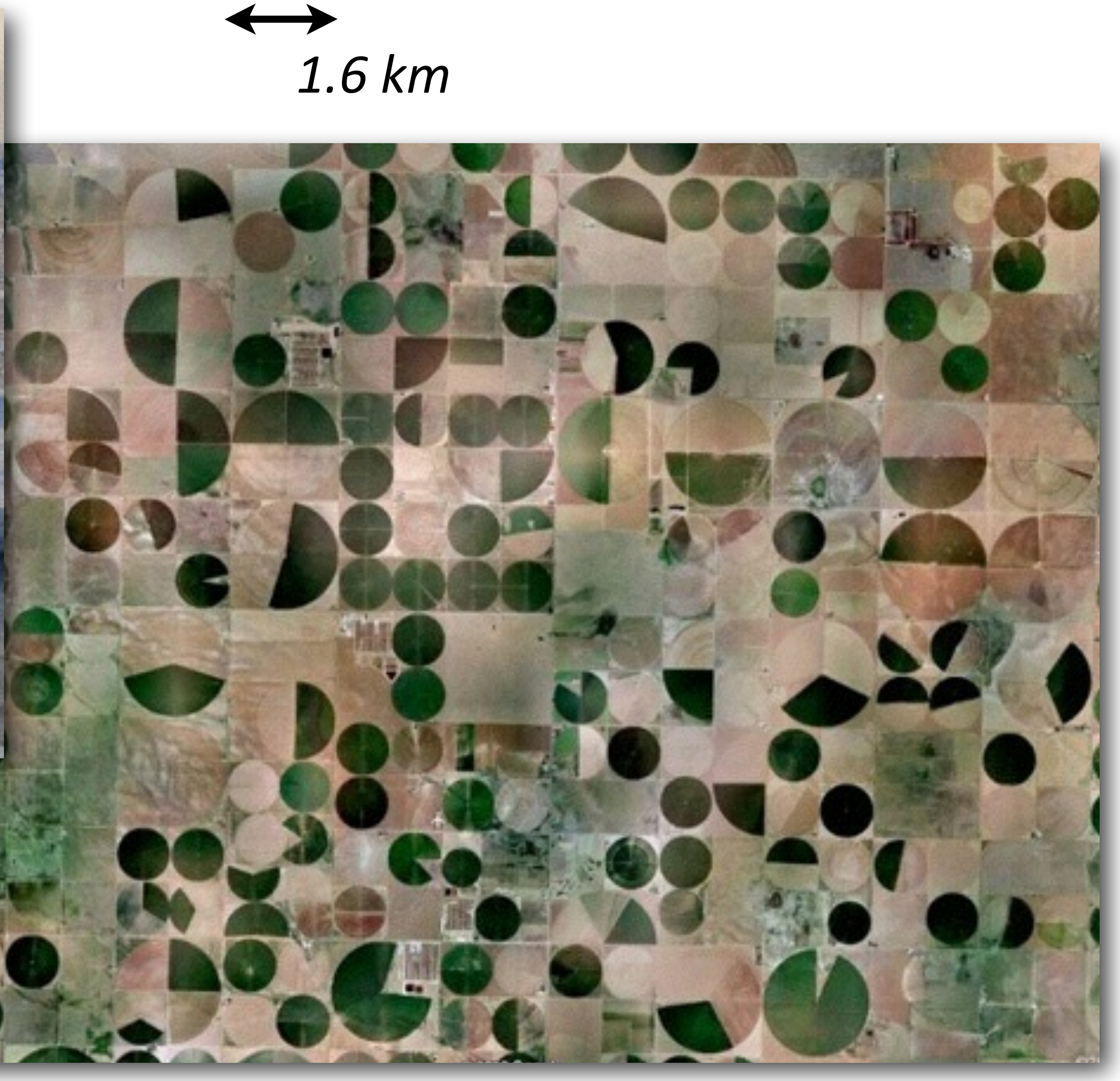
- Heterogeneous heating of a CBL leads to secondary circulations that can influence the turbulence, surface energy balance or cloud formation



- Under which conditions do the strongest secondary circulations occur?
  - *Patton et al. (2005): heterogeneity size* X_H *= 4 - 9 times CBL height.*
- When does the transition to a horizontally homogeneous CBL occur?

Two examples of a heterogeneously heated atmosphere

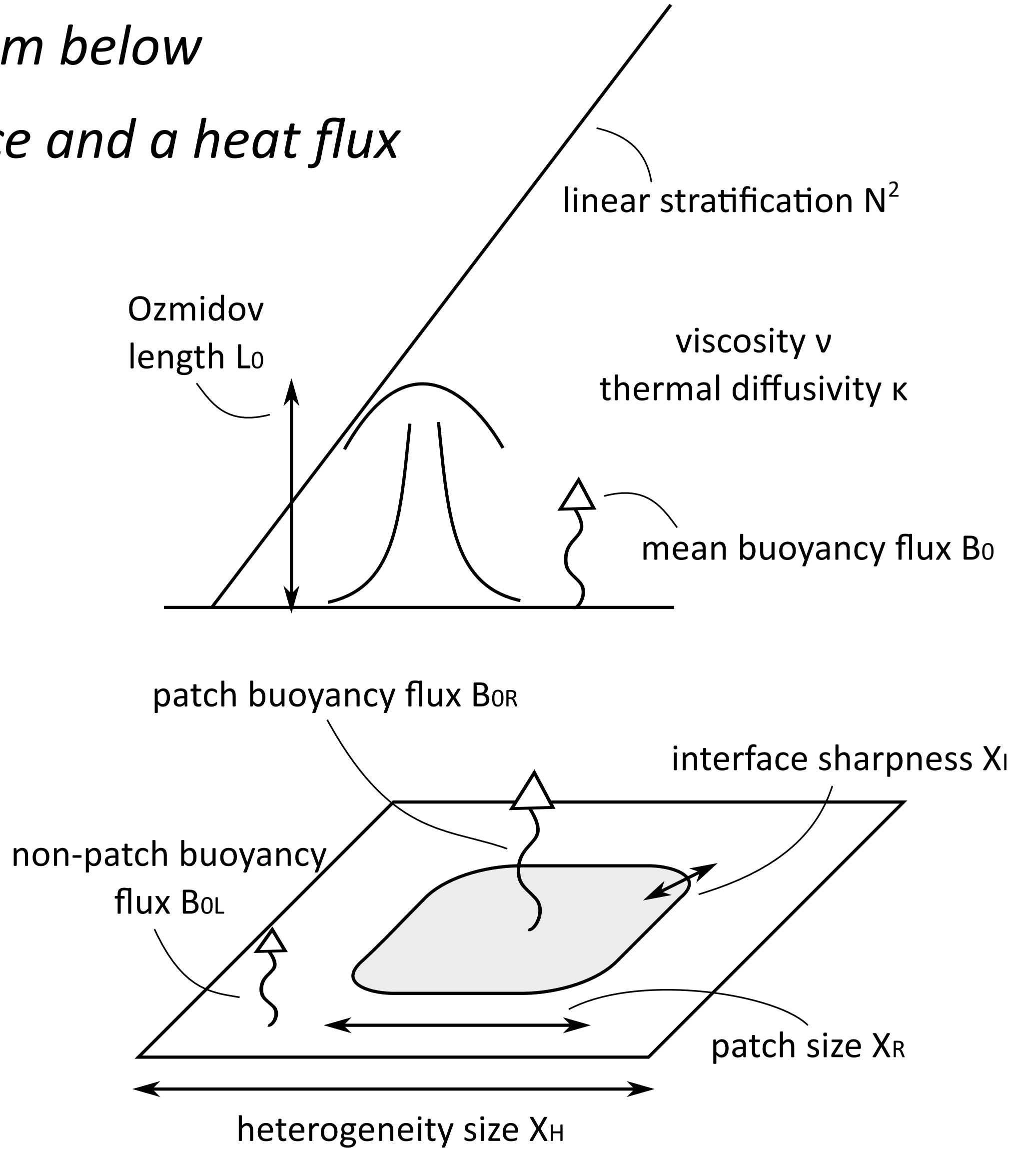
Sea ice in the polar regions
(Photo by Dirk Notz)



Agriculture near Amarillo, TX, USA
(Google Earth)

How can we study this problem?

- What do these meteorological cases have in common?
  - *Heterogeneous heating of a stratified atmosphere from below*
  - *Surface contains heterogeneities with a size, a distance and a heat flux*



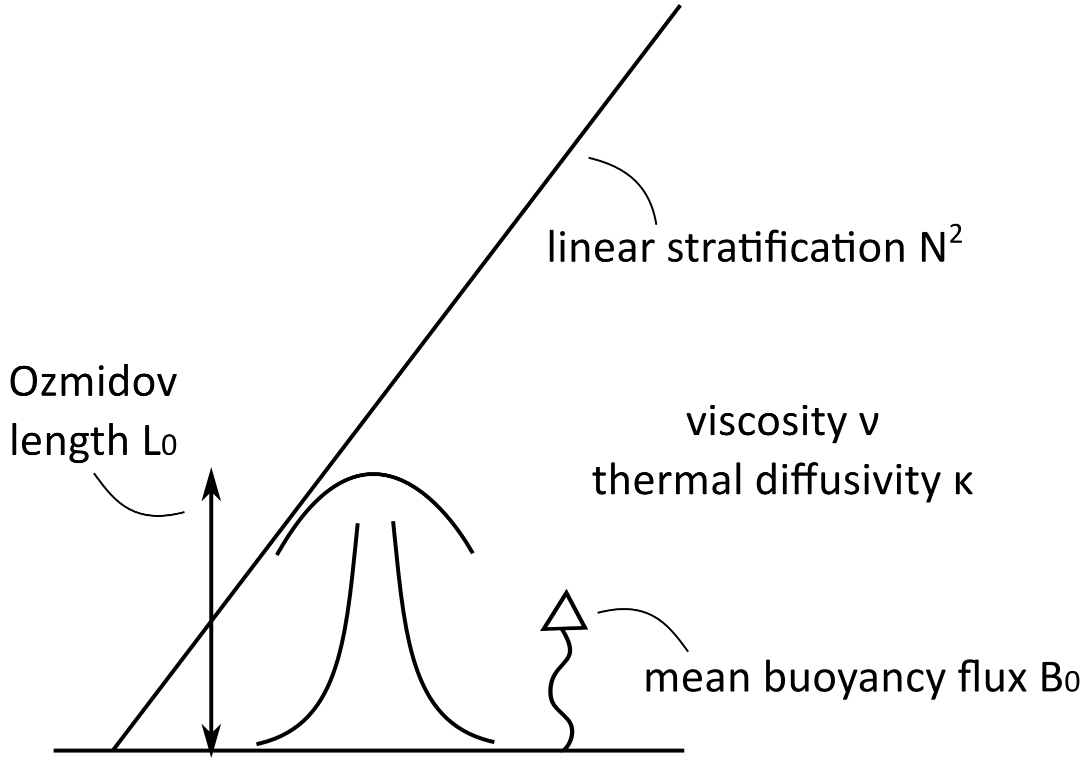
- Two canonical cases in fluid mechanics can be found in this system
  - *Isolated thermals in a stratified fluid (Morton et al., 1956)*
  - *Convective boundary layer (Deardorff, 1970; Businger et al., 1971; Kaimal et al., 1976)*

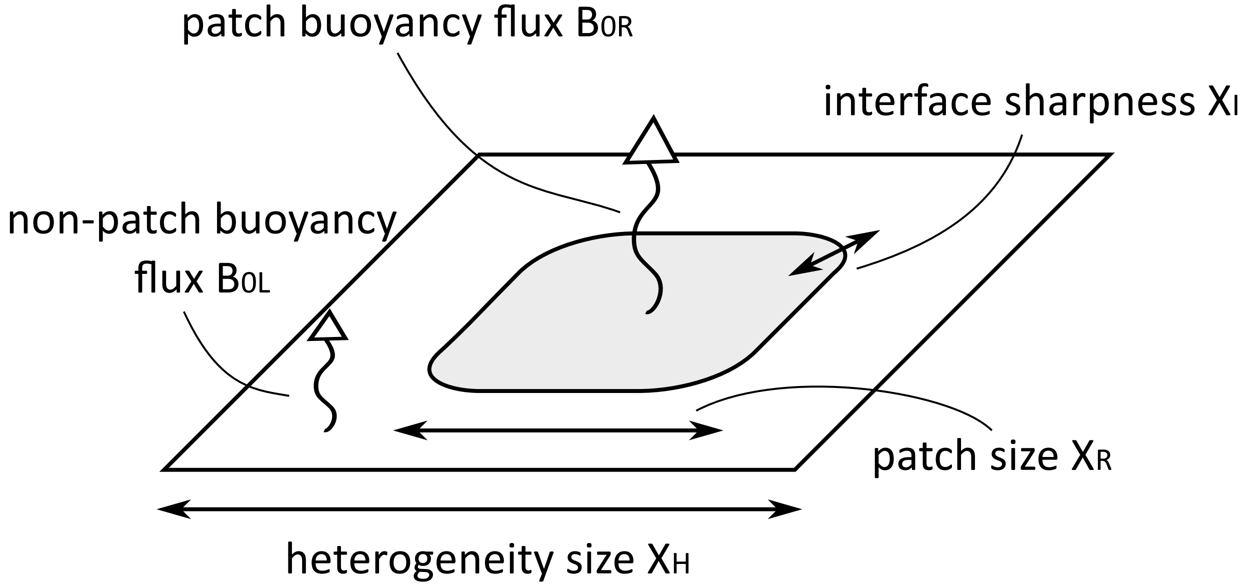
Derivation of scaling laws requires a non-dimensional system

- Set of non-dimensional parameters:

$$\left\{ \frac{\nu}{\kappa}, \frac{L}{\eta}, \frac{X_H}{L_0}, \frac{X_R}{L_0}, \frac{B_{0L}}{B_0}, \frac{X_I}{L_0} \right\}$$

  - *Prandtl number*
  - *Scale separation (equal to Reynolds number $Re^{3/4}$)*
  - *Heterogeneity size over plume size*
  - *Patch size over plume size*
  - *Surface flux over non-patch areas over mean surface flux (heterogeneity amplitude)*
  - *The interface sharpness*

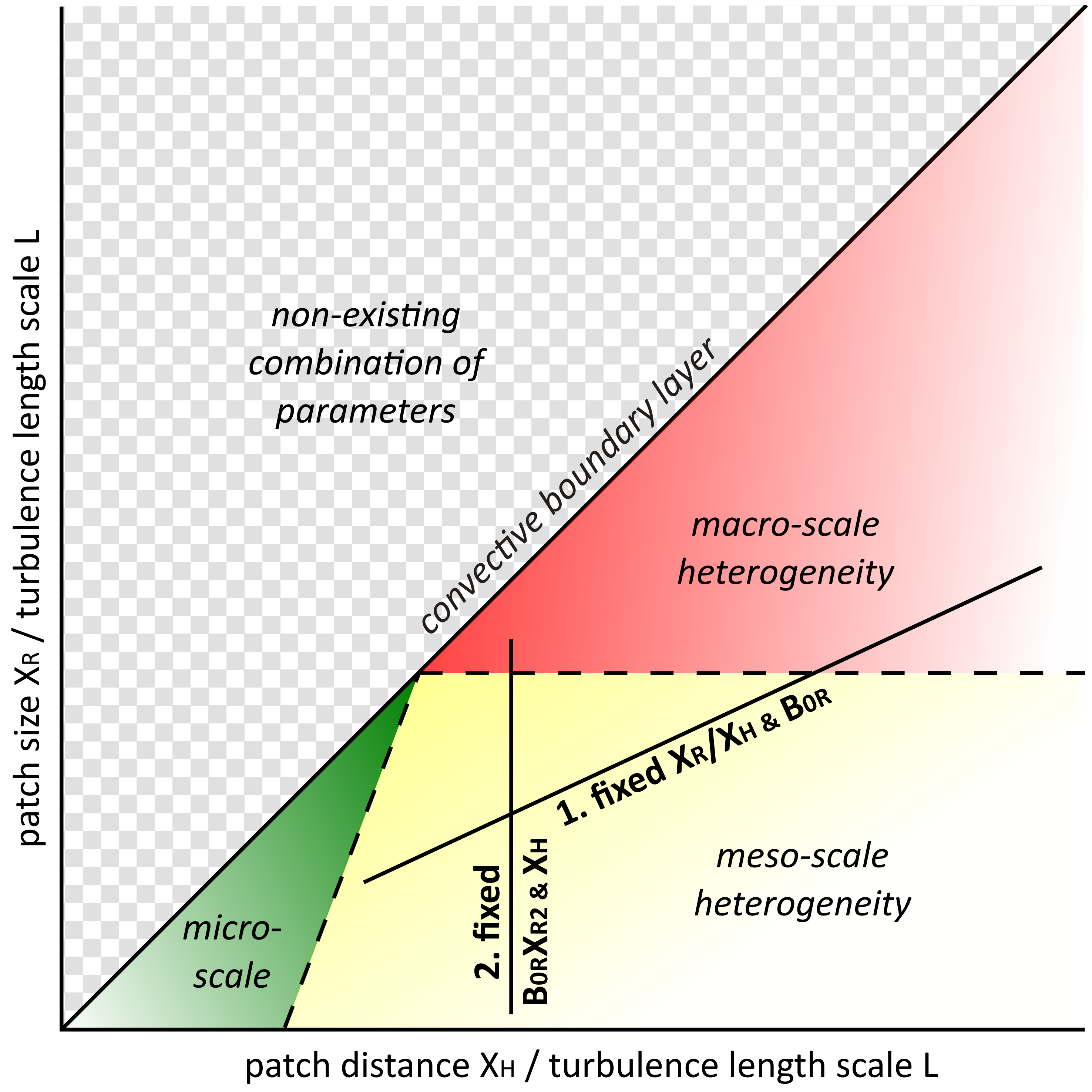


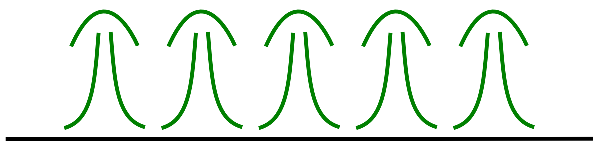


$$L_0 = \left(\frac{B_0}{N^3}\right)^{\frac{1}{2}}$$ *Ozmidov length (largest length scale)*

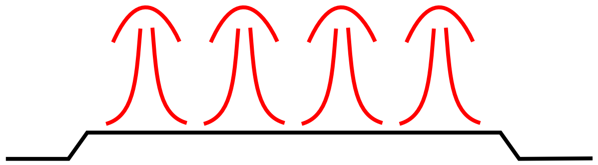
$$\eta = \left(\frac{\nu^3}{B_0}\right)^{\frac{1}{4}}$$ *Kolmogorov length (smallest length scale)*

Two-dimensional parameter space

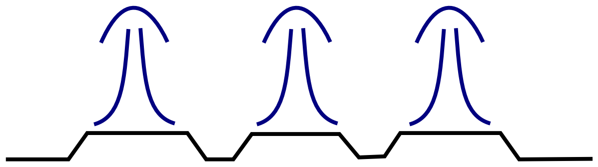




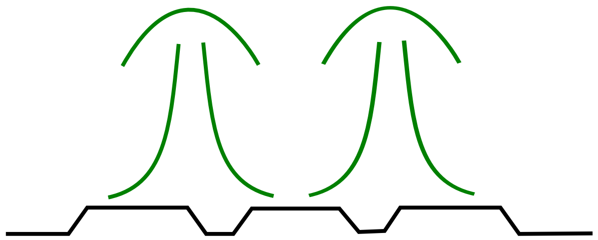
convective boundary layer



macro-scale heterogeneity



meso-scale heterogeneity

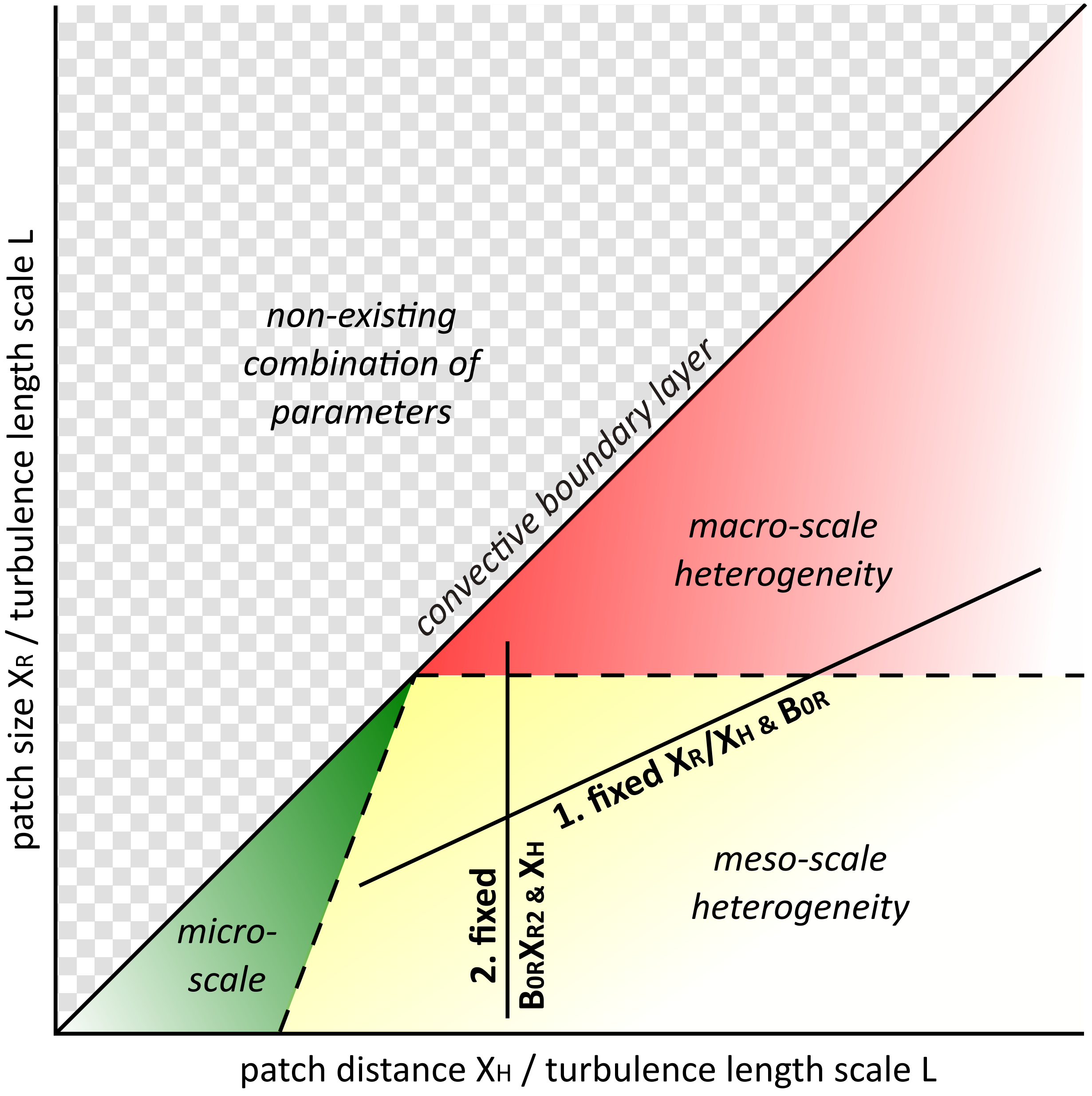


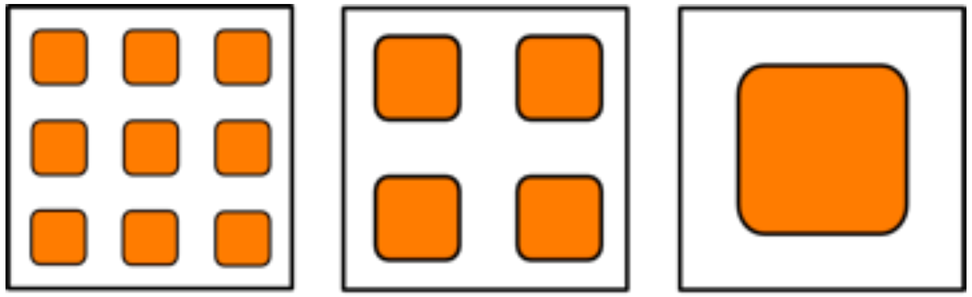
micro-scale heterogeneity

Regimes according to Mahrt (2000)

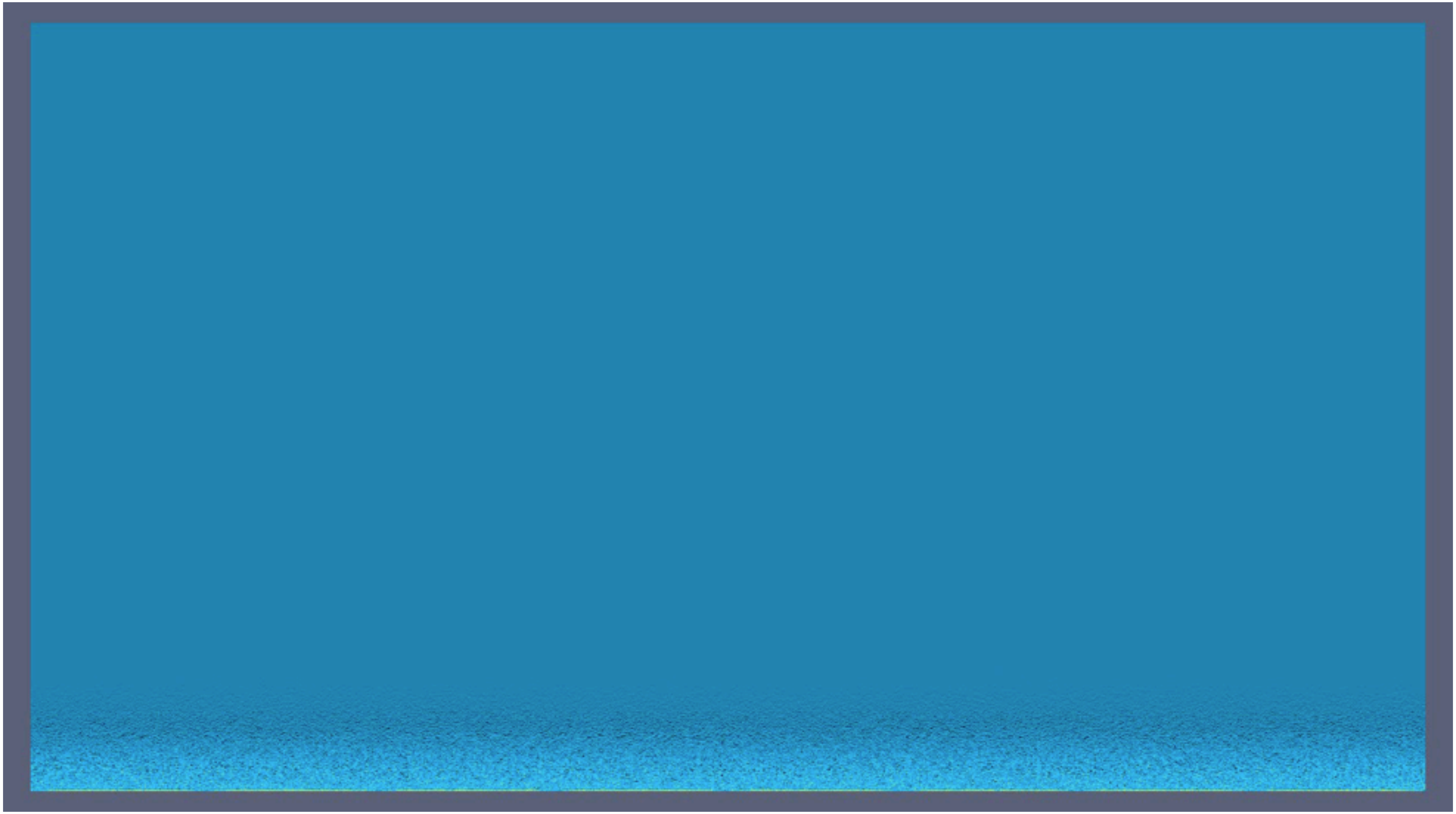
LES / DNS experiment: influence of the heterogeneity size X_H/L_0

- Maintain area coverage (X_R^2/X_H^2) and heterogeneity amplitude (B_{0L}/B_0)
- Increase heterogeneity size (X_H/L_0)
- Three series of experiments
  - *$B_{0L}/B_0 = 0$ (100% flux over patch)*
  - *$B_{0L}/B_0 = 0.4$ (80% flux over patch)*
  - *$B_{0L}/B_0 = 0.8$ (60% flux over patch)*

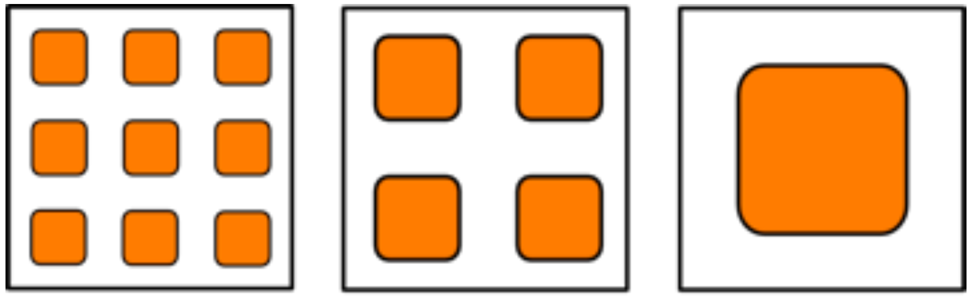




Transition from the meso-scale to the micro-scale regime

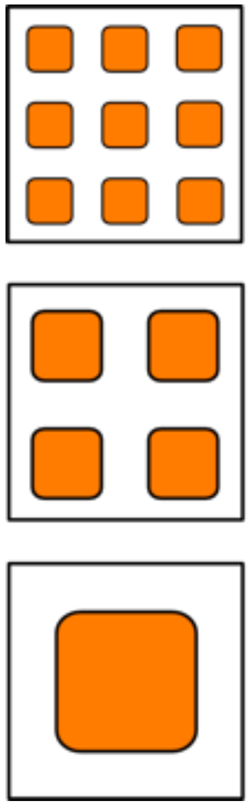


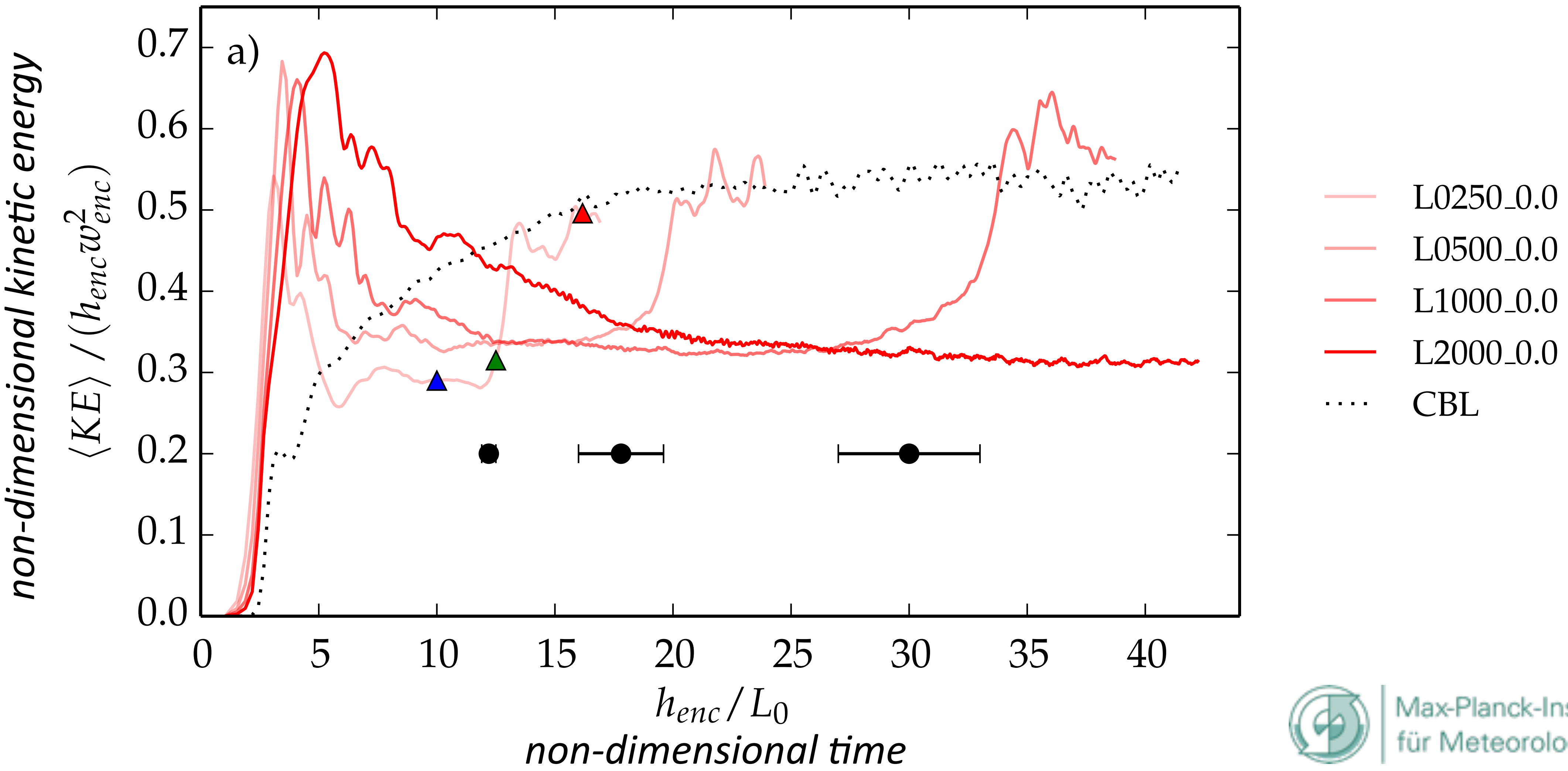
Results: the influence of heterogeneity size X_H/L_0



Simulations without flux in non-patch areas ($B_{0L}/B_0 = 0$)

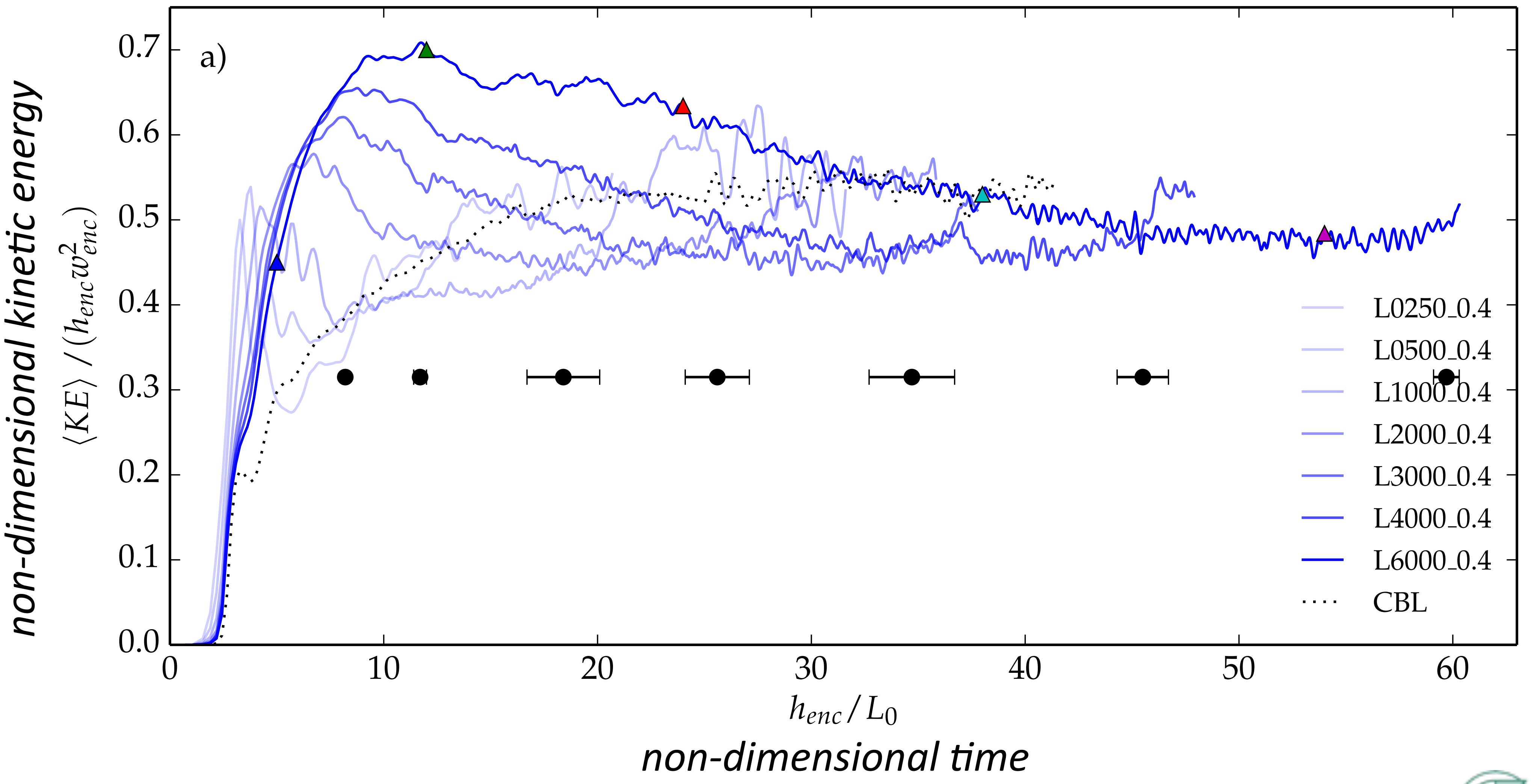
- Three different phases
  - *Peak in kinetic energy,*
  - *Phase of constant normalized kinetic energy (size does not matter)*
  - *Transition from the meso- to the micro-scale regime*
- Transition not at fixed ratio X_H/h, but at a lower ratio for larger X_H/L_0
  - *In other words, larger heterogeneity sizes merge relatively easier*





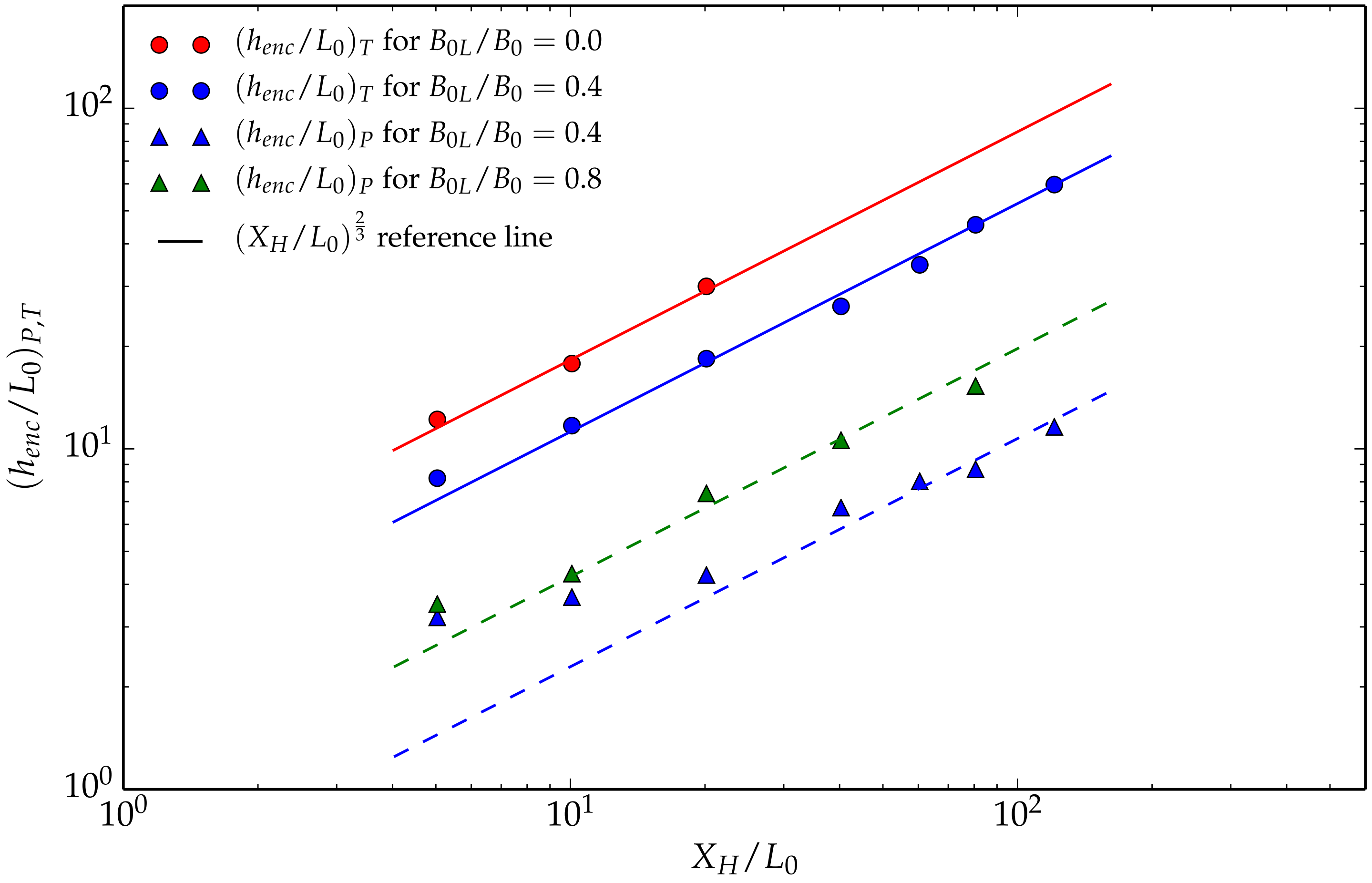
Simulations with a flux in non-patch area ($B_{0L}/B_0 = 0.4$)

- Time of occurrence peak and transition function of heterogeneity amplitude
  - *Optimal state occurs later, while transition occurs earlier compared to $B_{0L}/B_0 = 0$*
- Integrated kinetic energy increases with heterogeneity size
- Time of occurrence of peak does not scale with X_H/h either



Dependence on heterogeneity size consistent over simulations

- Timing of optimal state *(dots)* and of transition *(triangles)* scales in all experiment

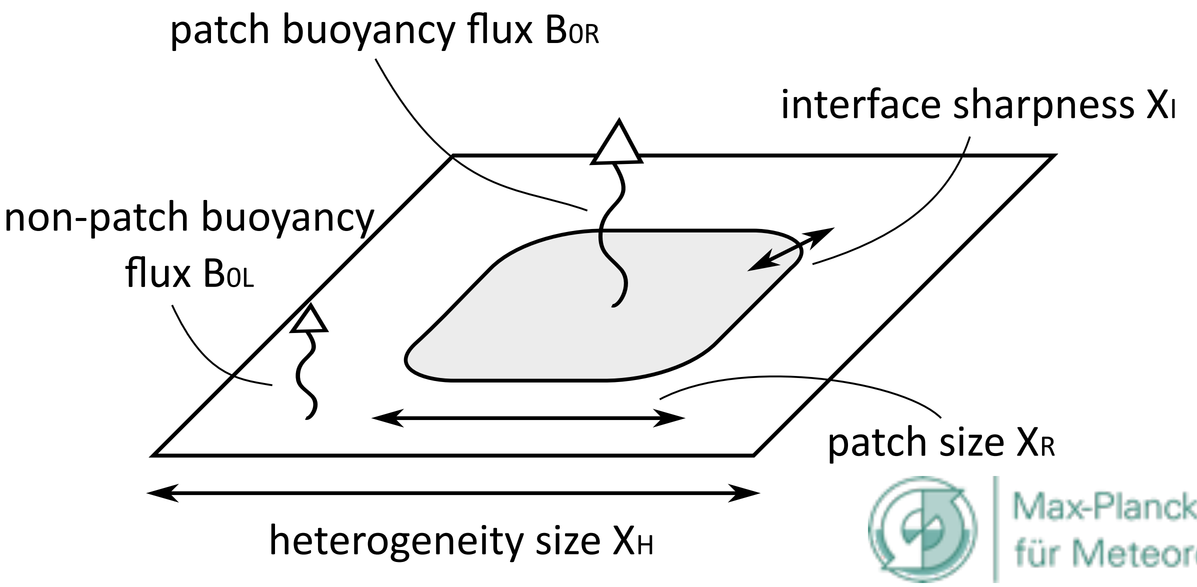


time of peak (P) and transition (T)

non-dimensional heterogeneity size

- Scaled time axis of the form:
  - *X_R/X_H term comes from experiment 2*

$$\gamma\left(\frac{h_{enc}}{L_0}\right)\left(\frac{X_R}{X_H}\right)\left(\frac{X_H}{L_0}\right)^{-\frac{2}{3}}$$



patch buoyancy flux B_{0R}

interface sharpness X_I

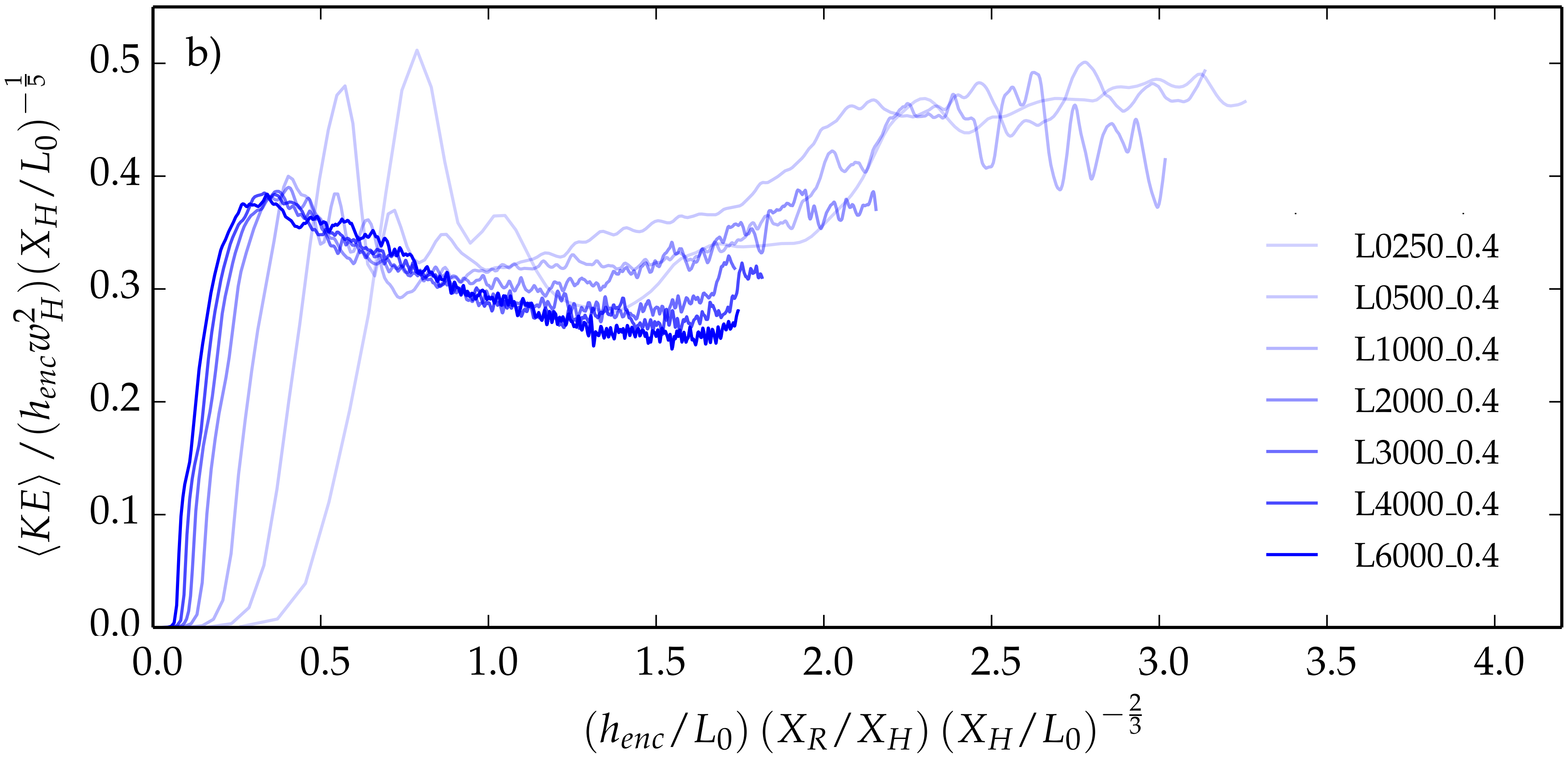
non-patch buoyancy flux B_{0L}

patch size X_R

heterogeneity size X_H

Scaling leads to collapsing time evolution

- Optimal state and the transition from meso- to micro-scale regime occur under same scaled time
- Kinetic energy scaling effective in scaling the energy in the peak (*part of study, not shown in presentation)*

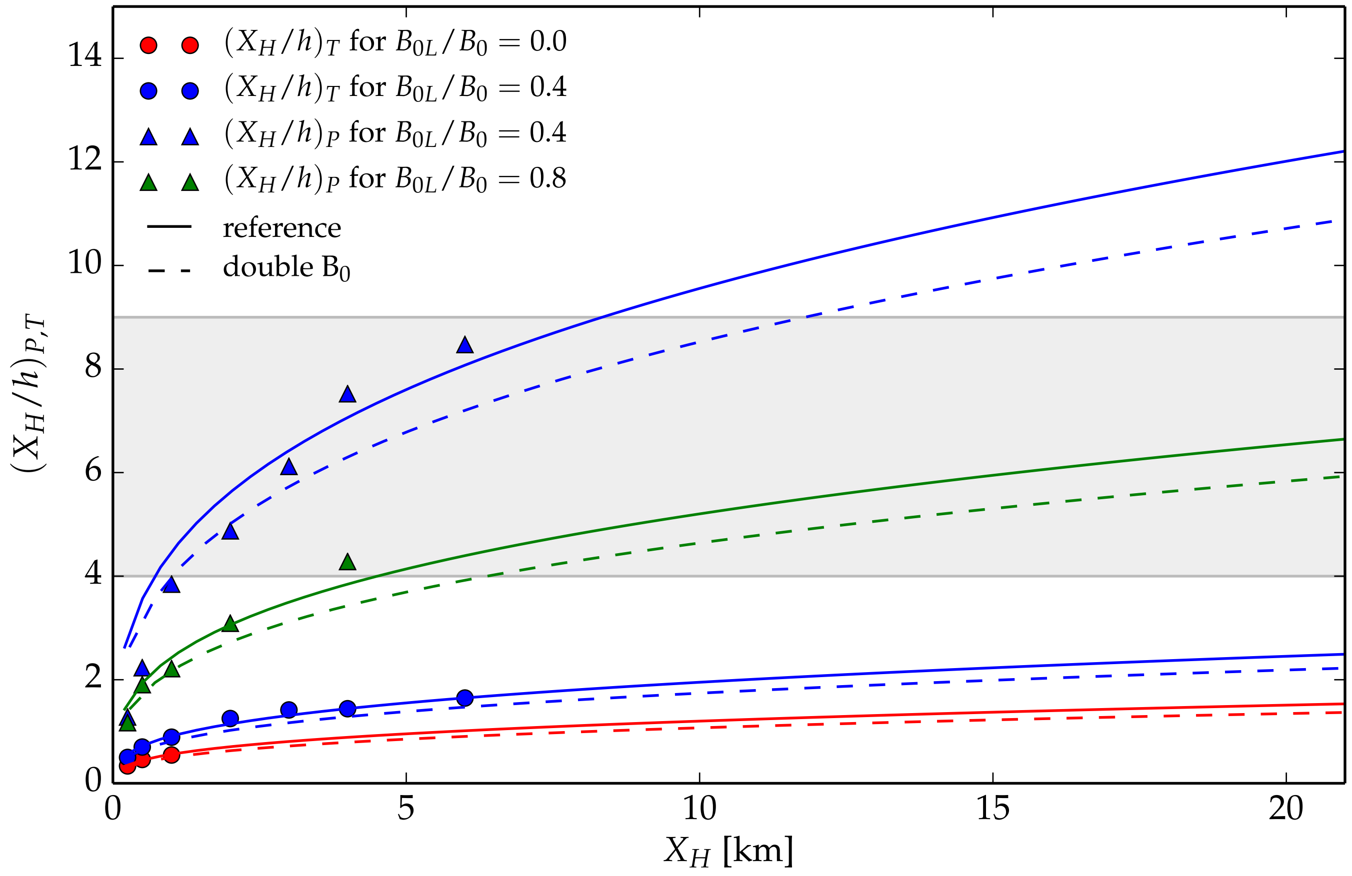


scaled non-dimensional kinetic energy

scaled non-dimensional time

Conclusion: a comparison with previous work

- Patton et al. (2005): optimal state between 4 and 9 X_H/h (shaded area)
- Our results are able to explain the wide range and to be more exact



time of peak (P) and transition (T)

heterogeneity size

- Strongest circulations occurs at a higher ratio of X_H/h for larger heterogeneity sizes
- Time of peak and transition very sensitive to heterogeneity amplitude