Pathways of self-aggregation in atmospheric convection

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Joint work with:
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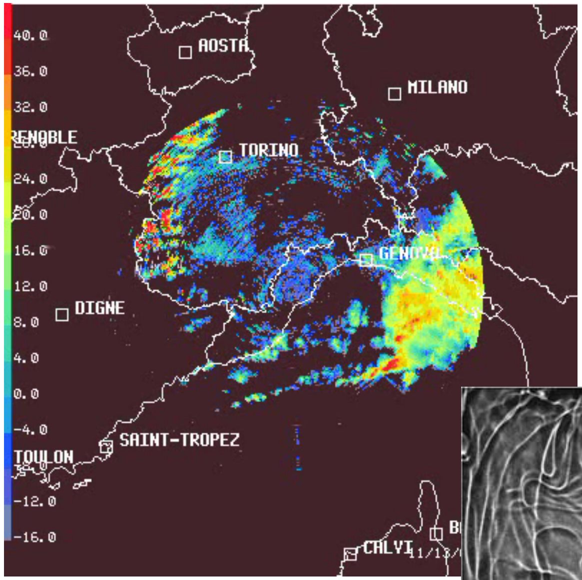
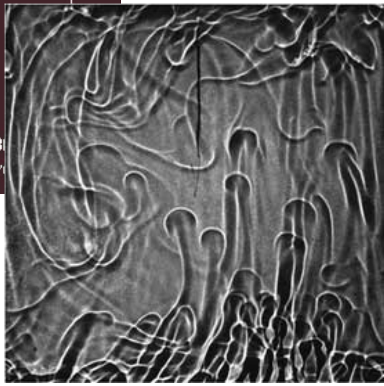
Self-aggregation of convective plumes

- Intense convection is dominated by the action of plumes, coherent structures which mix the fluid and are responsible for a large fraction of the vertical heat transport in the bulk of the fluid

- There is a wide range of cases where convective plumes are found to cluster together in large-scale structures, while mantaining their identity: in laboratory exps, numerical exps and observed in natural systems (e.g. mesoscale clusters in rain storms, large-scale cloud structures, solar convection)





L.P. Kadanoff, *Physics Today* 2001

Clustering of plumes in Rayleigh-Bénard Convection

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + T\hat{\mathbf{z}} + \left(\frac{\sigma}{R}\right)^{1/2} \nabla^2 \mathbf{u},$$

$$\nabla \cdot \mathbf{u} = 0,$$

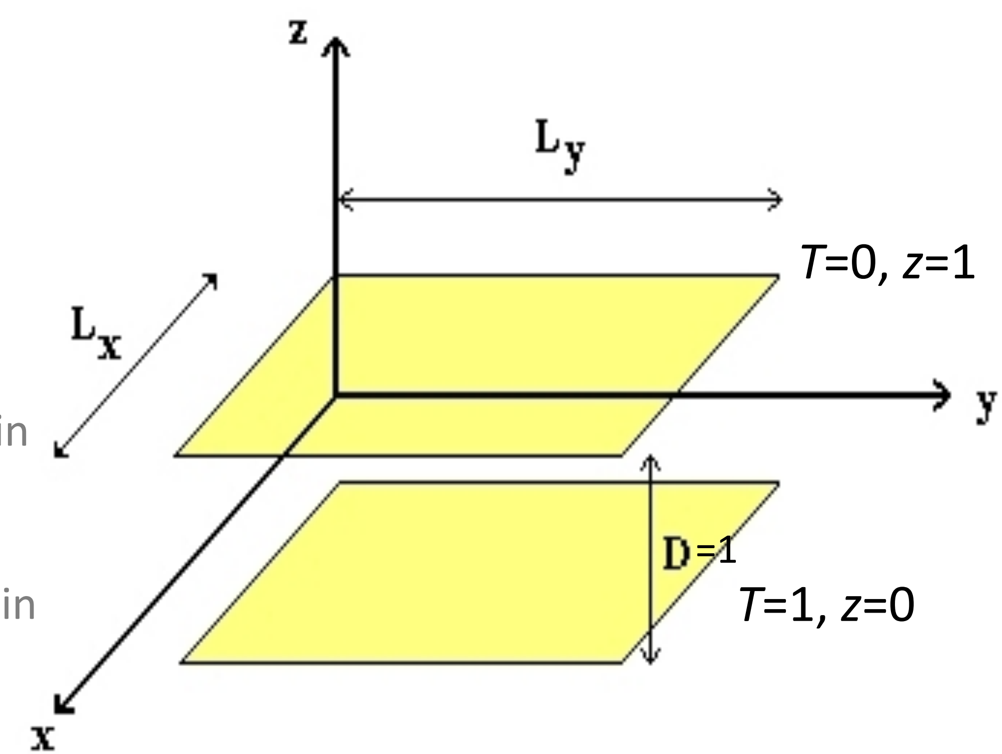
$$\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T = \frac{1}{(\sigma R)^{1/2}} \nabla^2 T,$$

$$\nabla \cdot \boldsymbol{u} = 0$$

$$\sigma = \nu/\kappa$$

$$R = g\alpha \Delta T d^3/(\kappa \nu)$$

- von Hardenberg J, Parodi, Passoni, Provenzale, Spiegel, Large-scale patterns in Rayleigh-Bénard convection, PLA (2007)
- Parodi, A., von Hardenberg, Passoni, Provenzale, Spiegel, Clustering of Plumes in Turbulent Convection, PRL (2004)



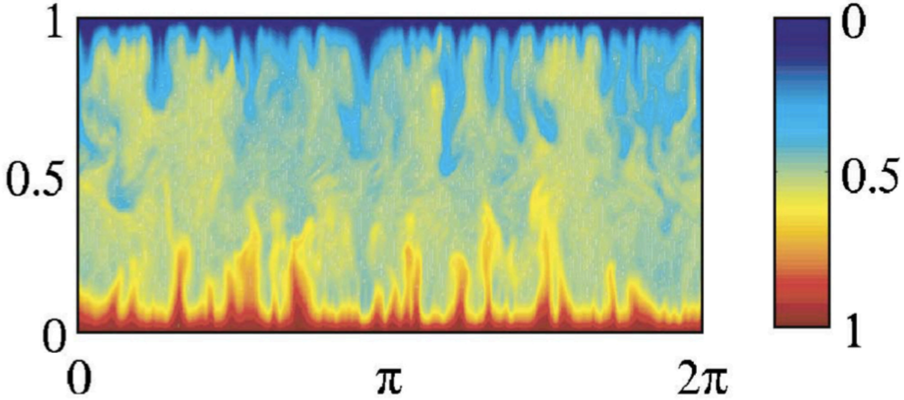
Temperature sections

$R = 10^7$

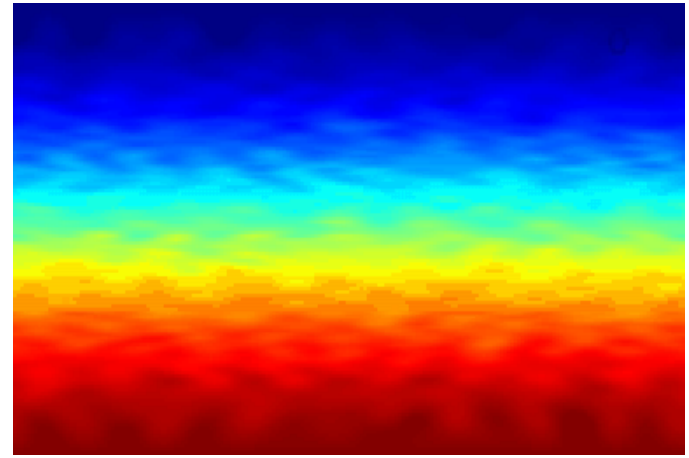
$\sigma = 0.71$

t=13

z

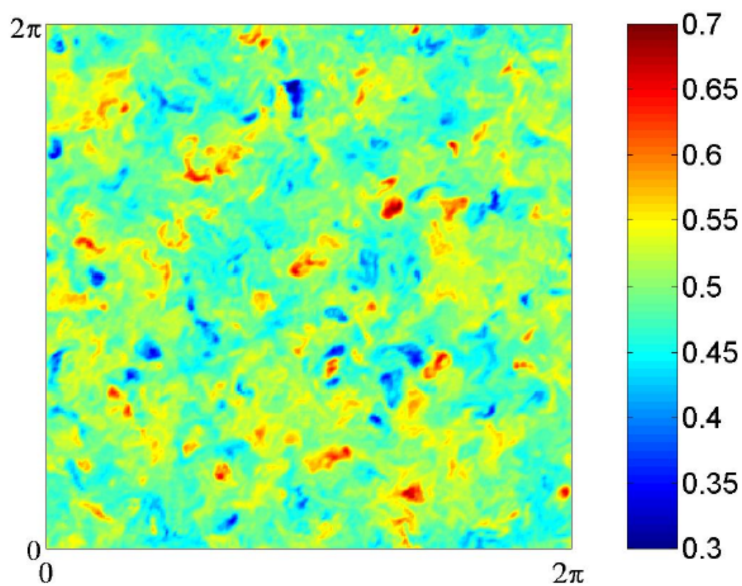


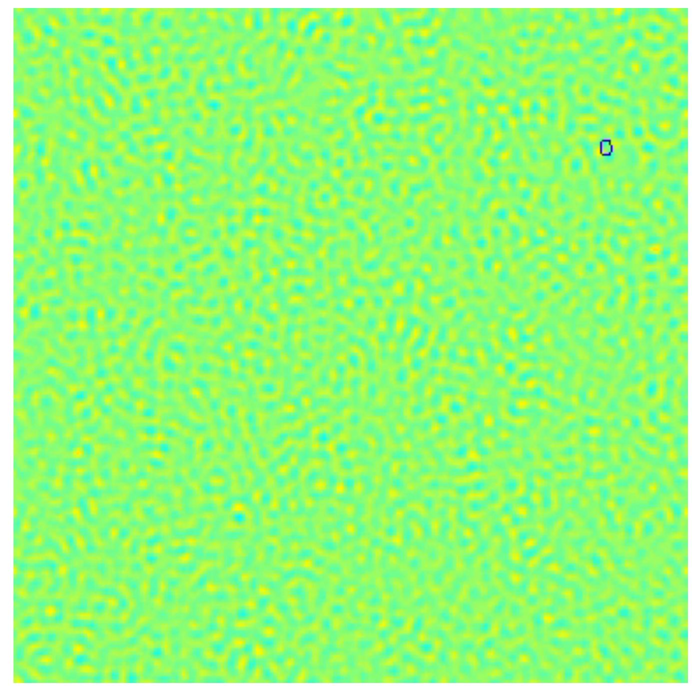
x



z=0.5

y



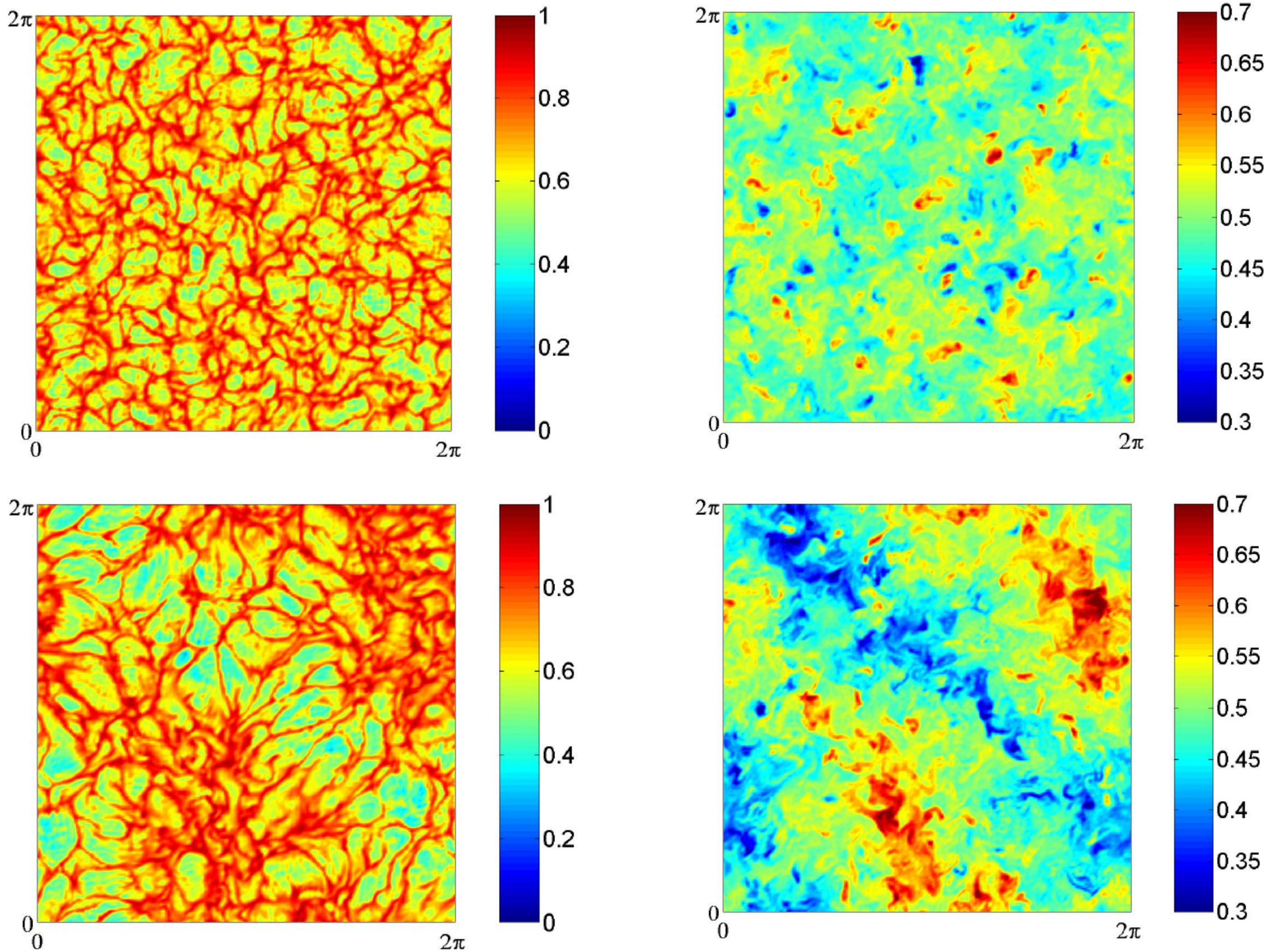


Evolution of horizontal sections of temperature

z=0.02 z=0.5

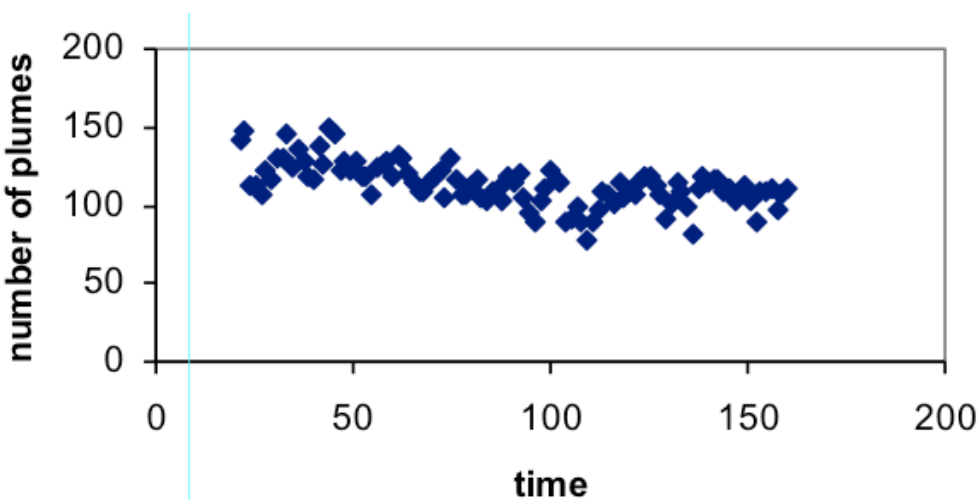
t=13

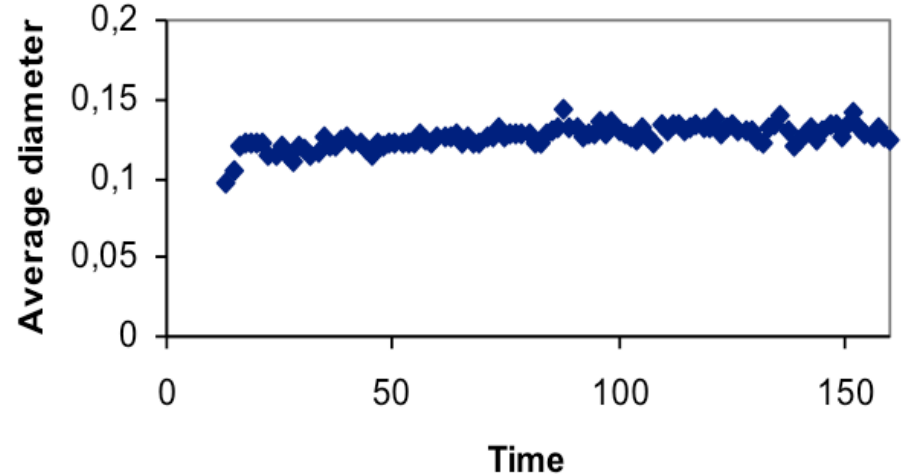
t=160



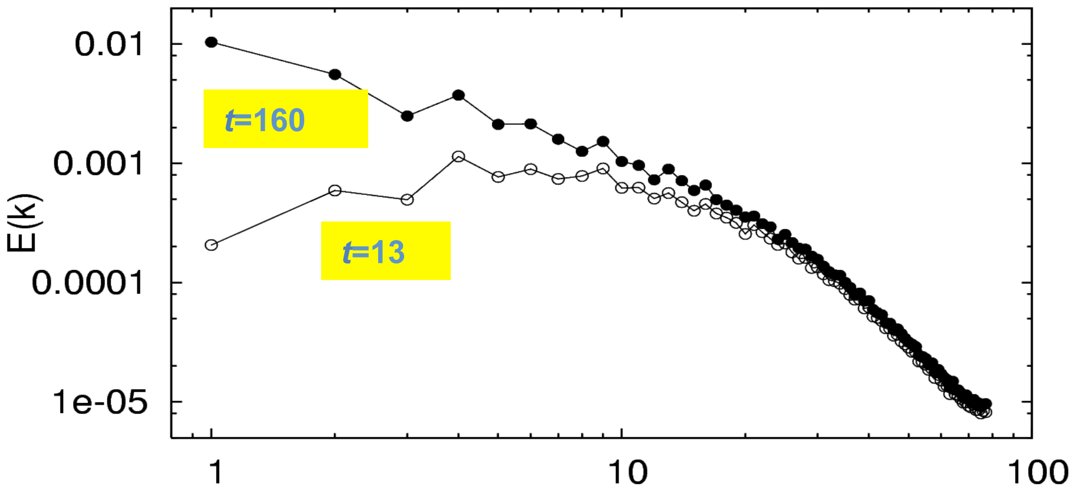
Plume statistics

- We identify plumes by detecting local maxima in the turbulent heat transport $w\theta'$ on the midplane, keeping connected regions with heat flux larger than $4 < w\theta' >$
- Plumes occupy 8% of the area of the midplane.
- Plumes carry about 50% of the total heat transported.
- The number of plumes N_p and their average area A_p remain approximately constant over time!





Power spectra and evolution of scales

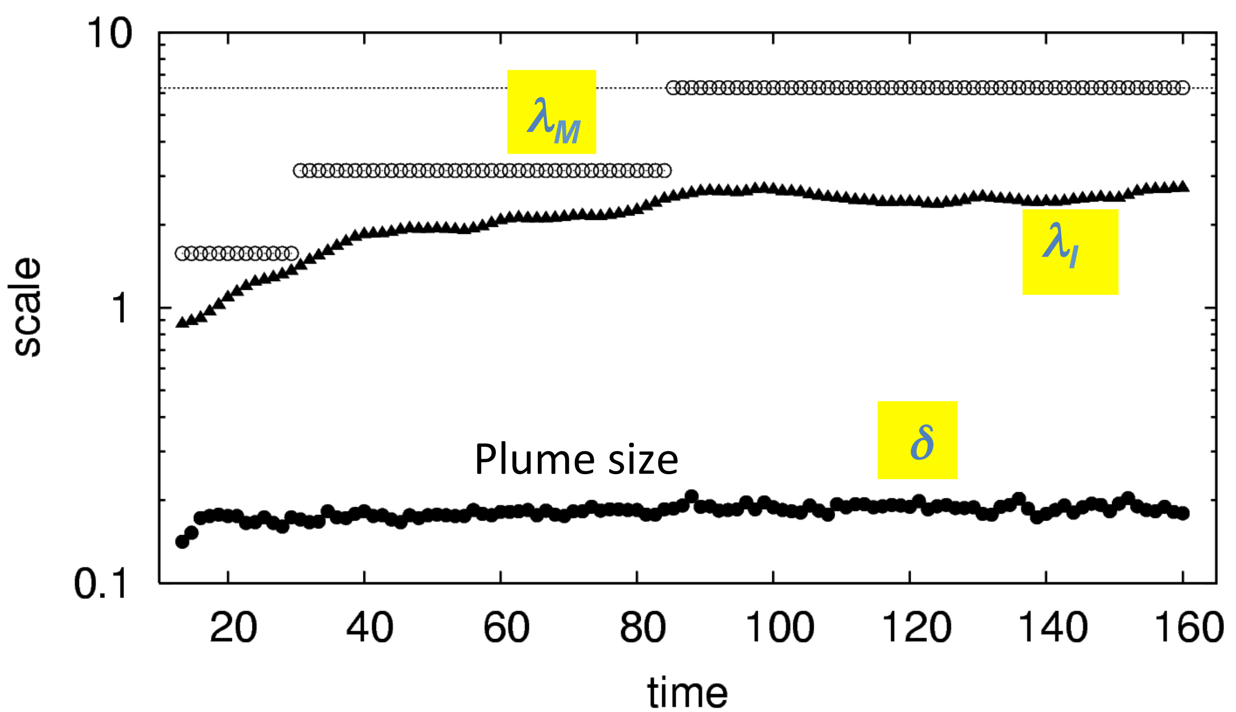


Integral scale:

$$\lambda_I = \frac{2\pi \int \left(E(k)/k \right) dk}{\int E(k) dk}$$

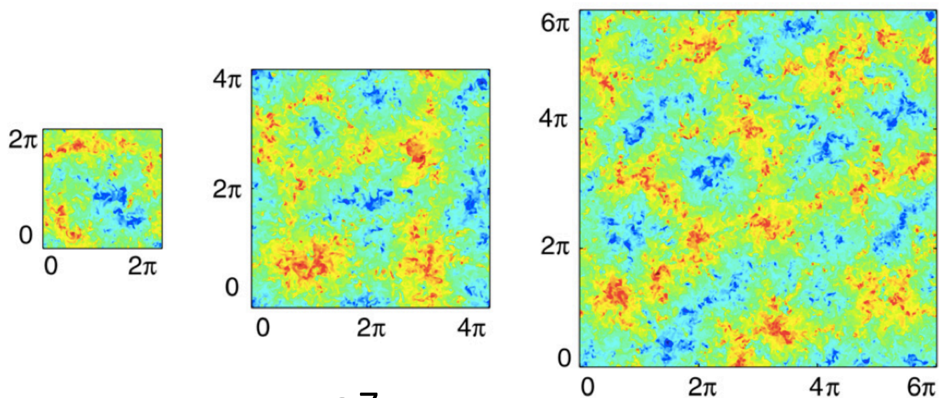
Spectral peak scale:

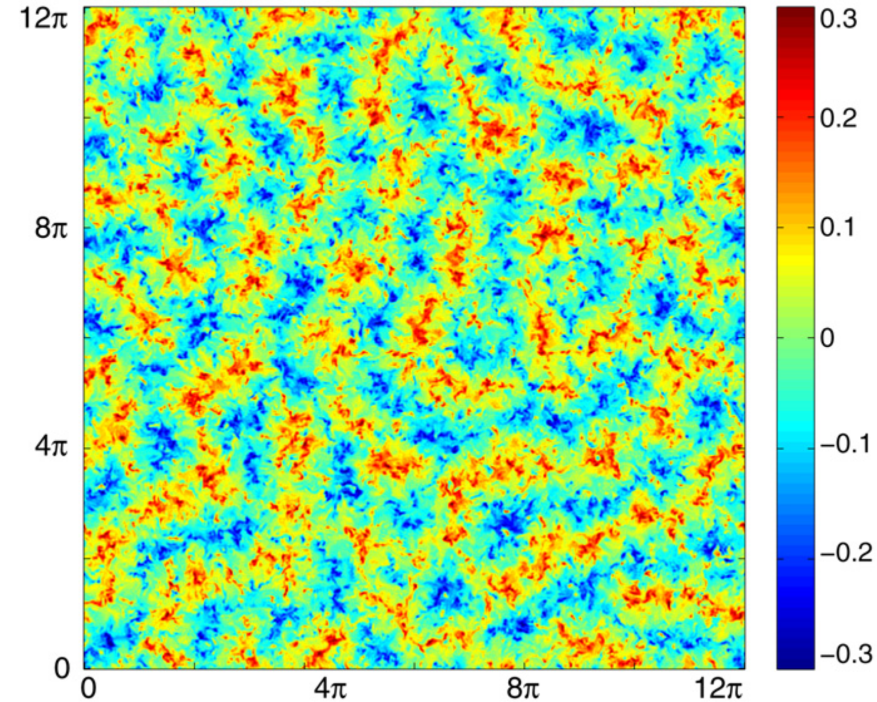
$$\lambda_M / E = \max$$



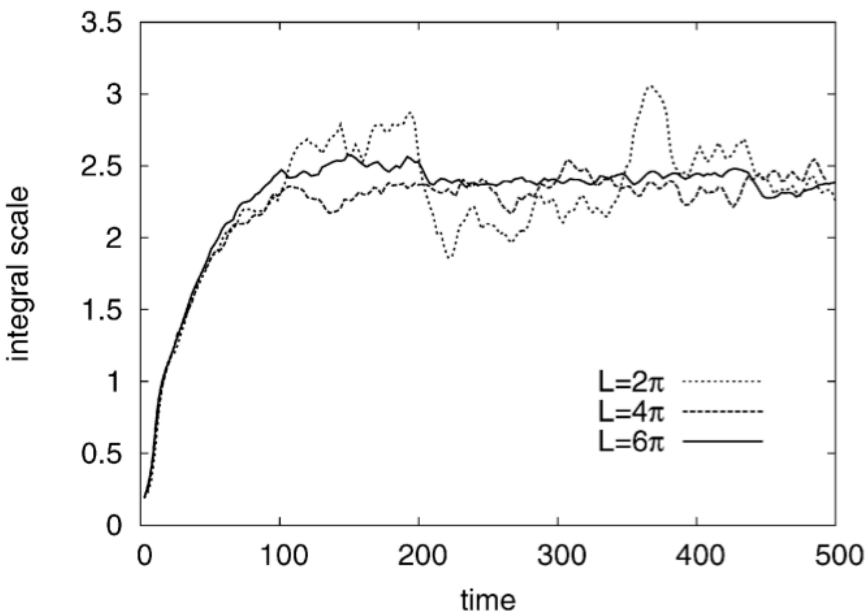
Dependency on domain size

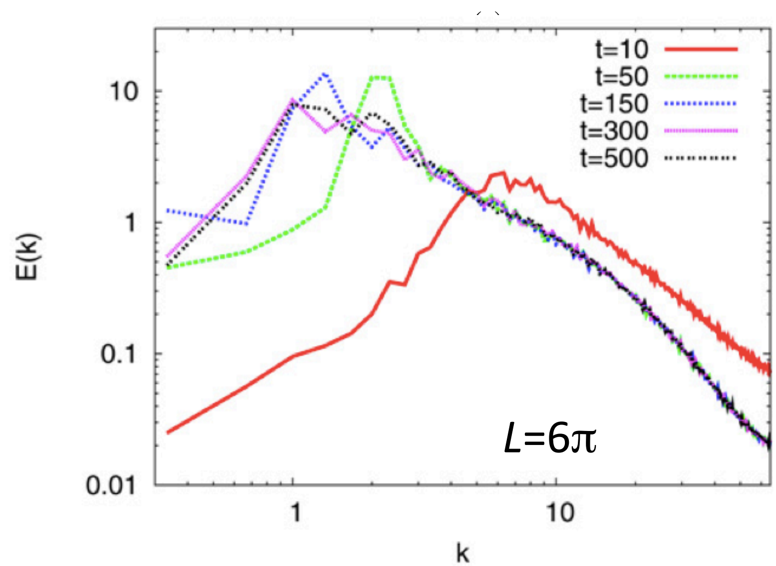
R=10^6



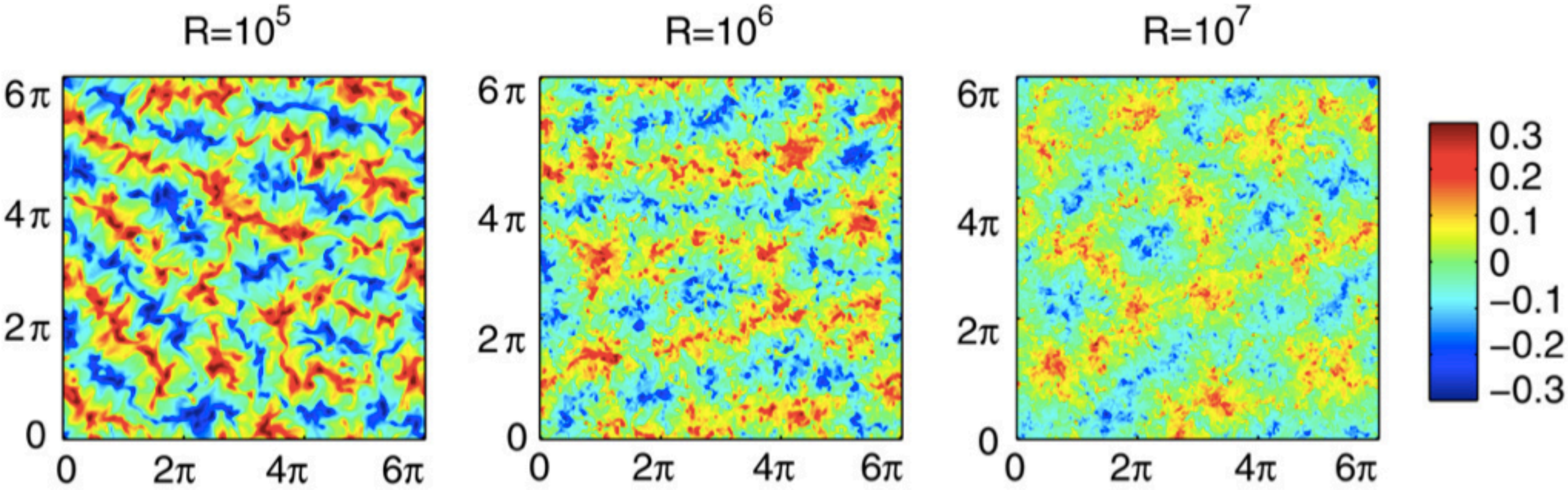


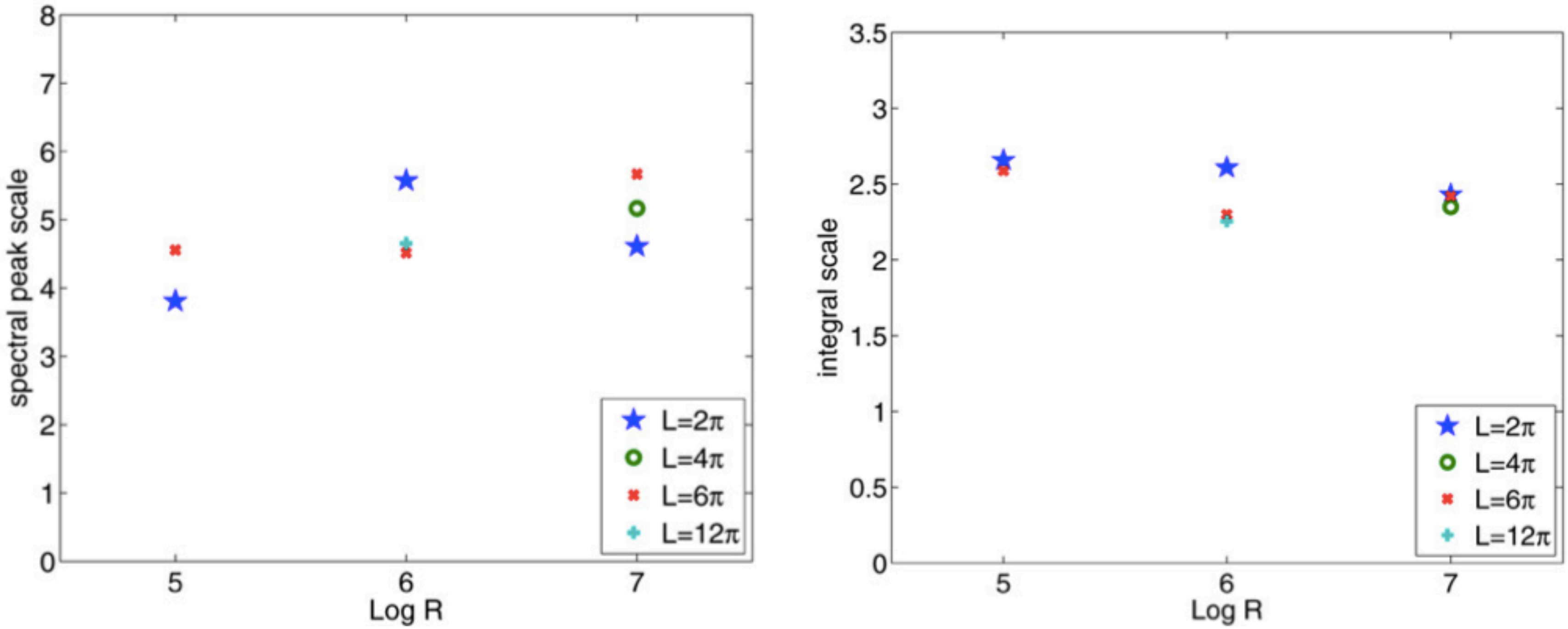
R=10^7





Dependency on the Rayleigh number





Causes of the clustering process ?

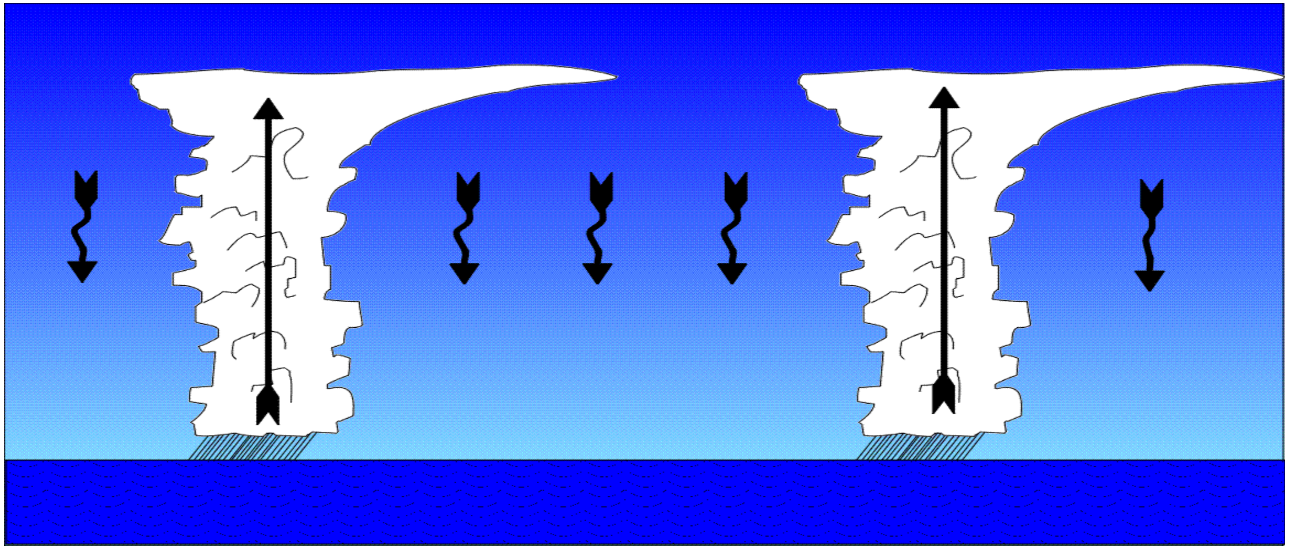
- Divergence of the horizontal velocity field caused by impinging plumes → strong feedbacks
- The clustering process seems to be a result of the interaction between the two BLs, through the action of the plumes traversing the fluid.
- Is there a saturation scale for the clusters?

Other interpretations:

1) T. Elperin, N. Kleeorin, I. Rogachevskii, *Phys. Rev. E* **66**, 066305 (2002)
2) T . Hartlep, A. Tilgner and F. Busse, *Phys. Rev. Lett.* **91** (6), 064501 (2003)

What happens in more realistic models?

- RB is up-down simmetric, fixed temperature BC
- The real atmosphere: moist, precipitating, with radiative effects, non Boussinesq…



A slightly richer model: including a constant radiative cooling and an adiabatic lapse rate

$$\frac{D\mathbf{u}}{Dt} = -\nabla p + T\hat{\mathbf{z}} + \frac{\tau_c}{\tau_e}\nabla^2\mathbf{u},$$

$$\nabla \cdot \mathbf{u} = 0,$$

$$\frac{DT}{Dt} + \gamma w = -\frac{\tau_c}{\tau_{rad}} + \frac{\tau_c}{\tau_e}\nabla^2 T.$$

$$\tau_c = (\alpha T_0 g/H)^{-1/2}$$

$$\tau_e = H^2/K_e$$

$$\tau_{rad} = \rho c_p T_0/J_0$$

$$\gamma = \Gamma H/T_0 \qquad Ra = \tau_e^2/\tau_c^2 = Re^2$$

$$\frac{\partial T}{\partial z} = 0 \quad \text{(top)}$$

$$-K_e\frac{\partial T}{\partial z} = c(T - T_{ground}) \quad \text{(bottom)}$$

$$\tilde{D}\tilde{T}/\tilde{D}\tilde{t} + \Gamma\tilde{w} = -J_0/(\rho c_p) + K_e\tilde{\nabla}^2\tilde{T}$$

$$J_0 = \tilde{\nabla} \cdot \mathbf{F}$$

$$\tau_c = \tau_{rad} \;\Rightarrow\; T_0 = \left[HJ_0^2/(g\alpha\rho^2 c_p^2)\right]^{1/3}$$

- Berlengiero, M, Provenzale A, Emanuel K A, E A Spiegel, A Minimal Model of Atmospheric Convection, NPG (2005)
- Berlengiero M, K A Emanuel, von Hardenberg J, Provenzale A, E A Spiegel, Internally cooled convection, Commun Nonlin Sci Numer Sim, (2012)

A slightly richer model: including a constant radiative cooling and an adiabatic lapse rate

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u} = -\nabla p + T\hat{\mathbf{z}} + \left(\frac{\sigma}{R}\right)^{1/2}\nabla^2\mathbf{u}$$

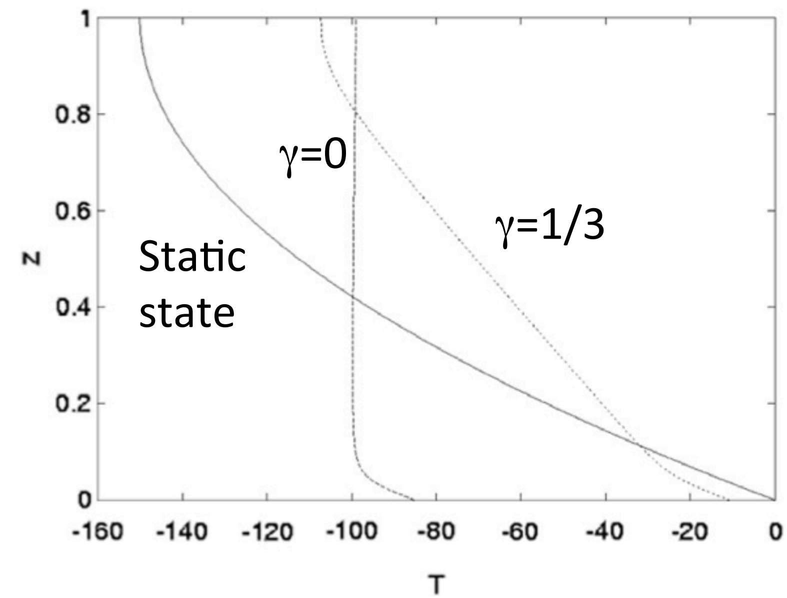
$$\nabla\cdot\mathbf{u} = 0$$

$$\frac{\partial T}{\partial t} + \mathbf{u}\cdot\nabla T + \gamma w = Q + \frac{1}{(\sigma R)^{1/2}}\nabla^2 T$$

$$Q = -1$$

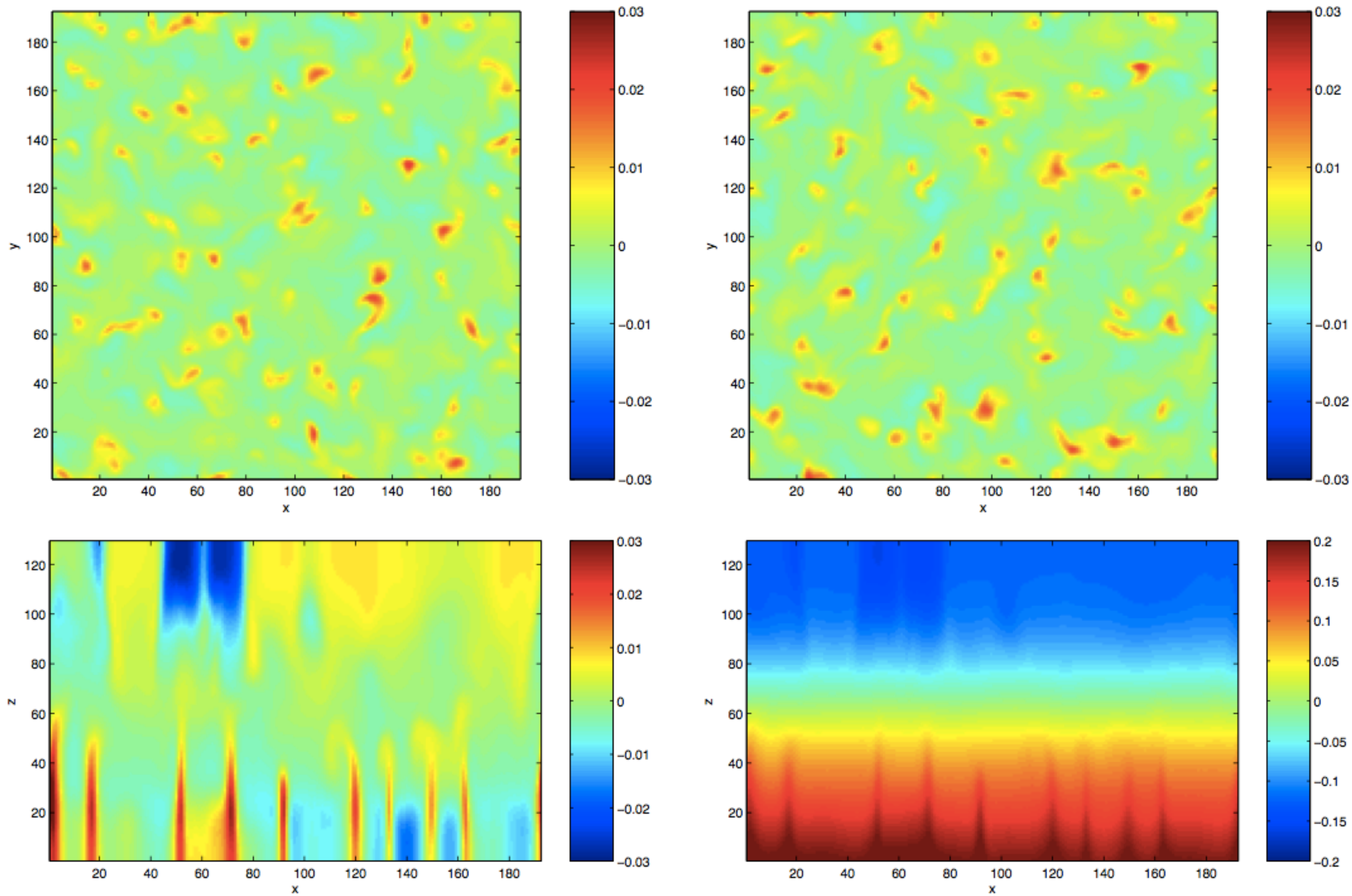
$$\frac{\partial T}{\partial z} = 0 \quad \text{(top)}$$

$$\frac{\partial T}{\partial z} = -1 \quad \text{(bottom)}$$

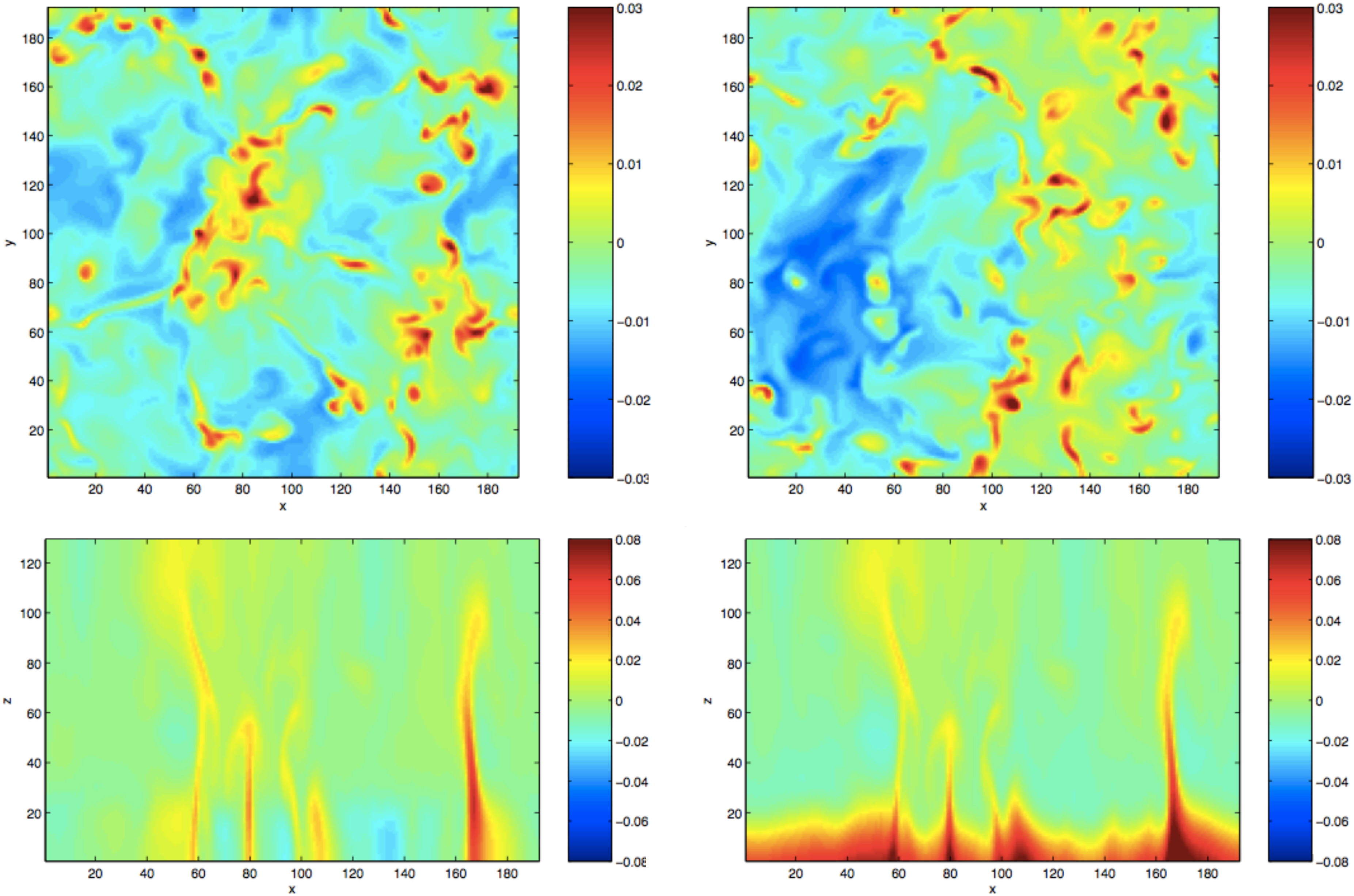


- Berlengiero, M, Provenzale A, Emanuel K A, E A Spiegel, A Minimal Model of Atmospheric Convection, NPG (2005)
- Berlengiero M, K A Emanuel, von Hardenberg J, Provenzale A, E A Spiegel, Internally cooled convection, Commun Nonlin Sci Numer Sim, (2012)

$\gamma = 1/3$

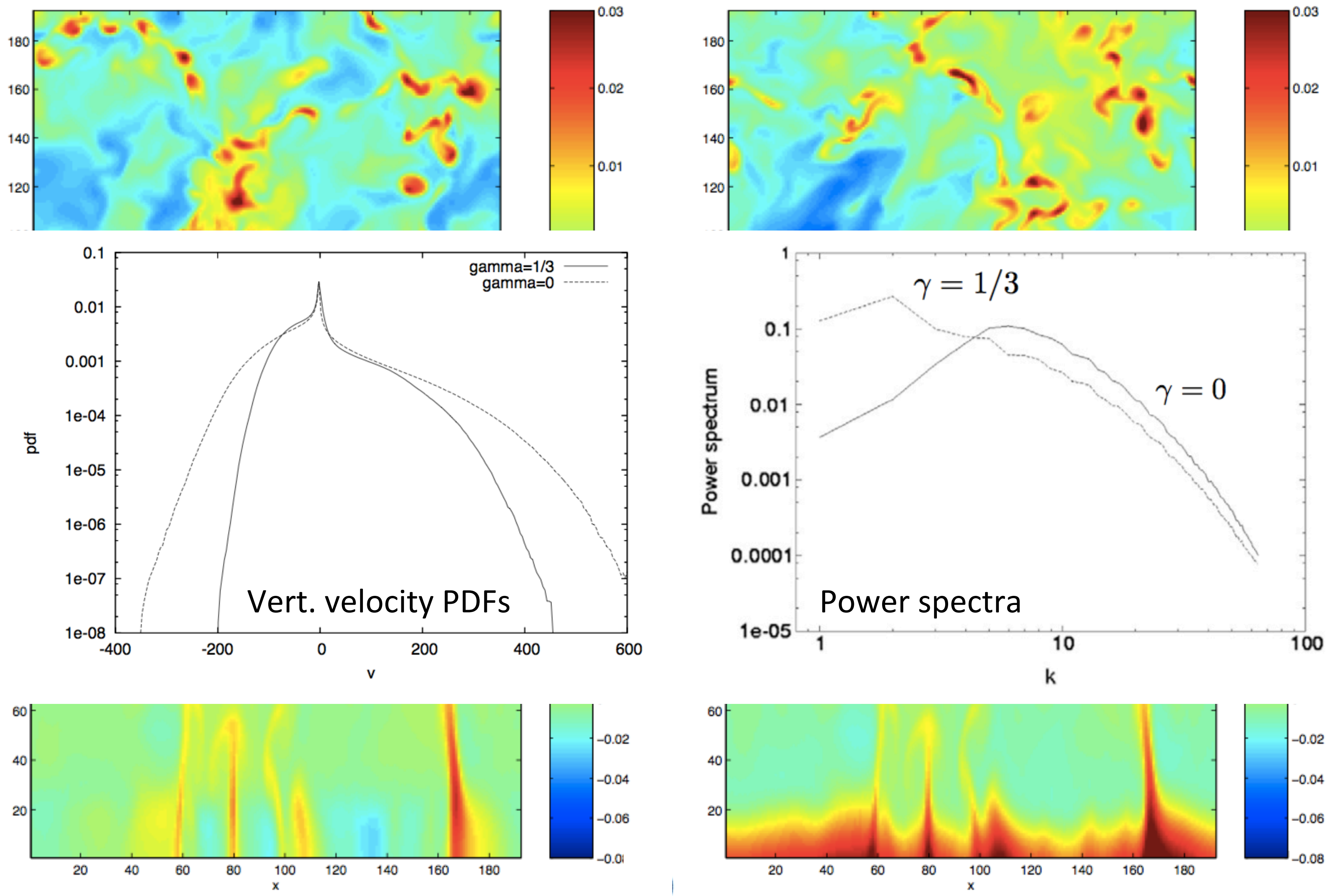


$\gamma = 0$



x
y
z
0.03
0.02
0.01
0
−0.01
−0.02
−0.03
0.08
0.06
0.04
0.02
−0.02
−0.04
−0.06
−0.08
20
40
60
80
100
120
140
160
180

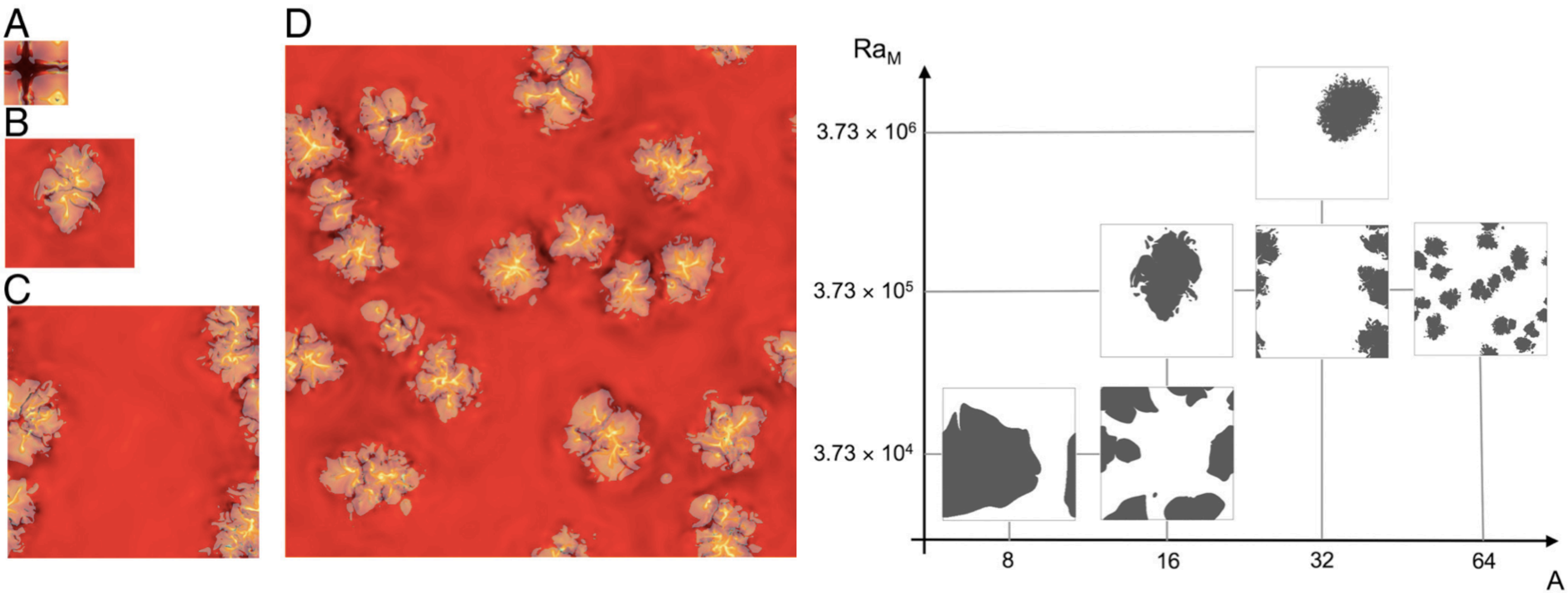
$\gamma = 0$



180
160
140
120
0.03
0.02
0.01
0.1
0.01
0.001
1e-04
1e-05
1e-06
1e-07
1e-08
pdf
gamma=1/3
gamma=0
Vert. velocity PDFs
-400
-200
0
200
400
600
v
1
0.1
0.01
0.001
0.0001
1e-05
Power spectrum
$\gamma = 1/3$
$\gamma = 0$
Power spectra
1
10
100
k
60
40
20
20
40
60
80
100
120
140
160
180
x
-0.02
-0.04
-0.06
-0.08

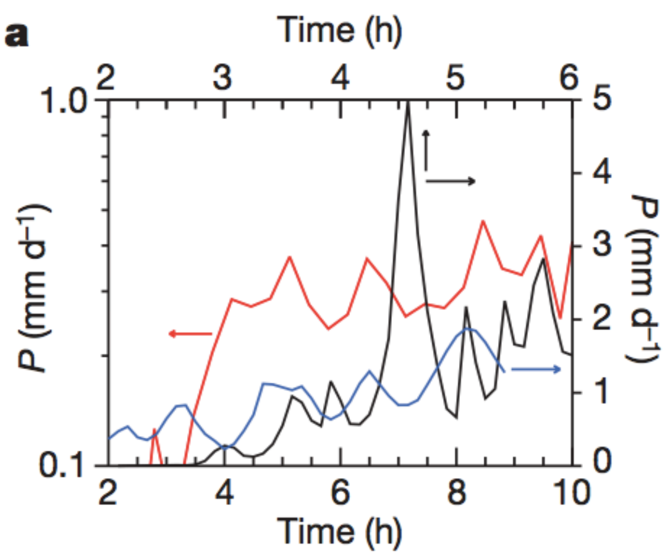
Moist Rayleigh-Bénard convection

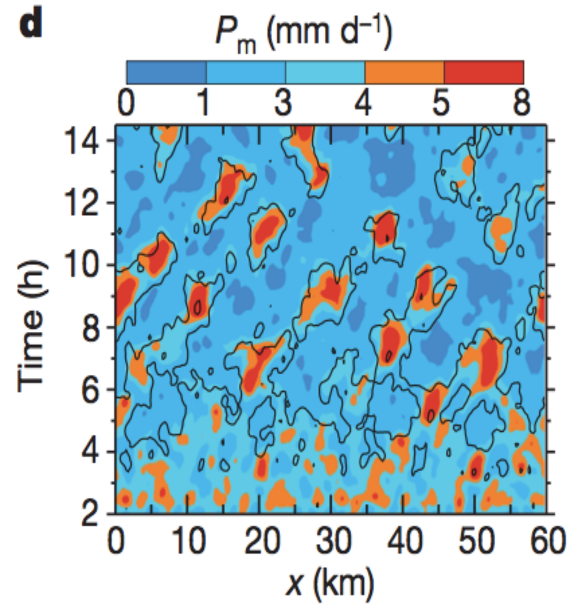
(from: Pauluis and Schumacher 2011)

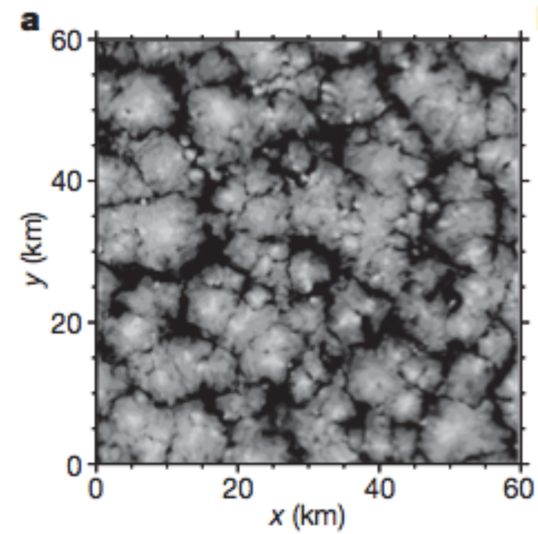


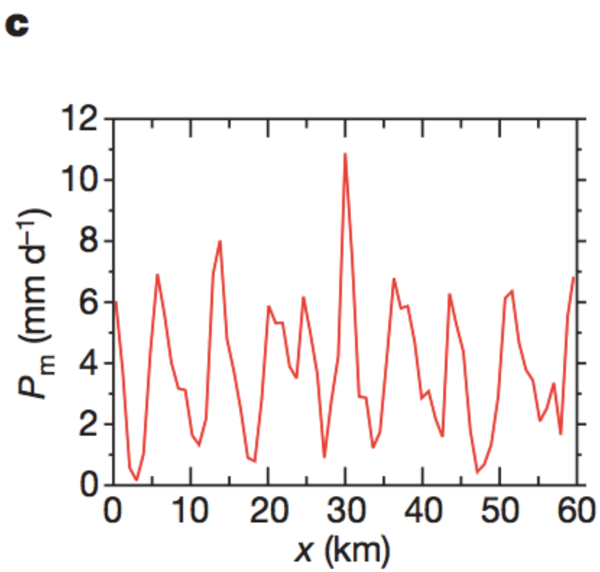
Oscillations in open cellular cloud fields

(from: Feingold et al. 2010)





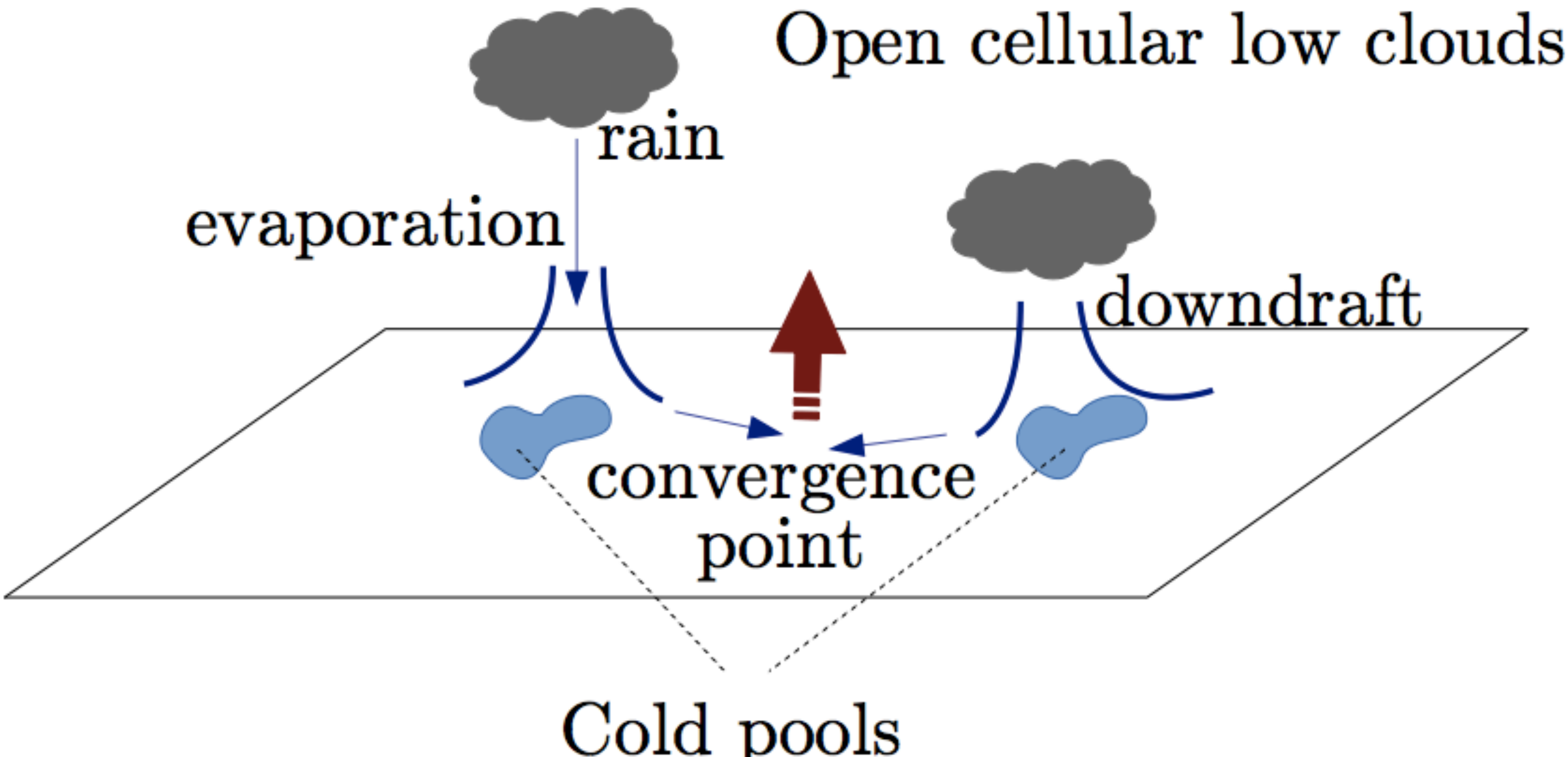




Precipitation-generated oscillations in open cellular cloud fields

Graham Feingold[1], Ilan Koren[2], Hailong Wang[3], Huiwen Xue[4] & Wm. Alan Brewer[1]

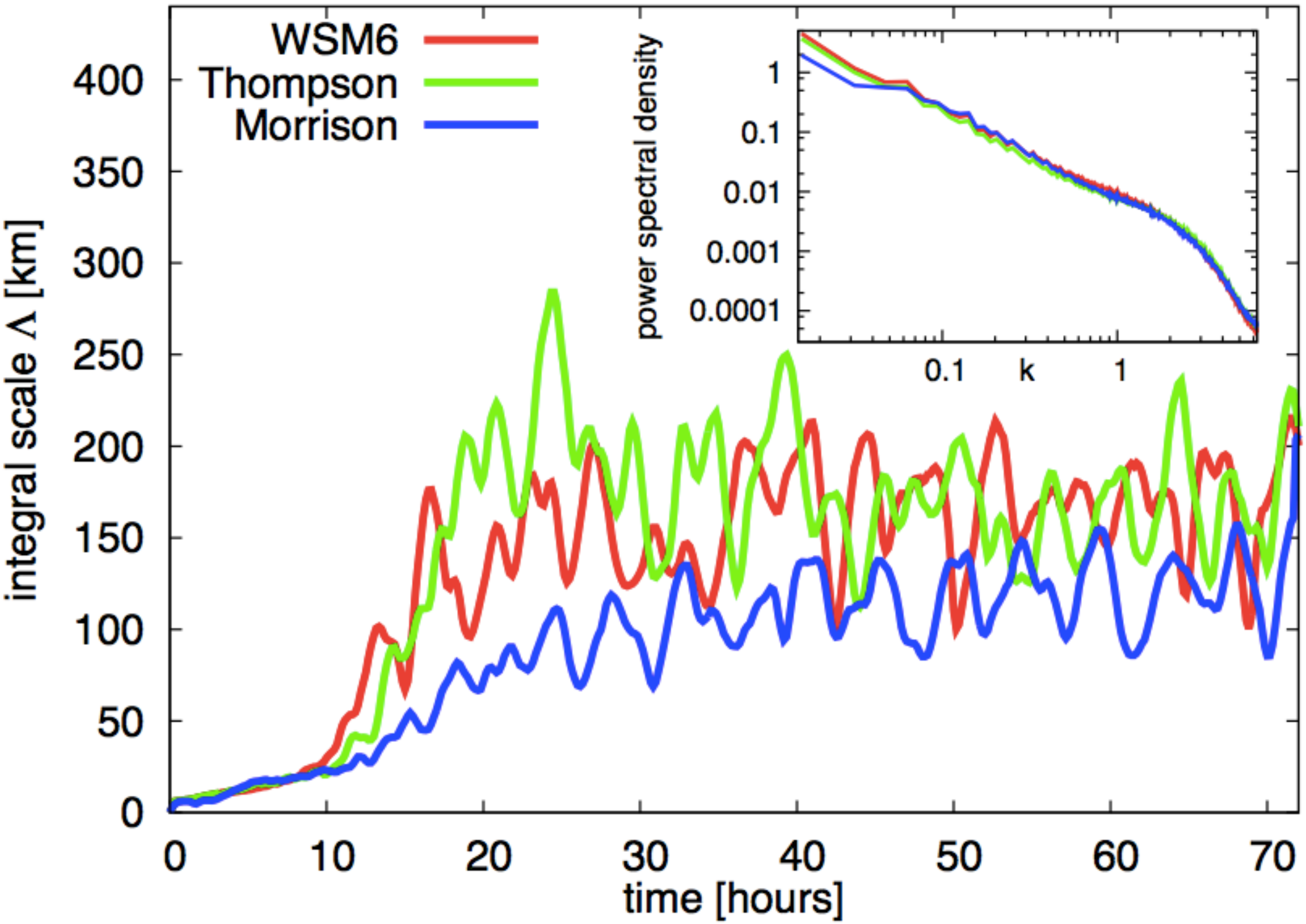
Vol 466 | 12 August 2010 | **doi:10.1038/nature09314**


Open cellular low clouds
rain
evaporation
downdraft
convergence
point
Cold pools

Idealized experiments with a realistic model (WRF)

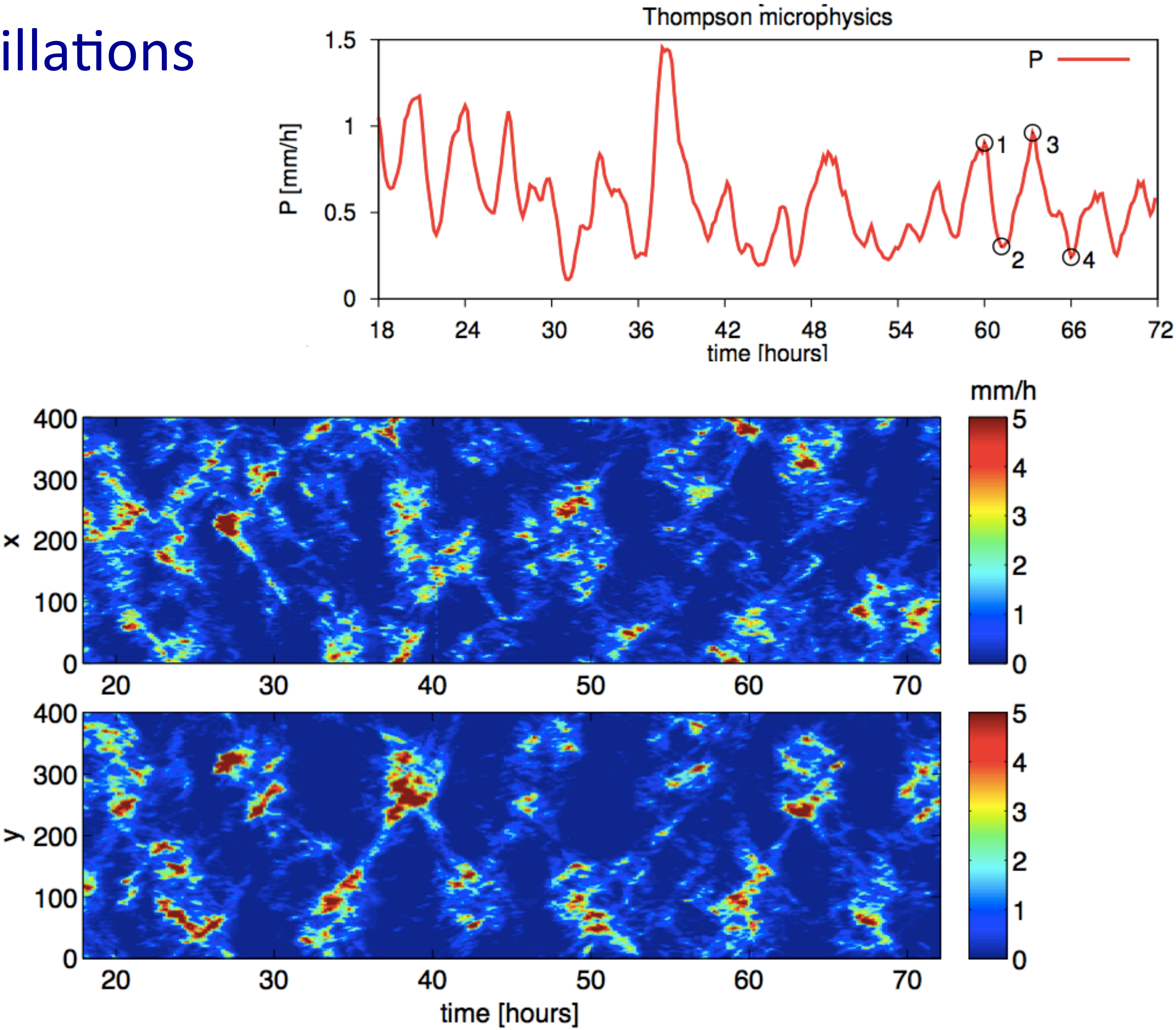
- Numerical simulations are done using the fully 3D, compressible, non-hydrostatic Weather Research and Forecast (WRF) model
- Different microphysics schemes (Thompson, Morrison, WSM6). All consider vapor, rain, snow, ice, graupel.
- Convective-radiative equilibrium experiments, using a constant cooling Q=-4K/day
- Constant surface T=300K
- Homogeneous bottom surface, periodic boundaries and no external large-scale flow
- Doubly periodic, square domain 400km × 400km × 20km Horizontal resolution 500m. Vertical resolution : 60 pressure levels.

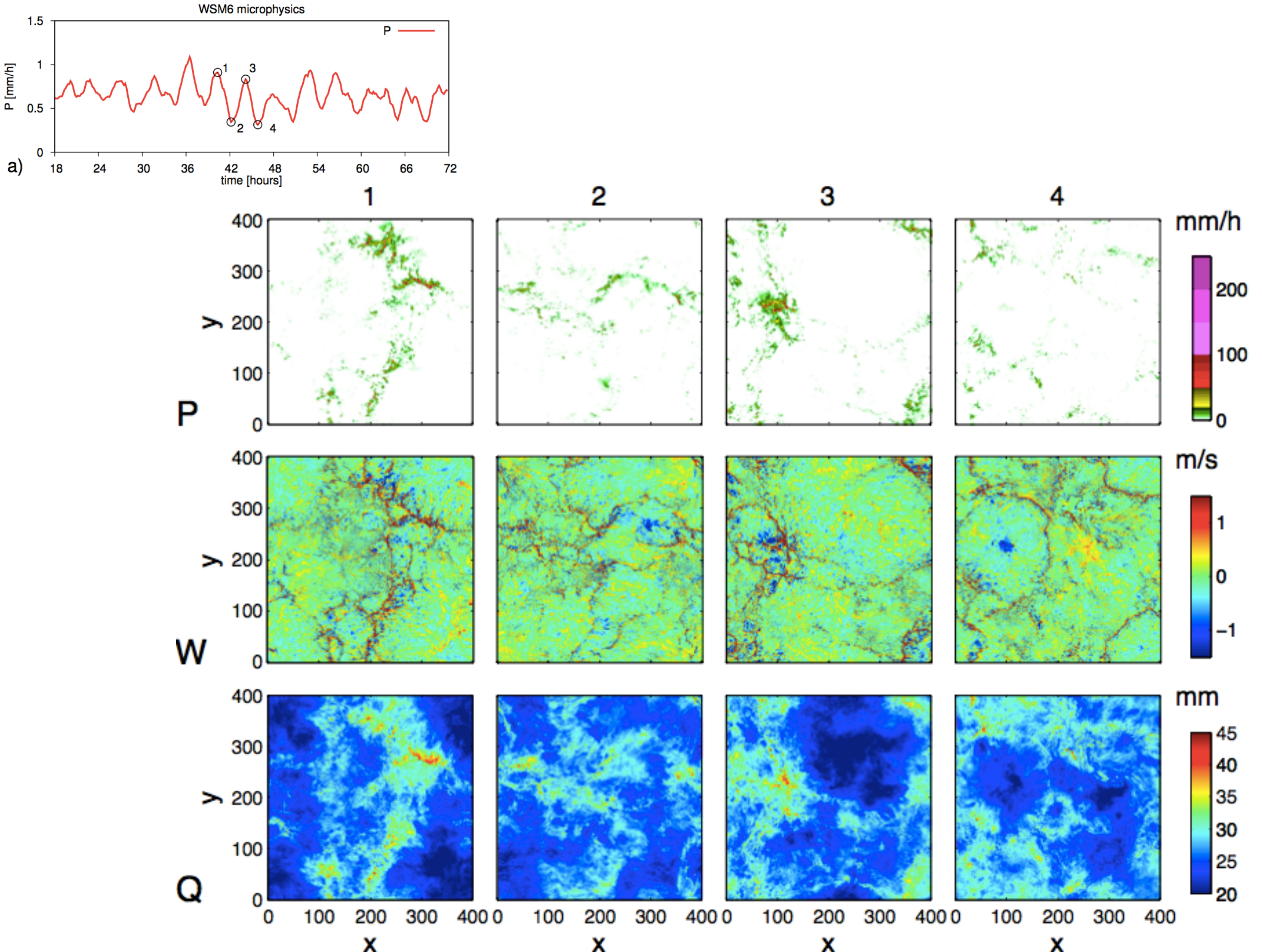
Clustering



WSM6
Thompson
Morrison
integral scale Λ [km]
400
350
300
250
200
150
100
50
0
0
10
20
30
40
50
60
70
time [hours]
power spectral density
1
0.1
0.01
0.001
0.0001
0.1
k
1

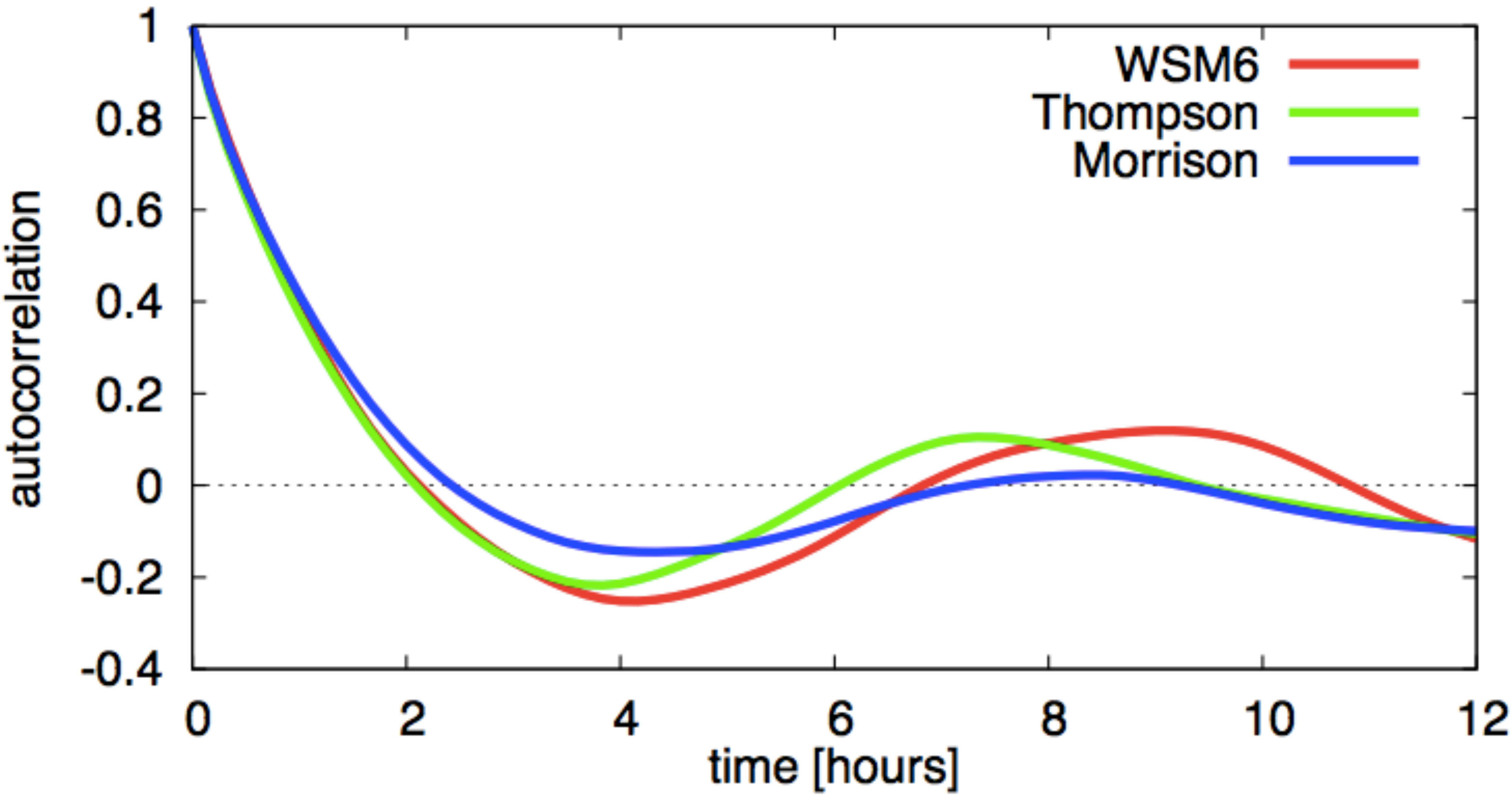
Oscillations



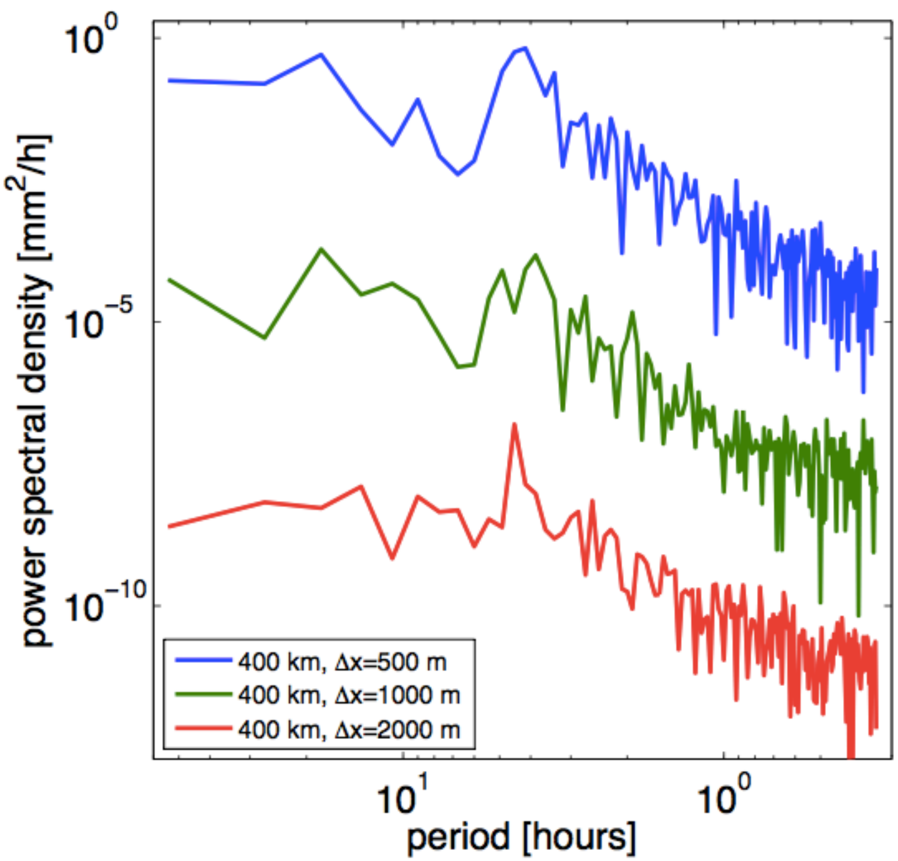


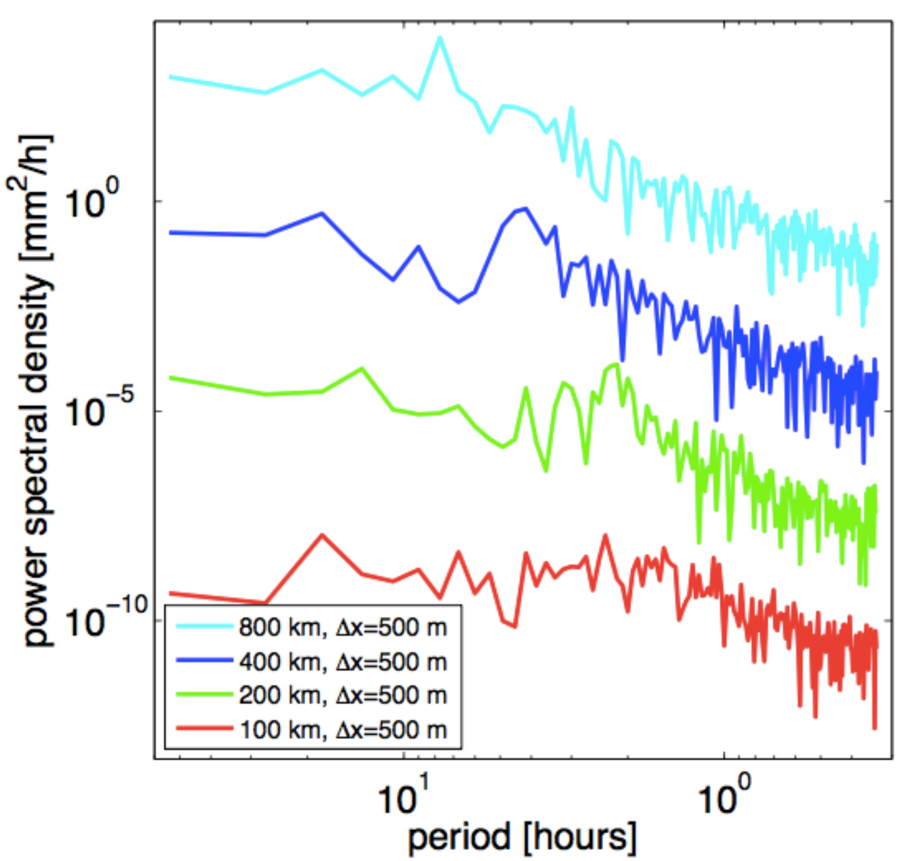
WSM6 microphysics
P [mm/h]
P
1
2
3
4
time [hours]
a)
1
2
3
4
mm/h
m/s
mm
P
W
Q
y
x

Temporal autocorrelation of the columnar water vapor content



Dependence on resolution and on domain size





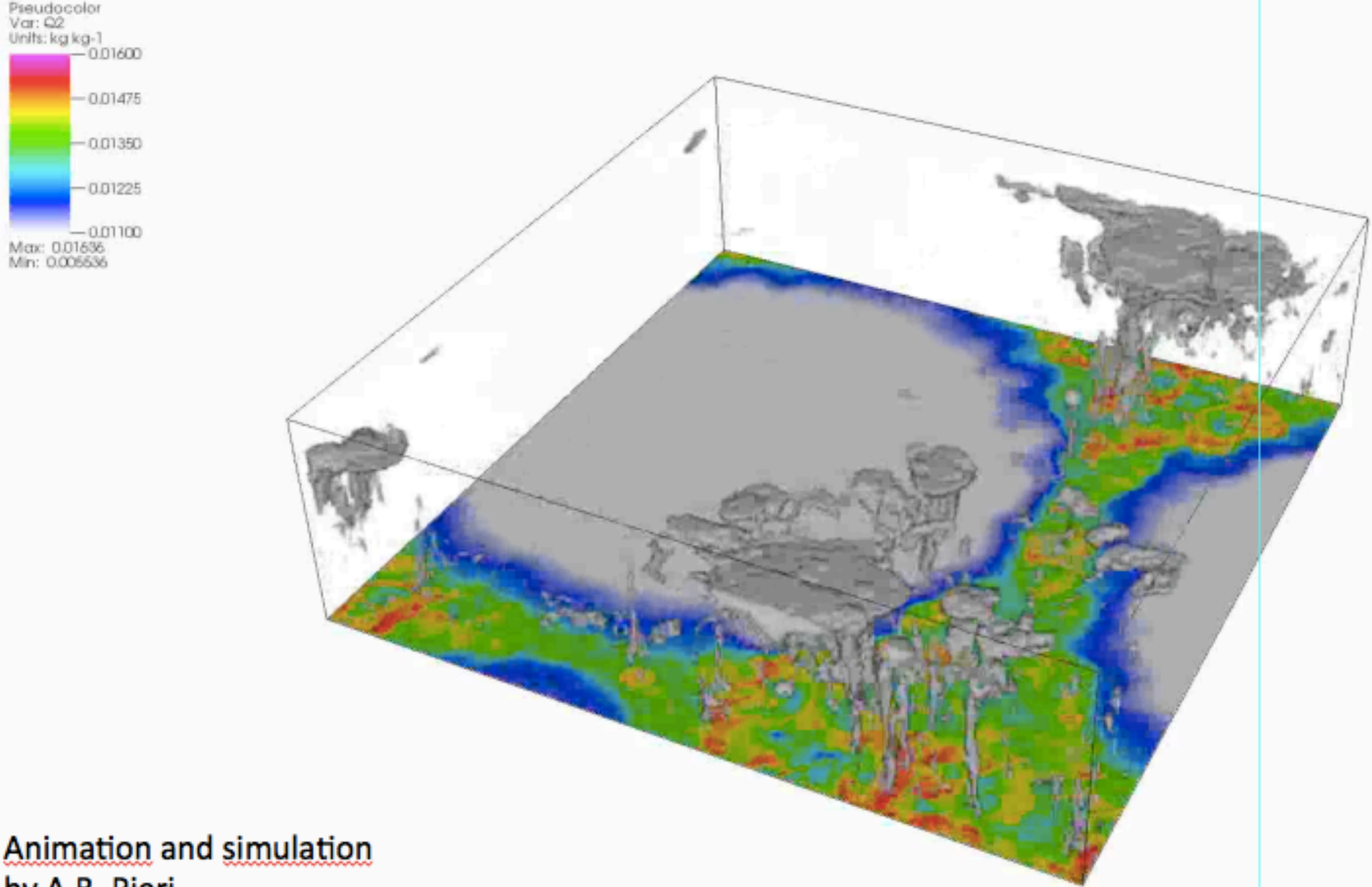
No dependence of period on resolution

Period depends on domain size

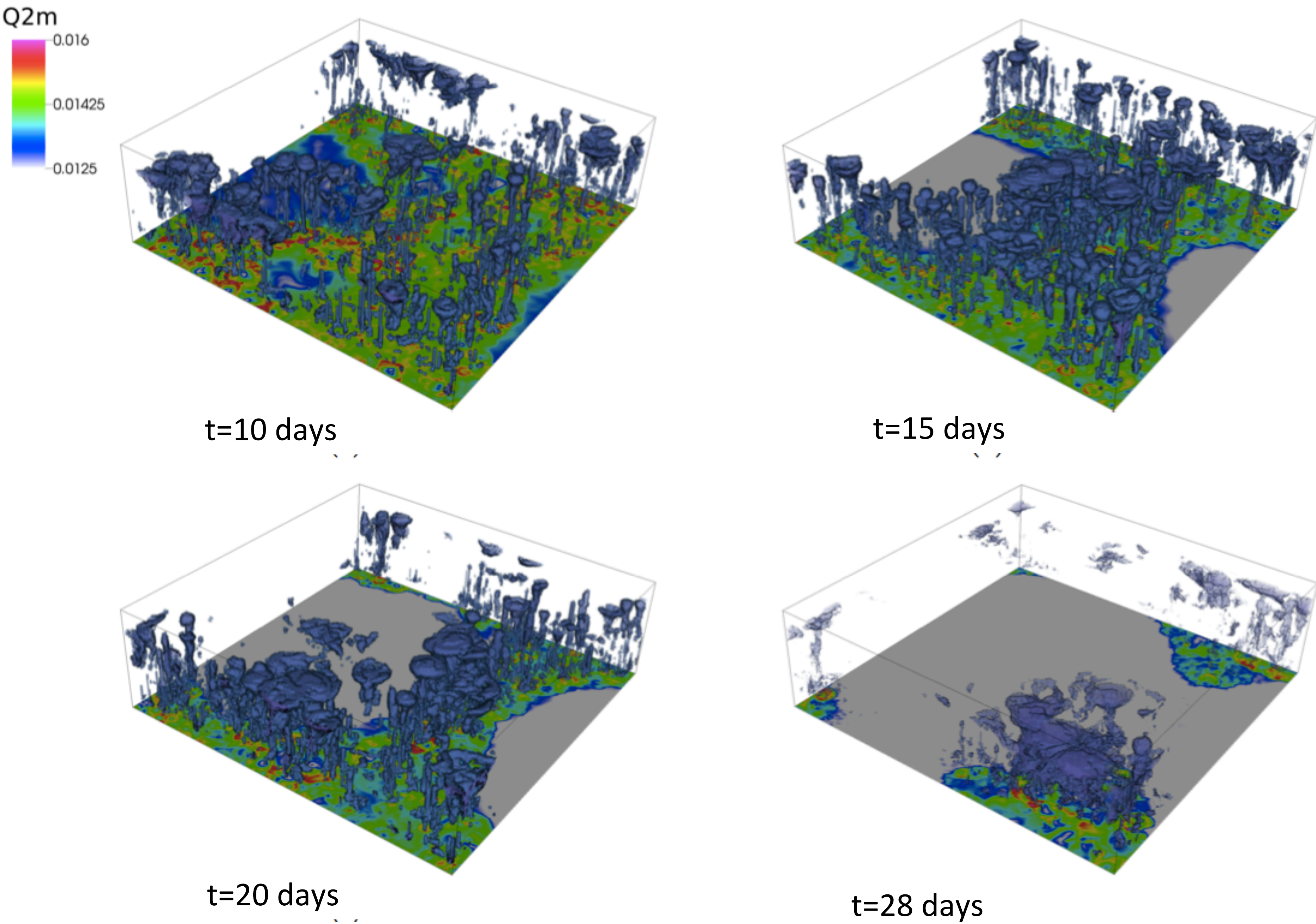
Self-aggregation in radiative-convective experiments with a full interactive radiation scheme

- Bretherton et al., An energy balance analysis of deep convective self-aggregation above uniform SS, JAS (2005)
- Muller & Held, Detailed investigation of the self-aggregation of convection in cloud resolving simulations, JAS (2012)

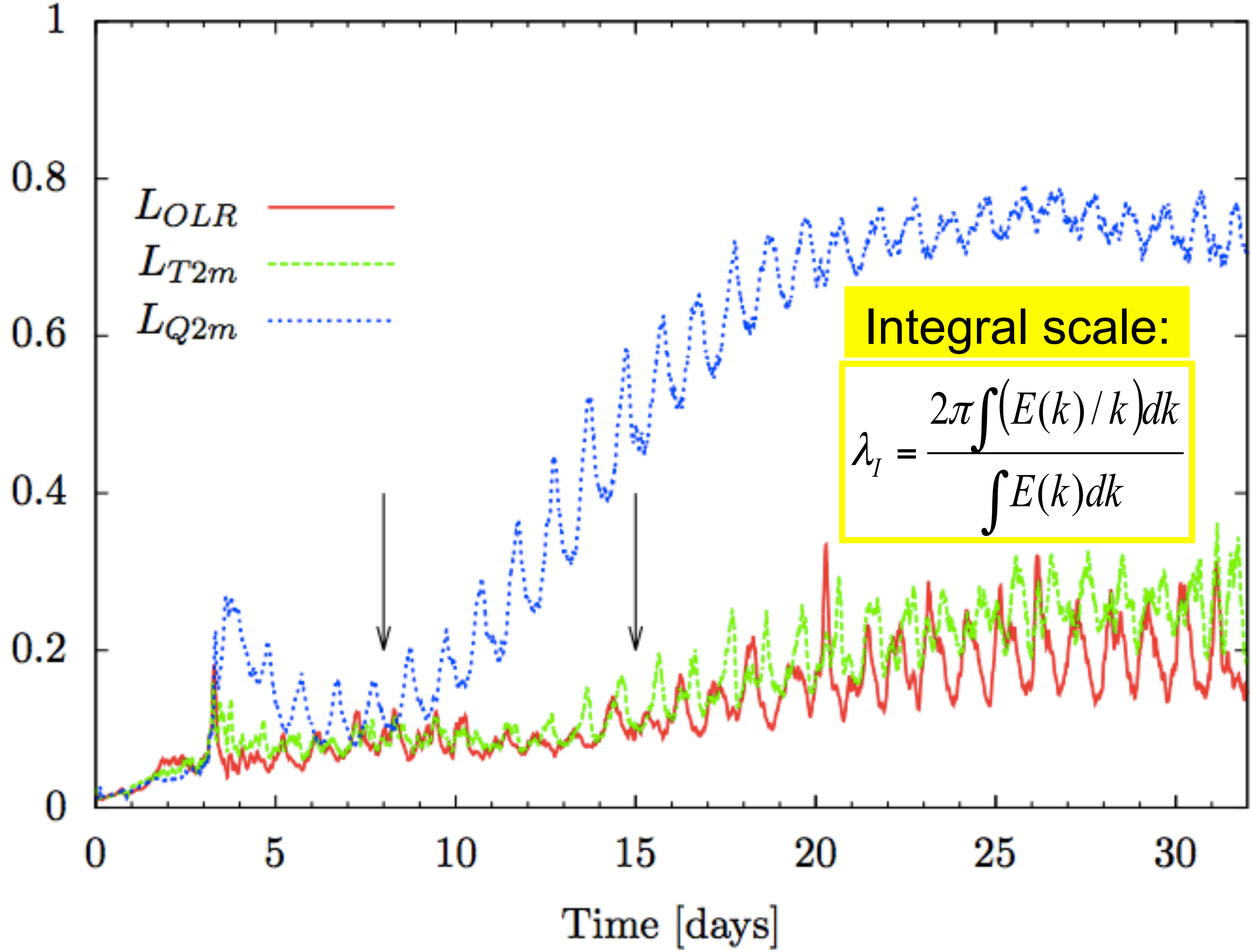
- We explore this problem with WRF, WSM6, square, periodic domain 400km x 400km, 2km resolution.
- Surface T=300K
- RRTM radiation

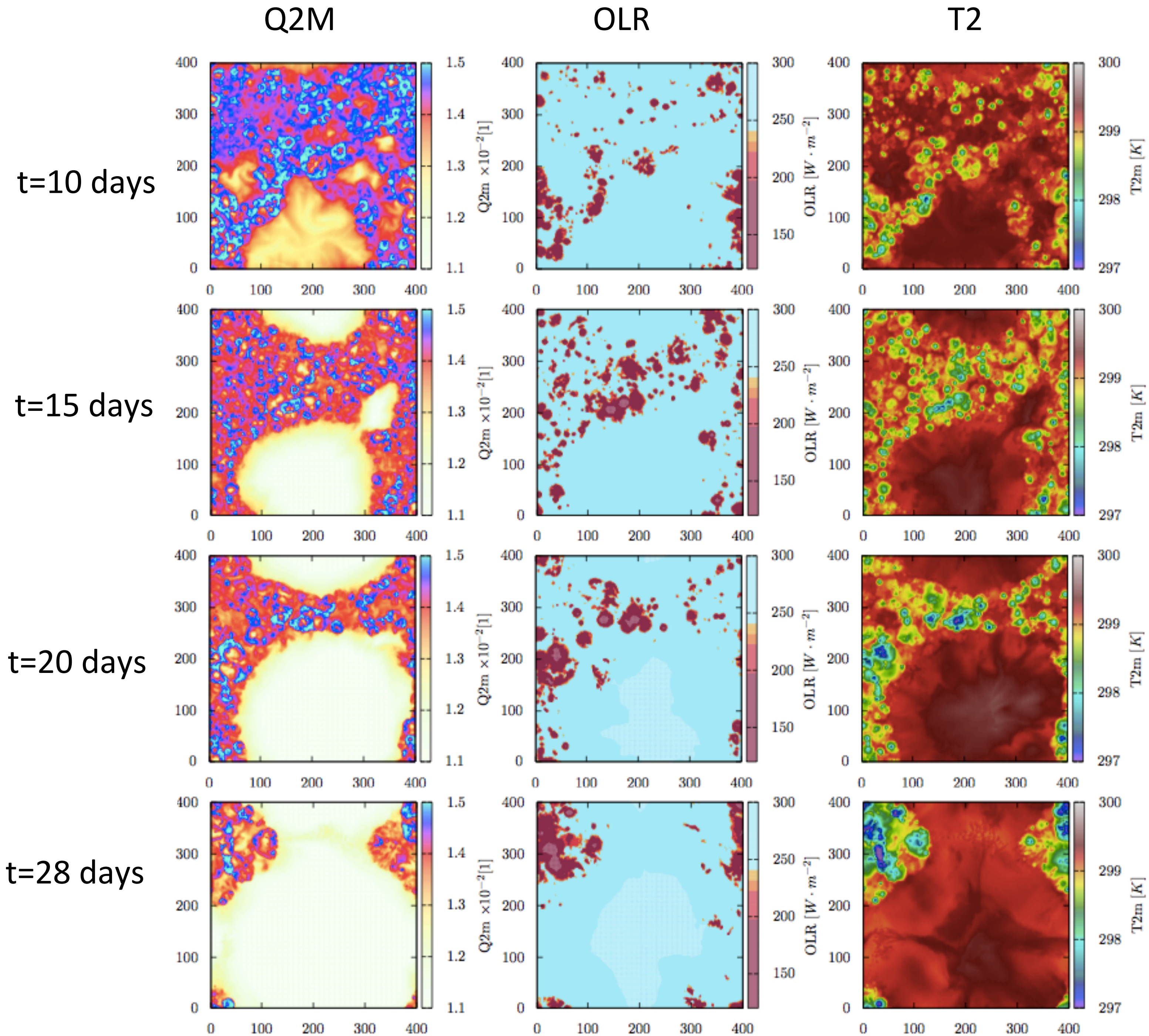


Animation and simulation
by A.B. Pieri


Q2m
0.016
0.01425
0.0125
t=10 days
t=15 days
t=20 days
t=28 days

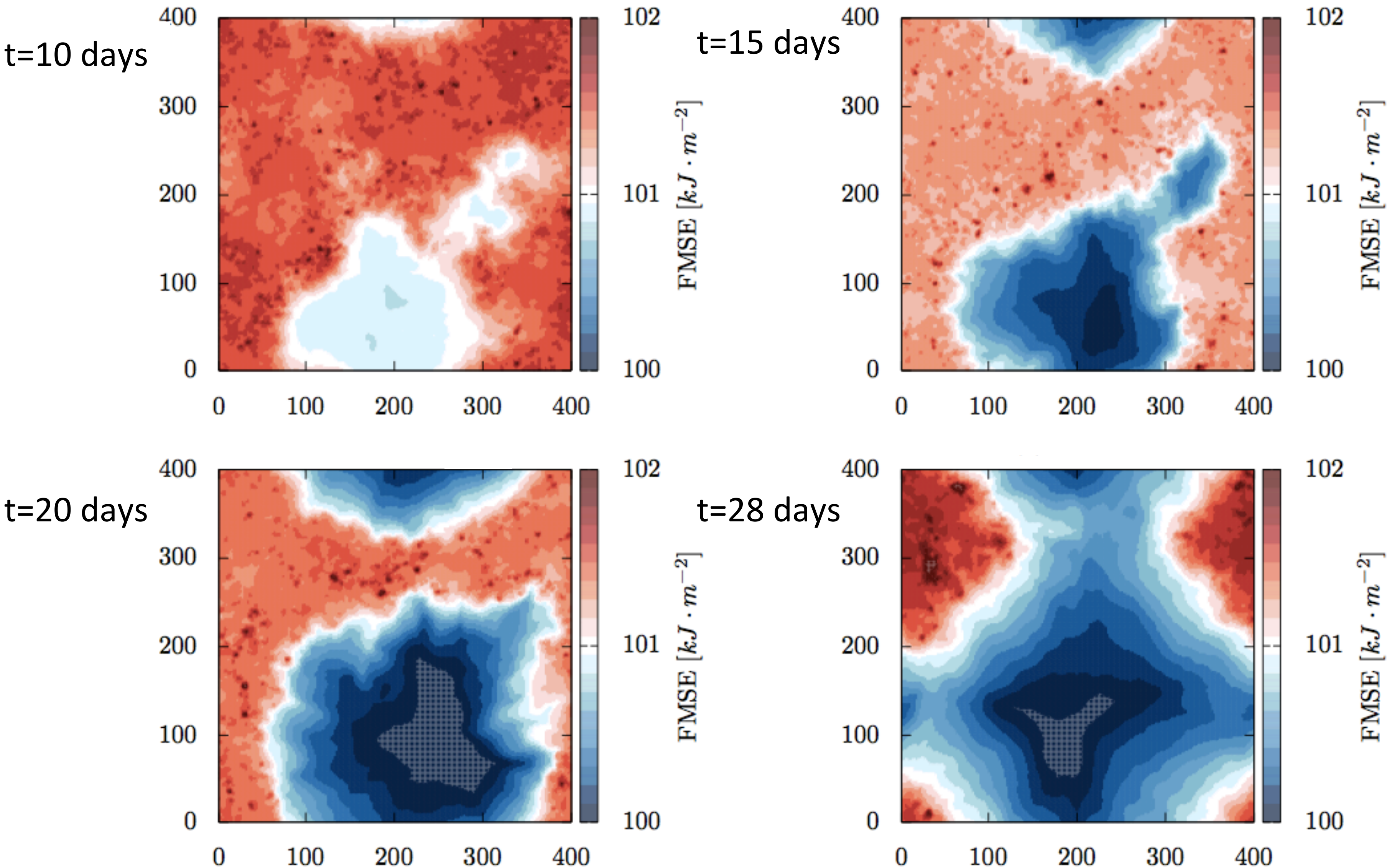
Evolution of the integral length scale



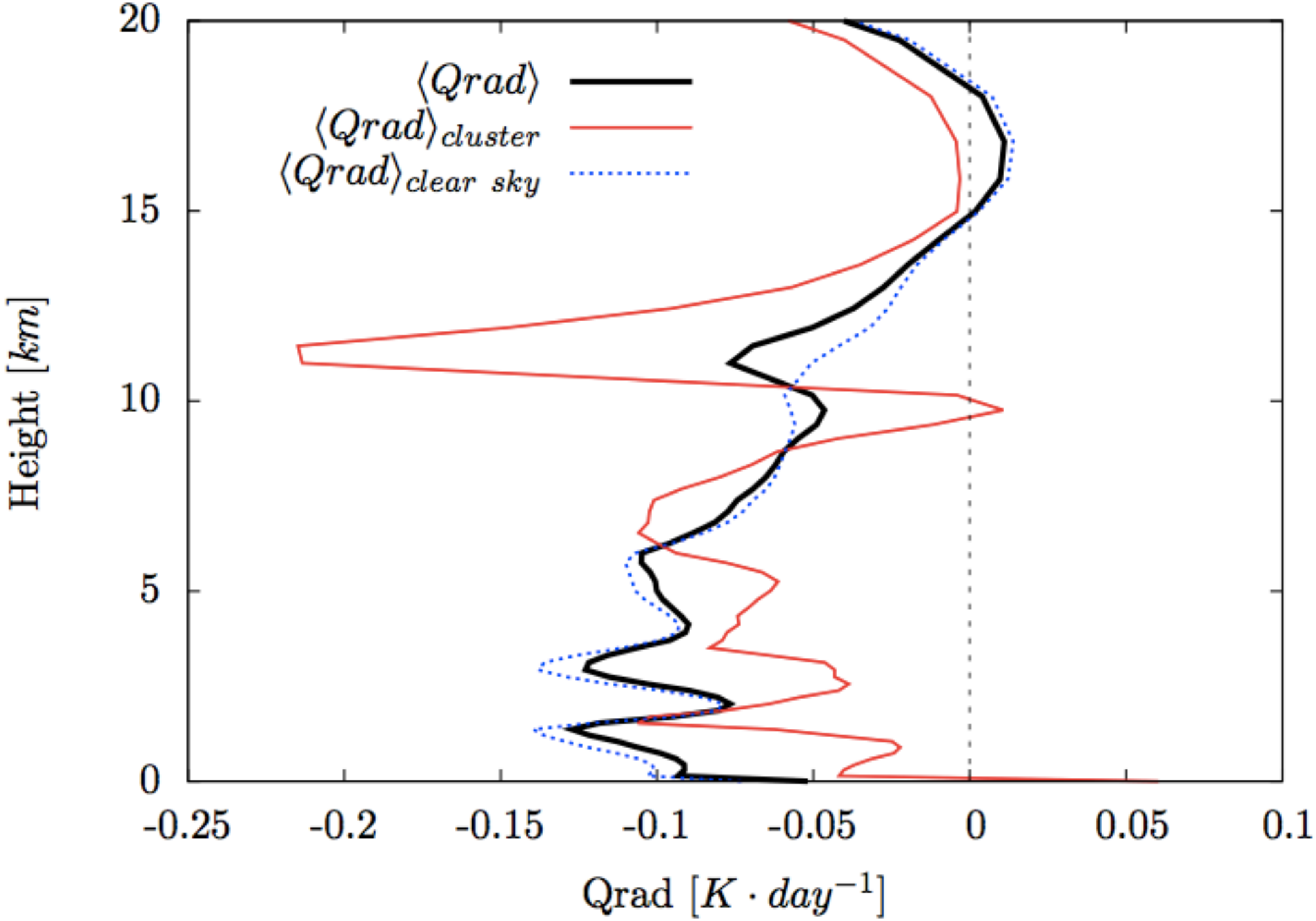


Q2M
OLR
T2
t=10 days
t=15 days
t=20 days
t=28 days
Q2m ×10^-2[1]
OLR [W · m^-2]
T2m [K]

Frozen Moist Static Energy



$$FMSE = (c_{pd} + q_t c_l)T + L_v(T)q_v - L_f(q_{ice} + q_{snow} + q_{graupel}) + (1 + q_t)gz$$



20
15
10
5
0
Height [km]
-0.25
-0.2
-0.15
-0.1
-0.05
0
0.05
0.1
Qrad [K · day^-1]
⟨Qrad⟩
⟨Qrad⟩cluster
⟨Qrad⟩clear sky

Conclusions

- We have found that the self-aggregation or clustering of convective plumes is a common phenomenon in very different models of atmospheric convection, from RB convection to a full non-hydrostatic model.
- Of course different mechanisms at work in all these cases, but the study of these structures and of their formation may be crucial since they may affect significantly the flow dynamics (see also the salt fingering talk of yesterday)
- Some of these structures may not be robust under realistic conditions (e.g. long formation times under undisturbed conditions)