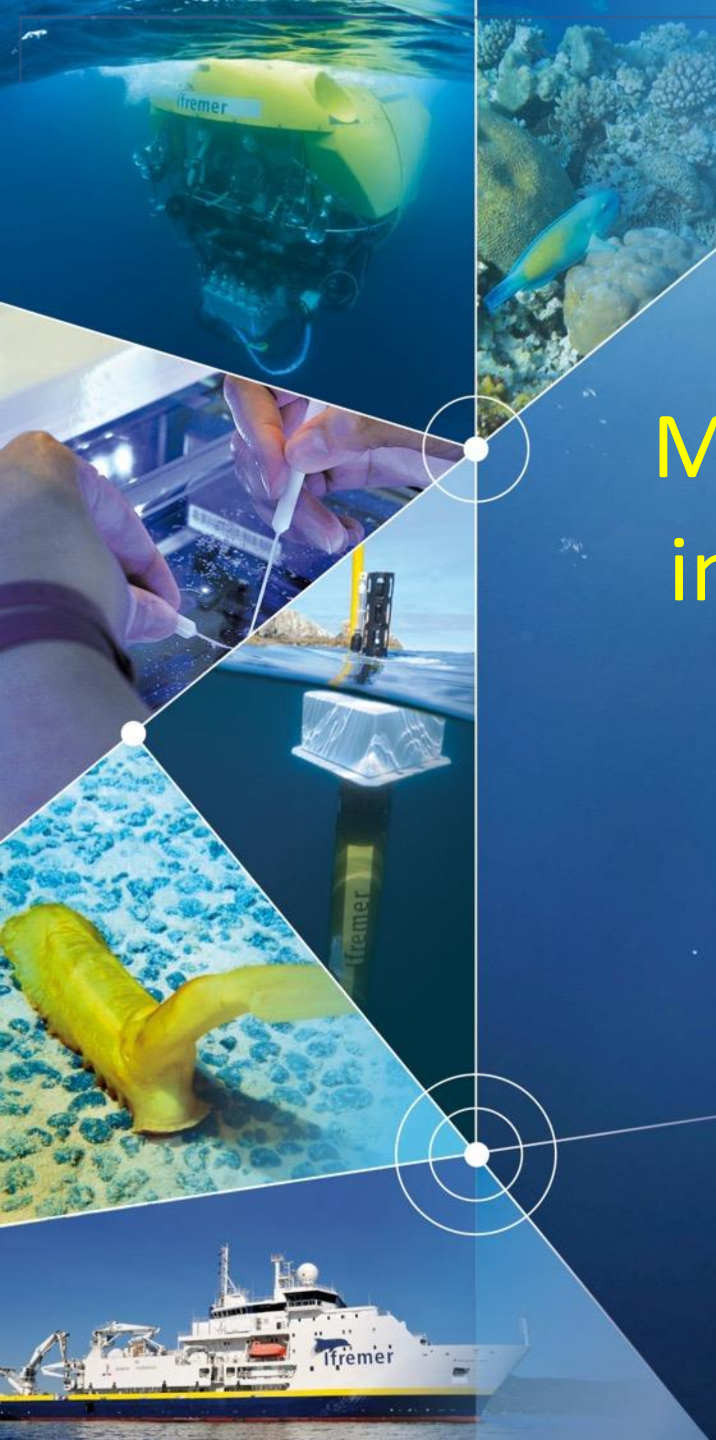


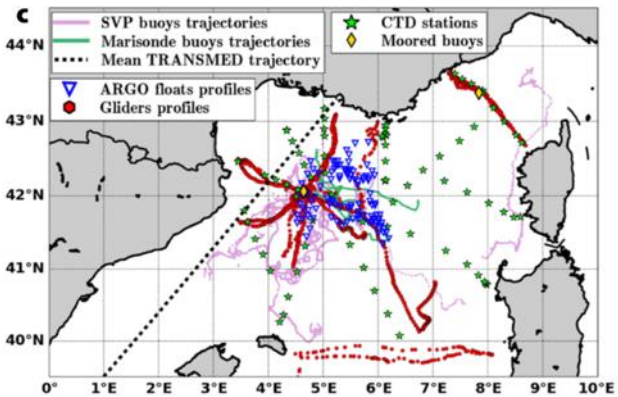
Ifremer

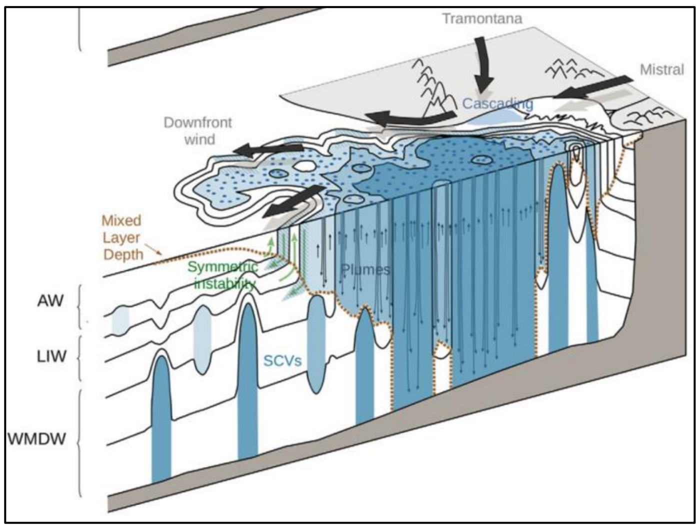
Modelling Convective plumes in the framework of a Quasi-Non-Hydrostatic approach

Pierre.Garreau@ifremer.fr

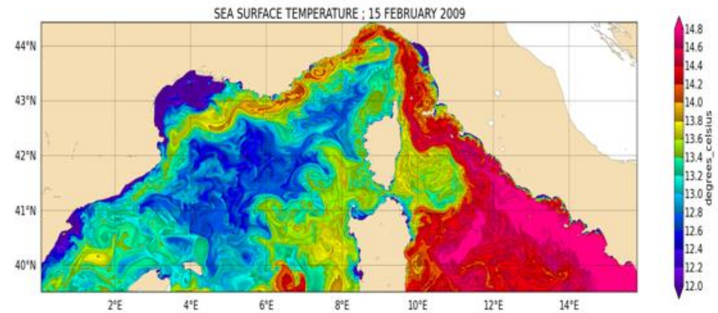
SIMULATING THE DEEP CONVECTION
WESTERN MEDITERRANEAN SEA

2012-2013 : an intensive field experiment

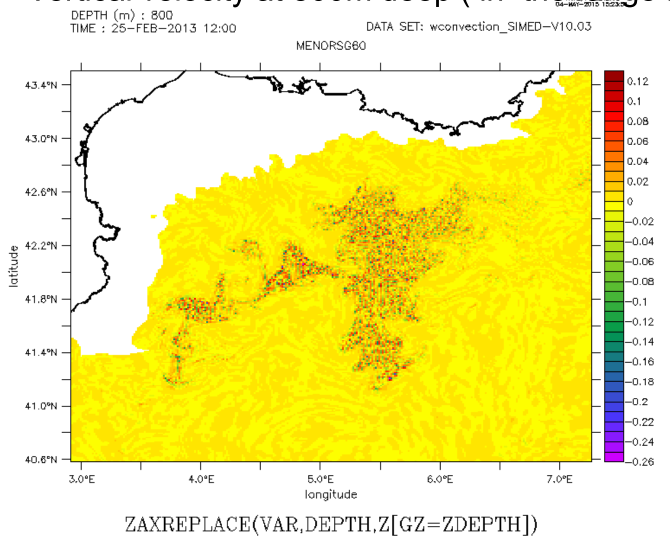




Regional Numerical Modelling
Mars3d (MENOR) (1.2 km, 400m)



Vertical velocity at 800m deep (in the range !)



Testor, P et al.2018. Multiscale Observations of Deep Convection in the Northwestern Mediterranean Sea During Winter 2012–2013 Using Multiple Platforms. Journal of Geophysical Research: Oceans 123, 1745–1776. https://doi.org/10.1002/2016JC012671

Estournel, C. et al. (2016). HyMeX-SOP2: The Field Campaign Dedicated to Dense Water Formation in the Northwestern Mediterranean. Oceanography 29, 196–206. https://doi.org/10.5670/oceanog.2016.94

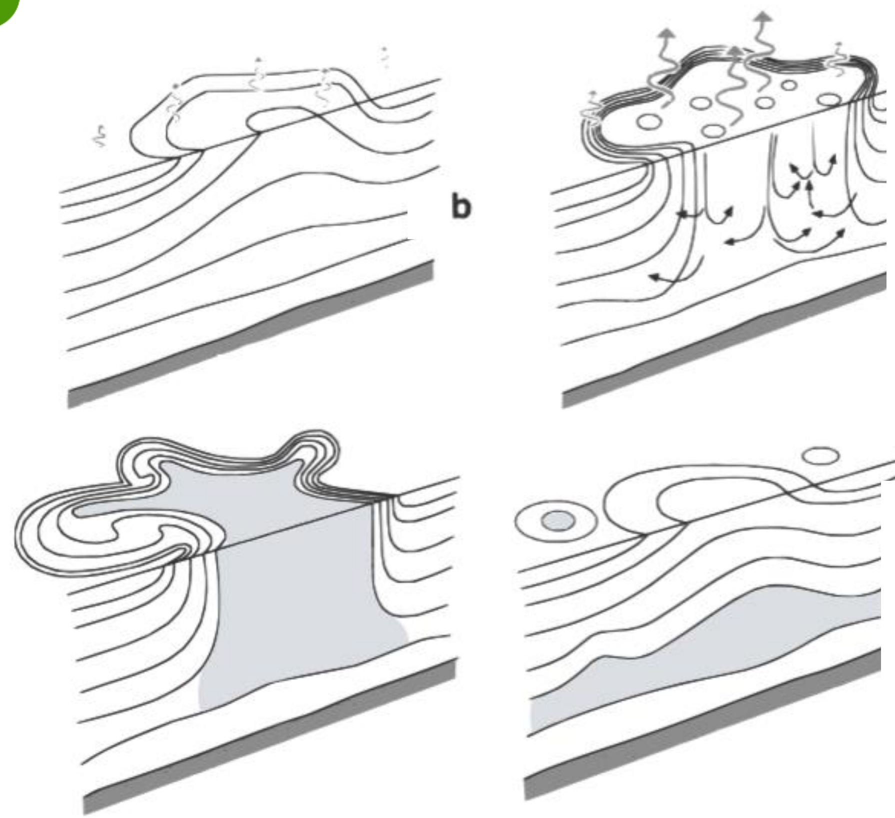
SIMULATING THE DEEP CONVECTION :
A CHALLENGE FOR THE MODELER

a) Pre-conditionning

- Existing cyclonic circulation
- isopycnal dome
- Erosion of the stratification
- Lost of buoyancy
- T ~weeks
- L ~ 10-100km

b) Convection

- Lost of buoyancy
- Gravitational instability
- Convective cells
- w=0.2m/s
- T ~ hours
- L ~ 1-3 km



c) Meso-echelles

- Restratification
- Geostrophic balance
- Formation of SCV's
- w=0.02m/s
- T ~ days
- L ~ 10-50 km

d) Spreading

- The dense water formed spreads to the bottom of the entire basin
- T ~ Months
- L ~ 100 km

Marshall, J., Schott, F., 1999. Open-ocean convection: Observations, theory, and models. Rev. Geophys. 37, 1–64. https://doi.org/10.1029/98RG02739

In the scope of "classical" numerical modeling

Need to be parametrized by convective adjustment (enhanced vertical diffusion) or non-hydrostatic modelling requested

HYDROSTATIC VS NON-HYDROSTATIC MODELLING :
THE CONVECTION STAY IN A « GRAY » ZONE

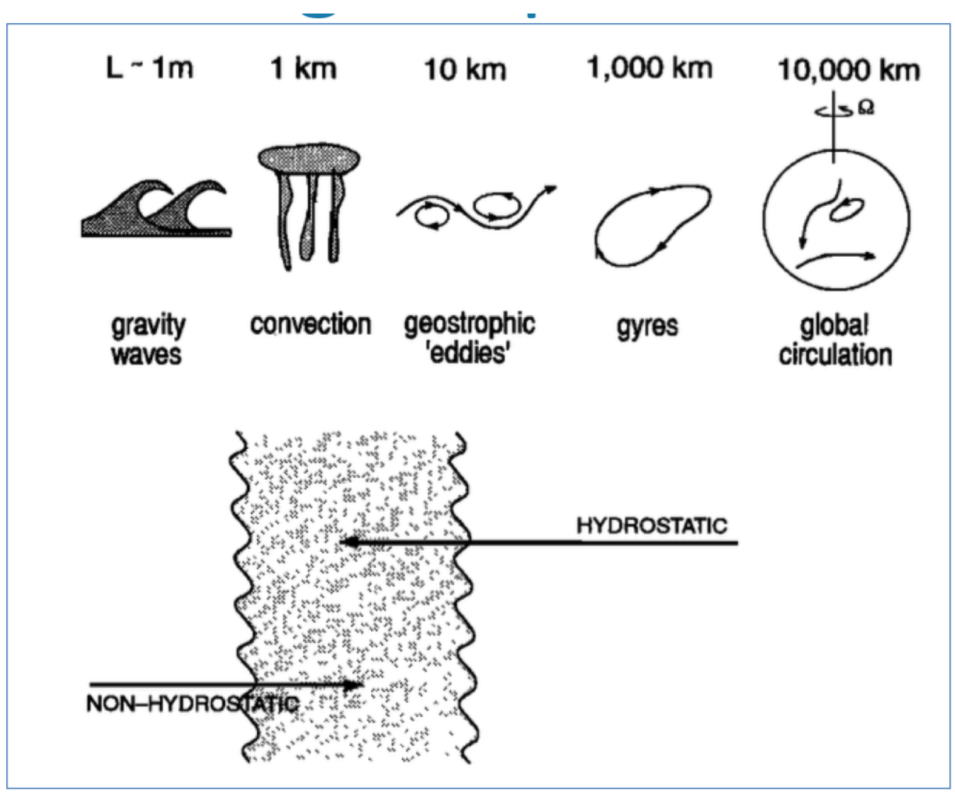
NON HYDROSTATIC

Full set of Navier Stokes Equations

Prognostic equation for the vertical momentum

Heavy computational cost
- efficient in idealized modeling of convection

- deceiving in realistic modelling of deep convection



dx = 100m -> 6 km

Modelers increase resolution…

HYDROSTATIC

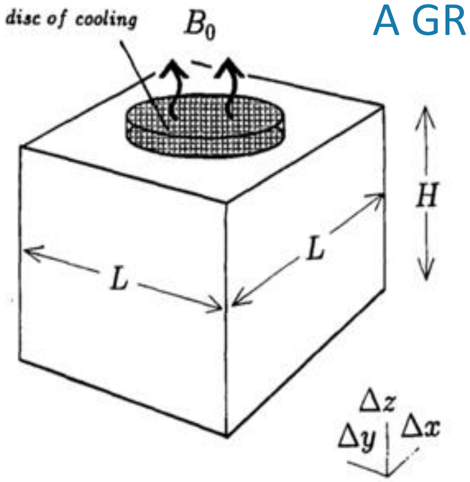
Simplified set of Navier-Stokes equations

Diagnostic equation for the vertical momentum

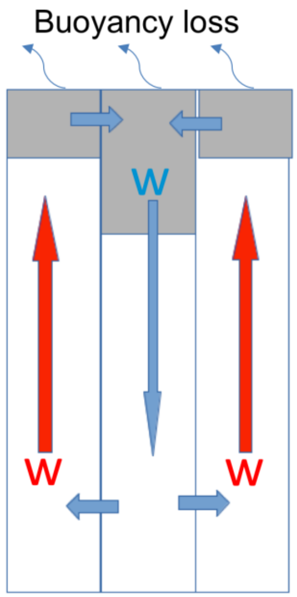
Currently performed for realistic modeling

Marshall, J., C. Hill, L. Perelman, and A. Adcroft. 1997. 'Hydrostatic, Quasi-Hydrostatic, and Nonhydrostatic Ocean Modeling'. Journal of Geophysical Research-Oceans 102 (C3): 5733–52. doi:10.1029/96JC02776.

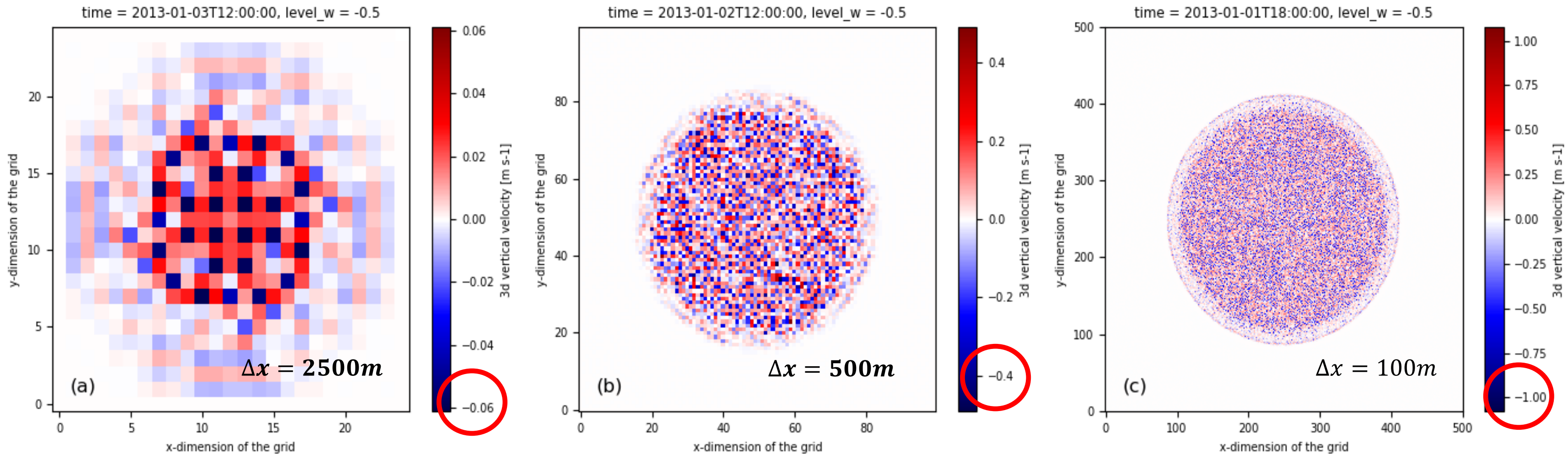
CONVECTION IN THE HYDROSTATIC FRAMEWORK :
A GRID INSTABILITY



Tank Modelling
L=50 km
H=2000 m
R= 15 km ε
B_0= -400 + w/m^2
No stratification



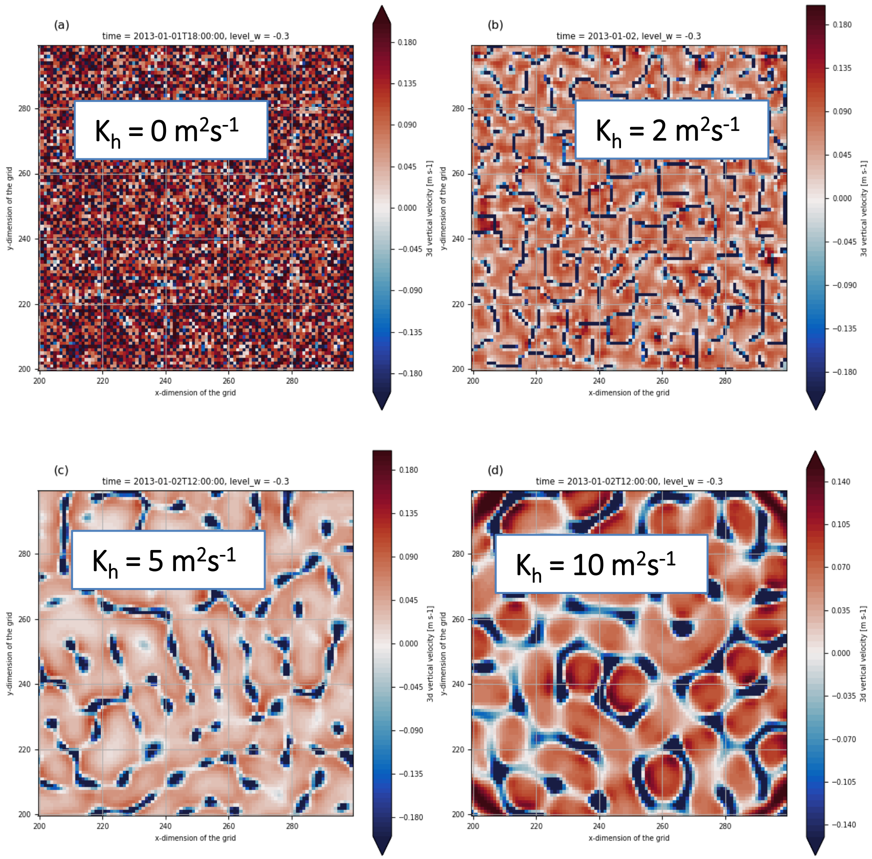
In hydrostatic modelling , the convection still exists
But is organized at grid size scale.



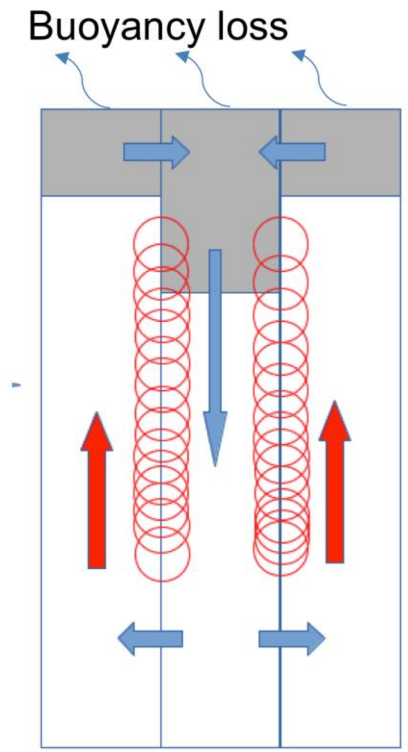
Vertical velocity at 1000m deep for different grid sizes; verticale velocity increase with the resolution.

CONVECTION IN THE HYDROSTATIC FRAMEWORK :

A question of horizontal diffusion



Vertical velocity at 100m deep for different values of horizontal diffusion (horizontal momentum and tracers)



$$L = \sqrt{\pi\, t\, K_h} = \sqrt{\frac{\pi\, H\, K_h}{w}}$$

L= 2km <~> K_h =$5m^2s^{-1}$

A L.E.S. (Large Eddy Simulation) formulation is possible (Samagorinsky)

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

HPE – QH – QNH – NH

Non-Hydrostatic set of equations

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

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

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

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

Complete but very heavy to manage (3D Poisson system)
A perturbed pressure method (klingbell et all 2013) can be implemented in hydrostatic coastal modeling :

$$P = P_{atm} + \int_z^\eta \rho g dz + \int_z^\eta \left(\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} - f_{hor}u - \frac{\partial \upsilon_h \frac{\partial w}{\partial x}}{\partial x} - \frac{\partial \upsilon_h \frac{\partial w}{\partial y}}{\partial y} \right) dz$$

But remains heavy (very small time step, modified time step scheme, instabilities, temporal filtering etc…)

Klingbeil, K. & Burchard, H. Implementation of a direct nonhydrostatic pressure gradient discretisation into a layered ocean model. *Ocean Modelling* **65**, 64–77 (2013).

HPE – QH – QNH – NH

Hydrostatic Primitive Equation

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

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

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

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

$$P = P_{atm} + \int_z^{\eta} \rho g dz$$

Pressure is hydrostatic
Largely used in oceanographic context but simplified

HPE – **QH** – QNH – NH

Quasi-**H**ydrostatic (Marshall et al. 1997)

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

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

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

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

$$P = P_{atm} + \int_z^{\eta} \rho g\, dz + \int_z^{\eta} (-f_{hor}u)\, dz$$

Pressure is now also a function of a non traditional Coriolis term.
Easy to implement in HPE code (Marshall et al. 1997)

Marshall, J., Hill, C., Perelman, L. & Adcroft, A. Hydrostatic, quasi-hydrostatic, and nonhydrostatic ocean modeling. *J. Geophys. Res.-Oceans* **102**, 5733–5752 (1997).

HPE – QH – **QNH** – NH

Quasi **N**on-**H**ydrostatic

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

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

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

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

$$P = P_{atm} + \int_z^\eta \rho g dz + \int_z^\eta \left(u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} - f_{hor}u - \frac{\partial \upsilon_h \frac{\partial w}{\partial x}}{\partial x} - \frac{\partial \upsilon_h \frac{\partial w}{\partial y}}{\partial y} \right) dz$$

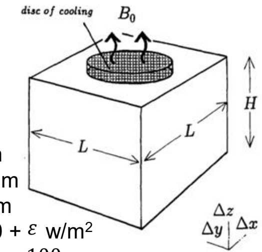
Dominant terms for convective dynamics

Pressure is now a function of a non traditional Coriolis term, and of momentum advection-diffusion of w

Easy to implement in HPE code. An Euler time-step is sufficient until $\frac{\partial w}{\partial t}$ is not considered

CONVECTION IN THE QNH FRAMEWORK :

Convection cells are simulated

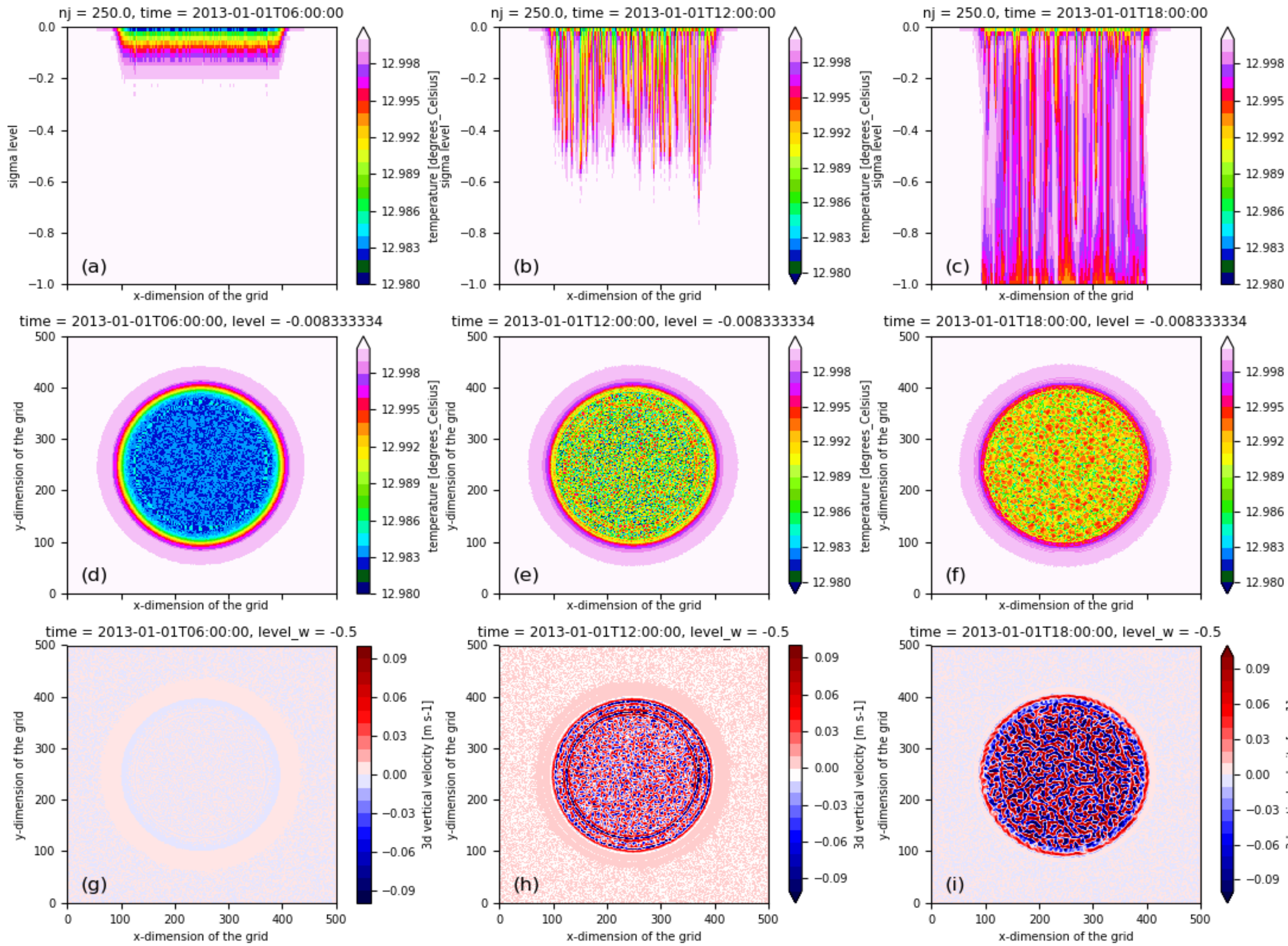


L=50 km
H=2000 m
R= 15 km
B_0= -400 + ε w/m²
$\Delta x = \Delta y = 100m$
No stratification

T=06h
Formation of an cold (dense) lens.
Diffusion dominates Convection
(Rayleigh Number)

T=12h
Partial convection

T=18 h
Deep convection.
Plumes reache the floor



Temperature transects

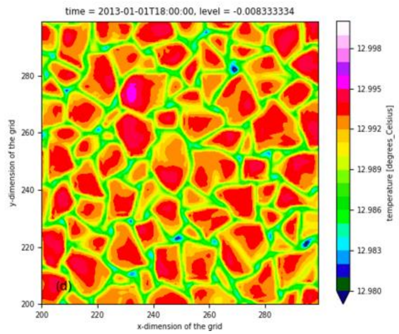
Sea Surface temperature

Vertical velocity at mid-depth

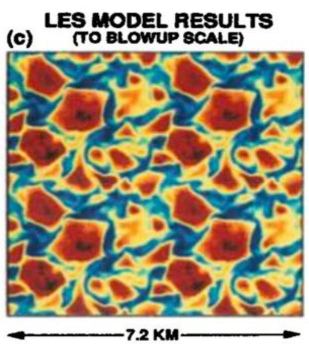
CONVECTION IN THE QNH FRAMEWORK :
The results are close to the previous NH approaches

QNH

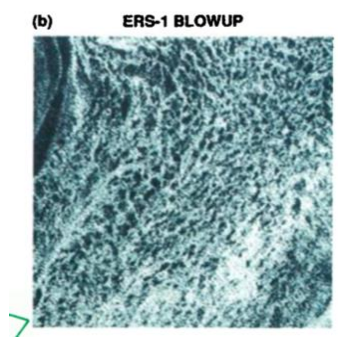
Sea Surface temperature pattern



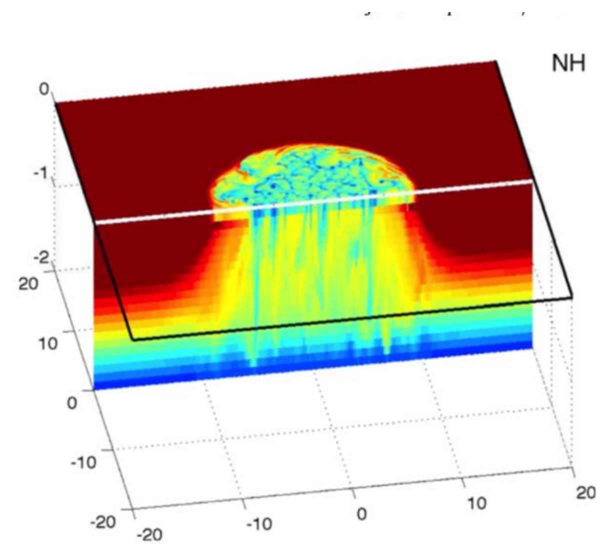
NH



OBS

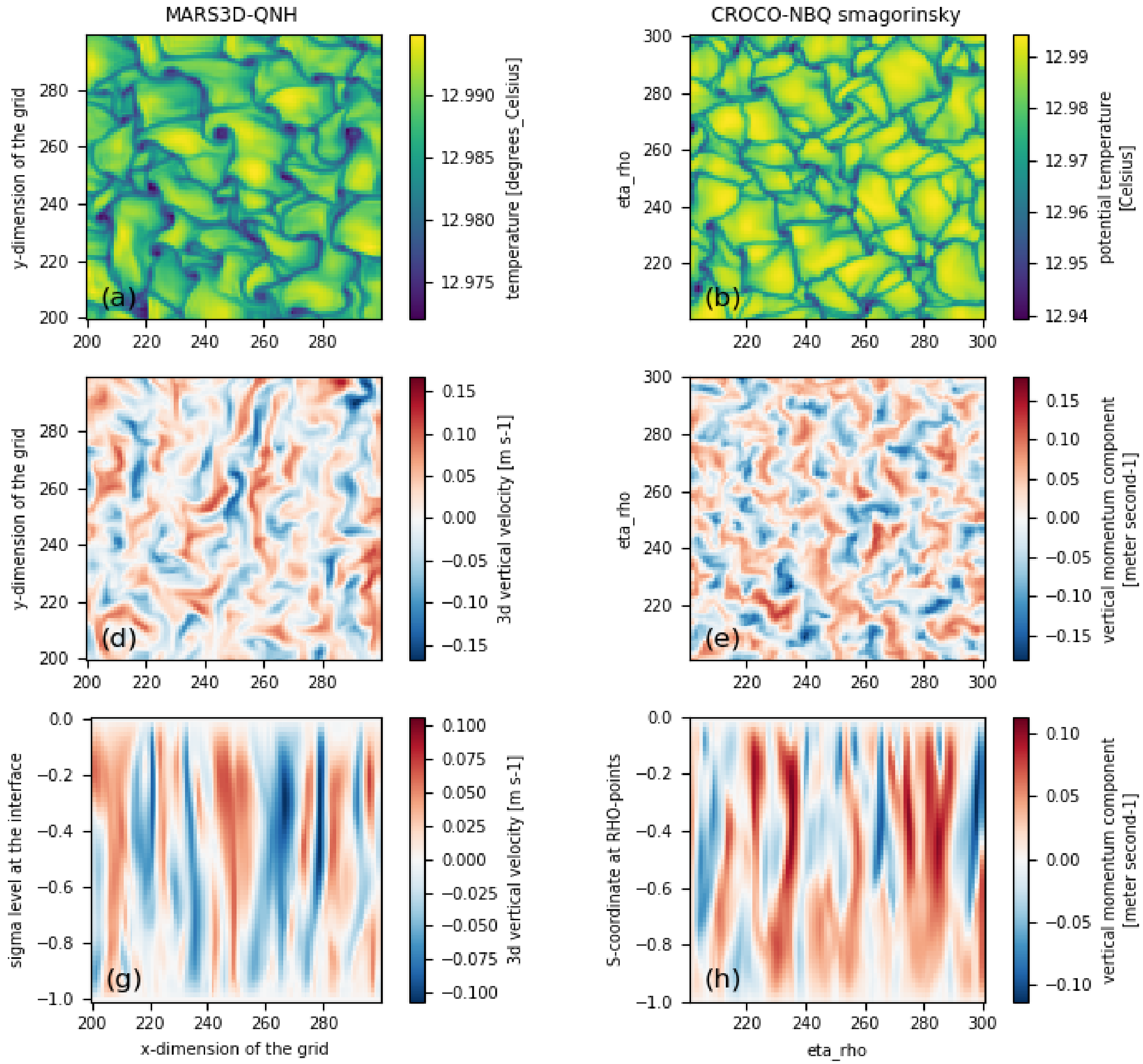


Carsey, F. D. & Garwood, R. W. Identification of modeled ocean plumes in Greenland Gyre ERS-1 SAR data. *Geophys. Res. Lett.* **20**, 2207–2210 (1993).

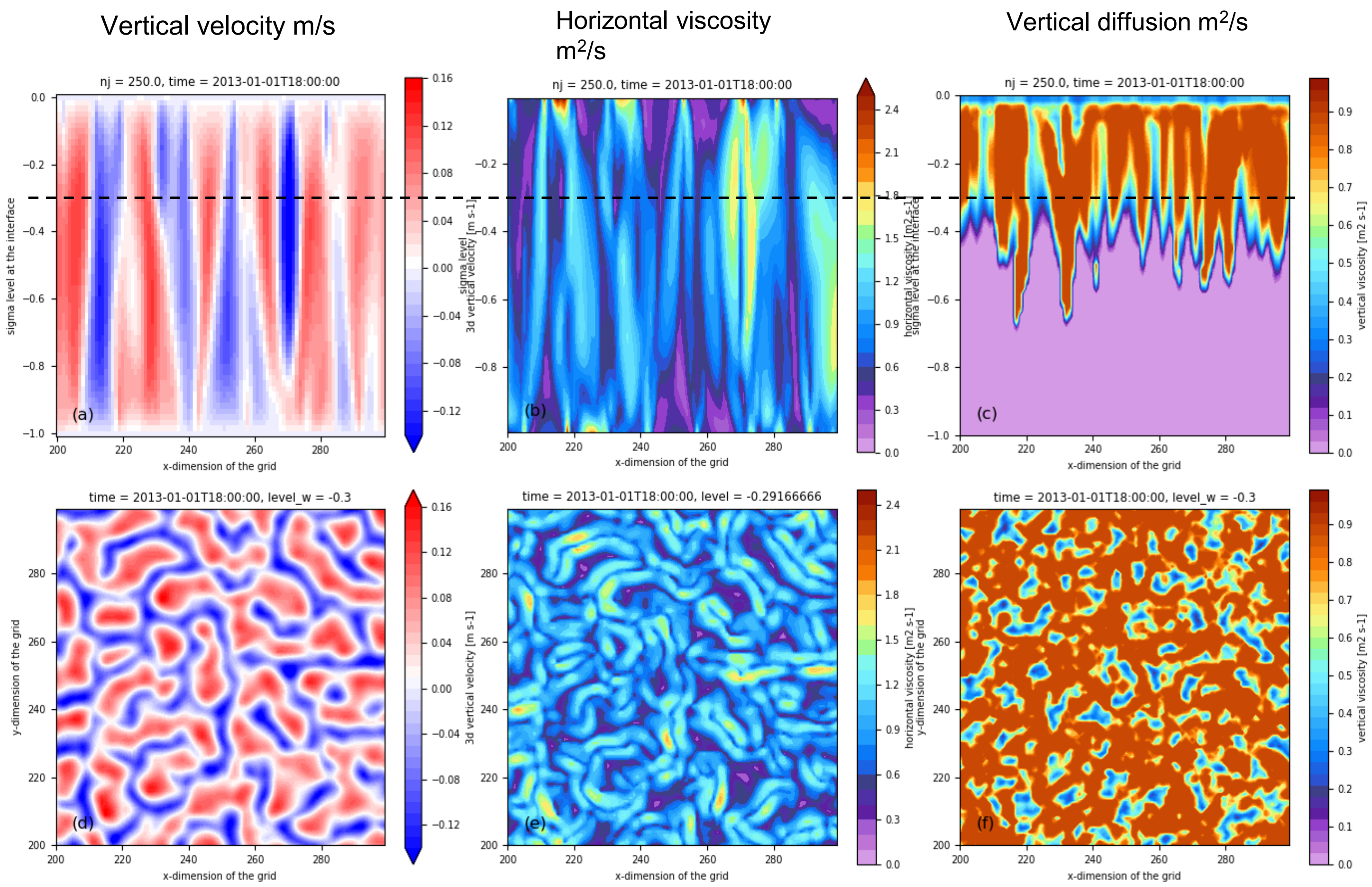


Campin, J.-M., Hill, C., Jones, H. & Marshall, J. Super-parameterization in ocean modeling: Application to deep convection. *Ocean Modelling* **36**, 90–101 (2011).

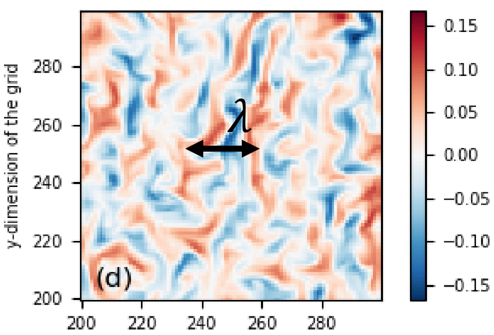
Comparison with Non-hydrostatic modelling (CROCO NBQ)



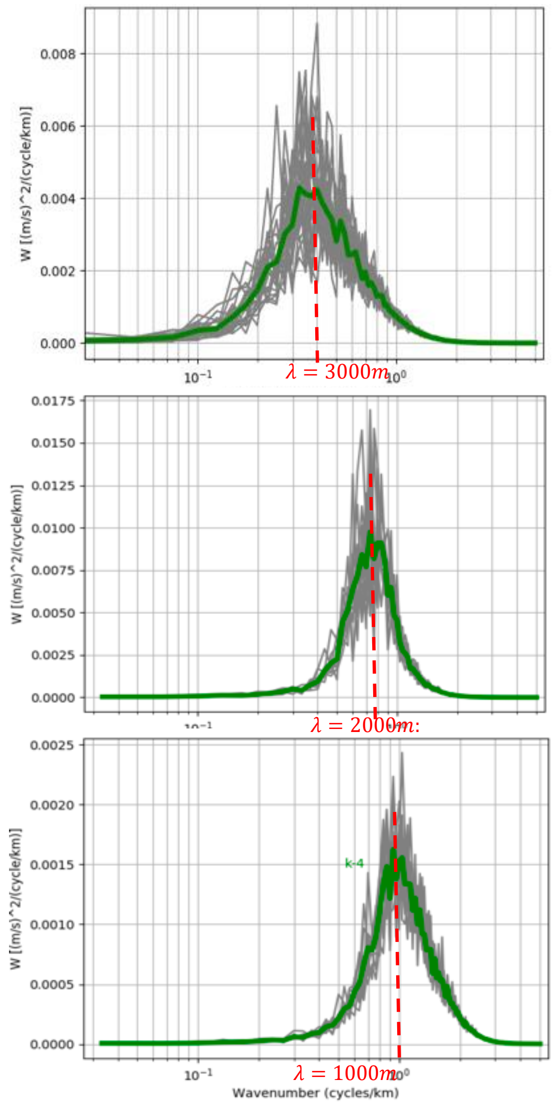
CONVECTION IN THE QNH FRAMEWORK :
Advection vs diffusion

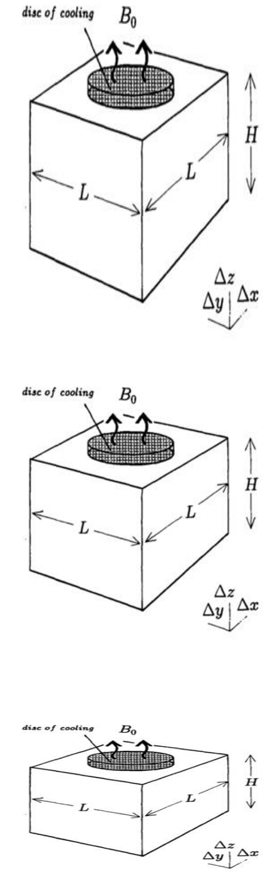


HORIZONTAL LENGTH SCALE OF CONVECTION

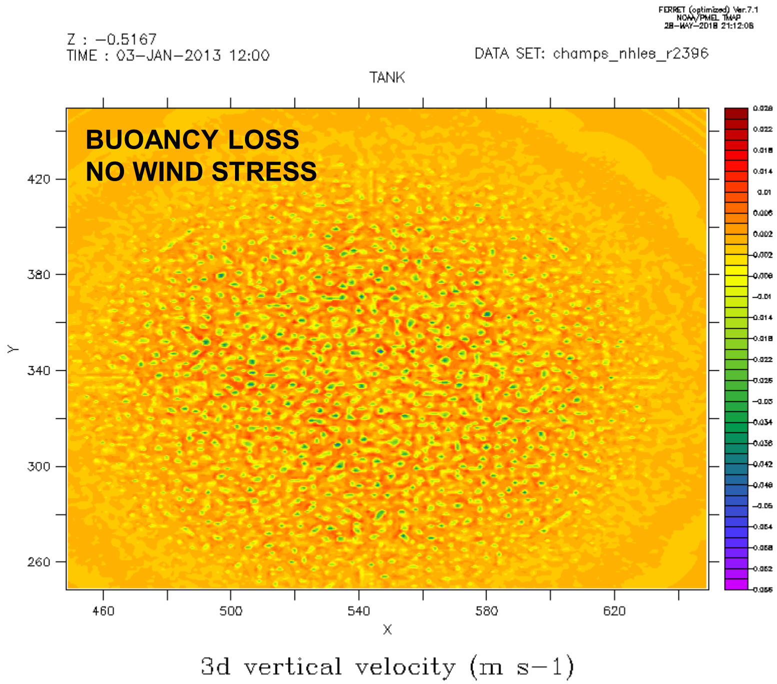


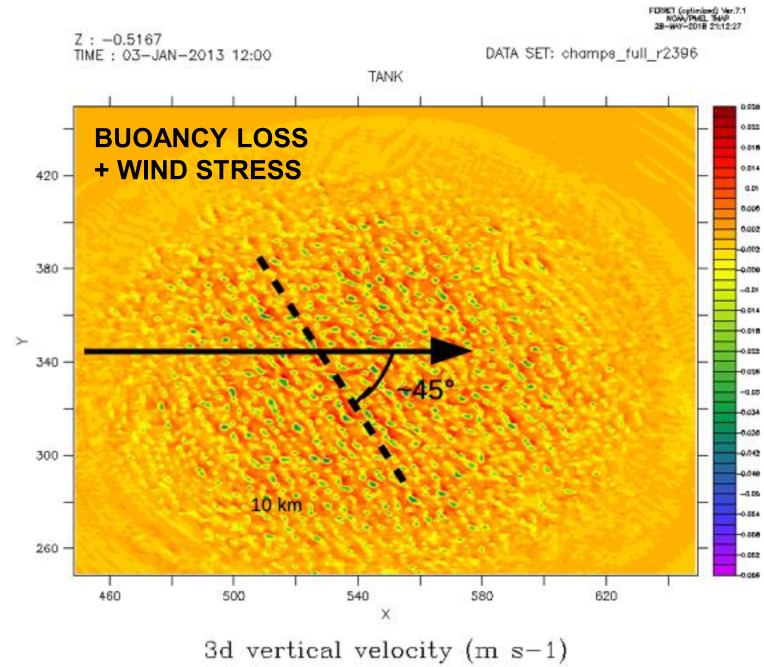
The horizontal length scale of the plumes is the depth of the convection

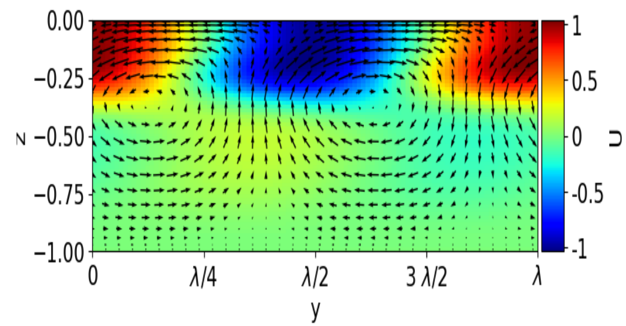




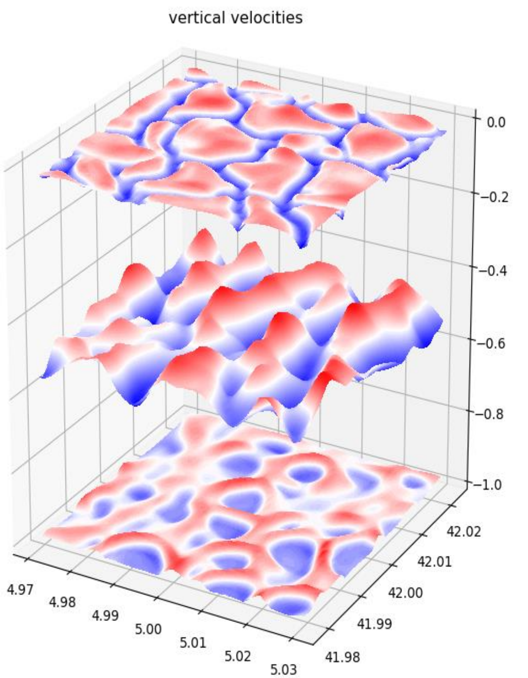
EFFECT OF THE WIND
EKMANN ROLL

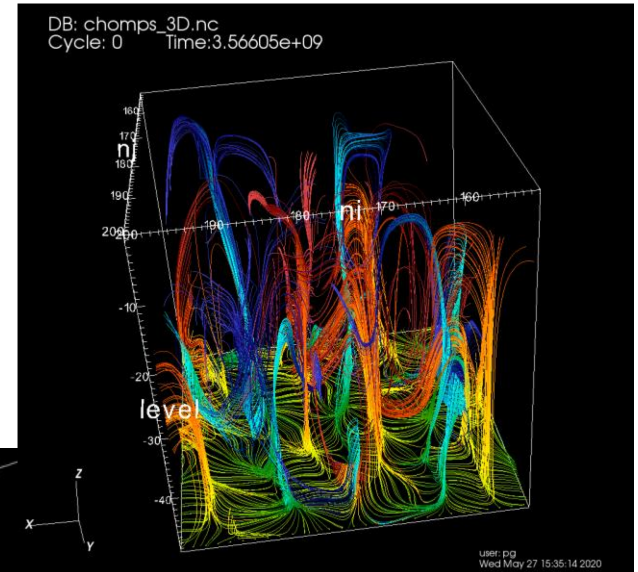


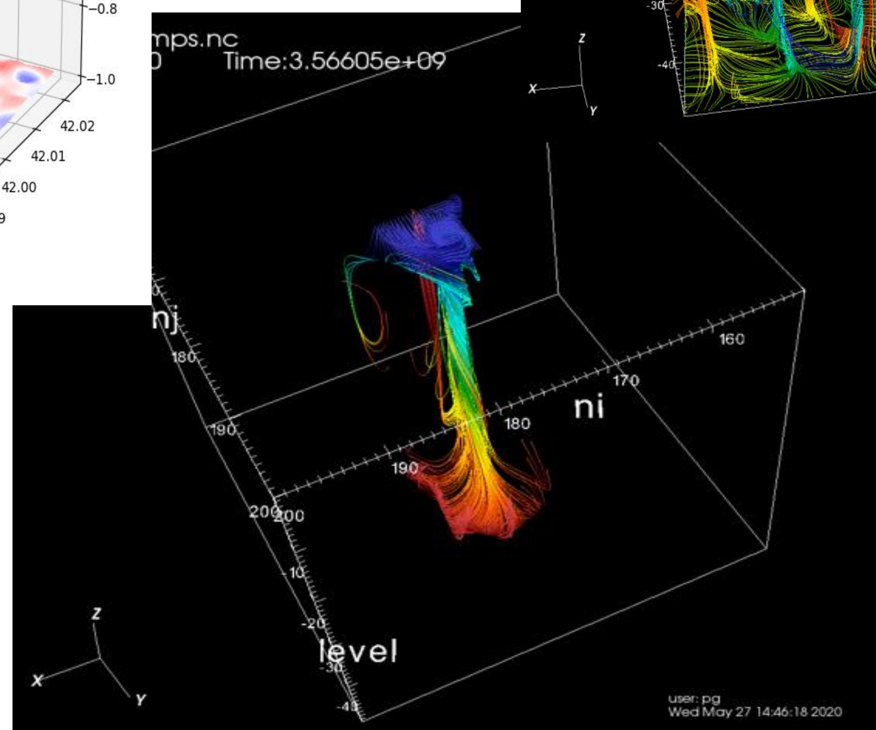




CONVECTION IN THE HYDROSTATIC FRAMEWORK :
Details of plumes

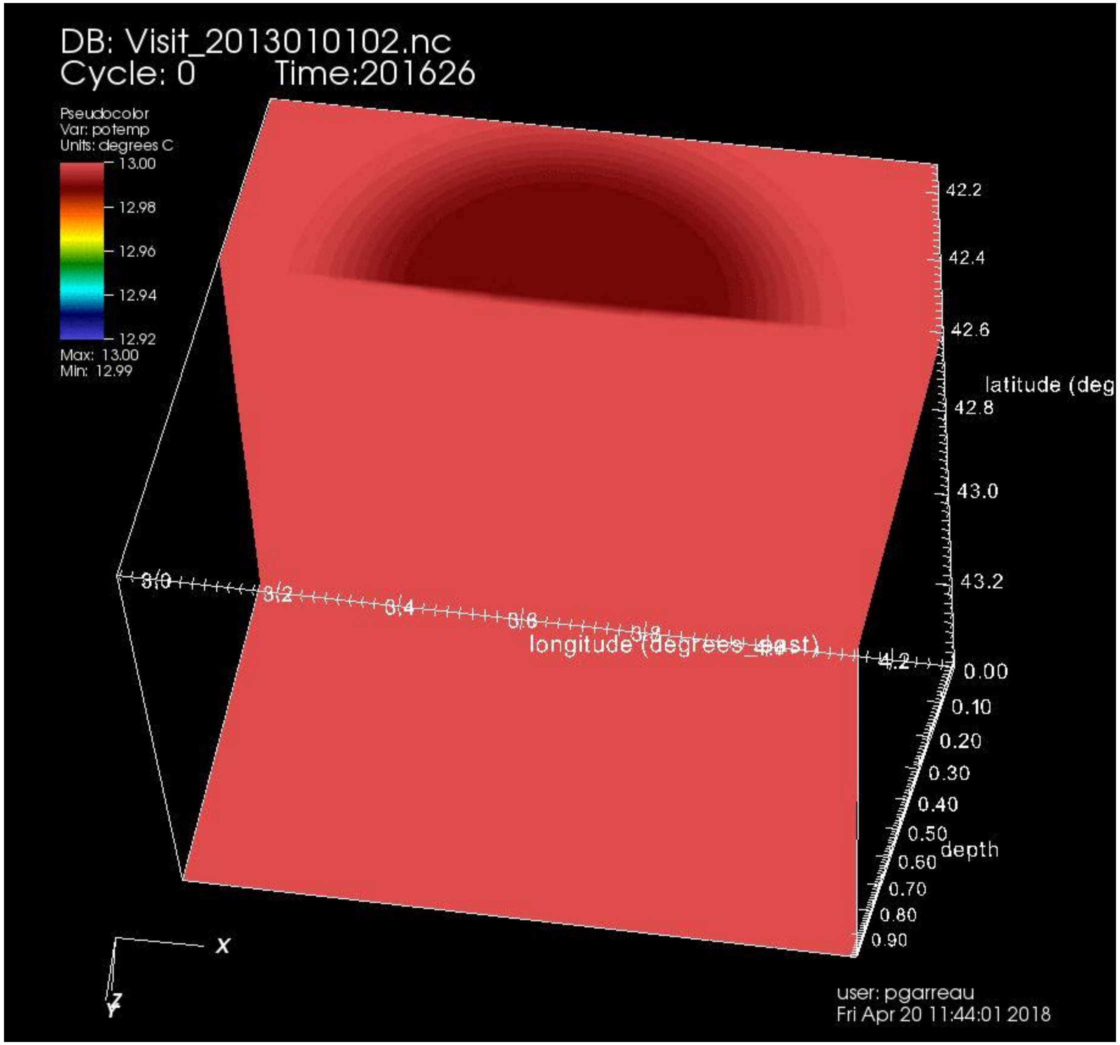






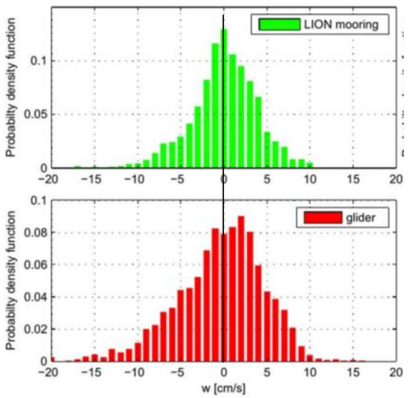
CONVECTION IN THE QNH FRAMEWORK :

Convection cells are simulated



Quasi Non-Hydrostatic Modelling of the 2013 convection event

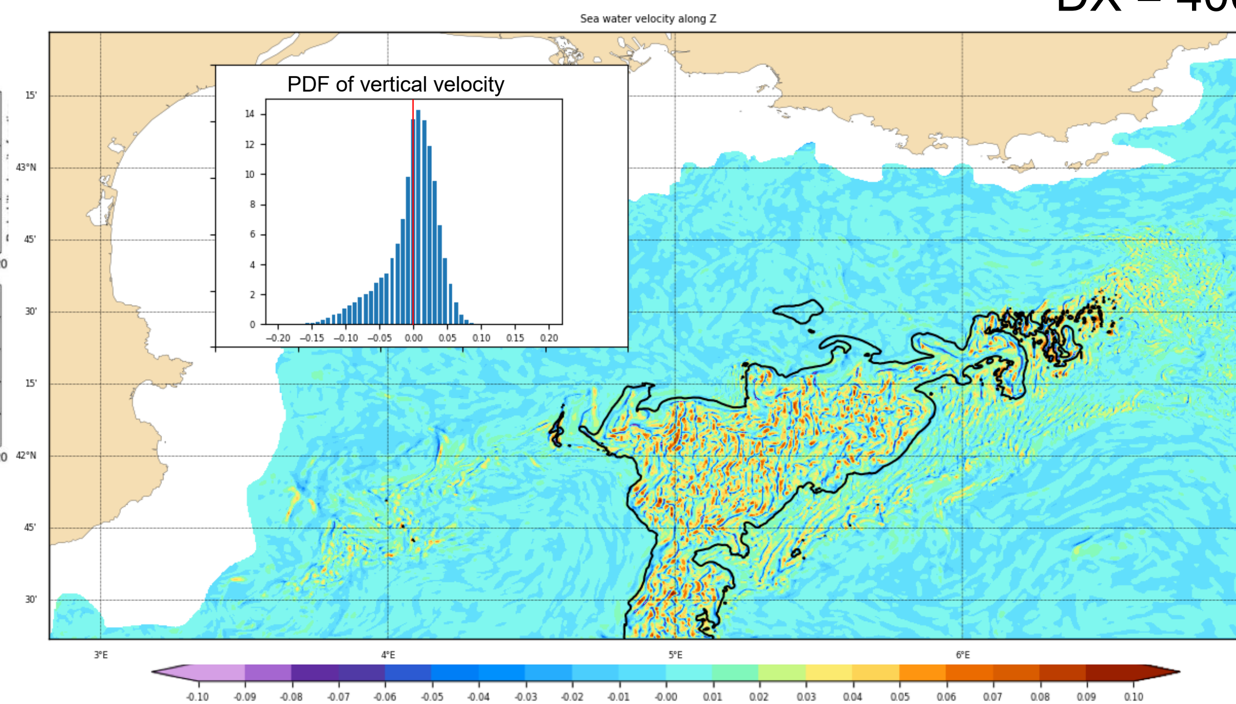
PDF of vertical velocity
Observations

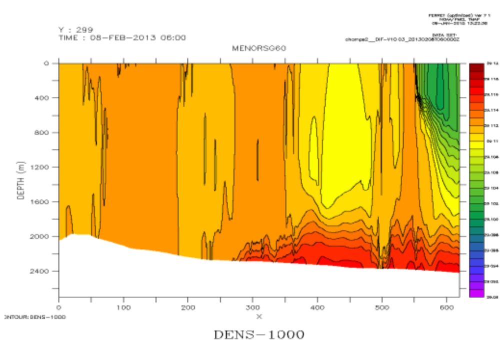


Margirier, F. et al. 2017. Characterization of Convective Plumes Associated With Oceanic Deep Convection in the Northwestern Mediterranean From High-Resolution In Situ Data Collected by Gliders. Journal of Geophysical Research: Oceans 122, 9814–9826.

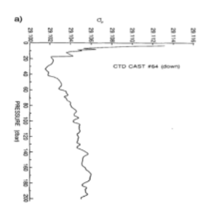
Modeled Vertical velocity during the first convection event (Feb. 10^{th} 2013)

DX = 400m

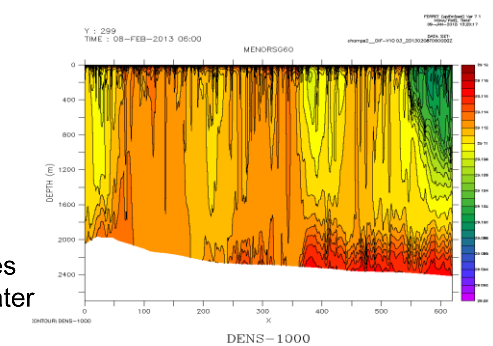




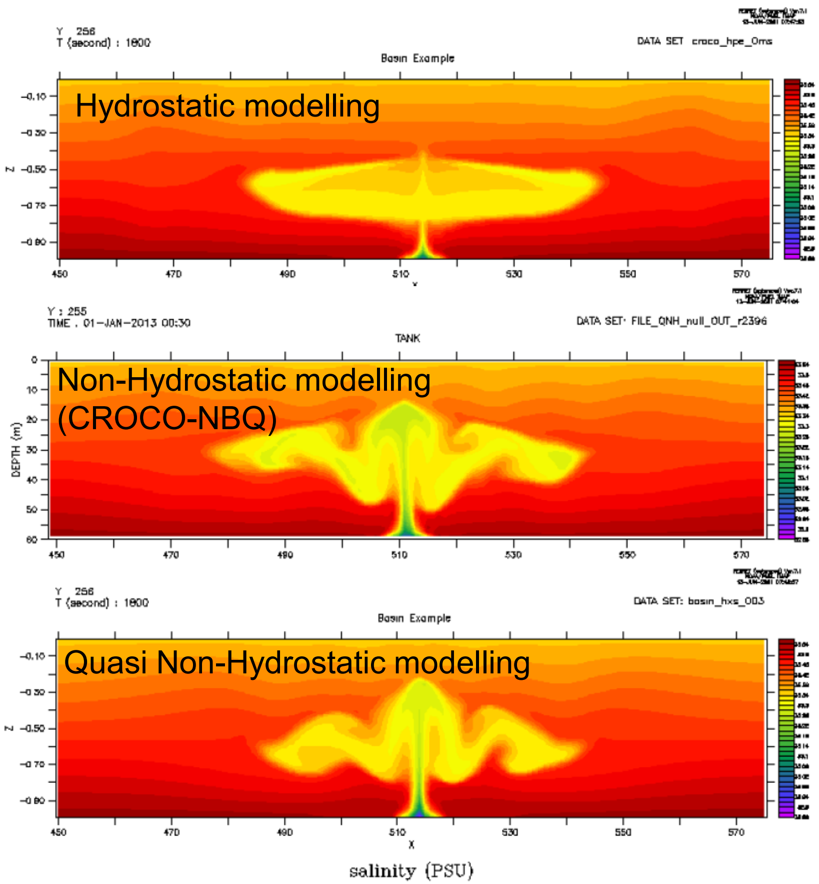
HPE approach
(enhanced vertical diffusion)
Complete vertical mixing



QNH approach :
- Convective plumes
- Surface dense water



CONVECTION IS UBIQUITOUS !



Buoyant release at the ocean floor. (wastewater outfall or karstic outflow)
See dedicated poster

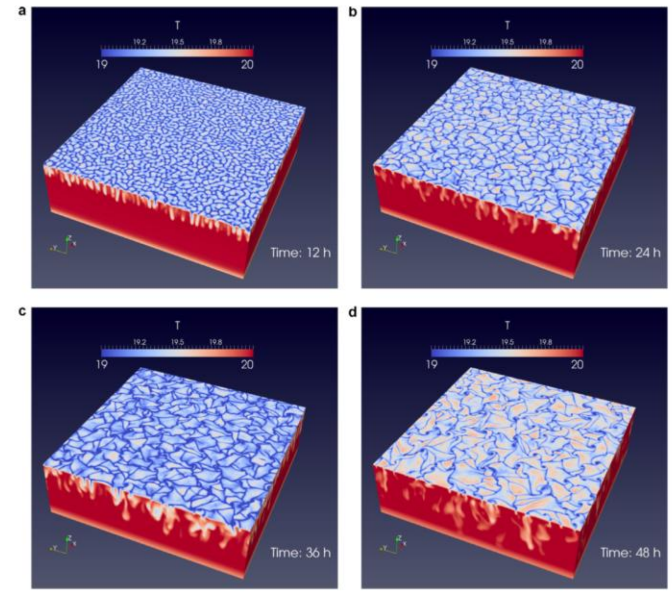
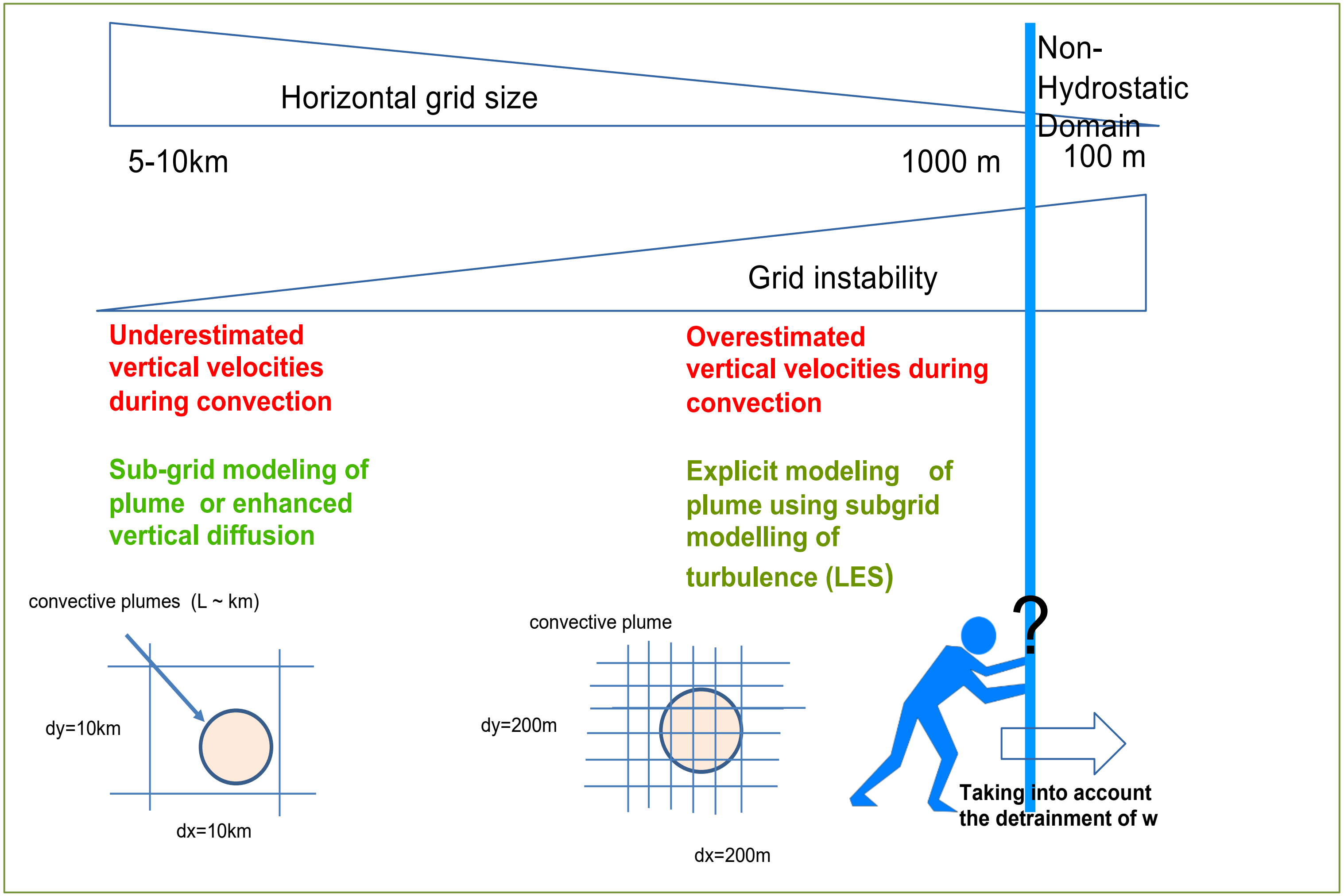


Fig. 2. Temperature field for Exp. *B* during the first two convective cycles: at the beginning of the surface heating ((a) at 12 h and (c) at 36 h) and at the end of the cycle of sur buoyancy forcing ((b) at 24 h and (d) at 48 h). The animation is available from: http://youtu.be/QtOrKF2z2gw.

Diurnal convection in surface mixed layer (Non-hydrostatic simulation)

Mensa, J. A., Özgökmen, T. M., Poje, A. C. & Imberger, J. Material transport in a convective surface mixed layer under weak wind forcing. *Ocean Modelling* **96**, 226–242 (2015).

TO SUMMARIZE



THANK YOU FOR YOUR ATTENTION

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