21st Arthur Thomas Ippen Lecture

Gravity Currents propagating over complex topography: implications for fluid entrainment and sediment transport

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SUMMARY

- **Introduction on gravity currents**

- **Laboratory experiments and LES on gravity currents flowing up a small slope**

- **Laboratory experiments on gravity currents interacting with a steep upslope**

- **Laboratory experiments on rotating gravity currents over a mobile bed**

- **Conclusions**

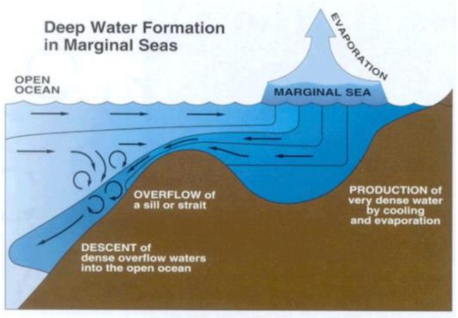
WHAT IS A GRAVITY CURRENT?

Gravity currents are flows driven by density differences between two fluids.

Density differences can be caused by gradients in temperature, salinity or particles in suspension.

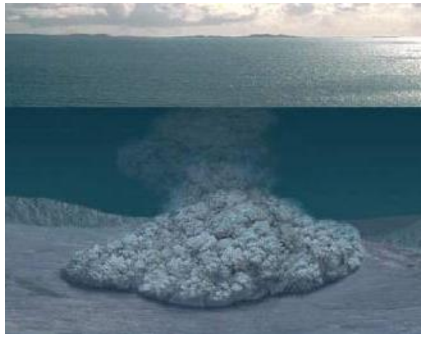
Earth rotation and bottom topography can affect the flow dynamics

Mediterranean overflow



Price, 1992

Turbidity currents



Dense currents in navigation locks

Physical model of IJmuiden sea lock at Deltares
Nogueira et al., 2018

Exchange flows in sea straits or estuaries

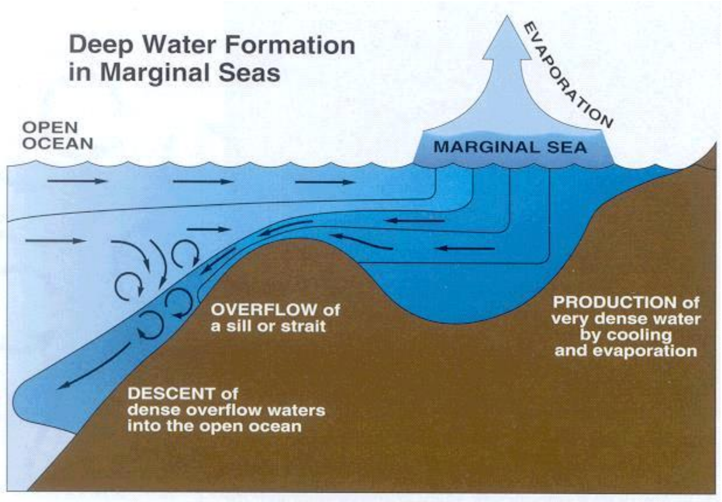
Narva River estuary,
Gulf of Finland, Baltic Sea

ENTRAINMENT IN GRAVITY CURRENTS

In the ocean gravity currents flow over the continental slope and entrain ambient water with a decrease in density.

The final location of oceanic dense overflows will depend on the amount of entrained ambient water.

Gravity currents play an important role for the transport of sediments in lakes and oceans.



Price, 1992

PARAMETERIZATION OF ENTRAINMENT IN GRAVITY CURRENTS

Gravity currents entrain ambient fluid (Ellison & Turner, JFM 1959; Hacker et al., DAO 1996; Cenedese & Adduce, JFM 2008; Nogueira et al., EFM 2014) and several entrainment parameterizations have been developed for simplified models.

ENTRAINMENT PARAMETER

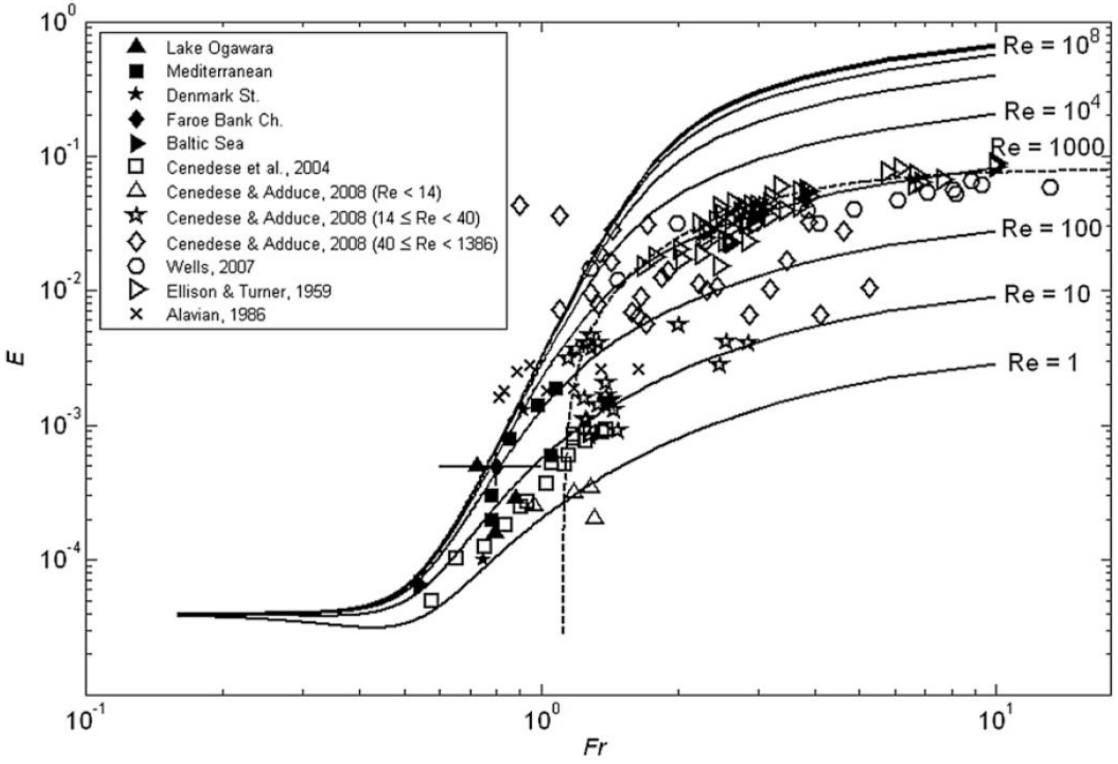
$$E = \frac{W_e}{U}$$

Continuity Equations for a two-layer Shallow-Water Model

$$\frac{\partial(\rho_1 h_1)}{\partial t} + \frac{\partial(\rho_1 h_1 V_1)}{\partial x} = \rho_2 W_e$$

$$\frac{\partial(\rho_2 h_2)}{\partial t} + \frac{\partial(\rho_2 h_2 V_2)}{\partial x} = -\rho_2 W_e$$

Cenedese and Adduce, Journal of Fluid Mechanics 2008
Cenedese & Adduce, Journal of Physical Oceanography 2010



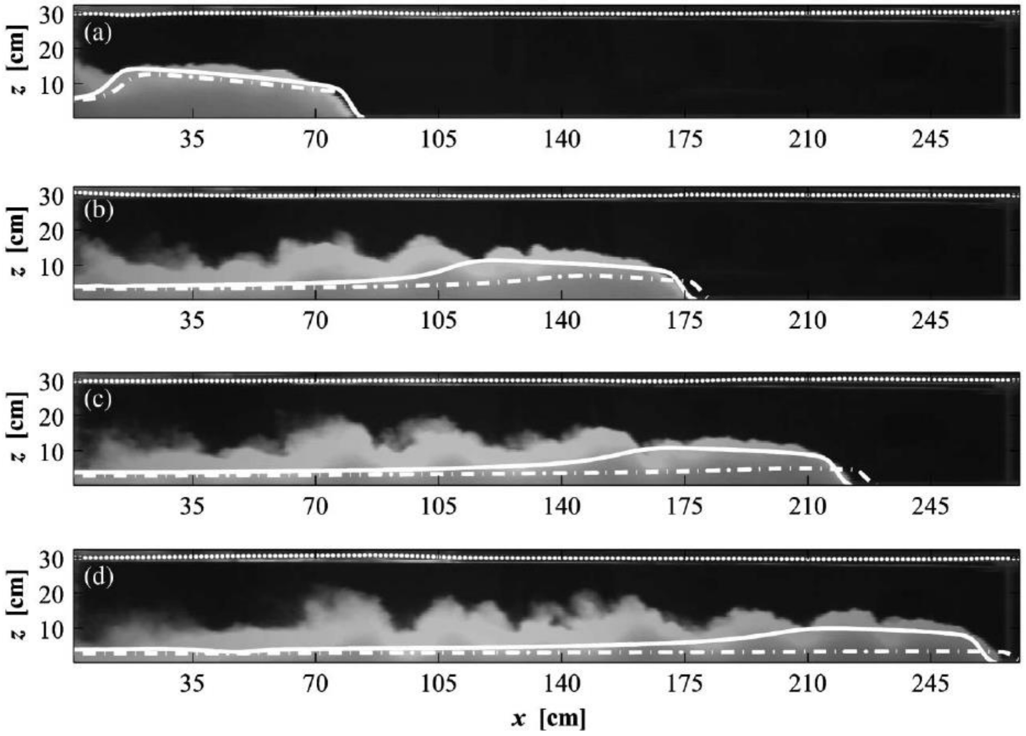
Turner JFM (1986)

Cenedese & Adduce JPO (2010)

EFFECT OF ENTRAINMENT ON GRAVITY CURRENTS SIMULATIONS

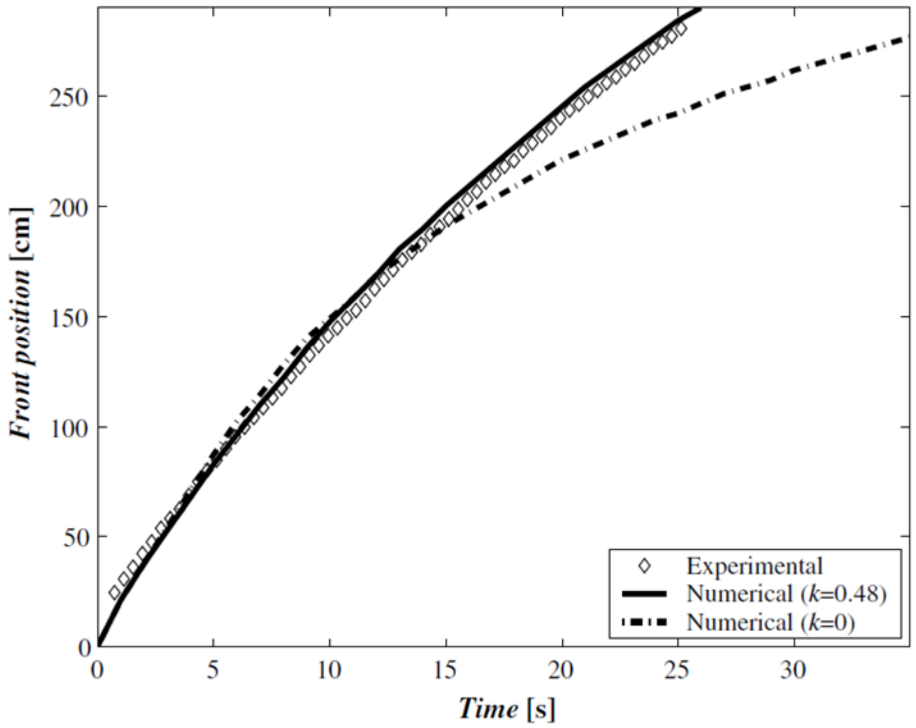
Numerical models not resolving small-scale mixing processes use entrainment parameterizations affecting the evolution of gravity currents (Ross et al., JFM 2006; Adduce et al., JHE 2012).

Adduce, Sciortino & Proietti, Journal of Hydraulic Engineering 2012



Solid white line: simulation with entrainment

Dash-dot white line: simulation without entrainment

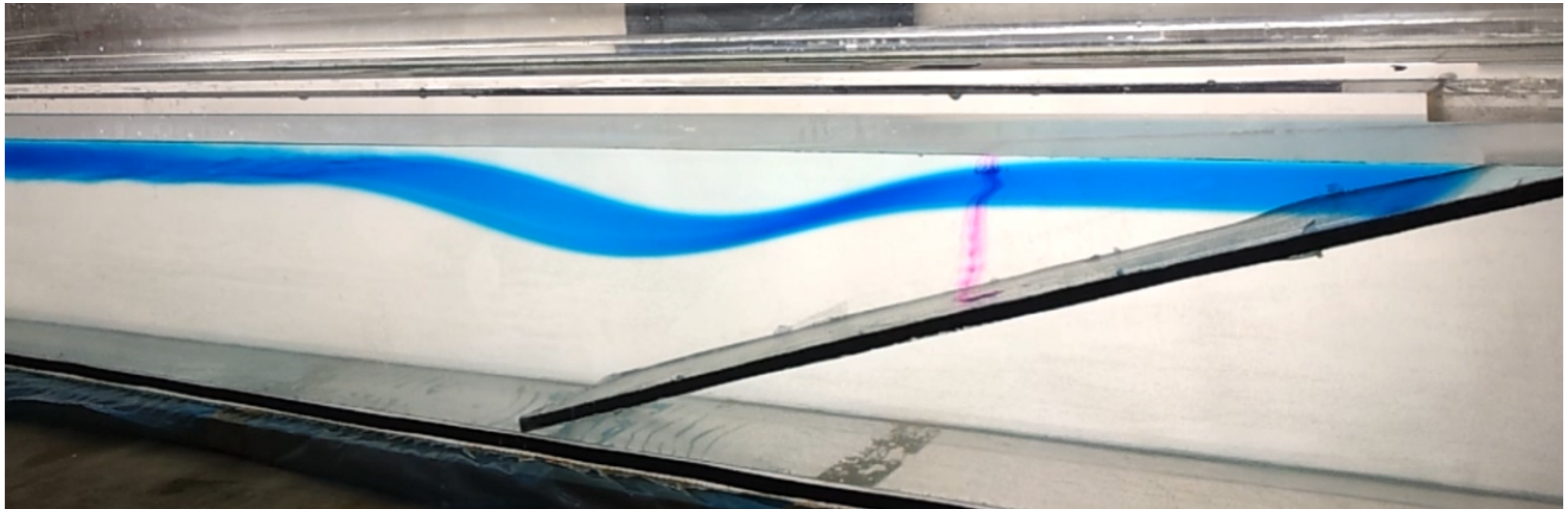


Solid black line: simulation with entrainment

Dash-dot black line: simulation without entrainment

GRAVITY CURRENTS FLOWING UP A SLOPE

- The sea breeze flowing over coastal lands
- Estuarine salt wedge which can occur at the mouth of rivers
- Internal waves breaking while approaching a constant upslope



La Forgia, Adduce & Falcini, Advances in Water Resources 2018

GRAVITY CURRENTS FLOWING UP A SLOPE

- The sea breeze flowing over coastal lands
- Estuarine salt wedge which can occur at the mouth of rivers
- Internal waves breaking while approaching a constant upslope

What is the upslope effect on the dynamics of a gravity current?

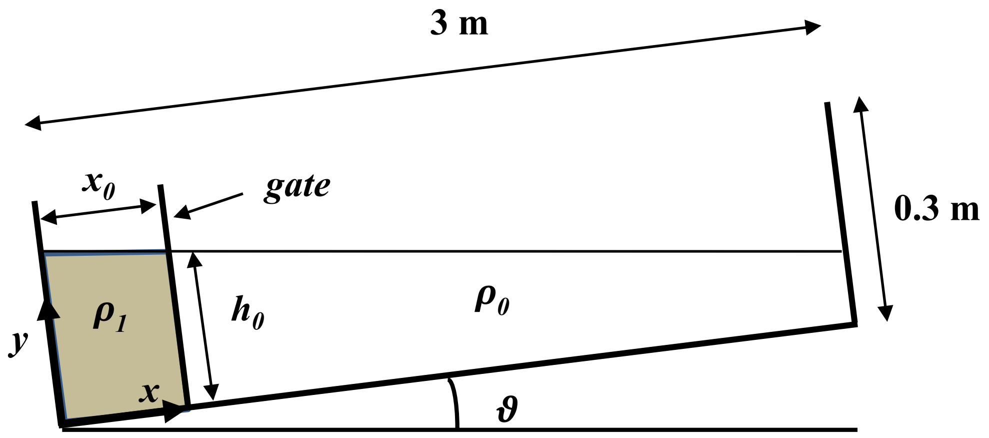
Does an upslope affect the entrainment in gravity currents?

THE LOCK-EXCHANGE EXPERIMENT

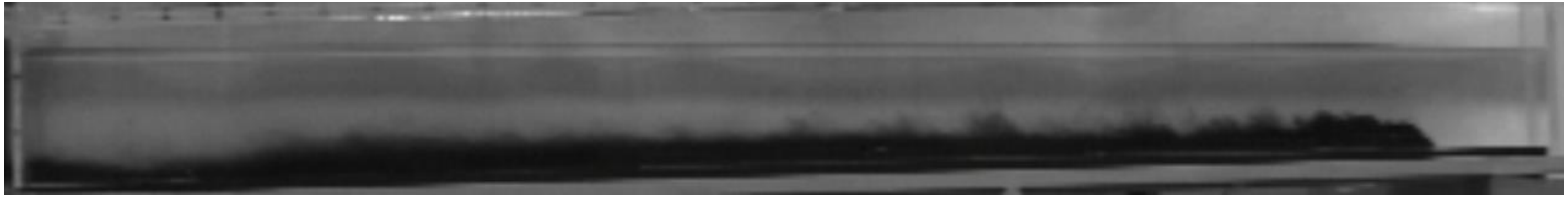
Phases of development of a lock-release gravity current

I	**Slumping Phase**	$x_f \sim t^1$
II	**Self-similar phase**	$x_f \sim t^{2/3}$
III	**Viscous Phase**	$x_f \sim t^{1/5}$

GRAVITY CURRENT FLOWING UP A SMALL SLOPE



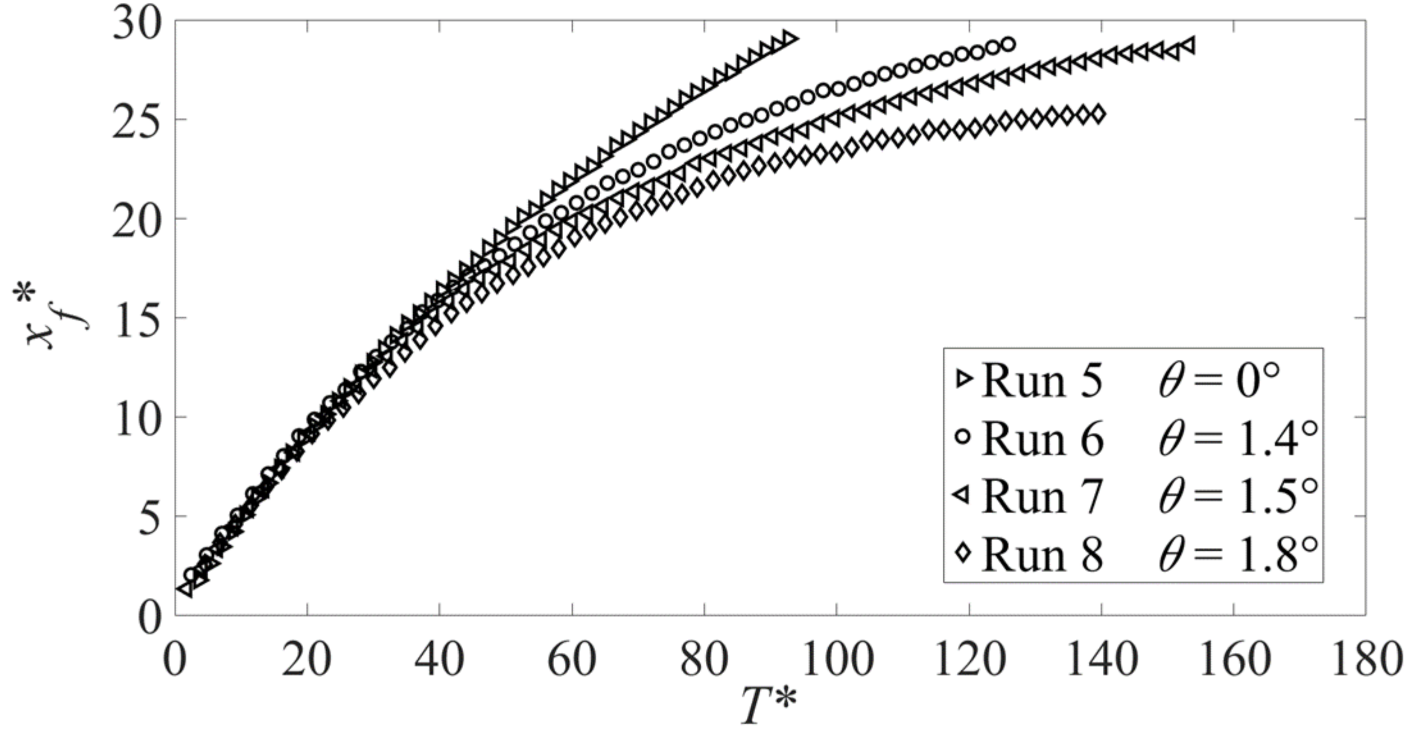
Lombardi, Adduce, Sciortino & La Rocca, Physics of Fluids 2015



Laboratory experiments performed at the Hydraulics Laboratory of Roma Tre University

FRONT POSITION VS TIME

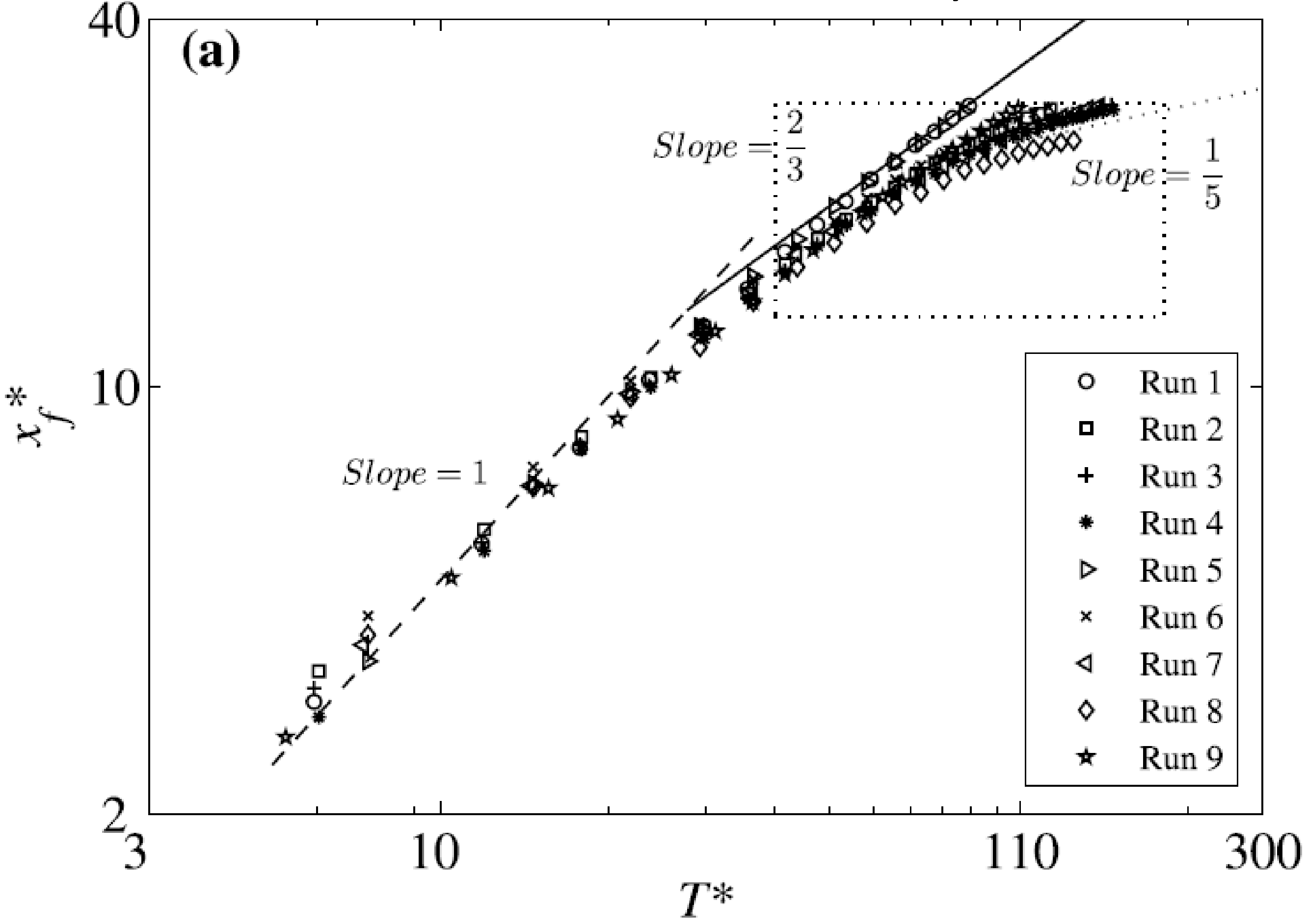
Lombardi, Adduce, Sciortino & La Rocca, Physics of Fluids 2015



$$x_f^* = \frac{x_f - x_0}{x_0} \qquad T^* = \frac{t}{t_0} \qquad t_0 = \frac{x_0}{\sqrt{g_0' h_0}}$$

COMPARISON WITH THEORY

Lombardi, Adduce, Sciortino & La Rocca, Physics of Fluids 2015



$x_f^* = \frac{x_f - x_0}{x_0}$ $T^* = \frac{t}{t_0}$ $t_0 = \frac{x_0}{\sqrt{g_0' h_0}}$

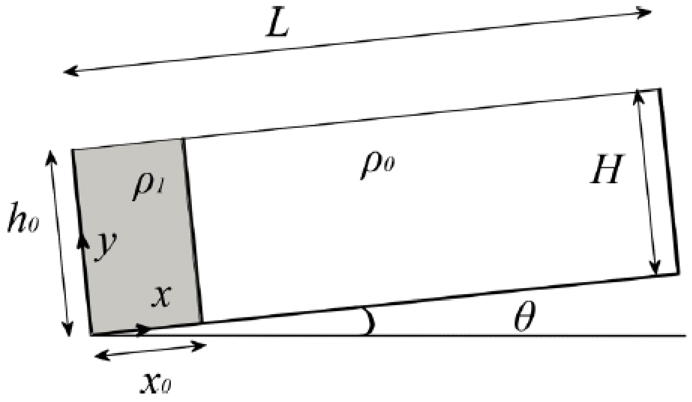
LABORATORY EXPERIMENTS AND 3D LES

Ottolenghi, Adduce, Inghilesi, Armenio & Roman, Physics of Fluids 2016
Ottolenghi, Adduce, Roman & Armenio, Ocean Modelling 2017

Name	θ [±]	g_0' [m/s^2]	x_0 [m]	$R=h_0/x_0$	$\Phi=h_0/H$	Re	Fr_{sl}	*EXP*
RUN0	0.0	0.29	0.1	2	1	48522	0.43	√
RUN1	1.4	0.29	0.1	2	1	48522	0.42	√
RUN2	2.5	0.29	0.1	2	1	48522	0.42	-
RUN3	5.0	0.29	0.1	2	1	48522	0.40	-
RUN4	1.4	0.29	0.2	1	1	48522	0.42	√
RUN5	2.5	0.29	0.2	1	1	48522	0.41	-
RUN6	1.4	0.29	0.3	0.67	1	48522	0.42	√
RUN7	2.5	0.29	0.3	0.67	1	48522	0.40	-
RUN8	1.4	0.29	0.2	1	0.5	17155	0.47	-
RUN9	2.5	0.29	0.2	1	0.5	17155	0.47	-

$$Re = \frac{u_b H}{\nu}$$

$$Fr_{sl} = \frac{U_{slu}}{\sqrt{g_0^{'} h_0}}$$



NUMERICAL MODEL – LES COAST

- **CONTINUITY EQUATION**

$$\frac{\partial \bar{u}_j}{\partial x_j} = 0$$

- **MOMENTUM EQUATION**

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_j \bar{u}_i}{\partial x_j} = -\frac{1}{\rho_0}\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\nu \frac{\partial \bar{u}_i}{\partial x_j}\right) - \frac{\rho'}{\rho_0} g \delta_{ij} - \frac{\partial \tau_{ij}}{\partial x_j}$$

- **DISPERSION OF SCALAR QUANTITIES EQUATION**

$$\frac{\partial \bar{s}}{\partial t} + \frac{\partial \overline{u_j} \bar{s}}{\partial x_j} = \frac{\partial}{\partial x_j}\left(k_S \frac{\partial \bar{s}}{\partial x_j}\right) - \frac{\partial \lambda_j}{\partial x_j}$$

- **STATE EQUATION**

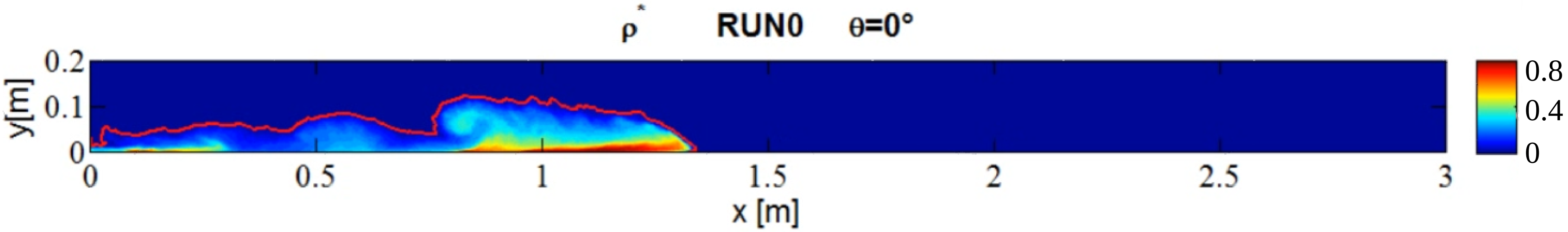
$$\rho = \rho_0[1 + \beta(s - s_0)]$$

$\bar{\bullet}$ = **filter operator**

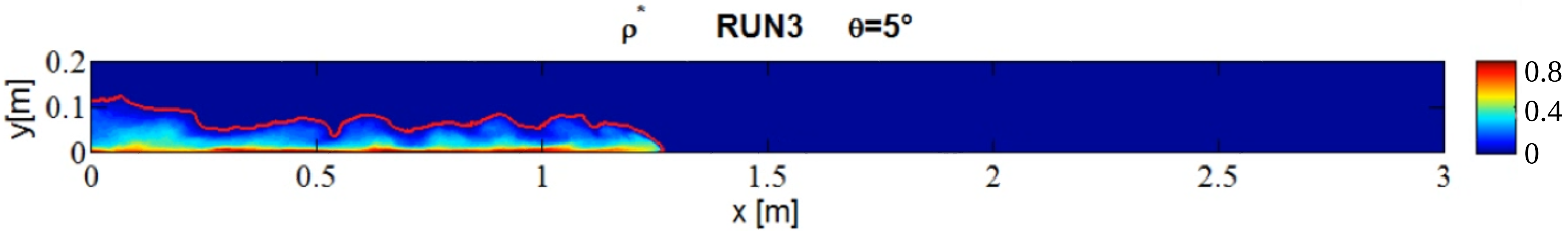
- ✓ **Boussinesq and ‘rigid lid’ approximations**
- ✓ **Smagorinsky dynamical model for the subgrid stresses**
- ✓ **Computational grid: n_x x n_y x n_z = 2048 x 128 x 64 cells with Δx=0.01H, 0.002H<Δy<0.01H and Δz=0.016H**

DYNAMICS OF A GRAVITY CURRENT FLOWING UP A SLOPE

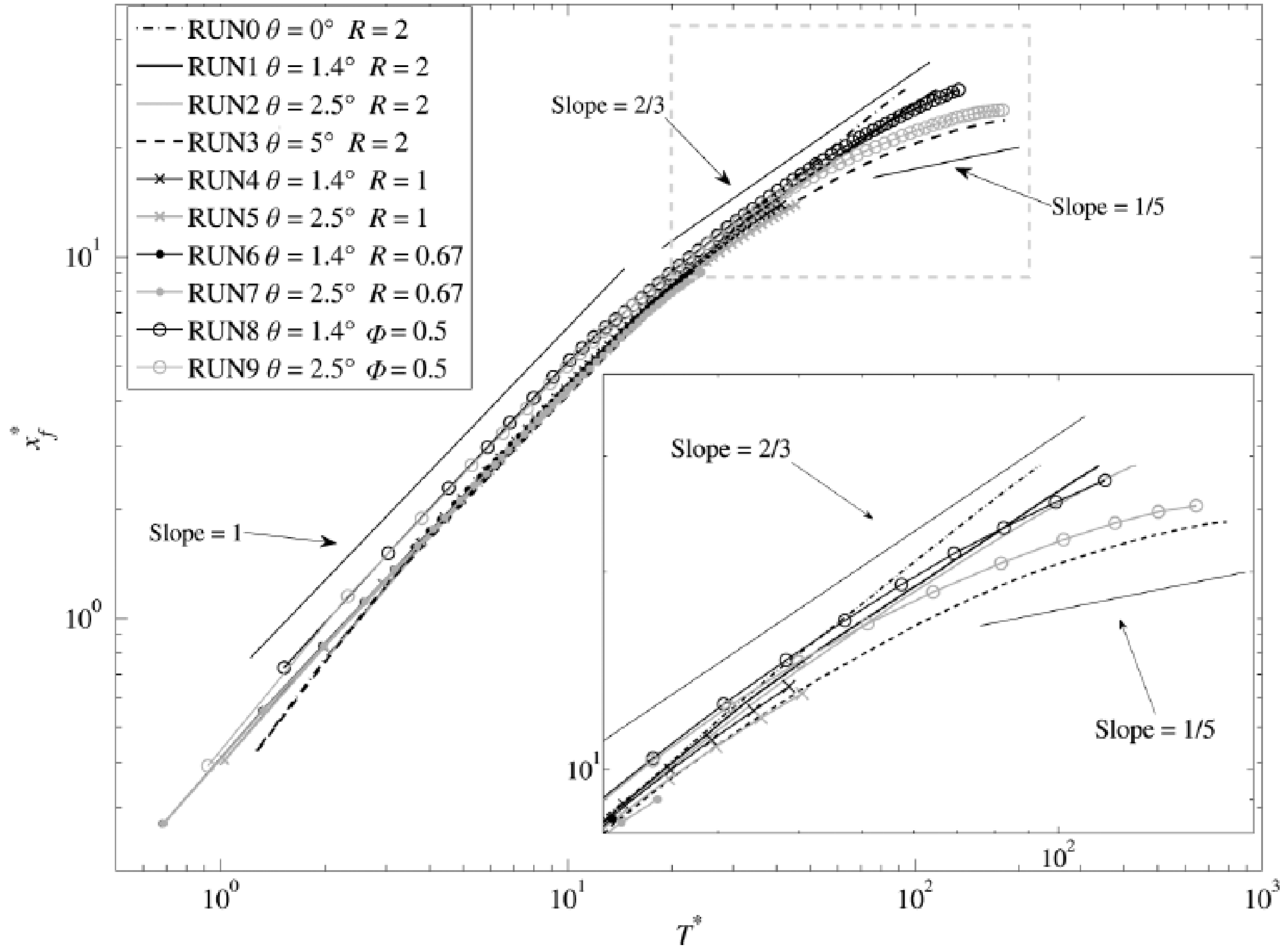
HORIZONTAL BED



UPSLOPE



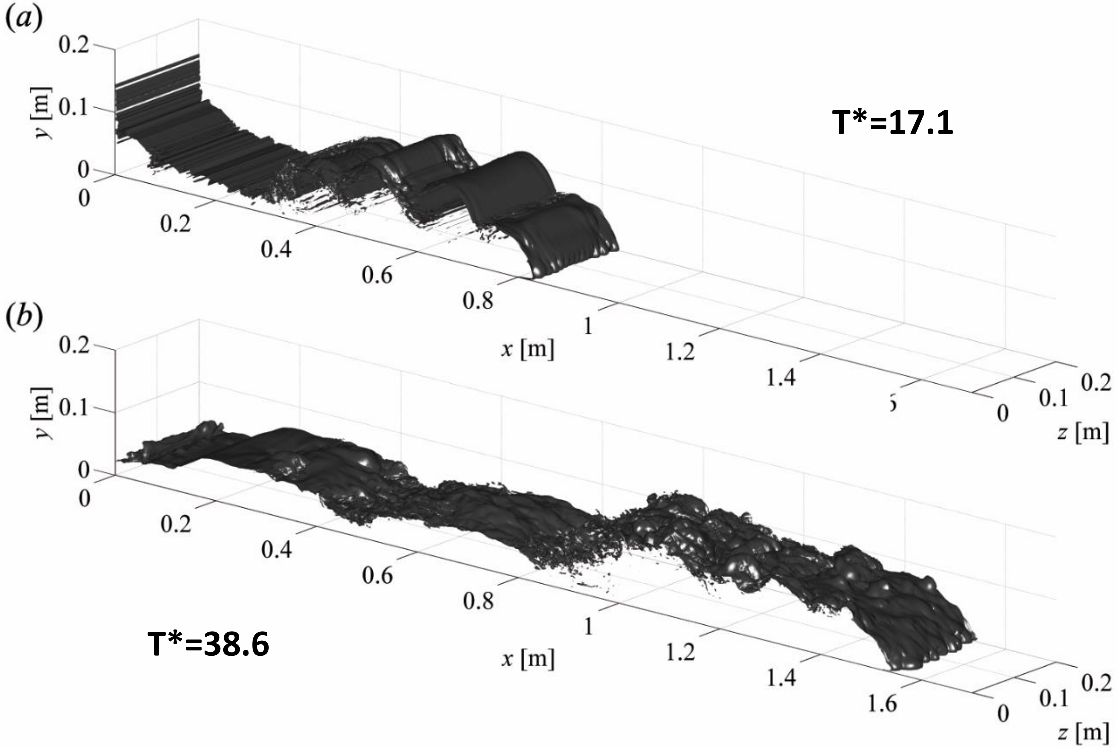
LES VS THEORY - PHASES IN A GRAVITY CURRENT



Ottolenghi, Adduce, Inghilesi, Armenio & Roman, Physics of Fluids 2016

INSTABILITIES DEVELOPMENT AT THE INTERFACE

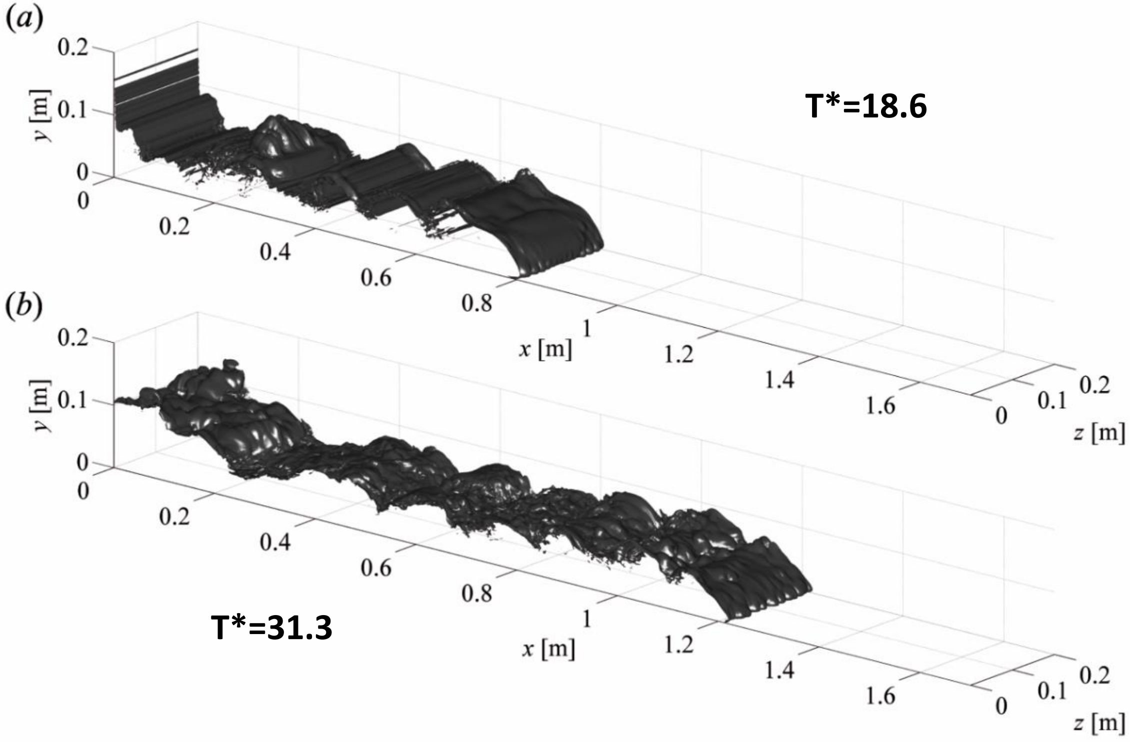
HORIZONTAL BED θ=0°



T*=17.1

T*=38.6

UPSLOPE θ=5°



T*=18.6

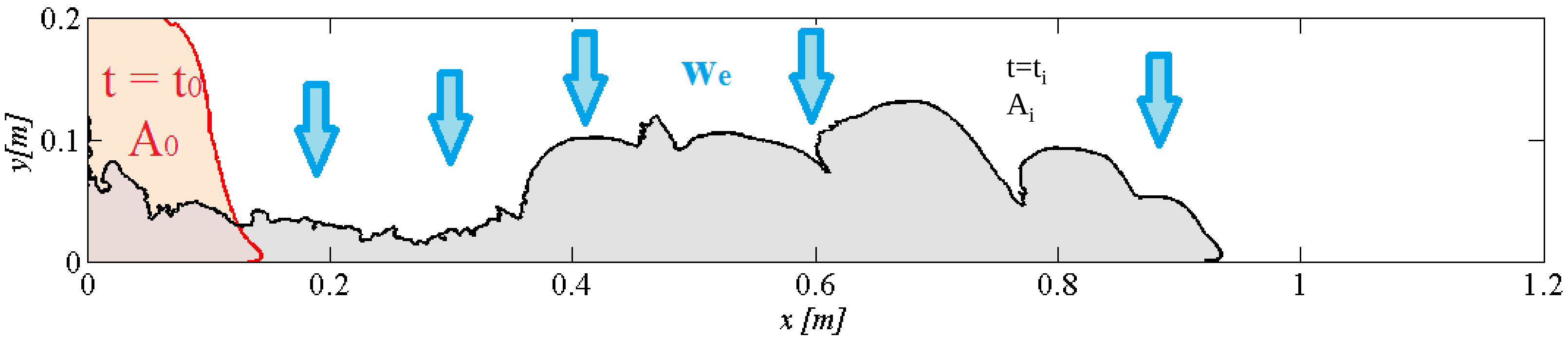
T*=31.3

Ottolenghi, Adduce, Roman & Armenio, Ocean Modelling 2017

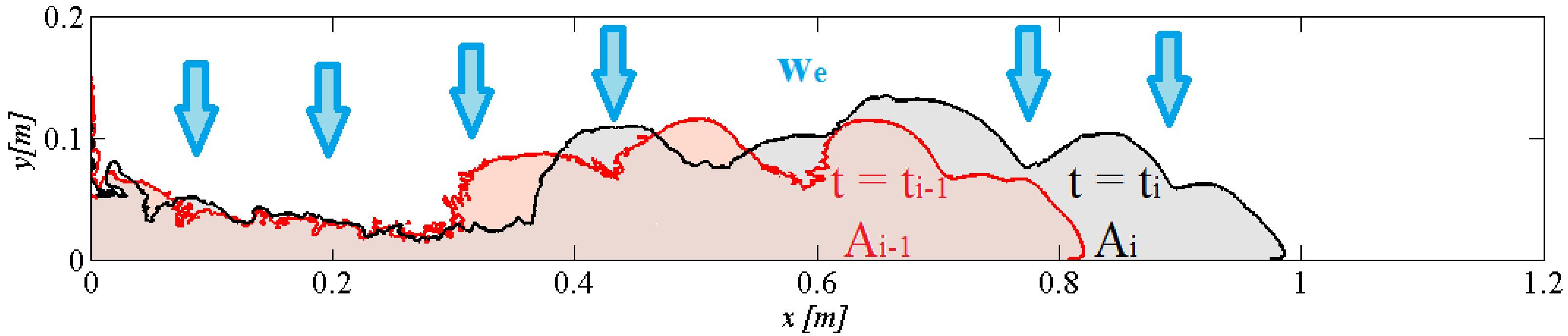
BULK AND LOCAL ENTRAINMENT PARAMETER

$$E = \frac{W_e}{U} \quad \Rightarrow \quad W_e = \frac{Q_e}{S} \quad \Rightarrow \quad Q_e = \frac{(A_i - A_0) \cdot \mathrm{d}}{t_i - t_0}$$

d= width of the tank



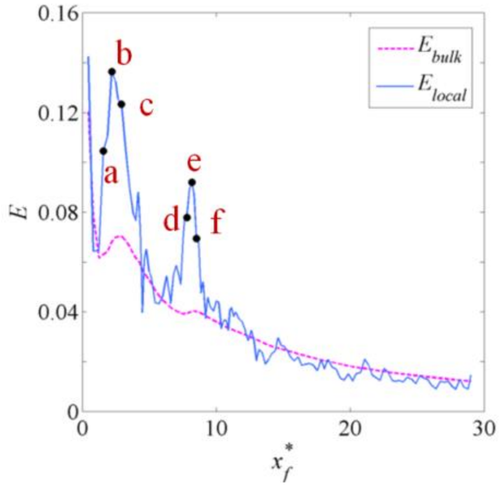
BULK ENTRAINMENT

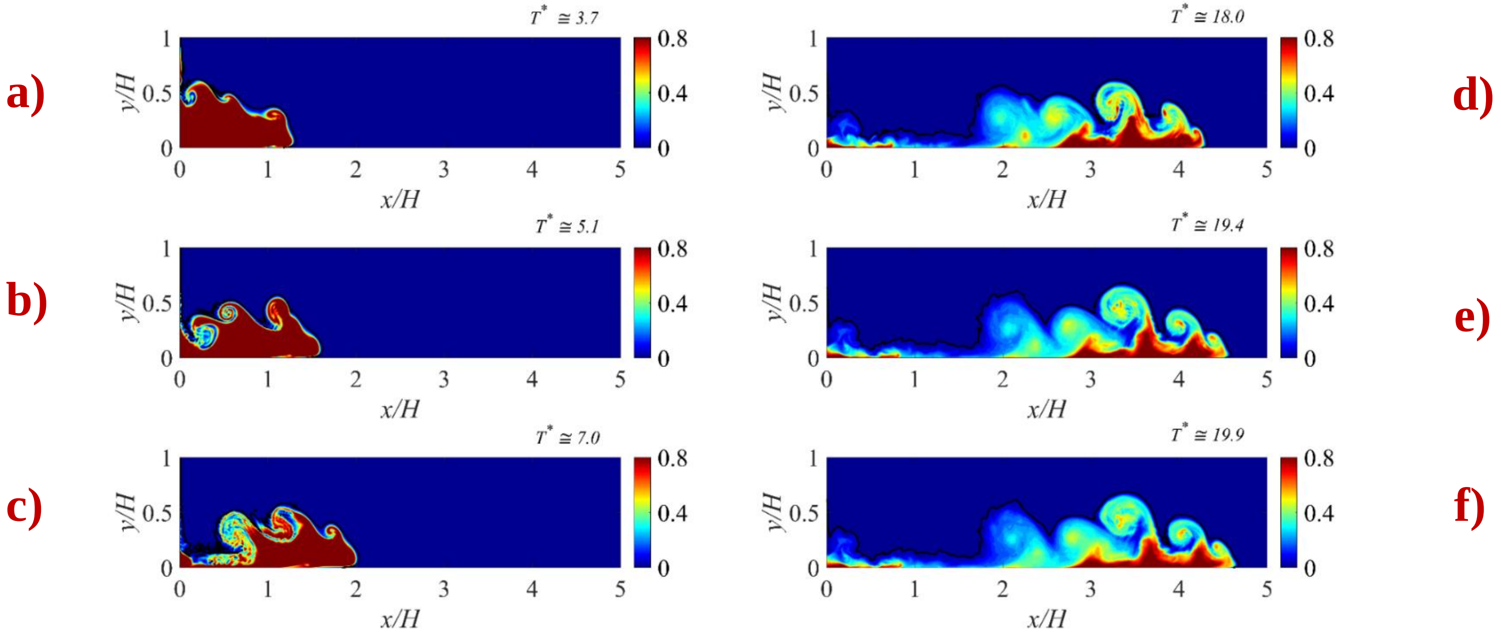


LOCAL ENTRAINMENT

BULK AND LOCAL ENTRAINMENT

HORIZONTAL BED

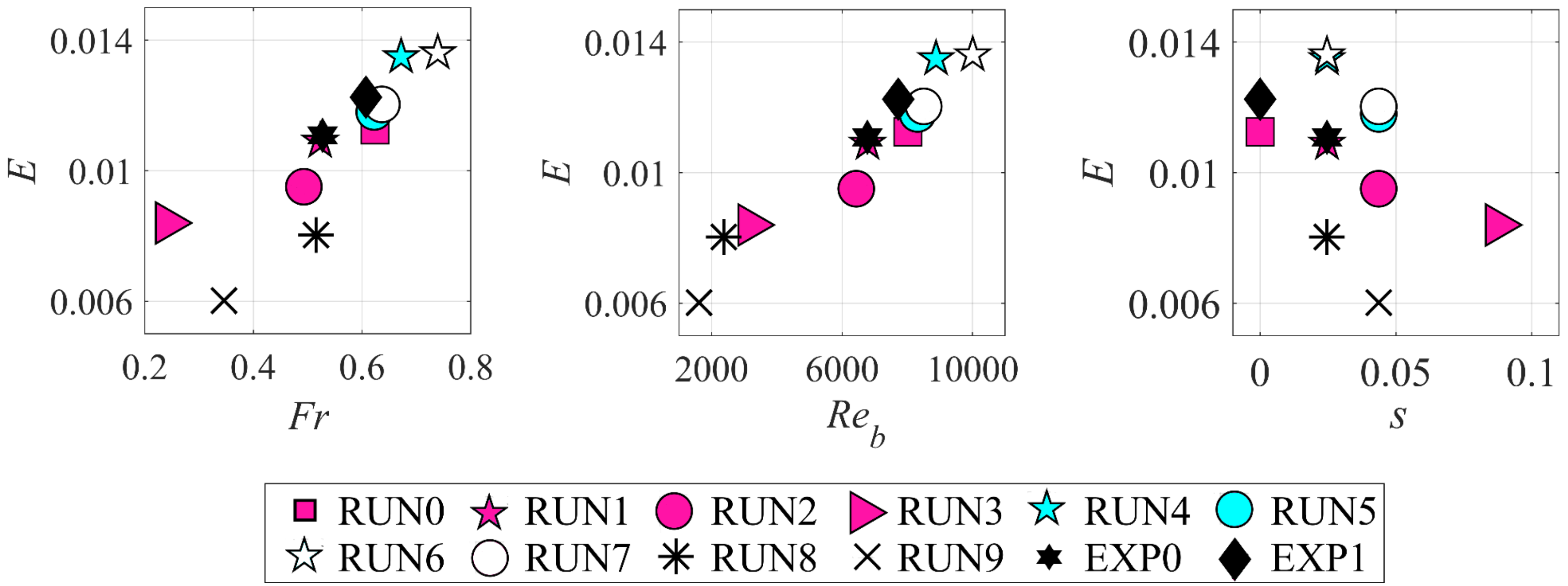




Ottolenghi, Adduce, Inghilesi, Armenio & Roman, Journal of Hydraulic Research 2016

BULK ENTRAINMENT PARAMETER

Ottolenghi, Adduce, Inghilesi, Armenio & Roman, Physics of Fluids 2016

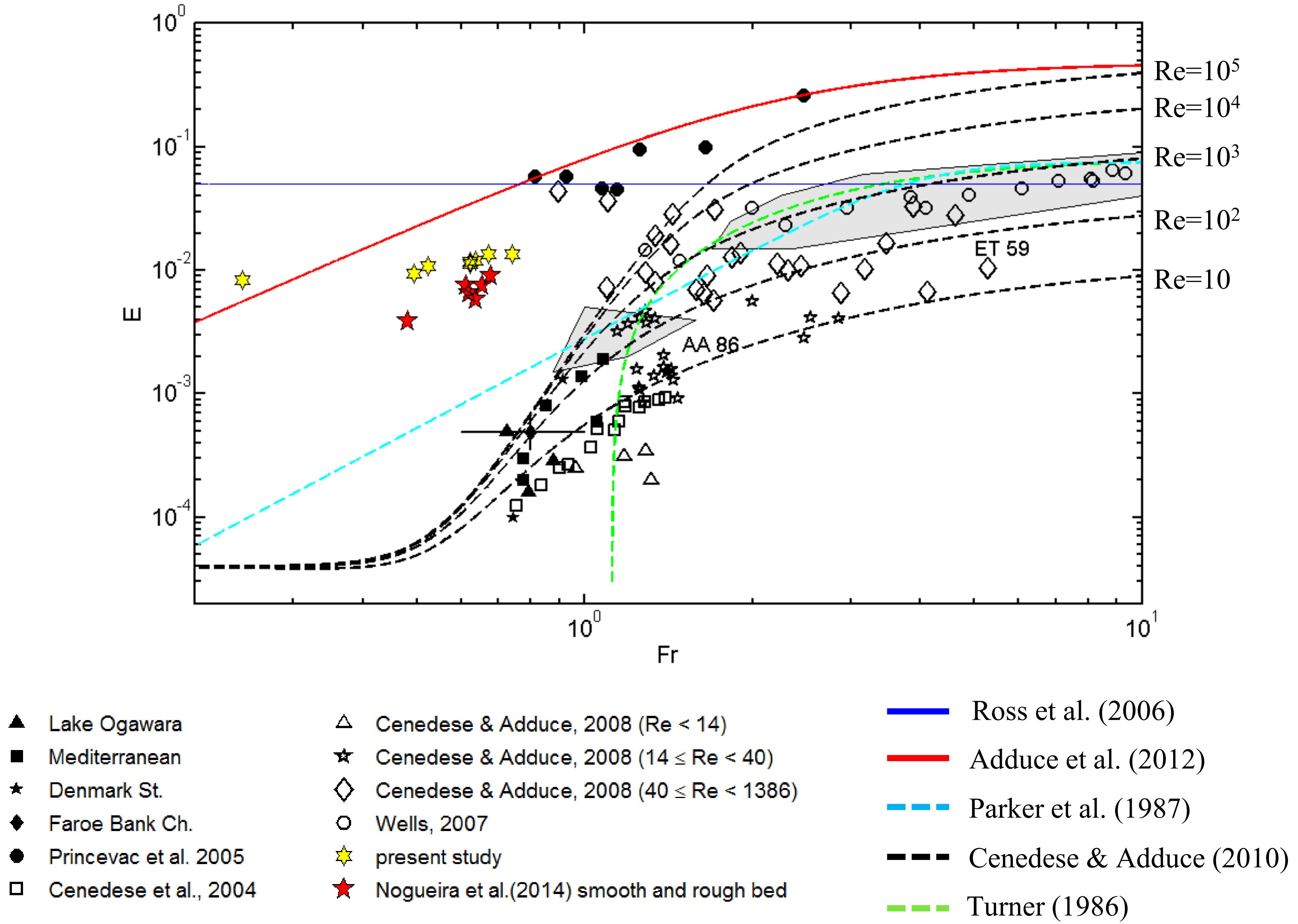


$$Fr = \frac{U_{bulk}}{\sqrt{g'_m h_0/2}}$$

$$Re_b = \frac{U_{bulk}\frac{h_0}{2}}{\nu}$$

$$g'_m = \frac{g'_0 + g'_{end}}{2}$$

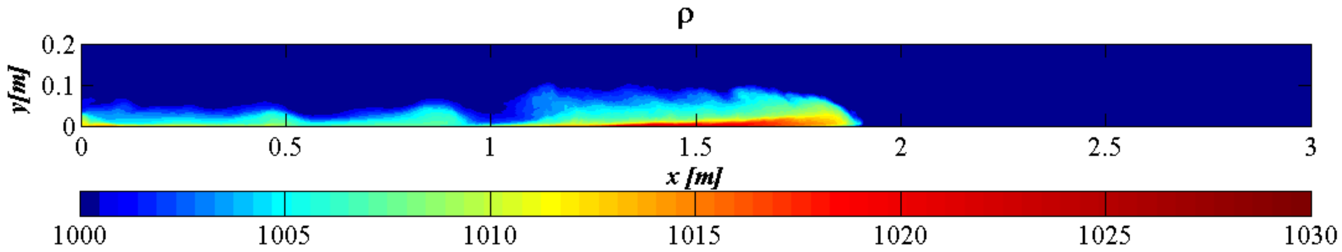
ENTRAINMENT PARAMETERIZATIONS



MIXING IN A GRAVITY CURRENT

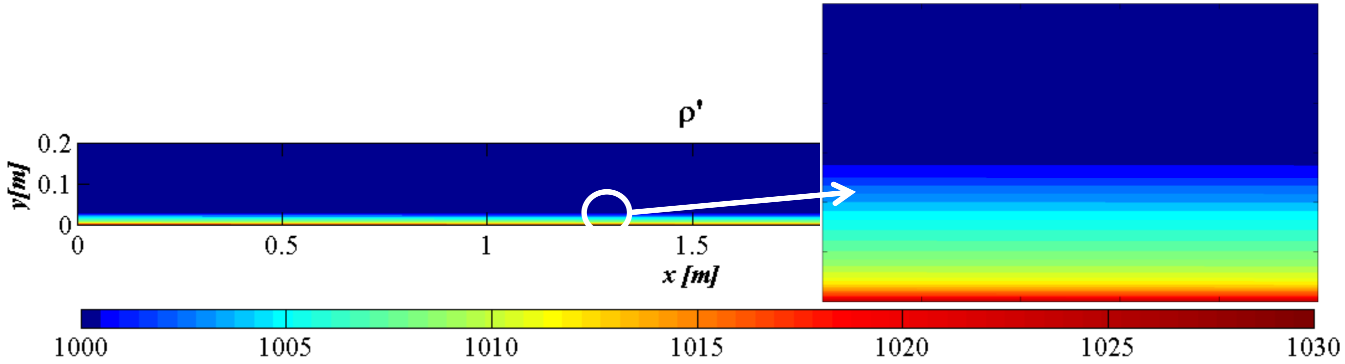
POTENTIAL ENERGY

$$E_p(t) = g \int \rho(x, y, z, t)\, y\, dV$$



BACKGROUND POTENTIAL ENERGY

$$E_b(t) = g \int \rho'(x, y, z, t)\, y\, dV$$



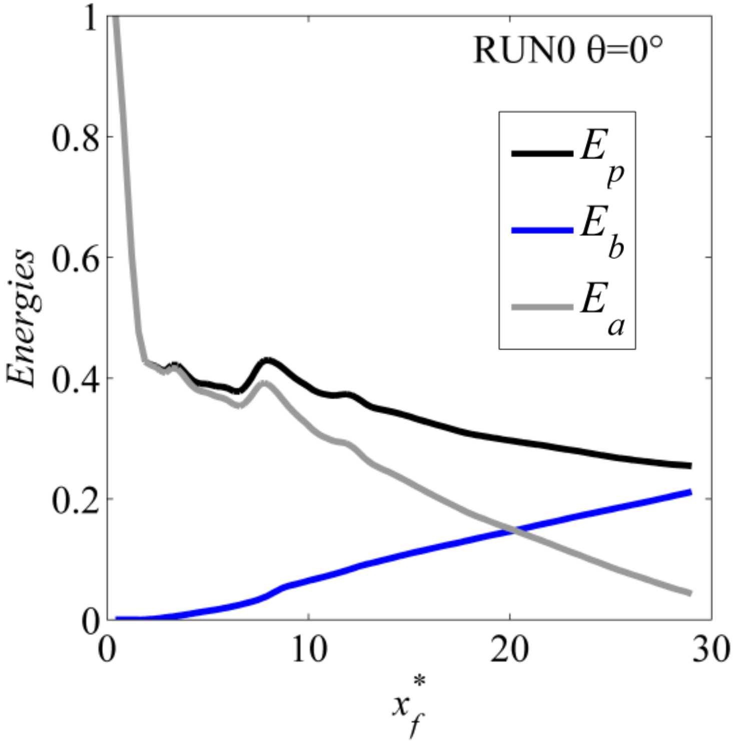
E_b results by a spatial redistribution of the density field from ρ to ρ', with fluid particles set in the minimum state of the potential energy (Winters et al., JFM 1995)

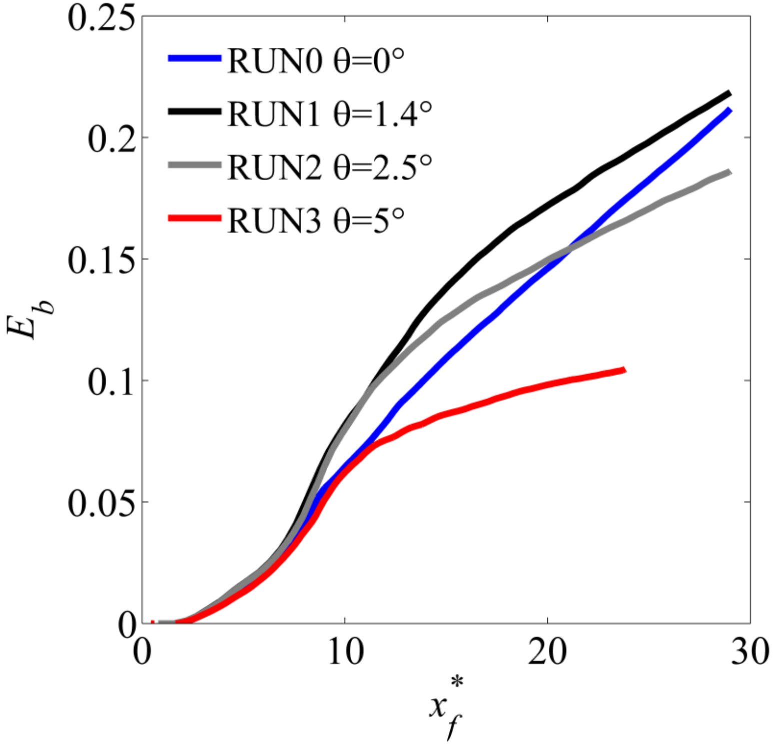
AVAILABLE ENERGY

$$E_a = E_p - E_b$$

E_a can be used to transfer potential energy to kinetic energy through adiabatic processes in a reversible way

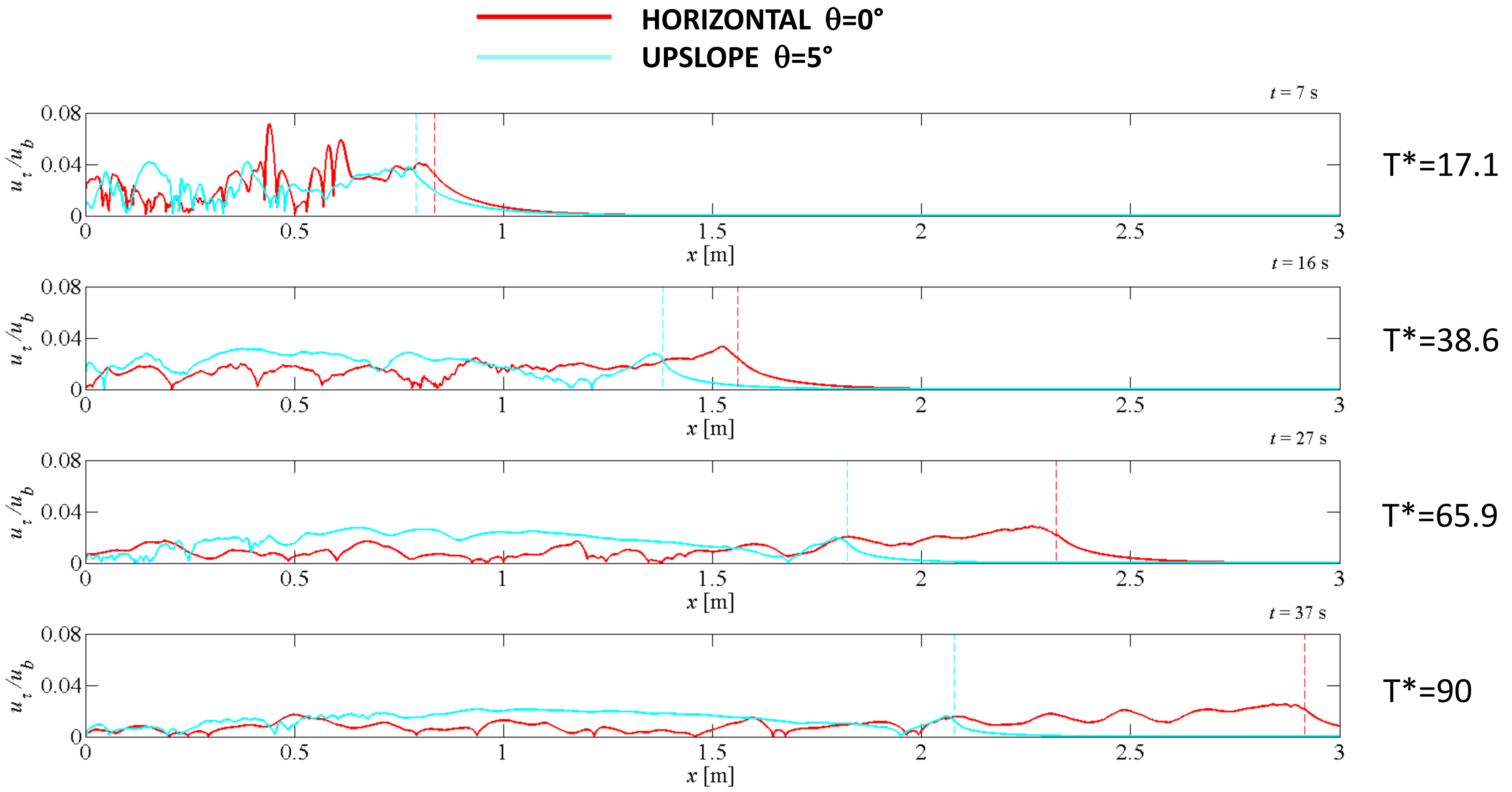
MIXING IN A GRAVITY CURRENT





Ottolenghi, Adduce, Inghilesi, Armenio & Roman, Physics of Fluids 2016

UPSLOPE EFFECT ON THE FRICTION VELOCITY

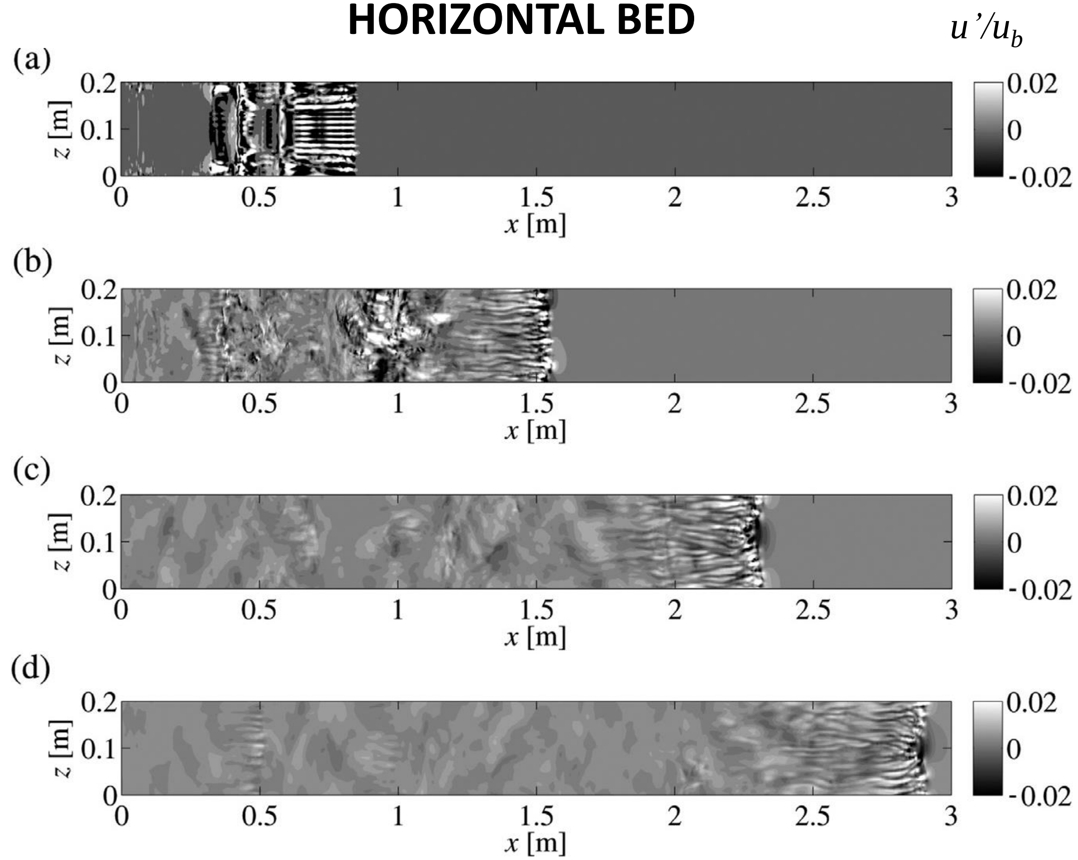


$u_\tau = \sqrt{|\tau_b|/\rho}$ $\quad$ $u_b = \sqrt{g_0' h_0}$

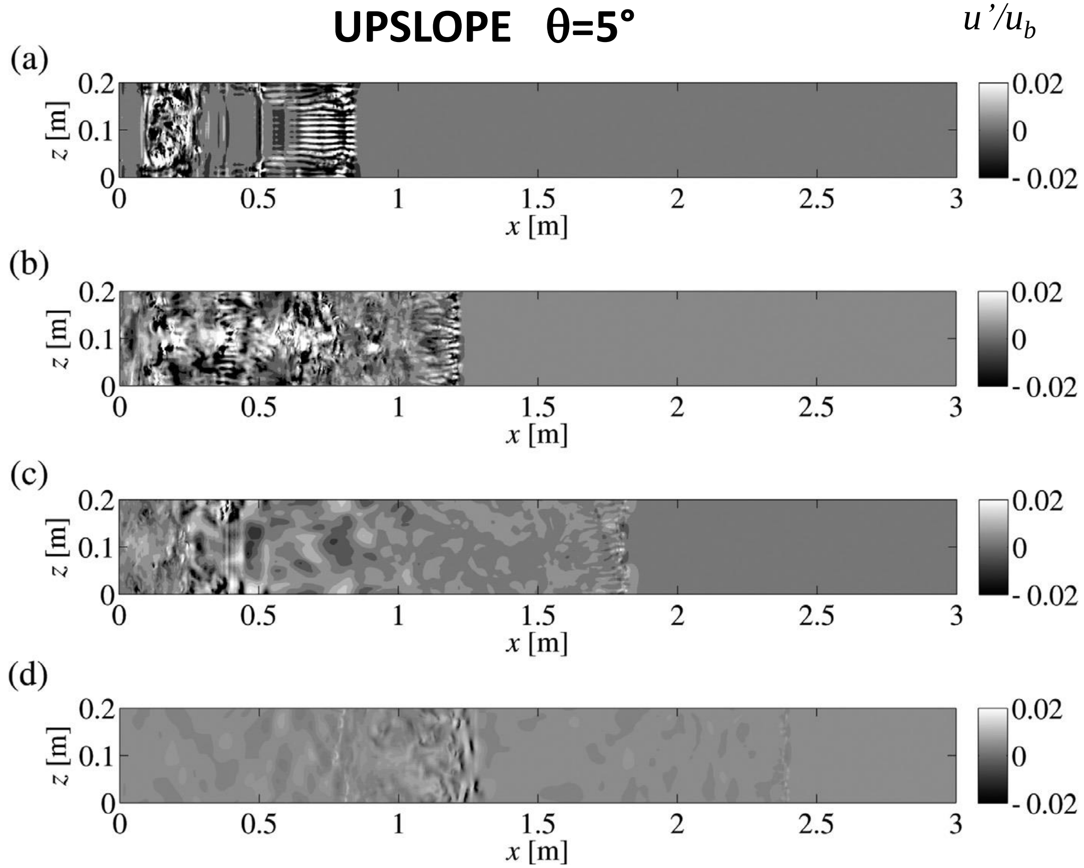
Ottolenghi, Adduce, Roman & Armenio, Ocean Modelling 2017

UPSLOPE EFFECT ON NEAR-WALL TURBULENT STRUCTURES

HORIZONTAL BED



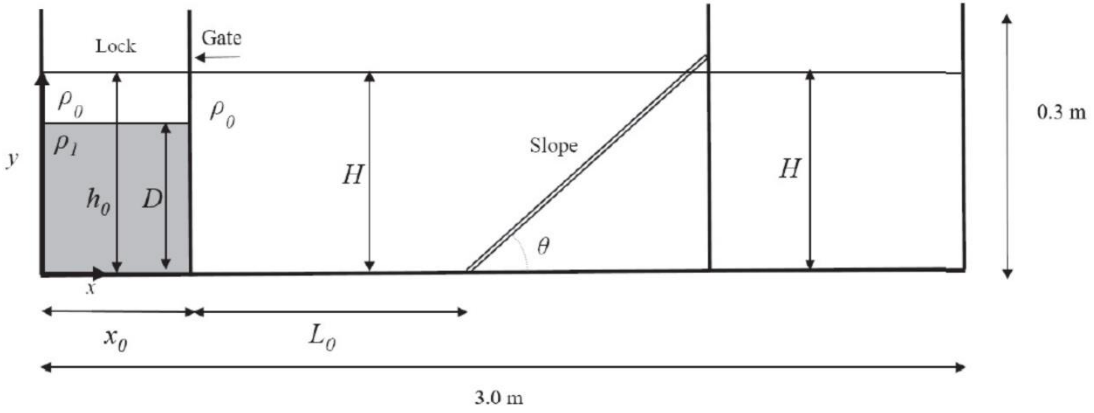
UPSLOPE θ=5°



$y^* = y/H = 0.001$

Ottolenghi, Adduce, Roman & Armenio, Ocean Modelling 2017

LABORATORY EXPERIMENTS



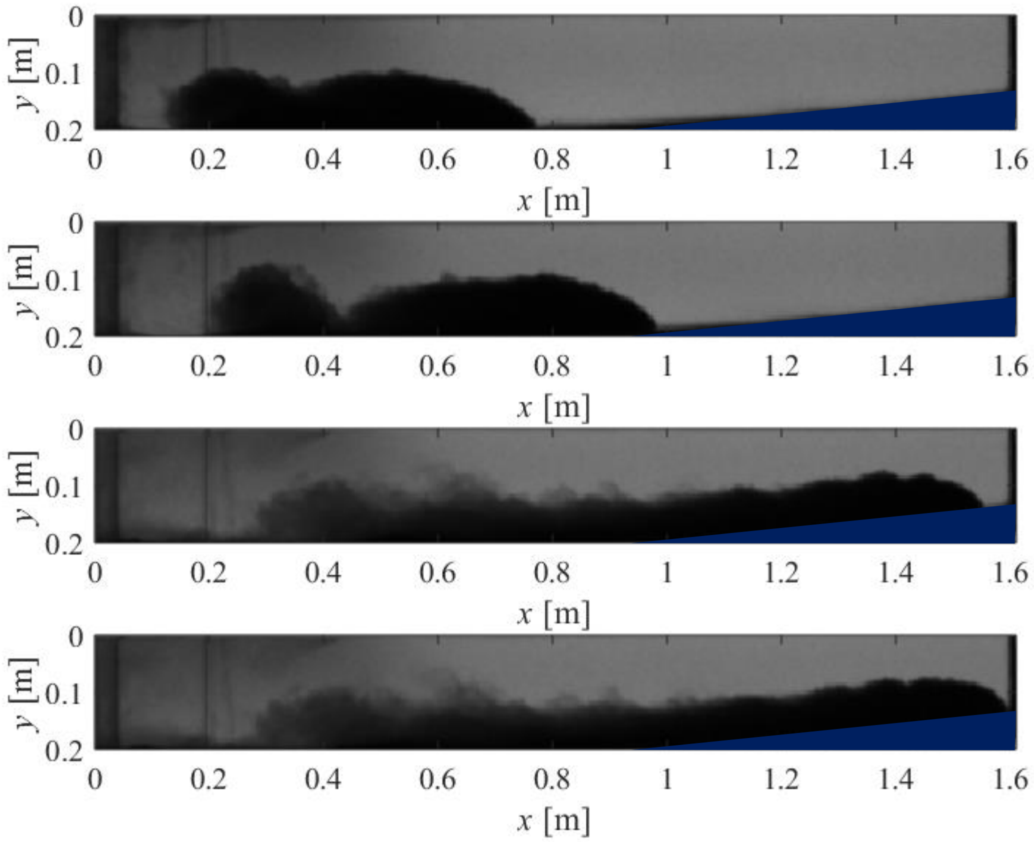
Depth ratio $\Phi = \frac{D}{H}$

<table>
<tr><th>Φ</th><th colspan="8">Θ</th><th>Re</th></tr>
<tr><td>1</td><td>0</td><td>1.4</td><td>2.5</td><td>5</td><td>7.5</td><td>10</td><td>15</td><td>20</td><td>48500</td></tr>
<tr><td>0.7</td><td rowspan="3">0</td><td rowspan="3">1.4</td><td rowspan="3">5</td><td rowspan="3">10</td><td rowspan="3">20</td><td rowspan="3" colspan="3"></td><td>28400</td></tr>
<tr><td>0.5</td><td>17150</td></tr>
<tr><td>0.3</td><td>7970</td></tr>
</table>

De Falco, Ottolenghi & Adduce, Journal of Hydraulic Engineering (in press)

GRAVITY CURRENT INTERACTING WITH A SMALL UPSLOPE

De Falco, Ottolenghi & Adduce, Journal of Hydraulic Engineering (in press)



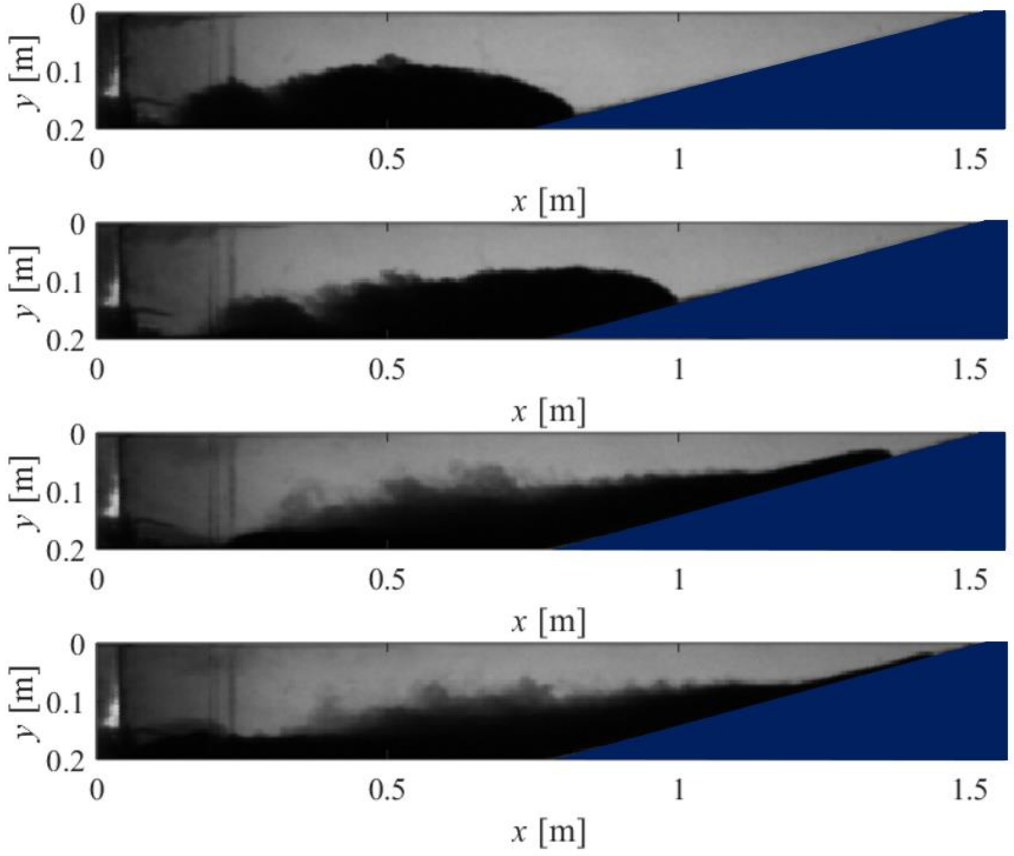
θ=5°

- **Most of the body of the dense current propagates upslope**
- **The head of the current becomes thinner, but it is still visible in the front region**
- **Development of instabilities at the interface**

GRAVITY CURRENT INTERACTING WITH A STEEP UPSLOPE

De Falco, Ottolenghi & Adduce, Journal of Hydraulic Engineering (in press)

- For large *ϴ*, the gravity current "feels" the upslope as an obstacle: part of the current flows upslope, while part of it is reflected.
- The head becomes thinner and thinner and no instabilities occur
- A backward flow develops: it is composed by the dense current, detached from the main flow due to gravity and the current which is reflected by the upslope.

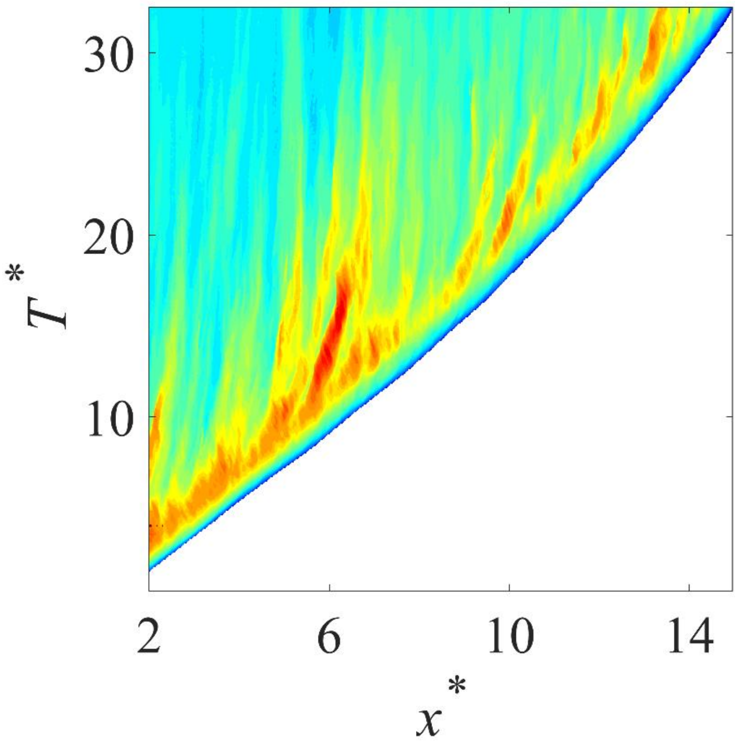


θ=20°

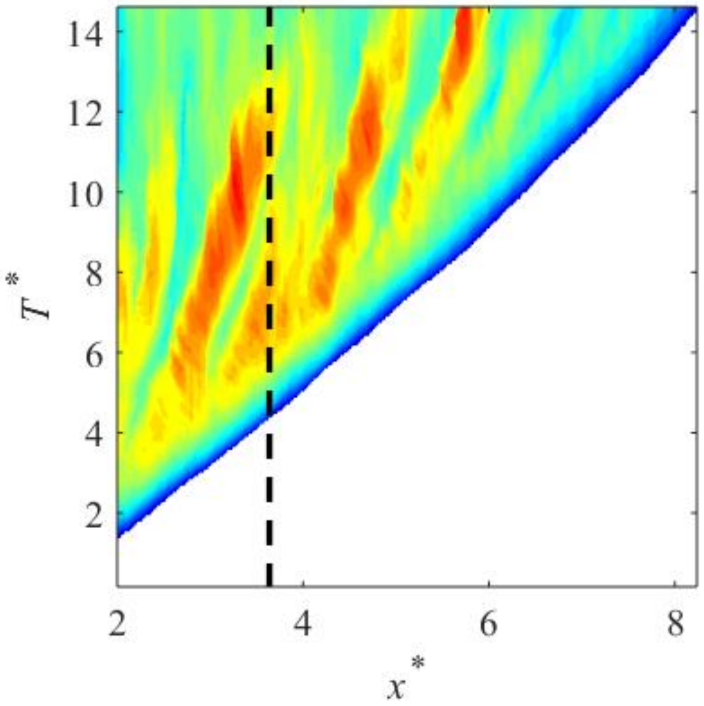
DIMENSIONLESS HEIGHT OF THE CURRENT

$$h^* = \frac{h(x,t)}{D}$$

HORIZONTAL BED

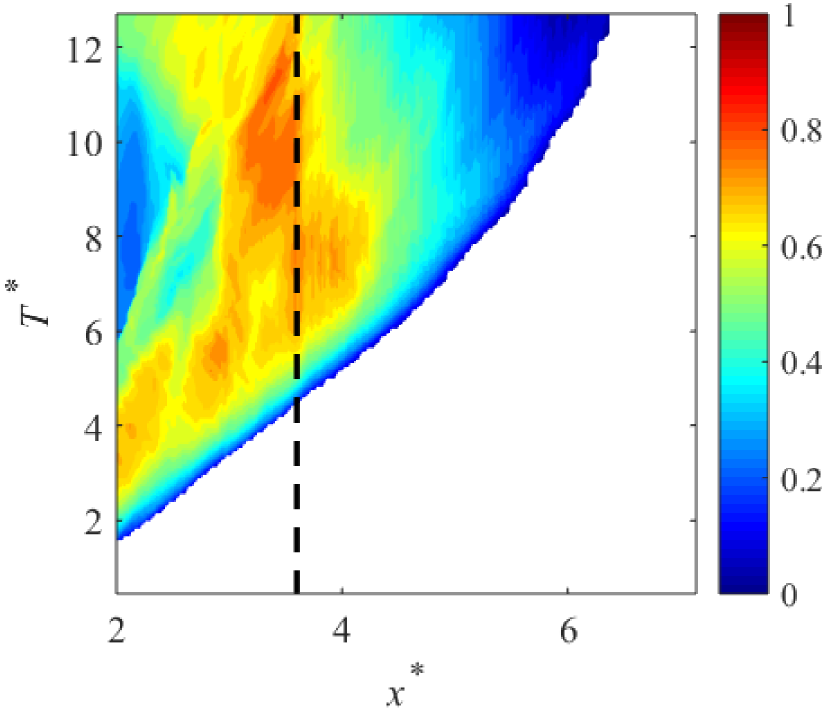


SMALL UPSLOPE



Φ=0.7 θ=5°

STEEP UPSLOPE



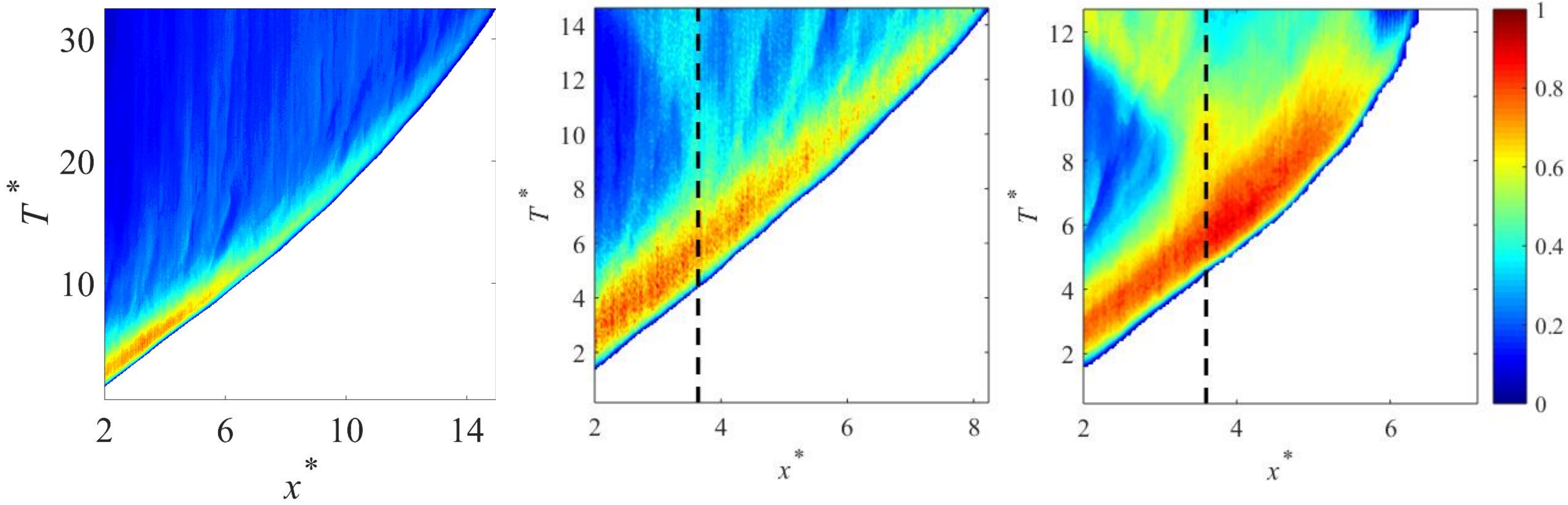
Φ=0.7 θ=20°

De Falco, Ottolenghi & Adduce, Journal of Hydraulic Engineering (in press)

DEPTH-AVERAGED DENSITY FIELDS

$$\overline{\rho_v}^* = \frac{\overline{\rho_v}(x,t) - \rho_0}{\rho_1 - \rho_0}$$

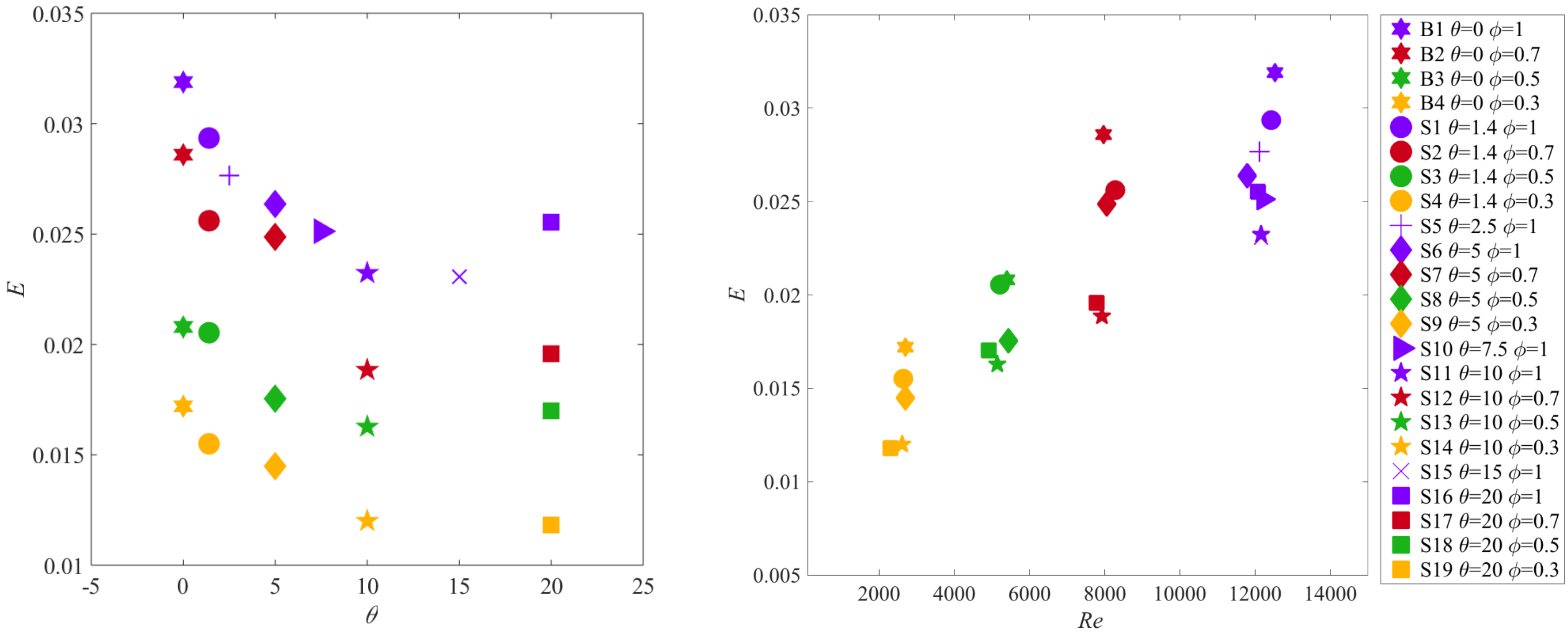
HORIZONTAL BED **SMALL UPSLOPE** **STEEP UPSLOPE**



Φ=0.7 *θ=5°* *Φ=0.7* *θ=20°*

De Falco, Ottolenghi & Adduce, Journal of Hydraulic Engineering (in press)

ENTRAINMENT PARAMETER

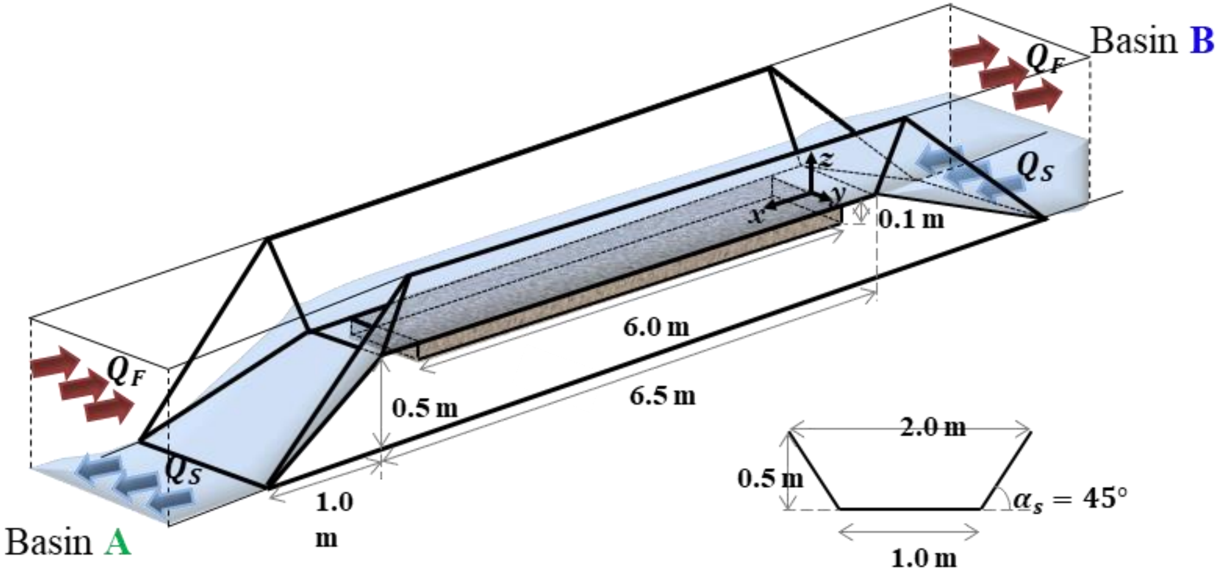


De Falco, Ottolenghi & Adduce, Journal of Hydraulic Engineering (in press)

ROTATING EXCHANGE FLOWS INTERACTING WITH A MOBILE BED

Experimental facility: Coriolis Rotating Platform at LEGI

- 13 m diameter × 1.2 m deep rotating tank at LEGI, Grenoble
- 6.5 m long × 2 m (1 m) wide × 0.5 m deep trapezoidal channel
- Impoundment (river) A and marine B basins with fresh and salt water inflows at opposite ends of channel
- 0.1 m deep sediment trap for the experiments with an erodible bed



Team members of the Hydralab+ Project:

Claudia Adduce (PI)

Alan Cuthbertson

Janek Laanearu

Daniela Malcangio

Eletta Negretti

Joel Sommeria

hydralab+

EFFECT OF ROTATION ON A GRAVITY CURRENT

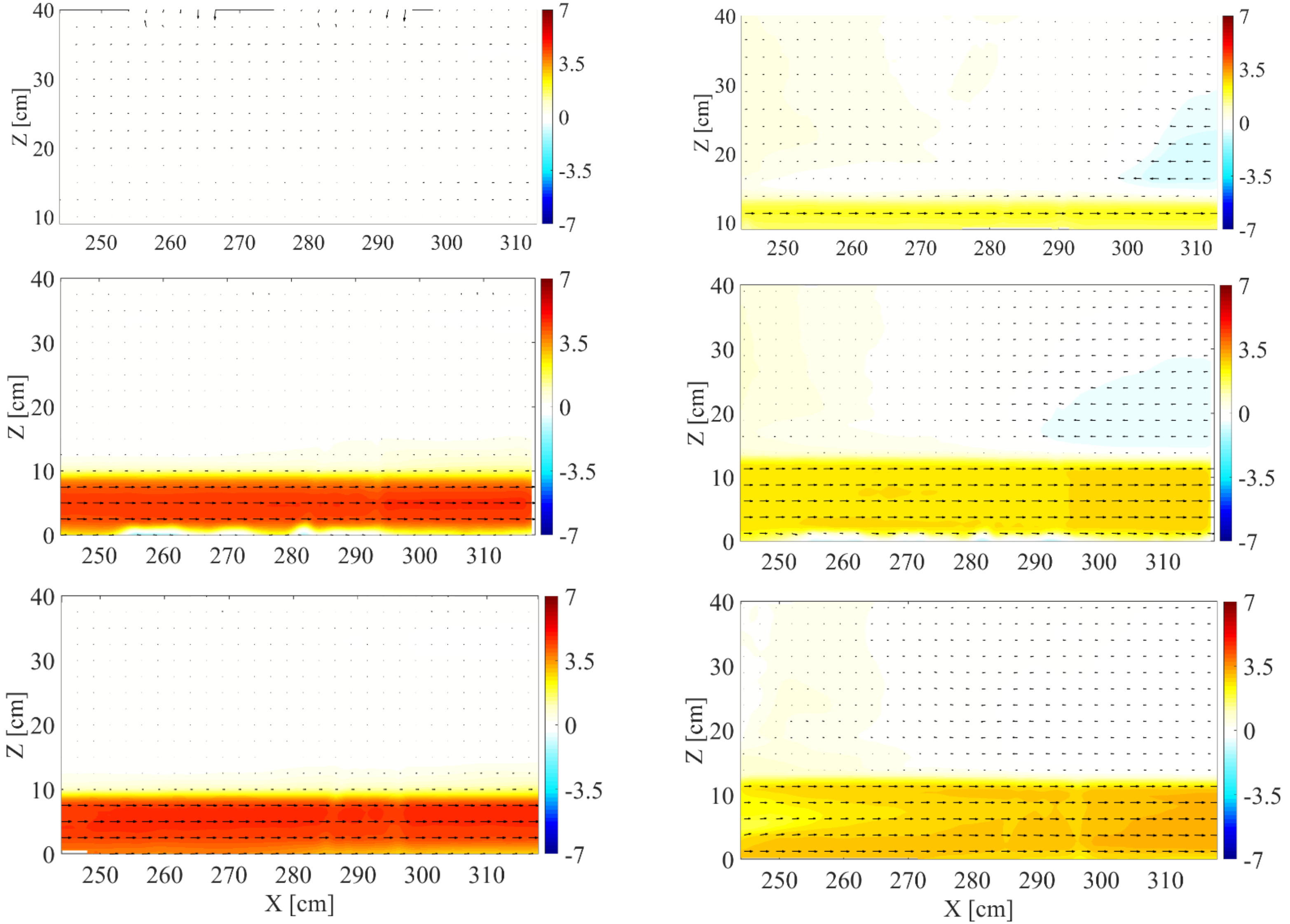
RIGID BED

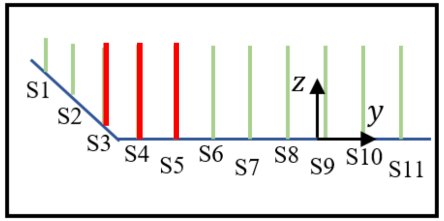
$\Omega = 0\ s^{-1}$ | $\Omega = 0.05\ s^{-1}$

S3

S4

S5

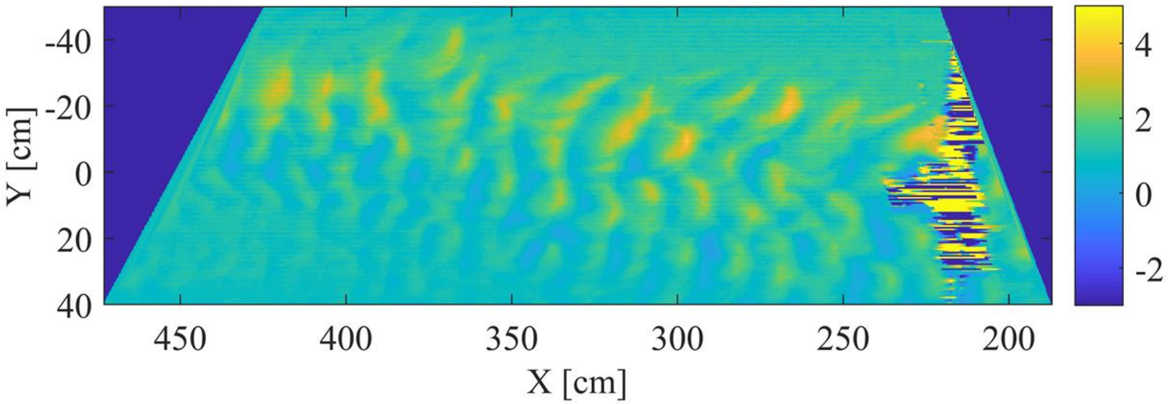




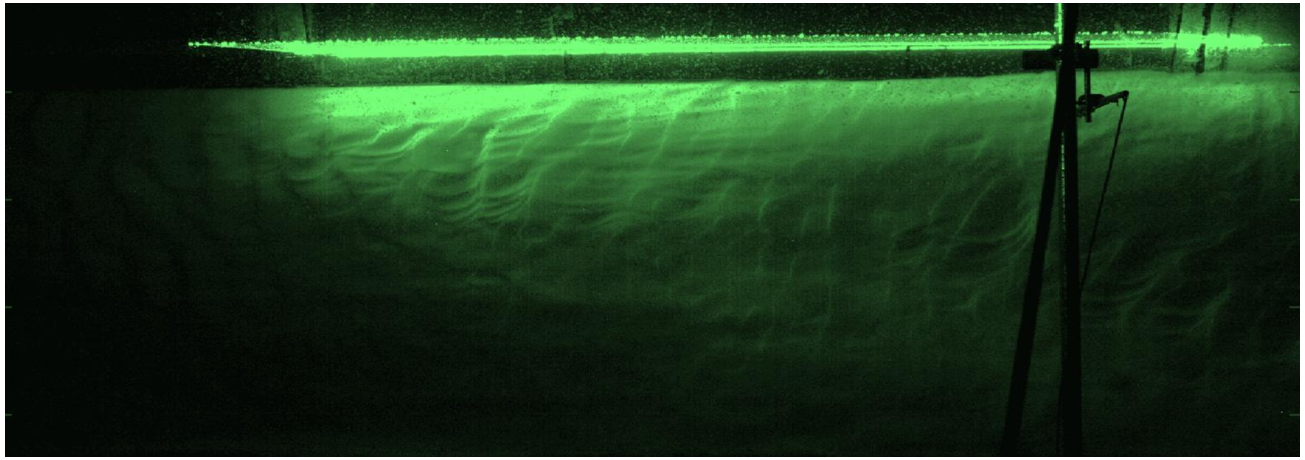
EFFECT OF ROTATION ON THE SEDIMENT BED

GRAVITY CURRENT FLOWING OVER AN ERODIBLE BED

$\Omega = 0.1\ s^{-1}$



Bed elevation (cm)

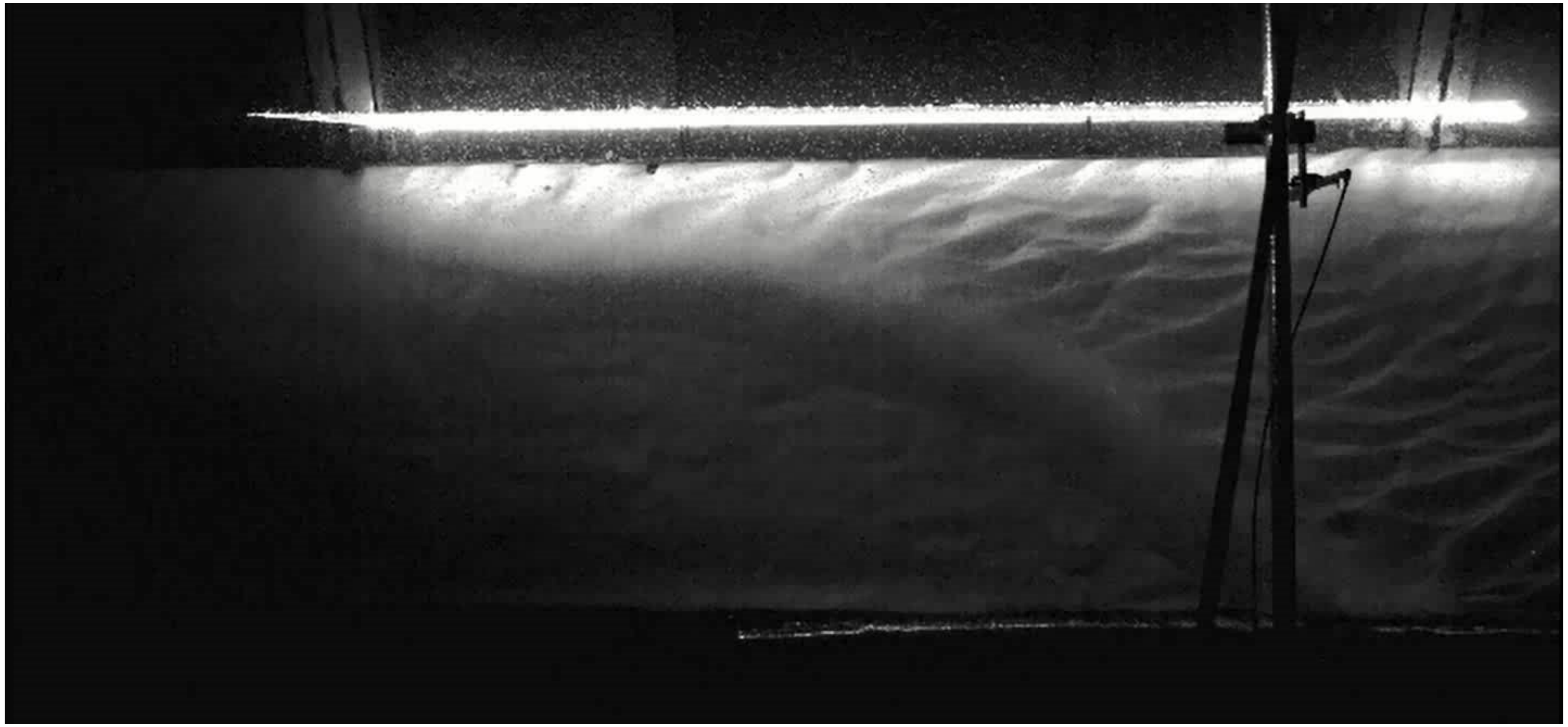


EFFECT OF ROTATION ON THE SEDIMENT BED

GRAVITY CURRENT FLOWING OVER AN ERODIBLE BED

$$\Omega = 0.2\ s^{-1}$$

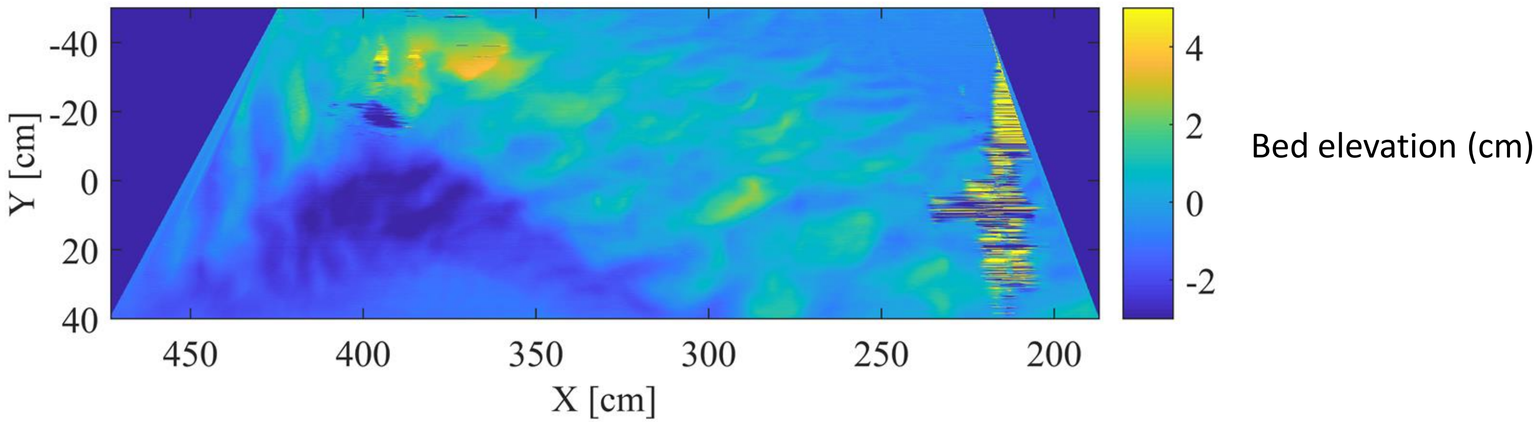
For large rotation rates a meandering pattern develops within the salty layer

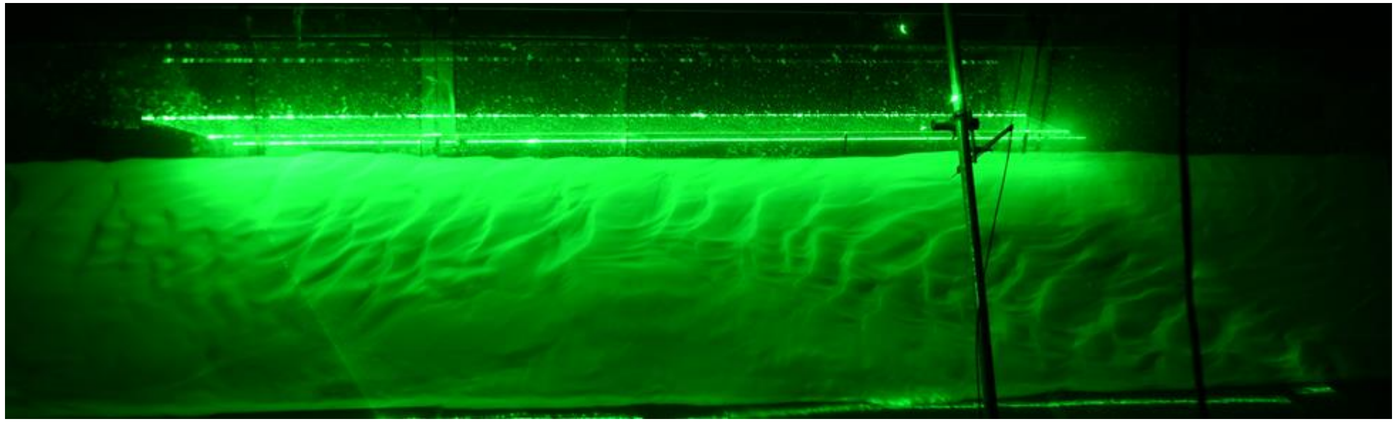


EFFECT OF ROTATION ON THE SEDIMENT BED

GRAVITY CURRENT FLOWING OVER AN ERODIBLE BED

$$\Omega = 0.2\ s^{-1}$$





CONCLUSIONS

GRAVITY CURRENTS FLOWING UP SMALL AND STEEP SLOPES

- **A small upslope affects the dynamics of the gravity current causing:**

- **a back flow in the tail of the current;**
- **a reduction of the front velocity;**
- **low entrainment and mixing.**

• **A steep upslope behaves as an obstacle and part of the dense fluid is reflected at the toe of the slope:**

- **as ϴ increases the dense current becomes thinner and thinner with no head dilution, the instabilities at the interface do not develop and a back flow is observed;**

- **the entrainment decreases as ϴ increases up to a minimum value.**

ROTATING GRAVITY CURRENTS OVER A MOBILE BED

- **Ambient rotation causes a deflection of the dense flow to the right of the channel**
- **As the ambient rotation increases a meandering pattern can develop within the salty flow affecting the bed morphology evolution.**

Thank you

My PhD students and me

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Luisa Ottolenghi

Giovanni La Forgia

Roberto Inghilesi

Maria Chiara De Falco