Dimensionality influence on passive scalar transport across a turbulent energy gradient

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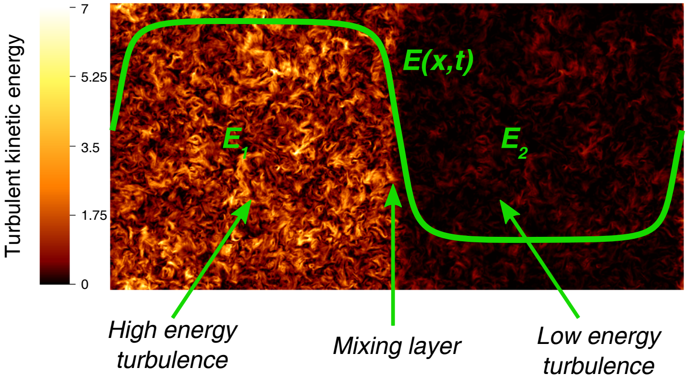
Turbulent shearless mixing

General flow configuration:

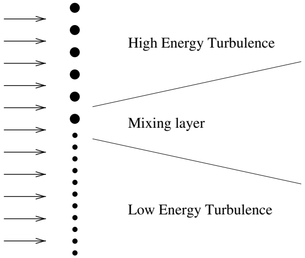


Flow

Parameters: Reynolds number, Energy Ratio E_1/E_2, Scale ratio ℓ_1/ℓ_2

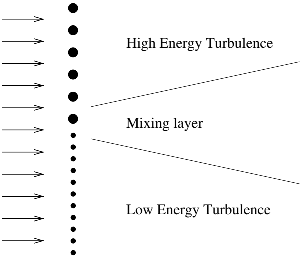
movie

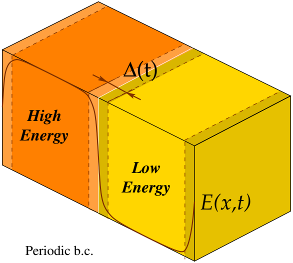
State of the art



- Grid turbulence experiments:
  - Gilbert *JFM* 1980
  - Veeravalli-Warhaft *JFM* 1989, 1990, 2009

State of the art





Periodic b.c.

- Grid turbulence experiments:
  - ▶ Gilbert *JFM* 1980
  - ▶ Veeravalli-Warhaft *JFM* 1989, 1990, 2009

- Numerical experiments:
  - ▶Briggs *et al. JFM* 1996
  - ▶Knaepen *et al. JFM* 2004
  - ▶Tordella-Iovieno *JFM* 2006
  - ▶Iovieno-Tordella-Bailey *PRE* 2008
  - ▶Kang-Meneveau *Phys.Fluids* 2008
  - ▶Tordella-Iovieno *Phys.Rev.Lett.* (accepted)

Main features of mixing layers

Shearless mixing layers shows the following properties:

- no gradient of mean velocity, thus no kinetic energy production
- the mixing is generated by the inhomogeneity in the turbulent kinetic energy and integral scale
- the mixing layer becomes very intermittent at both large and small scales [Tordella-Iovieno *Phys.Rev.Lett.* 2011]
- the presence of a gradient of energy is a sufficient condition for the onset of intermittency [Tordella and Iovieno *JFM* 2006; Tordella et al. *Phys. Rev.* 2008]
- 2D and 3D mixings: different asymptotic layer thickness growth exponent

Passive scalar

Basic phenomenology

- A passive scalar is a contaminant present in so low concentration that it has no dynamical effect on the fluid motion.
- Turbulence transports the scalar by making particles follow chaotic trajectories and disperses the scalar concentration if exists scalar concentration gradient.
- Fluctuations reach the smaller scales.

Passive scalar

Basic phenomenology

- at large scales:
  - the mean concentration, variance and flux are strongly influenced by the boundary conditions and scalar injection
- at small scales:
  - scalar differences are not gaussian,
  - intermittency observed at inertial range scales as well as at the dissipation scales, with ramp/cliff structures

see, e.g.:

Warhaft *Ann.Rev.Fluid Mech.* 2000,
Shraiman and Siggia, *Nature* 2000,
Gotoh, *Phys.Fluids* 2006, 2007.

Passive scalar transport

We solve the passive scalar advection-diffusion equation

$$\frac{\partial \vartheta}{\partial t} + u_j \frac{\partial \vartheta}{\partial x_j} = \frac{(-1)^{n+1}}{Re\, Sc} \nabla^{2n} \vartheta$$

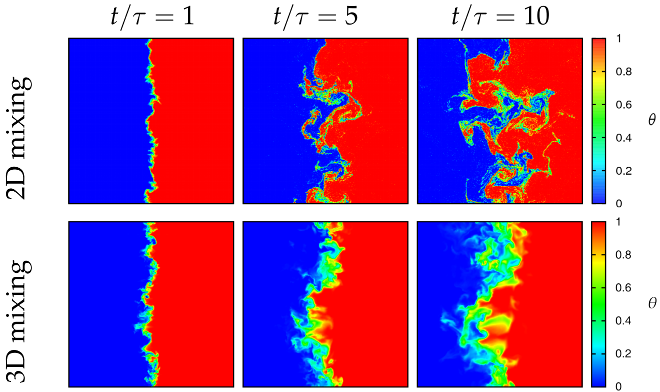
for the shearless mixing configuration with $E_1/E_2 = 6.6$, $\ell_1 = \ell_2$.

DNS simulations have been performed for:

3D turbulence: $600^2 \times 1200$ grid points, $n = 1$, $Re_\lambda = 150$
2D turbulence: 1024^2 grid points, $n = 2$ (hyperviscosity)

Schmidt number $Sc = 1$

Passive scalar concentration

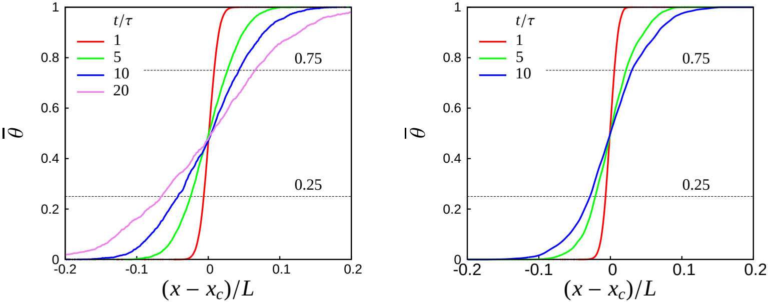


2D movie

3D movie

Mean Scalar Diffusion

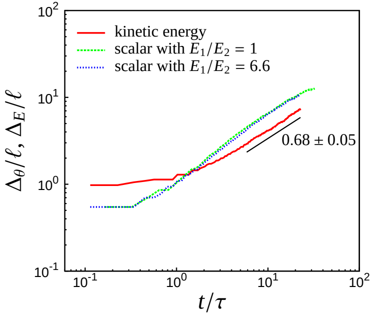
2D Mixing   3D Mixing



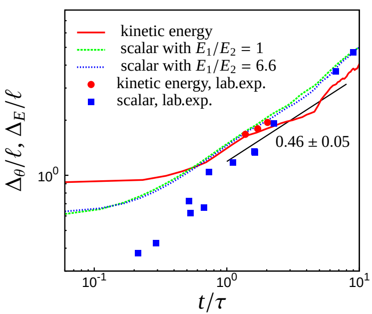
Energy ratio $E_1/E_2 = 6.6$

Scalar mixing layer thickness

2D Mixing



3D Mixing

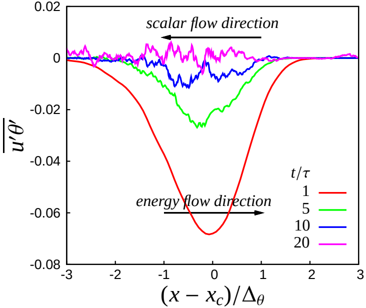


Scalar layer thickness: $\Delta_\vartheta = x_{(\vartheta=0.75)} - x_{(\vartheta=0.25)}$

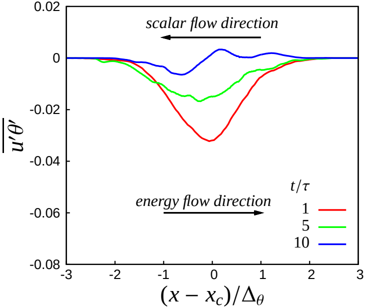
3D mixing: $\Delta_\vartheta \sim t^{0.46}$, 2D mixing: $\Delta_\vartheta \sim t^{0.68}$

Scalar flux

2D Mixing



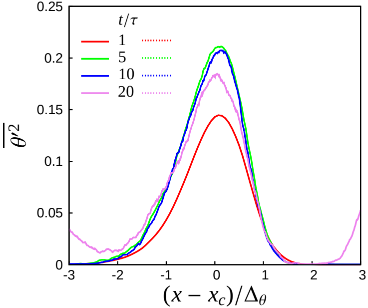
3D Mixing



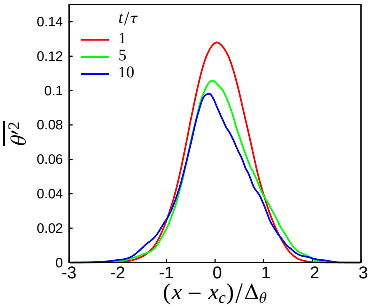
$$\overline{u'\vartheta'} \sim 1/\Delta_\vartheta(t)$$

Scalar variance

2D Mixing

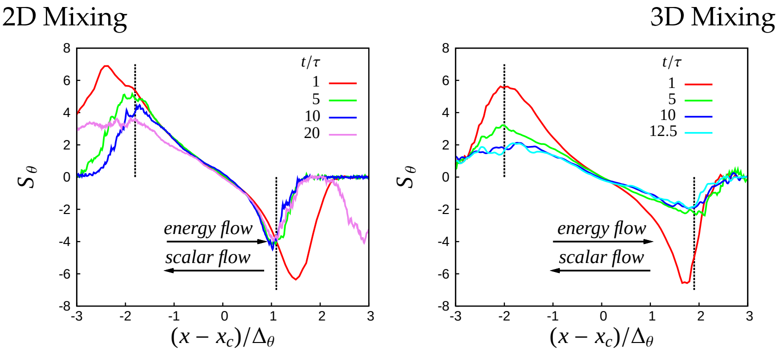


3D Mixing



Self-similar distribution, peak shifted toward the high kinetic energy region

Scalar skewness

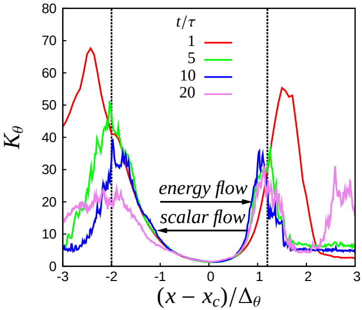


Strong non-gaussian statistic at the mixing layer border

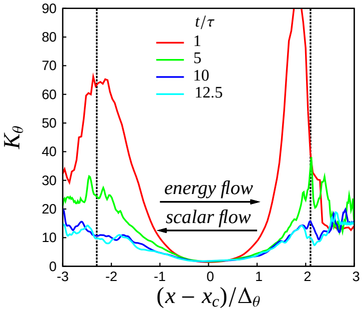
2D: intermittency penetrates more in the direction opposite to the energy gradient.

Scalar kurtosis

2D Mixing



3D Mixing



2D: higher asymmetry of the peaks.

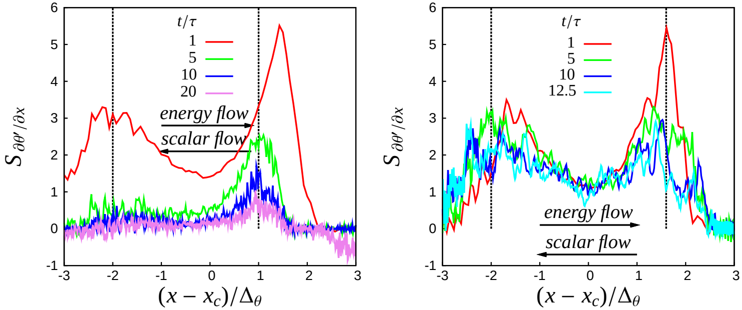
Intermittency gradually reduces as the mixing procedes

Small scale intermittency

Scalar derivative skewness

2D Mixing

3D Mixing

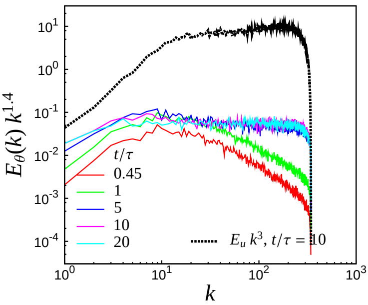


2D: higher asymmetry of the peaks.

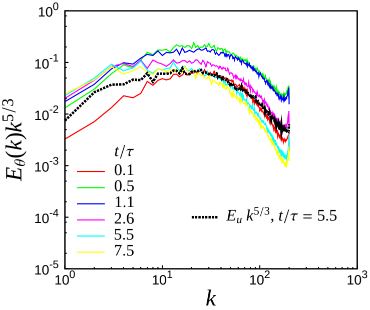
Intermittency decay faster in 2D

Spectra in the mixing layer

2D Mixing



3D Mixing



Compensated scalar and velocity one-dimensional spectra in the same position

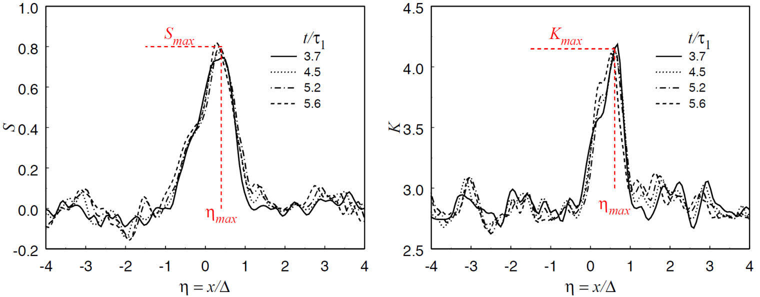
Conclusions

Passive scalar transport

- Growth rate:
  2D flow : $(\Delta_\vartheta \sim \Delta_E \sim t^{0.68})$, 3D flow : $(\Delta_\vartheta \sim \Delta_E \sim t^{0.46})$.
- Self-similar profiles of first and second order moments. The scalar flow is about two times larger in 2D than in 3D. The scalar variance in the center of the mixing layer is 50% higher in 2D case.
- Large intermittency and non-gaussian behaviour on both sides of the mixing, even where the scalar flux is small.
- Larger asymmetry in moment distributions in 2D mixing.
- Intermittency involves also the small scales
- Inertial range spectra exponent:
  scalar: 3D $\sim -5/3$, 2D ~ -1.4,
  velocity: 3D $\sim -5/3$, 2D ~ -3

Large scale intermittency

$S = \overline{u^3}/\overline{u^2}^{3/2}$ $\qquad$ $K = \overline{u^4}/\overline{u^2}^2$

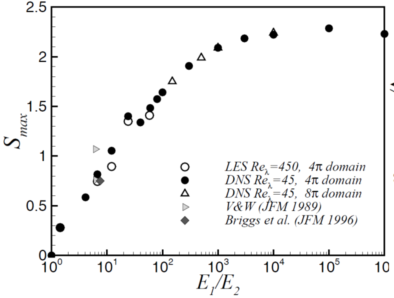


u = velocity component in the mixing direction
S_{max}, K_{max} = maximum of Skewness and Kurtosis in the mixing layer
η_{max} = normalized position of the maximum in the mixing layer

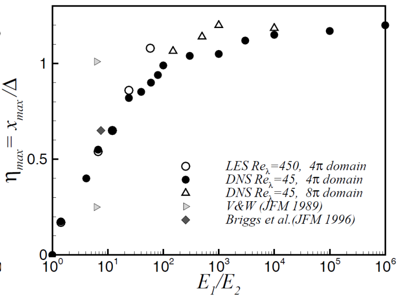
(Figures: sample data from simulations with $E_1/E_2 = 6.7$, $\ell_1 = \ell_1$, $Re_\lambda = 45$)

Intermittency vs. Energy ratio

Skewness

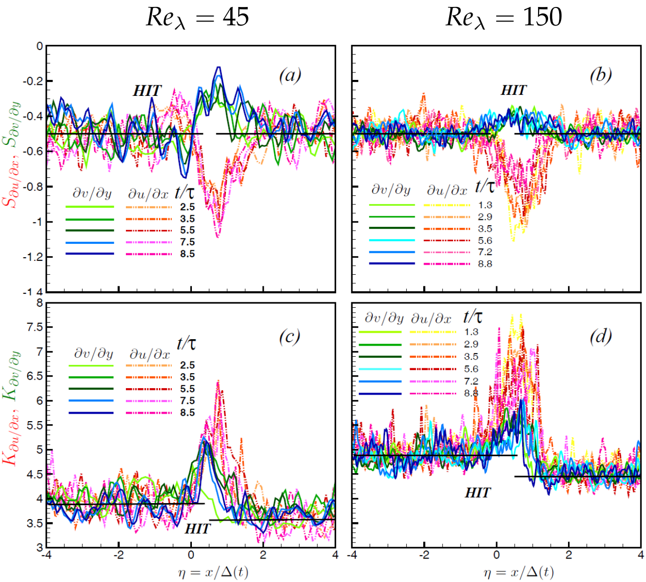


Penetration



We define the penetration as the position of the maximum of the skewness normalized over the mixing layer thickness: $\eta = \frac{x_s(t)}{\Delta(t)}$

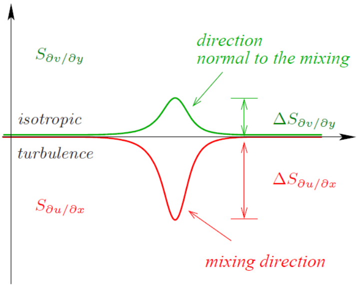
Velocity derivative

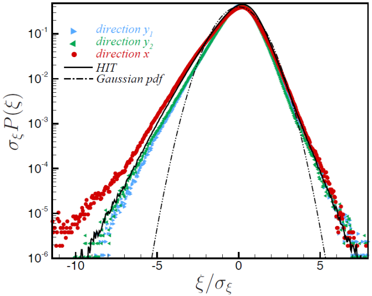


Phys.Rev.Lett., 2011 (accepted)

Velocity derivative skewness

General behaviour

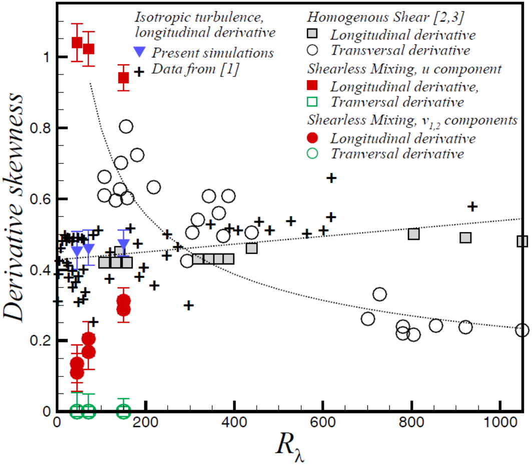




$\xi = \partial u_i/\partial x_i$, $i = x, y_1$ and y_2
($Re = 150$, $t/\tau = 3.5$)

Increase of fluid filaments compression in the energy gradient direction, reduction of fluid filaments compression in the other directions

Small scale anisotropy



(1) Sreenivasan-Antonia *Ann.Rev.Fluid Mech* 1997

(2,3) Warhaft-Shen *Phys.Fluids* 2000 and 2002.

Shear flows: large transiversal skewness

Shearless mixings: strong differentiation of the longitudinal skewness