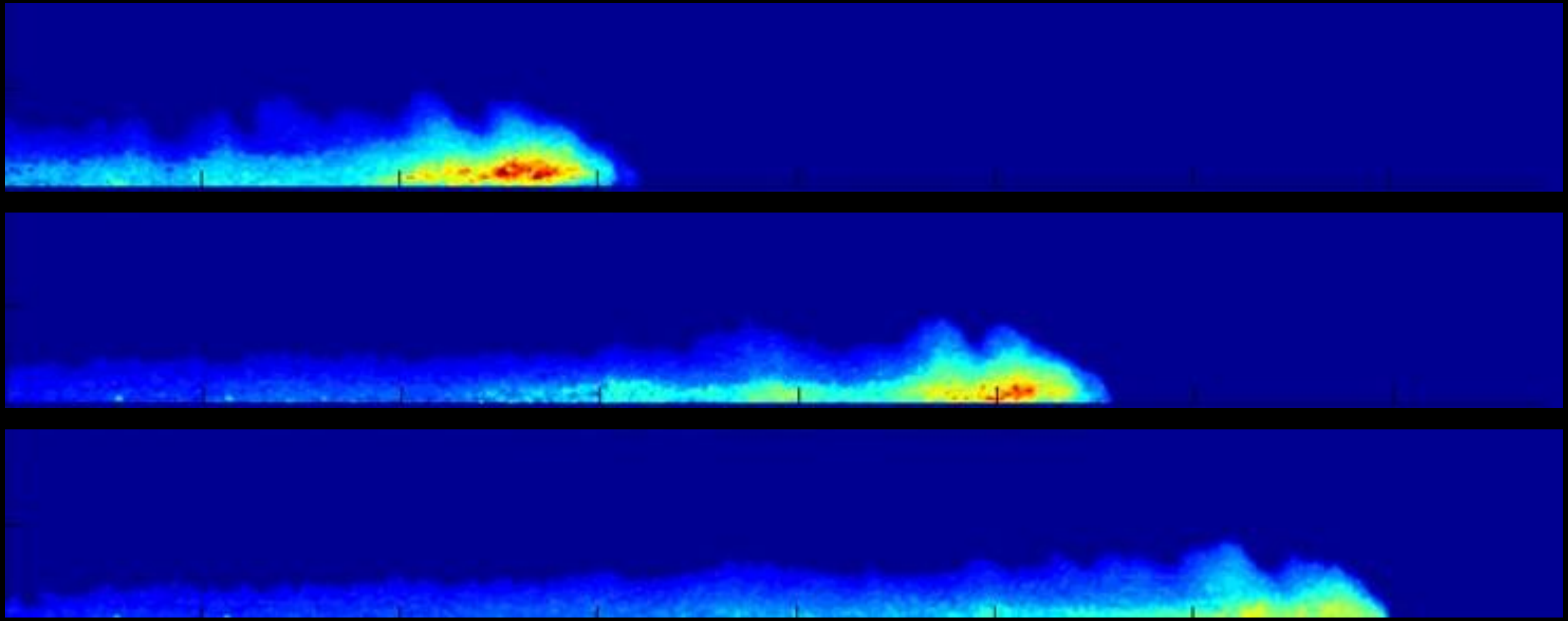
Density currents: theory and experimental results

XXXVI International School of Hydraulics, Jachranka 26rd May 2017



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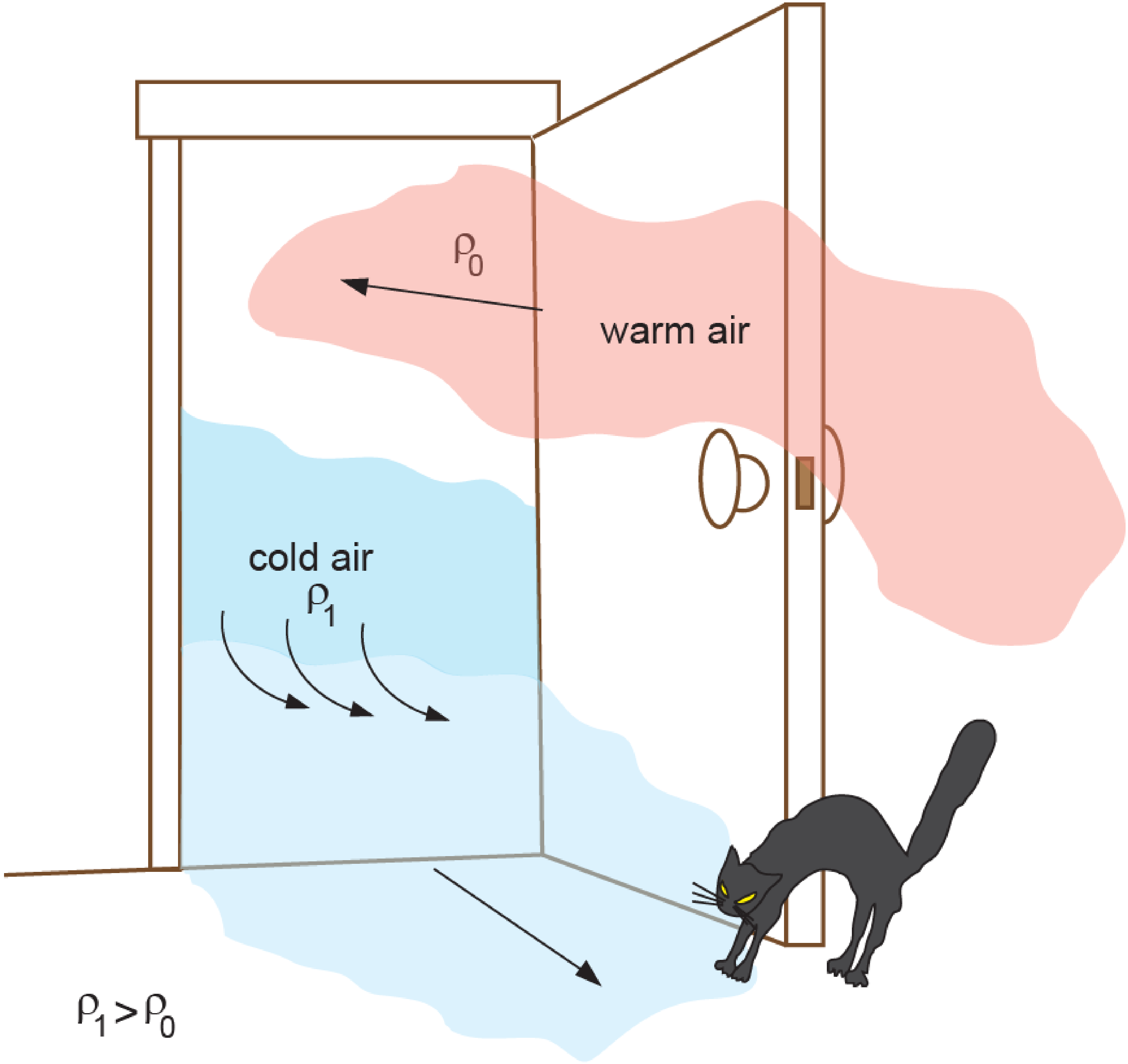
EFFECTS OF DENSITY



ρ_0
warm air
cold air
ρ_1
$\rho_1 > \rho_0$

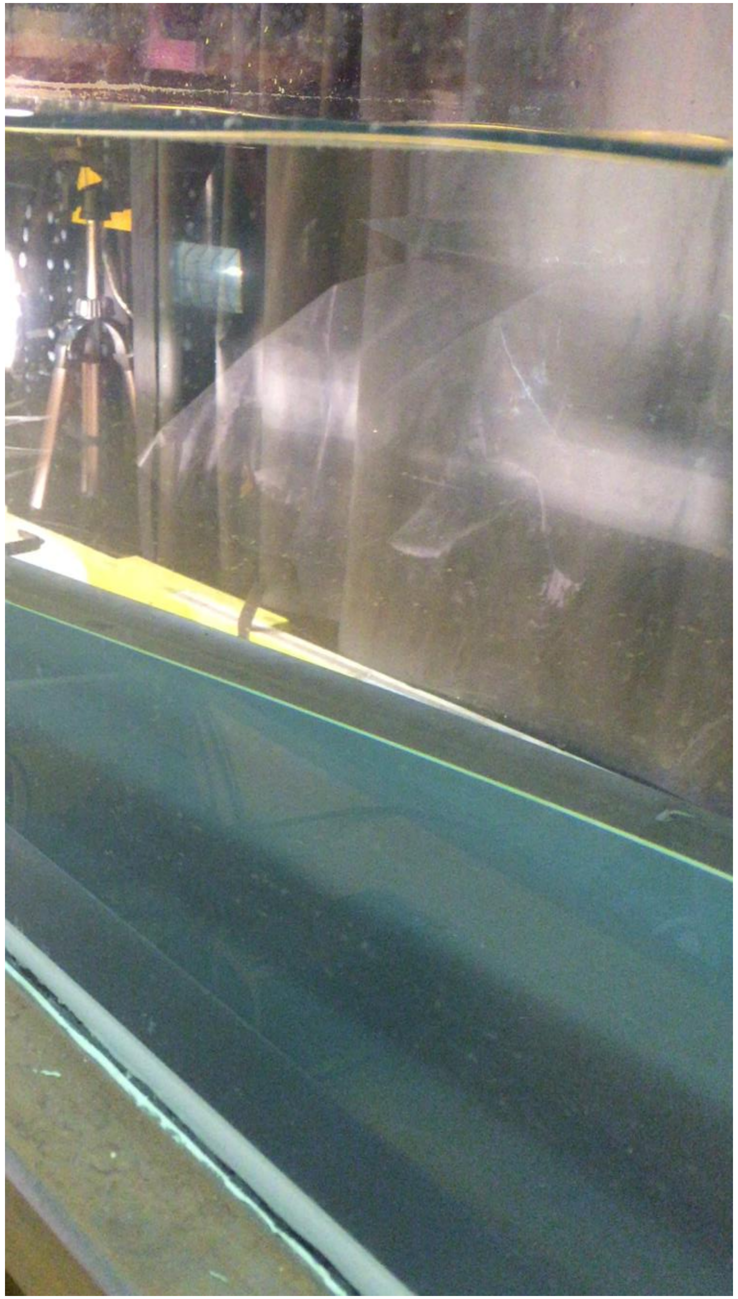
DEFINITION

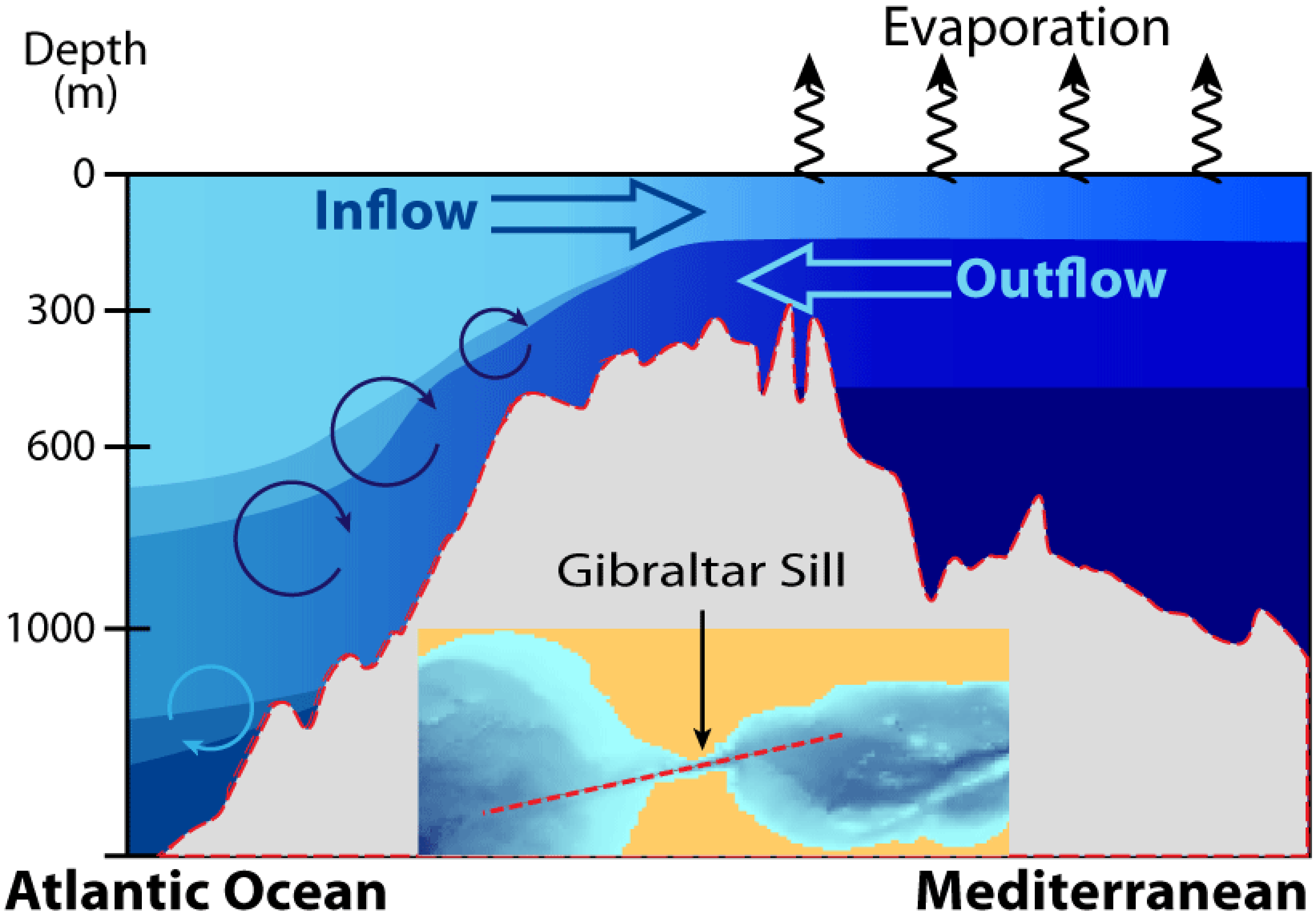
Gravity or density currents are **buoyancy driven flows** in which differences in density between two contacting fluids result from temperature gradients, dissolved substances or solid particles in suspension.


TURBIDITY CURRENT


MANGROVE FORESTS

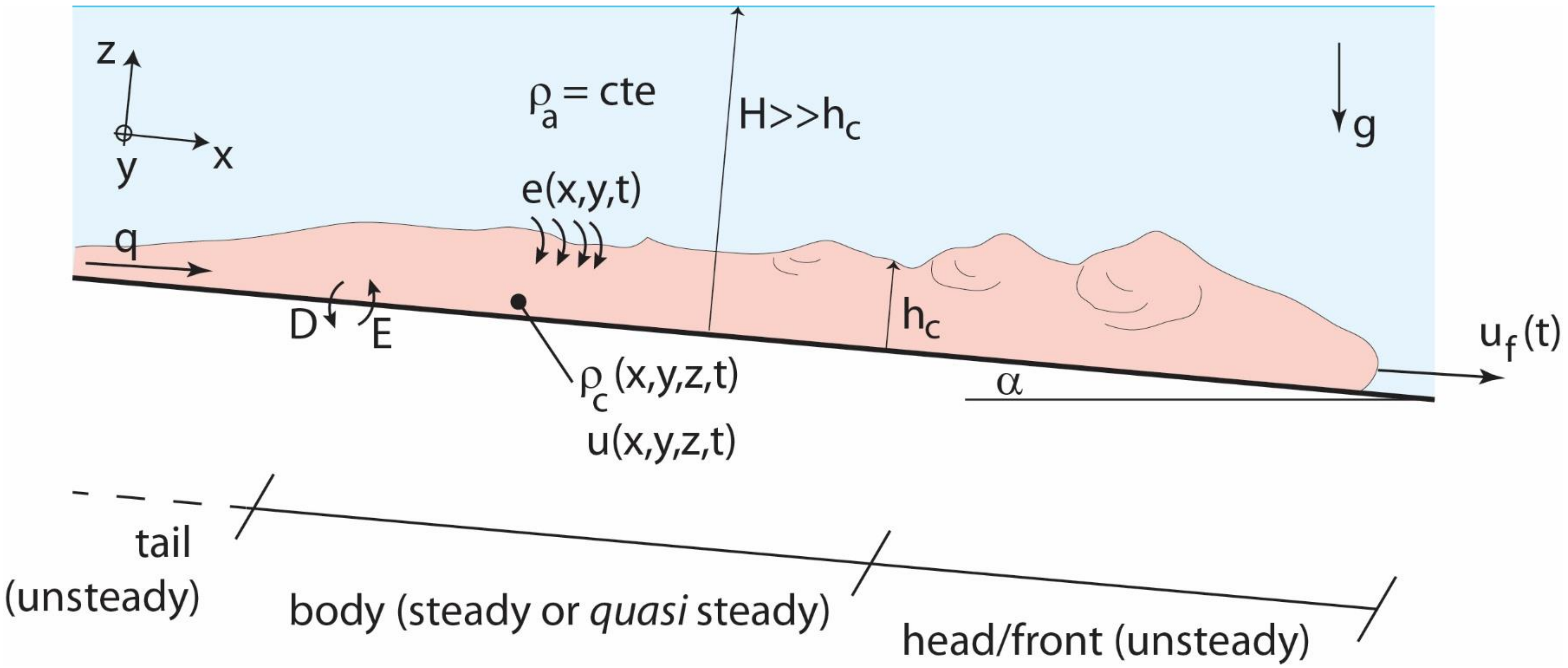
GIBRALTAR STRAIGHT



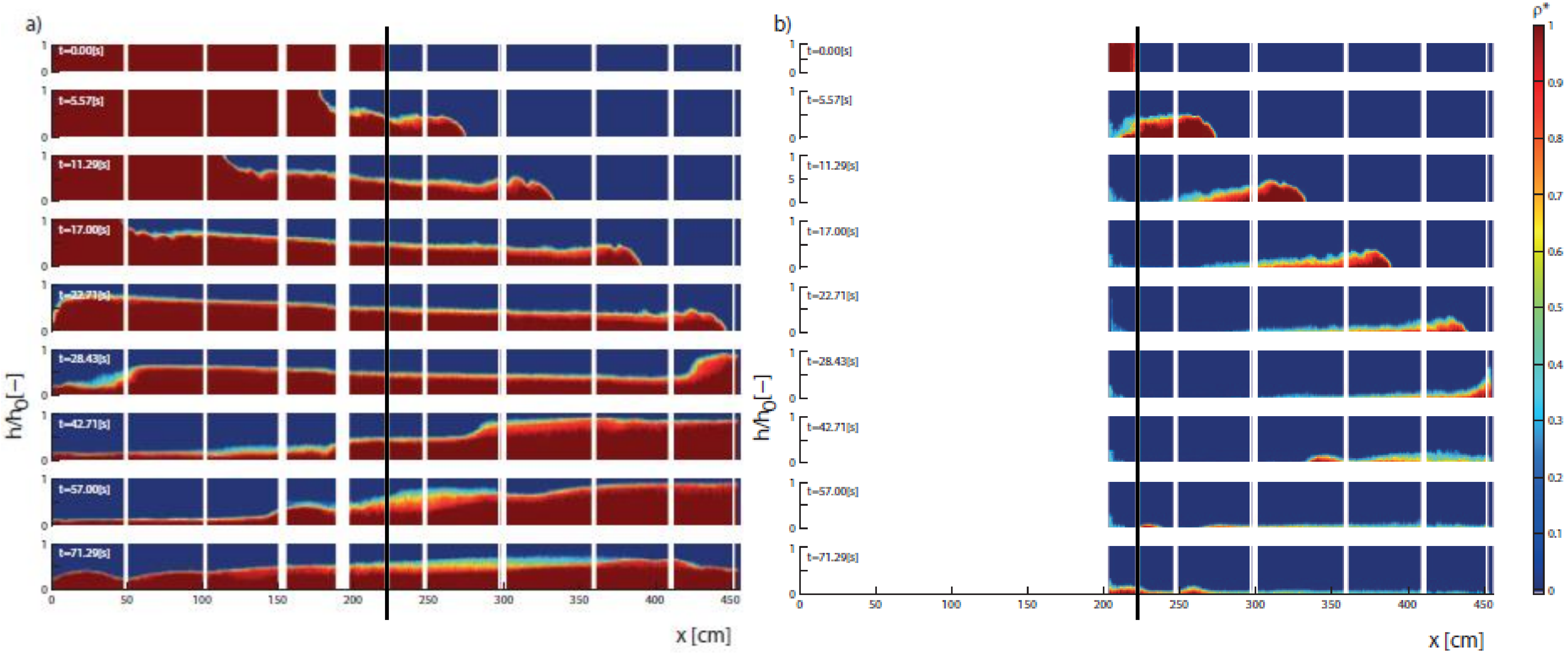


LOCK IN THE NAVIGATION CHANNEL OF IJMUIDEN (NL)

ANATOMY OF DENSITY CURRENTS



INFLUENCE OF THE VOLUME OF RELEASE

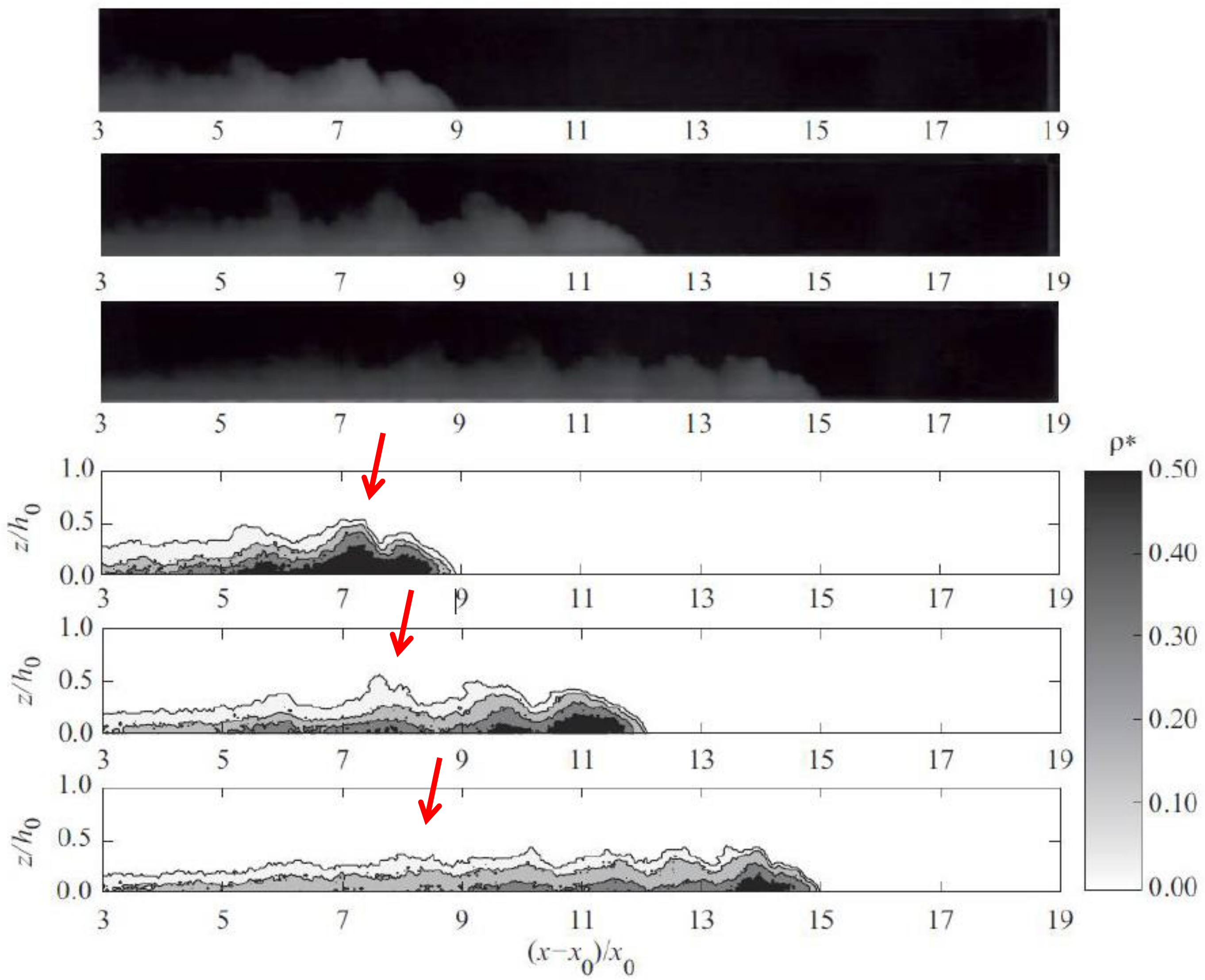


head + body + tail

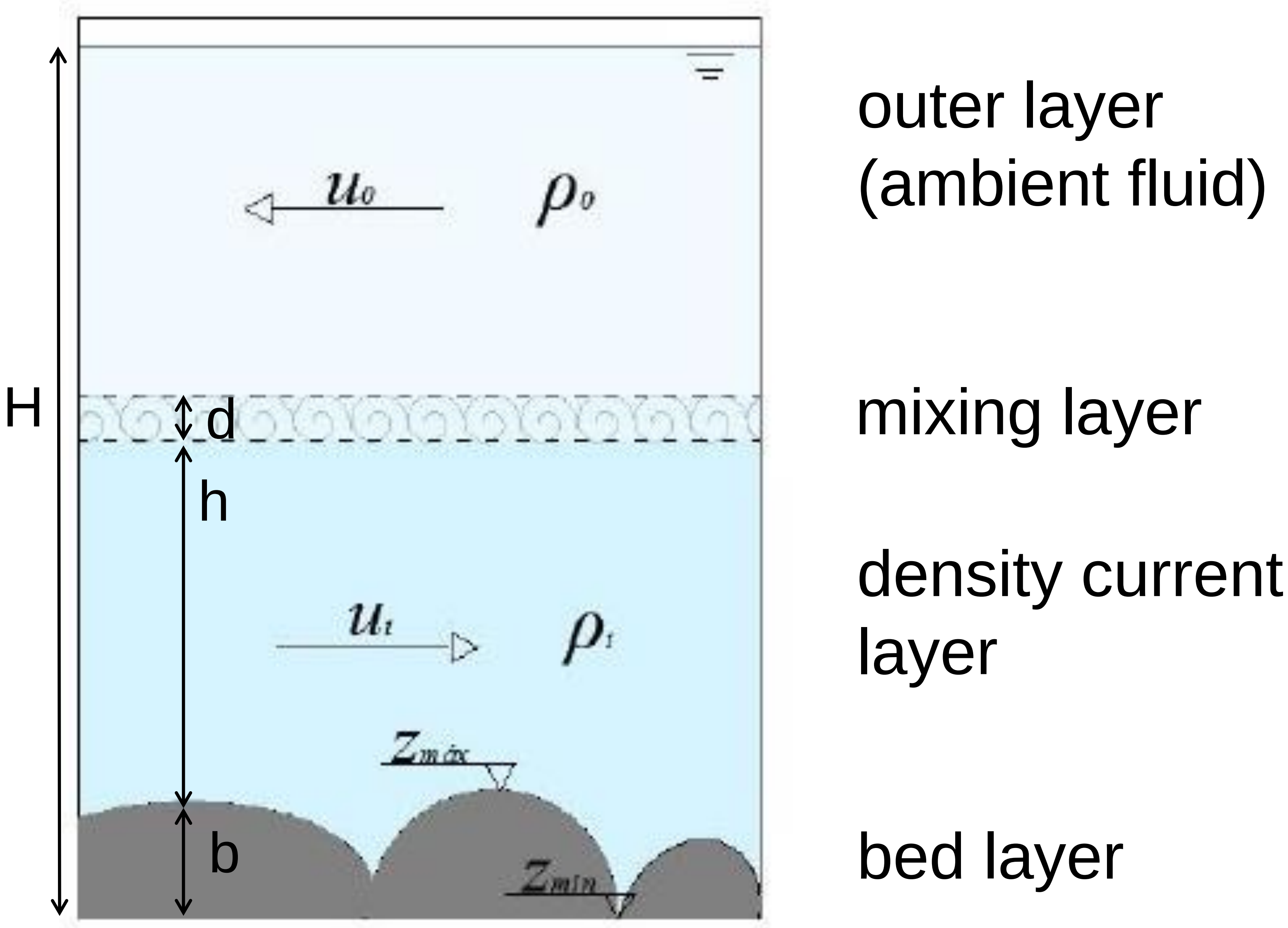
head + tail

The existence and length of the body depends on the release volume

KELVIN-HELMHOLTZ BILLOWS



Density field (Nogueira et al., JHR 2013)

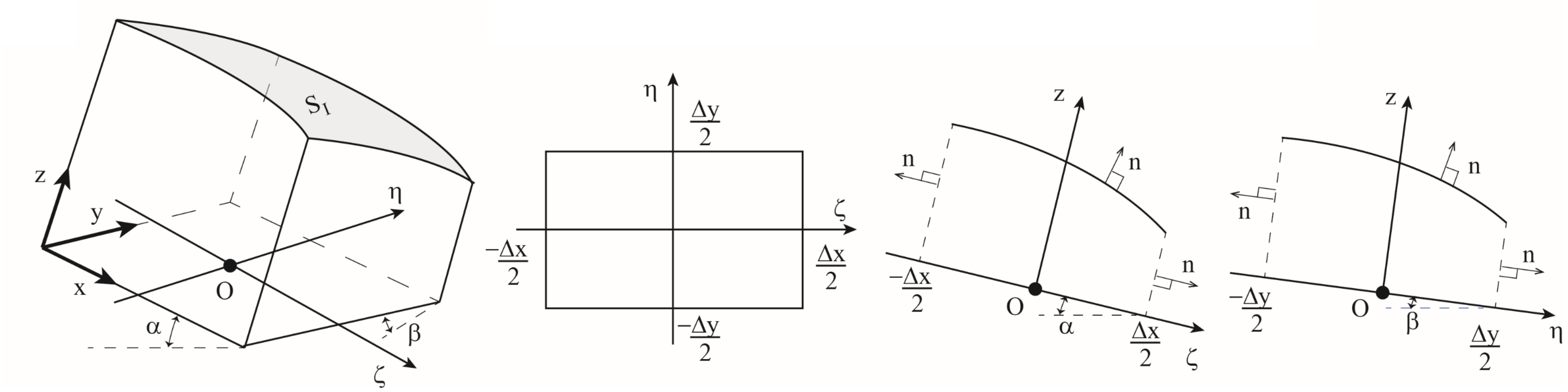


Lopes et al. (2012)

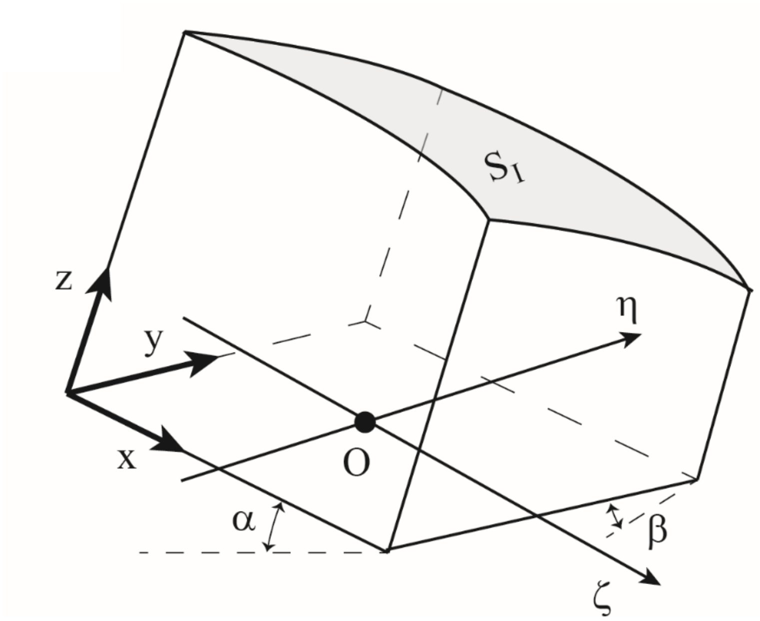
FRAMEWORK OF 2D SHALLOW WATER EQUATIONS

Sara Venuleo

Pokrajac, Venuleo & Franca (JHR, 2017)



2D SWE for mass conservation



$$\frac{\partial \langle \rho \rangle_H H}{\partial t} + \frac{\partial \langle \rho u \rangle_H H}{\partial x} + \frac{\partial \langle \rho v \rangle_H H}{\partial y} - e = 0$$

rate of change of mass

surface mass flux

e is the net mass flux, per unit plan area, through the current interface S_I

$<>_H$ is the depth-average operator defined as

$$\langle \psi \rangle_H (x, y, t) = \frac{1}{H} \int_{z=0}^{z=H} \psi(x, y, z, t) dz$$

2D SWE for momentum conservation

$$\frac{\partial \langle \rho u \rangle_h h}{\partial t} + \frac{\partial \langle \rho u u \rangle_h h}{\partial x} + \frac{\partial \langle \rho u v \rangle_h h}{\partial y} - e_u =$$

$$\langle \rho - \rho_0 \rangle_h h g_x + \frac{1}{2} g \frac{\partial a_p \langle \rho - \rho_0 \rangle_h h^2}{\partial x} cos\alpha - \tau_{Bx} + \tau_{Ix} + \frac{\partial \langle \tau_{xx} \rangle_h h}{\partial x} + \frac{\partial \langle \tau_{yx} \rangle_h h}{\partial y}$$

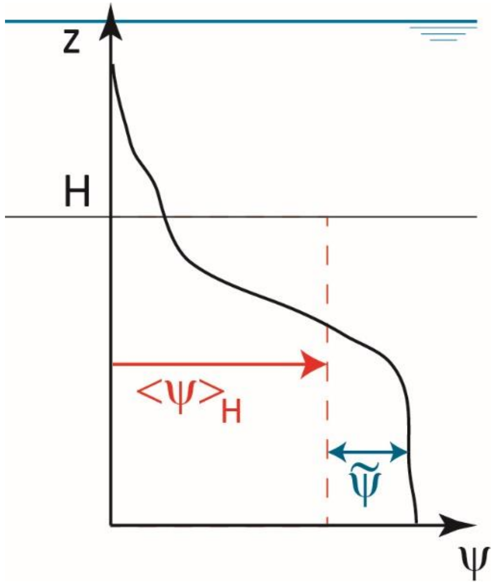
$$\frac{\partial \langle \rho v \rangle_h h}{\partial t} + \frac{\partial \langle \rho u v \rangle_h h}{\partial y} + \frac{\partial \langle \rho v u \rangle_h h}{\partial x} - e_v =$$

$$\langle \rho - \rho_0 \rangle_h h g_y + \frac{1}{2} g \frac{\partial a_p \langle \rho - \rho_0 \rangle_h h^2}{\partial y} cos\beta - \tau_{By} + \tau_{Iy} + \frac{\partial \langle \tau_{yy} \rangle_h h}{\partial y} + \frac{\partial \langle \tau_{xy} \rangle_h h}{\partial x}$$

e_u *and* e_v are the momentum fluxes (in x and y directions), per unit plan area, through the current interface S_I

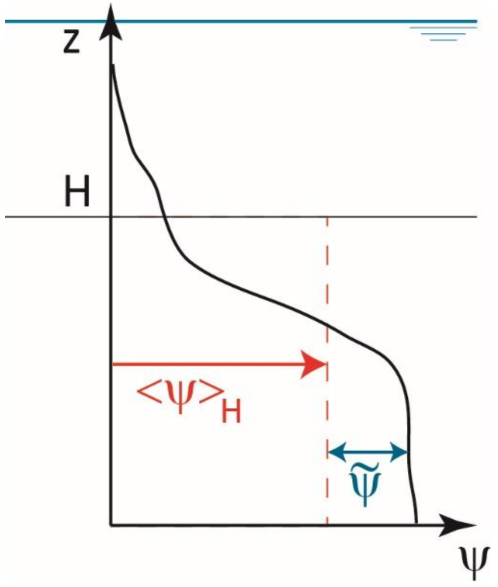
$$\langle \rho u \rangle_H, \langle \rho v \rangle_H, \langle \rho uu \rangle_h, \langle \rho vv \rangle_h, \langle \rho uv \rangle_h$$

$$\langle \rho u \rangle_H, \langle \rho v \rangle_H, \langle \rho uu \rangle_h, \langle \rho vv \rangle_h, \langle \rho uv \rangle_h$$



$$\psi(x, y, z, t) = \langle \psi \rangle_H(x, y, t) + \tilde{\psi}(x, y, z, t)$$

$$\langle \rho u \rangle_H, \langle \rho v \rangle_H, \langle \rho u u \rangle_h, \langle \rho v v \rangle_h, \langle \rho u v \rangle_h$$



$$\psi(x,y,z,t) = \langle \psi \rangle_H(x,y,t) + \tilde{\psi}(x,y,z,t)$$

$$\langle \rho u \rangle_H = \left\langle \left(\langle \rho(x,y,t) \rangle_H + \tilde{\rho}(x,y,z,t)\right) \times \left(\langle u(x,y,t) \rangle_H + \tilde{u}(x,y,z,t)\right) \right\rangle_H =$$

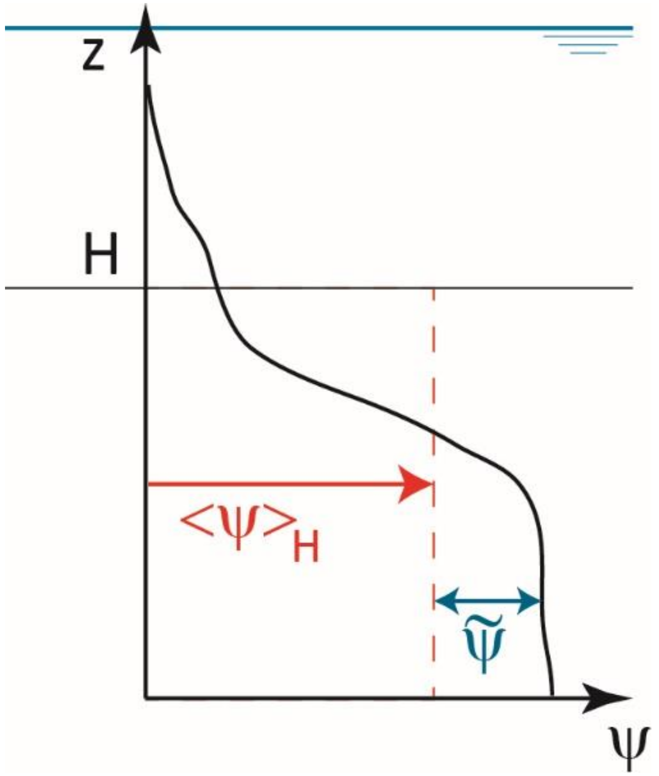
$$\langle \rho(x,y,t) \rangle_H \langle u(x,y,t) \rangle_H + \langle \tilde{\rho}(x,y,z,t) \tilde{u}(x,y,z,t) \rangle_H =$$

$$\boldsymbol{\langle \rho \rangle_H \langle u \rangle_H + \langle \tilde{\rho} \tilde{u} \rangle_H}$$

2D SWE for mass conservation

$$\frac{\partial \langle \rho \rangle_H H}{\partial t} + \frac{\partial \langle \rho u \rangle_H H}{\partial x} + \frac{\partial \langle \rho v \rangle_H H}{\partial y} - e = 0$$

$$\frac{\partial \langle \rho \rangle_H H}{\partial t} + \frac{\partial \langle \rho \rangle_H \langle u \rangle_H H}{\partial x} + \frac{\partial \langle \tilde{\rho}\tilde{u} \rangle_H H}{\partial x} + \frac{\partial \langle \rho \rangle_H \langle v \rangle_H H}{\partial y} + \frac{\partial \langle \tilde{\rho}\tilde{v} \rangle_H H}{\partial y} - e = 0$$



$$\psi(x,y,z,t) = \langle\psi\rangle_H(x,y,t) + \tilde{\psi}(x,y,z,t)$$

Shape function ξ_ψ which leads to shape factors with which we **avoid the non-linearity**

$$\xi_\psi(x,y,z,t) = \frac{\psi}{\langle\psi\rangle_H}$$

$$\psi(x,y,z,t) = \langle\psi\rangle_H \xi_\psi$$

$$a_\psi = \frac{1}{H}\int_0^H \xi_\psi dz = 1$$

$$a_{\psi_1\psi_2} = \frac{1}{H}\int_0^H \xi_{\psi_1}\xi_{\psi_2} dz \neq 1$$

Interaction between two vertically varying variables!

we replace a non-linear term
by the product of linear terms

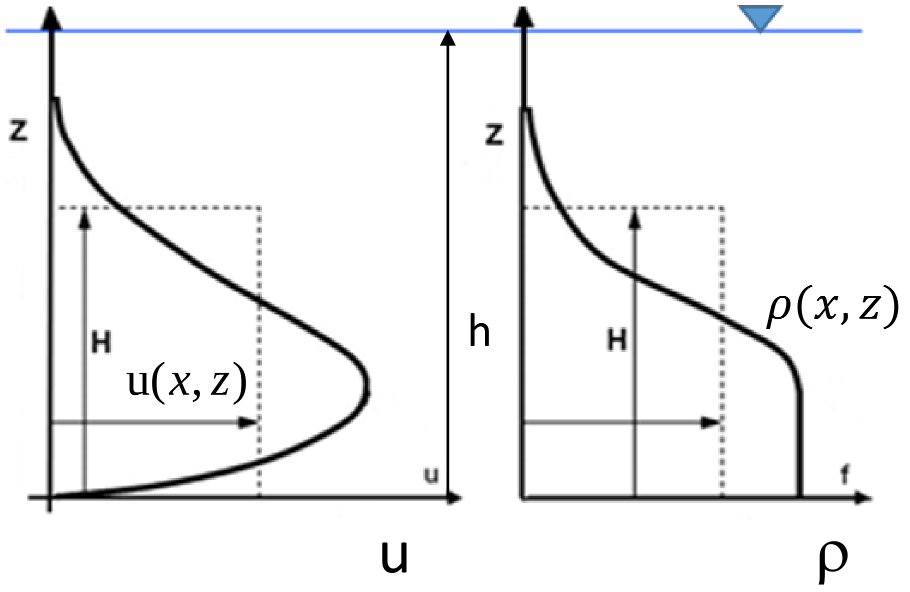
$$\langle \rho u \rangle_H = \frac{1}{H}\int_0^H \rho u dz = \frac{1}{H}\int_0^H \underbrace{\langle \rho \rangle_H \xi_\rho}_{\rho} \underbrace{\langle u \rangle_H \xi_u}_{u} dz = \langle \rho \rangle_H \langle u \rangle_H a_{\rho u}$$

$$a_{\psi_1 \psi_2} = \frac{1}{H}\int_0^H \xi_{\psi_1} \xi_{\psi_2} dz \neq 1$$

$$\frac{\partial\langle\rho\rangle_H H}{\partial t}+\frac{\partial\langle\rho u\rangle_H H}{\partial x}+\frac{\partial\langle\rho v\rangle_H H}{\partial y}-e=0$$

$$\frac{\partial\langle\rho\rangle_H H}{\partial t}+\frac{\partial\langle\rho\rangle_H\langle u\rangle_H H}{\partial x}+\frac{\partial\langle\tilde{\rho}\tilde{u}\rangle_H H}{\partial x}+\frac{\partial\langle\rho\rangle_H\langle v\rangle_H H}{\partial y}+\frac{\partial\langle\tilde{\rho}\tilde{v}\rangle_H H}{\partial y}-e=0$$

$$\frac{\partial\langle\rho\rangle_H H}{\partial t}+\frac{\partial a_{\rho u}\langle\rho\rangle_H\langle u\rangle_H H}{\partial x}+\frac{\partial a_{\rho v}\langle\rho\rangle_H\langle v\rangle_H H}{\partial y}-e=0$$

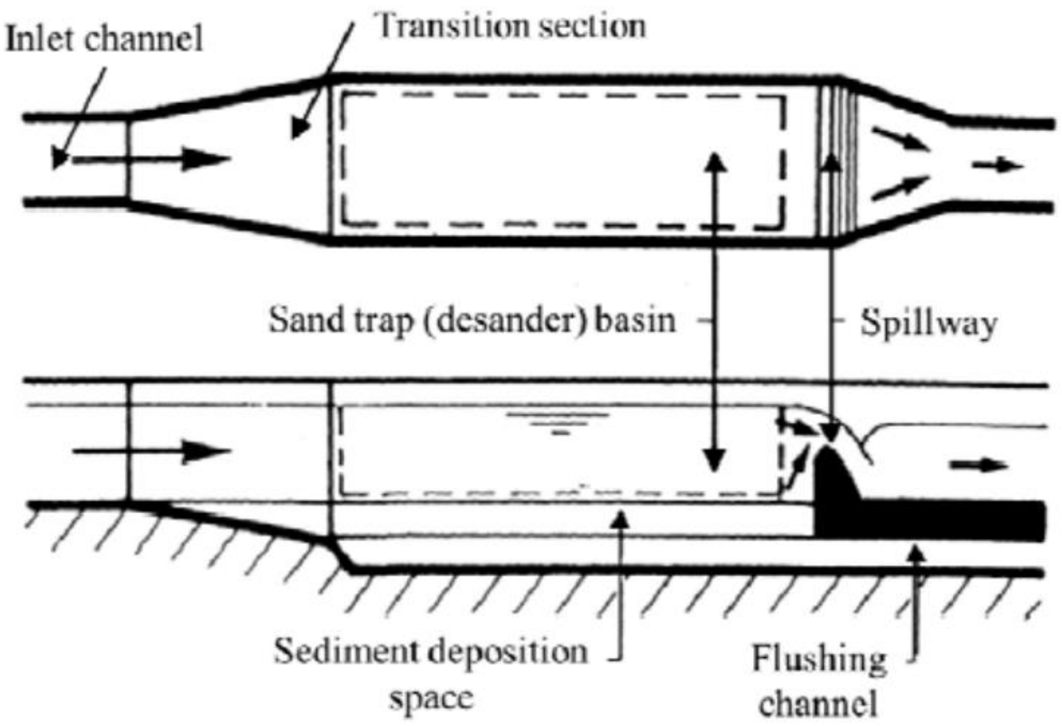


Shape factors $a_{\rho u}$ and $a_{\rho v}$ apparently depend on Froude number, slope, bed roughness, grain size, etc!

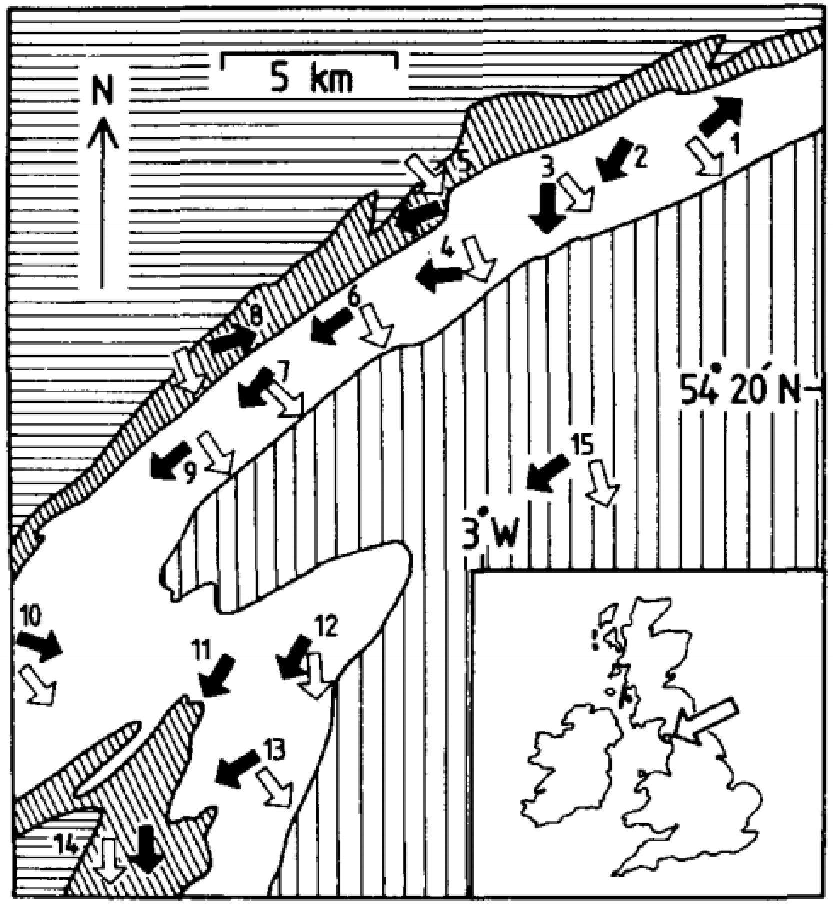
Sequeiros et al. (2010) Characteristics of velocity and excess density profiles of saline underflows and turbidity currents flowing over a mobile bed. J Hydr Eng, 136(7):412–433.

CONTAINED DENSITY CURRENTS

Theiler and Franca (Sedimentology, 2016)

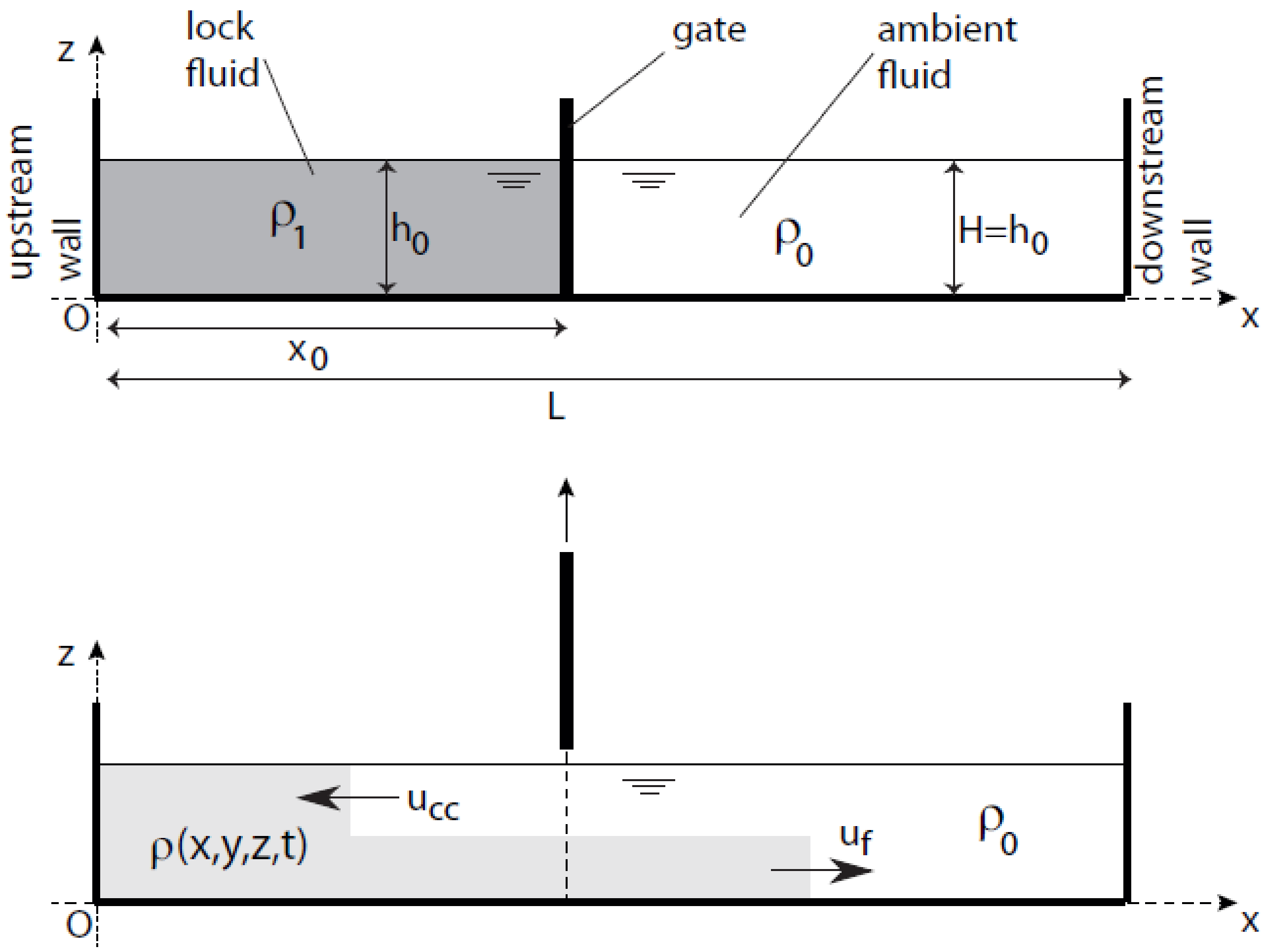


INDUSTRIAL CLARIFIERS



SEDIMENTARY BASINS

LABORATORY LOCK EXCHANGE EXPERIMENTS



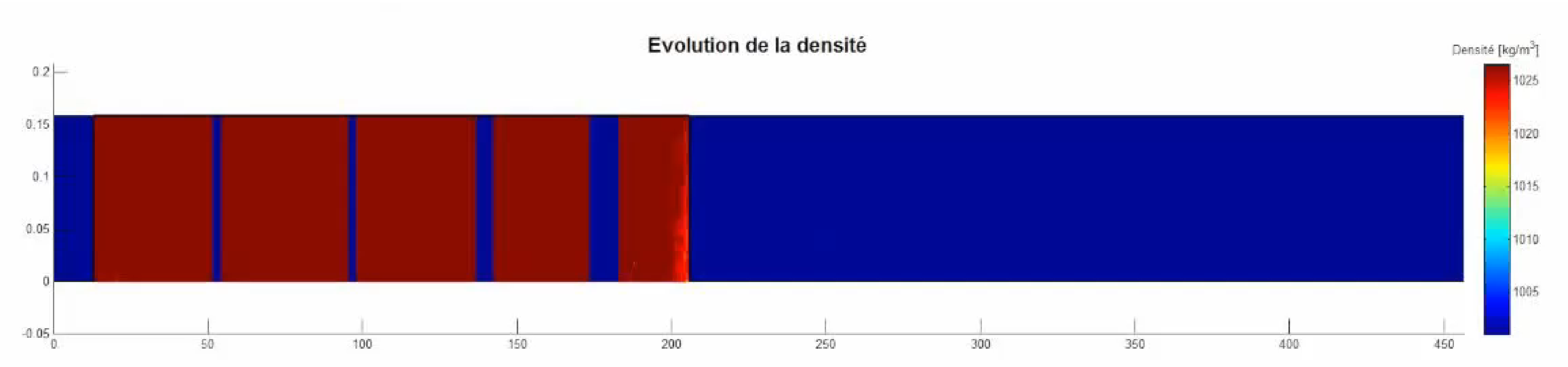
Is there any **scaling** corresponding to **similarity of the kinematics** of the contained oscillations of the contained density current?

Is there a **similarity** concerning the **mixing** of the current with the ambient fluid?

Lock-exchange currents (horizontal 4.55 m long, 0.14 m wide and 0.17 m channel)

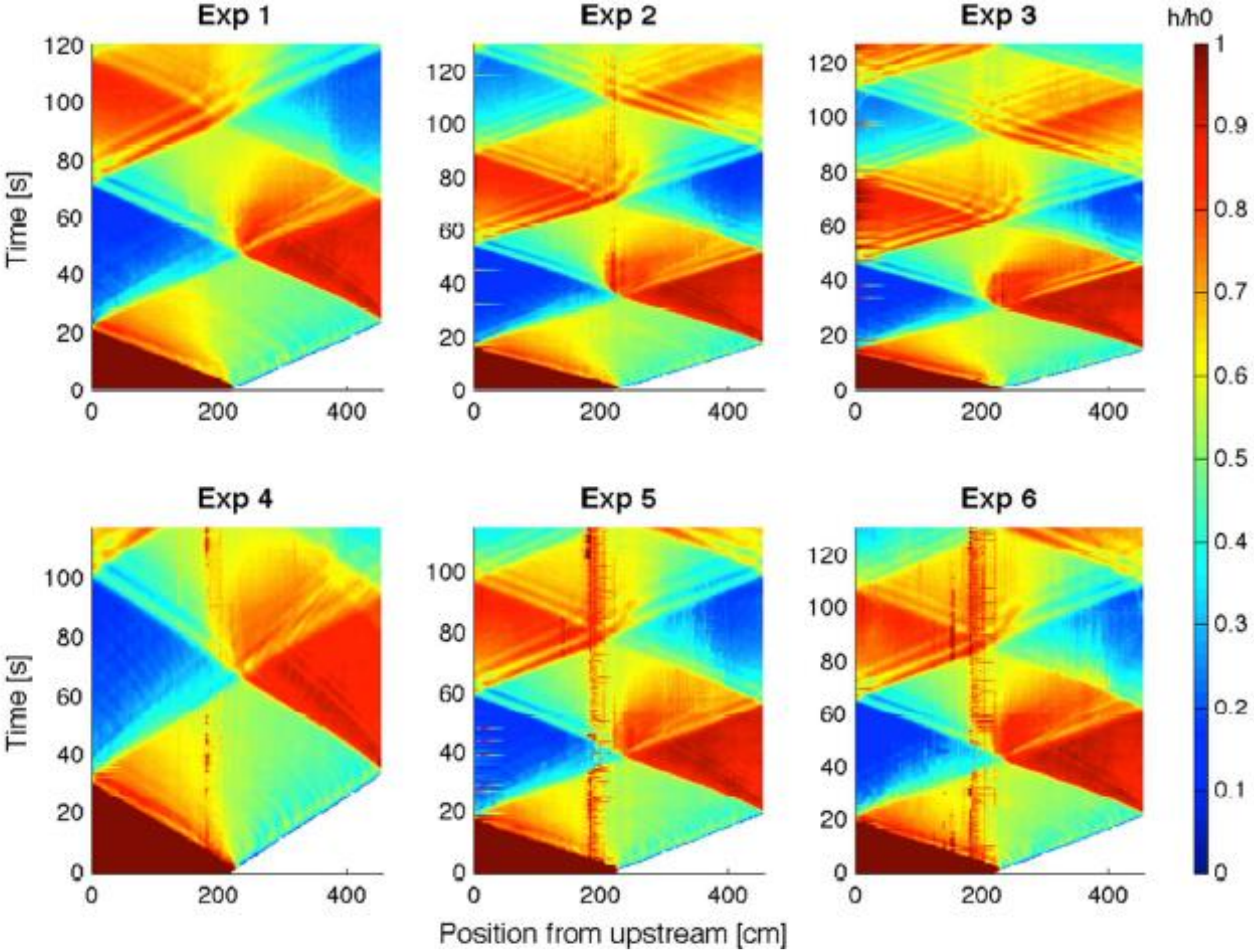
Saline Boussinesq currents with initial densities between **1015 to 1064 kg/m^3**

Six short tests
One long test
One test with low volume of release (for reference)



t>0.75T
$x_0/L=0.50$
$r_1=1027\ kgm^{-3}$
$g=r_0/r_1=0.976$

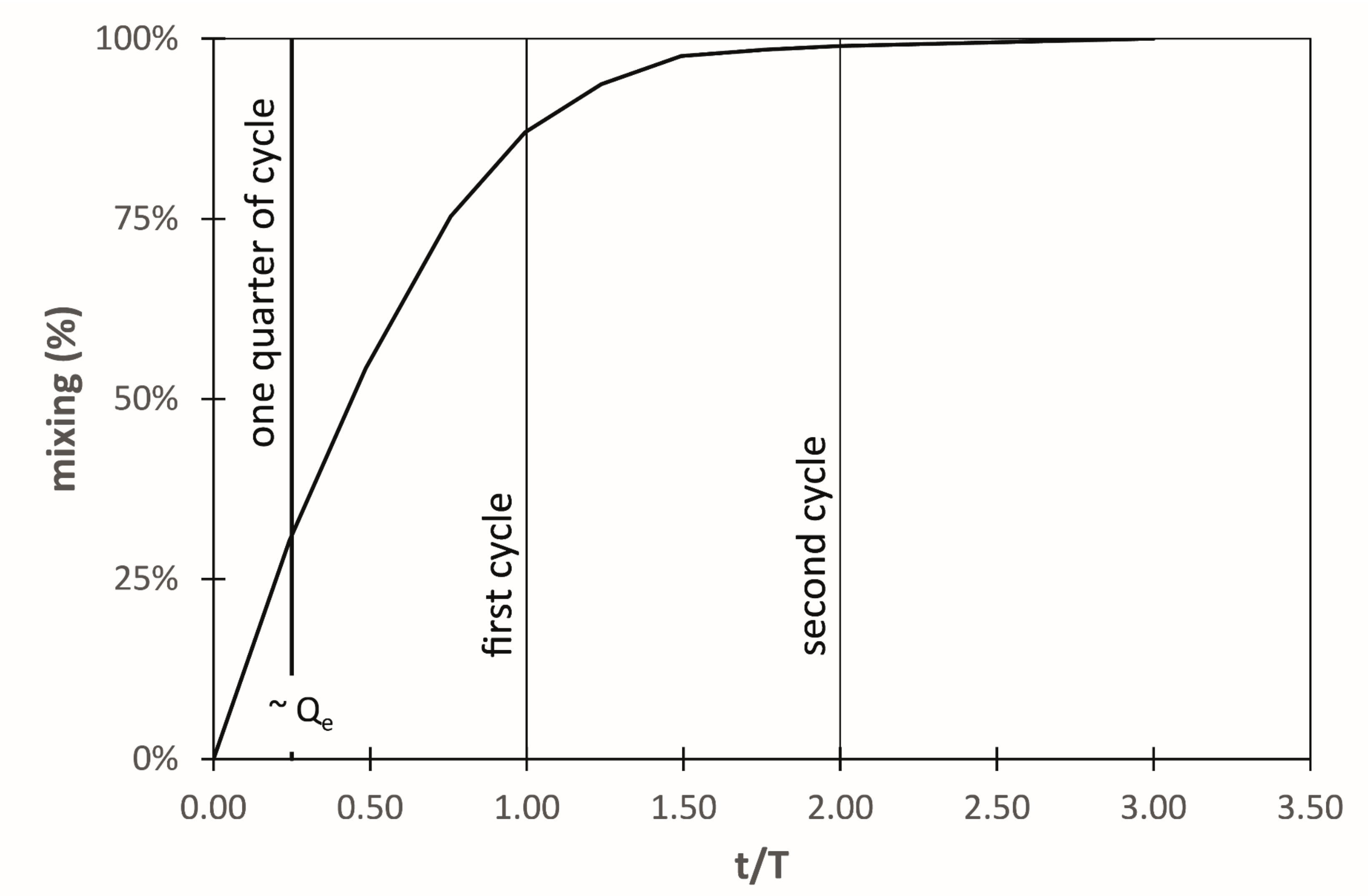
Density field measured by video analysis technique
(Nogueira et al., MST 2013)



Temporal and spatial evolution of the current height

Quasi-elastic (self similar with density difference) oscillation is observed

Solitons are visible which originate in the impact



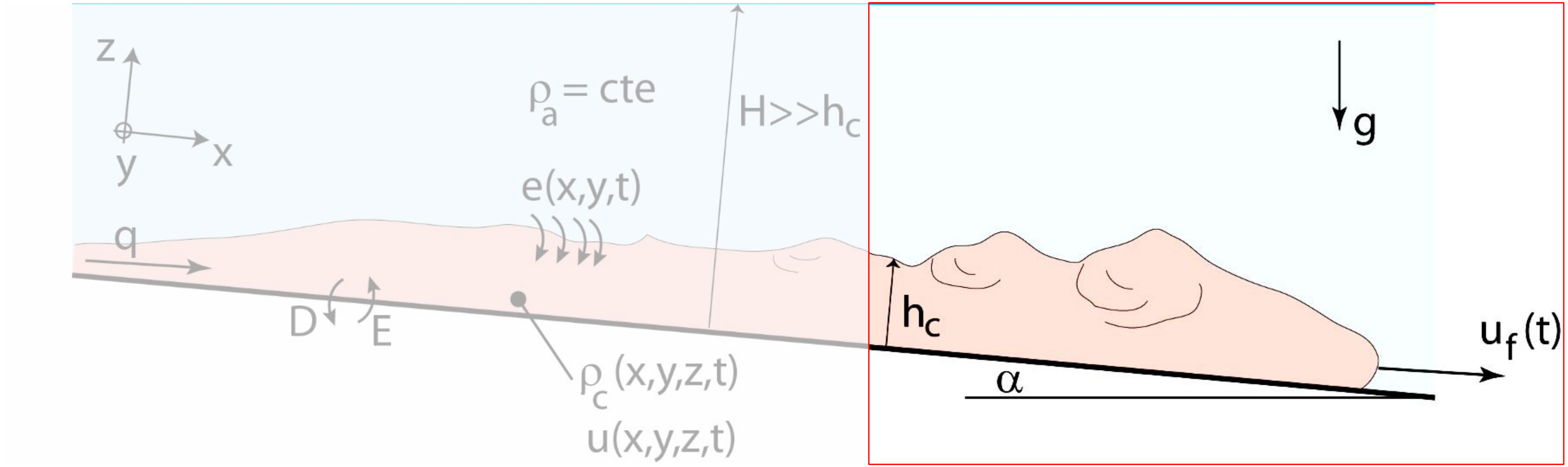
A **model for current mixing** is proposed based on the oscillation phase

After the first cycle of oscillation in the tank about **90%** of the asymptotic total mixing

The basin reached **full mixing after 2T**

THE HEAD OF THE CURRENT

Nogueira et al. (EFM, 2014)



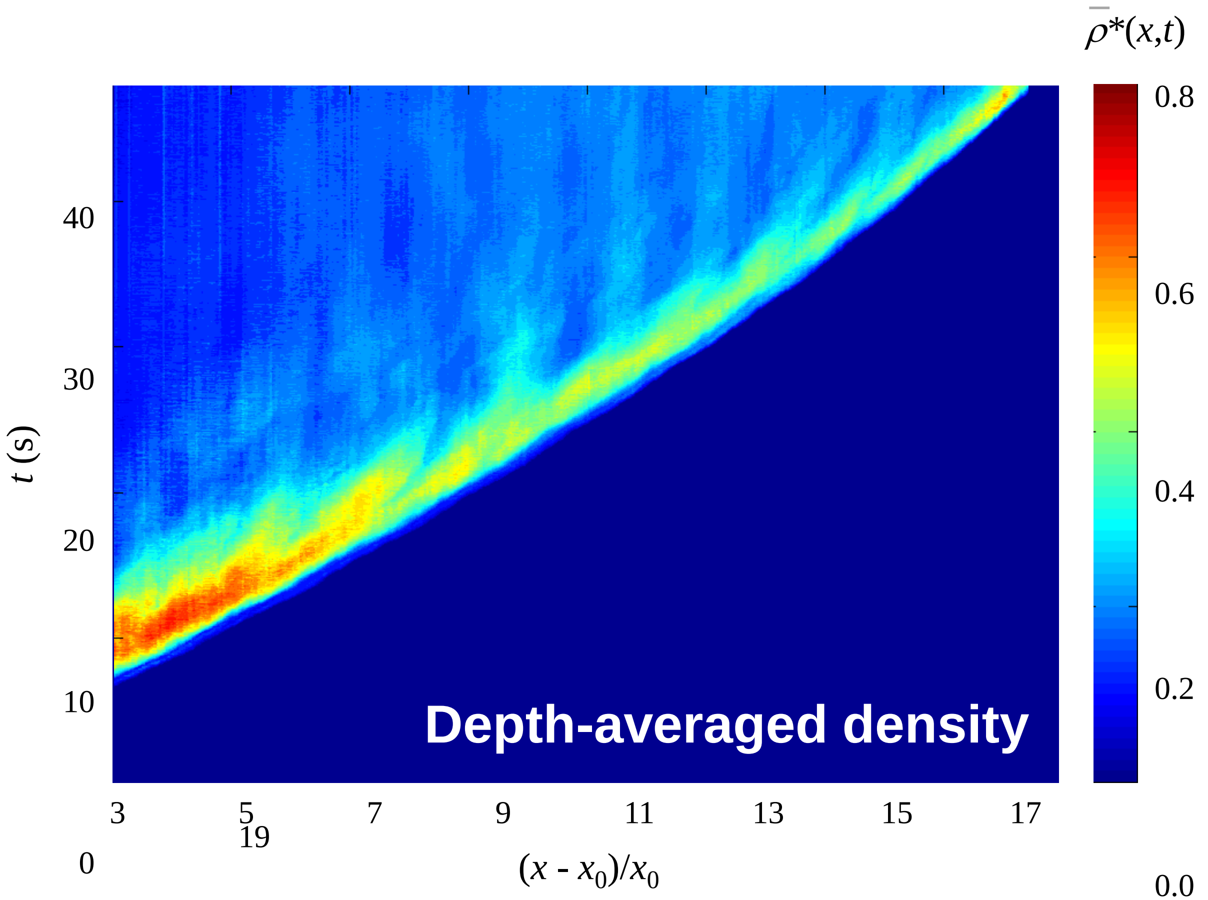
Is there any scaling corresponding to **self similar oscillations** of the head?

What is the contribution of the head to the global current **entrainment**?

LABORATORY LOCK EXCHANGE EXPERIMENTS WITH LOW VOLUME OF RELEASE

Runs	**D1**	**D2**	**D3**	**D4**
ρ_0 (kgm^{-3})	997.8	997.4	997.4	998.0
ρ_1 (kgm^{-3})	1014.7	1038.7	1044.6	1060.0
h_0 (m)	0.20	0.20	0.20	0.20
ε (mm)	0.0	0.0	0.0	0.0

Four initial densities in the lock were tested

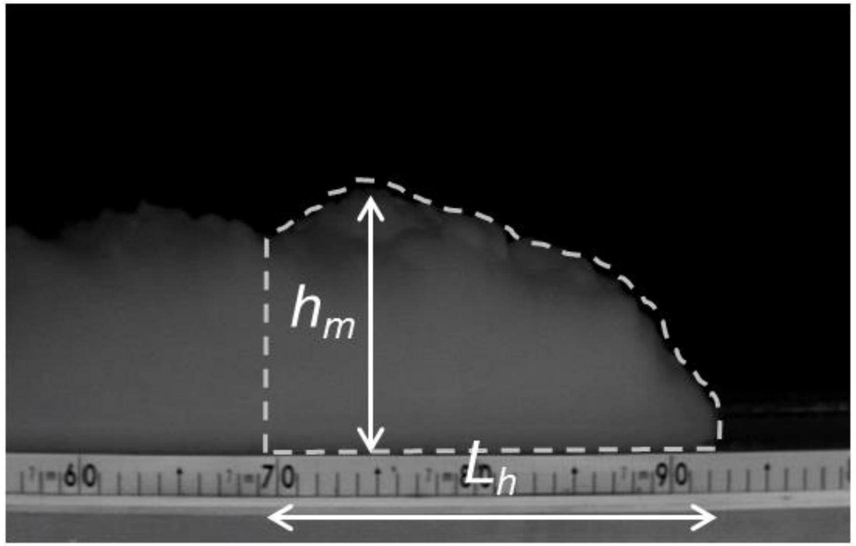


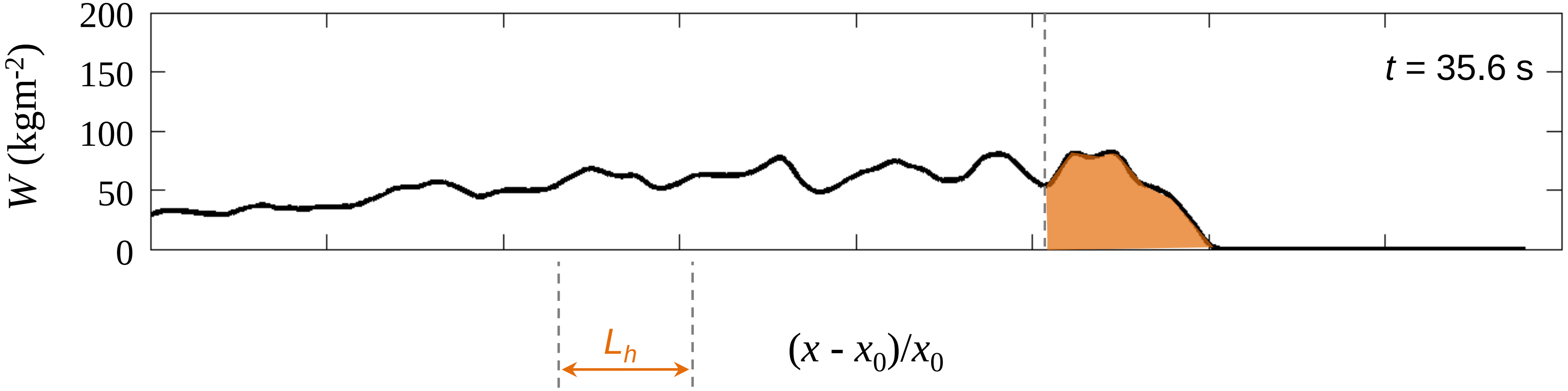
Density measured by video analysis techniques
(Nogueira et al., MST 2013)

HEAD DEFINITION

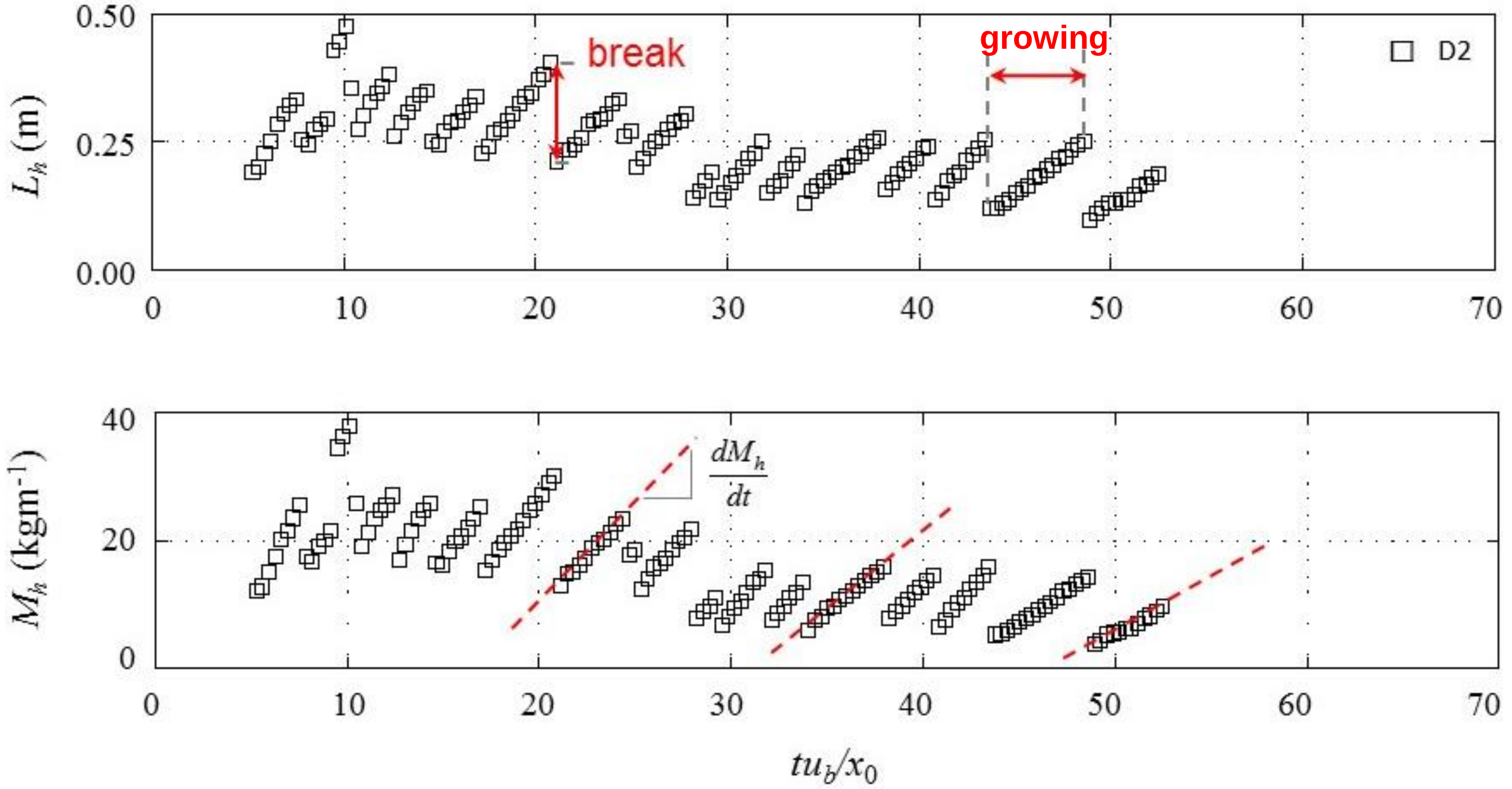
Local vertically-averaged mass

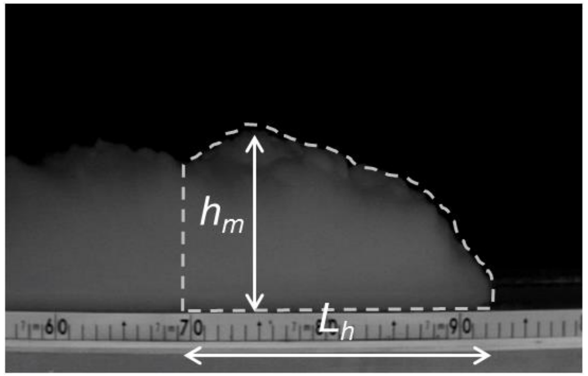
$$W(x,t) = \overline{\rho_v}(x,t) \cdot h(x,t)$$





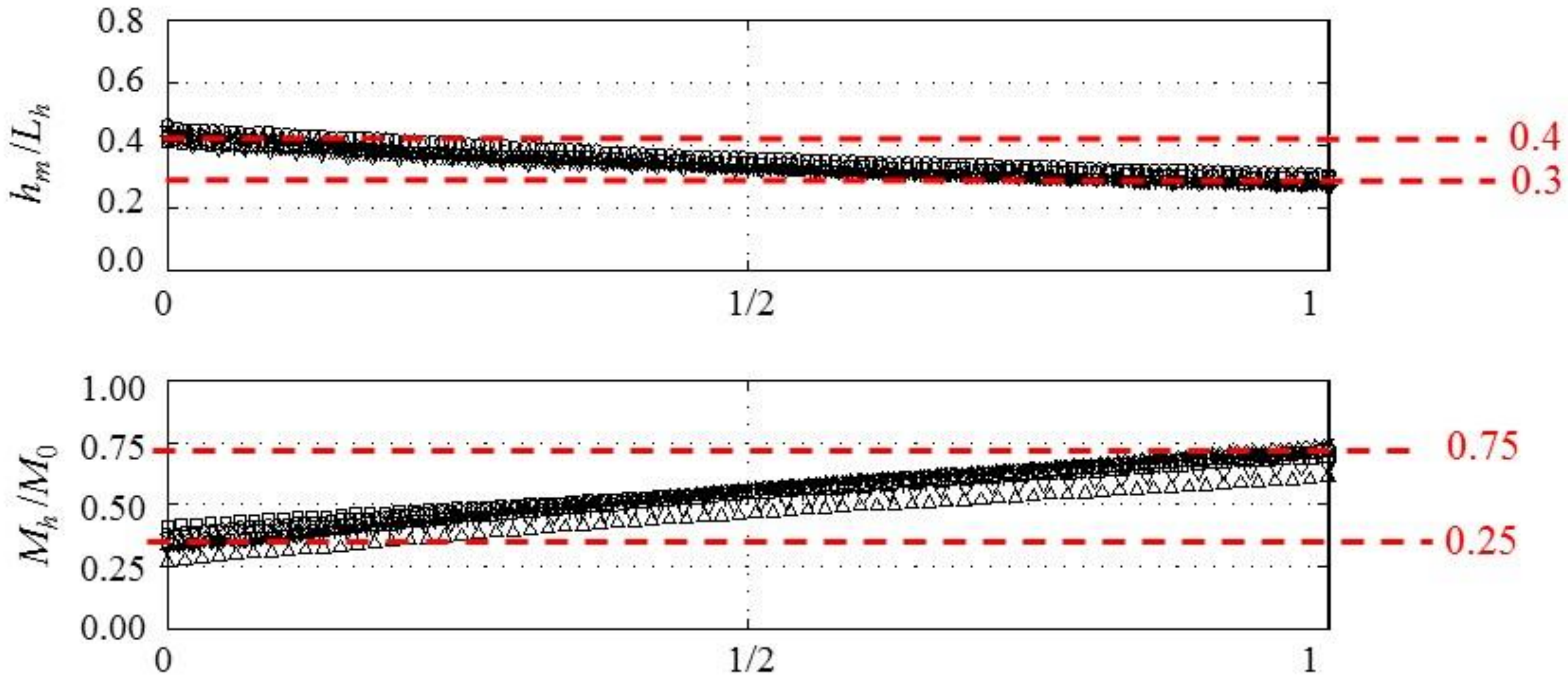
Length and mass of the head





The head presents a cycle evolution composed by periods of stretching/growing interrupted by a break

Phase-averaged cycles



Similarity between runs

Break:

- Head aspect ratio h_m/L_h = 0.3 (average)
- Head mass M_h/M_0 = 0.75 (average)

POSFACE

Basic definitions of gravity currents

Ongoing developments to define a 2D shallow water framework

Kinematics and mixing in contained density currents

Characterization of the head dynamics

RESEARCH NEEDS

Characterization of entrainment and flow resistance

Reynolds-Averaged-Depth-Integrated Navier-Stokes (RADINS)

Influence of roughness and slope in entrainment and mixing

The influence of a non-quiescent background

The influence of ambient depth

Temperature driven currents

Temperature driven currents in canopy forests (mangrove)

Erosive (self-feeding or self-accelerating) turbidity currents

Depositing (deccelerating) turbidity currents

Static mitigating measures against turbidity currents

Operational mitigating measures against turbidity currents

Guidelines for reservoir operators for dealing with turbidity currents

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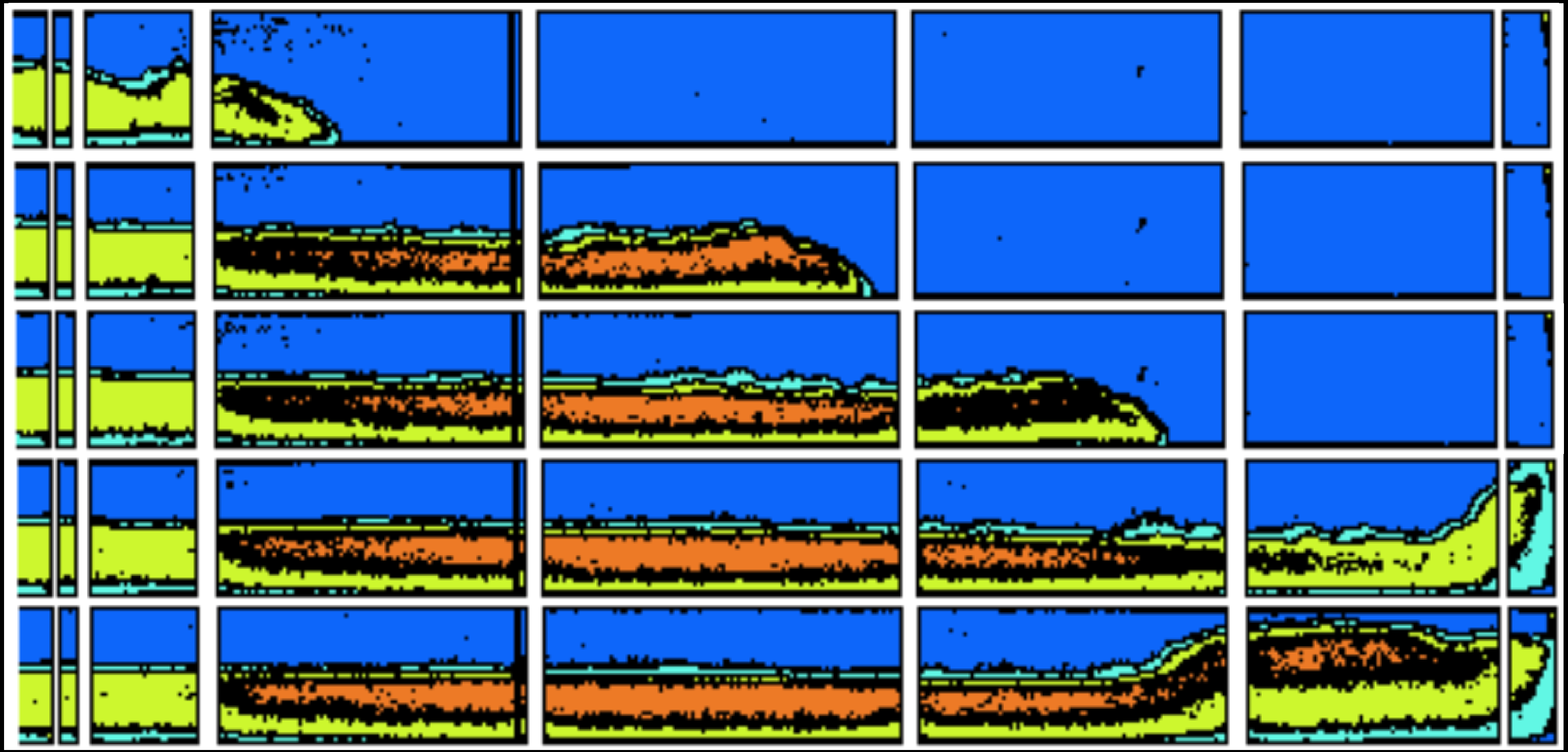

Mário J. Franca

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