CROCO

Coastal and Regional Ocean COmmunity model

Improved Gulf Stream separation through Brinkman penalization

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(Debreu et al., Ocean Modelling 2020, 2022)

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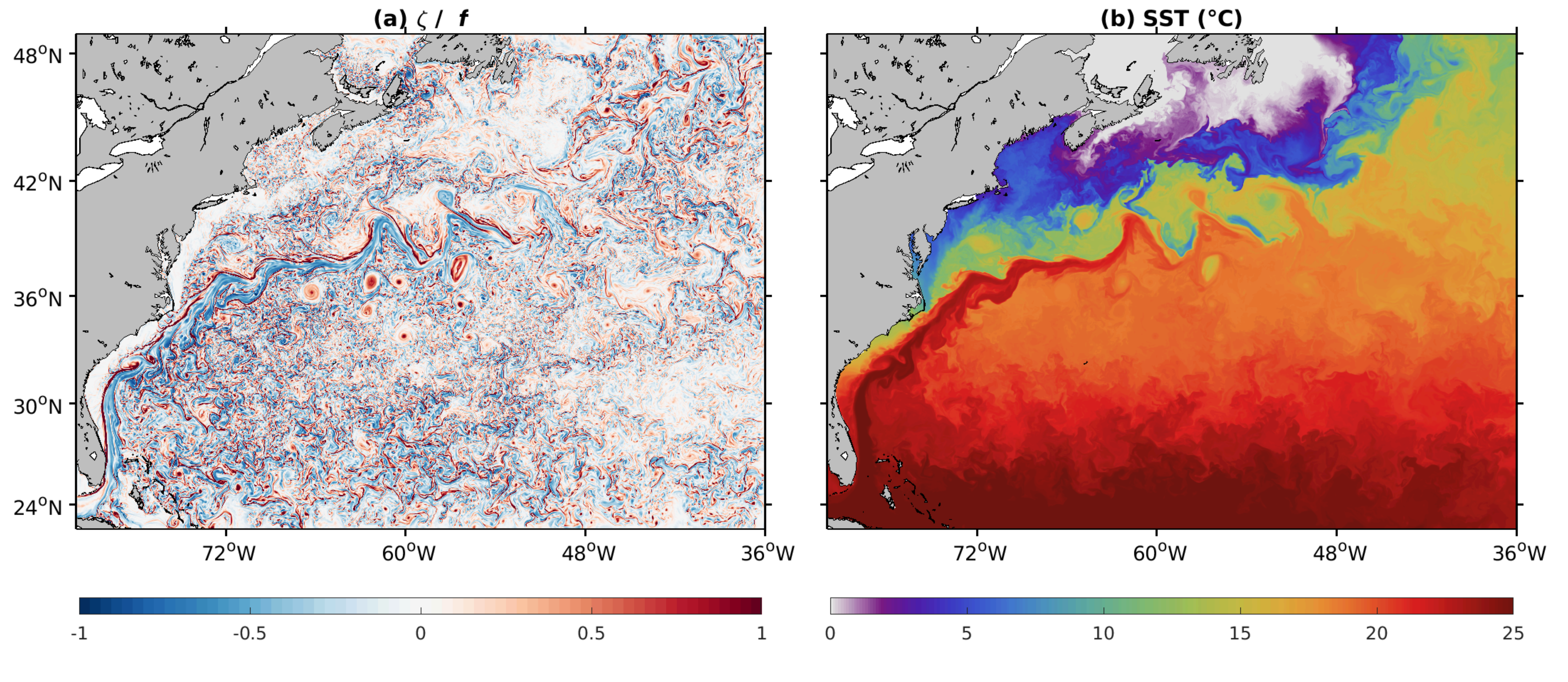
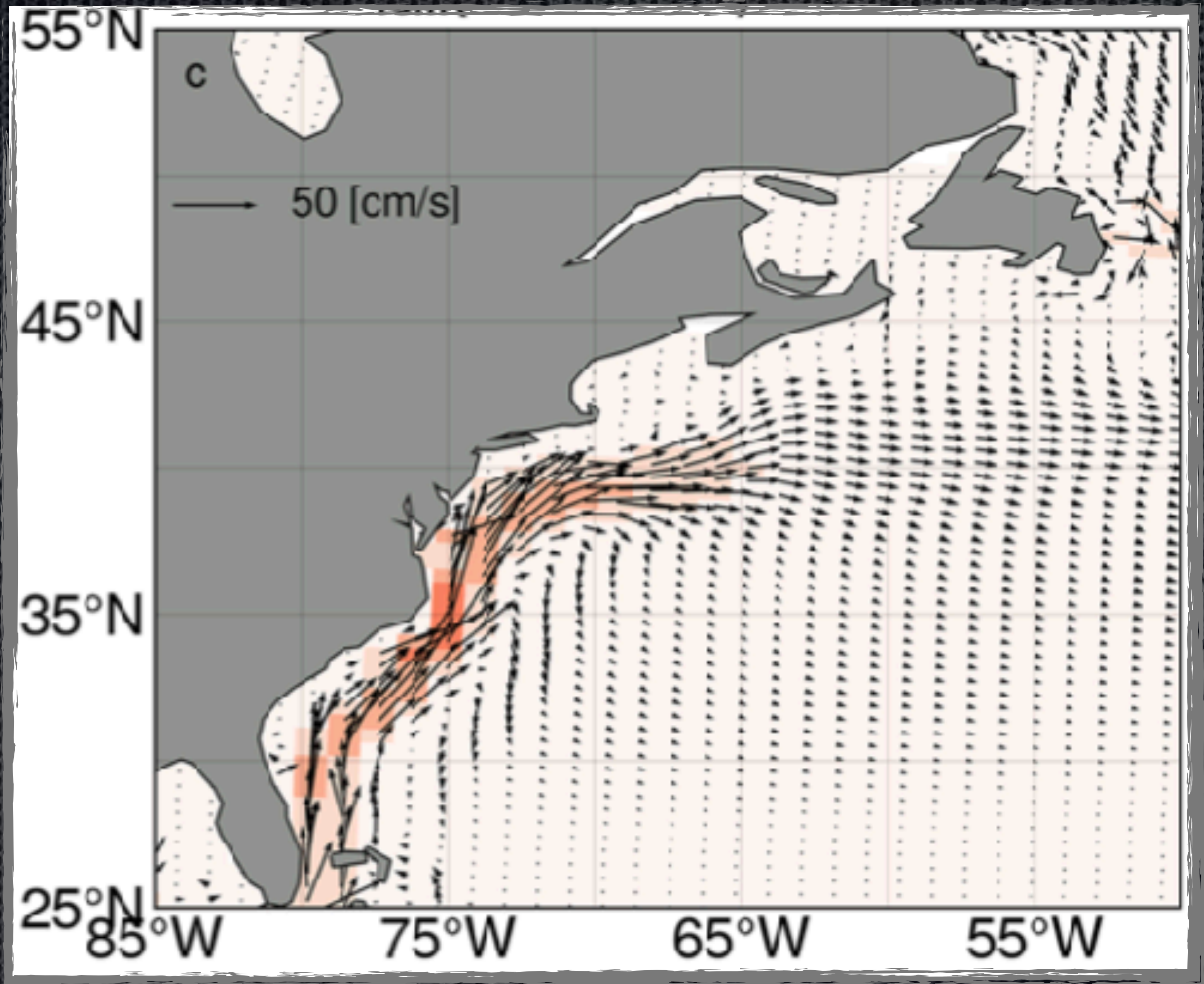
Realistic GS simulations at high resolution



Contreras et al. (2022)

2 km resolution
(submesoscale-permitting)

Low-resolution GS simulations



POP (CESM) 1° (Li et al. 2022)

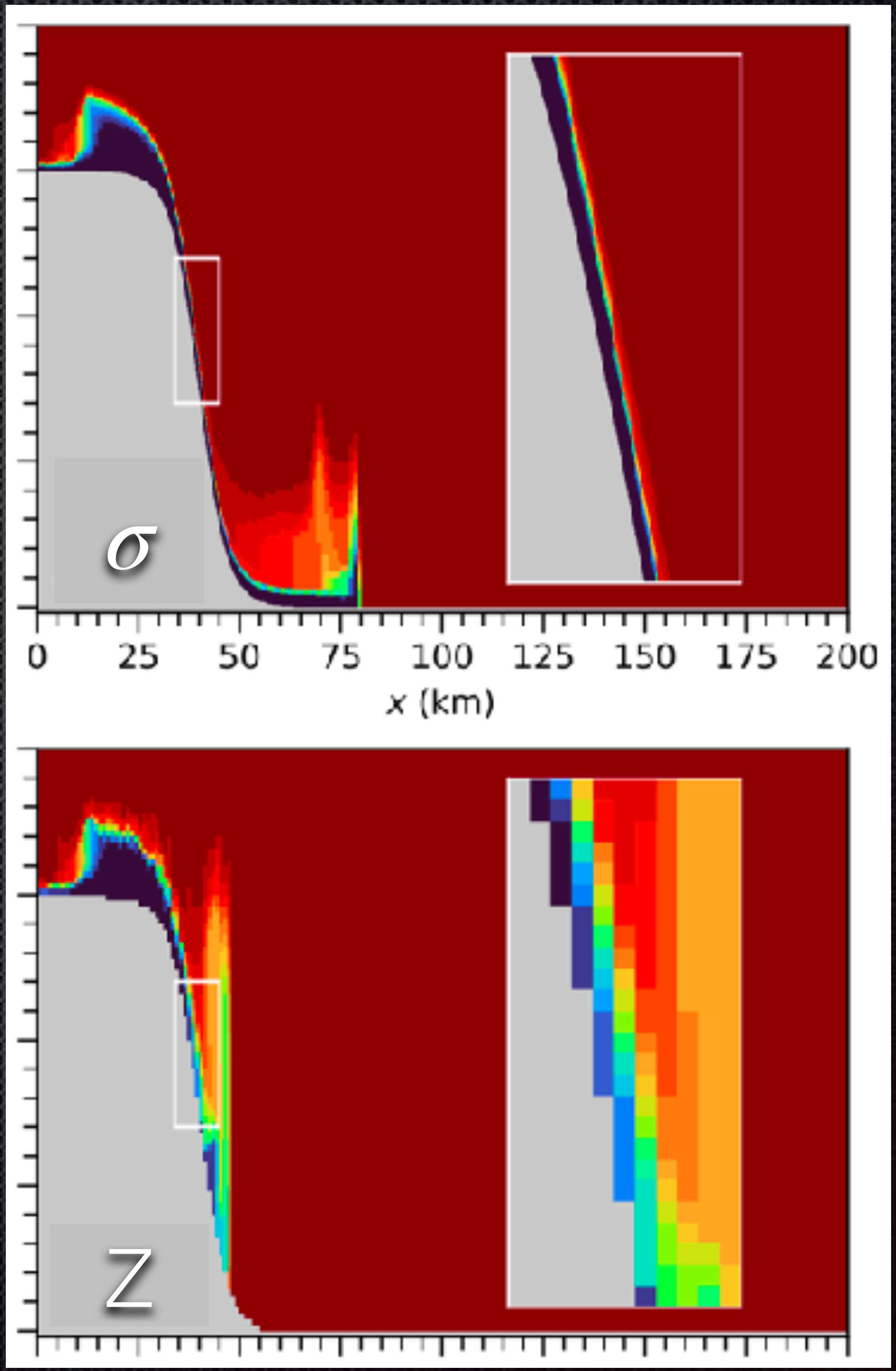
What's wrong with topographic slope at low resolution?

- Topography smoothing is needed in σ models to limit pressure gradient errors:

$$r = \frac{\Delta h}{h} = \frac{S\Delta x}{h} < r_0 \ \sim 0.2$$

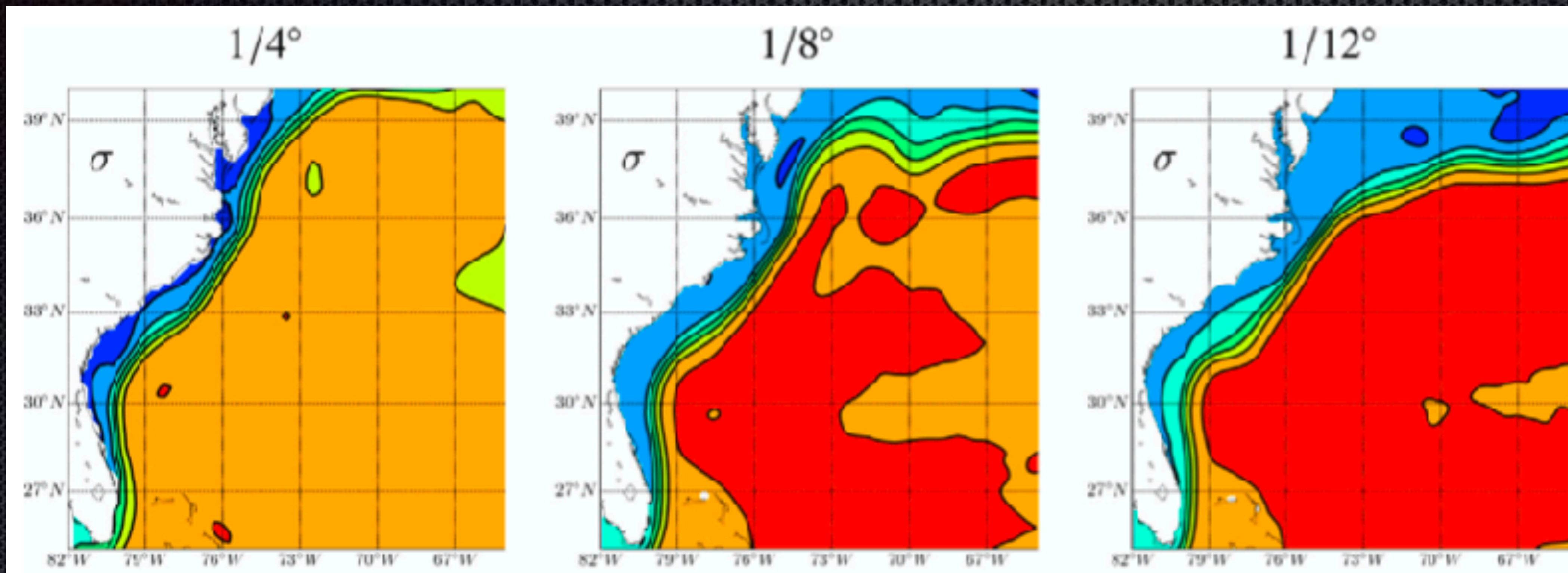
- Deterioration in both σ- and **z**-coordinate systems, and z-models have weaker flow-topography interaction (Penduff et al., 2002):

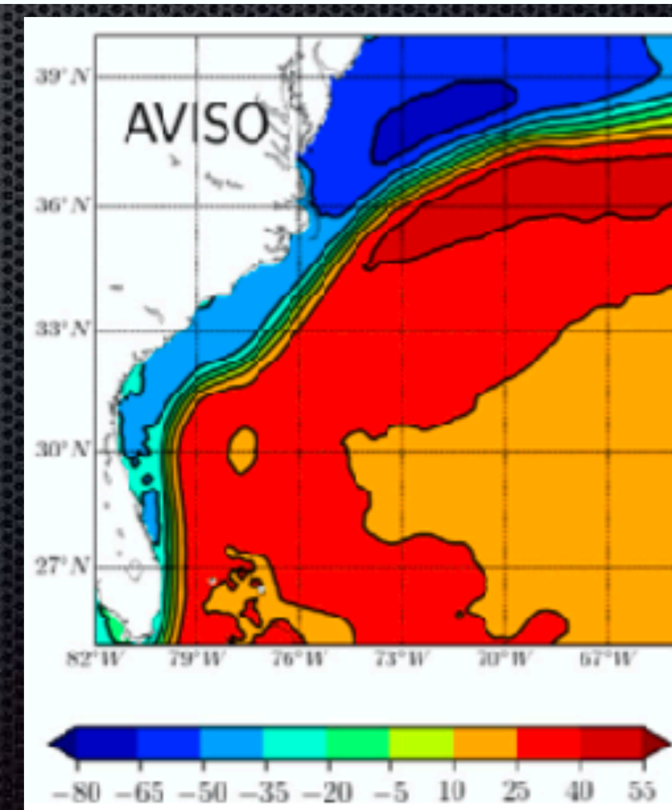
$$J(P_b, h) \sim -fw_b$$



Nasser (2023)

Resolution sensitivity using sigma coordinates





Mean SSH in CROCO climatological run (Debreu et al., 2022)

Brinkman Volume Penalization method (immersed boundary conditions)

Debreu et al., OM 2022

Volume penalization is an elegant way to impose Neumann (blocking) and Dirichlet (drag) boundary conditions in discretized PDEs

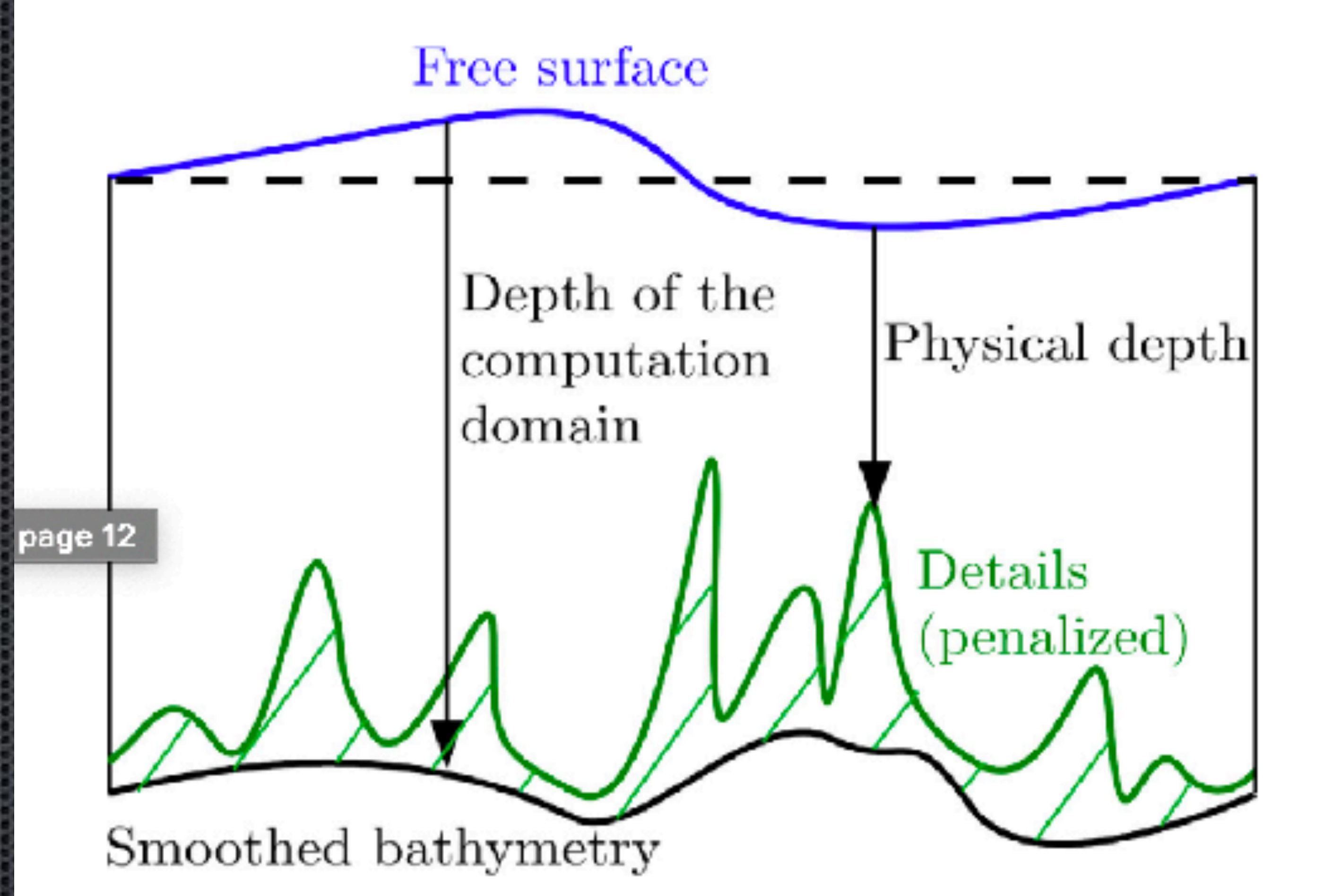


Fig. 1. Smoothed bathymetry profile defining the computational domain (black) and penalized area, defining small scale details in green.

Penalization method

Debreu et al., OM 2020, 2022

drag due to
permeability ϵ

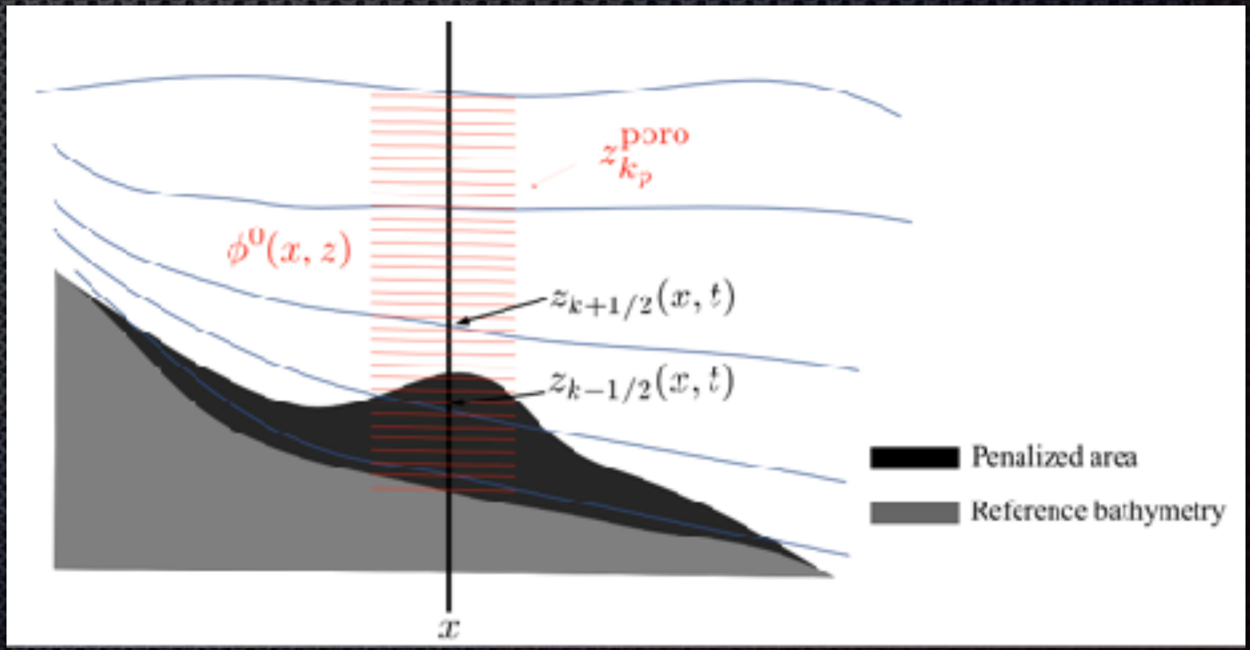
$$\frac{\partial \tilde{h}u}{\partial t} + \frac{\partial \tilde{h}u^2}{\partial x} + \frac{\partial \tilde{h}u\Omega}{\partial s} = -\tilde{h}\left(g\frac{\partial \eta}{\partial x} + \frac{1}{\rho_0}\frac{\partial p_h}{\partial x} + \frac{g\rho}{\rho_0}\frac{\partial z}{\partial x}\right) - \frac{1}{\epsilon}f(x,z)\tilde{h}u$$

$$\frac{\partial \tilde{h}}{\partial t} + \frac{\partial \tilde{h}u}{\partial x} + \frac{\partial \tilde{h}\Omega}{\partial s} = 0$$

ϵ : permeability → Drag

α : porosity $(\tilde{h} = \alpha h)$ → Blocking

$f(x,z)$: mask defining the penalized region $= f(\tau_b)$

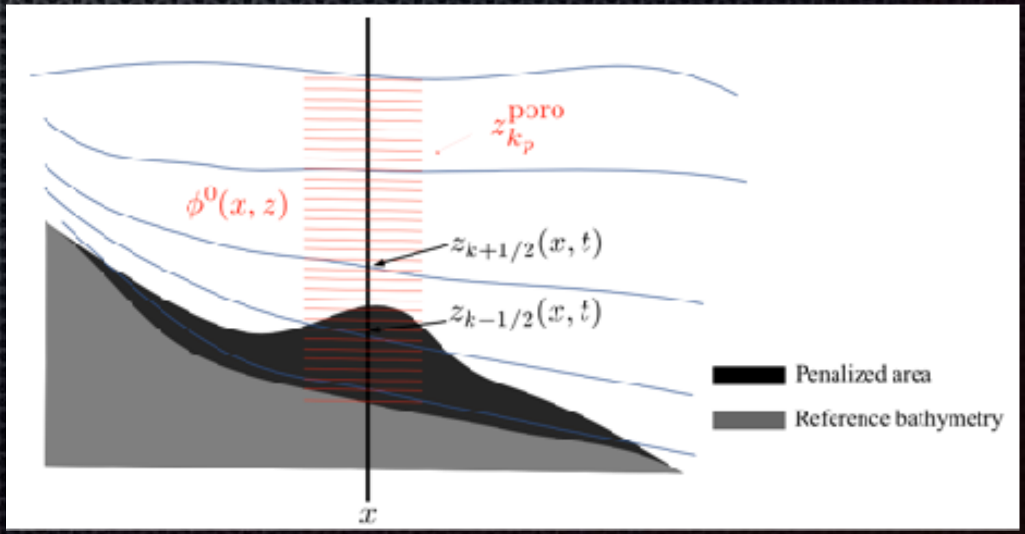


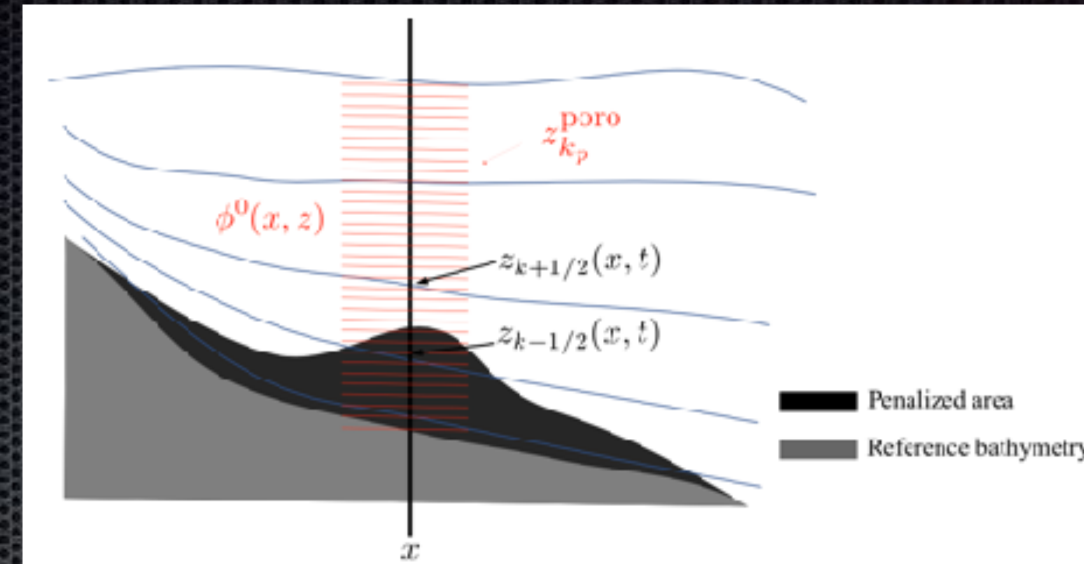
Numerical implementation

The principal challenges were:

- ✓ Conservation of total energy : ventilation of penalized Hz
- ✓ Stability of the drag term (stiff term) : $\epsilon \sim f(\Delta t)$
- ✓ Accounting for penalization in the correction of the barotropic–baroclinic mode splitting (to avoid spurious flow in the solid region)

In practice, the penalized simulations run nearly as fast as the original model simulations





- Code :
  - set_depth_porosity :
    - Hz, h -> Hzf, hgrid
    - hraw -> h_pena_target (get_grid, ana_grid)
    - Hz, h=ΣHz
  - set_depth_permeability:
    - pena_r
    - pena_u
    - pena_v

```
        do j=Jstr,Jend
# if defined PERMEABILITY
         if (nnew == 3) then
           do k=1,N
             do i=IstrU,Iend
               ru(i,j,k)=ru(i,j,k)*(1.-pena_u(i,j,k))
             enddo
           enddo
         endif
# endif
         do i=IstrU,Iend
           rufrc(i,j)=ru(i,j,1)
# ifndef BODYFORCE
#  ifdef BSTRESS_FAST
     &          + sustr(i,j)*om_u(i,j)*on_u(i,j)
#  else
#   if defined PERMEABILITY
     &          + sustr(i,j)*om_u(i,j)*on_u(i,j)
#   else
     &          +(sustr(i,j)-bustr(i,j))*om_u(i,j)*on_u(i,j)
#   endif
#  endif
# endif
```

Splitting method

$$\frac{\partial u}{\partial t} = F(u) - \frac{1}{\epsilon}\mathbb{1}(z)u.$$

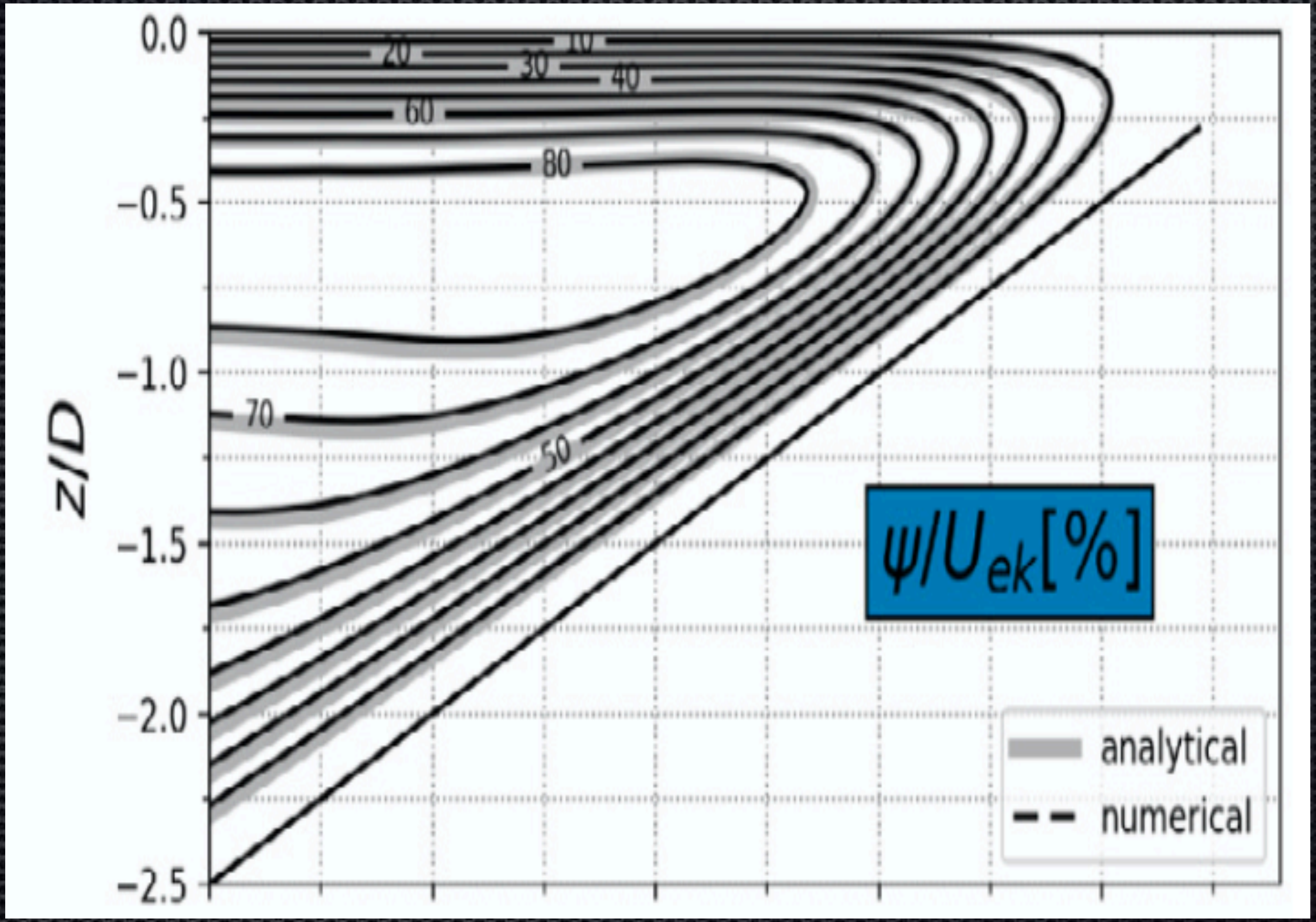
A splitting method can be used to integrate (12) in two steps,

$$(1)\ \frac{\partial u}{\partial t} = F(u), \quad (2)\ \frac{\partial u}{\partial t} = -\frac{1}{\epsilon}\mathbb{1}(z)u.$$

$$u^{n+1} = (1 - \text{pena\_u})\, u^{n+1,*}$$

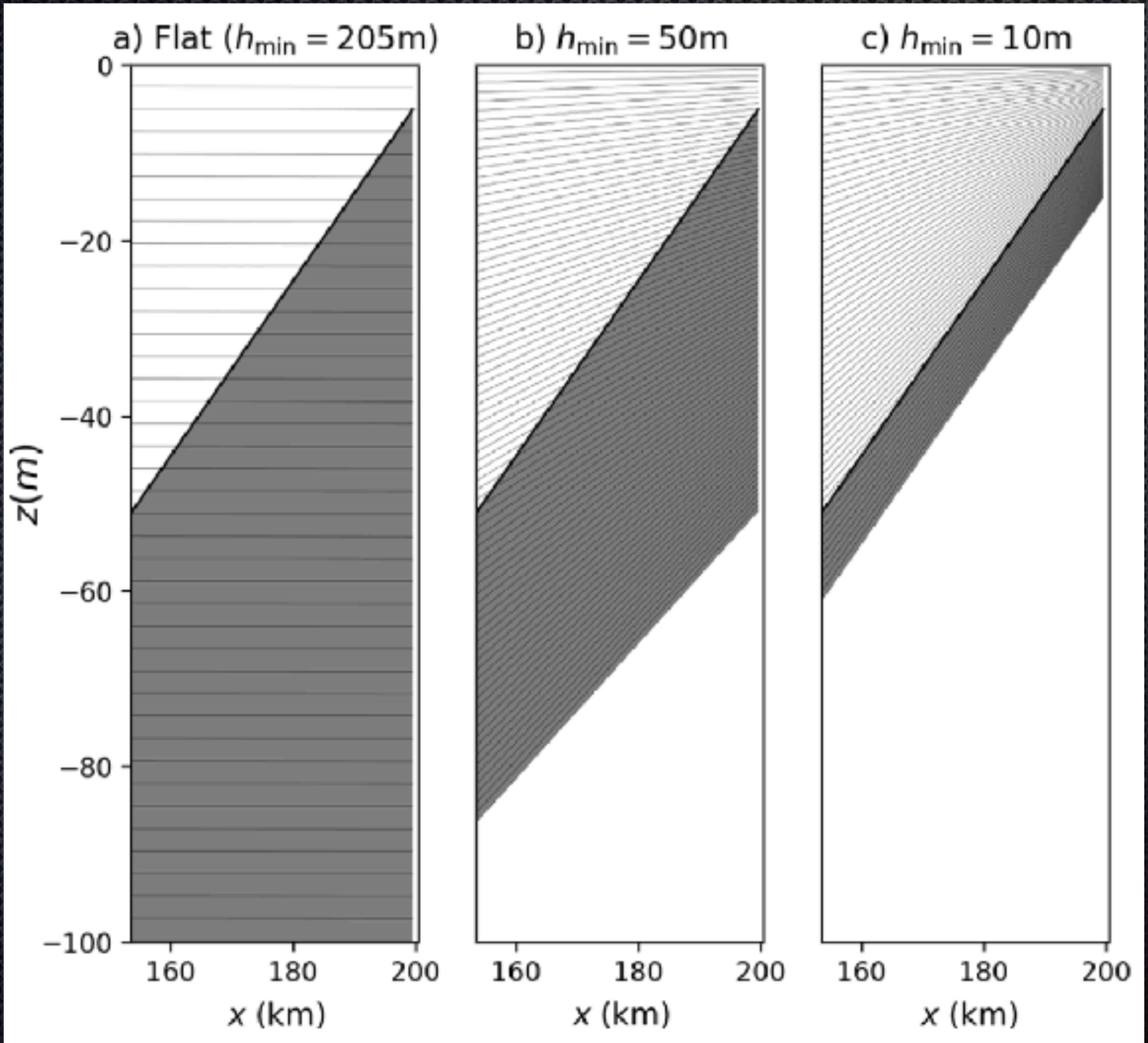
Upwelling test case

Debreu et al. (2020)



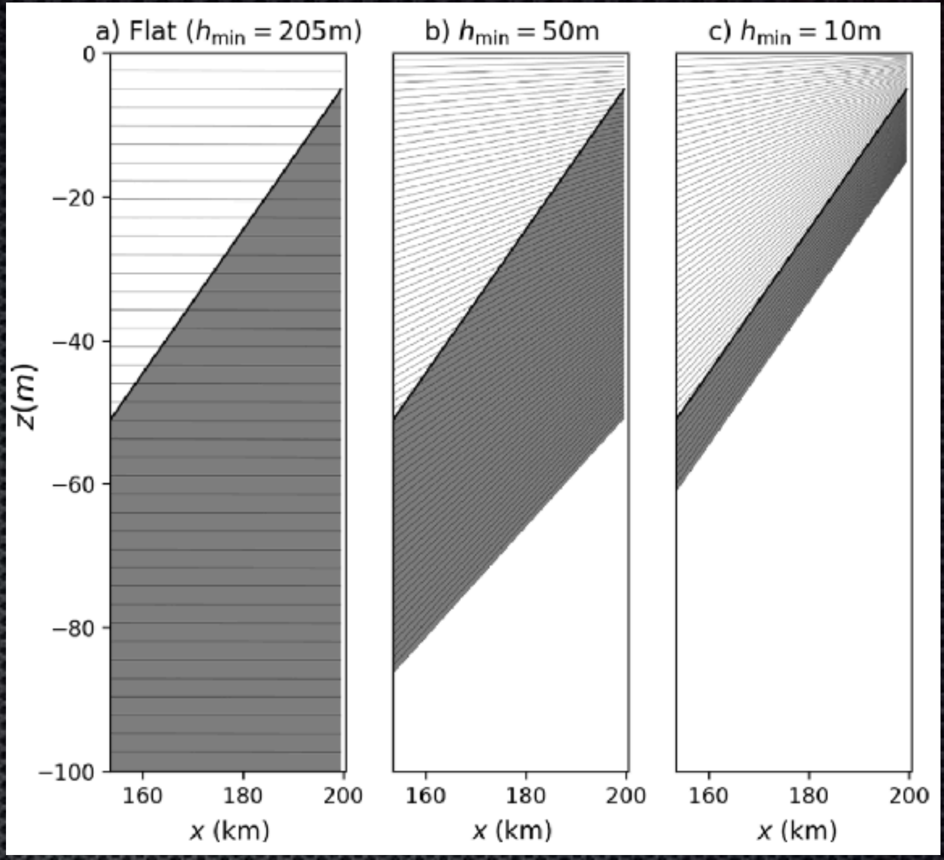
Upwelling test case

Debreu et al. (2020)

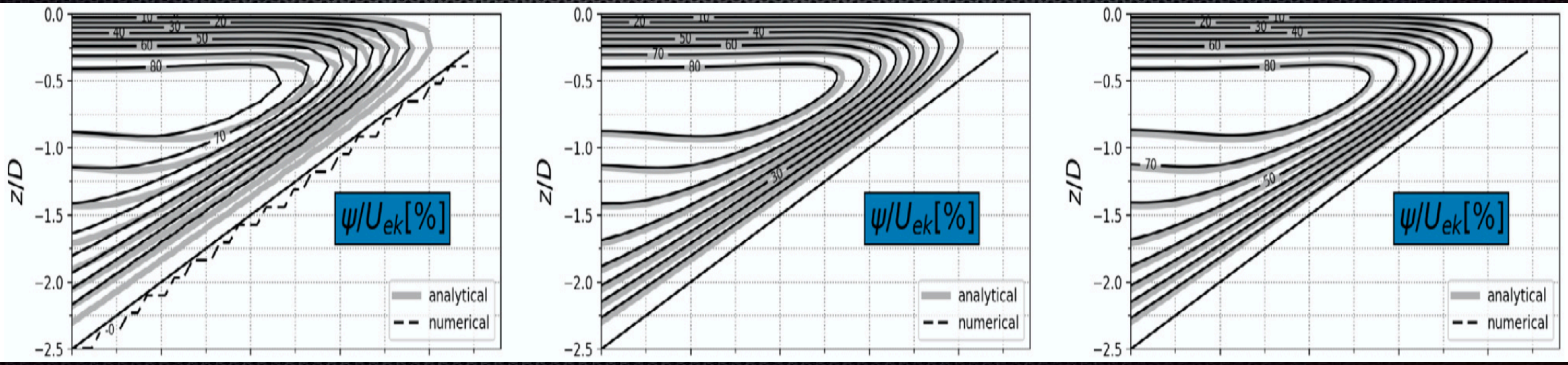


Upwelling test case

Debreu et al. (2020)



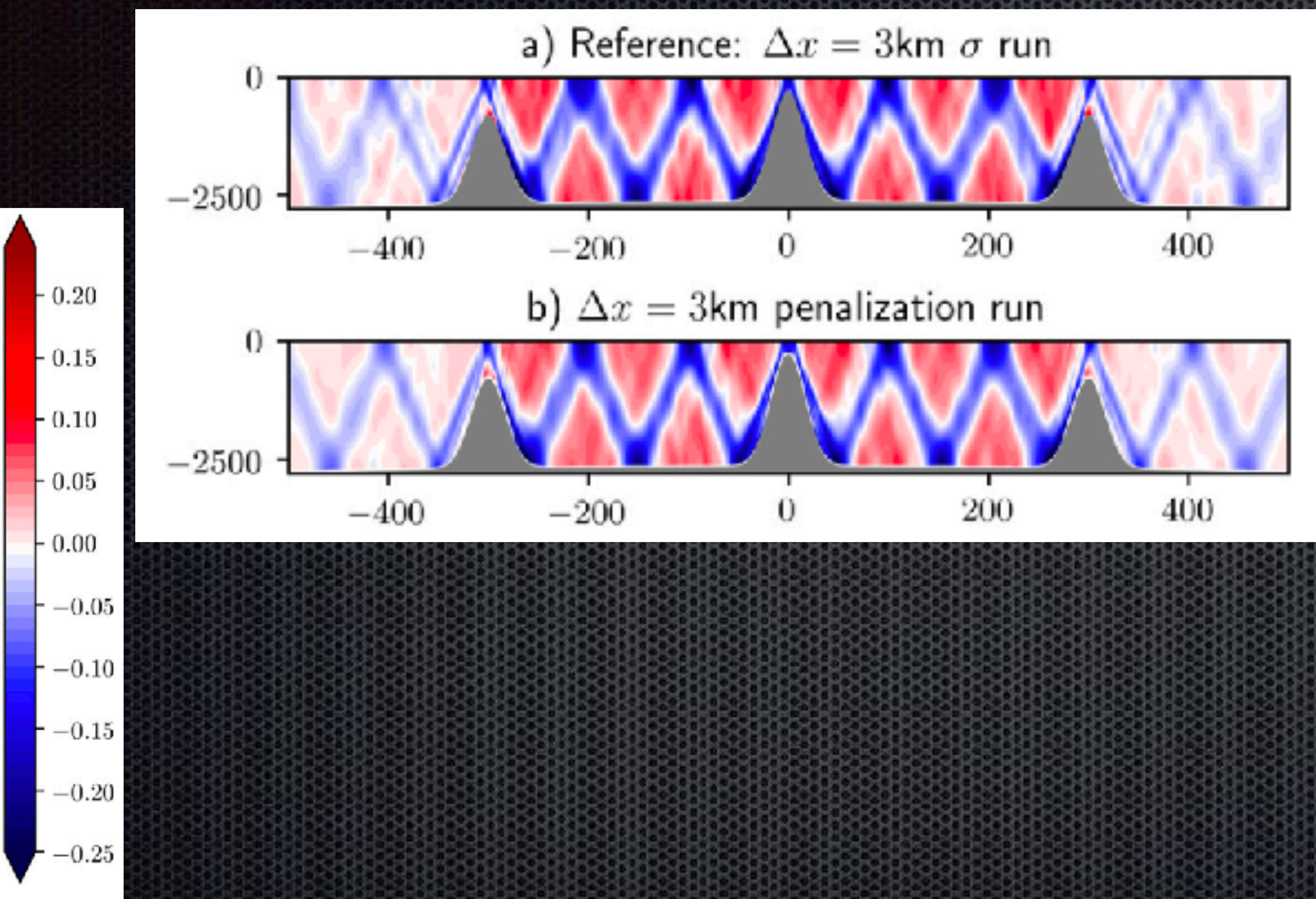
large penalization regions impact resolution but do not show staircase effects

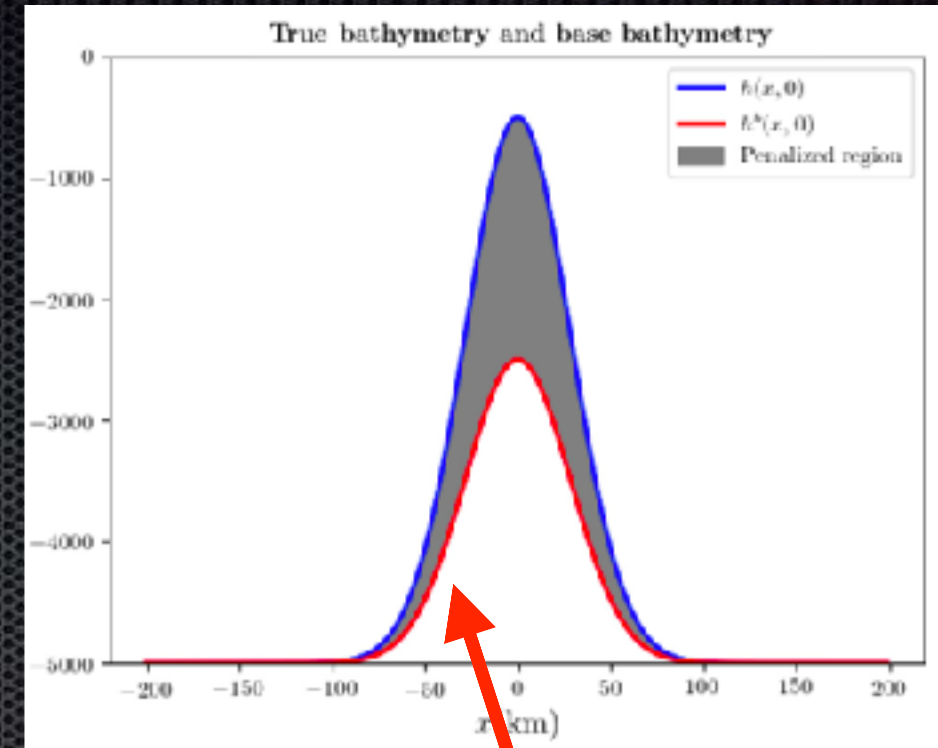


Internal tide test case

Debreu et al. (2020)

u (m/s)





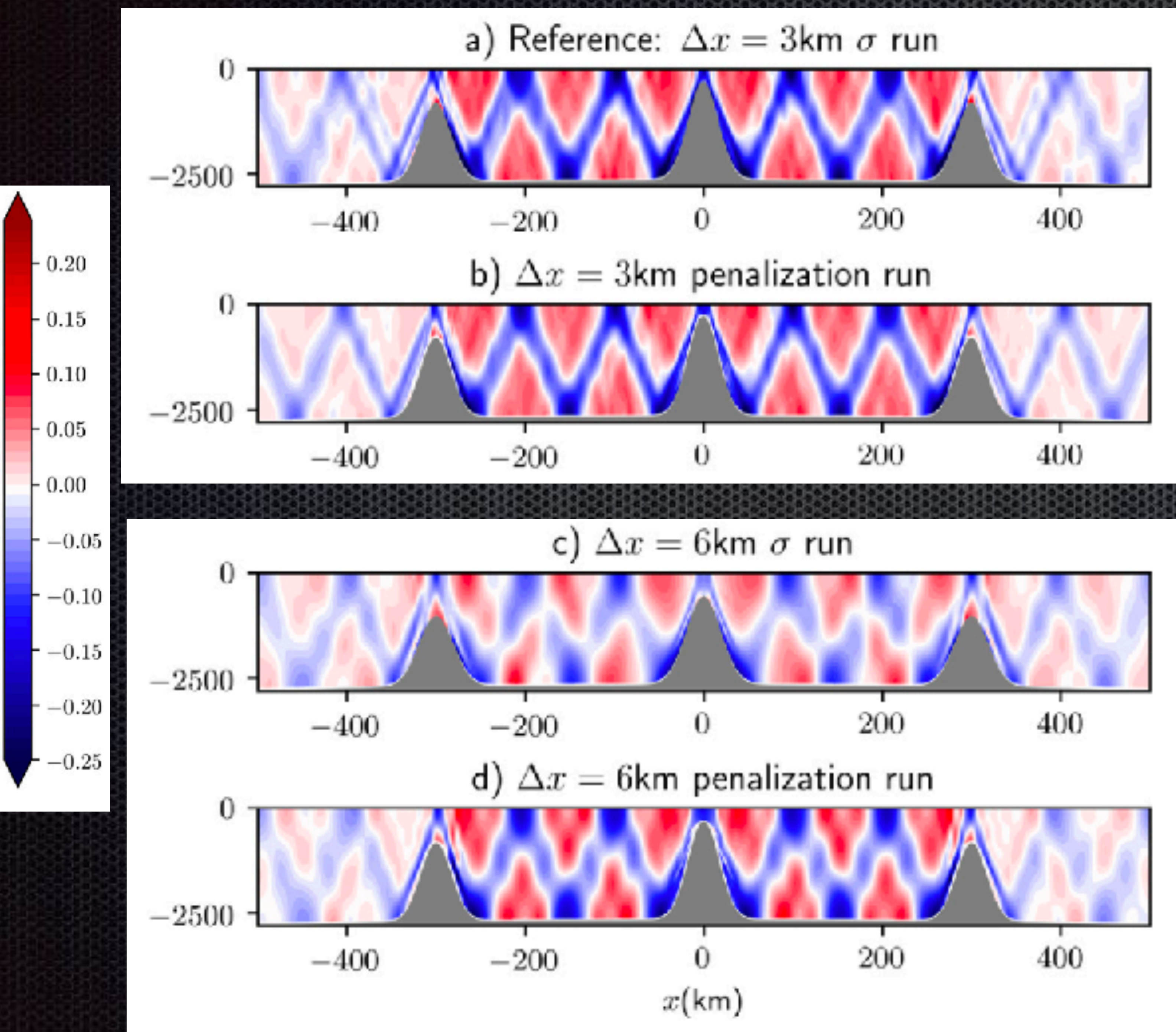
r limited

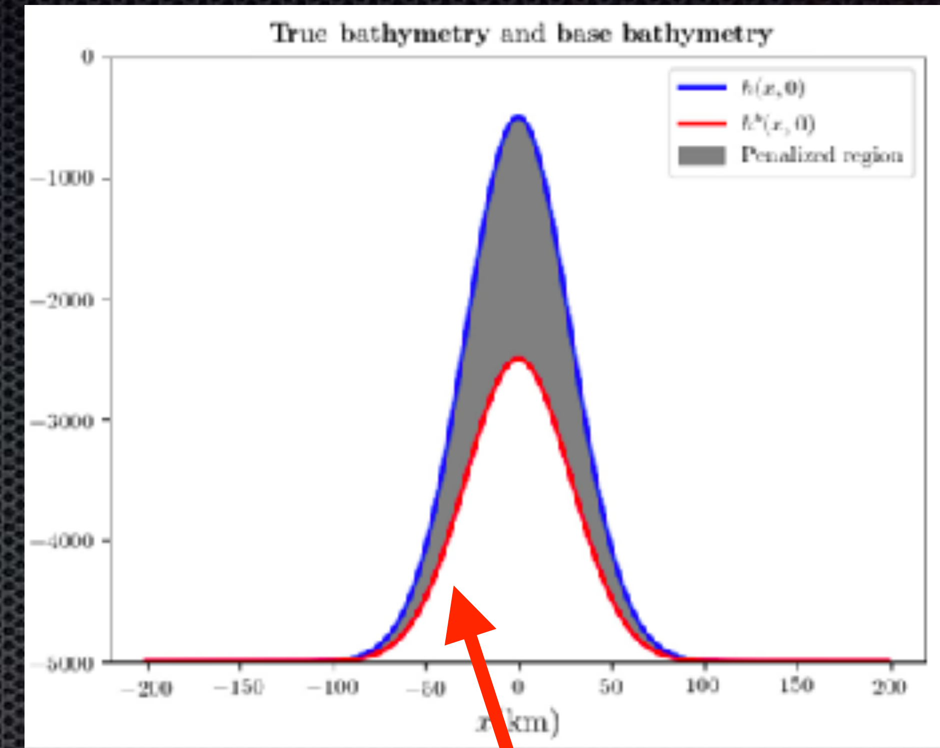
high-resolution

Internal tide test case

Debreu et al. (2020)

u (m/s)





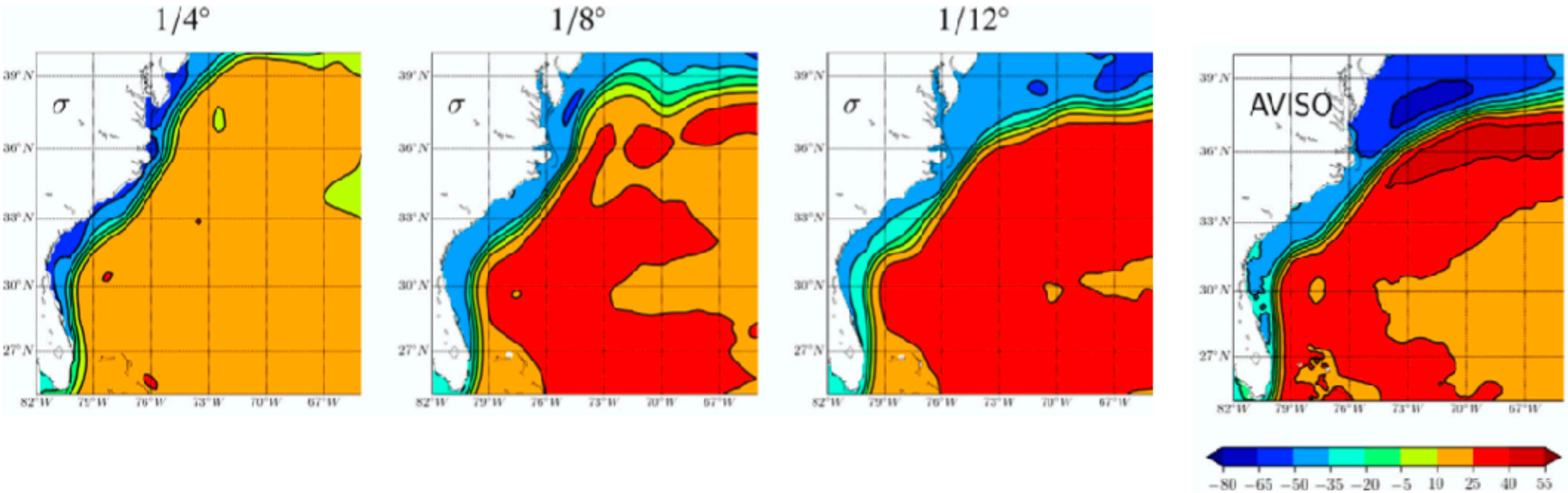
r limited

high-resolution

low-resolution: the penalized run retains much of the high-resolution energy

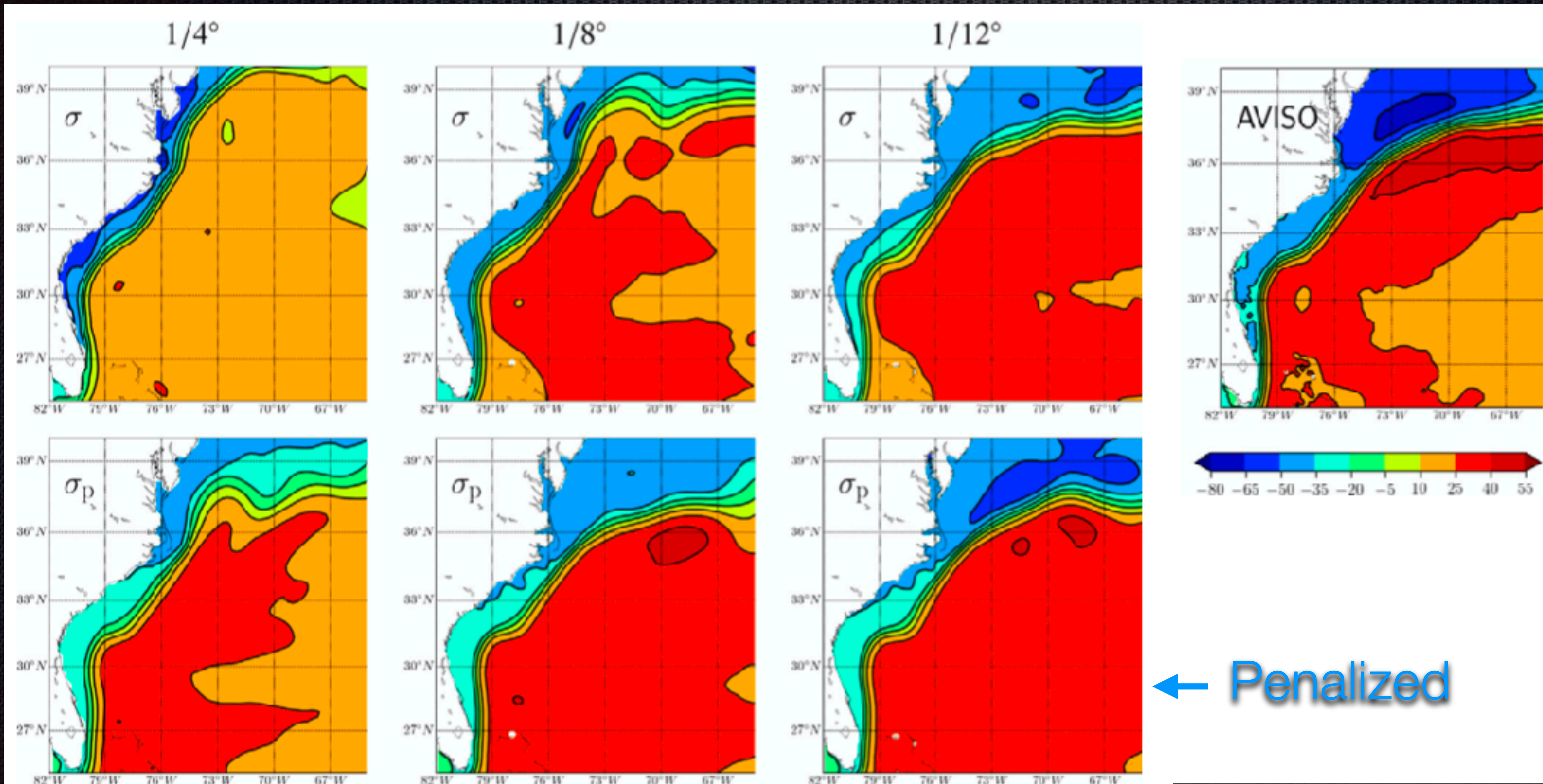
Gulf Stream penalization

Resolution sensitivity

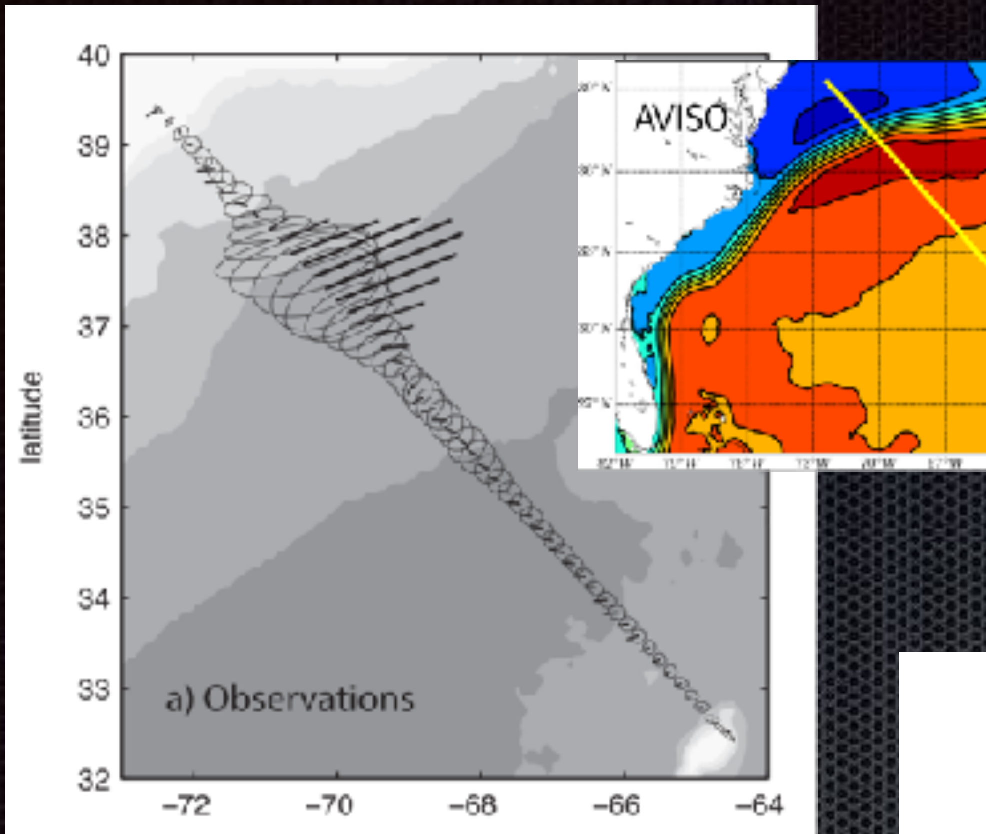


Gulf Stream penalization

Resolution sensitivity



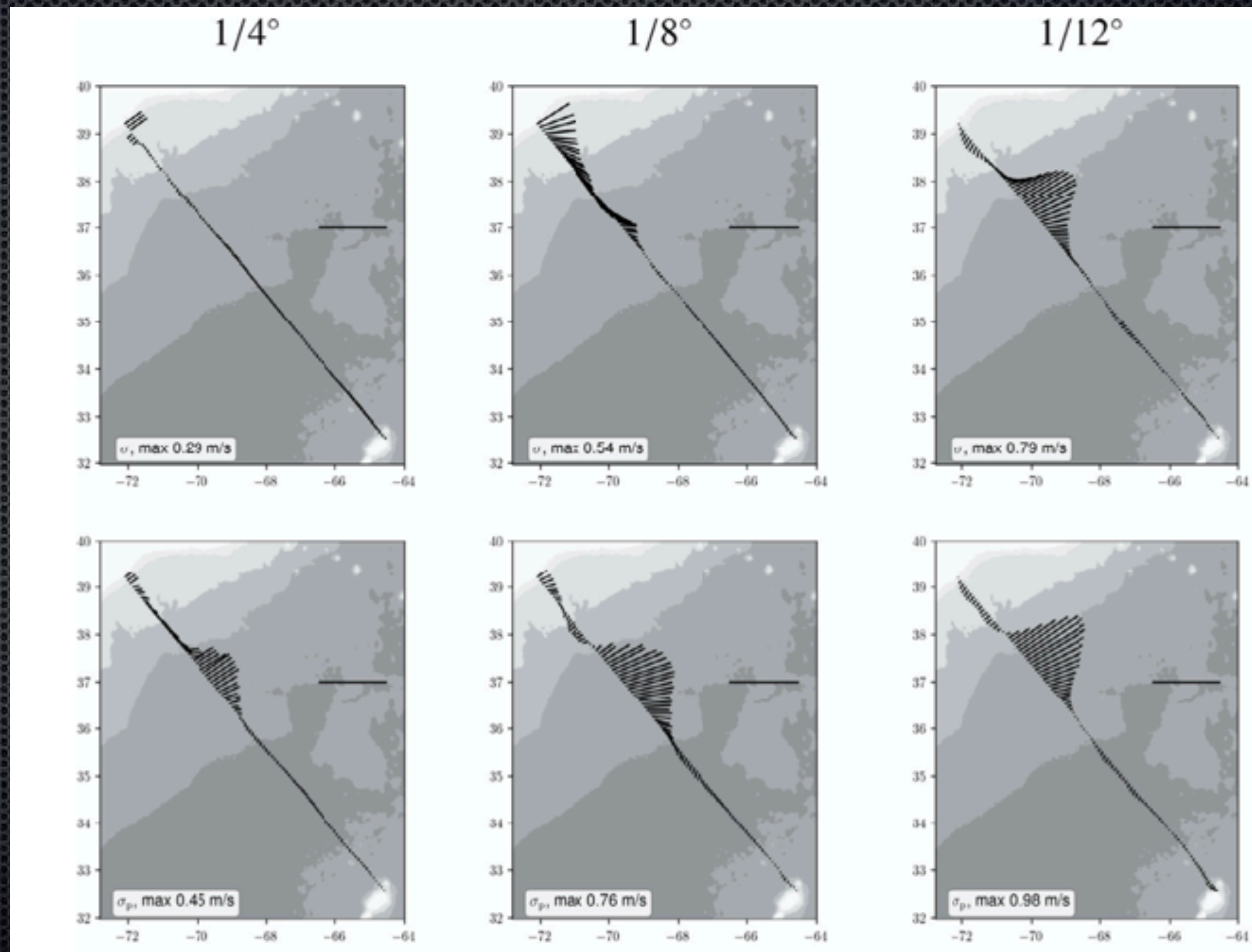
Comparison with in-situ data



Oleander ADCP transect
(1993-2012)

sigma

penalized



Barotropic Vorticity Budget

Planetary Vorticity Advection

Wind Stress Curl

Bottom Stress Curl

$$\frac{\partial \bar{\zeta}}{\partial t} = \frac{J(P_b, h)}{\rho_0} - \nabla \,.\, (f\mathbf{U}) - A + \frac{\nabla \times \tau}{\rho_0} - \frac{\nabla \times \tau_\mathbf{b}}{\rho_0} + D$$

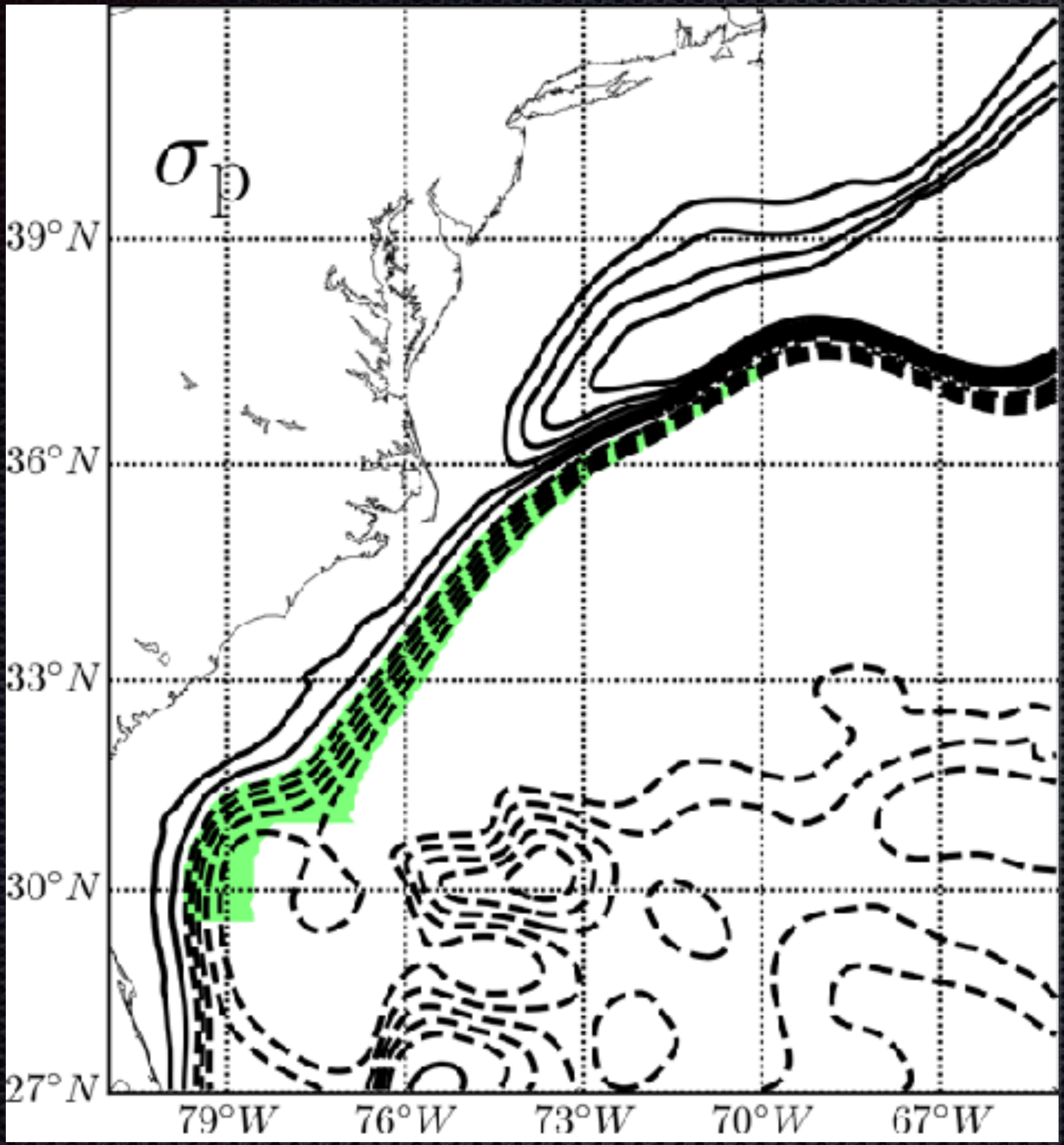
Bottom Pressure Torque

Advection Torque (eddy activity)

Viscous Torque

$\bar{\zeta} = (\nabla \times \mathbf{U}) \,.\, \hat{z}$ is the barotropic vorticity

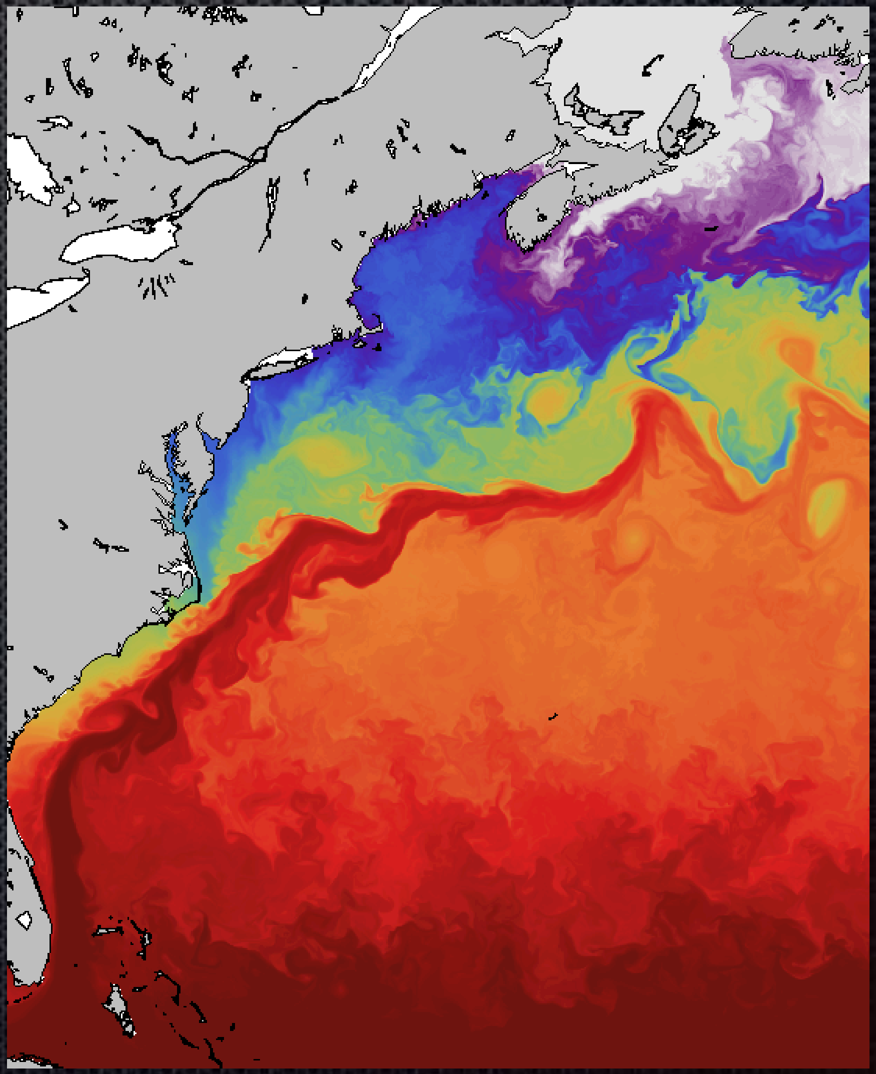
GS Barotropic Vorticity Budget



budget integrated between 1 and 30 Sv contours (Schoonover et al., 2016)

GS Barotropic Vorticity Budget

	steering	inertia	eddies
	BPT	BETA	ADV
σ 1/8^o	0.93	-1.78	0.54
σ 1/12^o	1.83	-2.48	0.29
pena 1/8^o	1.77	-2.65	0.26
pena 1/12^o	2.24	-2.75	0.04



NBQ : Test porous breakwater

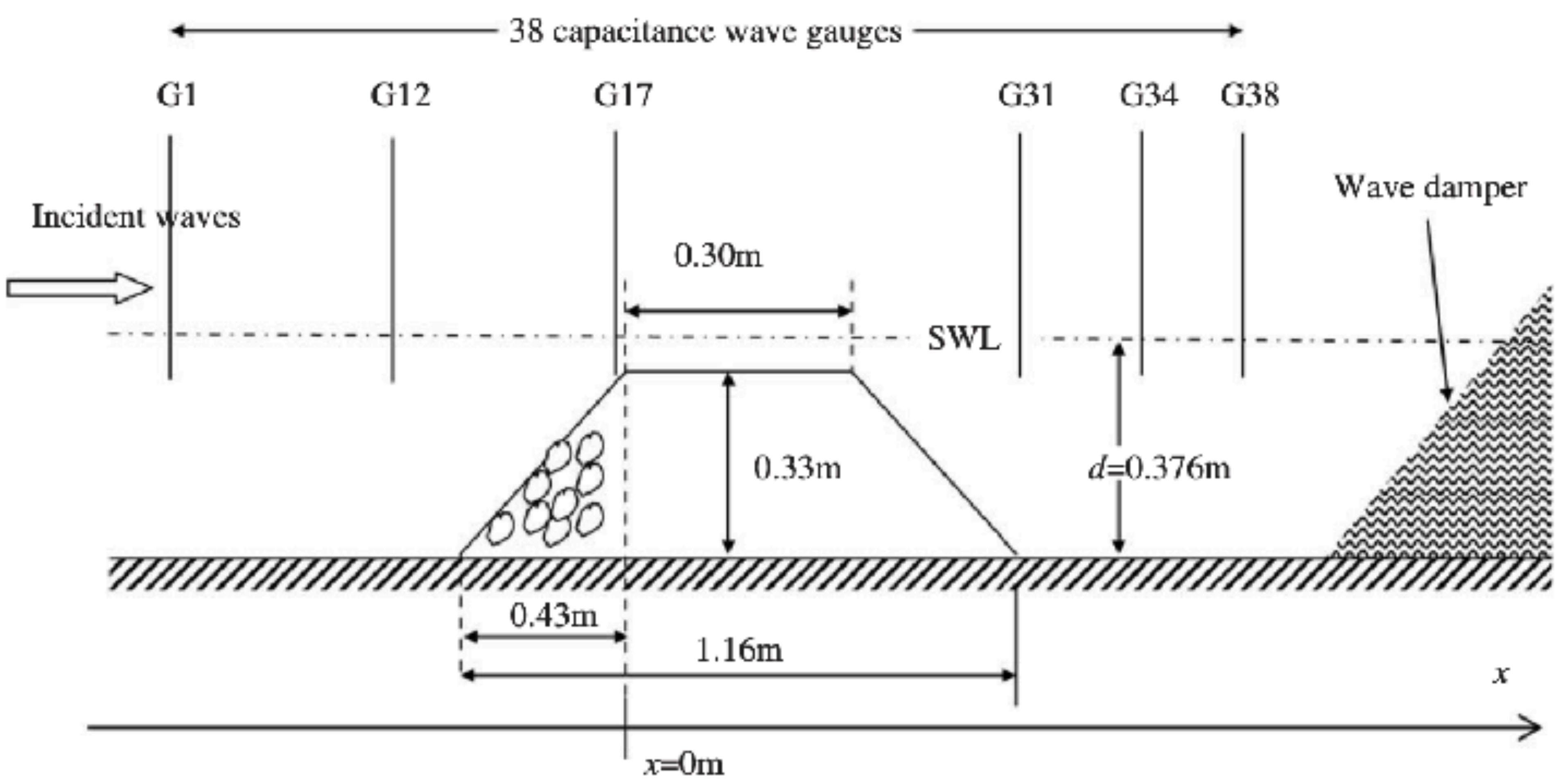
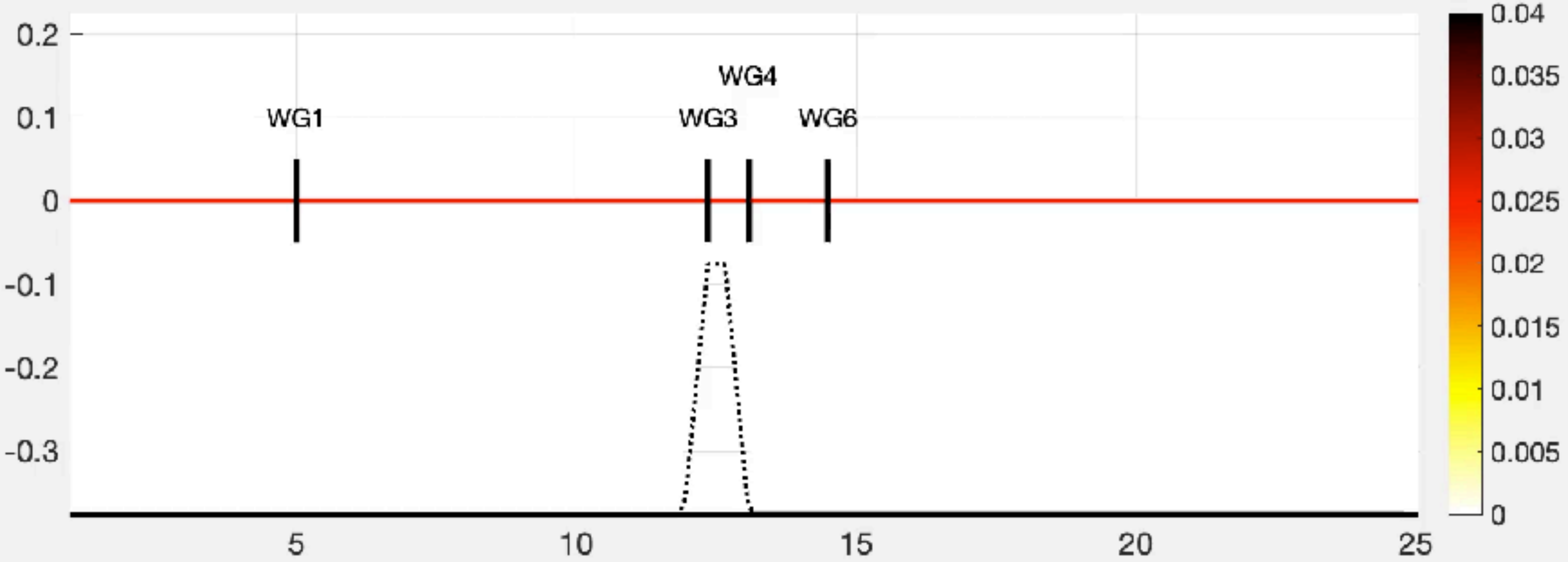
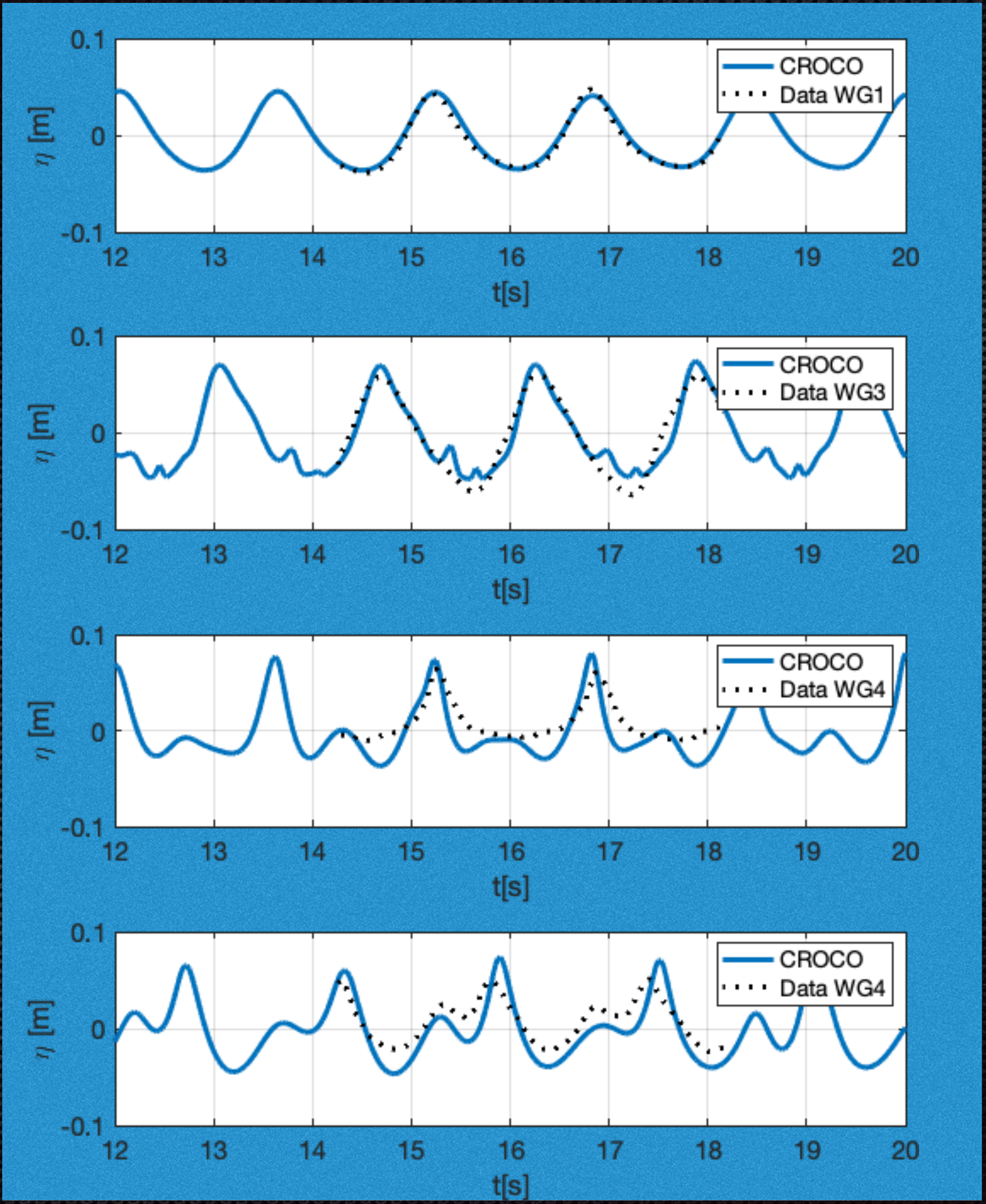


Fig. 7. Sketch of experiment and submerged porous breakwater.


0.2
0.1
0
-0.1
-0.2
-0.3
WG1
WG3
WG4
WG6
5
10
15
20
25
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0



CROCO
Data WG1
Data WG3
Data WG4
Data WG4
η [m]
t[s]
0.1
0
-0.1
12
13
14
15
16
17
18
19
20

Conclusion

- A simple and efficient penalization method is implemented in a working branch of CROCO
  - First immersed BCs in a realistic ocean model
- GS results relevant to climate modeling
- Many other possible applications
  - Subgrid bathymetry, vegetation, coastal protection, urban flooding