Pressure Transport in DNS of Turbulent Natural Convection in Horizontal Fluid Layers

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Introduction and Motivation

- statistical modelling of turbulent natural convection
- turbulent diffusion $D_{\phi,turb}$ balances local non-equilibrium between production/destruction of ϕ
  - turbulence kinetic energy $k = \frac{1}{2}\overline{u'_i u'_i}$

$$D_{k,turb} = -\frac{\partial}{\partial x_j}\left(\frac{1}{2}\overline{u'_j u'_i u'_i} + \overline{u'_j p'}\right)$$

  - turbulent heat fluxes $q_i = \overline{u'_i T'}$

$$D_{q_i,turb} = -\frac{\partial}{\partial x_j}\left(\overline{u'_i u'_j T'} + \delta_{ij}\overline{T'p'}\right)$$

- Proposal of Lumley: $\overline{u'_j p'} = -\frac{1}{5}\overline{u'_j u'_i u'_i}$
- Analysis of <u>**D**</u>irect <u>**N**</u>umerical <u>**S**</u>imulation data:
  - forced isothermal turbulent channel flow:

$$\mid \tfrac{1}{2}\overline{u'_j u'_i u'_i} \mid > \mid \overline{u'_j p'} \mid$$

  - natural convection (Rayleigh-Bénard convection):

$$\mid \tfrac{1}{2}\overline{u'_j u'_i u'_i} \mid < \mid \overline{u'_j p'} \mid, \quad \mid \overline{u'_3 u'_3 T'} \mid < \mid \overline{T'p'} \mid$$

Objective

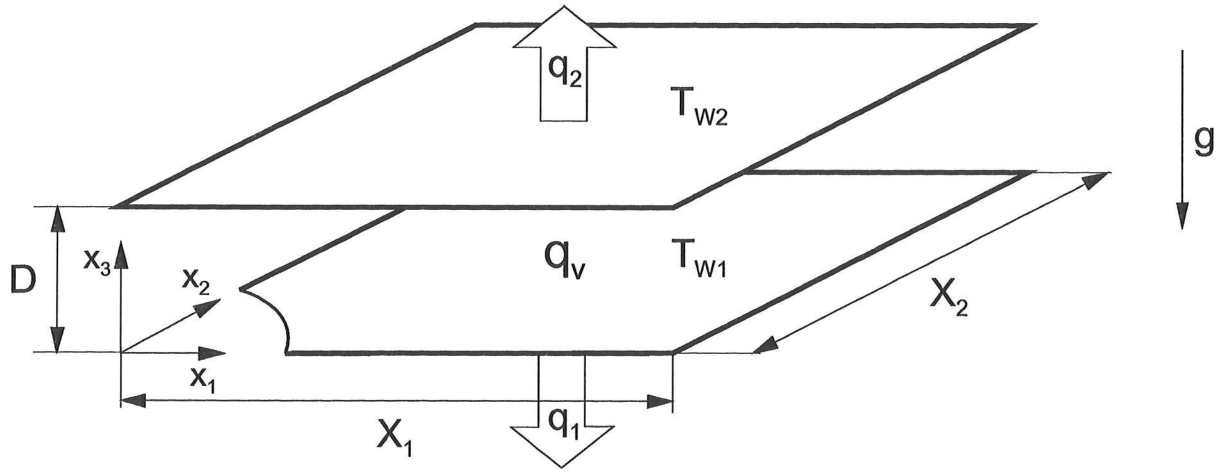
- **Question:** Is dominance of diffusive transport of pressure fluctuations specific to Rayleigh-Bénard convection or is it a general feature of natural convection in horizontal fluid layers?

  ⇒ Analyse DNS data of natural convection in a horizontal fluid layer internally heated by a homogeneous volumetric energy source

- Give physical interpretation for dominance of pressure correlations in turbulent diffusive transport in Rayleigh-Bénard convection

Internally heated fluid layer (IHFL)

Geometry



Dimensionless numbers

- Damköhler number $Da = q_v D^2/(\lambda \Delta T_{max})$
- internal Rayleigh number

$$Ra_I = \frac{g\beta q_v D^5}{\nu\kappa\lambda}$$

- external Rayleigh number

$$Ra_E = \frac{Ra_I}{Da} = \frac{g\beta \Delta T_{max} D^3}{\nu\kappa}$$

- Prandtl number $Pr = \nu/\kappa$
- Grashof number $Gr = Ra_E/Pr$

Direct Numerical Simulations

- Governing equations (dimensionless)

$$\frac{\partial u_j}{\partial x_j} = 0$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial (u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{\sqrt{Gr}} \frac{\partial^2 u_i}{\partial x_j \partial x_j} - (T_{ref} - T)\delta_{i3}$$

$$\frac{\partial T}{\partial t} + \frac{\partial (T u_j)}{\partial x_j} = \frac{1}{Pr\sqrt{Gr}} \left(\frac{\partial^2 T}{\partial x_j \partial x_j} + Da \right)$$

- DNS $\Rightarrow$ use spatial and temporal discretization which resolves all scales of turbulence
- Parameter of simulations considered

	IHFL	RBC
Da	35	0
Ra_I	10^8	0
Ra_E	$2,875,143$	$630,000$
Pr	7	0.71
$X_{1,2}$	4	7.92
$N_1 \cdot N_2 \cdot N_3$	$160 \cdot 160 \cdot 55$	$200 \cdot 200 \cdot 49$
Pe_t	30	107

Evaluation of statistical data

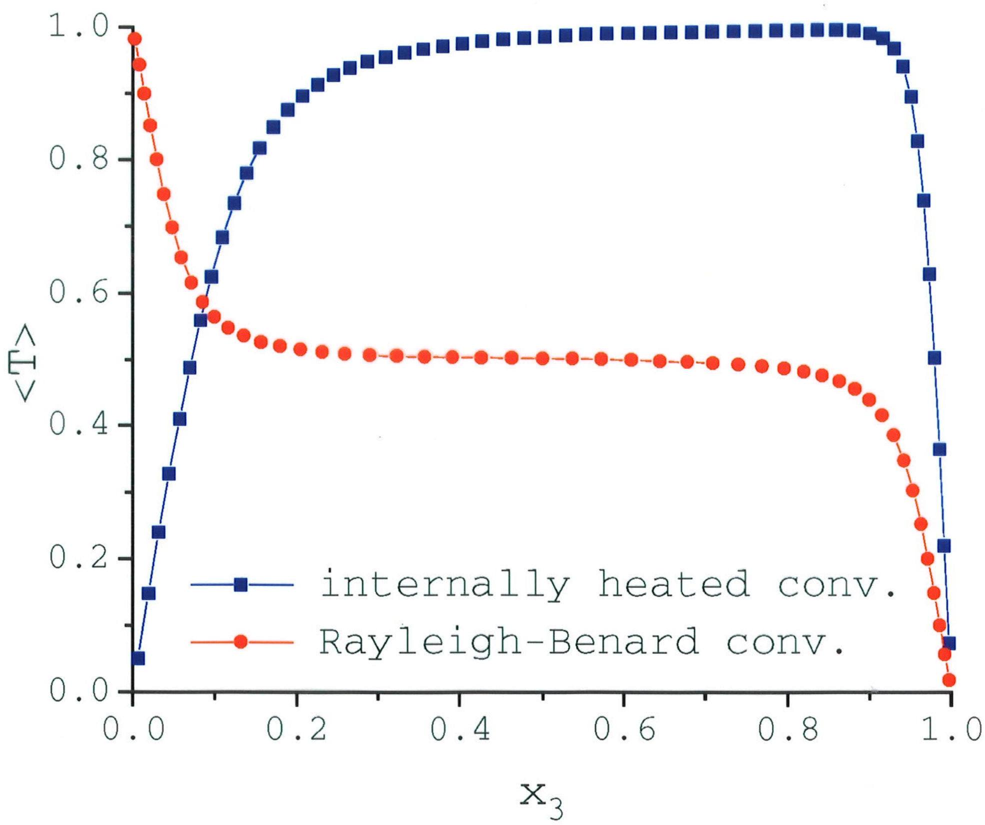
- Averaging procedure:

  ensemble averaging of ϕ over horizontal planes and additional time averaging

  $\Rightarrow \langle\phi\rangle = f(x_3)$

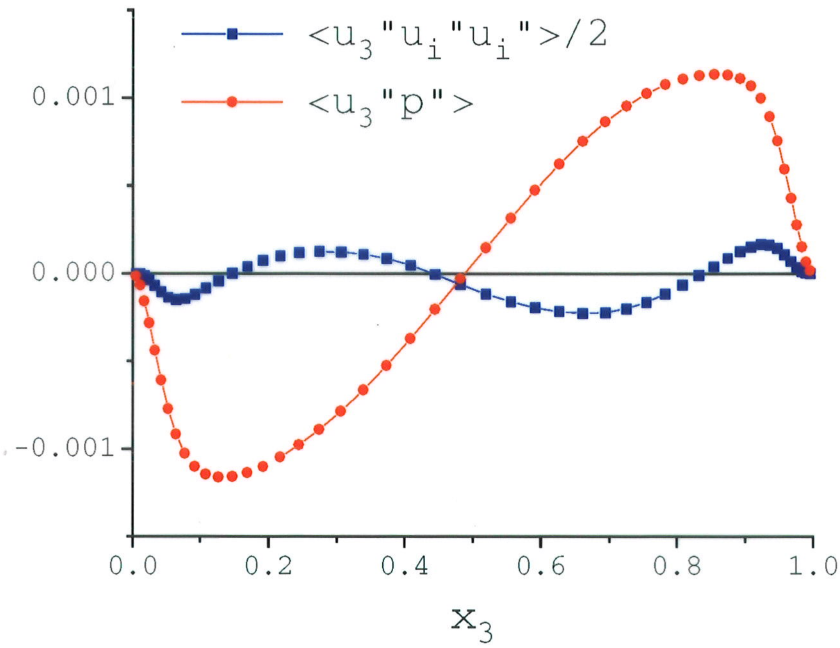
  $\phi'' = \phi - \langle\phi\rangle$

- Vertical profile of mean temperature $\langle T\rangle$

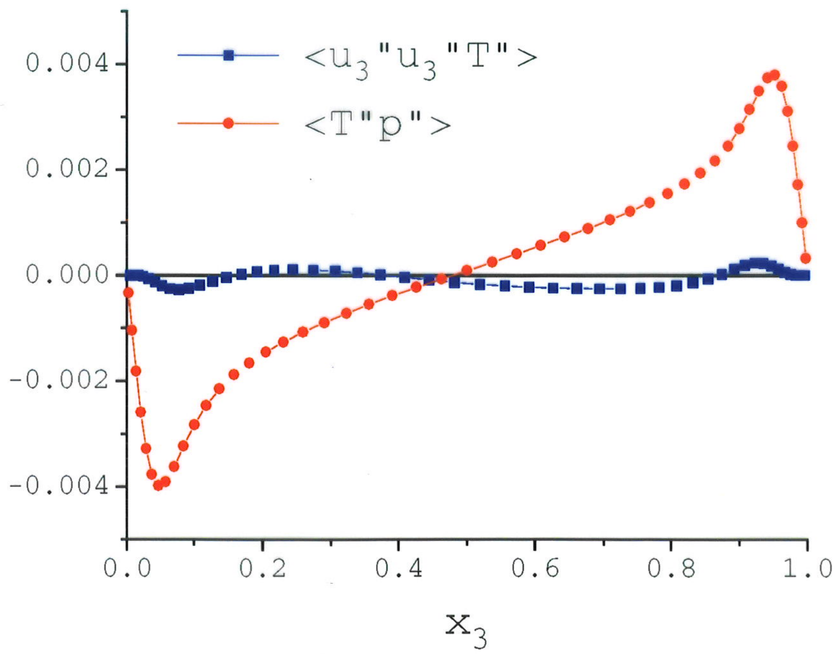


Rayleigh-Bénard convection in air

- Diffusion of turbulence kinetic energy $\langle k \rangle$

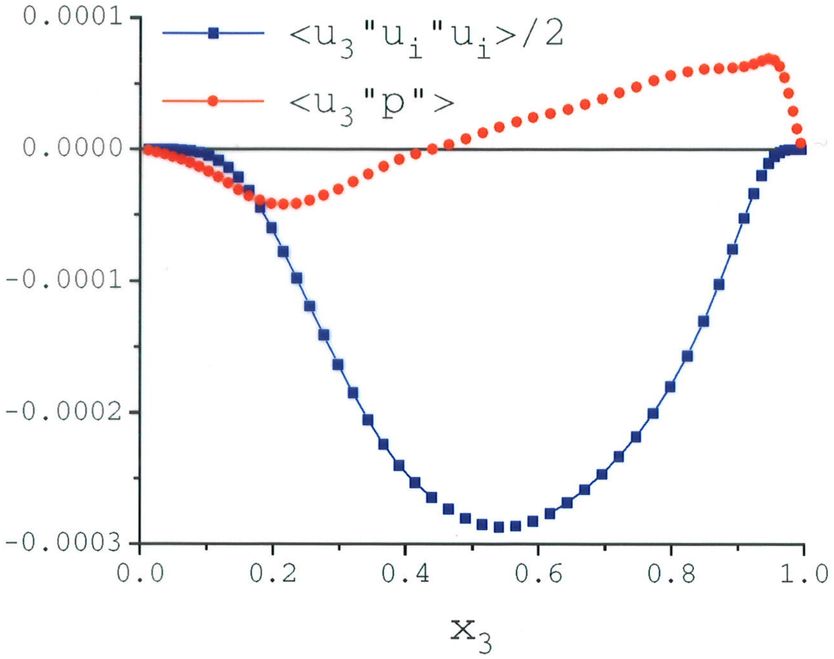


- Diffusion of vertical turbulent heat flux $\langle u_3'' T'' \rangle$

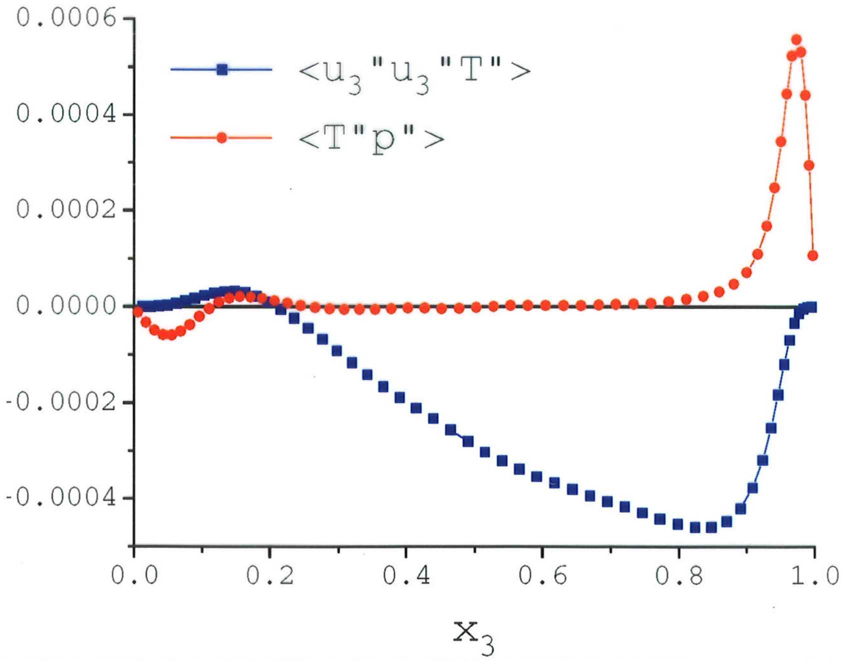


Internally heated fluid layer

- Diffusion of turbulence kinetic energy $\langle k \rangle$

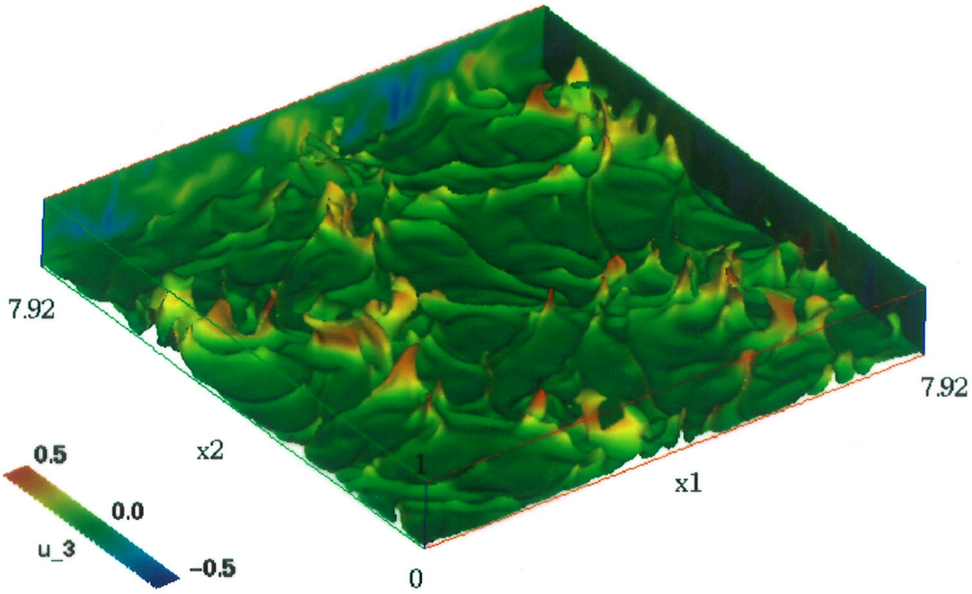


- Diffusion of vertical turbulent heat flux $\langle u_3'' T'' \rangle$

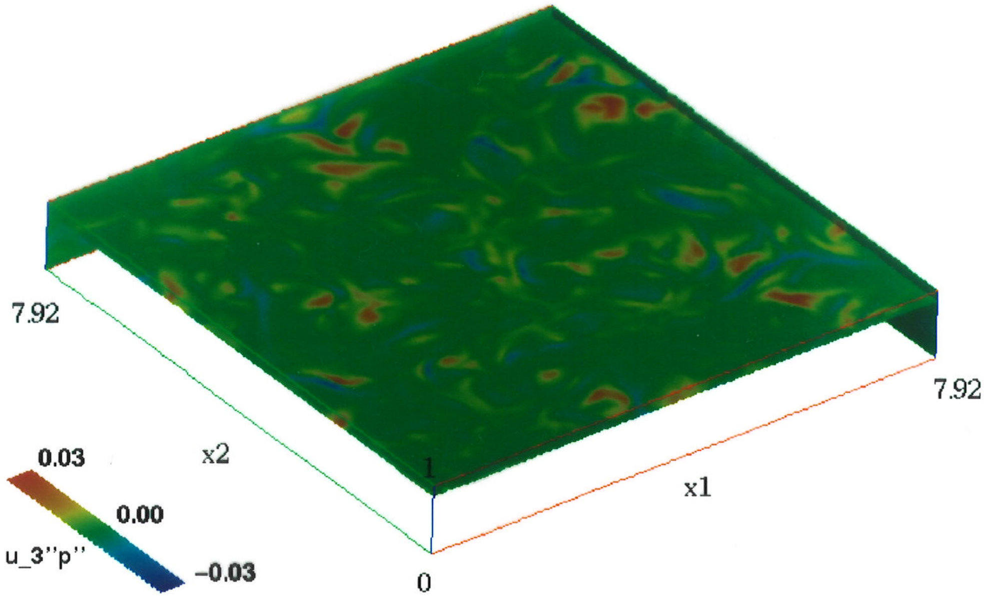


Pressure transport of k in RBC

- Isosurface: $T = 0.7$, Color: u_3

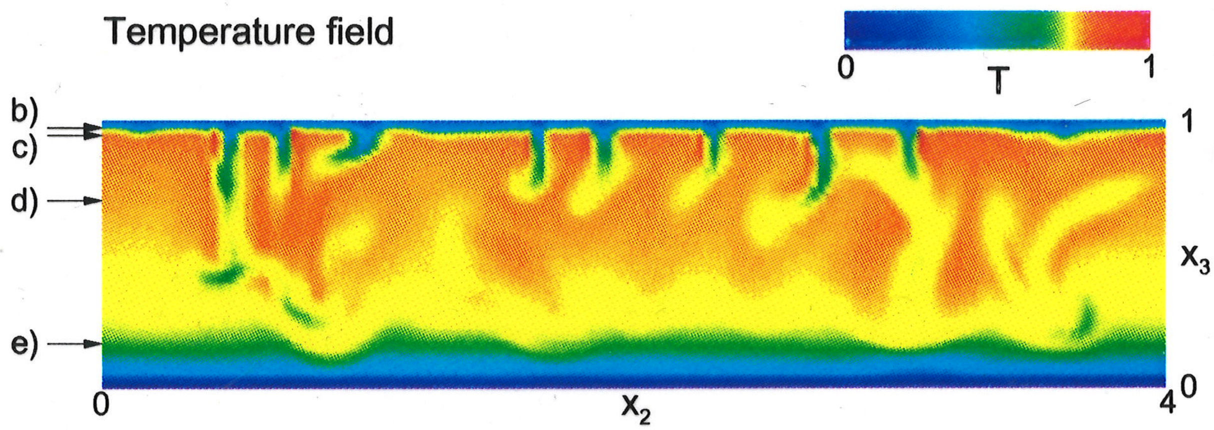


- Local correlation $u_3''p''$ in plane $x_3 = 0.852$

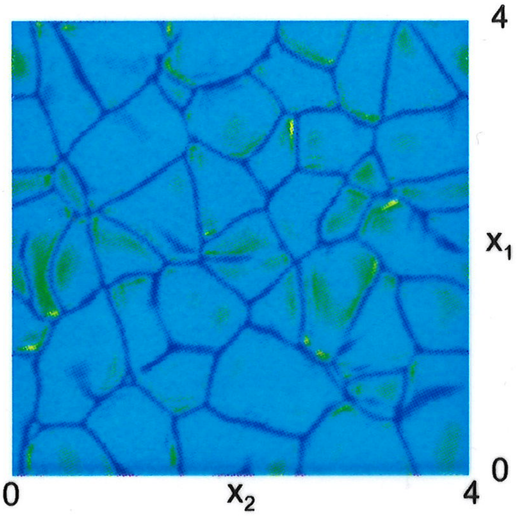


Internally heated convection ($Ra_I=10^8$)

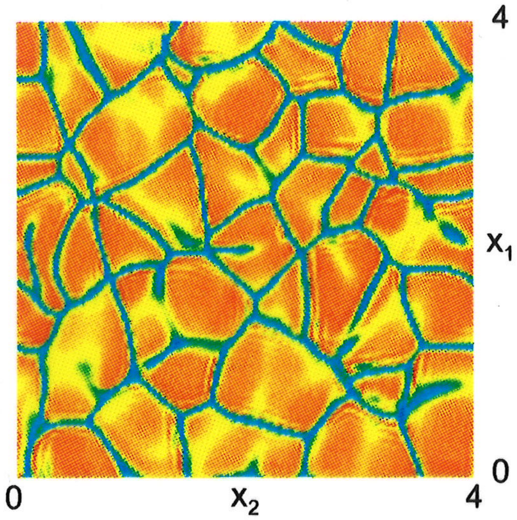
Temperature field



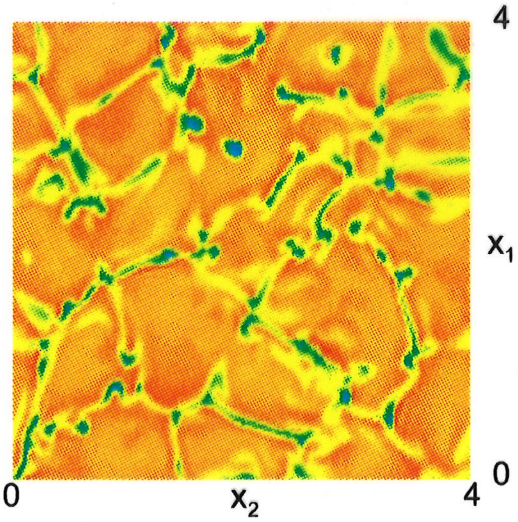
a) I=80, x_1=2.0.



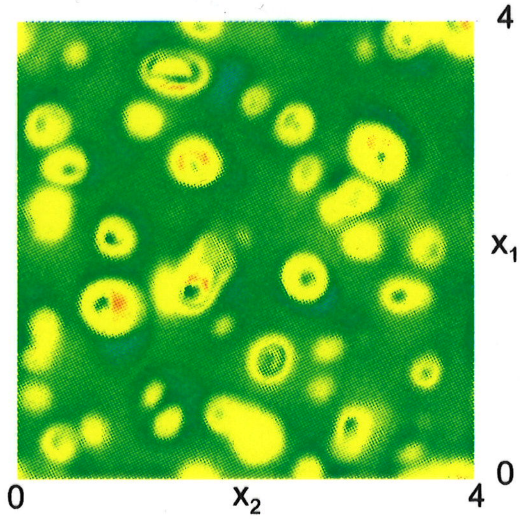
b) k=52, x_3=0.98.



c) k=47, x_3=0.94.



d) k=36, x_3=0.71.



e) k=13, x_3=0.17.

Conclusions

- analysis of $D_{k,turb}$ and $D_{q3,turb}$ by DNS data
  - Rayleigh-Bénard convection:
    pressure correlation is dominant term
  - Internally heated fluid layer:
    triple correlation is dominant term

- importance and efficiency of pressure transport is closely linked to coherent structures

- coherent structures are intermittent and exist only for limited time intervals

- Common closure for $D_{k,turb}$ and $D_{q3,turb}$:
  - pressure term is added to triple-correlation
  - triple-correlation is modelled by generalized gradient diffusion assumption

  $\Rightarrow$ model does not properly account for pressure transport of k and $\overline{u_3'T'}$ in natural convection
  $\Rightarrow$ need for separate pressure transport model