Turbulent anisotropic transport in a model cloud interface

Original
Turbulent anisotropic transport in a model cloud interface / Carbone, Maurizio; Iovieno, Michele; Gallana, Luca; Tordella, Daniela. - ELETTRONICO. - (2016). ((Intervento presentato al convegno 11th European Fluid Mechanic Conference tenutosi a Siviglia (Spagna) nel 12-16 Settembre.

Availability:
This version is available at: 11583/2681657 since: 2017-09-22T16:02:28Z

Publisher:
European Mechanics Society

Published
DOI:

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Turbulent Anisotropic Transport in a Model Cloud Interface

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11th EFMC - Sevilla
September 14, 2016
Flow configuration – motivation

Mean Temperature Gradient
\(-G_0 = 0.0065\) K/m

Computational domain

Top interface

Bottom interface
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 $\approx 6.7$
- $Re_\lambda \approx 250$. 

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### Objective

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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 $\nabla E$ 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 $\mu$m droplet growth is mainly determined by collisions
- Droplets accumulate in regions with high strain
- Can a shearless mixing layer change the collision 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 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

\[ \xi = \frac{\partial u_i}{\partial x_i}, \quad i = x, y_1 \text{ and } y_2 \]

\( (Re\lambda = 150, \ t/\tau = 3.5) \)

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

\[ S_{\partial u/\partial x} \]

\[ S_{\partial u/\partial y} \]

\[ \Delta S_{\partial u/\partial x} \]

\[ \Delta S_{\partial u/\partial y} \]

\( \text{direction normal to the mixing} \)

\( \text{mixing direction} \)
**Fluid flow**

**Droplets**

The cloud-clear air interface

Small-scale intermittency

---

**Turbulence data (reference altitude 1000 m s.l.)**

High energy region $E_1$: $u_{rms} = 0.2 \, m/s$, $\ell = 0.3 \, m$, $Re_\lambda \approx 250$

$E_1/E_2 \approx 6.7$, $Pr = 0.72$, $Sc = 0.61$

---

**Initial Perturbation Stratification**

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

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

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

$Re_b = \frac{\varepsilon N_{ic}}{\nu}$ 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. \(- Fr^2 = 4.2\)

(b) Unstable strat. \(- Fr^2 = -4.2\)
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
- Very low energy inside the pit (reduced transport)
- Pit onset and intensity are a function of the stratification level
Instability growth factor

$$Fr^2 = -19$$

- Computed values
- Exponential fit $\zeta = 0.7(t/\tau)^{1.532}$

**Growth factor**

- Growth given by the ratio respect to no stratification
- $\zeta = \frac{E_{Fr^2=-3}}{E_{Fr=31}} - 1$
- 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

**Stable**

\[ \| \hat{u}_3^{F=4} - \hat{u}_3^{F=60} \| / (\| \hat{u}_3^{F=4} + \hat{u}_3^{F=60} \|) \]

\[ \| \hat{u}_3^{F=4} - \hat{u}_3^{F=60} \| / (\| \hat{u}_3^{F=4} + \hat{u}_3^{F=60} \|) \]

\[ \| \hat{u}_{1,2}^{F=4} - \hat{u}_{1,2}^{F=60} \| / (\| \hat{u}_{1,2}^{F=4} + \hat{u}_{1,2}^{F=60} \|) \]

\[ \| \hat{u}_{1,2}^{F=4} - \hat{u}_{1,2}^{F=60} \| / (\| \hat{u}_{1,2}^{F=4} + \hat{u}_{1,2}^{F=60} \|) \]

**Unstable**

\[ \| \hat{u}_3^{F=4} - \hat{u}_3^{F=60} \| / (\| \hat{u}_3^{F=4} + \hat{u}_3^{F=60} \|) \]

\[ \| \hat{u}_3^{F=4} - \hat{u}_3^{F=60} \| / (\| \hat{u}_3^{F=4} + \hat{u}_3^{F=60} \|) \]

\[ \| \hat{u}_{1,2}^{F=4} - \hat{u}_{1,2}^{F=60} \| / (\| \hat{u}_{1,2}^{F=4} + \hat{u}_{1,2}^{F=60} \|) \]

\[ \| \hat{u}_{1,2}^{F=4} - \hat{u}_{1,2}^{F=60} \| / (\| \hat{u}_{1,2}^{F=4} + \hat{u}_{1,2}^{F=60} \|) \]

vertical velocity

horizontal velocity
Dissipation

$Fr = 1.8$

Dissipation rate

- $\varepsilon$ 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 regardless of vertical position

Movie: Dissipation
Dissipation

\[ F \tau^2 = -4.2 \]

**Dissipation rate**

- \( \varepsilon \) turbulence dissipation rate
  \[ C_\varepsilon = \varepsilon \ell / u'^{3/2} \]
- Dissipation remains almost constant inside and outside the mixing region
- Self-similarity in PDFs regardless of vertical position
Derivative statistics

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

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

(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
## 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 $\nabla E$ 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 $\mu$m droplet growth is mainly determined by collisions
- Droplets accumulate in regions with high strain
- Can a shearless mixing layer change the collision rate of droplets?
Droplet dynamics model - small scale DNS

Droplet motion: Stokes drag & gravity

\[
\frac{dx_k}{dt} = v_k \\
\frac{dv_k}{dt} = \frac{u(x_k, t) - v_k}{\tau_{p,k}} + g
\]

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

Evaporation-Condensation \((R_k = \text{radius})\)

Each droplet can change its mass by condensation and evaporation:

\[
\frac{dR_k}{dt} = c \frac{\varphi(x_k, t) - 1}{R_k}
\]

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

Collisions

Droplets are assumed to coalesce when \(|x_i - x_j| \leq R_i + R_j\):

\[
m_i + m_j = m^*, \quad m_i v_i + m_j v_j = m^* v^*
\]

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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
- \( \kappa \) = thermal diffusivity in the air (\( Pr \approx 0.7 \))
- \( D \) = diffusivity of vapour in air (\( Sc \approx 0.5 \))
- \( \rho_w \) = density of water
- \( T \) = temperature
- \( p_{sat}(T) \) = saturation pressure

Saturation pressure (Clausius-Clapeyron)

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

\( p_R = 1103 \text{ Pa} \) is the saturation pressure at temperature \( T_R = 281.65 \text{ K} \).
Flow model

Navier-Stokes, Boussinesq approximation, plus vapour transport

\[ \nabla \cdot \mathbf{u} = 0 \]
\[ \frac{D\mathbf{u}}{Dt} = -\nabla \tilde{p} + \nu \nabla^2 \mathbf{u} + Bg + f_p \]
\[ \frac{D\rho_v}{Dt} = \kappa_v \nabla^2 \rho_v - C_v \]
\[ \frac{DT}{Dt} = \kappa \nabla^2 T + \frac{L}{c_p} C_v \]

\( L \) is the latent heat of evaporation, \( C_v \) the condensation rate per unit volume, \( f_p \) the particle force per unit mass on the flow

Coupling terms: droplets/flow interaction

\[ f_p = -\frac{1}{\rho_0 V(x,\delta)} \sum_{x_k \in V(x,\delta)} m_k \frac{d\mathbf{v}_k}{dt} = -\frac{1}{\rho_0 V(x,\delta)} \sum_k m_k \frac{\mathbf{u}(x_k, t) - \mathbf{v}_k}{\tau_{p,k}} \]
\[ C_v = \frac{1}{V(x,\delta)} \sum_{x_k \in V(x,\delta)} \frac{dm_k}{dt} = -\frac{4\pi \rho_w}{3V(x,\delta)} \sum_k c(\varphi(x_k, t) - 1) R_k \]
Particle movement

Flow

\[ Re_\lambda \approx 50 \]
\[ E_1/E_2 = 6.7 \]

Particles

\[ N_p = 10^6, \quad St = 2 \] (30 \( \mu \)m 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**

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

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

**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

\[ \langle n \rangle \]

\[ \frac{t}{\tau} = 1 \]

\[ \frac{t}{\tau} = 5 \]

\[ \langle n \rangle \]

\[ \frac{x_3}{L} \]

\[ \langle u_2^3 \rangle \]

\[ \frac{x_3}{L} \]

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

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

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