Turbulent Anisotropic Transport in a Model Cloud Interface

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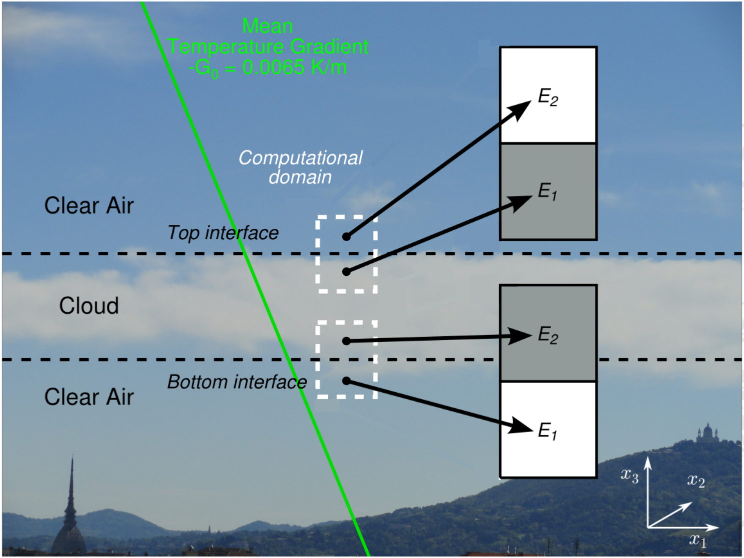
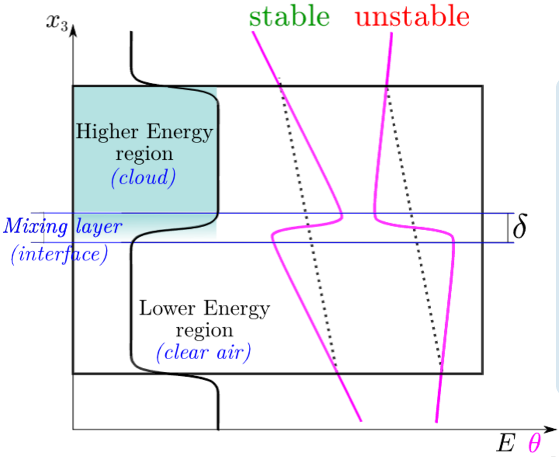
Flow configuration – motivation



Flow configuration



DNS – NS with Boussinesq approximation

domain: $L_z \approx 12$ m

grid: $1024^2 \times 2048$

initial interface thickness $\Delta \approx 0.3$ m

energy ratio ≈ 6.7

$Re_\lambda \approx 250.$

Objective

Small scale	Focus on last part of inertial range and dissipative range
Intermittency	Presence of intermittent layers deeply influence small-scale dynamics. Different effects of **stable** and **unstable** layer
Shearless	Shearless mixing between two turbulent flows
Stratification	Effect of stratification on the turbulent mixing and droplet motion
Entrainment	Influence of the stratification on clear air entreinment
Instability	Short term instability simulation and growth factor evaluation
Droplet motion	Influence of flow inhomogeneity and stratification on the collision rate and growth of droplets

Context

Turbulent mixings

- A kinetic energy gradient creates an intermittent region (shearless mixing layer)
- It creates an additional compression of fluid elements in the direction of ∇E and a stretching in the other directions

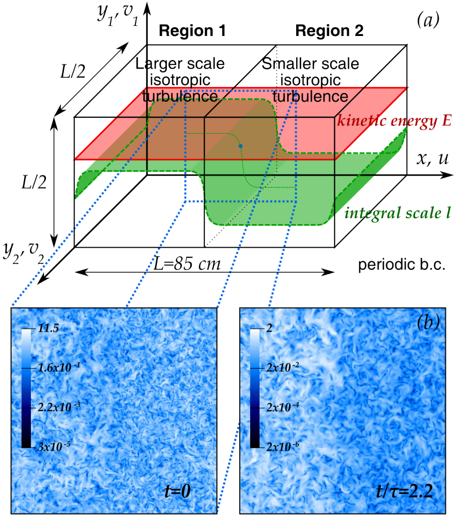
Cloud droplet collisions

- warm cloud have more turbulent kinetic energy than the surrounding clear air ($\Rightarrow \nabla E$ at the interface)
- Above 30-40 μm droplet growth is mainly determined by collisions
- droplets accumulate in regions with high strain
- Can a shearless mixing layer change the collison rate of droplets?

Working hypothesis

- Top/bottom cloud-clear air interfaces can be seen as turbulent shearless mixing regions
- **The compression of fluid elements at small scale, typically met across a shearless mixing layer, may increase the collision rate and particle numerical density**
- Considering the bottom interface, gravity favours droplet exit from the the cloud. Large droplets may become rain.

The role of the integral scale inhomogeneity

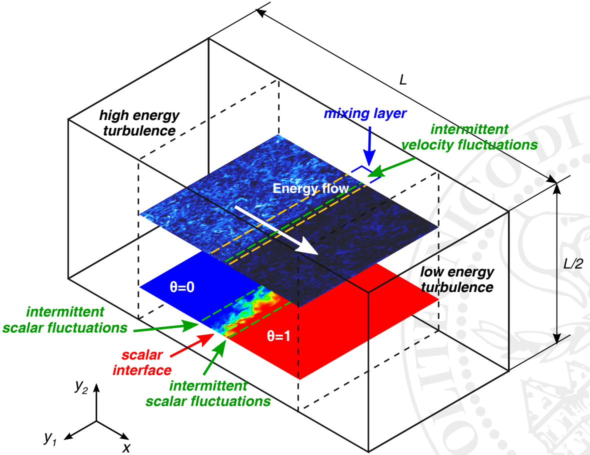


Uniform kinetic energy, inhomogeneous scale

Physica D, 2012.

Movie: Turbulent kinetic energy

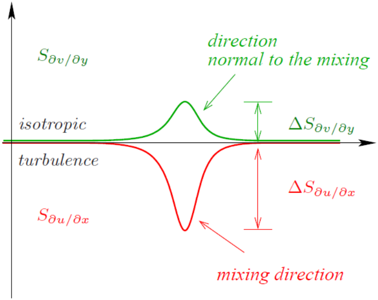
Energy and Passive scalar transport

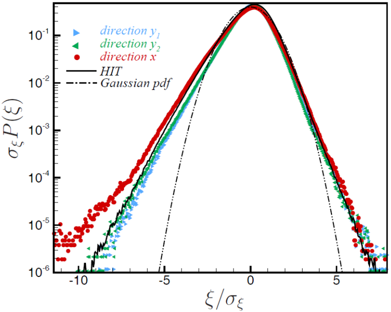


Movie: Turbulent kinetic energy

Movie: Scalar transport

Velocity derivative skewness
General behaviour





$$\xi = \partial u_i/\partial x_i,\ i = x,\ y_1 \text{ and } y_2$$
$$(Re_\lambda = 150,\ t/\tau = 3.5)$$

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

Turbulence data (reference altitude $1000\ m$ s.l.)

High energy region E_1: $u_{rms} = 0.2\ m/s$, $\ell = 0.3\ m$, $Re_\lambda \approx 250$
E_1/E_2 ≈6.7, $Pr = 0.72$, $Sc = 0.61$

Initial Perturbation Stratification

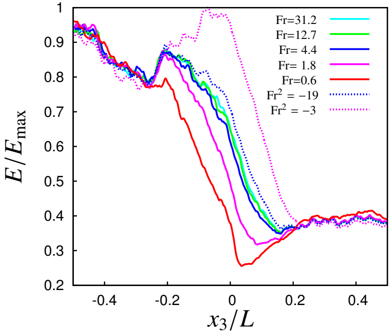
$\nabla\theta\ [K/m]$	$\Delta\theta\ [K]$	$N_{ic}\ [s^{-1}]$	Fr_T^2	Re_b
0.013	0.004	0.021	970	7
0.20	0.06	0.052	160	112
0.65	0.2	0.150	19	273
3.0	1.0	0.335	3	833
30.0	10.0	1.060	0.4	2635
-6.5	-0.2	/	-19	-273
-3.0	-1.0	/	-3	-833

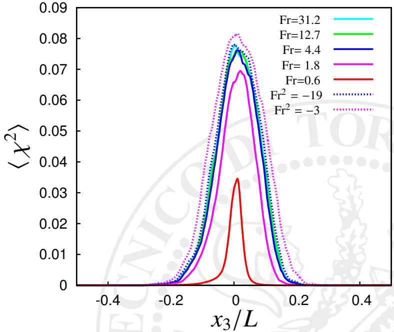
$N_{ic} = \sqrt{\alpha g \frac{d\theta}{dx_3}}$ is the Brunt-Väisälä frequency

$Fr_T^2 = \frac{u'^2_{rms}}{N_{ic}^2 \ell^2}$ is the ratio between kinematic and buoyancy forces

$Re_b = \frac{\varepsilon N^2}{\nu}$ is the ratio between diffusivity and buoyancy

Velocity and temperature variance – $t/\tau = 6$





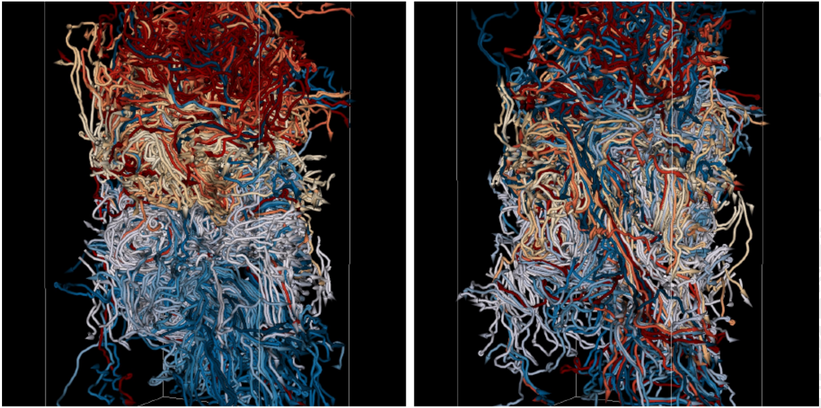
Stable stratification

- Formation of a pit of kinetic energy (strong strat)
- Reduction of scalar fluctuation

Unstable stratification

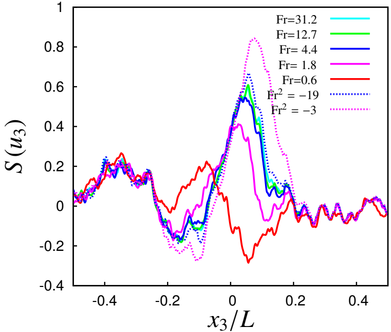
- Increases kinetic energy
- Enhances scalar fluctuation

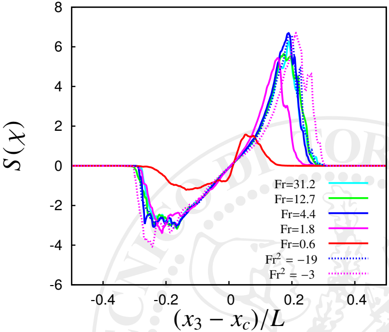
Flow Structure



(a) Stable strat. – $\mathrm{Fr}^2 = 4.2$ (b) Unstable strat. – $\mathrm{Fr}^2 = -4.2$

Higher order moments – $t/\tau = 6$





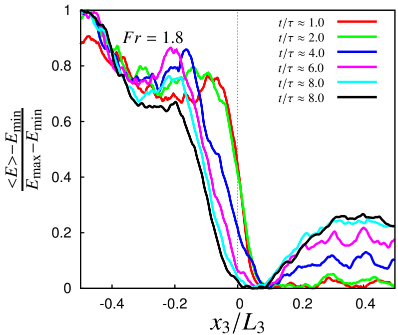
Stable stratification

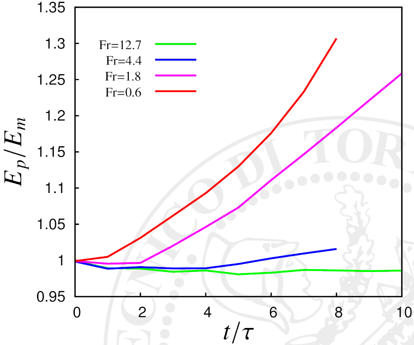
- General reduction of intermittency
- Strong stratification produces two velocity intermittent sublayers

Unstable stratification

- Increase of velocity intermittency
- Negligible effects on scalar
- No qualit. changes in behaviour

Stable stratification – kinetic energy pit

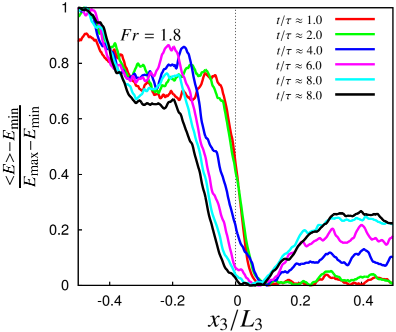


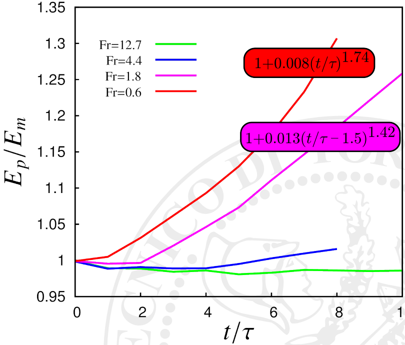


Creation of a pit of energy in the centre of the mixing:

- Presence of two opposite mean turbulent kinetic energy gradients
- Very low energy inside the pit (reduced transport)
- Pit onset and intensity are a function of the stratification level

Stable stratification – kinetic energy pit





Creation of a pit of energy in the centre of the mixing:

- Presence of two opposite mean turbulent kinetic energy gradients
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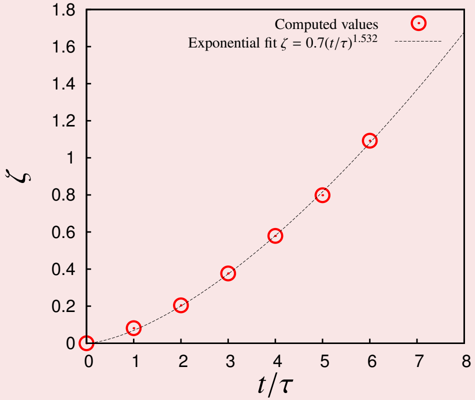
- Pit onset and intensity are a function of the stratification level

Instability growth factor

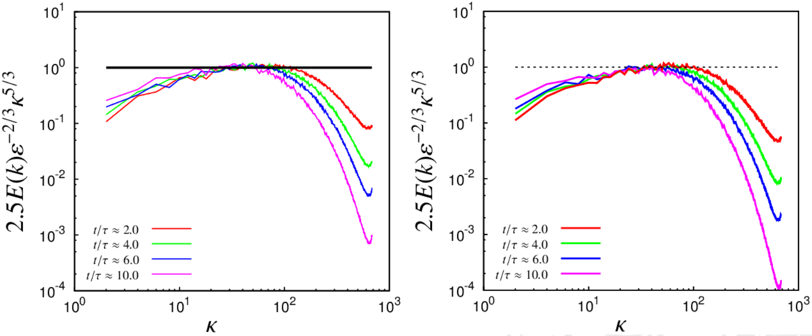
$$Fr^2 = -19$$



Growth factor

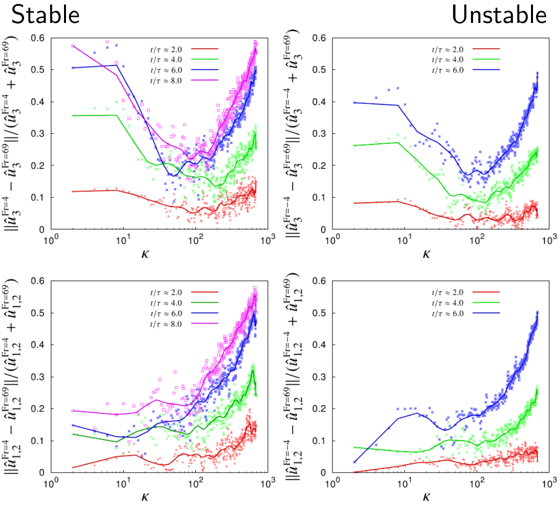
- Growth given by the ratio respect to no stratification
- $\zeta = E_{Fr^2=-3}/E_{Fr=31} - 1$
- Instability effects becomes relevant after $t = 2\tau$
- Growth rate exponent up to 1.8 (function of Fr^2)

Velocity spectra



energy spectra in the mixing layer, $Fr^2 = 4.2$

Velocity spectra

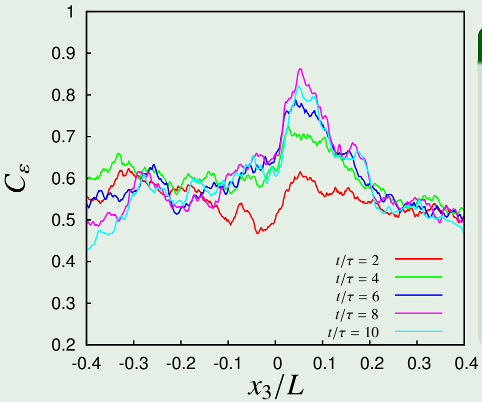


vertical velocity

horizontal velocity

Dissipation

$Fr = 1.8$



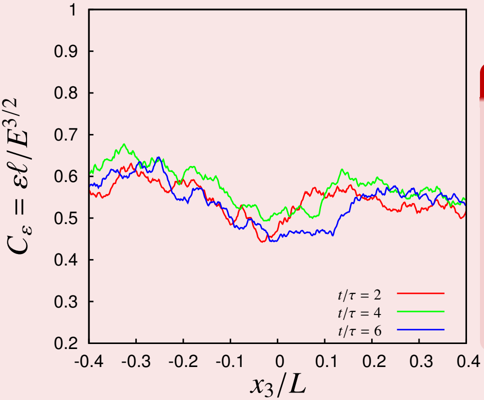
Dissipation rate

- ε turbulence dissipation rate $C_\varepsilon = \varepsilon\ell/u'^{3/2}$
- In the energy pit the dissipation is higher than its isotropic value $u'^{3/2}/\ell$ (about 30%)
- Self-similarity in PDFs regardeless vertical position

Movie: Dissipation

Dissipation

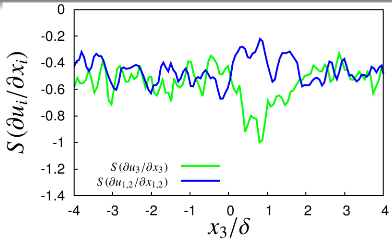
$Fr^2 = -4.2$



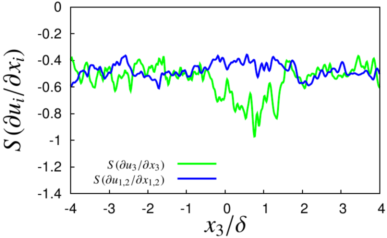
Dissipation rate

- ε turbulence dissipation rate $C_\varepsilon = \varepsilon\ell/u'^{3/2}$
- Dissipation remains almost constant inside and outside the mixing region
- Self-similarity in PDFs regardeless vertical position

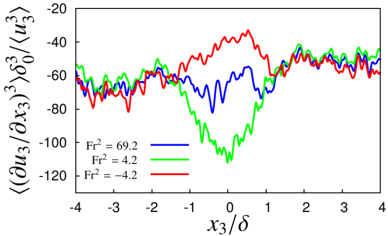
Derivative statistics



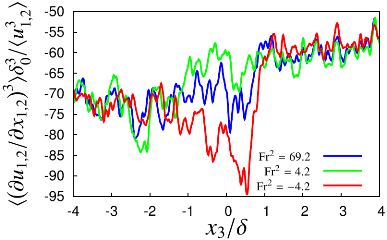
(a) $\mathrm{Re}\lambda = 45$, [5]



(b) $\mathrm{Re}\lambda = 150$, [5]



(c) Normalized third moment of longitudinal derivatives normal to the interface



(d) Normalized third moment of longitudinal derivatives parallel to the interface

any stratification highly enhances anisotropy

Droplet motion: objectives

Turbulent mixings

- A kinetic energy gradient creates an intermittent region (shearless mixing layer)
- It creates an additional compression of fluid elements in the direction of ∇E and a stretching in the other directions
- Stratification increases anisotropy, can create a barrier of kinetic energy

Cloud droplet collisions

- warm cloud have more turbulent kinetic energy than the surrounding clear air ($\Rightarrow \nabla E$ at the interface)
- Above 30-40 μm droplet growth is mainly determined by collisions
- droplets accumulate in regions with high strain
- Can a shearless mixing layer change the collison rate of droplets?

Droplet dynamics model - small scale DNS

Droplet motion: Stokes drag & gravity

$$\frac{\mathrm{d}\mathbf{x}_k}{\mathrm{d}t} = \mathbf{v}_k \qquad \frac{\mathrm{d}\mathbf{v}_k}{\mathrm{d}t} = \frac{\mathbf{u}(\mathbf{x}_k,t) - \mathbf{v}_k}{\tau_{p,k}} + \mathbf{g}$$

where $\tau_{p,k} = (2\rho_w R_k^2)/(9\mu)$ is the droplet relaxation time.

Evaporation-Condensation (R_k = radius)

Each droplet can change its mass by condensation and evaporation:

$$\frac{\mathrm{d}R_k}{\mathrm{d}t} = c\frac{\varphi(\mathbf{x}_k,t) - 1}{R_k}$$

where φ is the relative humidity, $\varphi = \rho_v/\rho_{sat}$ (Mason, 1971)

Collisions

Droplets are assume to coalesce when $|\mathbf{x}_i - \mathbf{x}_j| \leq R_i + R_j$:

$$m_i + m_j = m^*, \quad m_i\mathbf{v}_i + m_j\mathbf{v}_j = m^*\mathbf{v}^*$$

Droplet model

Condensation/evaporation model coefficient (e.g. Kumar et al. 2013)

$$c = \left[\rho_w \left(\frac{R_v T}{D p_{sat}(T)} + \frac{L^2}{\kappa R_v T}\right)\right]^{-1}$$

L=latent heat of evaporation condensation
κ=thermal diffusivity in the air ($Pr \approx 0.7$)
D=diffusivity of vapour in air ($Sc \approx 0.5$)
ρ_w=density of water
T= temperature $p_{sat}(T)$= saturation pressure

Saturation pressure (Clausius-Clapeyron)

$$\log \frac{p_{sat}}{p_R} = \frac{L}{R_v}\left(\frac{1}{T_R} - \frac{1}{T}\right)$$

$p_R = 1103$ Pa is the saturation pressure at temperature $T_R = 281.65$ K.

Flow model

Navier-Stokes, Boussinesq approximation, plus vapour transport

$$\nabla \cdot \mathbf{u} = 0 \qquad \frac{D\mathbf{u}}{Dt} = -\nabla \frac{\tilde{p}}{\rho_0} + \nu \nabla^2 \mathbf{u} + B\mathbf{g} + \mathbf{f}_p$$

$$\frac{DT}{Dt} = \kappa \nabla^2 T + \frac{L}{c_p} C_v \qquad \frac{D\rho_v}{Dt} = \kappa_v \nabla^2 \rho_v - C_v$$

$$B = g \left[\frac{T - T_0}{T_0} + \frac{\mathcal{M}_v}{\mathcal{M}_a} \frac{\rho_v - \rho_{v0}}{\rho_0} \right]$$

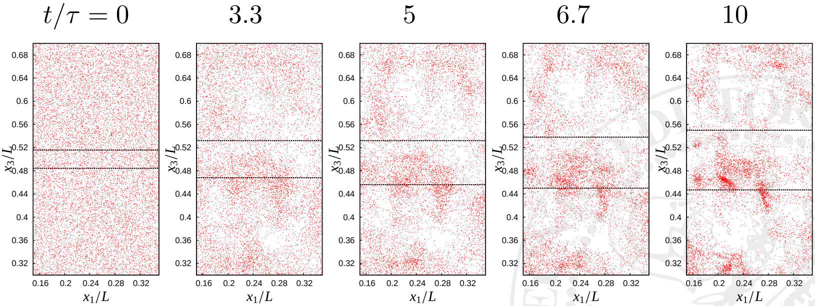
L is the latent heat of evaporation, C_v the condensation rate per unit volume, $\mathbf{f}_p$ the particle force per unit mass on the flow

Coupling terms: droplets/flow interaction

$$\mathbf{f}_p = -\frac{1}{\rho_0 V_{(\mathbf{x},\delta)}} \sum_{\mathbf{x}_k \in V_{(\mathbf{x},\delta)}} m_k \frac{\mathrm{d}\mathbf{v}_k}{\mathrm{d}t} = -\frac{1}{\rho_0 V_{(\mathbf{x},\delta)}} \sum_k m_k \frac{\mathbf{u}(\mathbf{x}_k, t) - \mathbf{v}_k}{\tau_{p,k}}$$

$$C_v = \frac{1}{V_{(\mathbf{x},\delta)}} \sum_{\mathbf{x}_k \in V_{(\mathbf{x},\delta)}} \frac{\mathrm{d}m_k}{\mathrm{d}t} = -\frac{4\pi\rho_w}{3V_{(\mathbf{x},\delta)}} \sum_k c(\varphi(\mathbf{x}_k, t) - 1) R_k$$

Particle movement



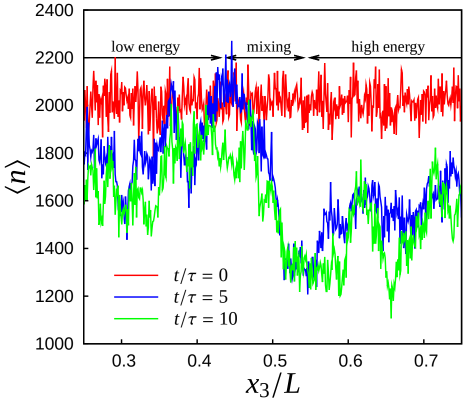
Flow

$Re_\lambda \approx 50$
$E_1/E_2 = 6.7$

Particles

$N_p = 10^6$, $St = 2$ (30 μm droplets),
collisions and coalescence

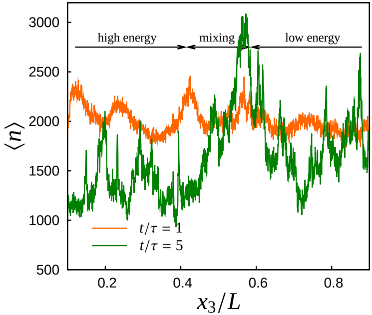
Particle density – effect of kinetic energy gradient



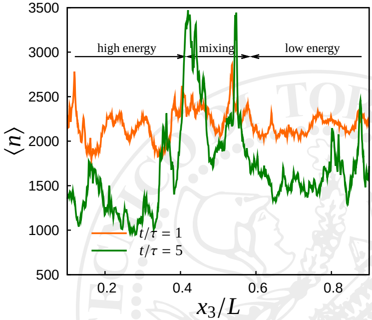
- Shearless mixing, $E_1/E_2 = 6.7$
- DNS $Re_\lambda \approx 50$
- $N_p = 10^6$ particles
- collisions and coalescence
- $St = 2$

Particle density – effect of statification

Unstable stratification



Stable stratification



Flow

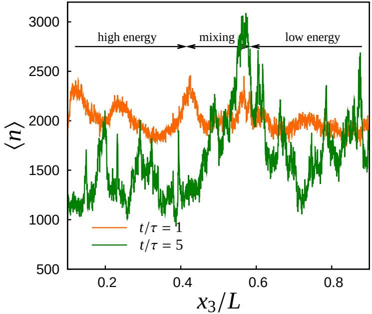
- DNS $Re_\lambda \approx 50$
- $Fr^2 = 4$

Particles

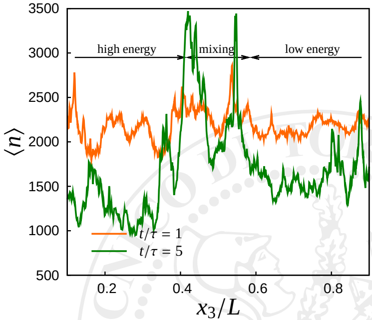
- $N_p = 10^6$ particles
- $St = 2$

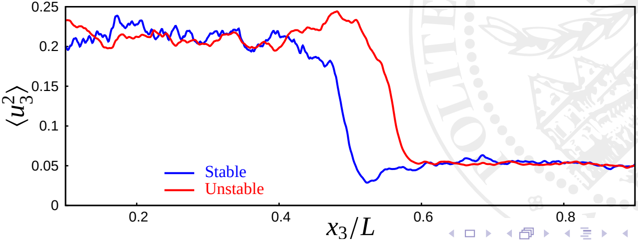
Particle density – effect of statification

Unstable stratification

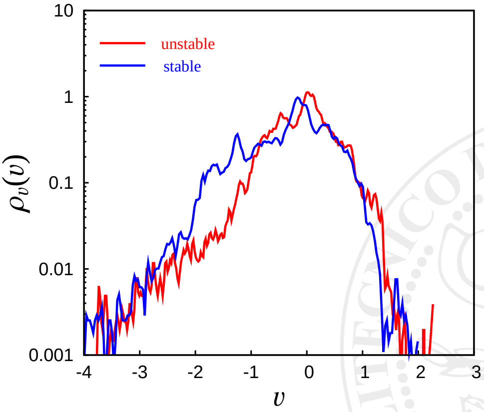


Stable stratification



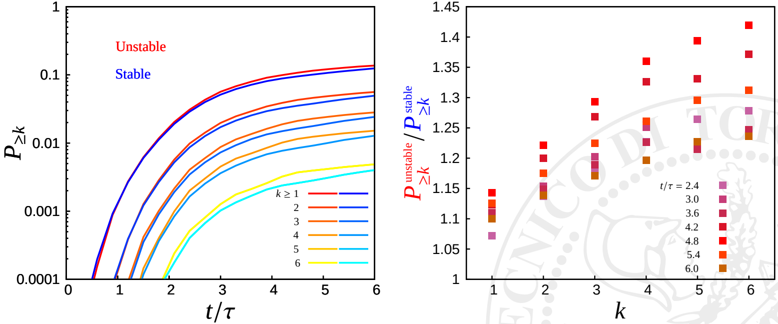


Particle velocity



Probability density function of the droplet vertical velocity in the mixing layer

Particle collisions



$P_{\geq k}(t)$= fraction of droplets which underwent at least k collisions at t

An unstable stratified mixing layer increases the collision/coalescence rate

Conclusions

stable stratification

- Horizontally layered structure characterized by a low kinetic energy sublayer in case of local, stable, intense stratification (pit of energy)
- It acts as a barrier and reduces entrainment
- Generates two intermittent regions with opposite kinetic energy gradient

unstable stratification

- Exponential growth of the energy in the mixing region respect to the external region.
- Greater intermittency in the mixing layer
- Faster thickening of the mixing layer
- No relevant differences in dissipation respect to unstratified cases

Droplets

- Droplets accumulate in the mixing layer
- An unstable stratification increases the collision rate