A low intrusive method to simulate buoyant effluent plume in “Coastal Hydrodynamics Models”

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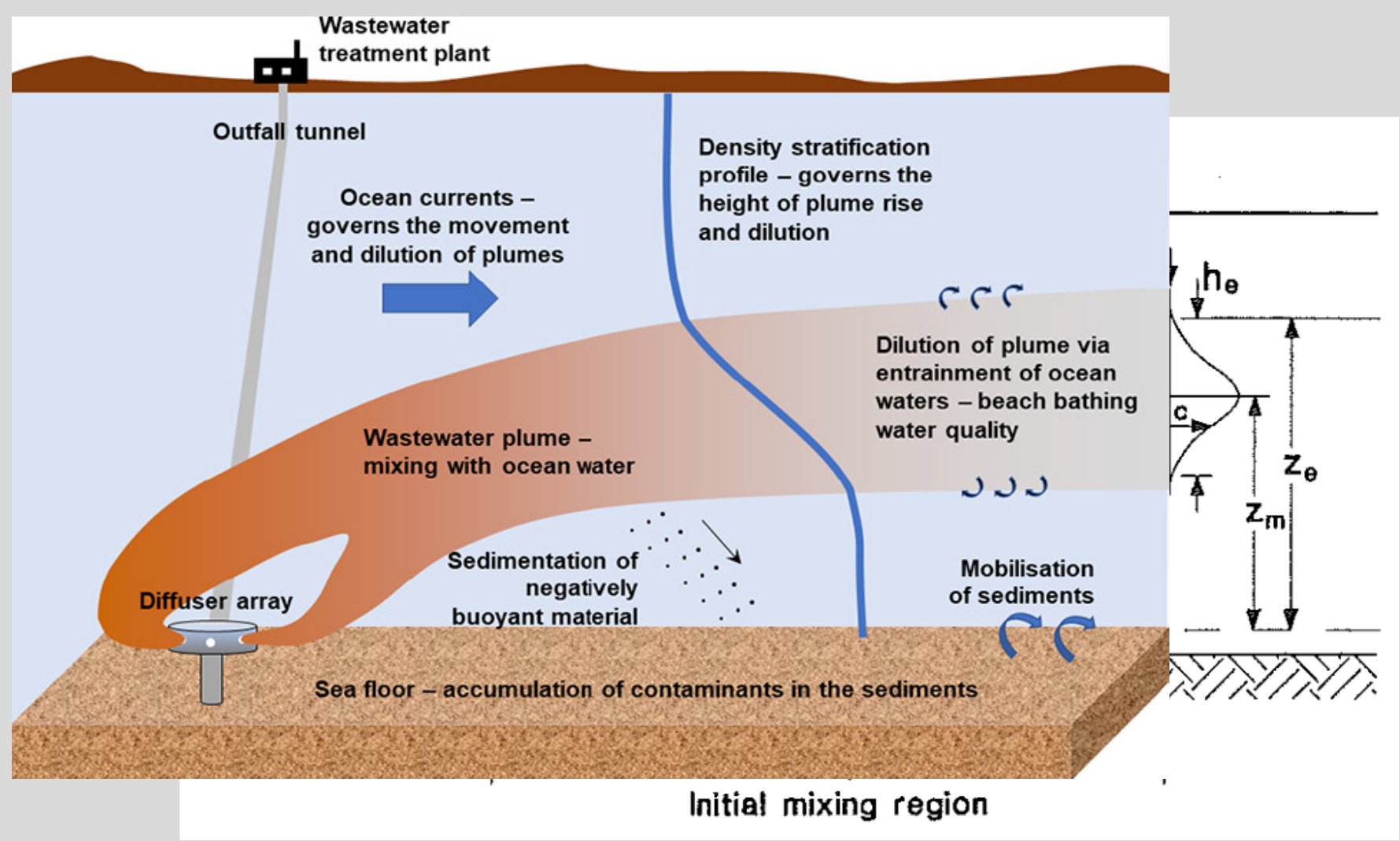
Simulating buoyant water discharge on the ocean floor

Coastal hydrodynamic models are not designed to manage buoyant plume and Non-Hydrostatic models are to heavy for environmental studies. Then, practically, a “**near field model** ” is coupled with a “**far field model**”.

Engineering tools :
CORMIX,
VISJET,
U3M,
RSM,
etc.



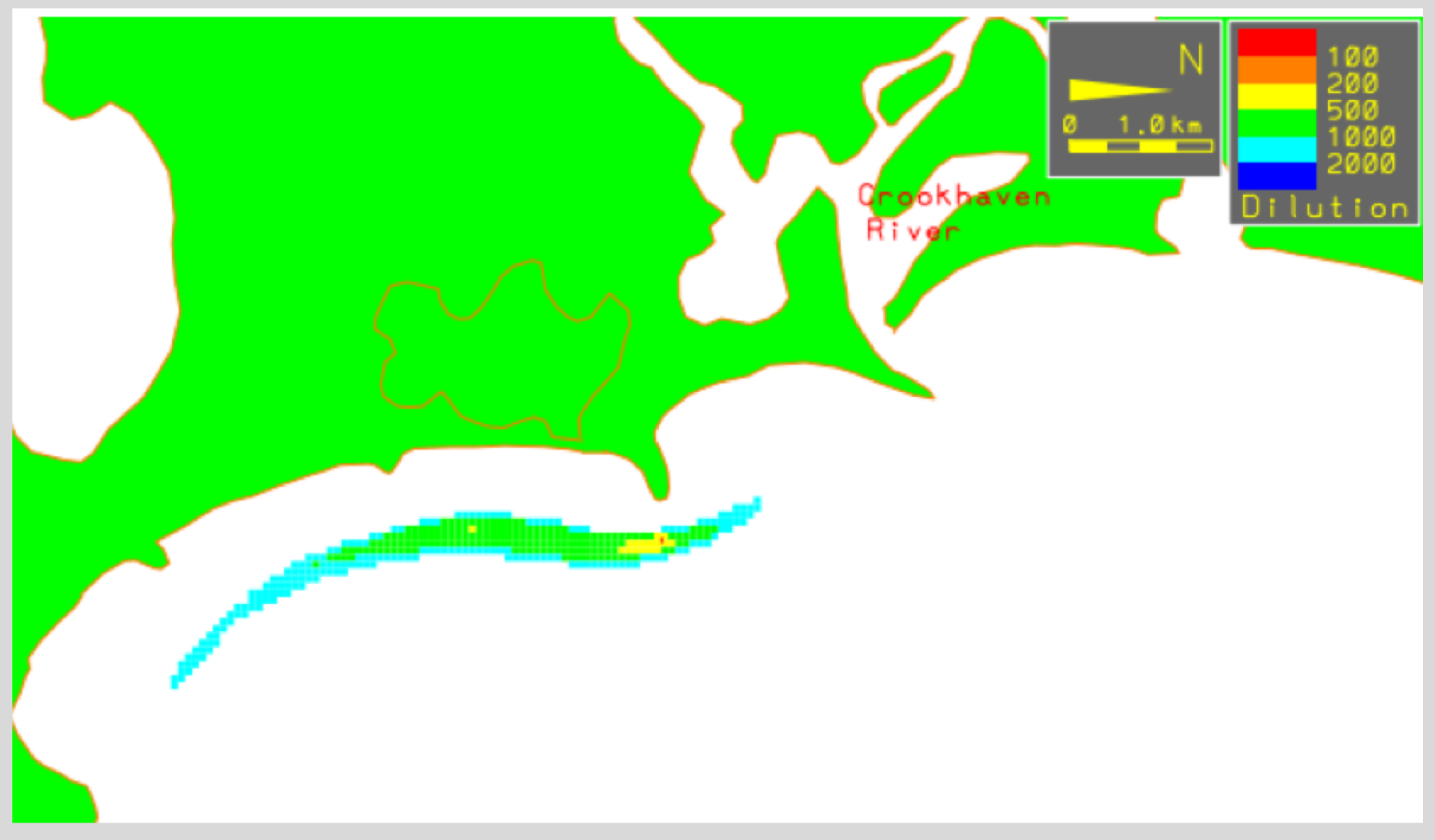
Near field

Near field models are abacus ,analytical or semi analytical calculations providing the characteristics of the plume until it is stabilized in the coastal flow and stratification:

- h_e the plume width or diameter
- C the plume concentration profile (generally gaussian)
- S the dilution rate ($s=C_0/C$)
- Z_m altitude of the maximum concentration
- Z_e altitude maximum of the plume.

Then the coastal **far field** model considers the advection- diffusion of the contaminants as a passive tracer

Tate, P.M., Holden, C.J., Tate, D.J., 2019. Influence of plume advection and particle settling on wastewater dispersion and distribution. Marine Pollution Bulletin 145, 678–690. https://doi.org/10.1016/j.marpolbul.2019.05.059



Far field

Coastal modelling :
ROMS,
CROCO,
MARS3D,
DELFT_3D,
FVCOM,
TELERMAC,
etc.

Building a quasi-non-hydrostatic modelling

$$0 = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} - f_{vert}v + f_{hor} = -\frac{1}{\rho_0}\frac{\partial P}{\partial x} + \frac{\partial \upsilon_h \frac{\partial u}{\partial x}}{\partial x} + \frac{\partial \upsilon_h \frac{\partial u}{\partial y}}{\partial y} + \frac{\partial \upsilon_v \frac{\partial u}{\partial z}}{\partial z}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} + f_{vert}u = -\frac{1}{\rho_0}\frac{\partial P}{\partial y} + \frac{\partial \upsilon_h \frac{\partial v}{\partial x}}{\partial x} + \frac{\partial \upsilon_h \frac{\partial v}{\partial y}}{\partial y} + \frac{\partial \upsilon_v \frac{\partial v}{\partial z}}{\partial z}$$

$$\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} - f_{hor}u = \underbrace{-\frac{\rho}{\rho_0}g - \frac{1}{\rho_0}\frac{\partial P}{\partial z}}_{\text{Hydrostatic (H)}} + \frac{\partial \upsilon_h \frac{\partial w}{\partial x}}{\partial x} + \frac{\partial \upsilon_h \frac{\partial w}{\partial y}}{\partial y} + \frac{\partial \upsilon_v \frac{\partial w}{\partial z}}{\partial z}$$

Hydrostatic **(H)**

Quasi-Hydrostatic (Marshall et al., 1997) **(QH)**

Quasi-Non-Hydrostatic (**QNH**)

Non-Hydrostatic **(NH)**

QNH

$$0 = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} - f_{vert}v + f_{hor} = -\frac{1}{\rho_0}\frac{\partial P}{\partial x} + \frac{\partial \upsilon_h \frac{\partial u}{\partial x}}{\partial x} + \frac{\partial \upsilon_h \frac{\partial u}{\partial y}}{\partial y} + \frac{\partial \upsilon_v \frac{\partial u}{\partial z}}{\partial z}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} + f_{vert}u = -\frac{1}{\rho_0}\frac{\partial P}{\partial y} + \frac{\partial \upsilon_h \frac{\partial v}{\partial x}}{\partial x} + \frac{\partial \upsilon_h \frac{\partial v}{\partial y}}{\partial y} + \frac{\partial \upsilon_v \frac{\partial v}{\partial z}}{\partial z}$$

With an an explicit évaluation of the pressure,

$$P = \underbrace{P_{atm} + \int_z^\eta \rho g dz}_{\text{Hydrostatic (H)}} + \underbrace{\int_z^\eta \left(u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} - f_{hor}u - \frac{\partial \upsilon_h \frac{\partial w}{\partial x}}{\partial x} - \frac{\partial \upsilon_h \frac{\partial w}{\partial y}}{\partial y} \right) dz}_{\text{Quasi-Non-Hydrostatic (QNH)}}$$

and a LES (Smagorinsky formulation) of the turbulent diffusions coefficients.

$$\upsilon_h = \alpha \Delta x \Delta y \left[\underbrace{\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \frac{1}{2}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2} + \underbrace{\frac{1}{2}\left(\frac{\partial w}{\partial x}\right)^2 + \frac{1}{2}\left(\frac{\partial w}{\partial y}\right)^2} \right]^{1/2}$$

-> It is possible to modify the pressure term in a coastal model introducing a pressure perturbation keeping from the vertical momentum balance time rate, horizontal diffusion and advection terms (Klingbeil et Burchard,2013).

-> As long as the time rate $\frac{\partial w}{\partial t}$ is not considered an explicit scheme remains efficient, without significant additional calculation costs.

-> The most important term is the horizontal diffusion of w, allowing to consider the detrainment of the plume.

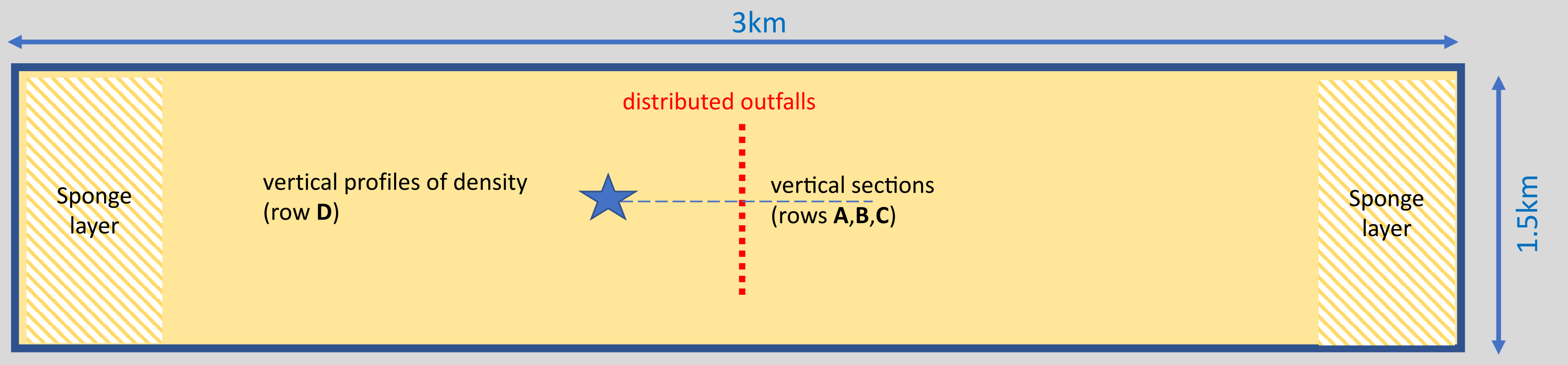
-> The Smagorinsky formulation consider also the horizontal shear of the vertical velocity to evaluate the turbulent diffusion coefficients.

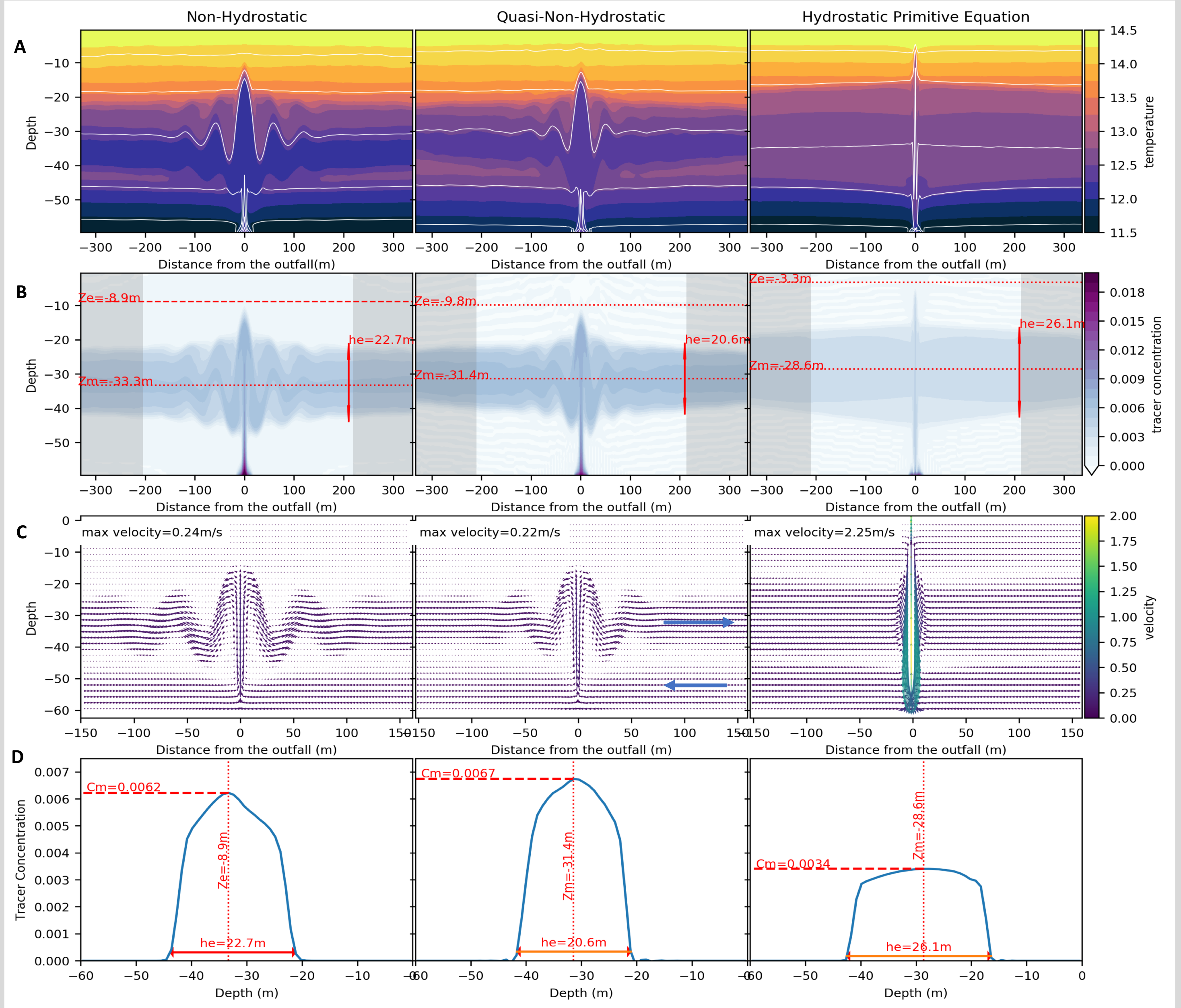
Klingbeil, K., Burchard, H., 2013. Implementation of a direct nonhydrostatic pressure gradient discretisation into a layered ocean model. Ocean Modelling 65, 64–77. https://doi.org/10.1016/j.ocemod.2013.02.002

Quasi-non-hydrostatic modelling compared to hydrostatic and Non-hydrostatic ones

Idealized case configuration

A release of 10 *m*3/*s* distributed on an outfall of 30 meters width and 900 m length at a depth of 60 meters was simulated by the Hydrostatic, Quasi-Non-Hydrostatic and Non-Hydrostatic models. The discharge temperature is set at 26.9°C and the salinity at 0 PSU. The density of the stratified environment verifies the following equation: $\rho(z) = 1.16 * 10{-}2 * z + 1024.8$ with z varying from 0 to $-60\ m$, corresponding to a temperature (resp. salinity) varying linearly from 11.5°C (resp. 35.55 PSU) near the bottom to 14.5°C (resp. 33.35 PSU) at the surface. A tracer with an arbitrary concentration of 1 was associated to the release. A channel of 1024 by 512 by 64 grid with 3 m horizontal and less than 1 m vertical resolution with flat bottom bathymetry is used to model all experiments.





Non-Hydrostatic and Quasi Non Hydrostatic modelling provide very similar plume behaviour. The plume overshoots slightly before oscillating and stabilizing around 30m deep.

QNH is designed to manage both the near and far field in a single code without any significant additional calculation costs.

Hydrostatic modelling leads to unrealistic vertical velocities and a strong overestimation of effluent mixing.

Coupling with a near-field approach is necessary.

Quasi-non-hydrostatic modelling applied to realistic case : IPANEMA BEACH outfall (Brazil).

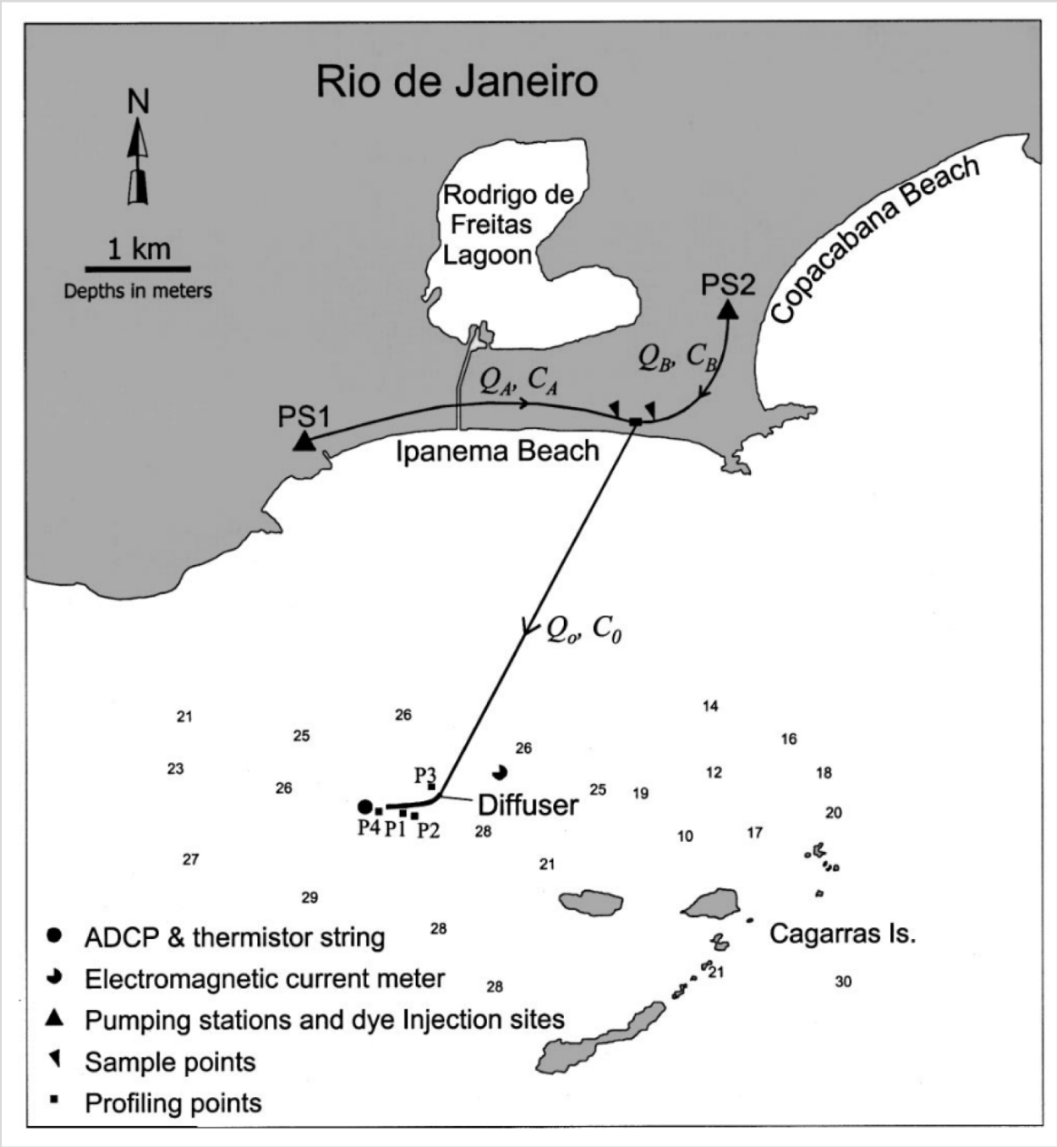


Figure 1 : Configuration of the outfall in Ipanema Bay

Dye experiments have been conducted around the sewage outfall of Ipanema Beach during stratified and unstratified condition to evaluate three commonly used near field models (UM3, RSB and CORMIX) (Carvalho et al. , 2002)

A Quasi Non Hydrostatic Coastal Hydrodynamic model (MARS3D, $\Delta x = 3m, \Delta z = 0.45m$) simulated the dynamics observed during the fields experiments (effluent flow rates and densities , far field current strength and direction, stratification…) .

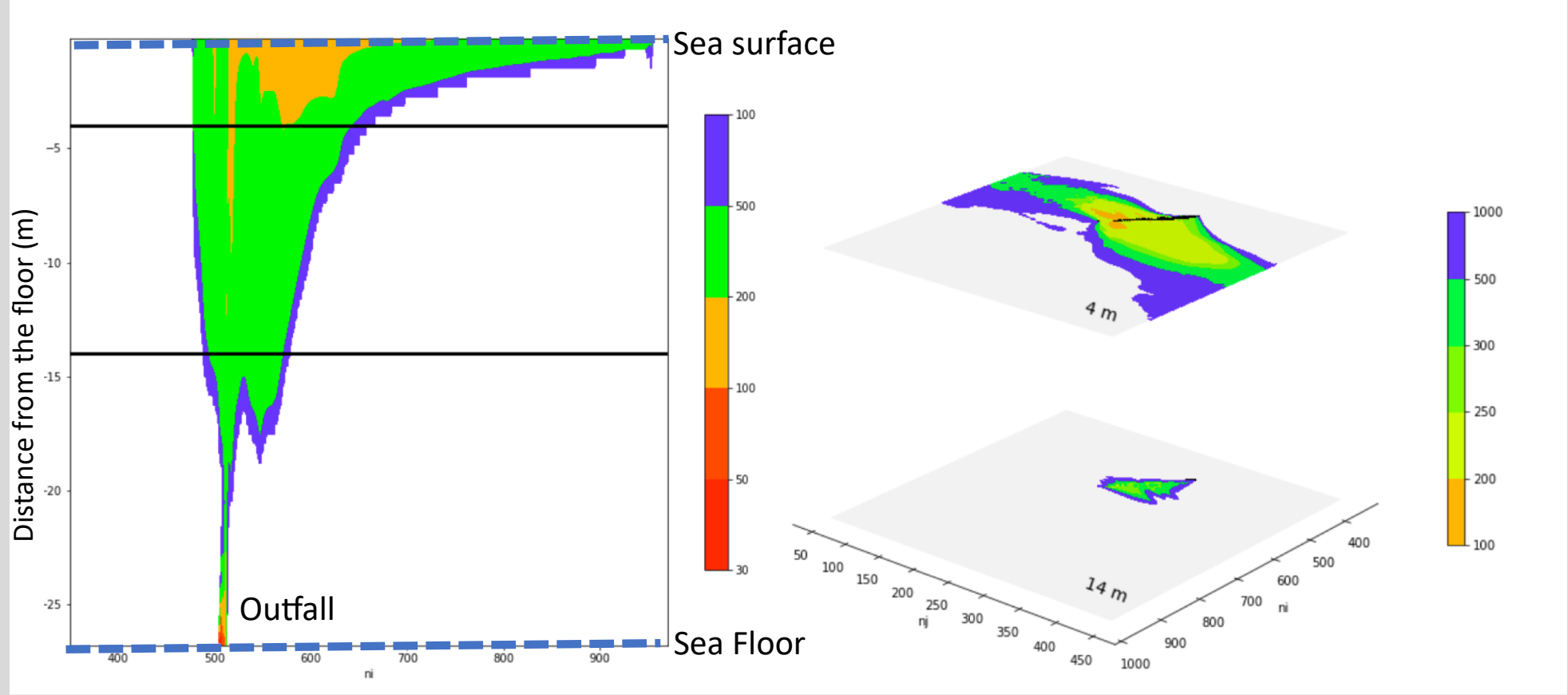


Figure 2 During winter experiment when the water column was unstratified. The plume reaches the surface and is advected by a mean current.

	QNH	*In-Situ*	RSB	UM3	CORMIX (MUIH)
S_m	172	130	139	152	140
Z_m	27.0 m	27.0 m	27.0 m	23.9 m	22.7 m
h_e	20.2 m	23.0 m	23.4 m	14.6 m	9.1 m

Table a

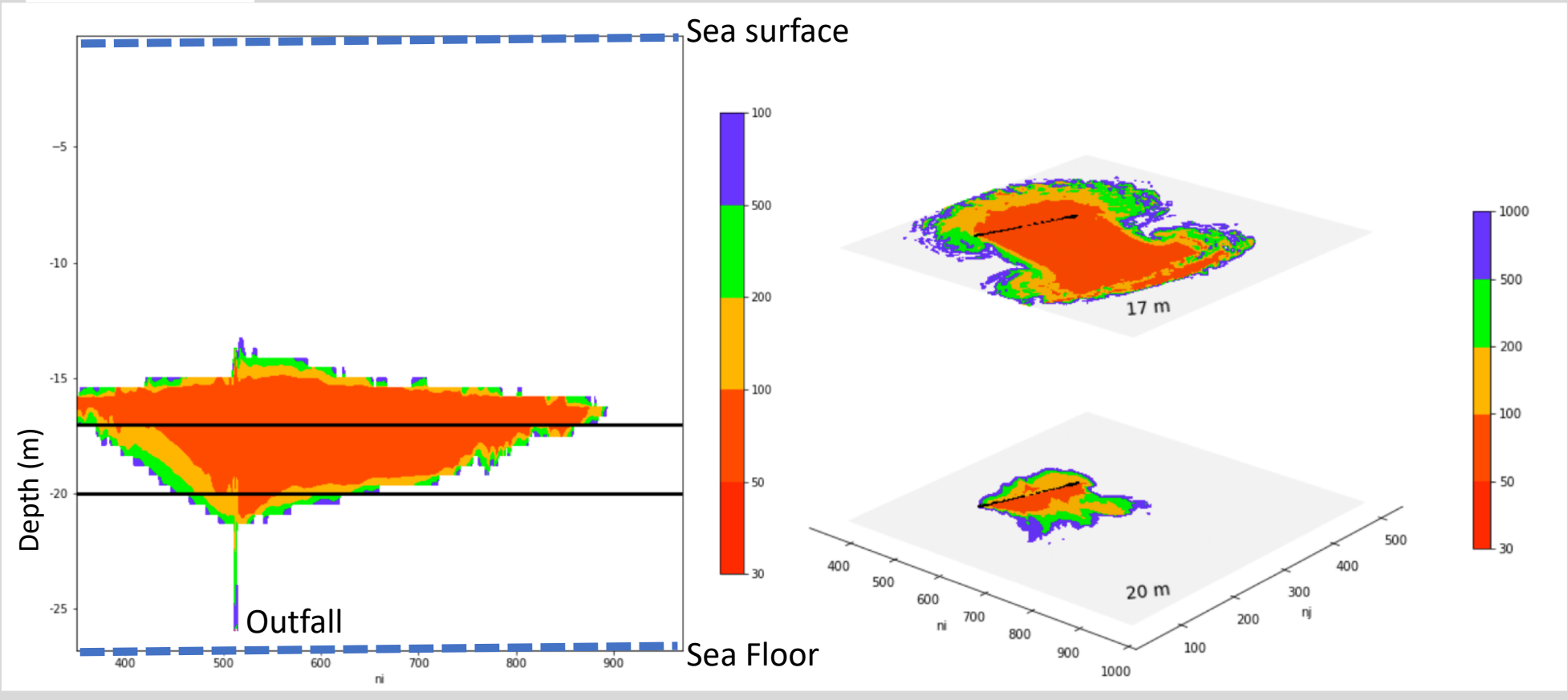


Figure 3 : During summer experiment when the water column was strongly stratified. The plume updraft is limited by the ambient buoyancy gradient. The plume remain confined under the thermocline and is less diluted than in winter.

	QNH	*In-Situ*	RSB	UM3	CORMIX (MS3)
S_m	57.3	59	38	40	39
Z_m	11.3 m	9.0 m	8.6m	13.1m	11.9 m
h_e	7.56 m	5.5 m	9.7m	14.9m	5.4 m

Table b

The minimum dilution ($S_m=C_0/C_{max}$) in the plume, the altitude of the minimum dilution Z_m and the width of the plume h_e at the near field boundary observed or computed by near field and QNH models are in agreement (table a,b)

Carvalho, J.L.B., Roberts, P.J.W., Roldão, J., 2002. Field Observations of Ipanema Beach Outfall. Journal of Hydraulic Engineering 128, 151–160. https://doi.org/10.1061/(ASCE)0733-9429(2002)128:2(151)