On the thermohaline circulation in semi−enclosed marginal seas

Michael Spall
WHOI

Don’t try to describe the ocean if you’ve never seen it

And don’t ever forget that you just may wind up being wrong

Jimmy Buffett

Questions :

How do regions of deep convection in the interior of the basin interact with the boundary currents that communicate with the open ocean ?

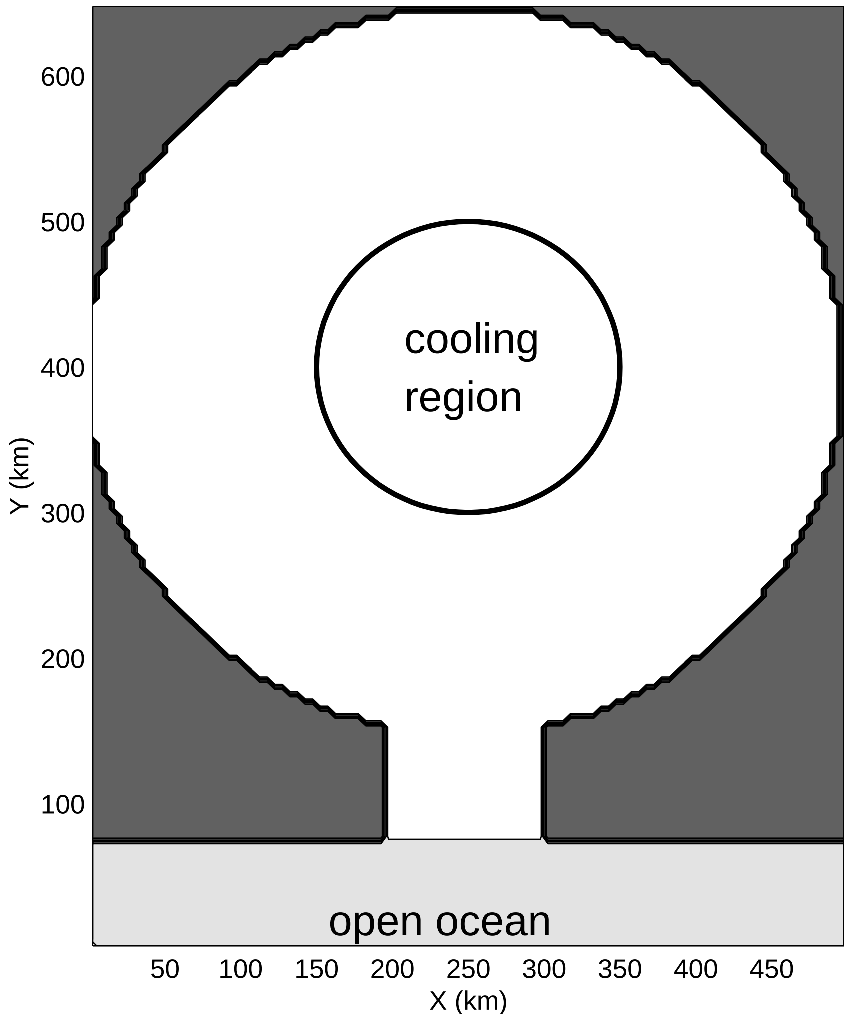
What processes control the vertical and lateral heat flux ?

What processes control the vertical mass flux ?

Where do these fluxes take place ?

What determines their magnitude ?

Consider an idealized semi−enclosed marginal sea



1. cooling in the interior of the marginal sea
   active for 2 months, no forcing for 10 months

2. restore T(z) to a uniform stratification in the
   "open ocean"

3. integrate the model for 10 years
   diagnose last three years

MIT hydrostatic primitive equation model
(Marshall et al. 1997; Adcroft et al. 1997)

level coordinates, free surface
finite differences, C−grid

5 km horizontal resolution (L$_d$ = 10 km)
12 levels in the vertical

1000 m deep, flat bottom

500 km diameter basin

f−plane, $f = 10^{-4}\ s^{-1}$

Laplacian viscosity, diffusivity ($50\ m^2 / s$)

no−slip lateral boundary conditions

linear EOS with temperature only

Consider a simple analytic model governed by linear voricity dynamics in a 2 layer fluid:

$$\frac{f\,w}{H} = -A\,v_{xxx}$$

one can derive a solution for the pressure anomaly (or upper layer thickness)

$$P = P_0\, e^{-\alpha y} \left(e^{i k1 x} - k_1/k_2\, e^{i k2 x} \right)$$

For a lateral diffusion of density,
the boundary current width is

$$\delta = L_d\, \sigma^{1/2}$$

and the along boundary decay scale is

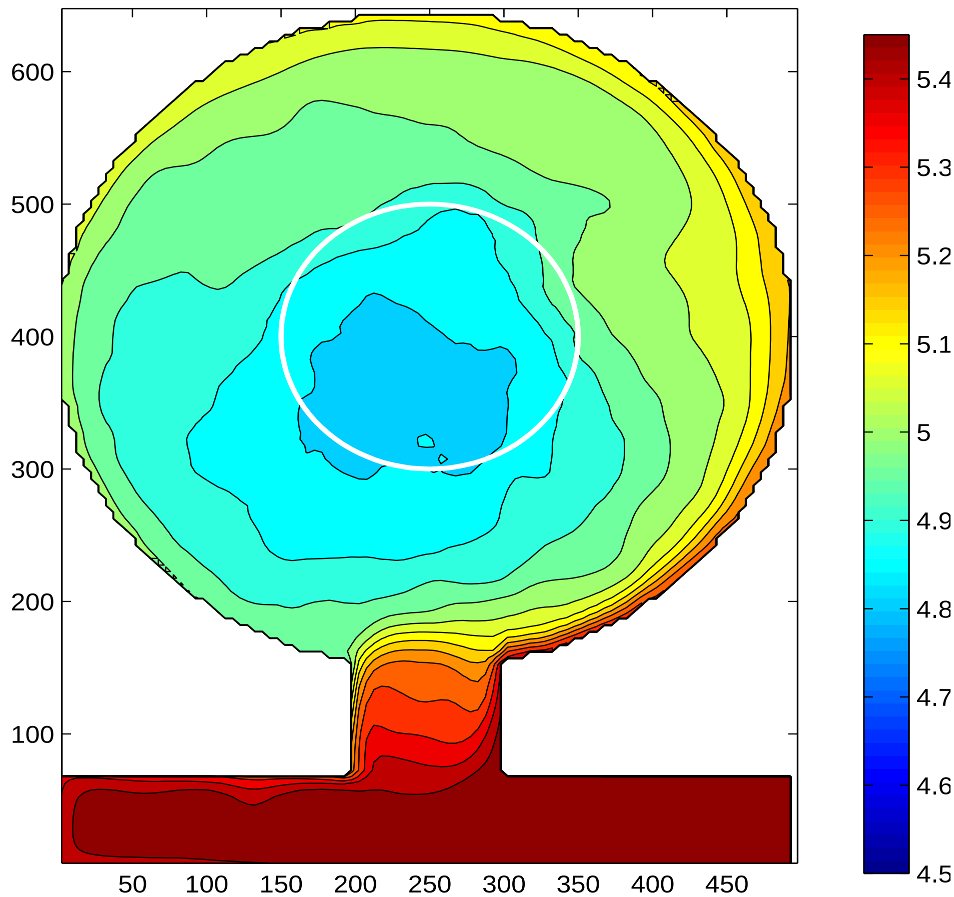
$$\alpha^{-1} = L_d\, \sigma^{3/2}\, E^{-1}$$

where $\sigma = A / K$ is the Prandtl number

L_d is the deformation radius

$E = A/f_0 L_d^2$ is the horizontal Ekman number

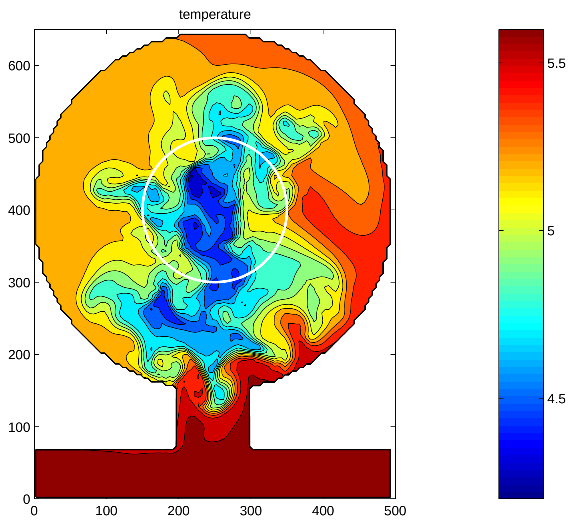
An example case with Q=200 W/m^2



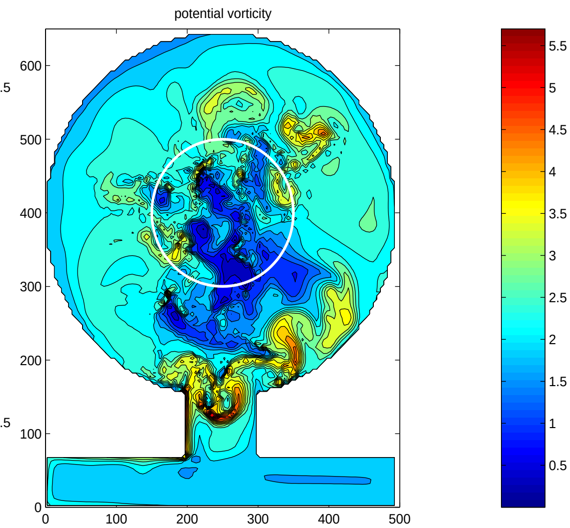
Mean temperature at level 1 (years 7−10)

- O cooling is applied within circle
- O takes ~ 5 years to spin−up basin ave temp
- O cold interior, warm inflow along boundary (note temperature gradient along bdy)
- O densest water is offset from center of cooling region

Restratification (not main focus today)



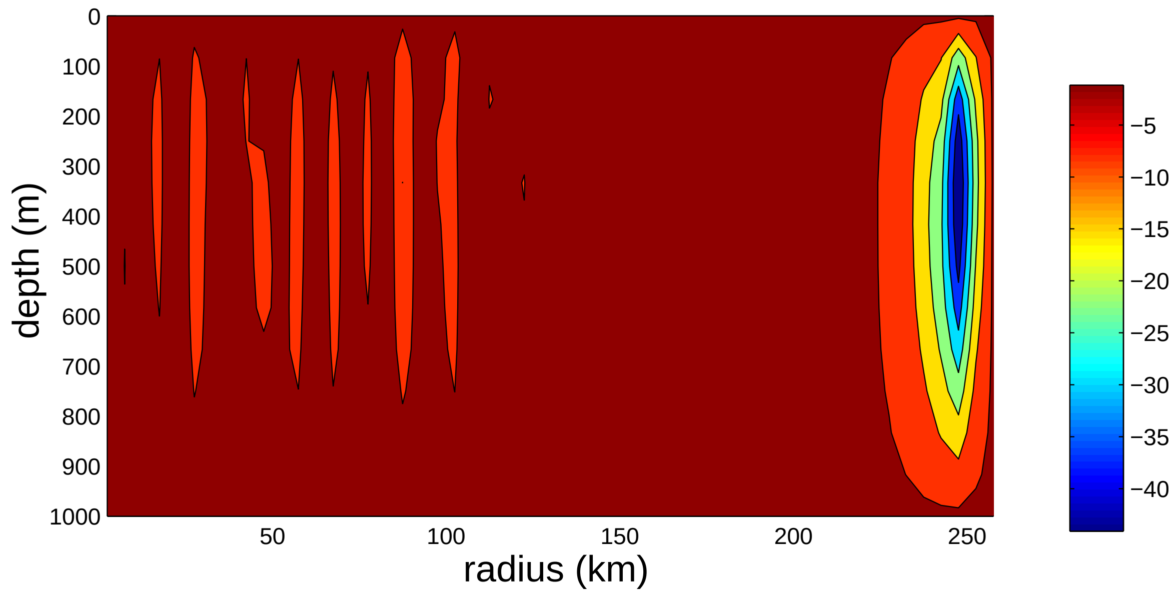
temperature



potential vorticity

- O 10 days after cooling has ceased, year 8
- O eddies spreading dense water laterally away from cooling region
- O inflowing boundary current is also unstable
- O dense water in eddies stays near the surface pv constrants limit sinking in the interior
- O high pv caps overlay recently formed eddies high stratification is not advected from the open ocean − generated internally via "pv sheet" boundary condition (Bretherton, 1967)

Where does the downwelling take place ?



center of marginal sea

outer boundary

Azimuthally integrated vertical velocity (m^2/s)

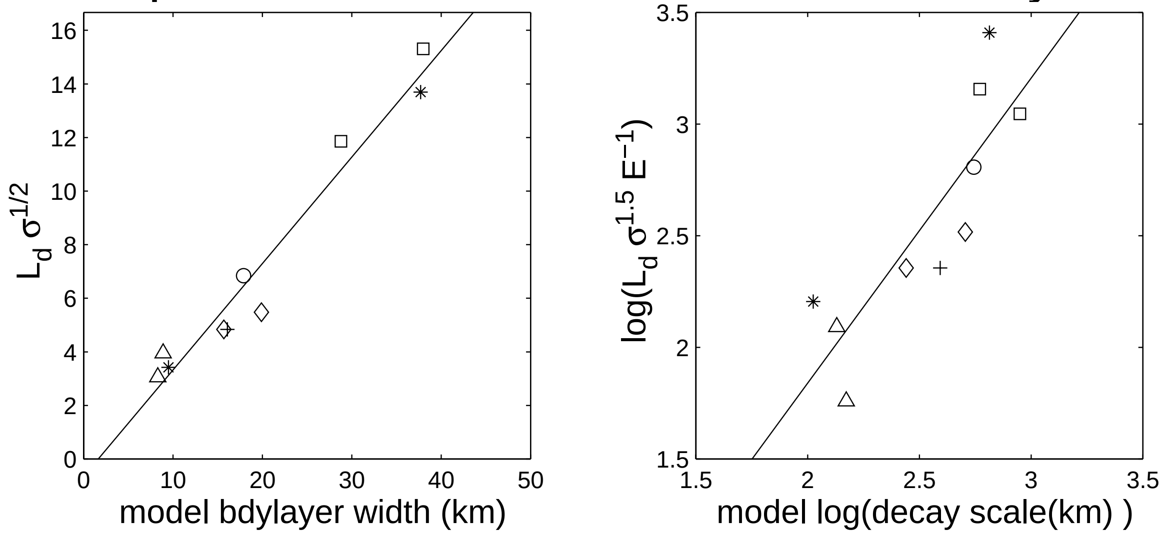
O Essentially all of the downwelling takes place near the lateral boundary

O width of downwelling ~ 20 km

O maximum at mid−depths

O total downwelling transport at 460 m is 0.5×10^6 m^3/ s

Comparison between PE model and theory

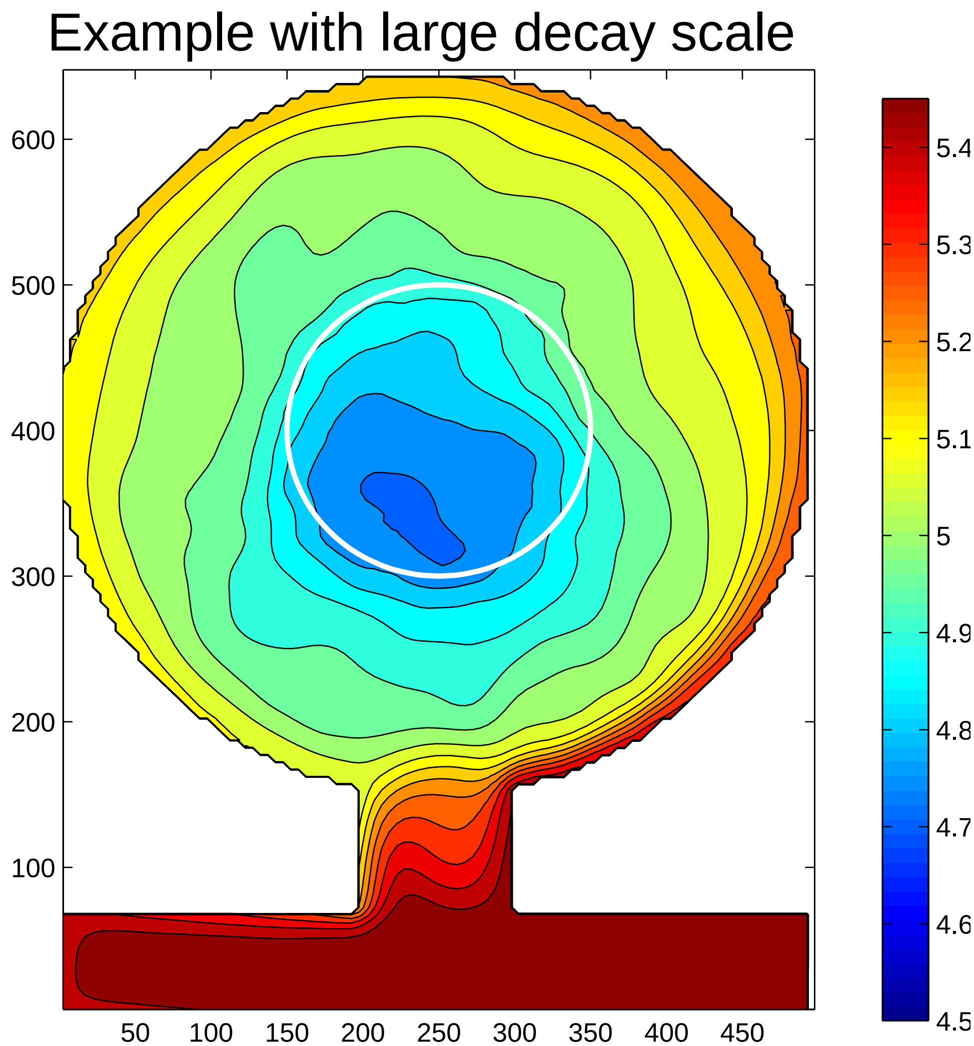


O region of downwelling in the PE model
scales well with $L_d\,\sigma^{1/2}$
varies between 10 − 40 km

O along boundary decay scale diagnosed
from the model compares well with $1/\alpha$
varies between 100 − 1000 km

O submesoscale parameterizations influence
characteristics of the THC

f=0.5, $2\times10^{-4}\ s^{-1}$ (asterisks) A =150, 250 m^2 / s (squares)
K = 150, 250 m / s (triangles) half stratification (+)
500 m, 2000 m depth (diamonds)



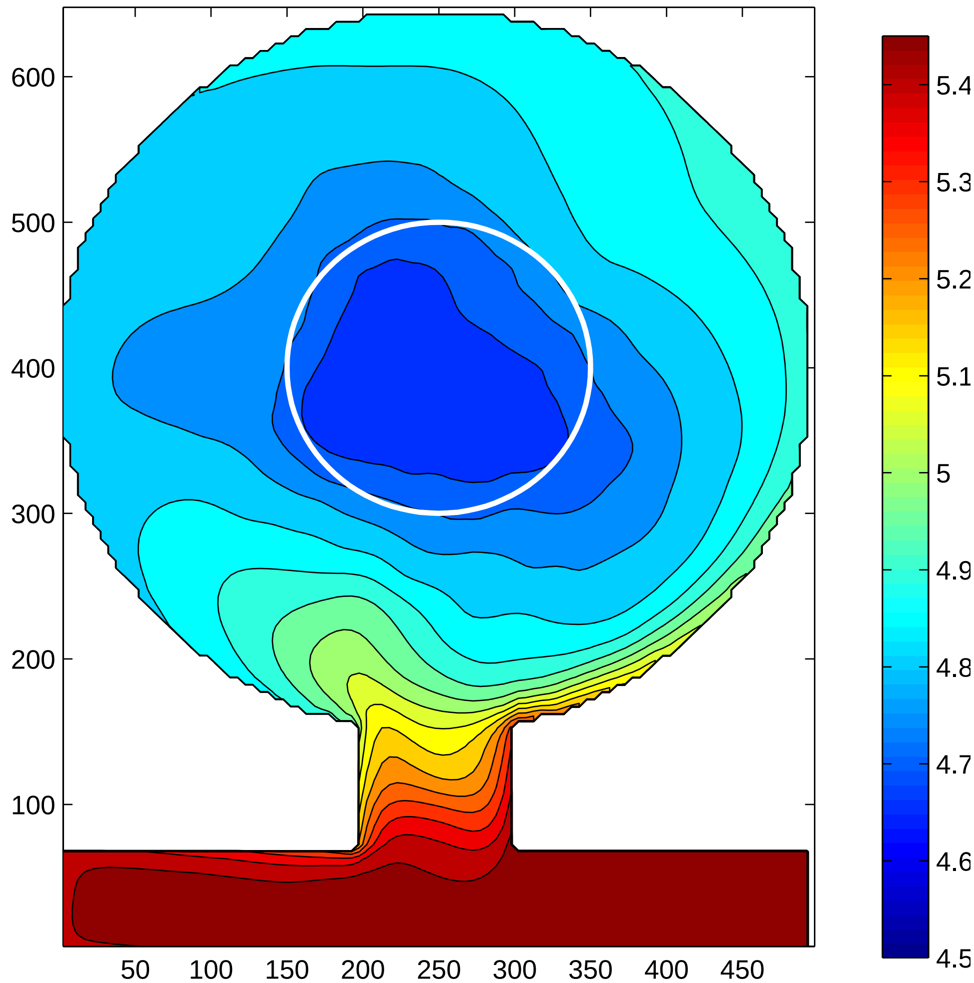
−1 2

α = 1100 km (increased A to 150 m / s)

O warm water extends farther around the marginal sea

O temperature is more symmetric around basin, larger horizontal gradient

Example with small decay scale



α^{-1} = 125 km (increased K to 150 m^2 / s)

O warm water is eroded very quickly

O basin−averaged temperature is
colder than standard case

Summary and conclusions

- Interior cooling is balanced by mean and low frequency (1−10 years) oscillations of barotropic gyres and mesoscale eddies

- Dense water Interacting with the boundaries develops a baroclinic boundary current that advects warm water into the basin to balance cooling

- downwelling limb of THC is concentrated in this boundary current

$$\text{width} \quad L_d\, \sigma^{1/2}$$

$$\text{length} \quad L_d\, \sigma^{3/2} / E$$

- characteristics of the THC are strongly influenced by lateral processes at the smallest scales