Fine-scale turbulent processes: mesoscale stirring and submesoscale instabilities

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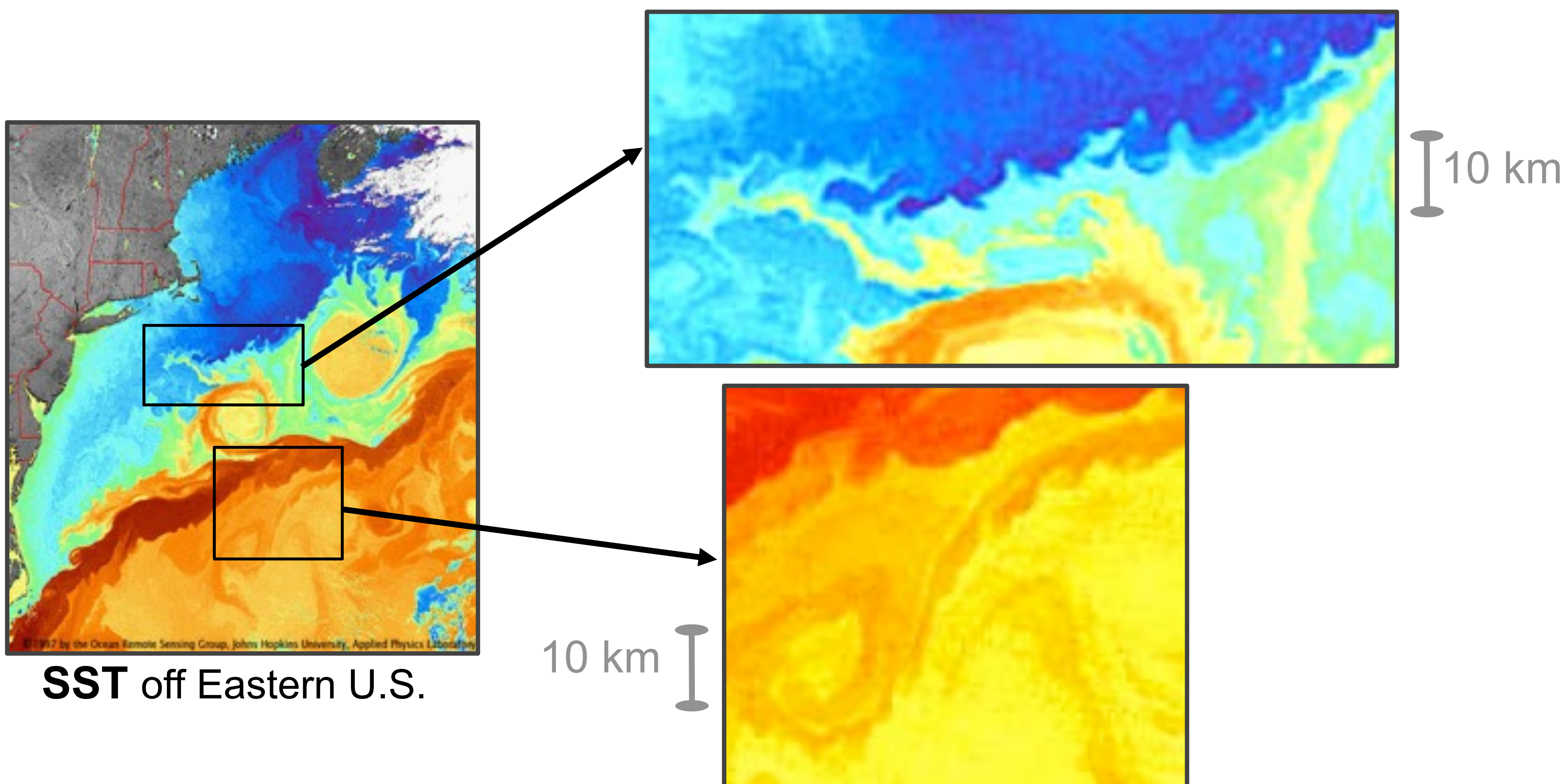
"***submesoscale turbulence***" shorthand for
"***upper-ocean frontal submesoscale turbulence***"

The upper ocean is filled with rapidly evolving structures that appear as tracer contrasts, *i.e.*, fronts. The cross-front length scale is of the order of 1-10 km.



SST off Eastern U.S.

Why is there an upper ocean submesoscale turbulence regime and how does it differ from region to region ?

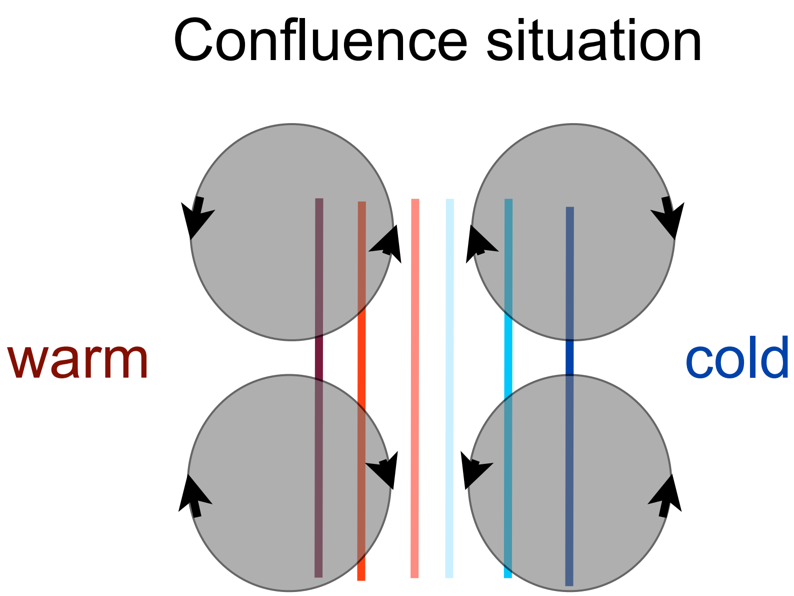
Position of the problem

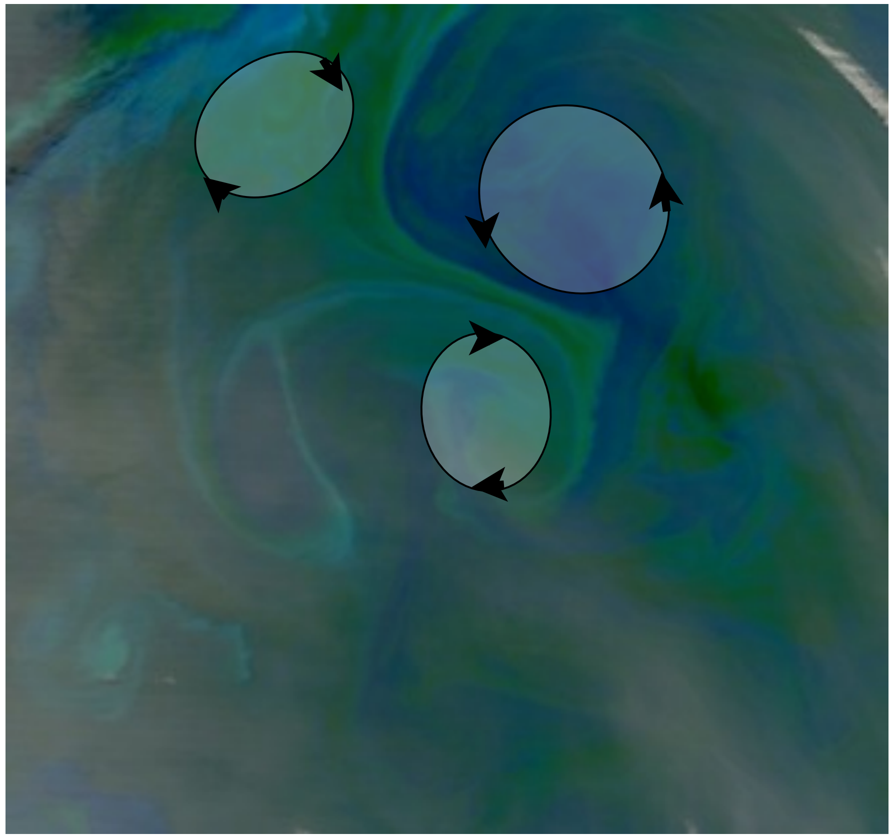
Most of our ROMS simulations resolve (at least partly) submesoscale turbulence nowadays. High order numerical schemes help in that regard (P. Marchesiello).

How do we interpret the type of turbulence that emerges at dx ~ 1 km or more ?

2 essential elements for submesoscale turbulence:

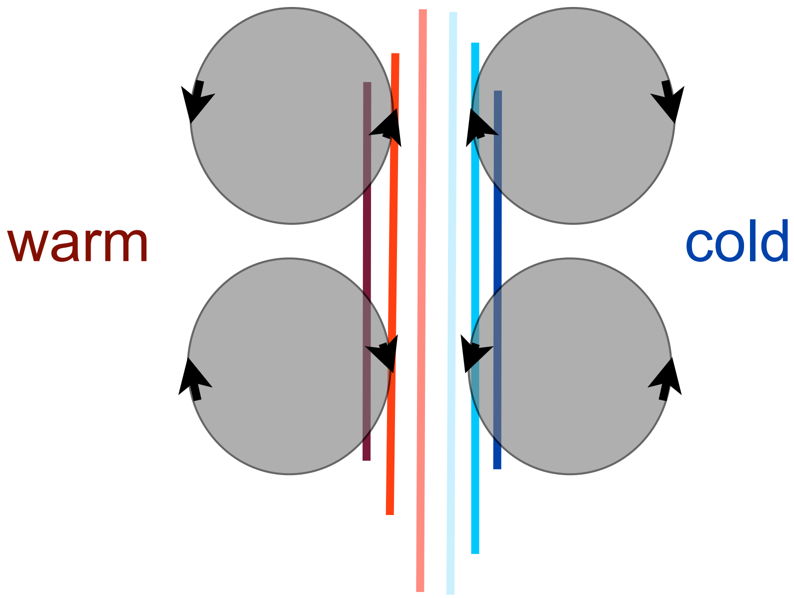
- frontogenesis
- flow instabilities (baroclinic)

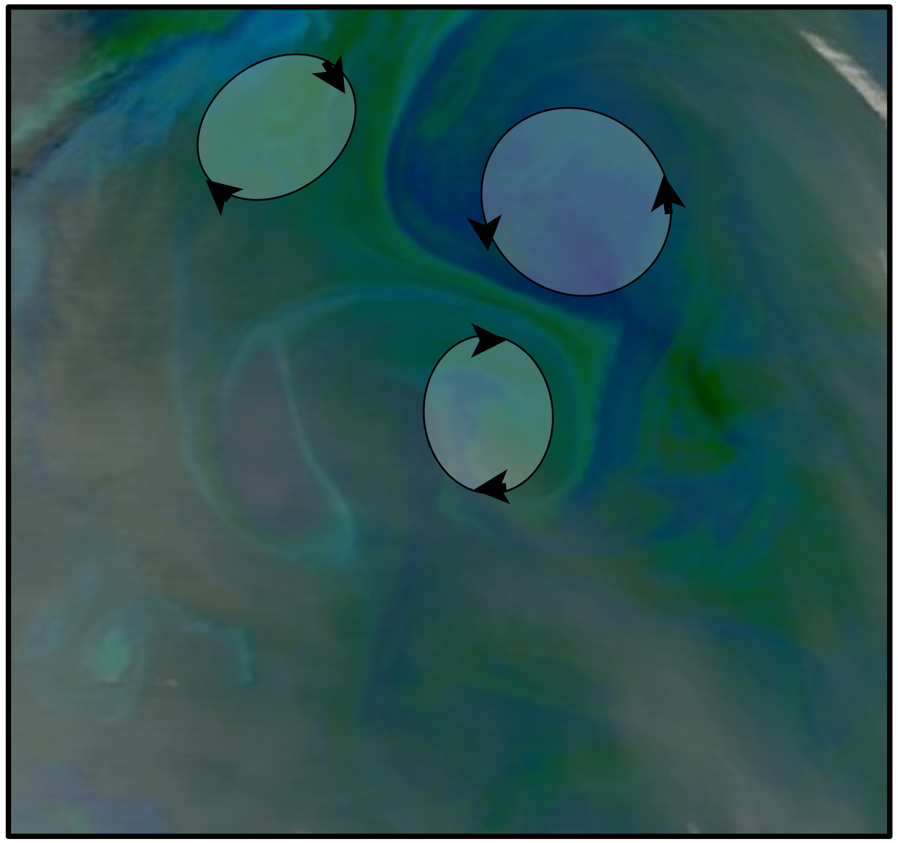




Kinematic argument: in a turbulent flow, **confluence** situations (due to mesoscale eddies) are common and will tend to increase preexisting tracer gradients.

Confluence situation





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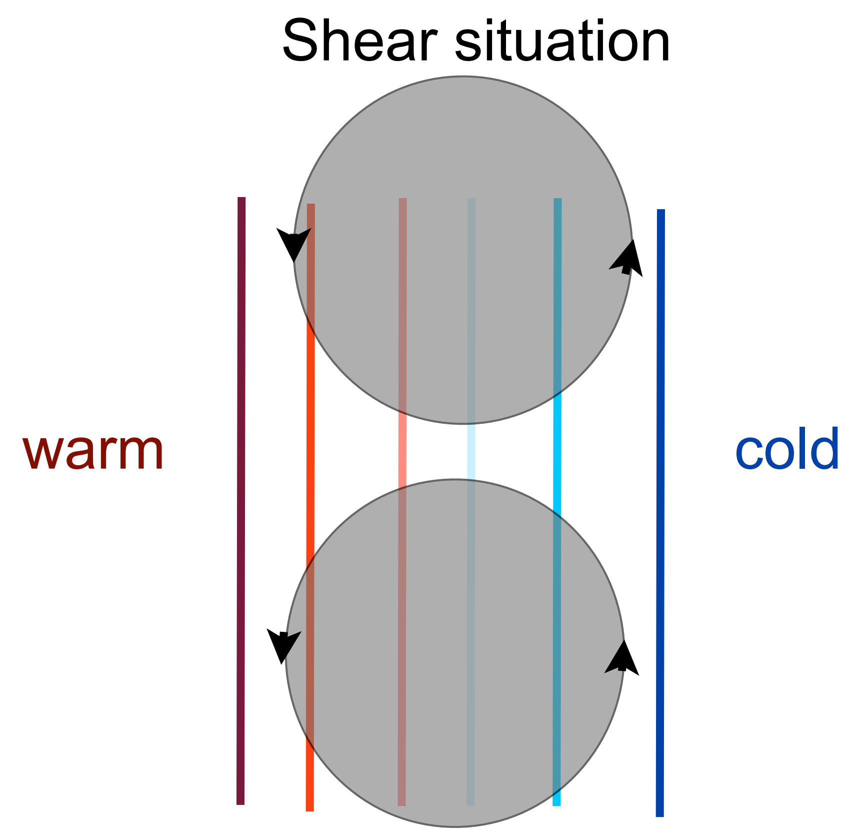
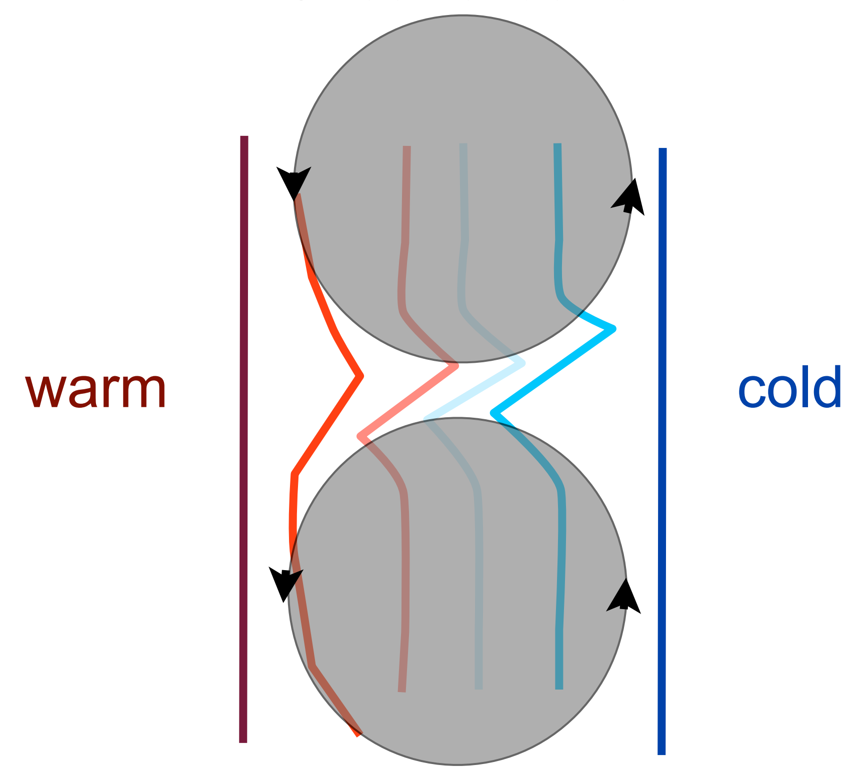


Kinematic argument: in a turbulent flow, **shear** situations (eg, due to mesoscale eddies) are common and will also tend to increase preexisting tracer gradients.

Shear situation



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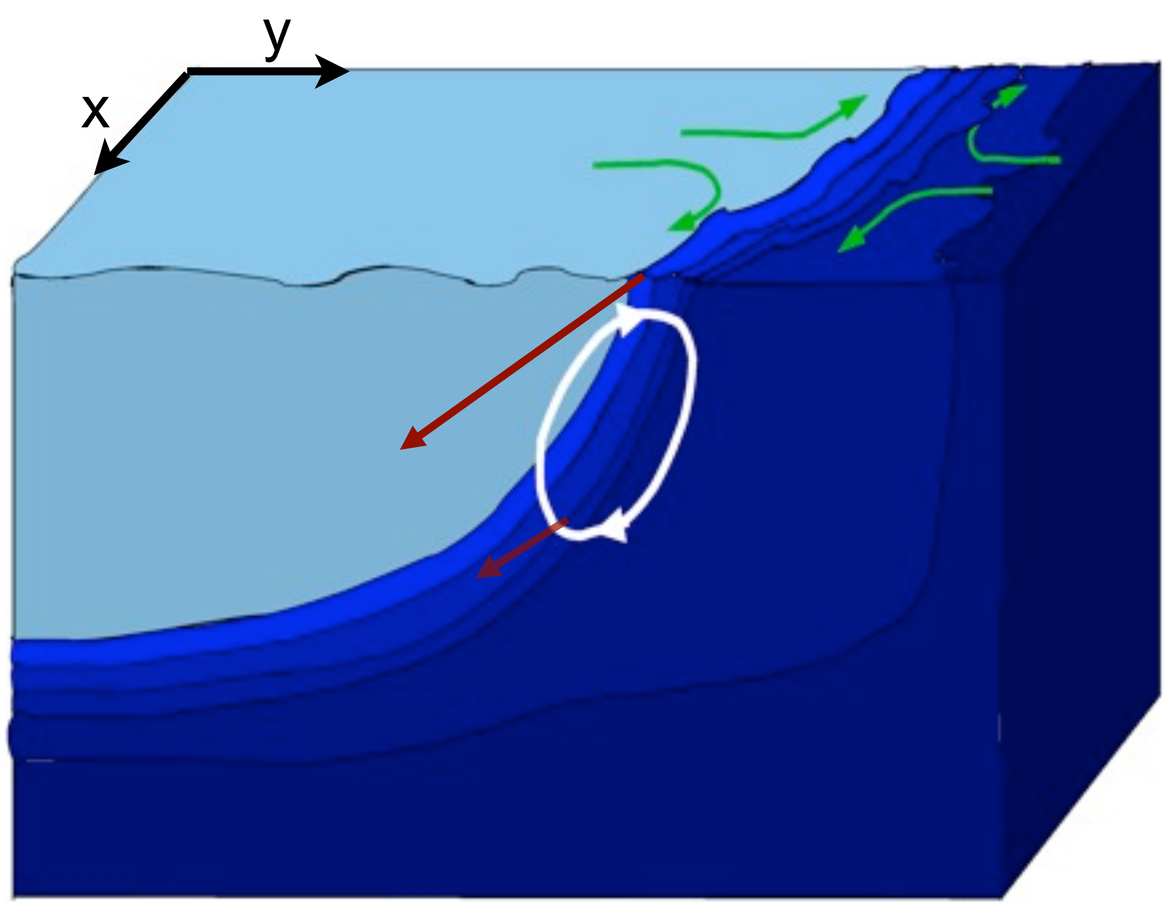
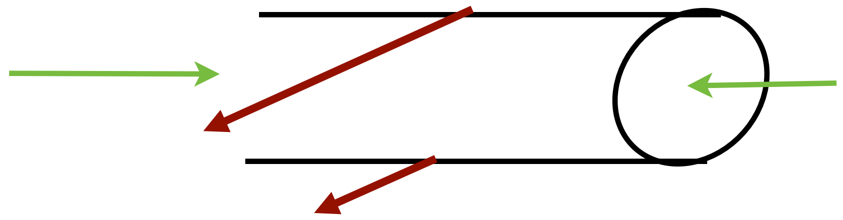
Frontogenesis: 2- dynamics (balanced)

Dynamic argument for geophysical fluids in which Coriolis-pressure force balance is important:

$$f\frac{\partial u}{\partial z} = -\frac{\partial b}{\partial y}$$

$$f\frac{\partial u}{\partial z} \searrow \quad -\frac{\partial b}{\partial y} \nearrow$$





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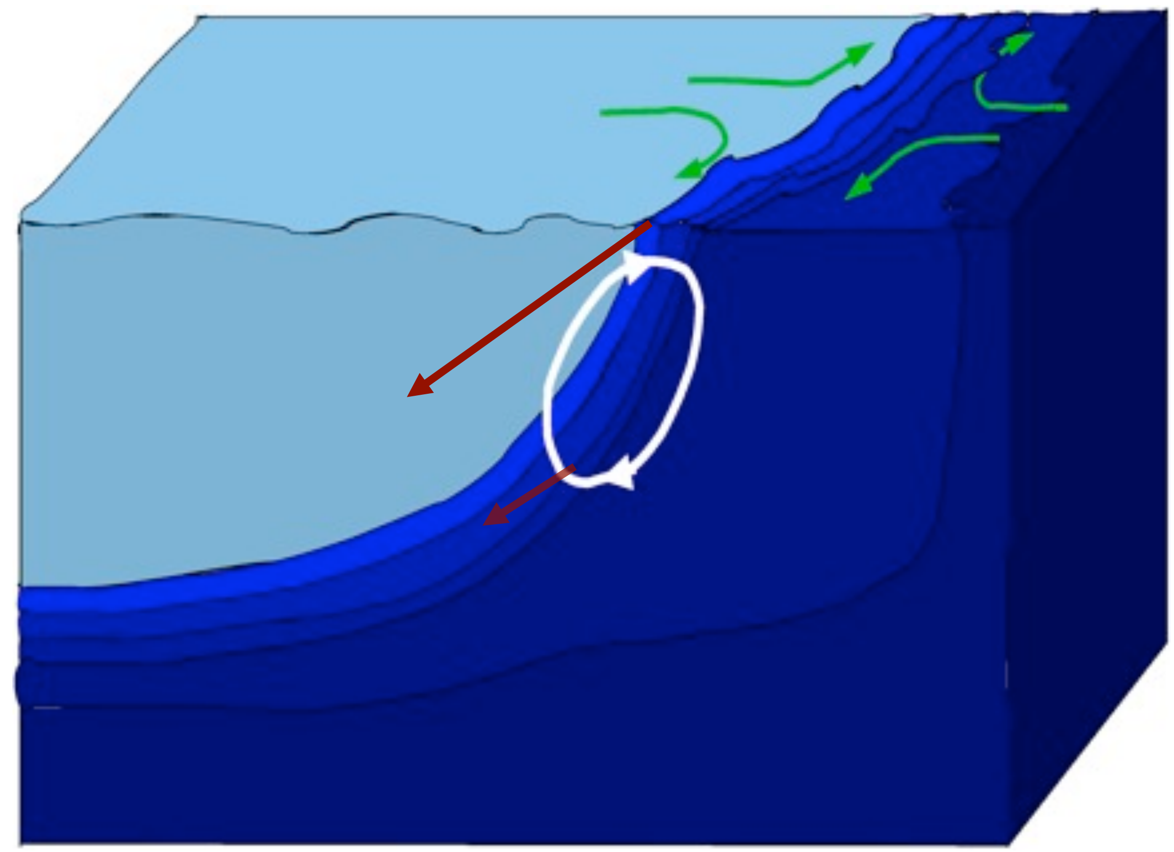
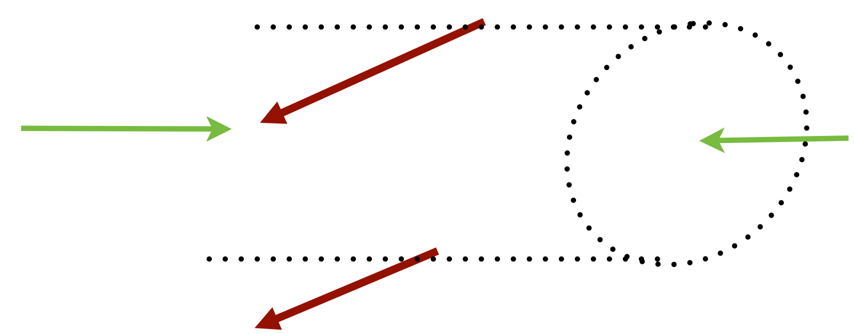


Mesoscale strain tends to destroy thermal wind balance. Thermal wind balance disruption leads to the development of an **ageostrophic secondary circulation** (ASC) which limits imbalance by restoring shear and limiting frontal intensification.



At the surface w~0 limits the efficiency of ASCs ➝ frontal intensification is difficult to halt ➝ intensification of ASCs with potentially large w.

Frontogenesis: 2- dynamics (balanced)

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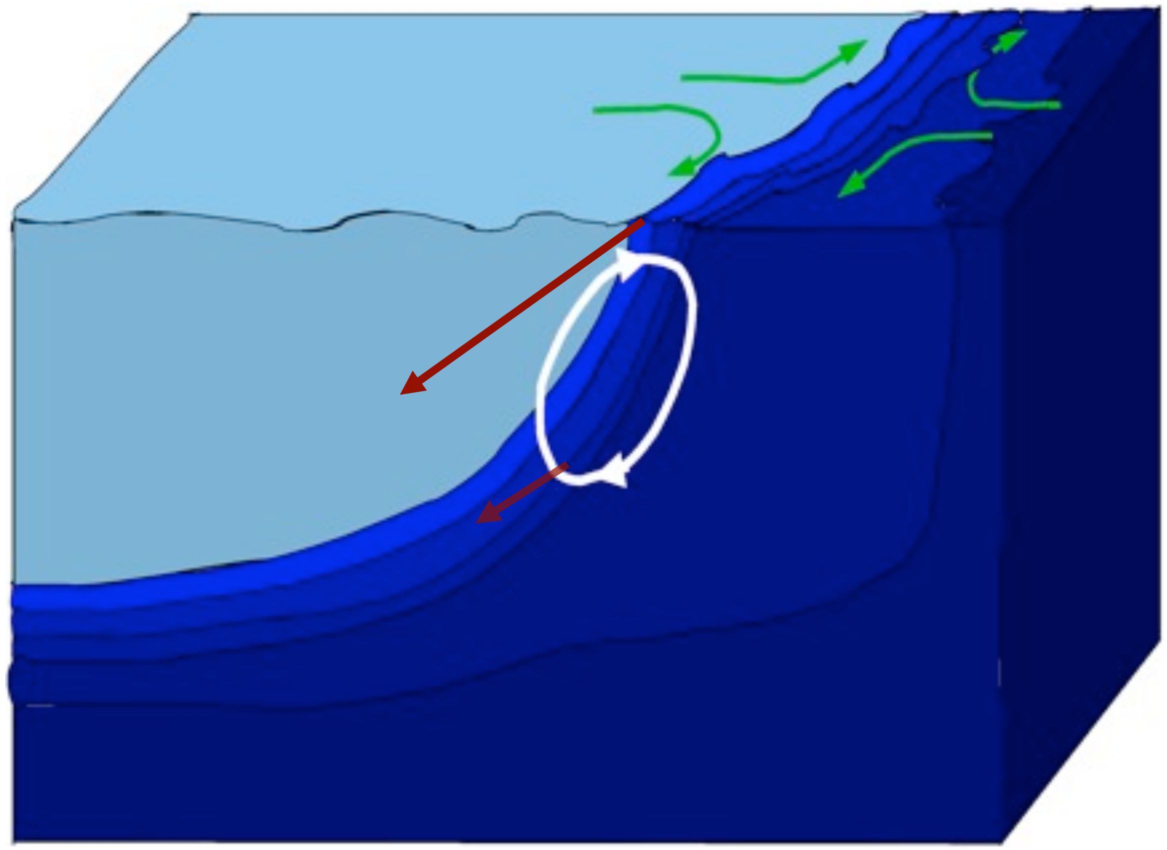

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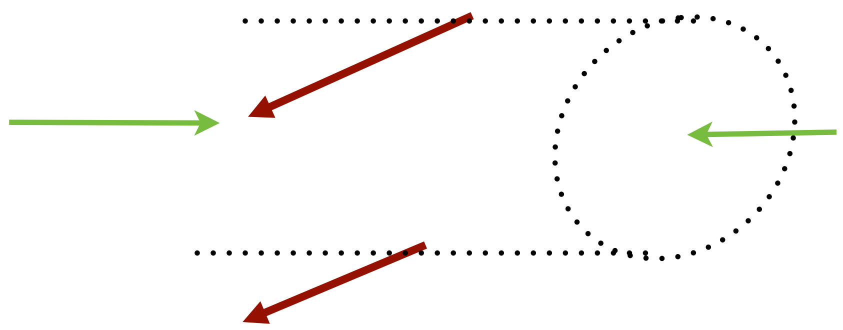
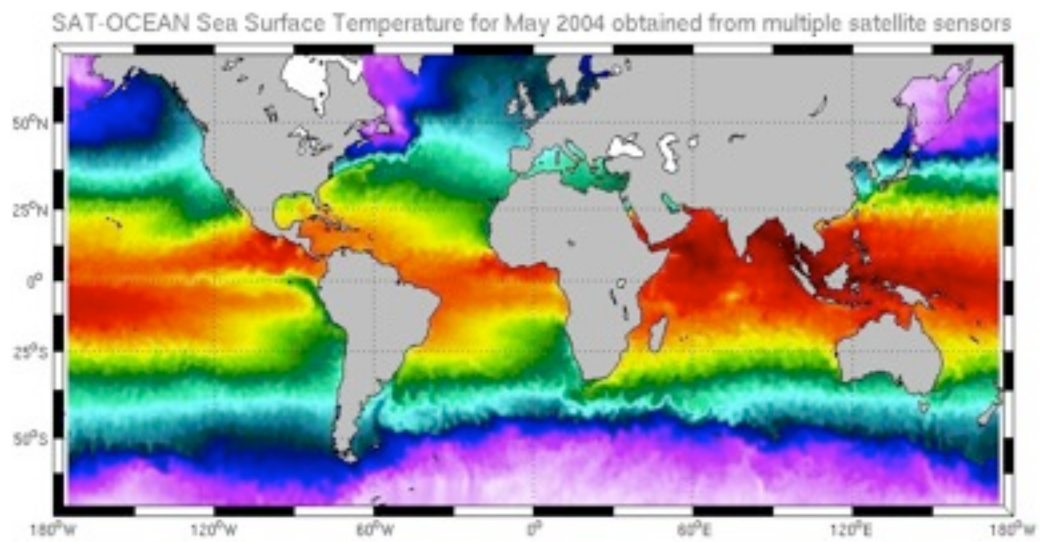


Vertical velocities develop that are concentrated within narrow frontal regions. Nonlinearities tend to enhance/concentrate the downward branch and weaken/broaden the upward branch. **The processes that limit the magnitude and the shrinking of cross-front length scale are still being investigated.**

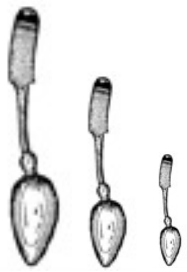
where does the stirring come from ?



Ingredients for frontogenesis:

Surface density gradients

Stirring spoons

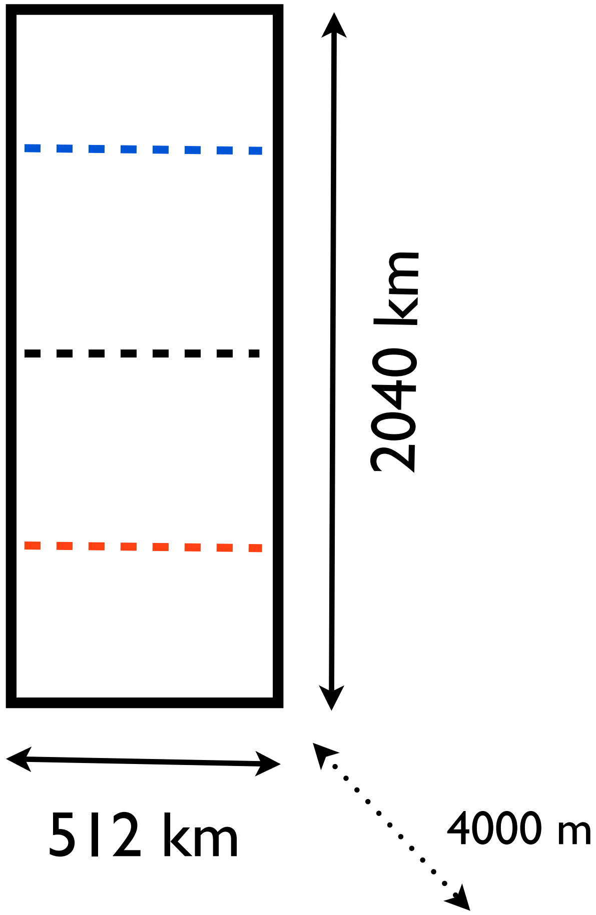


Purpose of this study: present and compare two situations with different distributions of stirring spoons associated with different flow instabilities.

2 essential elements concepts to understand submesoscale turbulence:

- frontogenesis
- flow instabilities (baroclinic)

Reentrant channel with a baroclinic jet (3D restoring of zonally averaged u and ρ)



512 x 2040 x 200 grid points.
1month: 9h wall clock time of 64 Sandy Bridge nodes (2 x 8 cores/node, 2.3 GHz)
ROMS UCLA, Ri based vertical diffusion.

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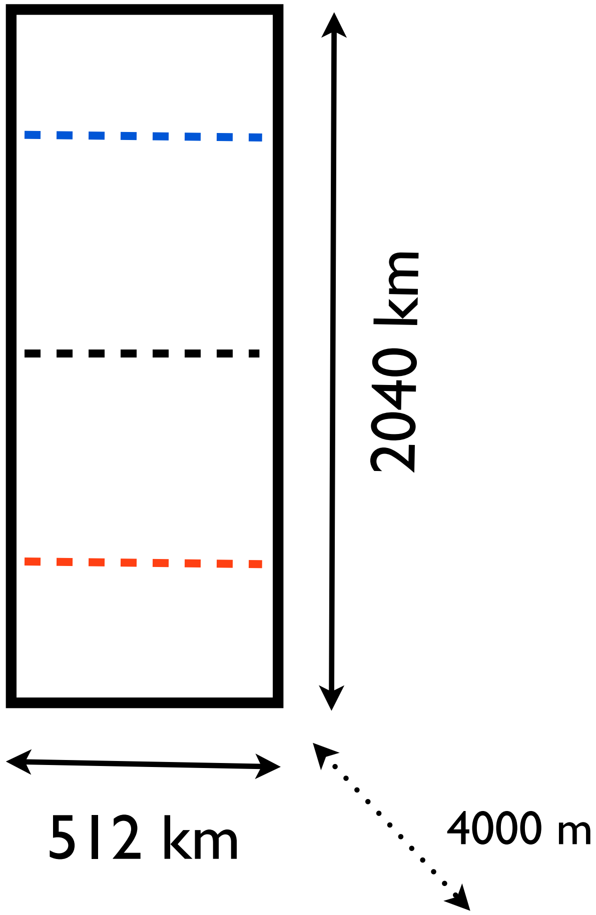
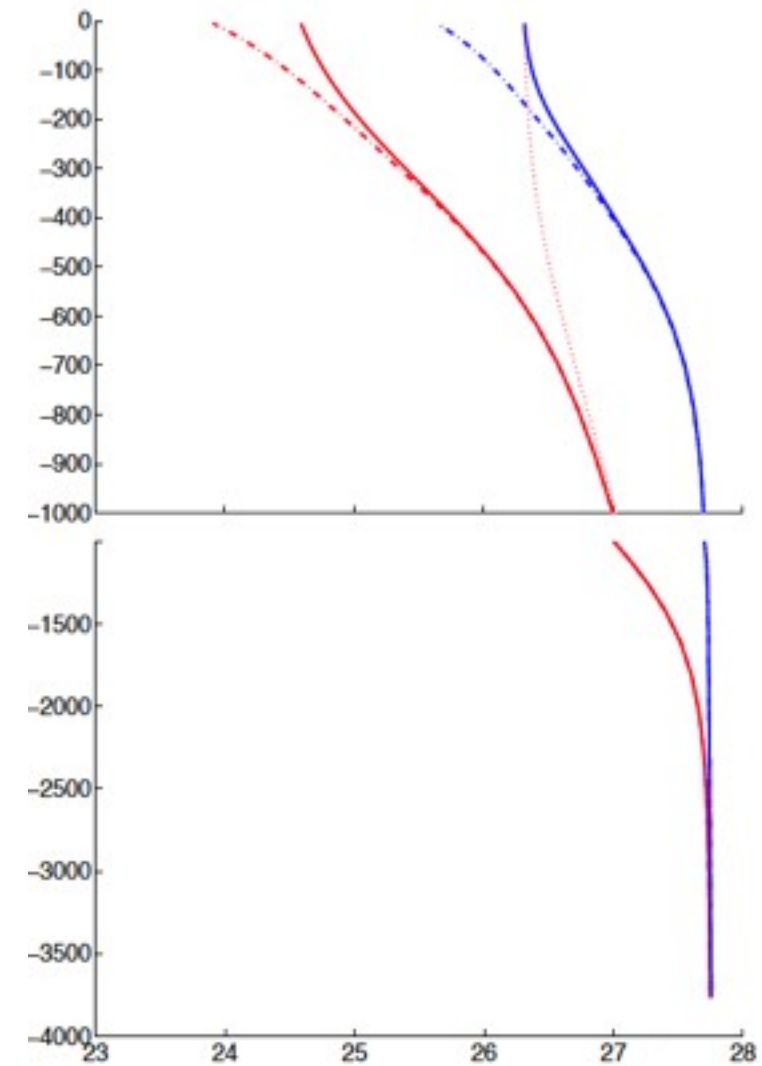
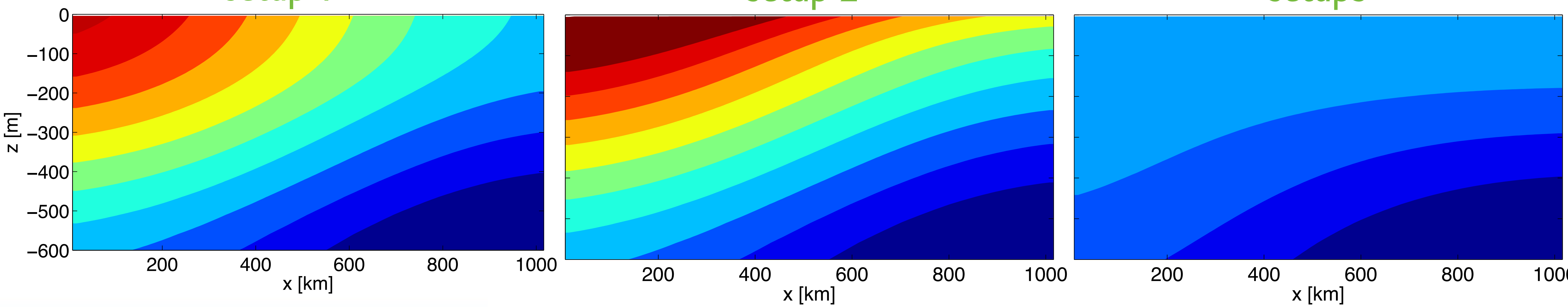
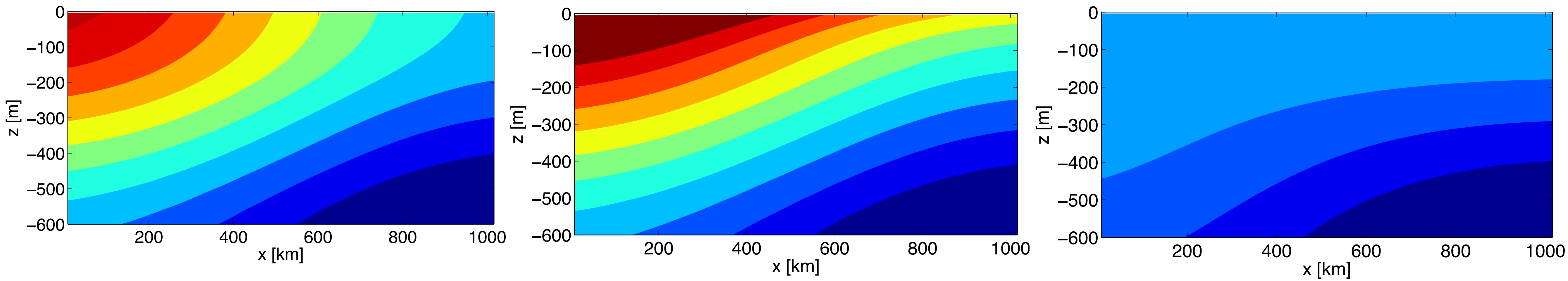




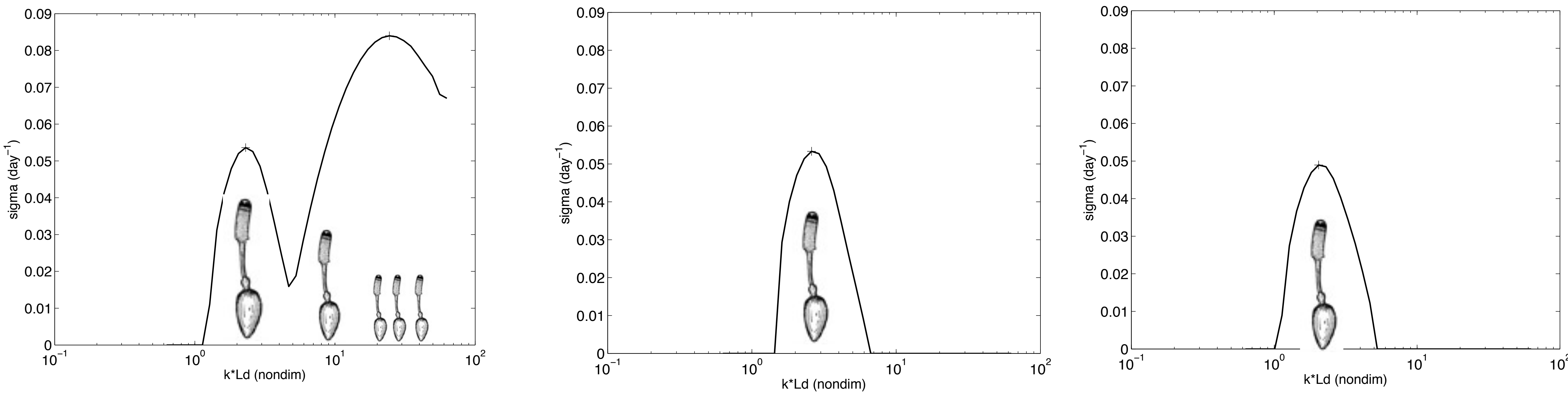
setup 1 setup 2 setup3



Linear instability analysis



Linear instability growth rates

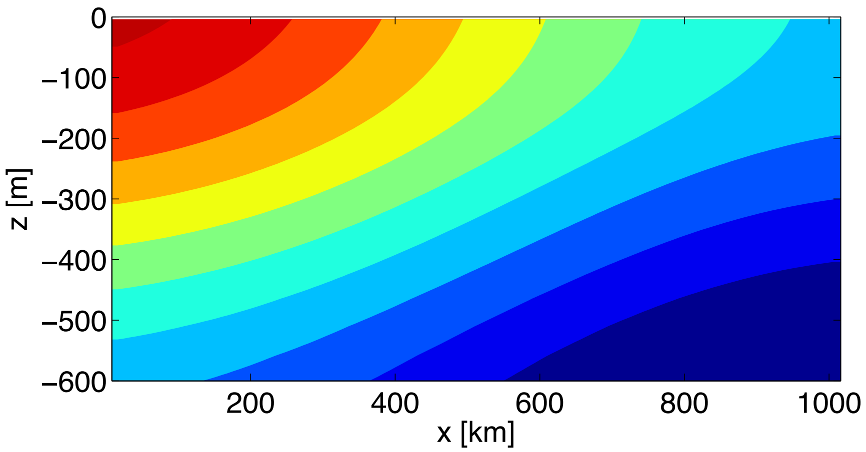


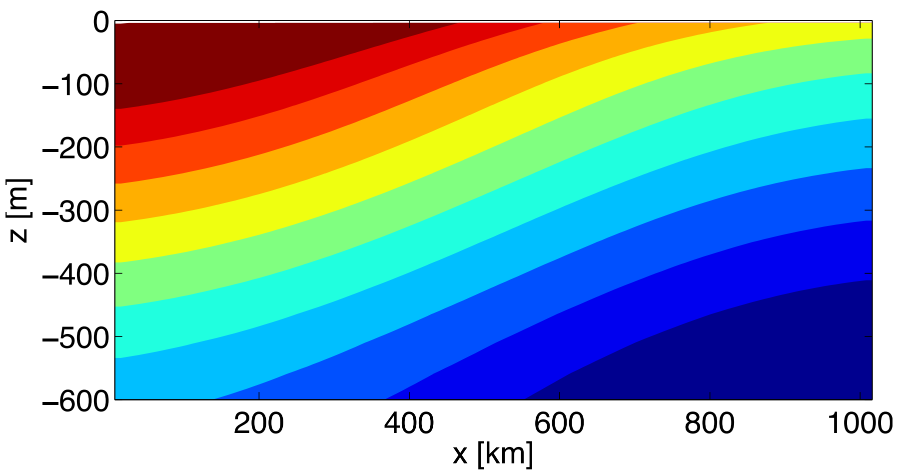
classical interior BCI + surface density gradient + Charney-like instability mode

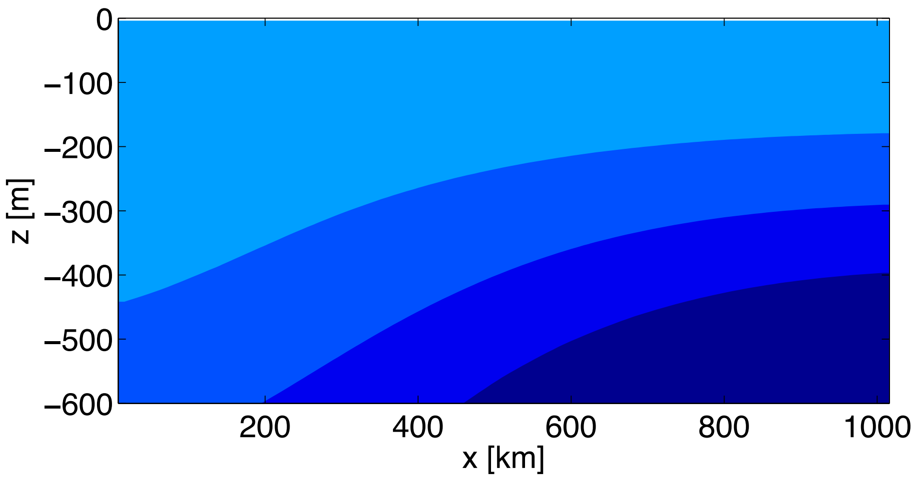
classical interior BCI + surface density gradient

classical interior BCI

Linear instability analysis







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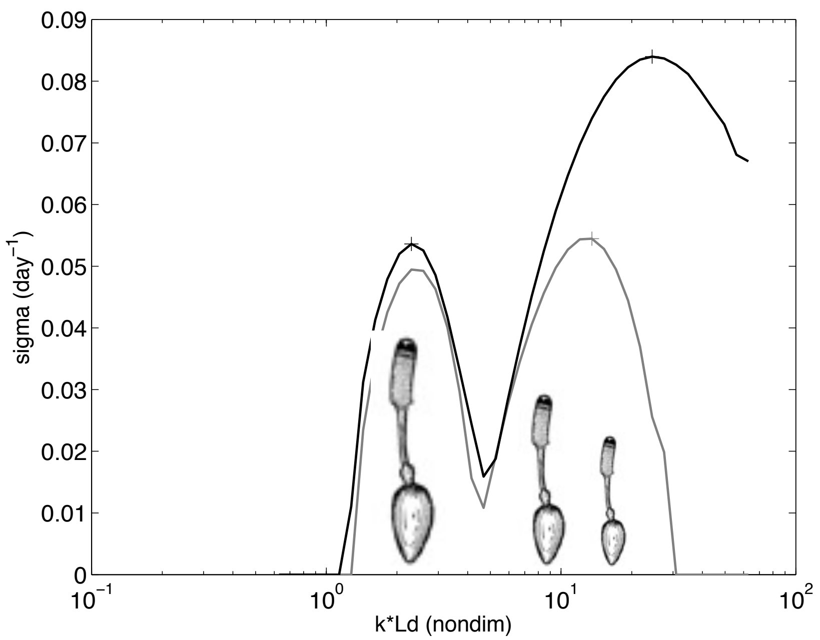
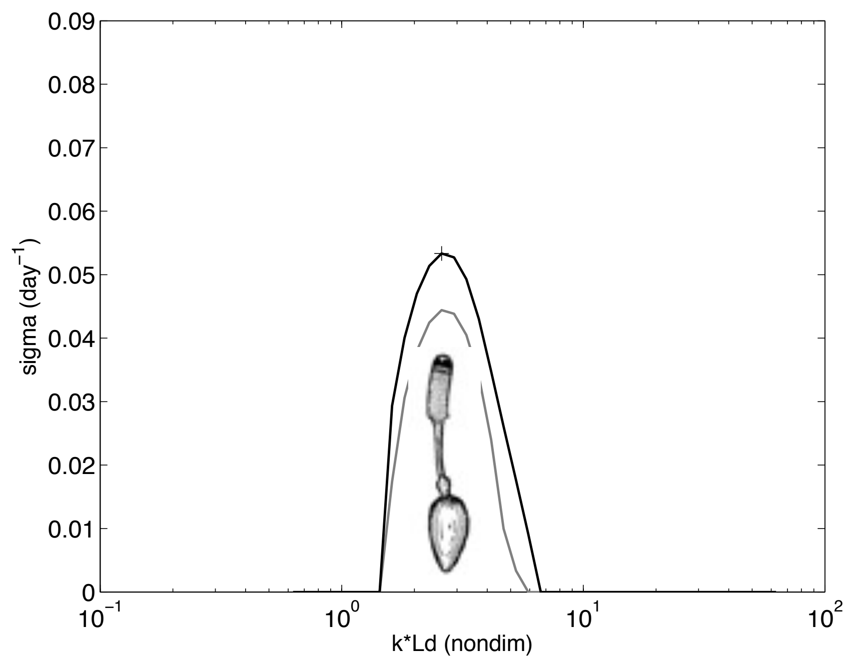


classical interior BCI +
surface density gradient +
Charney-like instability mode



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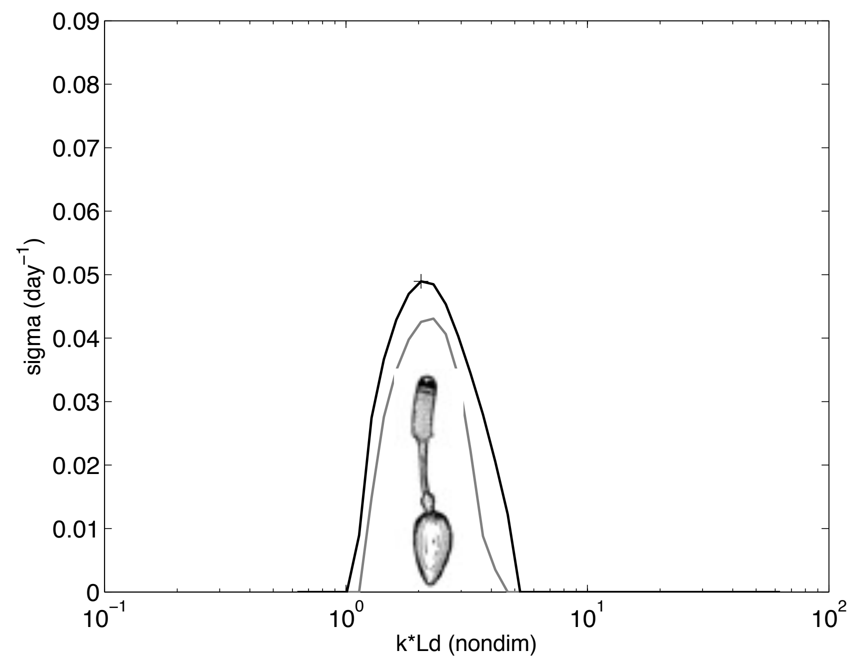
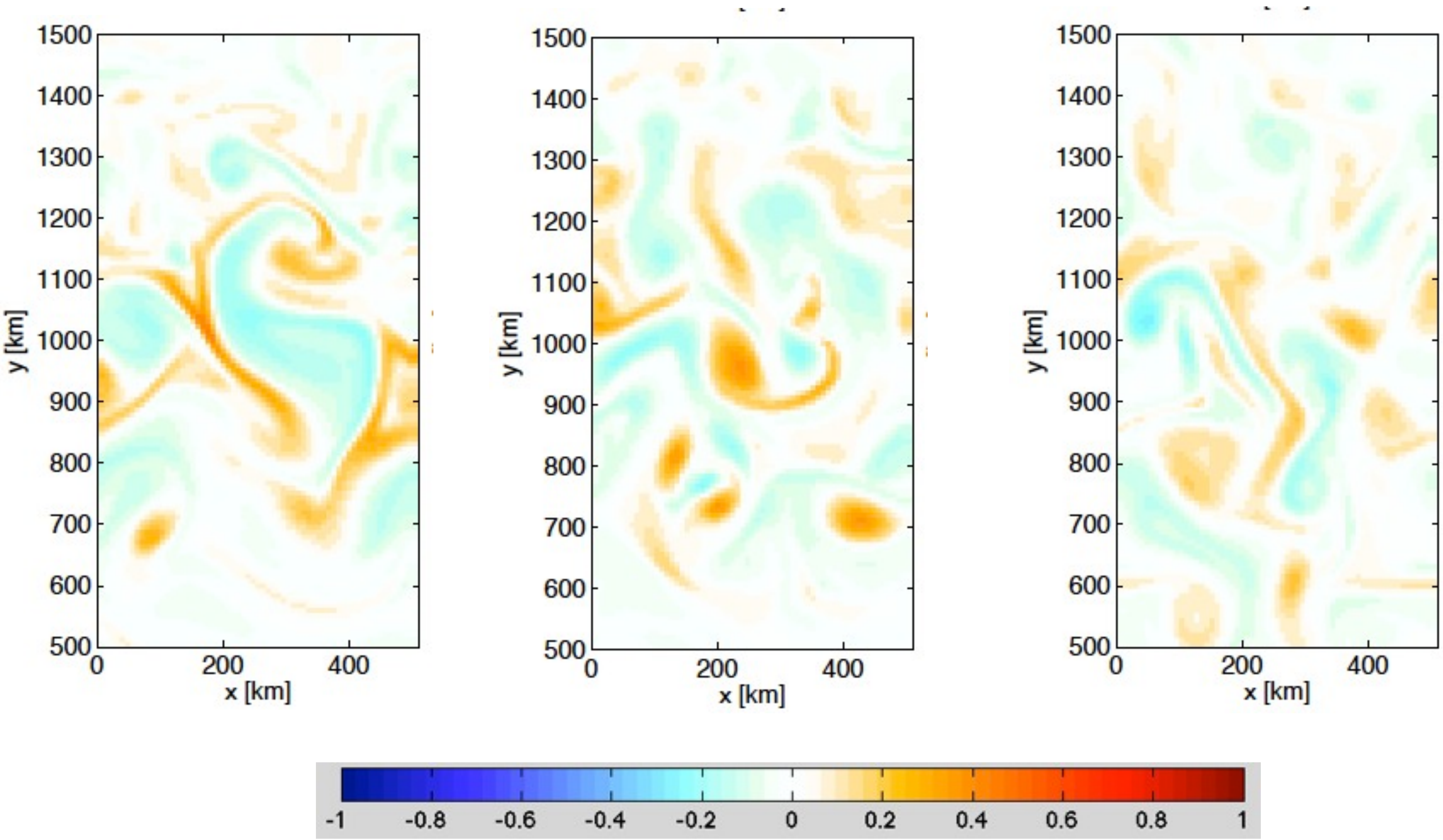


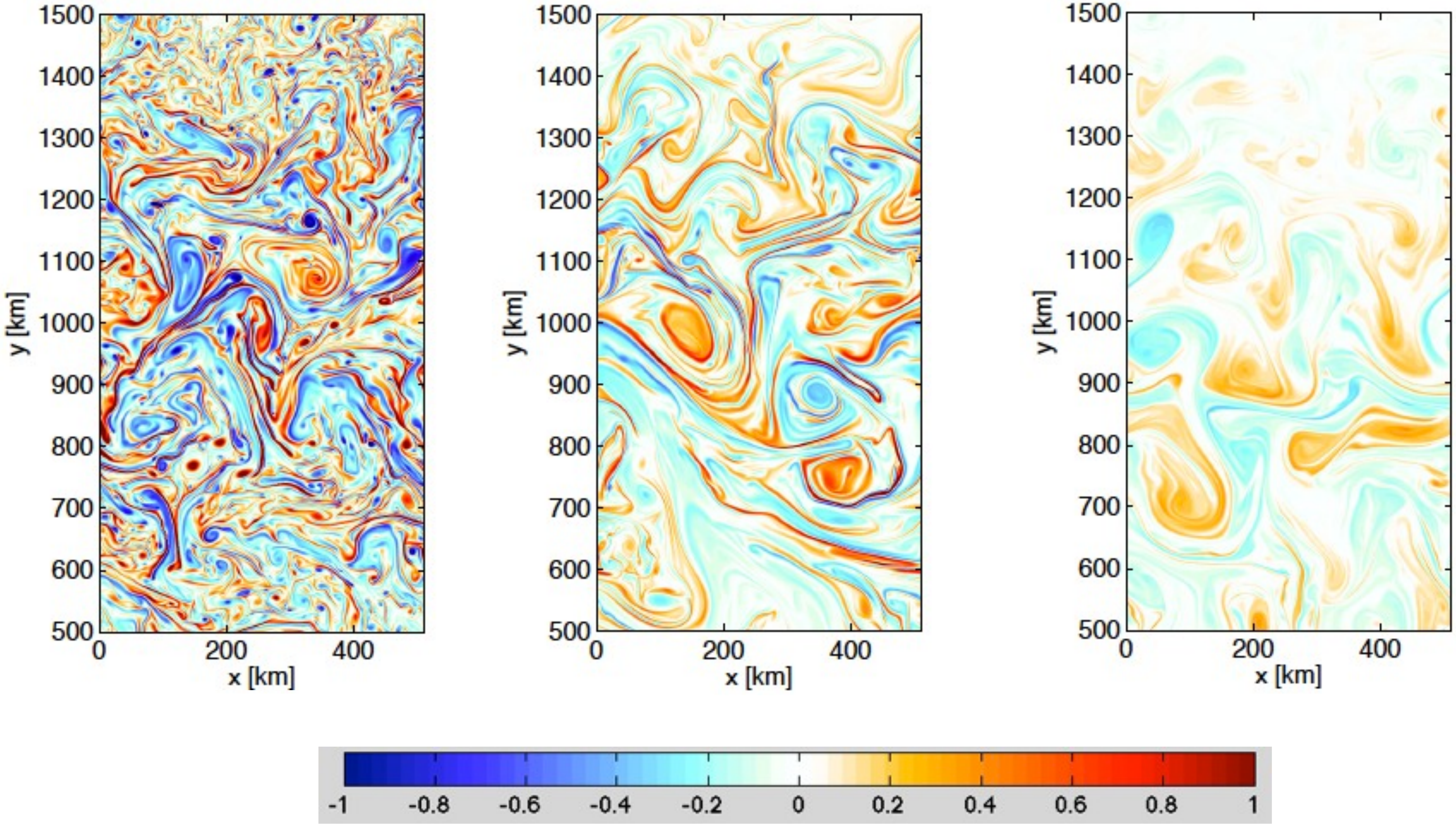
classical interior BCI

The Charney mode arises from the simultaneous presence of a i) poleward surface density gradient ii) a weakly stratified upper ocean

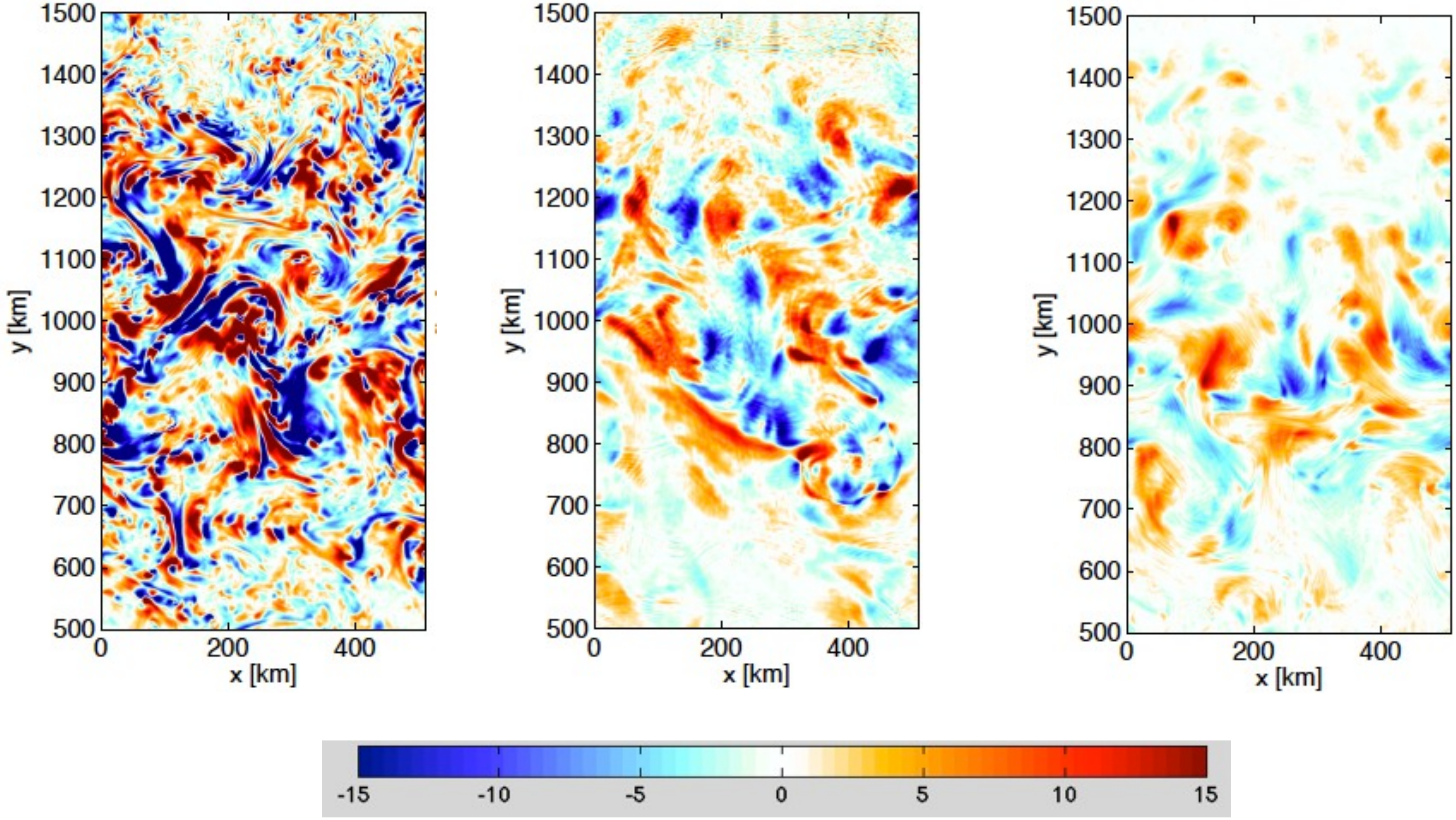
Surface ζ - 8 km



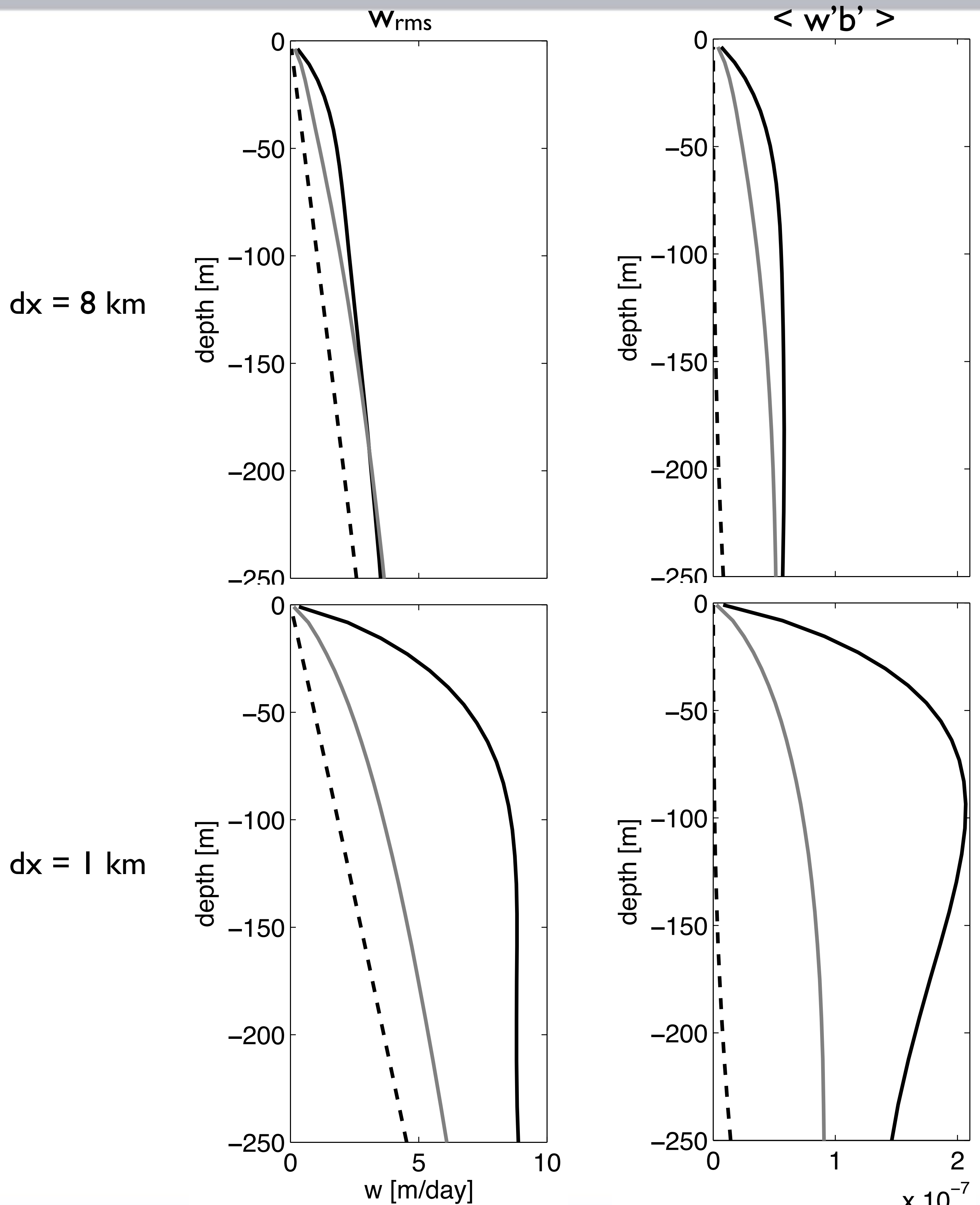
Surface ζ - 1 km



120 m w - 1 km

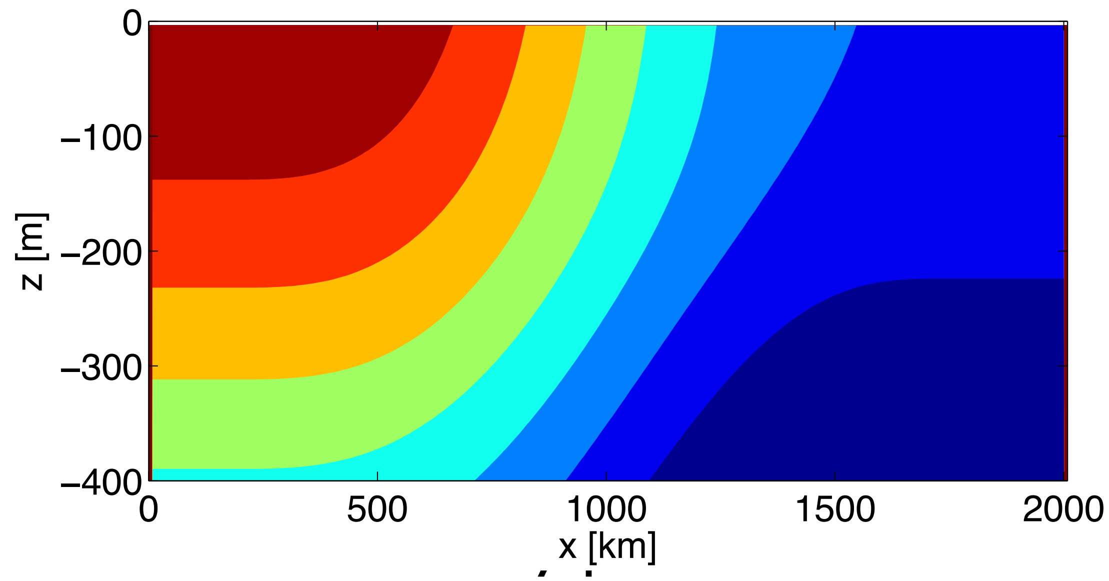

1500
1400
1300
1200
1100
1000
900
800
700
600
500
y [km]
0
200
400
x [km]
-15
-10
-5
0
5
10
15

Statistical properties

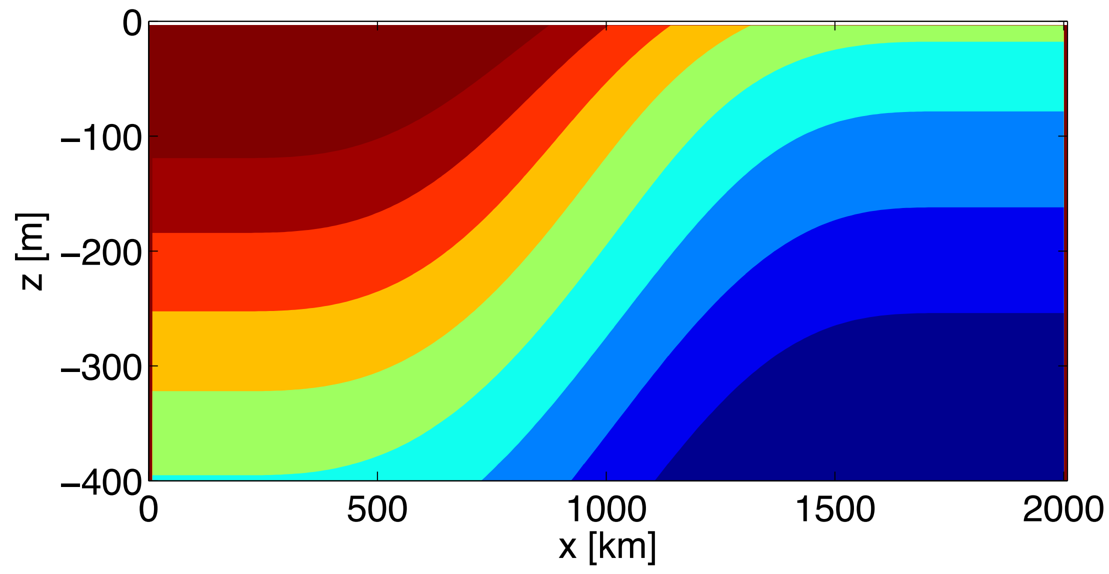


Setup 3 is not sensitive to resolution between beyond mesoscale resolving.
Very large increase in w_{rms} and <w'b'> for setup1 with increasing resolution; much less dramatic for setup 2.

setup 1



setup 2



$$\partial_y q = \beta - f \partial_z s + \left[\frac{g f}{\rho_0 N(0)^2} \, \partial_y \rho \ \delta(0) \right]$$

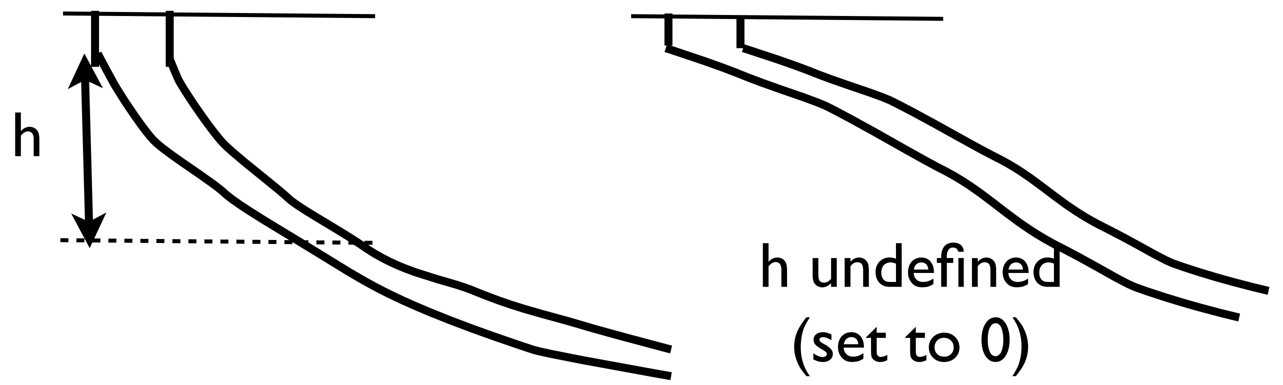
Charney-Stern criterion: ∂y q must change sign (in the vertical for baroclinic instability)

The Charney mode arises from the simultaneous presence of
- a poleward surface density gradient
- a weakly stratified upper ocean (precisely an increasing density slope)

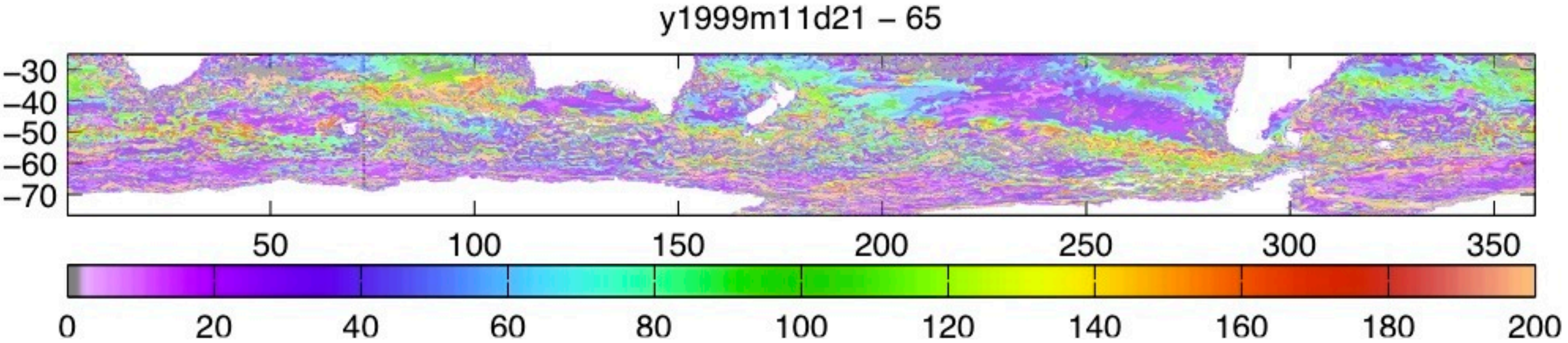
setup1 versus setup 2 in the real ocean

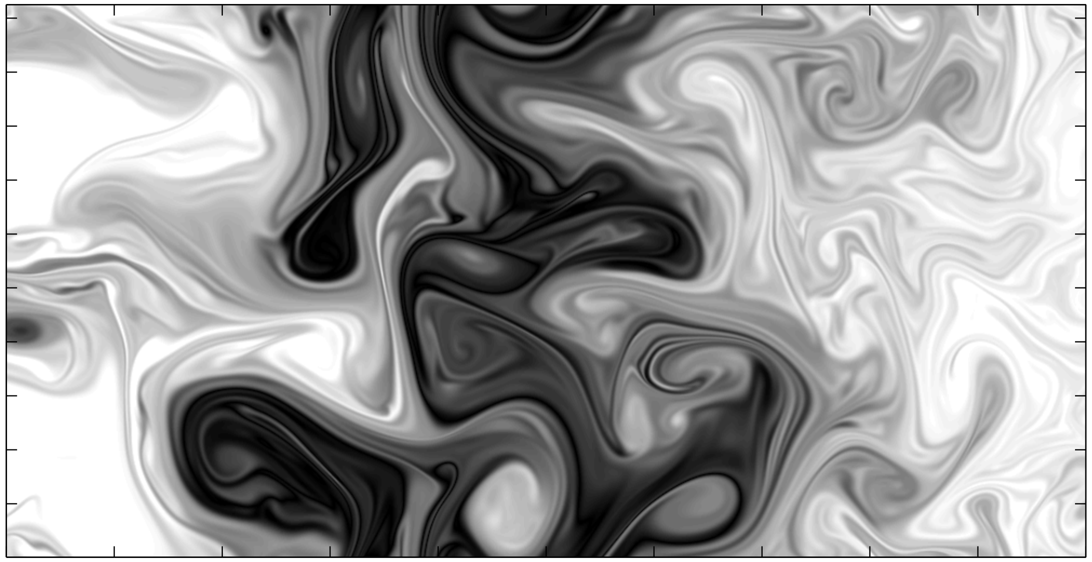
The Charney mode arises from the simultaneous presence of
- a poleward surface density gradient
- a weakly stratified upper ocean (precisely a change in concavity of density profile)

We search for thick subsurface layers close to the surface and in which ds/dz > 0 in the southern hemisphere



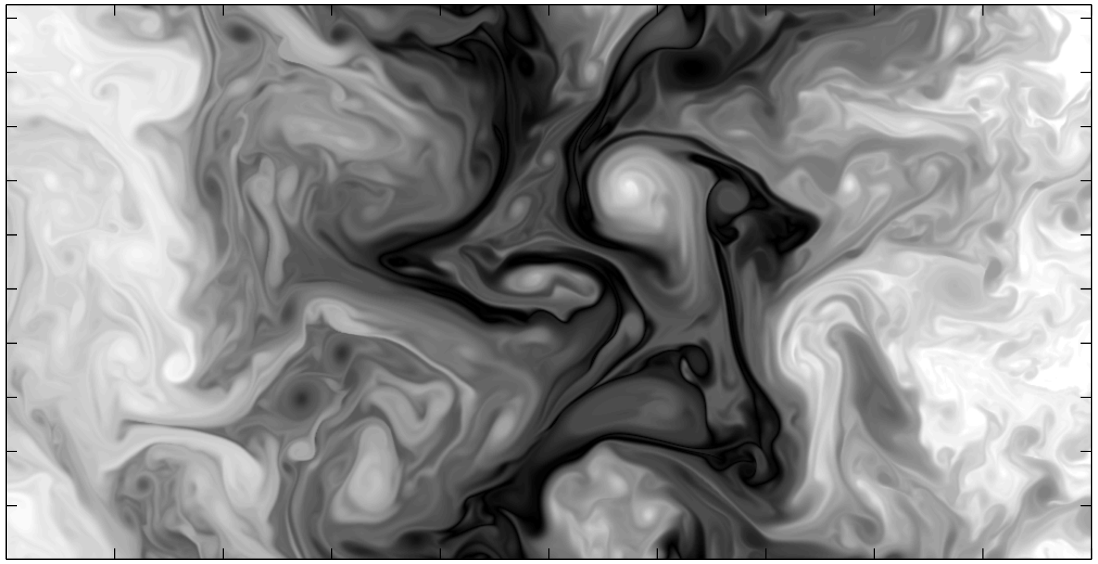
We find them in austral spring in places of mode water formation.





View of ocean turbulence until ~ 2000: there are mainly big spoons in the ocean. SST/density are passive tracer mainly stirred by these big spoons → tracer filaments wrapped around mesoscale eddies with no dynamical importance.

Present view: SST/density are active tracers that help energize the flow at scale smaller than the mesoscale through several processes:



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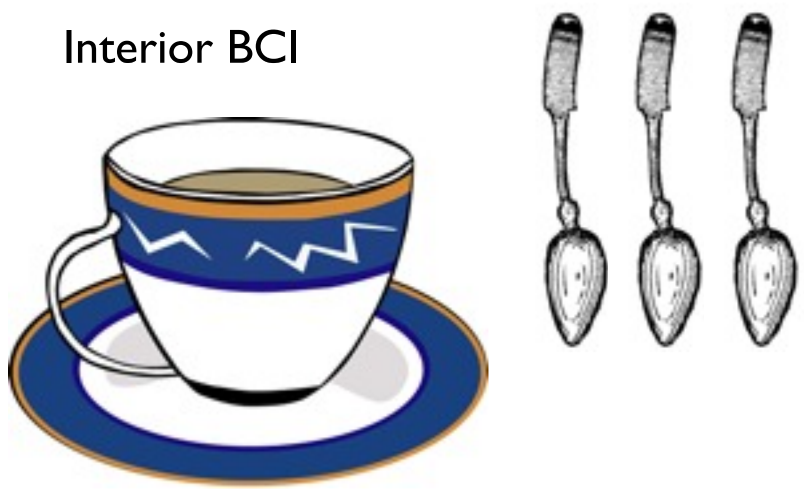
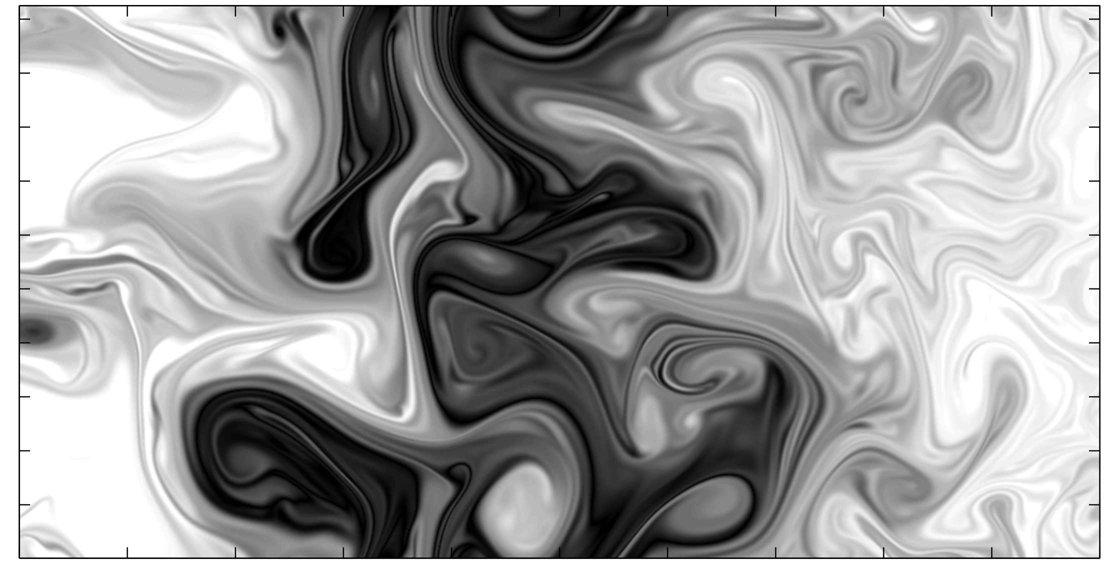
Present view: SST/density are active tracers that help energize the flow at scale smaller than the mesoscale through several processes:

- mesoscale driven frontogenesis
- O (1) km scale linear instabilities (MLI, **Charney type BCI** → symmetric, inertial, shear ...)
- wind can contribute to submesoscale energization in subtle ways (see Thomas, 2008, 2010 ...)

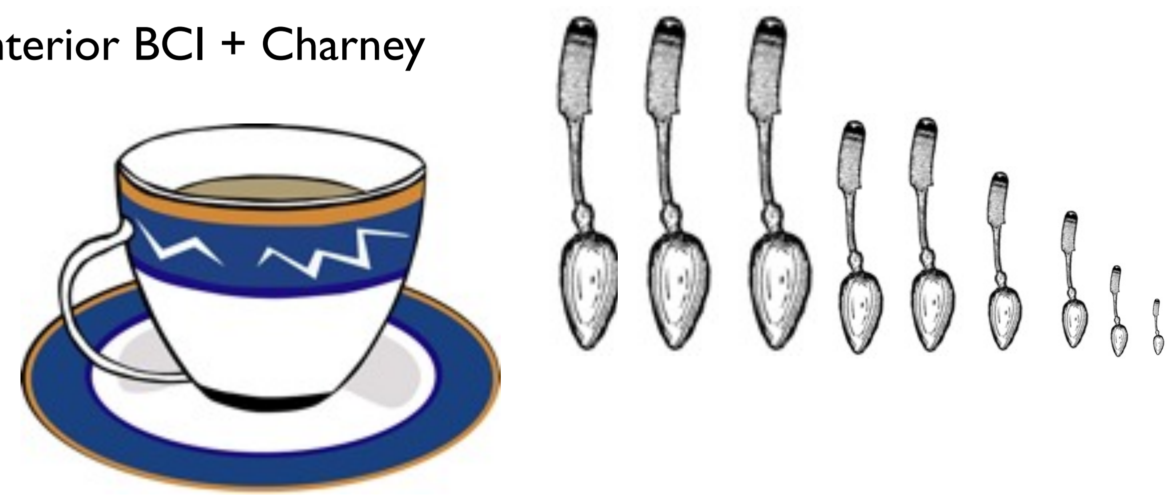
Conclusion

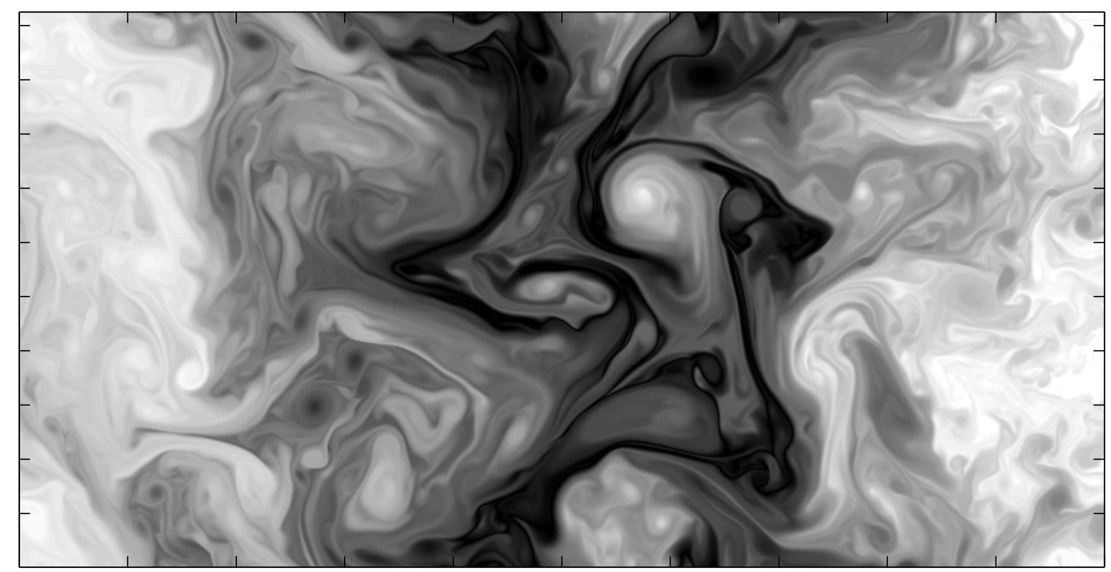
Interior BCI



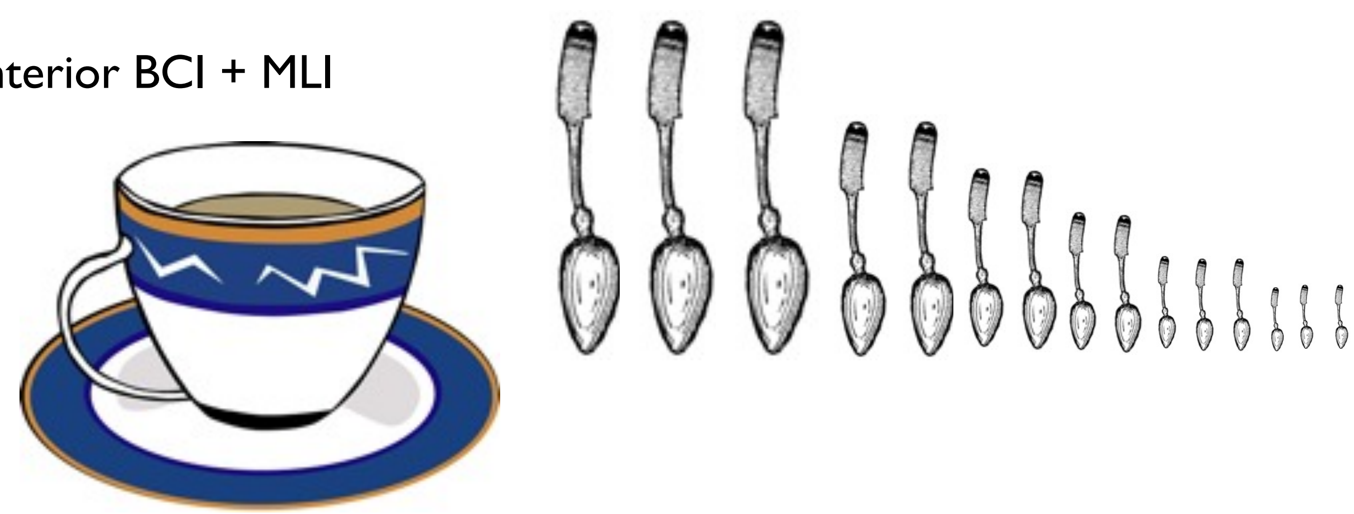


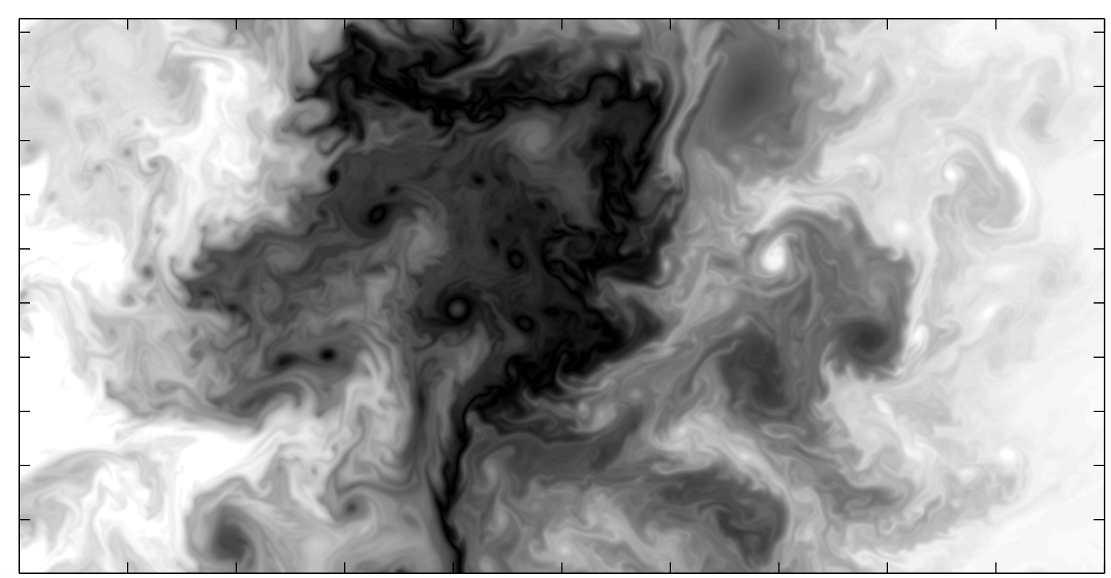
Interior BCI + Charney





Interior BCI + MLI





Conclusion

- Intense lateral density gradients are no guarantee for large vertical fluxes of tracers (and neither is resolution increase in numerical models)

- Subsurface stratification is a key parameter controlling these fluxes. One important way it does so is by controlling the existence and intensity of small scale instability modes (eg, Charney).

- Mode water regions are good candidates for Charney type instability and thus for effective connections between the subsurface and near surface

- MLE (FK08) are only one aspect of the dynamics not resolved in mesoscale-resolving numerical models. → what do we do with other aspects ?

- To be resolved: interactions between submesoscale turbulence and more complex/finer scale environmental processes (Langmuir cells, wind forcing ...)

Position of the problem

Difficulty in estimating the role played by submesoscale turbulence in fluxing tracers between the surface layer (typically the mixed layer) and the interior (typically below the nutricline):

- Fluxes are strongly sensitive to the tracer sink and source functions
- Eulerian w are not very informative and often misleading (Lagrangian quantity)
- Fluxes can be very large within the mixed layer but they generally decrease rapidly below its base (→ML instability)

We have become accustomed to the fact that submesoscale turbulence and its accompanying near-surface vertical tracer fluxes are highly sensitive to near-surface stratification (i.e. ML depth): MLI intensity scales as h_{bl}^2

(Fox-Kemper et al, 2008)