Boluder
February 27, 2008

Geostrophic Turbulence in the Ocean Mixed Layer

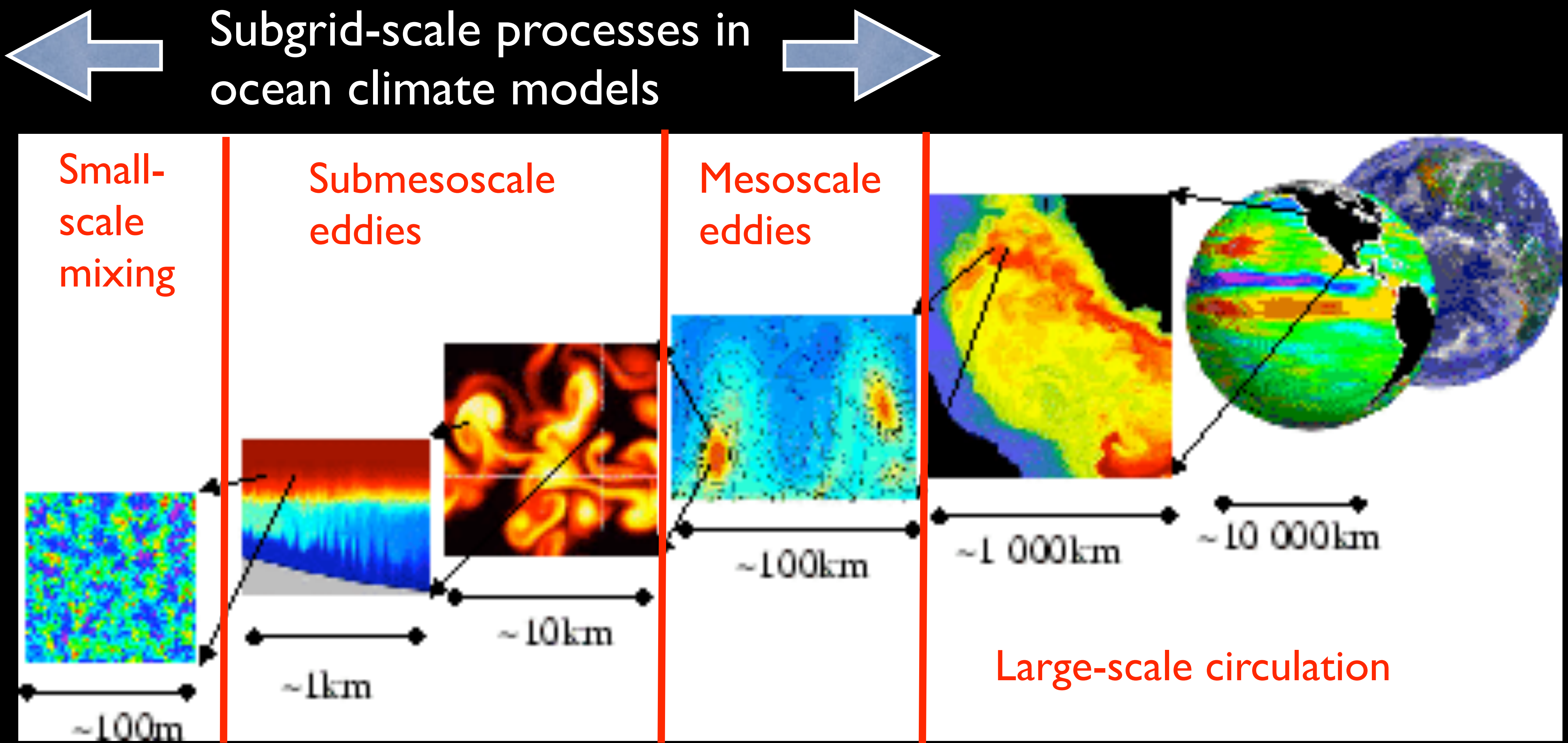
Raffaele Ferrari
EAPS

Collaborators:
Baylor Fox-Kemper, Glenn Flierl,
and the CPT-EMILIE team

Climate Process Team on Eddy-MIxed Layer IntEractions

The goal of the CPT-EMILIE is develop parameterizations of unresolved processes for models of the ocean mixed layer, a region key for coupled climate models

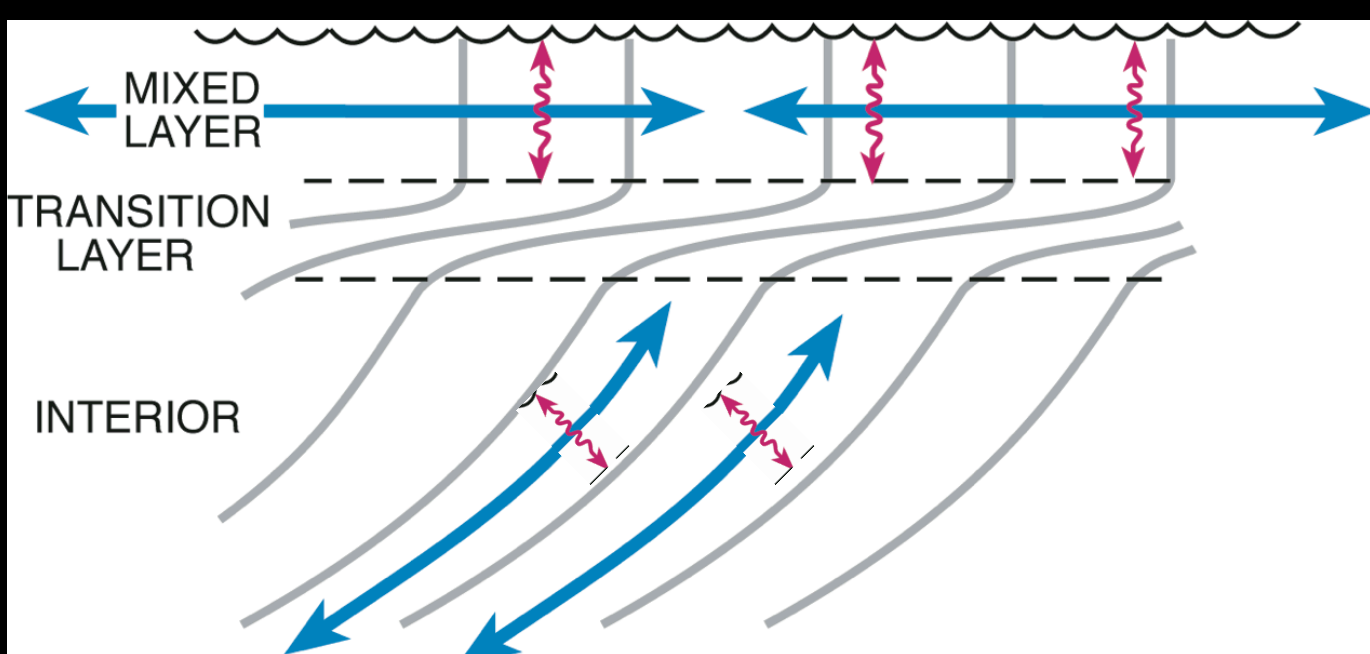
- mesoscale turbulence (10 km - 100 km)
- submesoscale turbulence (100 m - 10 km)
- small-scale turbulent mixing (10 cm - 100 m)

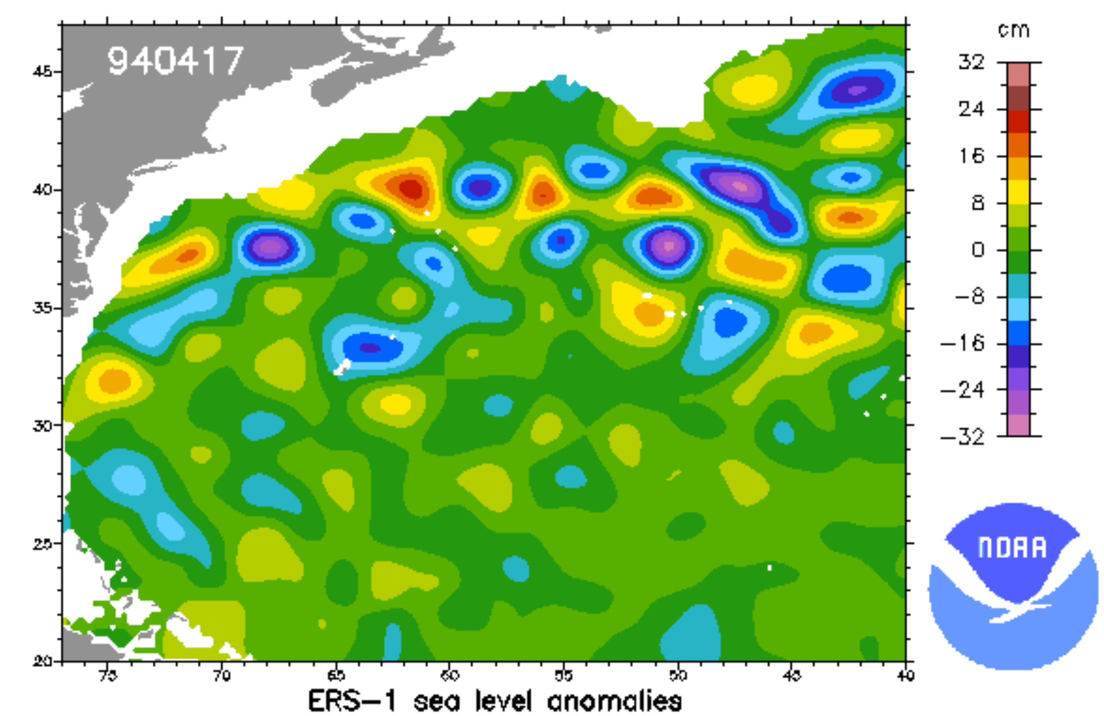


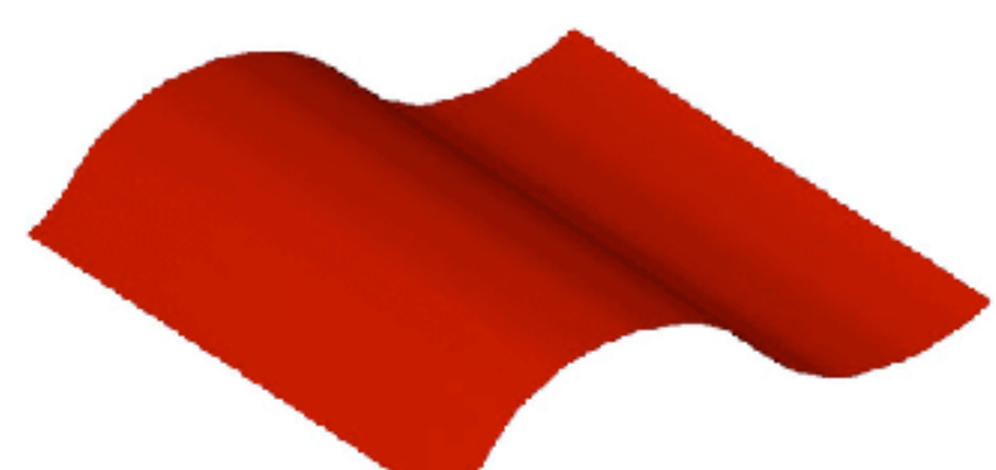
Interior ocean turbulence

- Traditional paradigm of ocean turbulence
  - mesoscale eddies dominate along-isopycnal transport
  - submesoscale eddies are subdominant
  - small-scale mixing dominates cross-isopycnal transport

$$\bar{b}_t + \bar{\boldsymbol{u}}\cdot\nabla\bar{b} \;=\; -\underbrace{\nabla_b\cdot\overline{\boldsymbol{u}_b' b'}}_{\text{mesoscale}} + \underbrace{\partial_z \kappa \bar{b}_z}_{\text{turbulent mixing}}$$



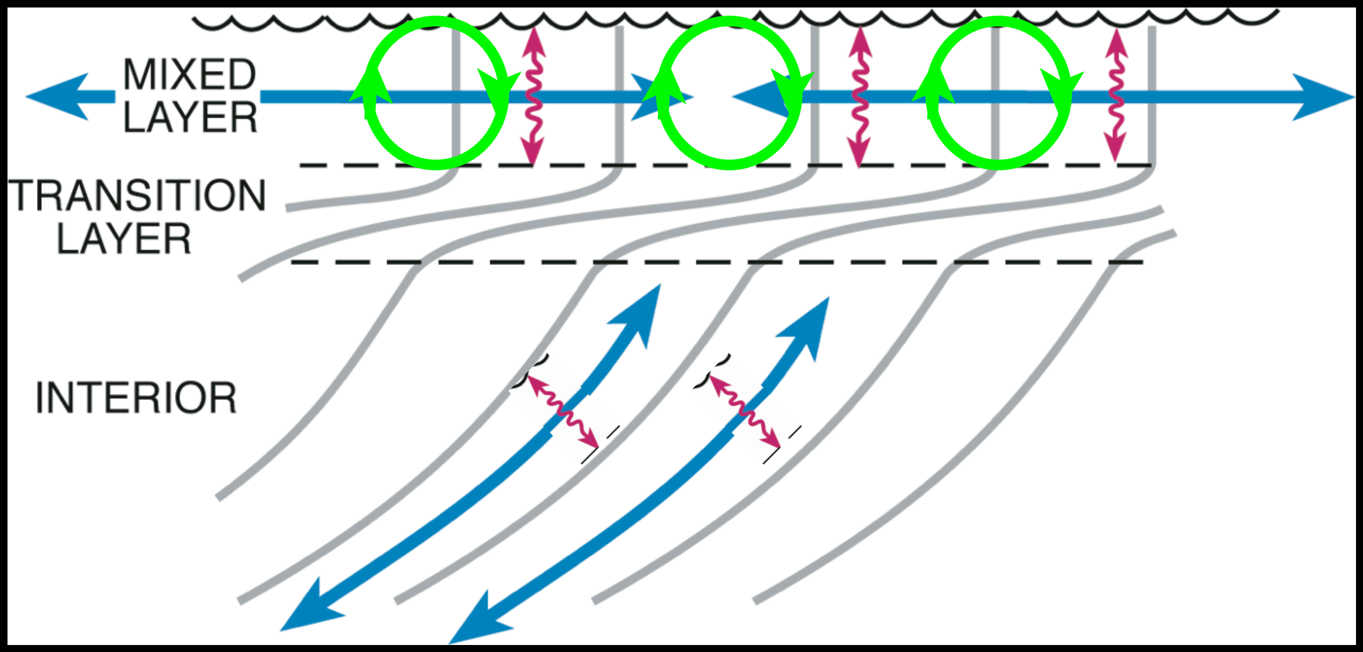


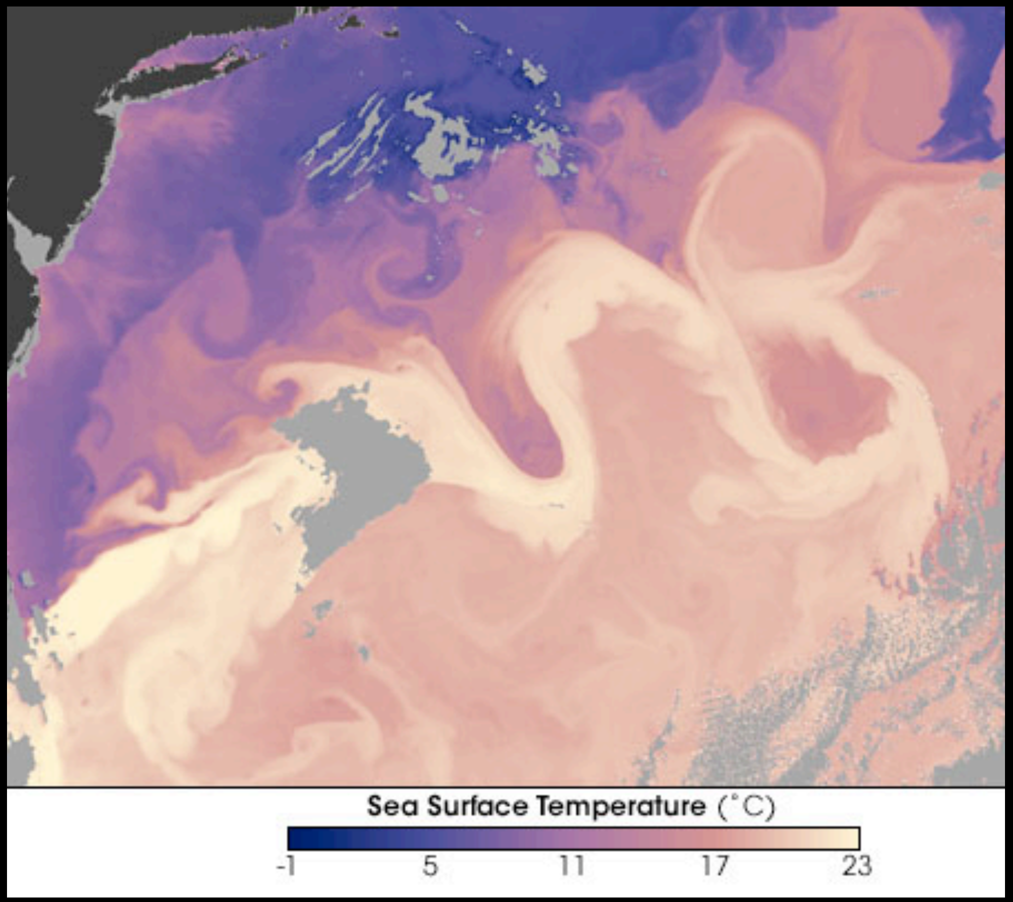


Mixed layer turbulence

- Paradigm of mixed layer turbulence
  - mesoscale eddies dominate horizontal transport
    - ➡ small Ro, large Ri and scales close to deformation radius
  - submesoscale eddies and small-scale mixing dominate vertical transport
    - ➡ large Ro and small Ri and scales close to mixed layer deformation radius

$$\bar{b}_t + \bar{\boldsymbol{u}} \cdot \nabla \bar{b} = -\underbrace{\nabla_H \cdot \overline{\boldsymbol{u}'_H b'}}_{\text{mesoscale}} - \underbrace{\partial_z \overline{w'b'}}_{\text{submesoscale}} + \underbrace{\partial_z \overline{\kappa \bar{b}_z}}_{\text{boundary layer}}$$





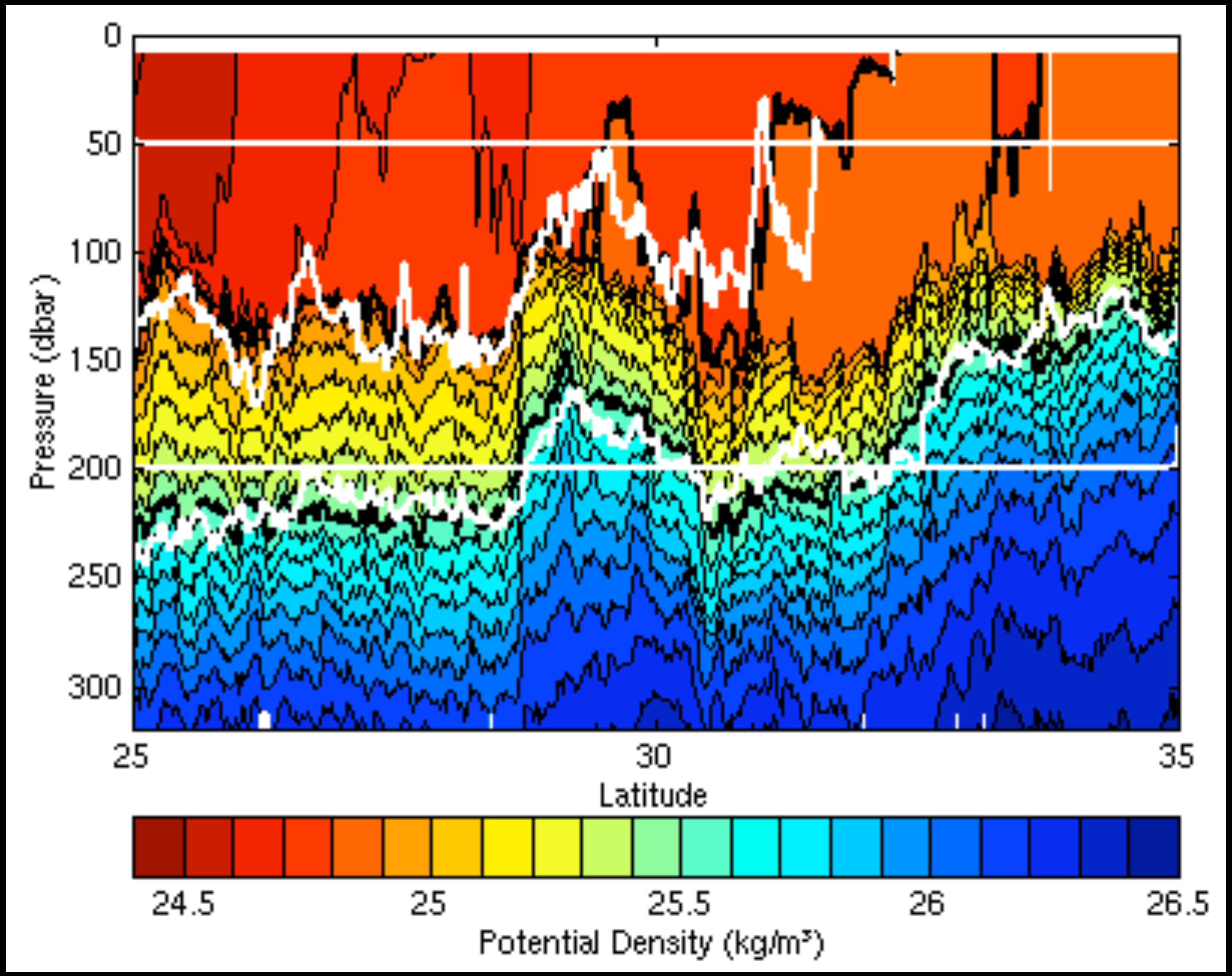
Outline of presentation

- Mesoscale and submesoscale turbulence in the mixed layer
  - effect of surface on ocean eddies
    - submesoscale frontogenesis
  - effect of weak mixed layer stratification on ocean eddies
    - submesoscale frontal instabilities

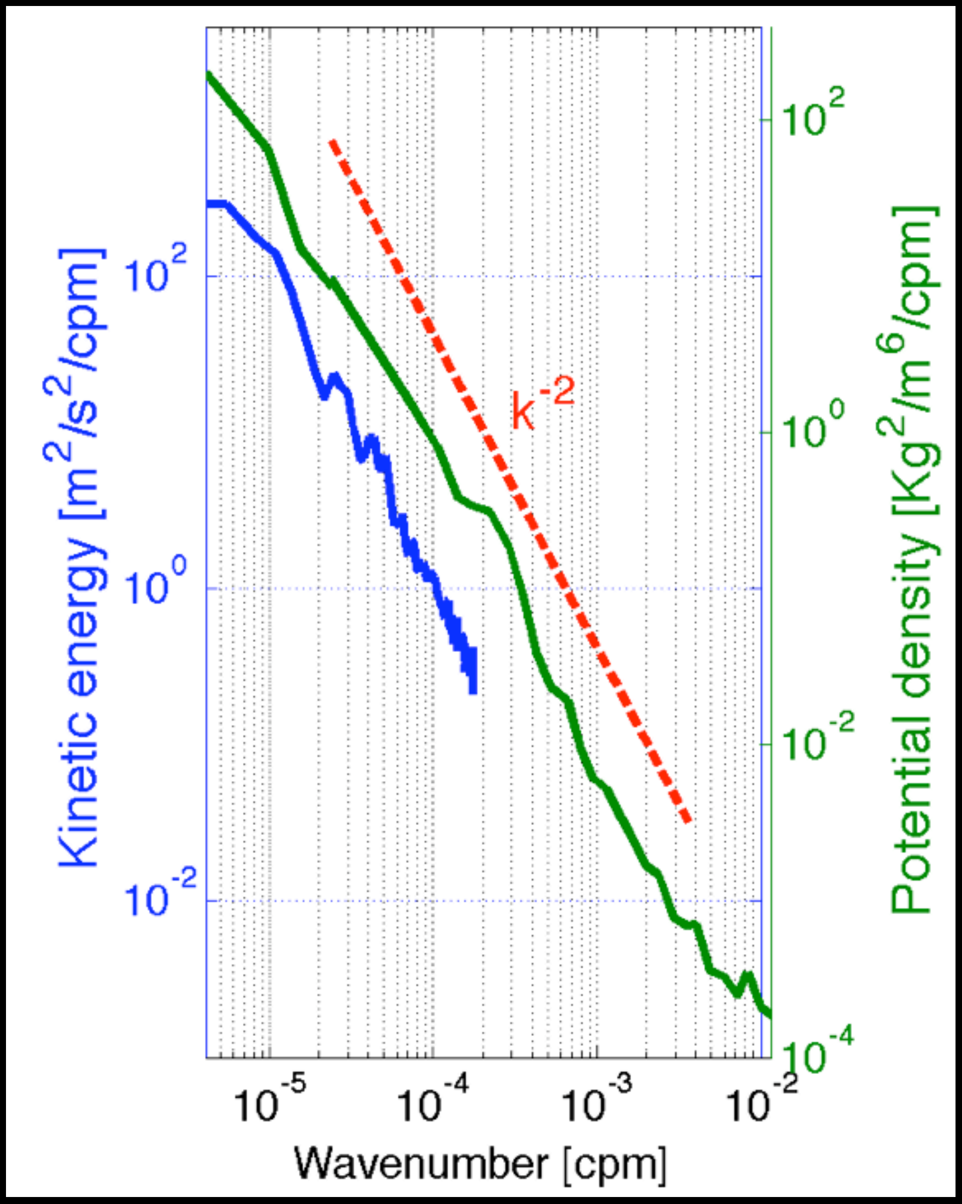
- Parameterization of submesoscale turbulence
  - scaling of vertical buoyancy fluxes

Part I. Effect of surface on mesoscale turbulence: frontogenesis

Horizontal SeaSoar section

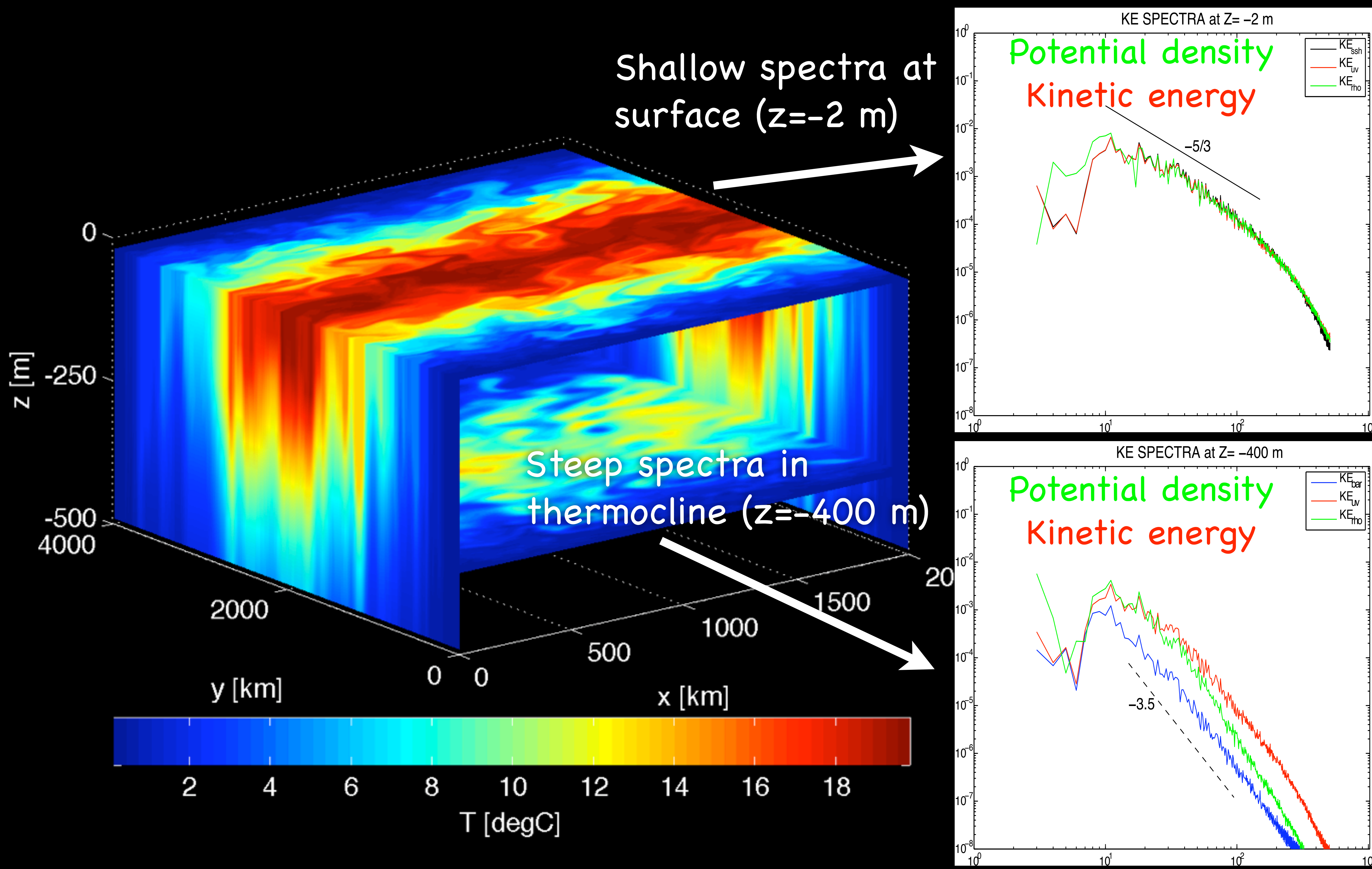


Horizontal spectra



Ferrari and Rudnick, 2000

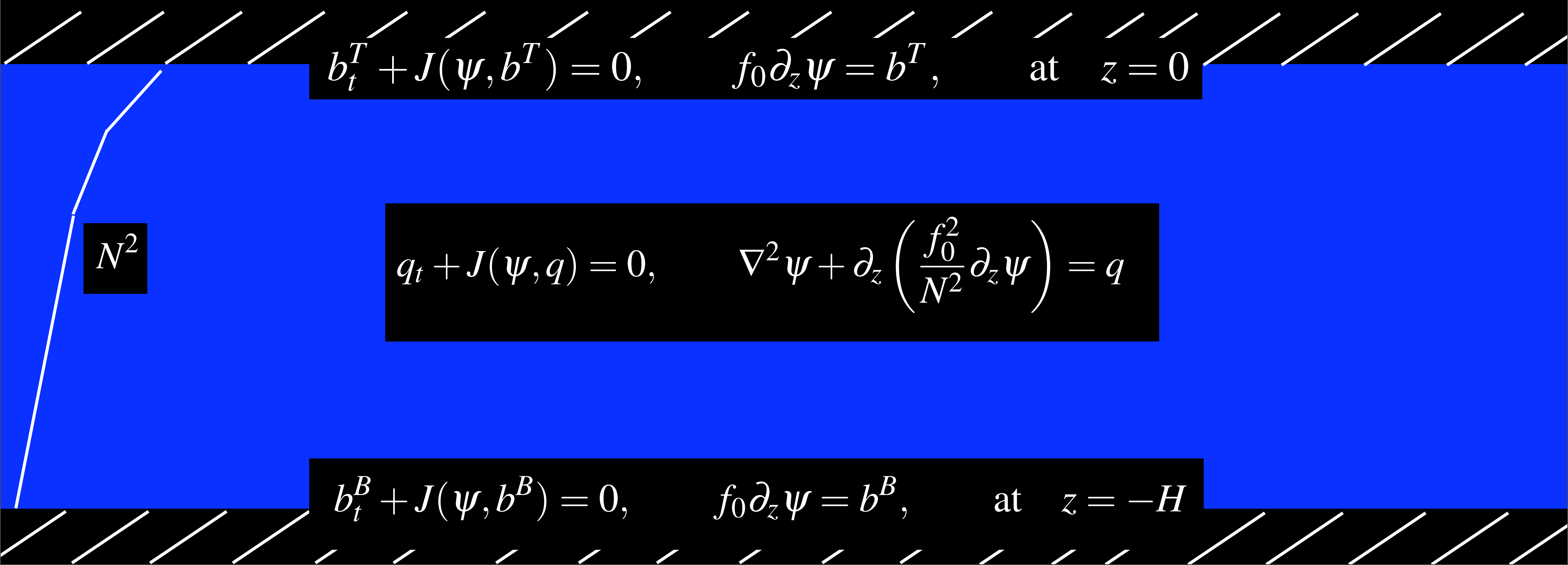
Mesoscale turbulence in the upper ocean



Klein et al., 2007

Quasi-geostrophic model of mesoscale turbulence

- Quasi-geostrophic approximation describes rotating stratified fluids with
  - small Rossby number, $Ro = \frac{U}{f_0 L} \ll 1$
  - motions with horizontal scales close to the deformation radius, $L \approx \frac{NH}{f_0}$
  - vertical stratification function of depth only, $N^2 = -\frac{g}{\rho_0}\partial_z \rho$



$$b_t^T + J(\psi, b^T) = 0, \qquad f_0 \partial_z \psi = b^T, \qquad \text{at} \quad z = 0$$

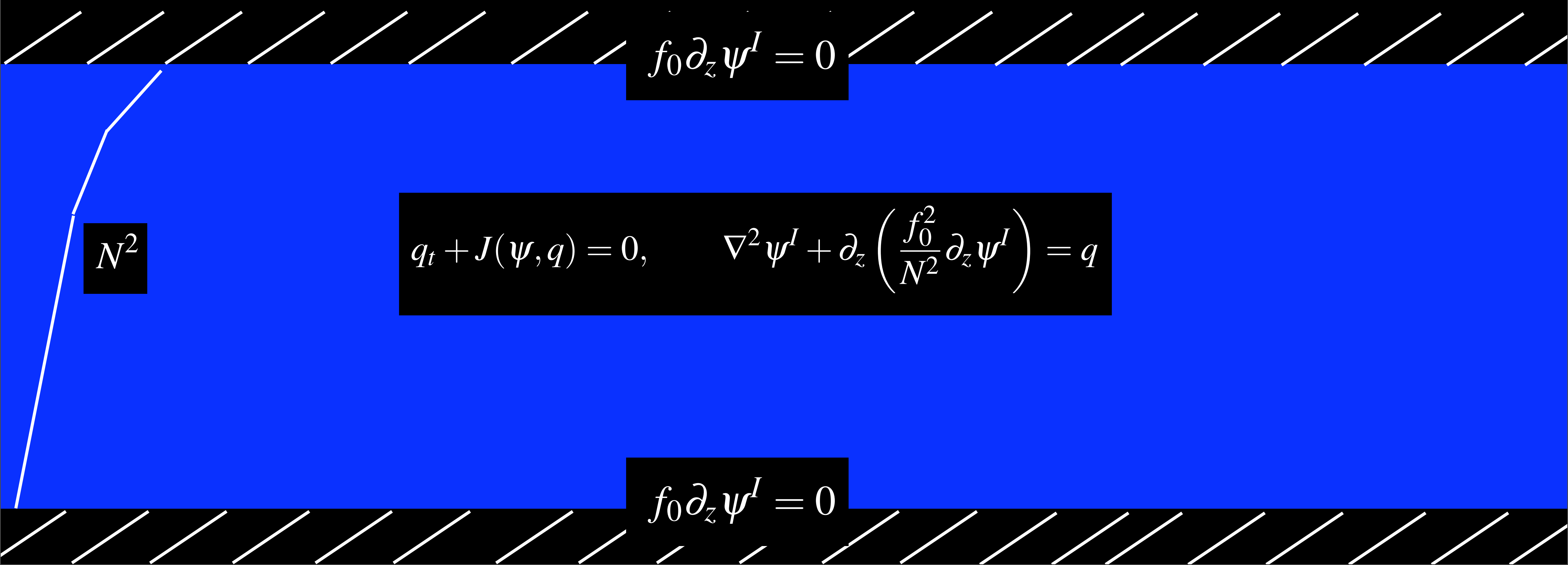
$$q_t + J(\psi, q) = 0, \qquad \nabla^2 \psi + \partial_z \left(\frac{f_0^2}{N^2} \partial_z \psi \right) = q$$

$$b_t^B + J(\psi, b^B) = 0, \qquad f_0 \partial_z \psi = b^B, \qquad \text{at} \quad z = -H$$

Separating surface from boundary dynamics

$$\psi = \psi^I + \psi^T + \psi^B$$

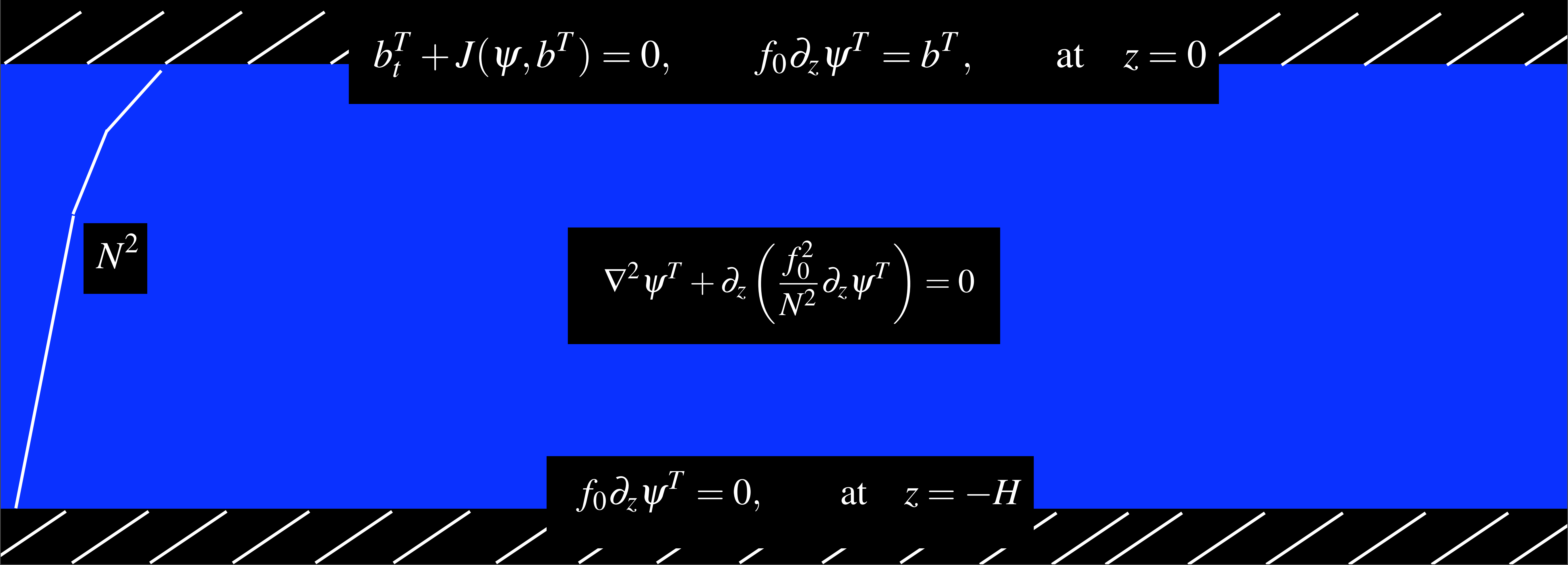
- Interior dynamics (quasi-geostrophy; Charney 1971)
- Surface dynamics (surface quasi-geostrophy; Blumen 1978)
- Bottom dynamics (surface quasi-geostrophy; Blumen 1978)



Separating surface from boundary dynamics

$$\psi = \psi^I + \psi^T + \psi^B$$

- Interior dynamics (quasi-geostrophy; Charney 1971)
- Surface dynamics (surface quasi-geostrophy; Blumen 1978)
- Bottom dynamics (surface quasi-geostrophy; Blumen 1978)



$$b_t^T + J(\psi, b^T) = 0, \qquad f_0 \partial_z \psi^T = b^T, \qquad \text{at} \quad z = 0$$

$$\nabla^2 \psi^T + \partial_z \left(\frac{f_0^2}{N^2} \partial_z \psi^T \right) = 0$$

$$f_0 \partial_z \psi^T = 0, \qquad \text{at} \quad z = -H$$

Ratio of kinetic and potential energies in the surface mixed layer

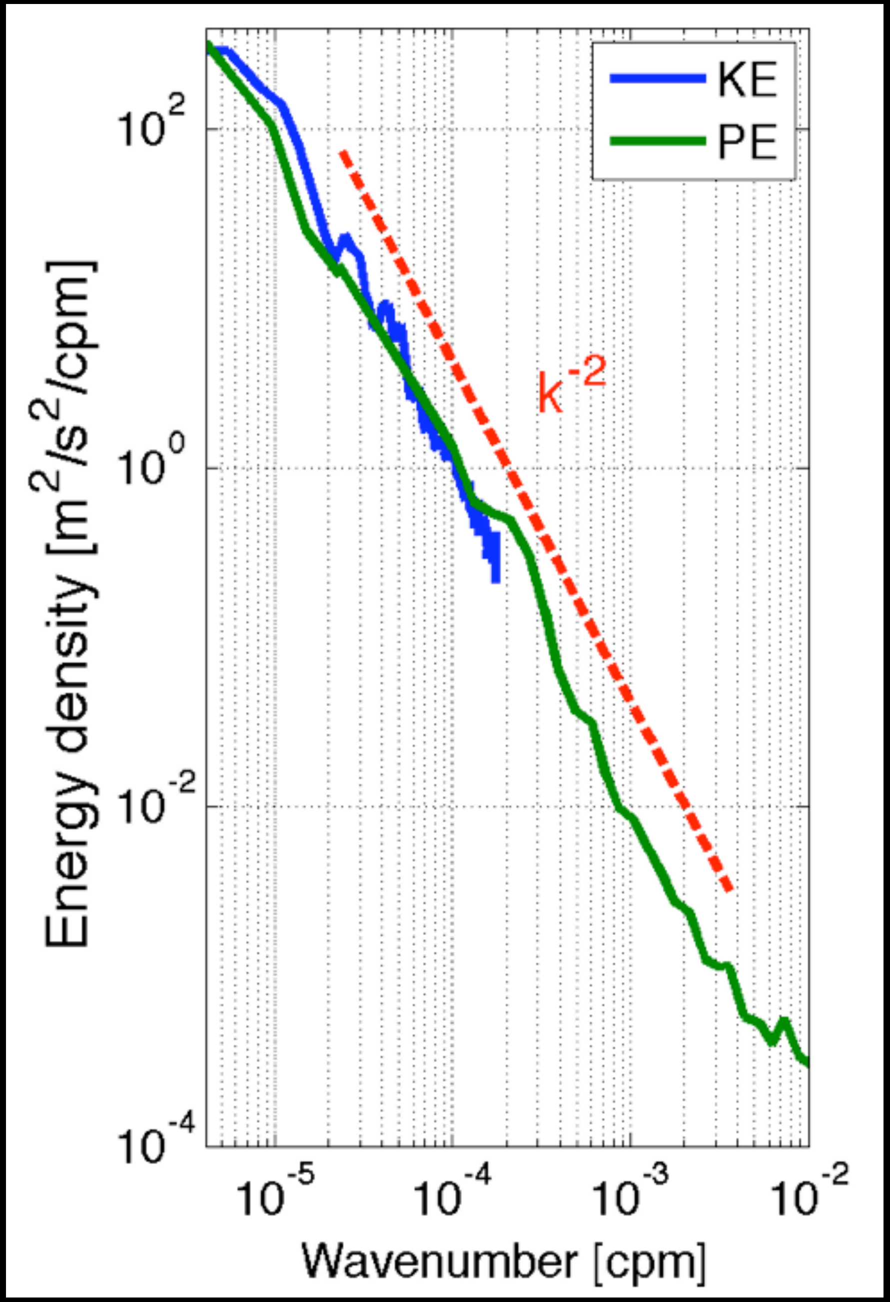
Horizontal spectra

- Surface modes (Held surface QG theory)
  - equipartition between kinetic and potential energy at all scales
  - kinetic and potential energy spectra roll off as $k^{-5/3}$

$$KE = \frac{1}{2}\langle u^2 + v^2 \rangle \sim k^{-5/3} e^{-2Nkz/f}$$

$$PE = \frac{1}{2}\langle \frac{b^2}{N^2} \rangle \sim k^{-5/3} e^{-2Nkz/f}$$

- Interior modes (Charney QG theory)
  - kinetic energy spectra roll off as k^{-3}
  - potential energy spectra roll off as k^{-5}

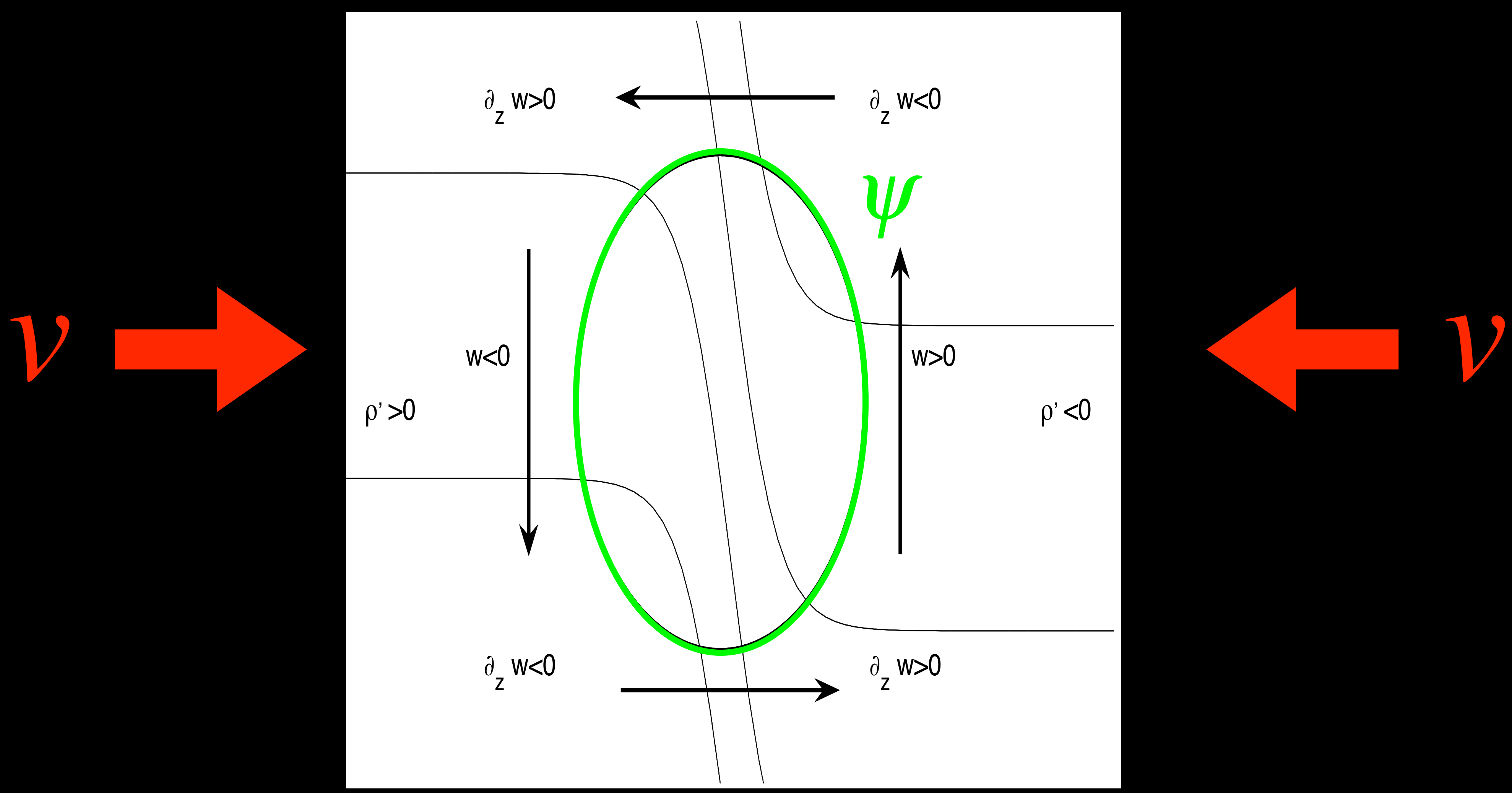


Ferrari and Rudnick, 2000

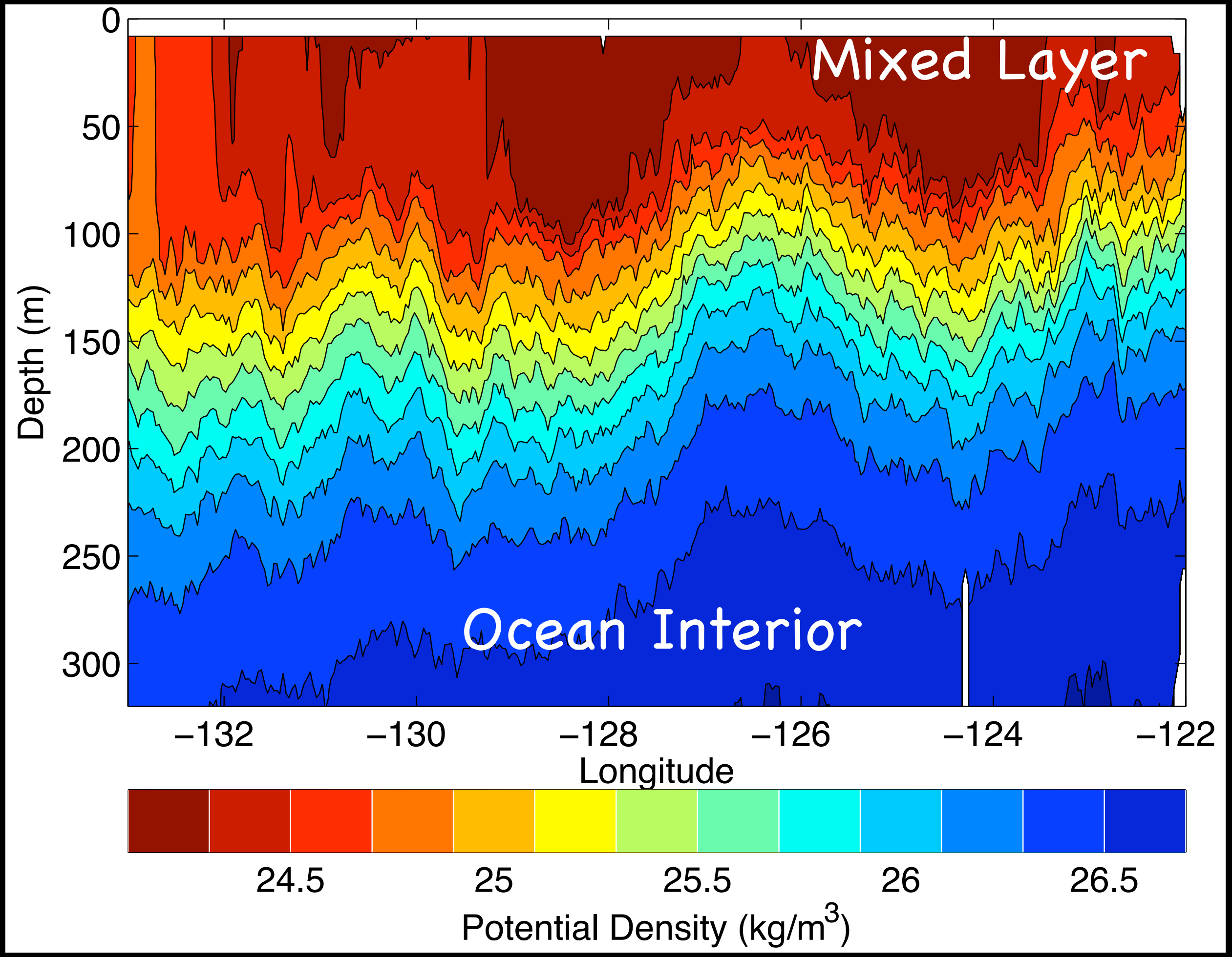
Mesoscale turbulence and surface frontogenesis

- Surface: submesoscales set rate of upwelling and restratification
- Interior: mesoscales set rate of upwelling and restratification

$$f^2 \psi_{zz} + N^2 \psi_{yy} = -2 v_y b_y$$

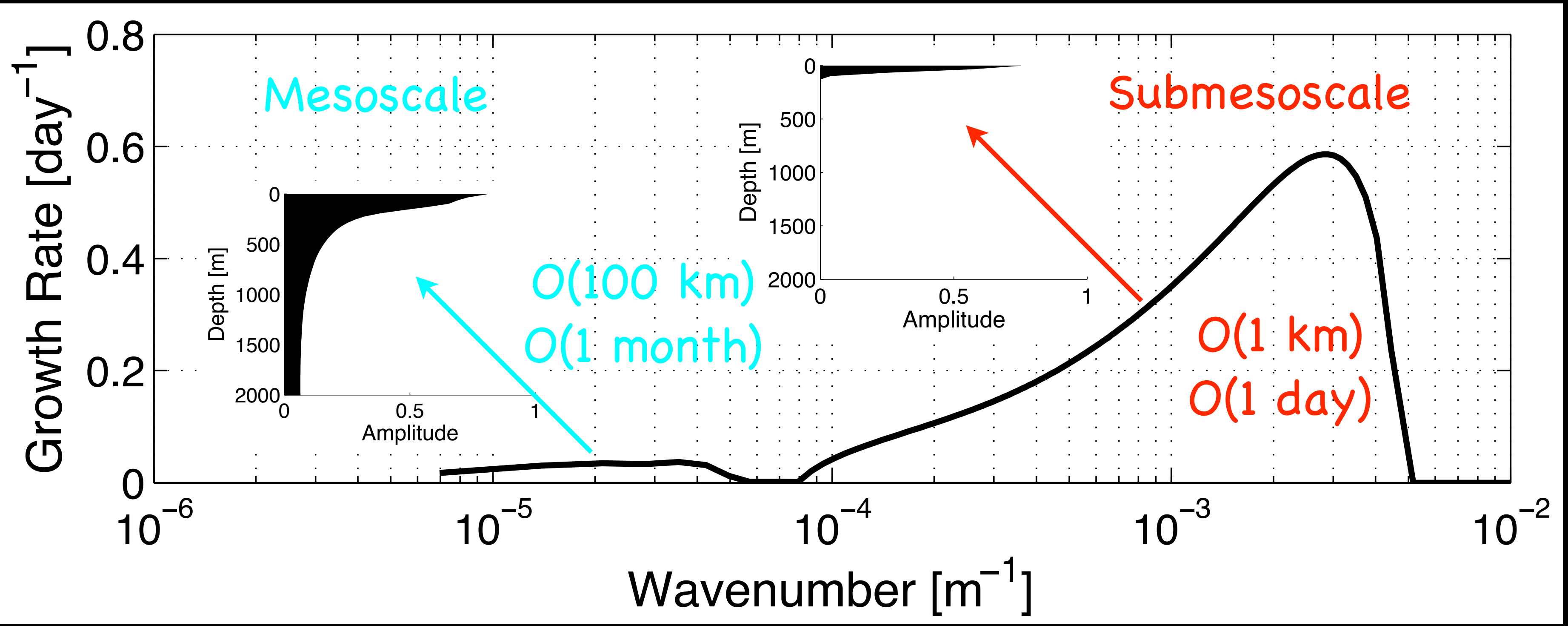


Part II. Effect of reduced stratification on mesoscale turbulence: frontal instabilities



- The mixed layer has weak vertical stratification (boundary layer mixing) and strong lateral gradients (frontogenesis)

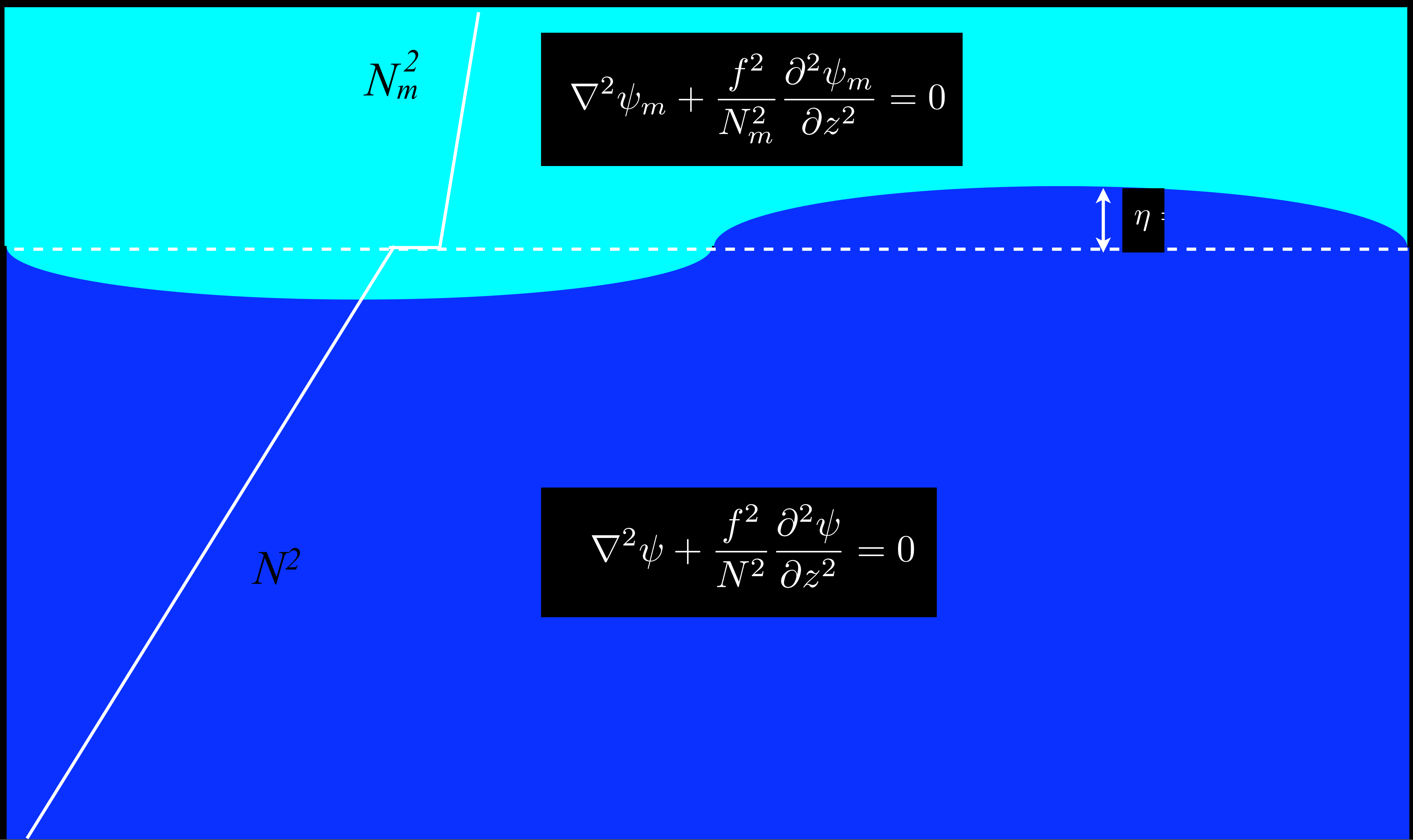
- The ocean interior is has strong vertical stratification and weak lateral gradients



- Two types of baroclinic instability

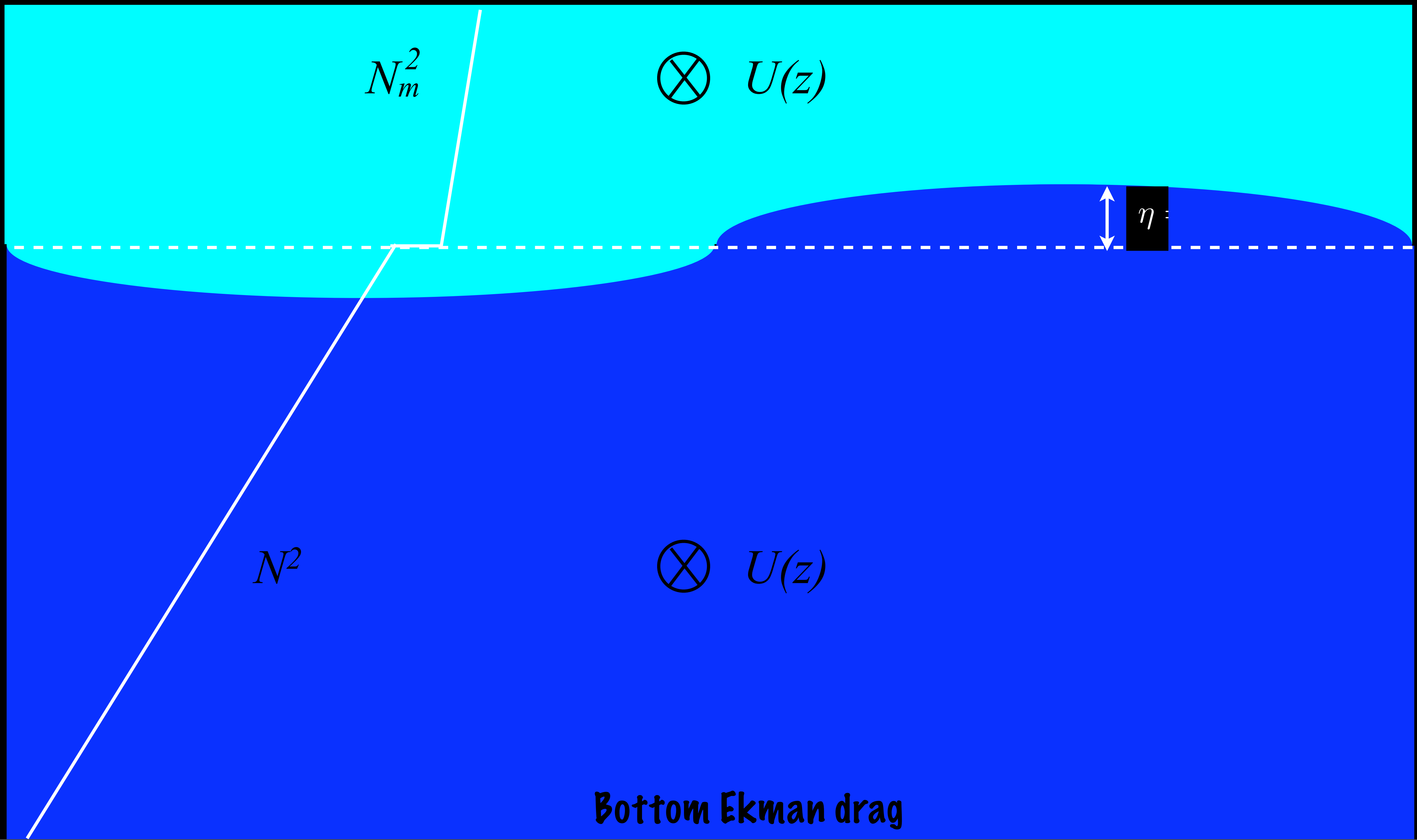
Surface quasi-geostrophic model with a mixed layer

- Two layers with uniform potential vorticity
  - upper layer with weak stratification represents mixed layer
  - lower layer with stronger stratification represents upper ocean

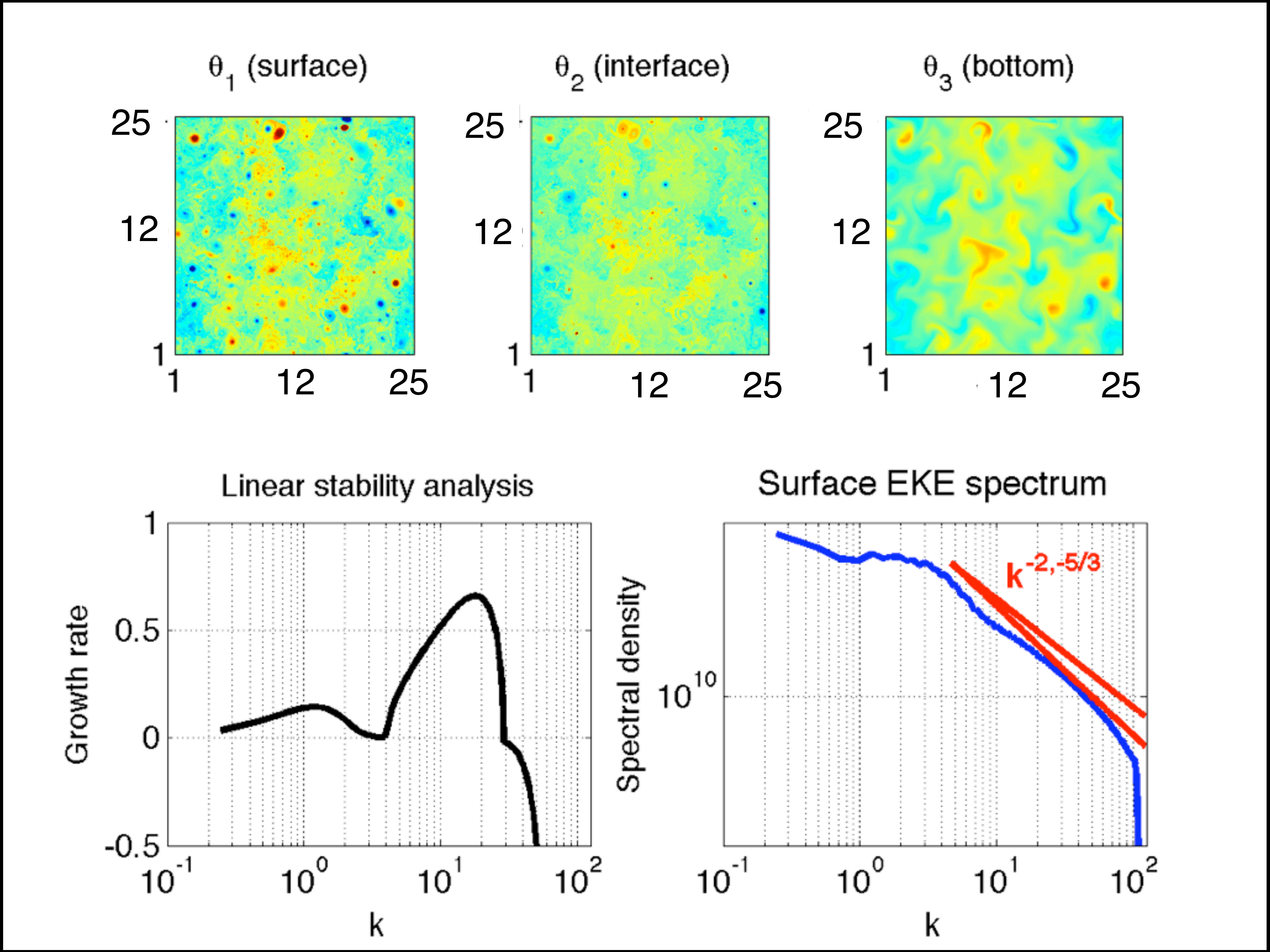


Surface quasi-geostrophic model with a mixed layer

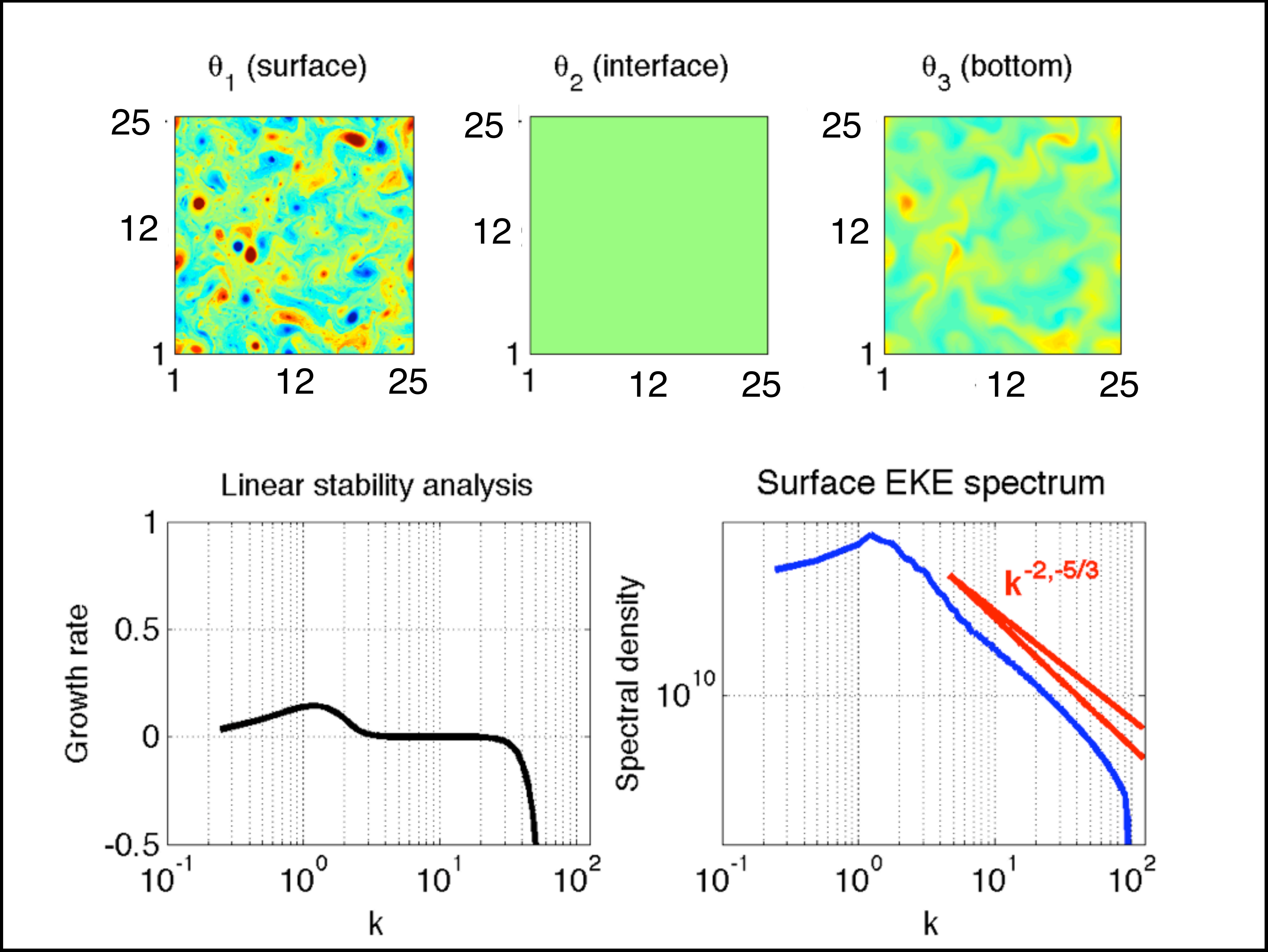
- Model configuration
  - prescribed meridional buoyancy gradients in thermal wind balance
  - linear bottom drag and hyperviscosity



Surface QG model with ML: frontogenesis and submesoscale intabilities



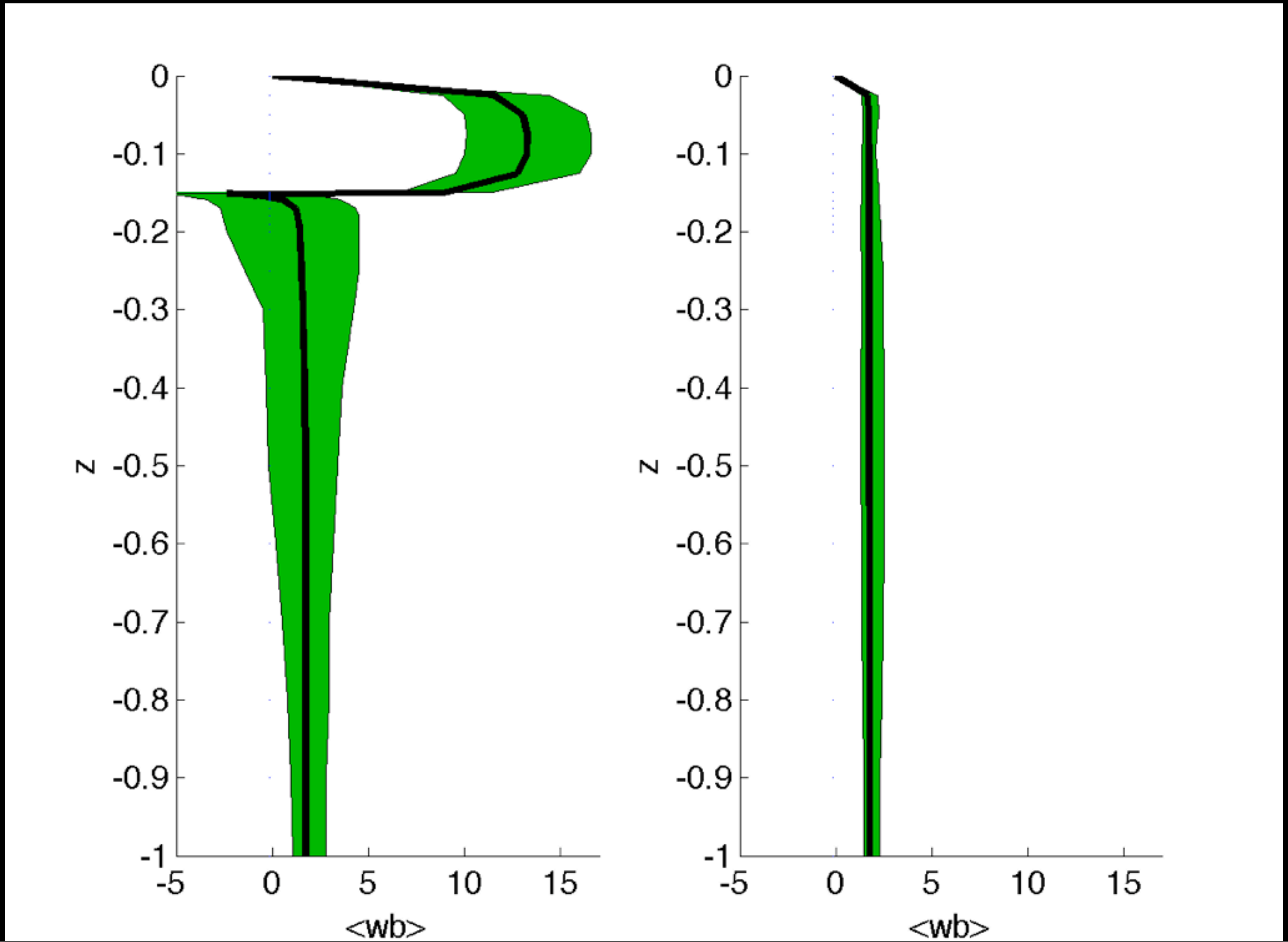
Surface QG model without ML: mesoscale frontogenesis



Vertical buoyancy flux at the ML base

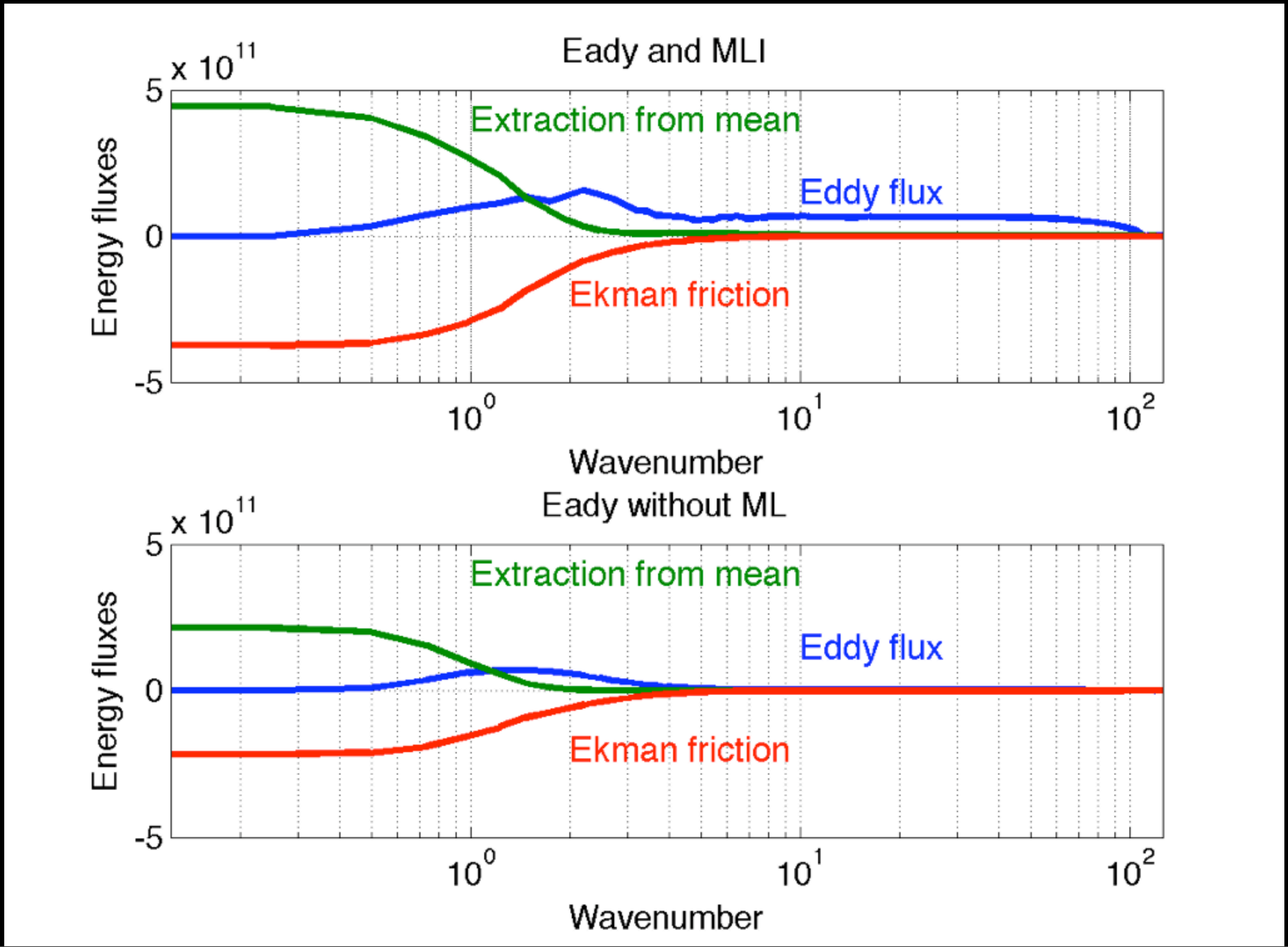
- Vertical buoyancy flux is positive => restratification
- Submesoscale instabilites at surface dominate the bouyancy flux

SQG model with ML (meso and submesoscale eddies) | SQG model without ML (mesoscale eddies)



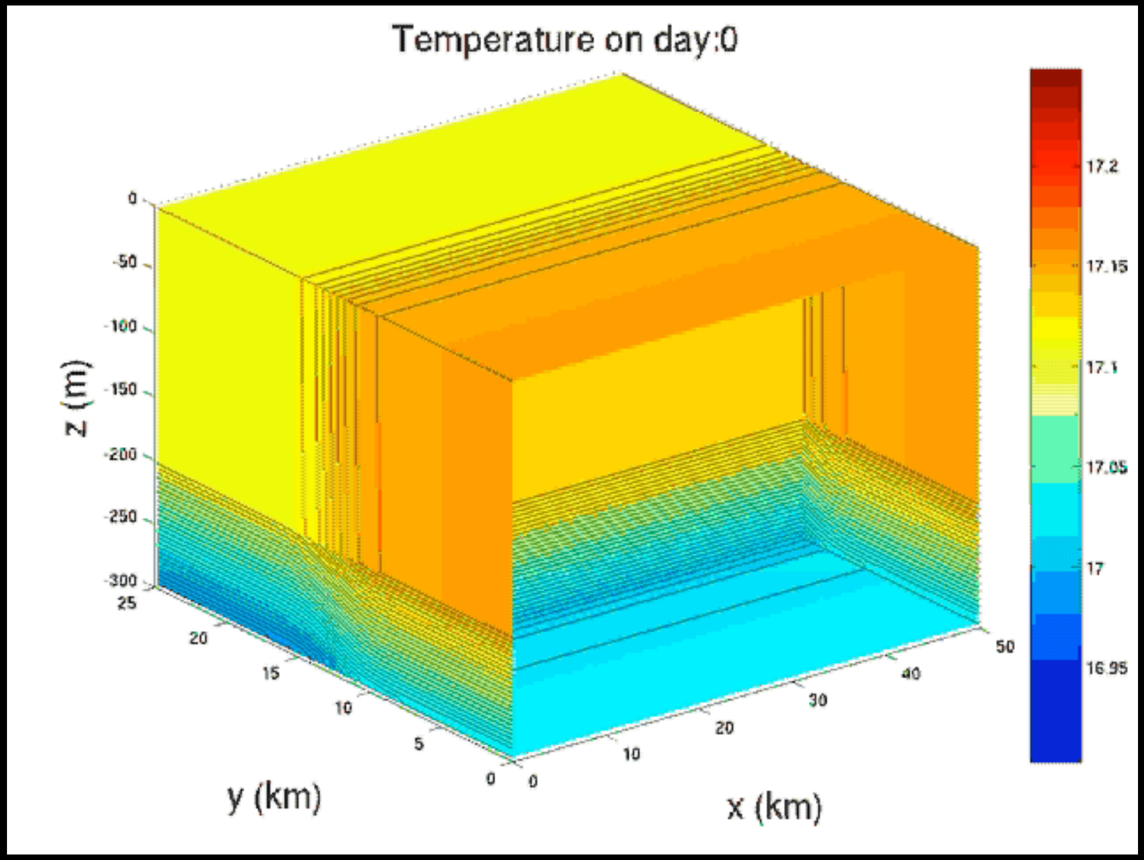
Energetics of surface QG with a ML

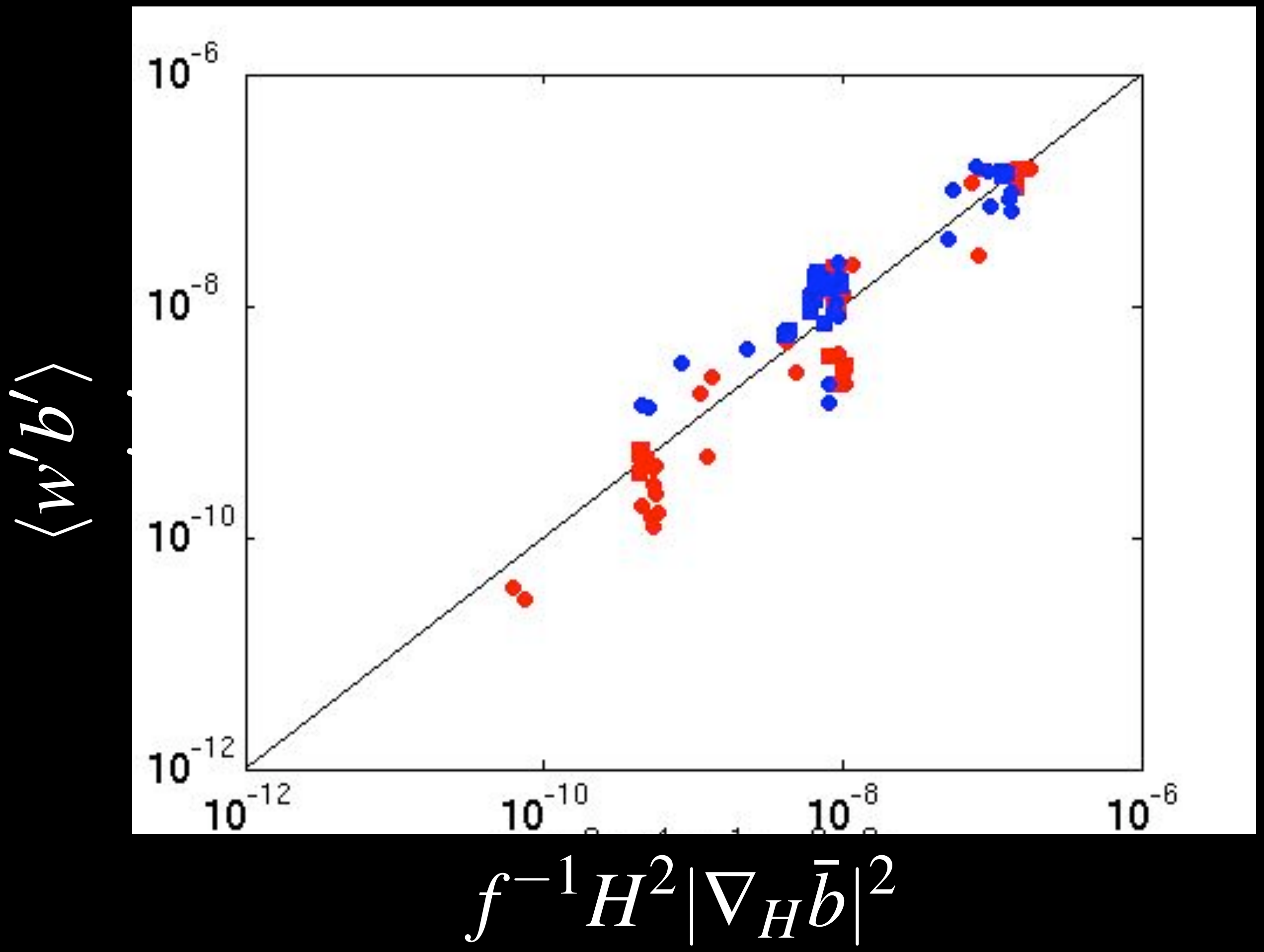
- Forward flux at the mesoscale
- Forward flux at the submesoscale only with the ML



Part III. Scaling laws for submesoscale vertical fluxes

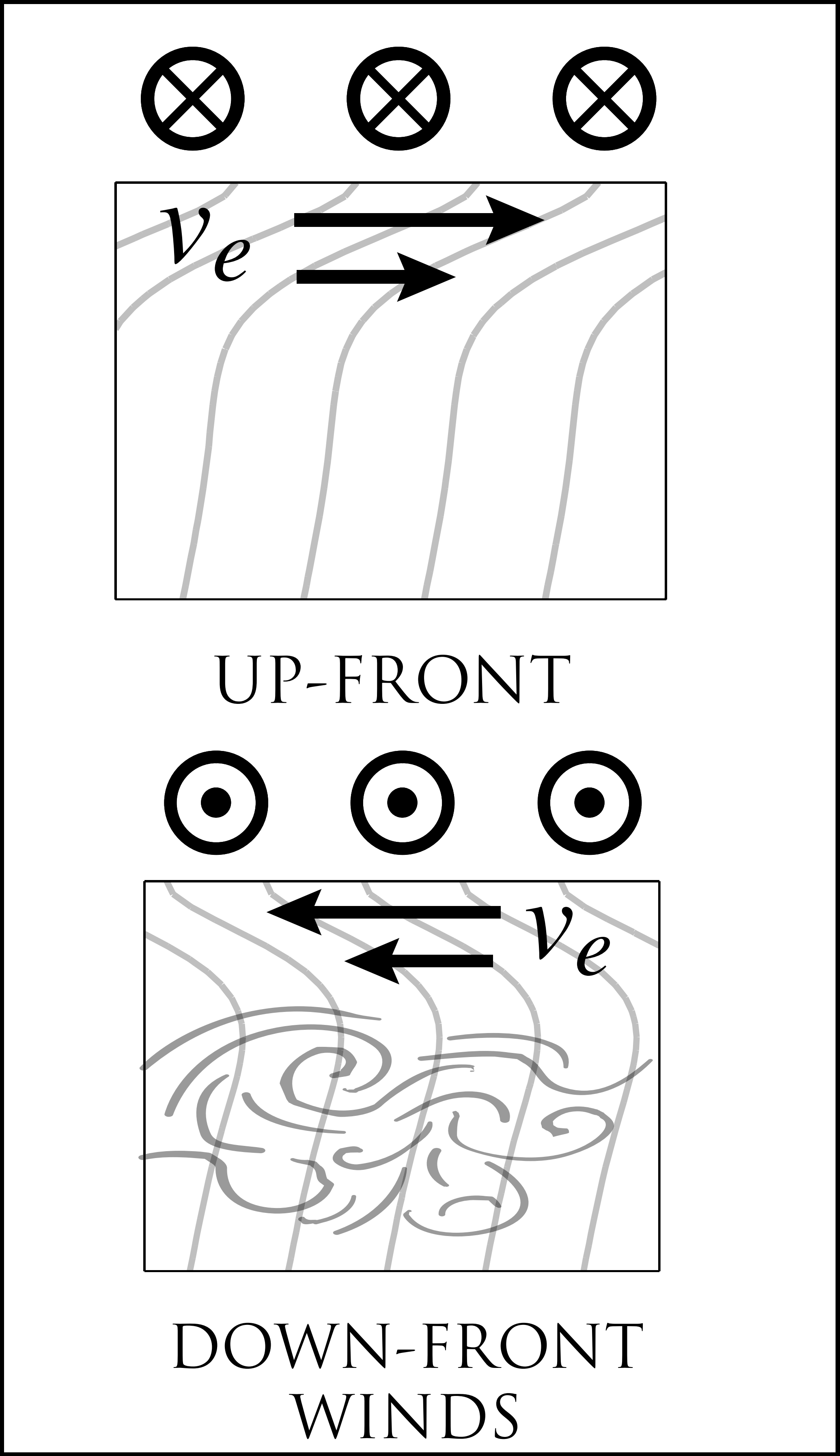
Restratification by free frontal instabilities



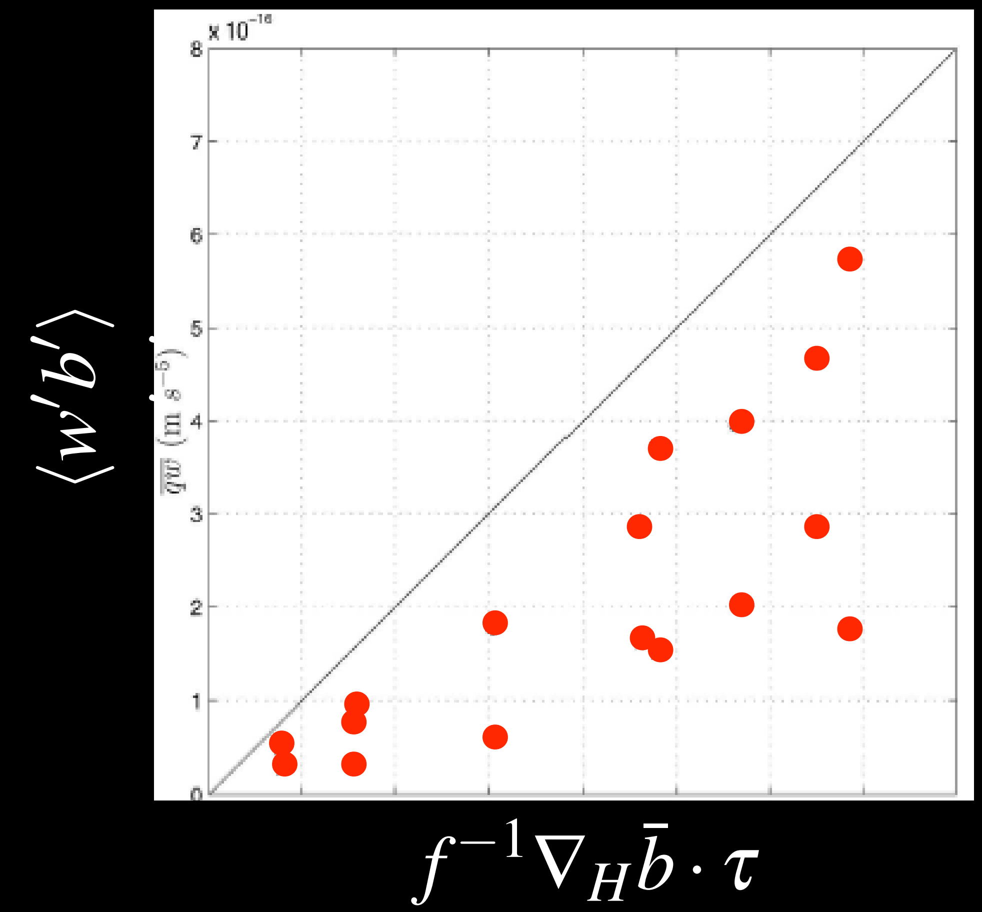


Fox-Kemper and Ferrari, 2007

Vertical buoyancy flux and wind forcing



)estratification by wind-driven frontal instabilities



Thomas and Lee, 2006

Thomas and Ferrari, 2008

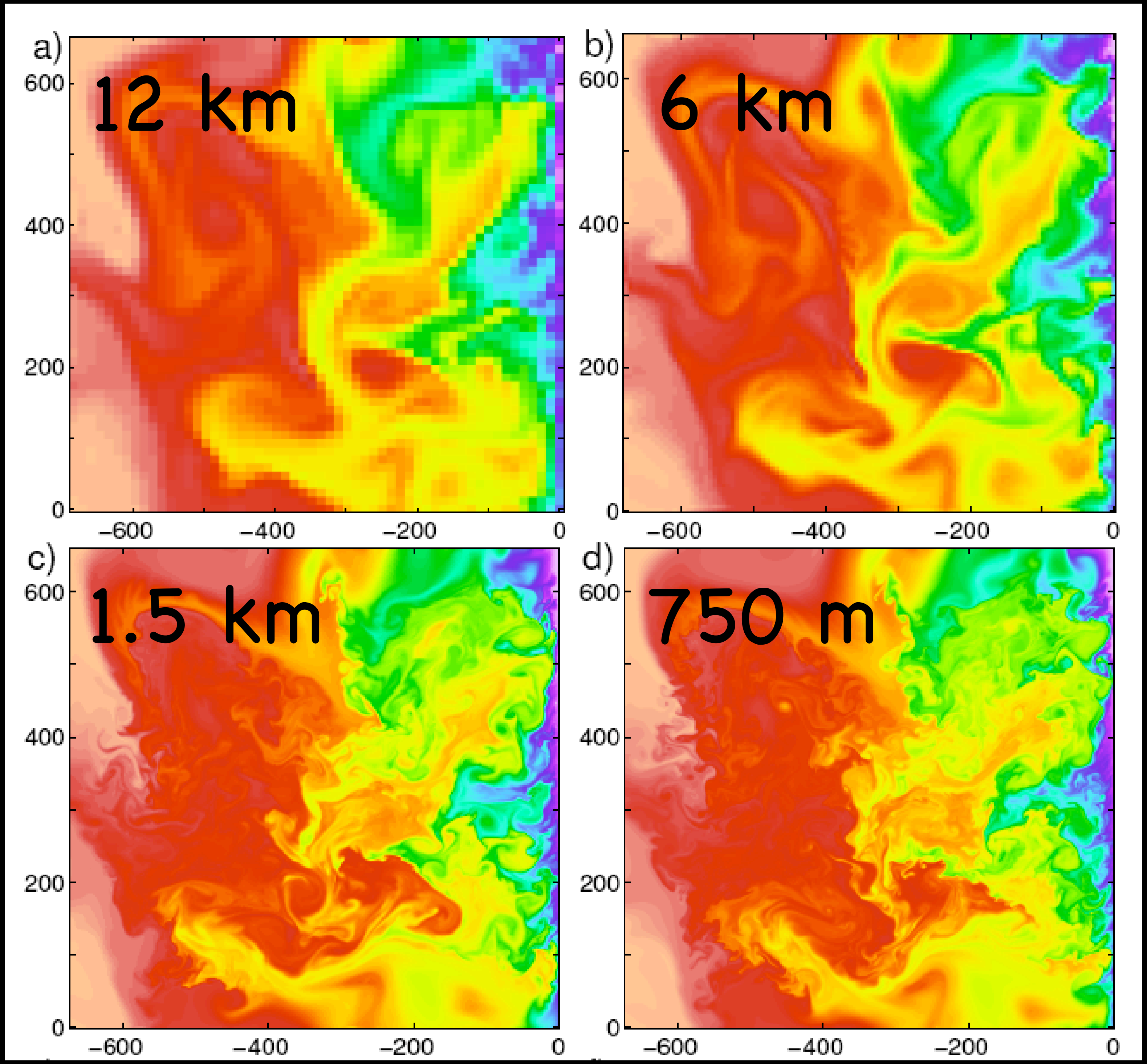
Conclusions

- Mesoscale eddies drive surface frontogenesis

- Submesoscale instabilities develop along surface fronts that
  - act to restratify the ocean surface mixed layers
  - drive strong upwelling/downwelling of tracers

- Scaling laws have been derived
  - for the combination of frontogenesis and submesoscale instabilities
  - for the effect of winds blowing over the surface fronts

Frontogenesis and frontal instabilities in the ocean mixed layer



Mesoscale straining generates ML fronts through frontogenesis.

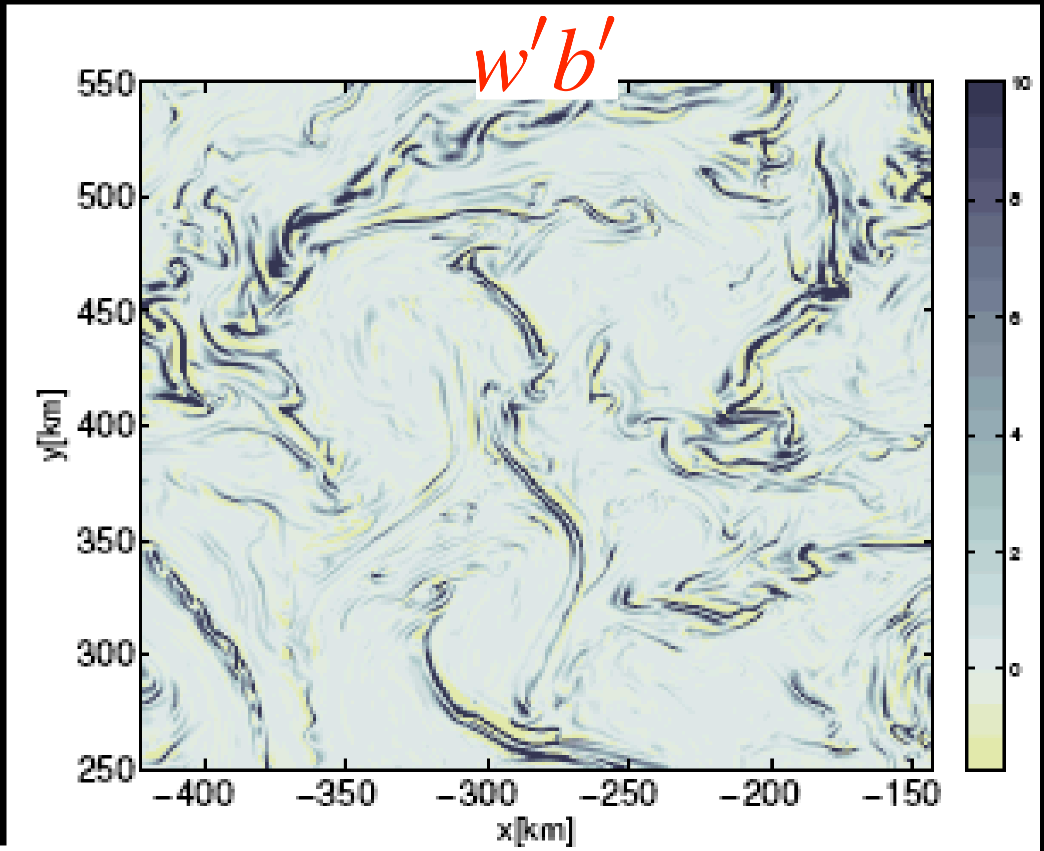
Frontal instabilties develop along ML fronts.

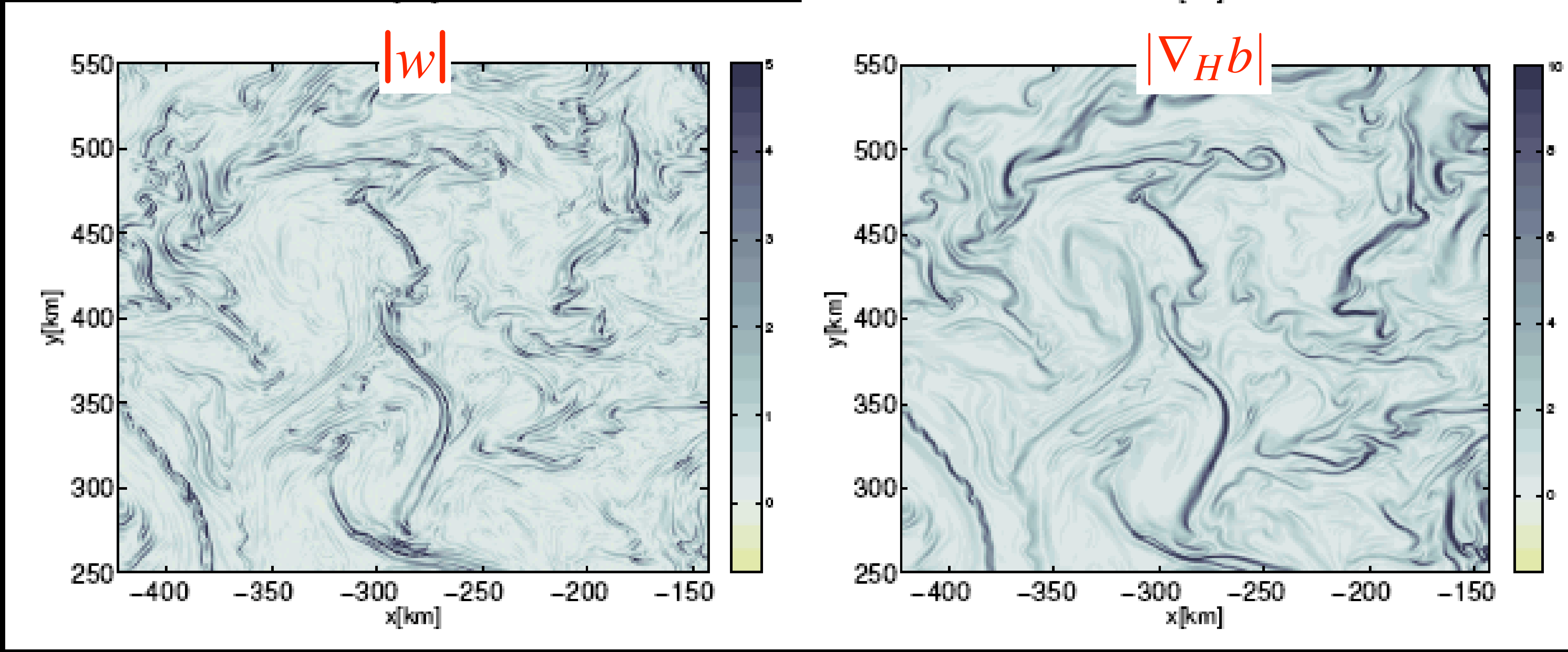
Capet et al., 2007

Submesoscale instabilities and ML restratification

Submesoscale vertical fluxes

- co-located with fronts
- mostly positive => restratification
- largest at wiggly fronts
- increase with resolution

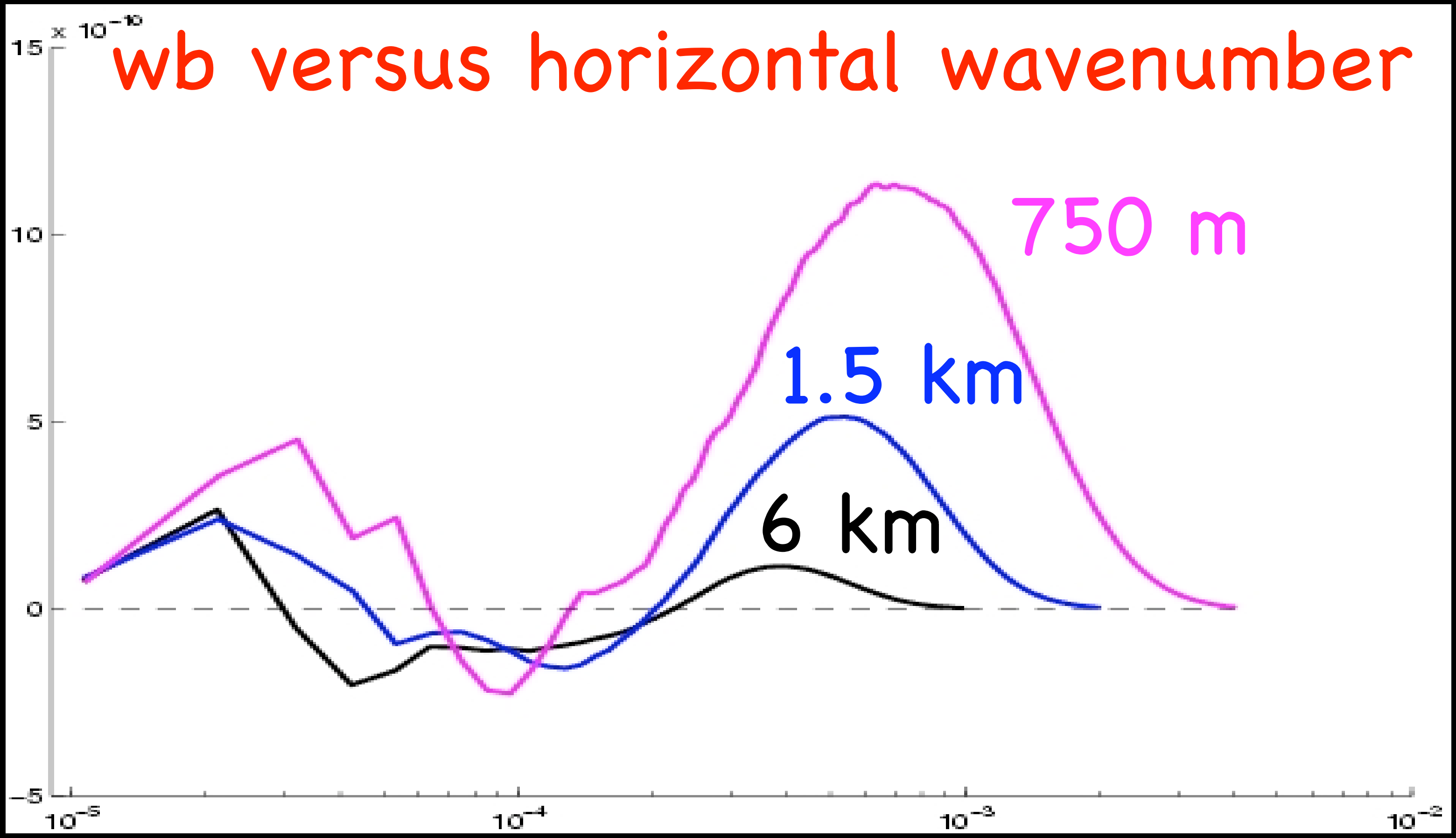




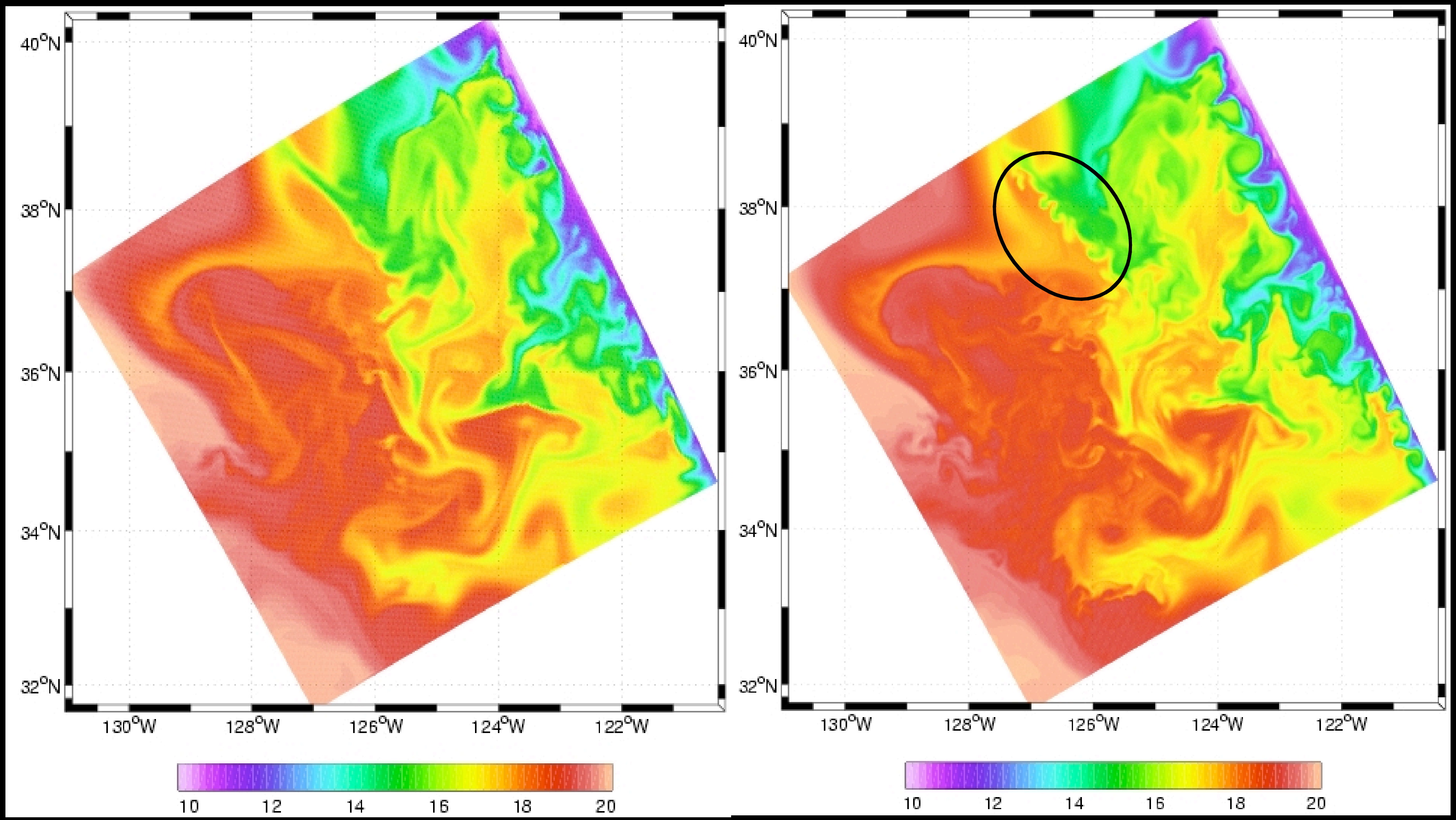
Submesoscale instabilities and ML restratification

Submesoscale vertical fluxes

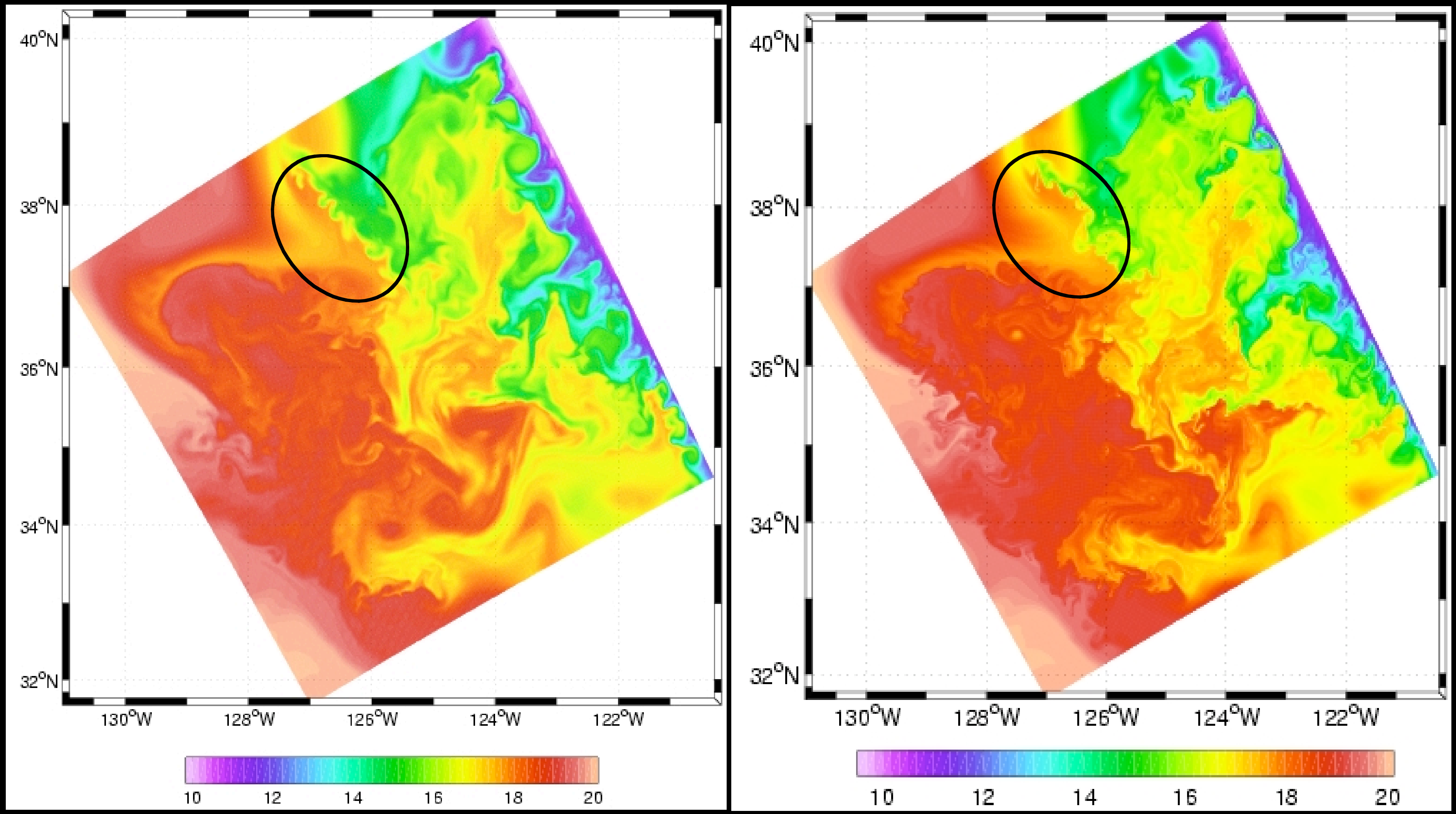
- co-located with fronts
- mostly positive => restratification
- largest at wiggly fronts
- increase with resolution



Submesoscale instabilities and ML restratification

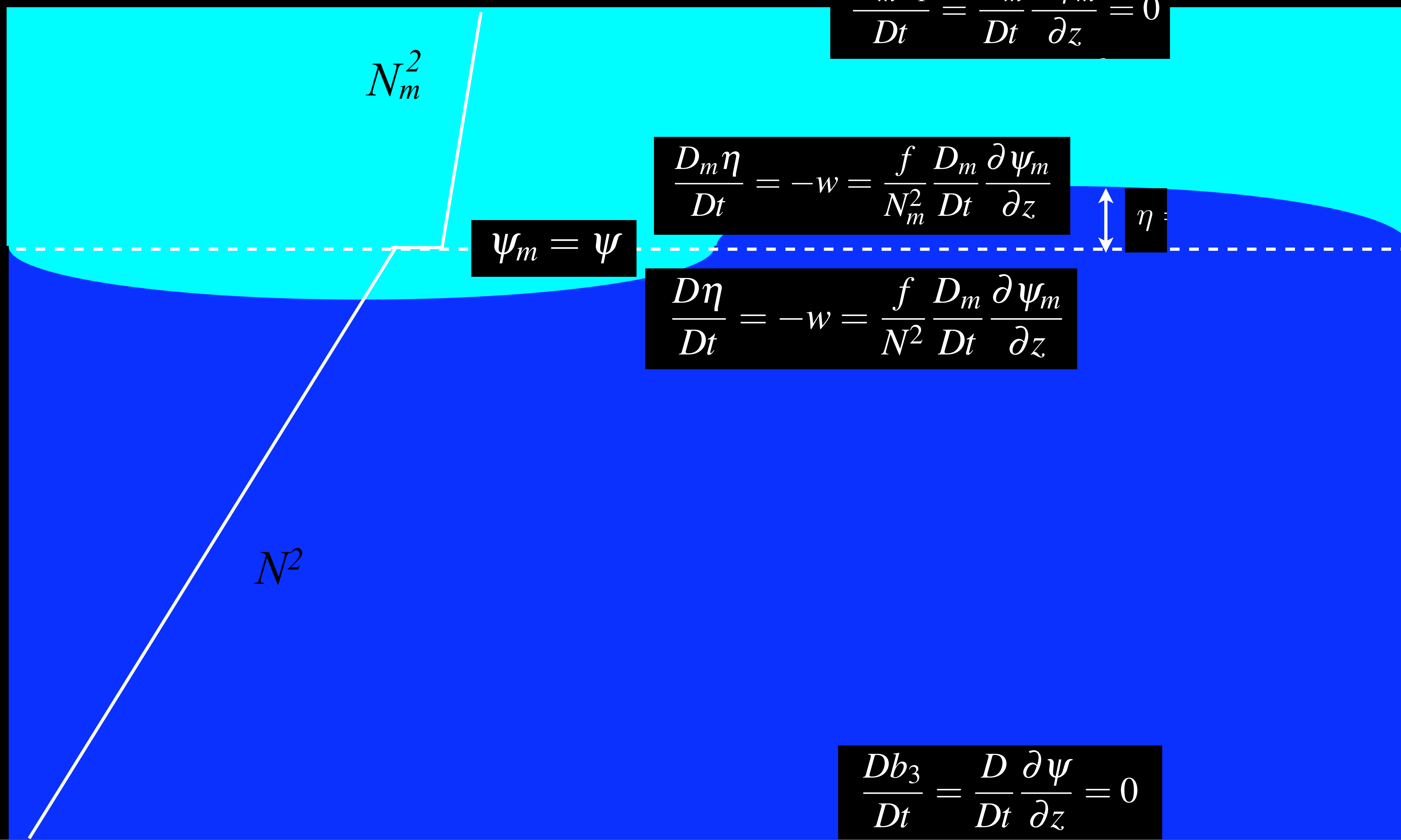


Submesoscale instabilities and ML restratification



Surface quasi-geostrophic model with a mixed layer

- Two layers with uniform potential vorticity
  - boundary condition of no vertical velocity at top and bottom
  - matching conditions at the interface



$$\frac{D_m b_1}{Dt} = \frac{D_m}{Dt}\frac{\partial \psi_m}{\partial z} = 0$$

$$\frac{D_m \eta}{Dt} = -w = \frac{f}{N_m^2}\frac{D_m}{Dt}\frac{\partial \psi_m}{\partial z}$$

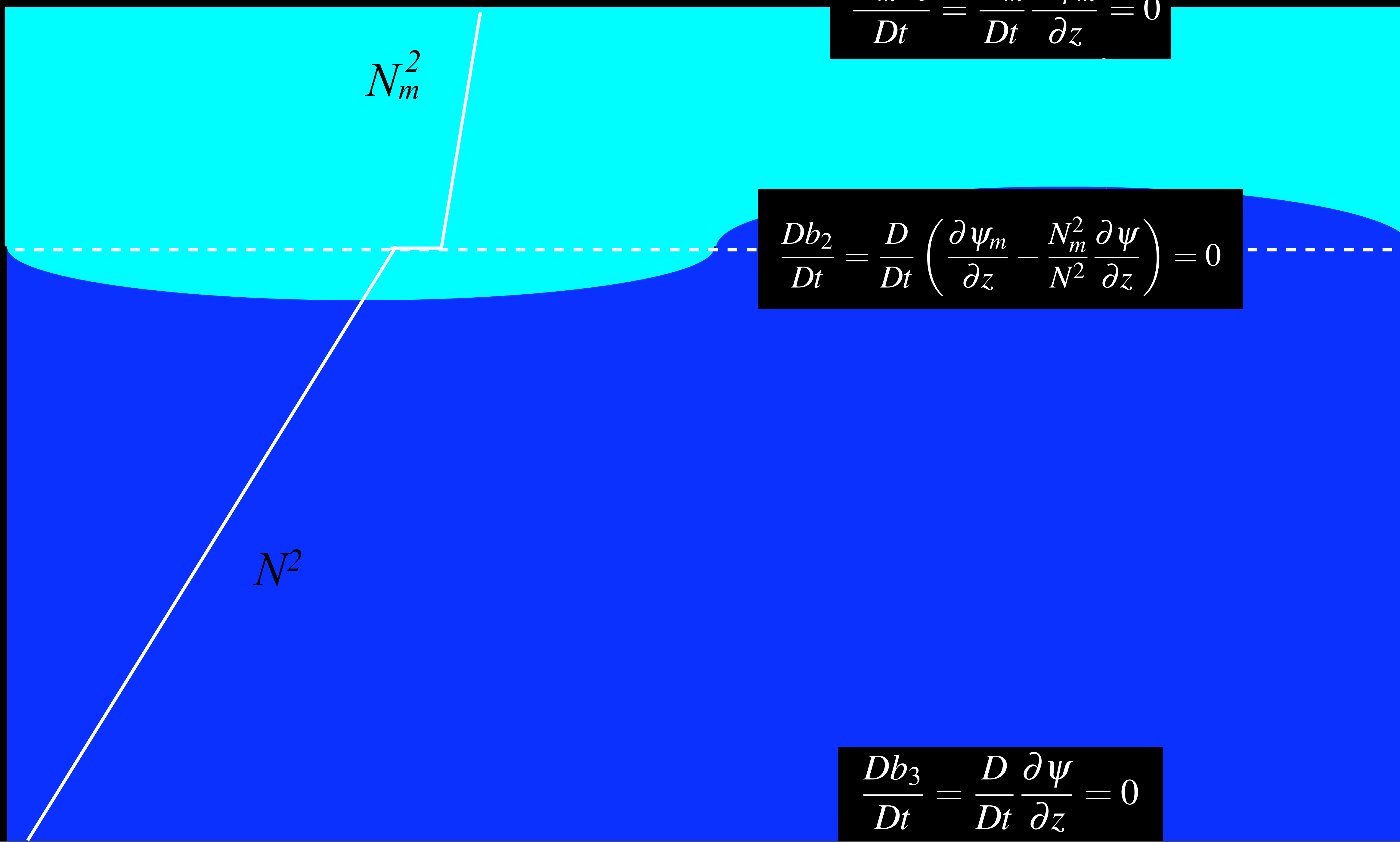
$$\psi_m = \psi$$

$$\frac{D\eta}{Dt} = -w = \frac{f}{N^2}\frac{D_m}{Dt}\frac{\partial \psi_m}{\partial z}$$

$$\frac{Db_3}{Dt} = \frac{D}{Dt}\frac{\partial \psi}{\partial z} = 0$$

Surface quasi-geostrophic model with a mixed layer

- Two layers with uniform potential vorticity
  - boundary condition of no vertical velocity at top and bottom
  - matching conditions at the interface

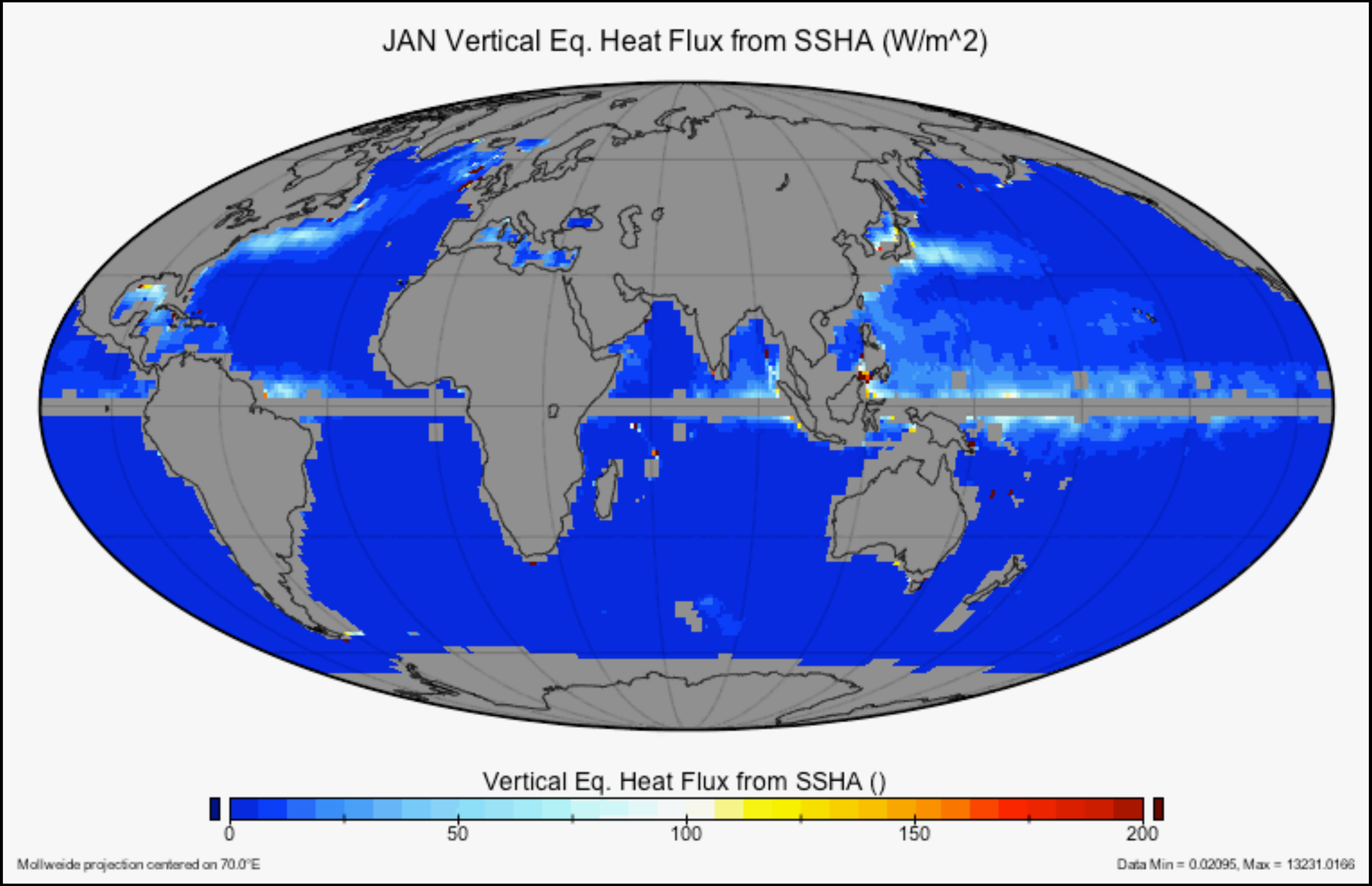


$$\frac{D_m b_1}{Dt} = \frac{D_m}{Dt}\frac{\partial \psi_m}{\partial z} = 0$$

$$\frac{Db_2}{Dt} = \frac{D}{Dt}\left(\frac{\partial \psi_m}{\partial z} - \frac{N_m^2}{N^2}\frac{\partial \psi}{\partial z}\right) = 0$$

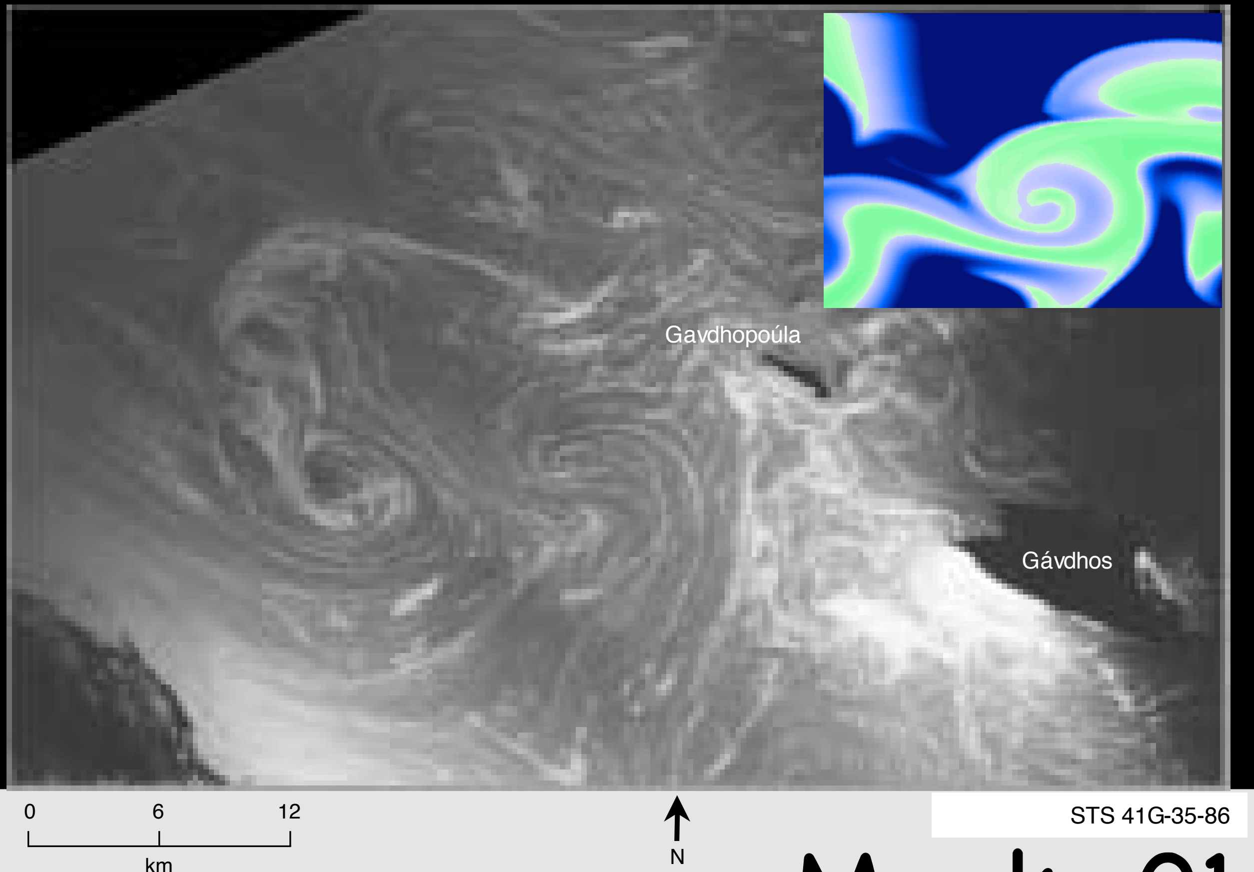
$$\frac{Db_3}{Dt} = \frac{D}{Dt}\frac{\partial \psi}{\partial z} = 0$$

Submesoscale heat fluxes



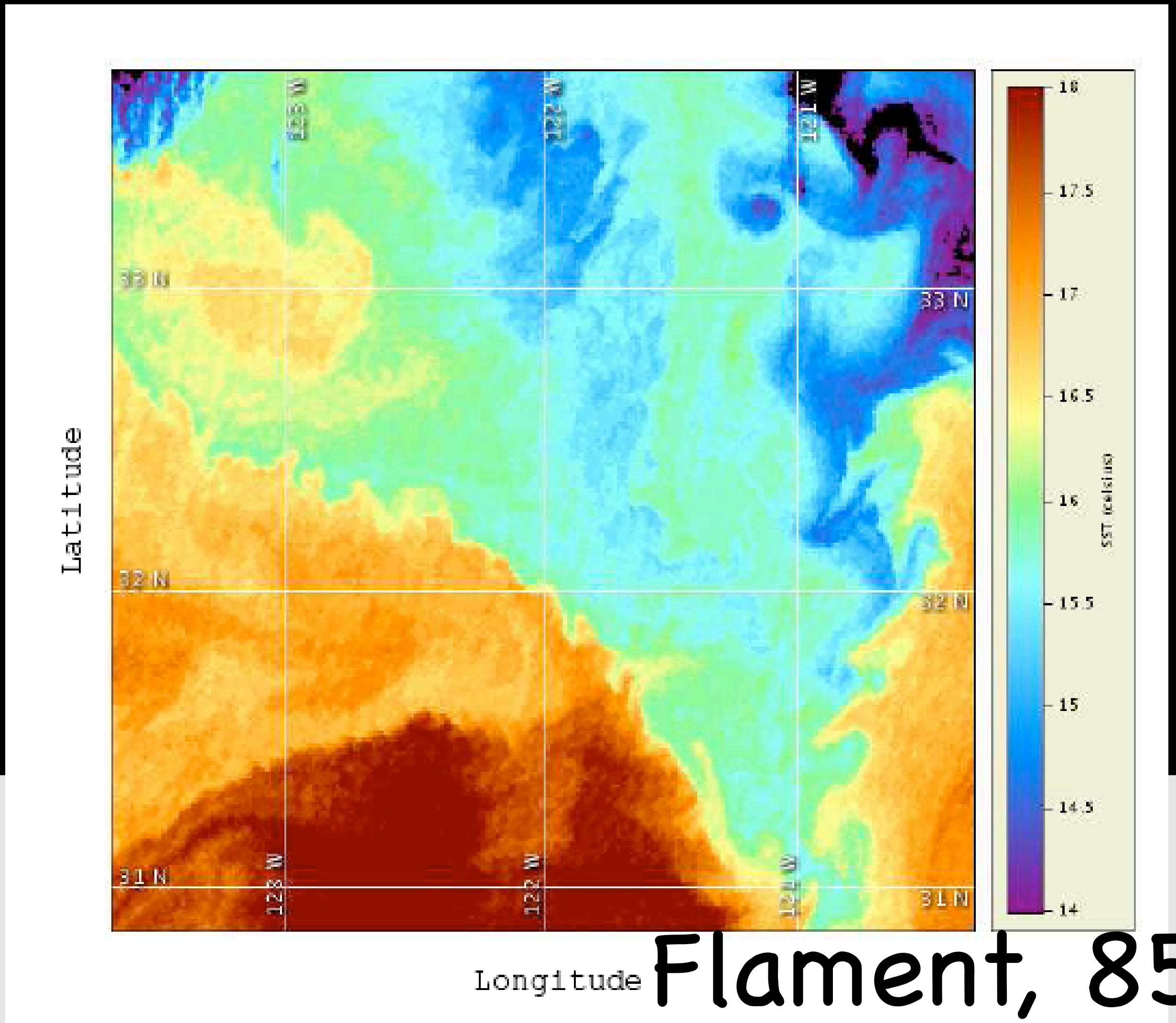
Observations of submesoscale instabilities

- Spirals in the sea (Munk '01)
- Frontal instabilities in the California Current System (Flament et al., '85)



Munk, 01

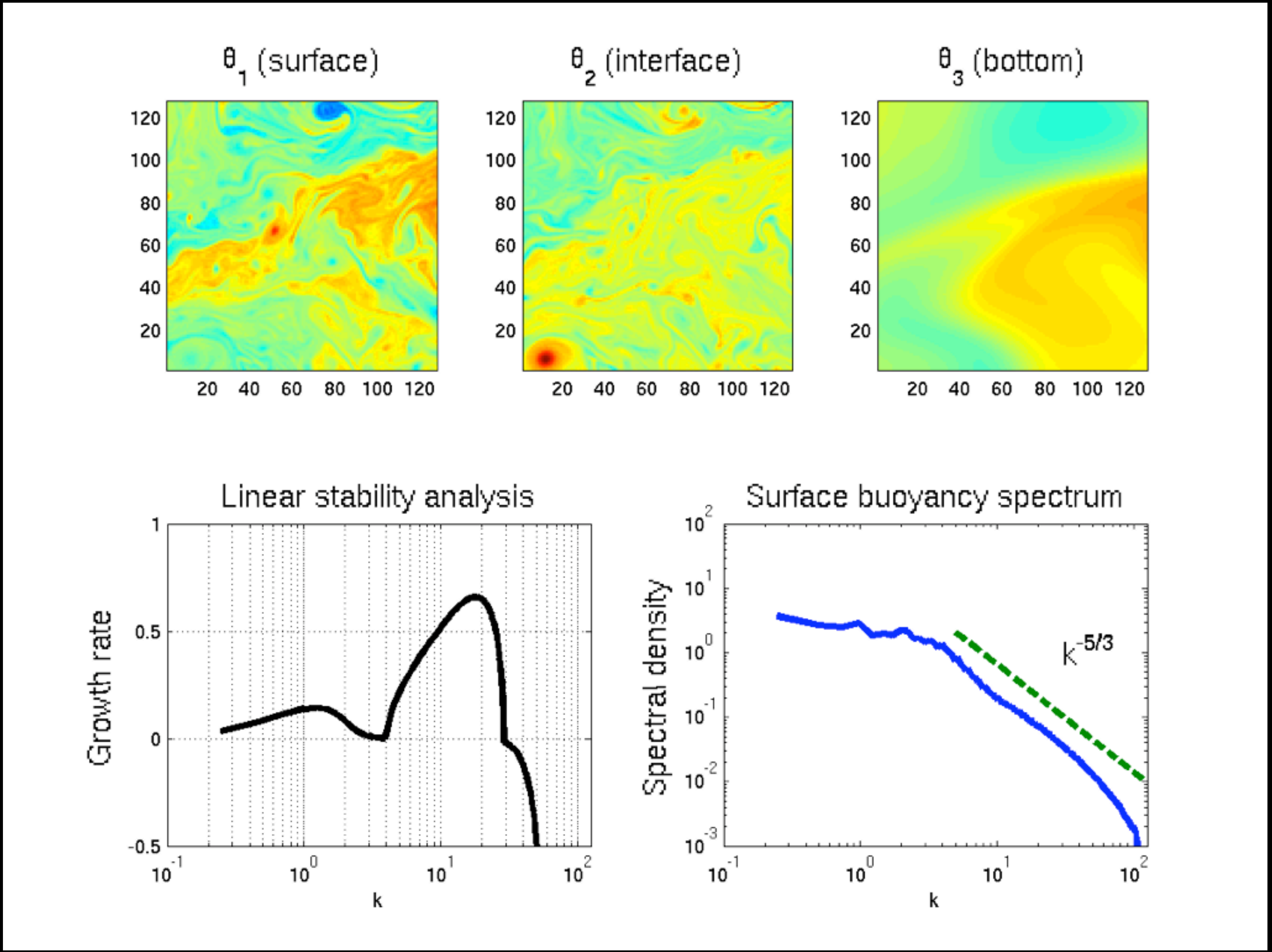
Figure 1. A pair of interconnected spirals in the Mediterranean Sea south of Crete. This vortex pair has a clearly visible stagnation point between the two spirals, the cores of which are aligned with the preconditioning wind field. 7 October 1984.



Flament, 85

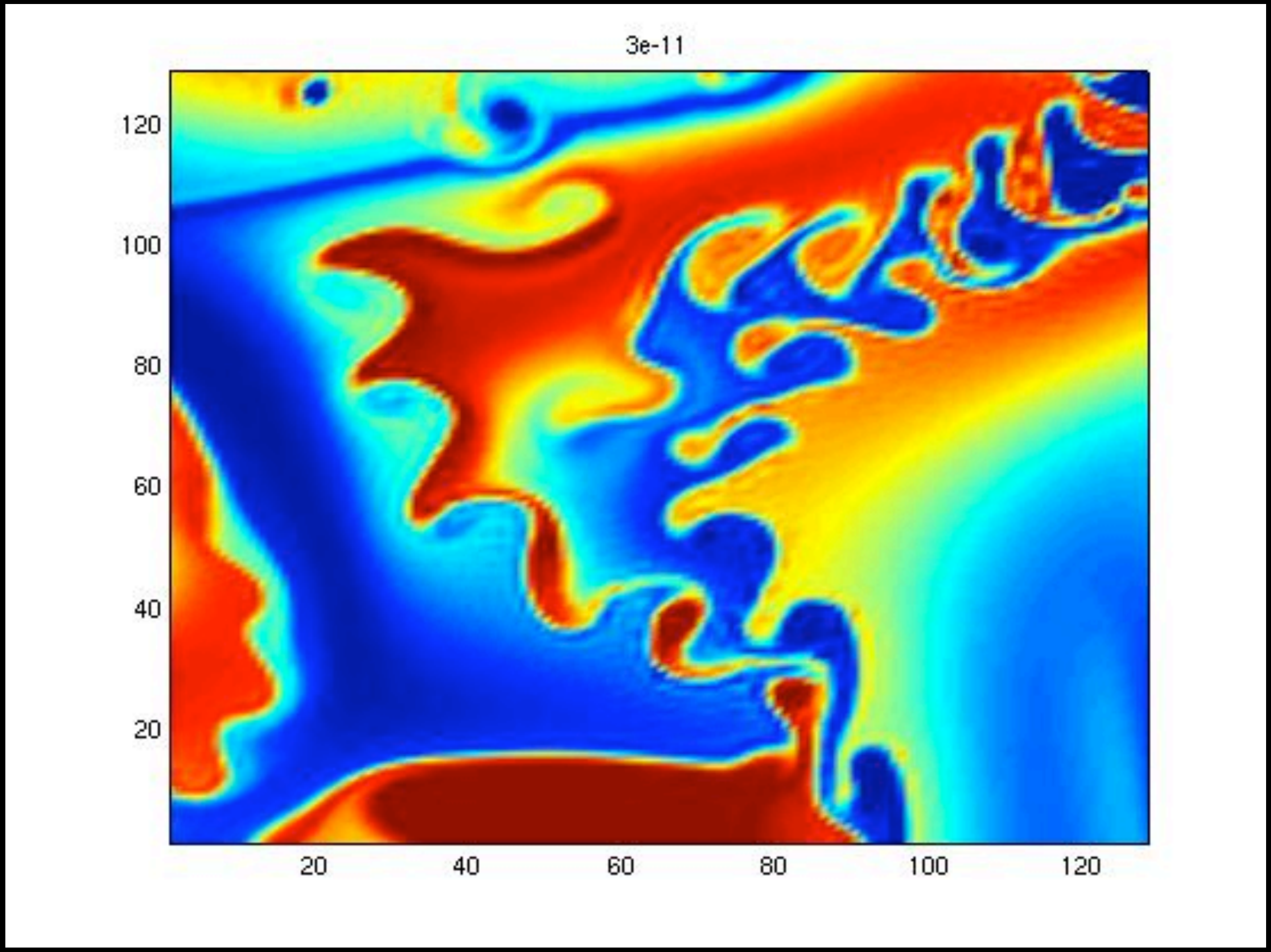
Enhanced AVHRR image showing submesoscale features in the California Current system related to an upwelling filament.

Surface QG model with ML

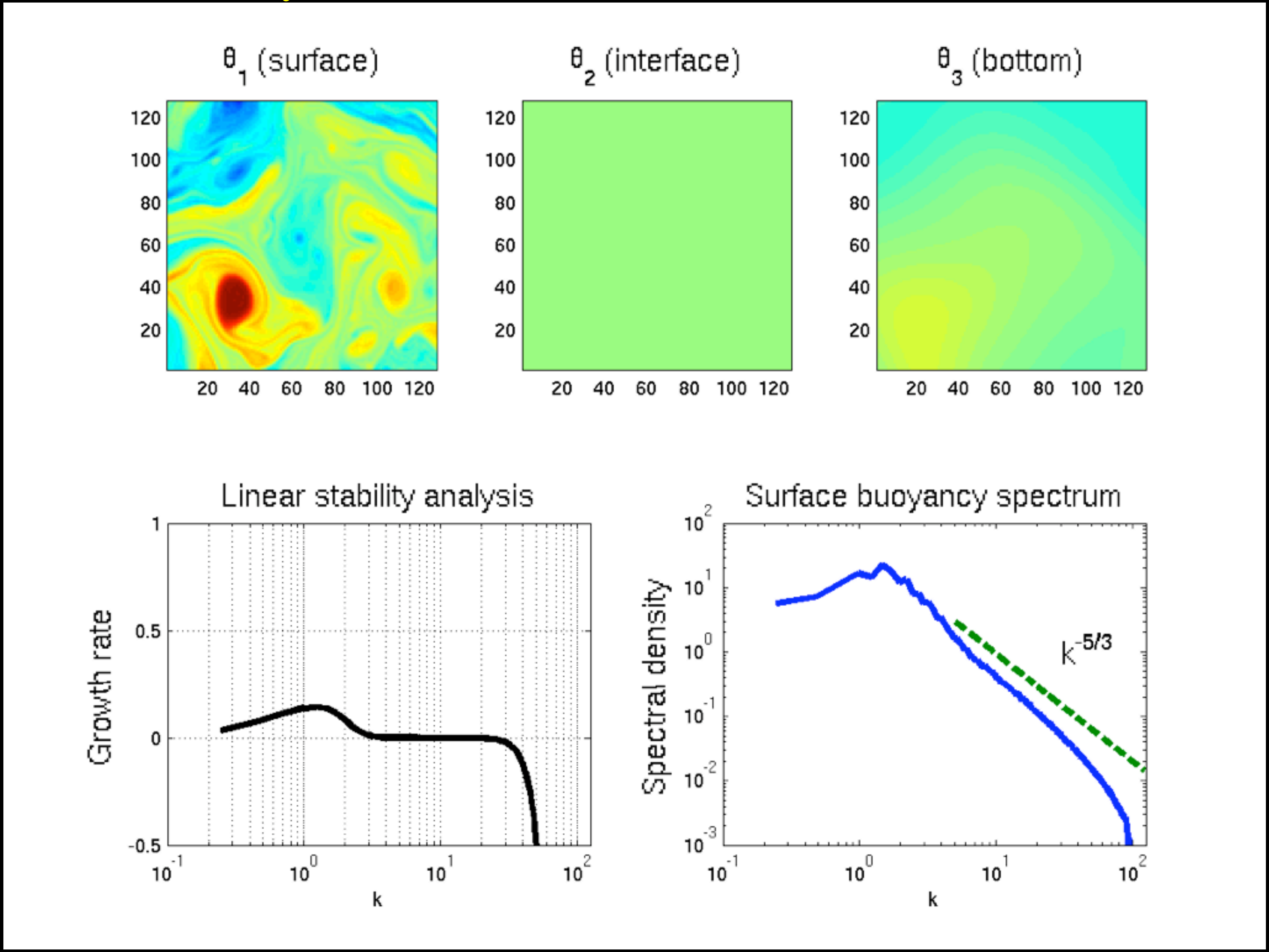


Surface QG model with ML: development of submesoscale instabilities

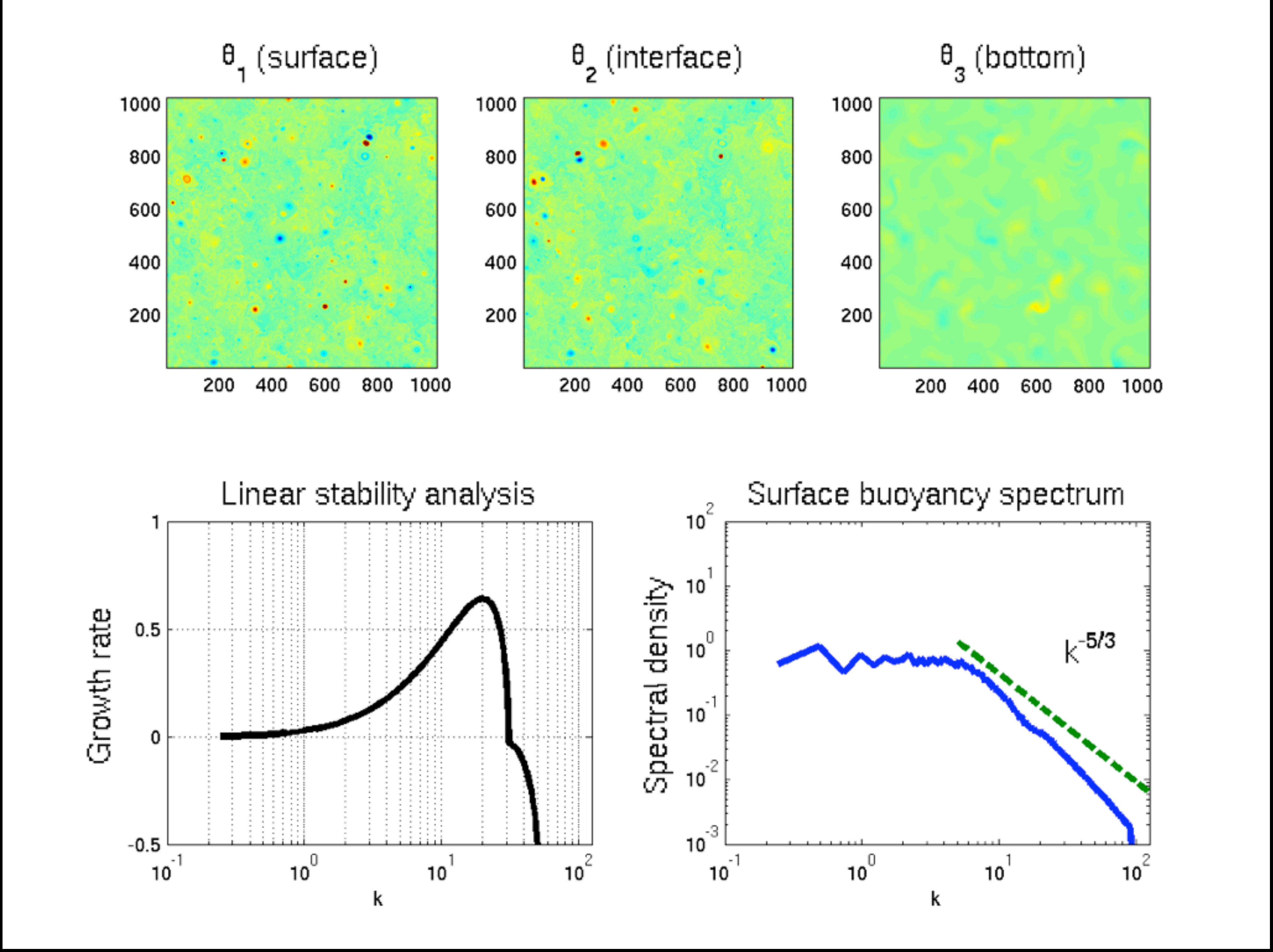
- Are submesoscale baroclinic instabilities suppressed by mesoscale strain (Bishop, 1993)?
  - mesoscale strain generates fronts at the surface, $(u,v)=(ax,-ay)$
  - submesoscale waves are stretched by strain $(k,l)=(k_0\, e^{-at}, l_0\, e^{at})$
  - instabilities are modulated not suppressed by mesoscale strain



Surface QG model without ML: only mesoscale instabilities

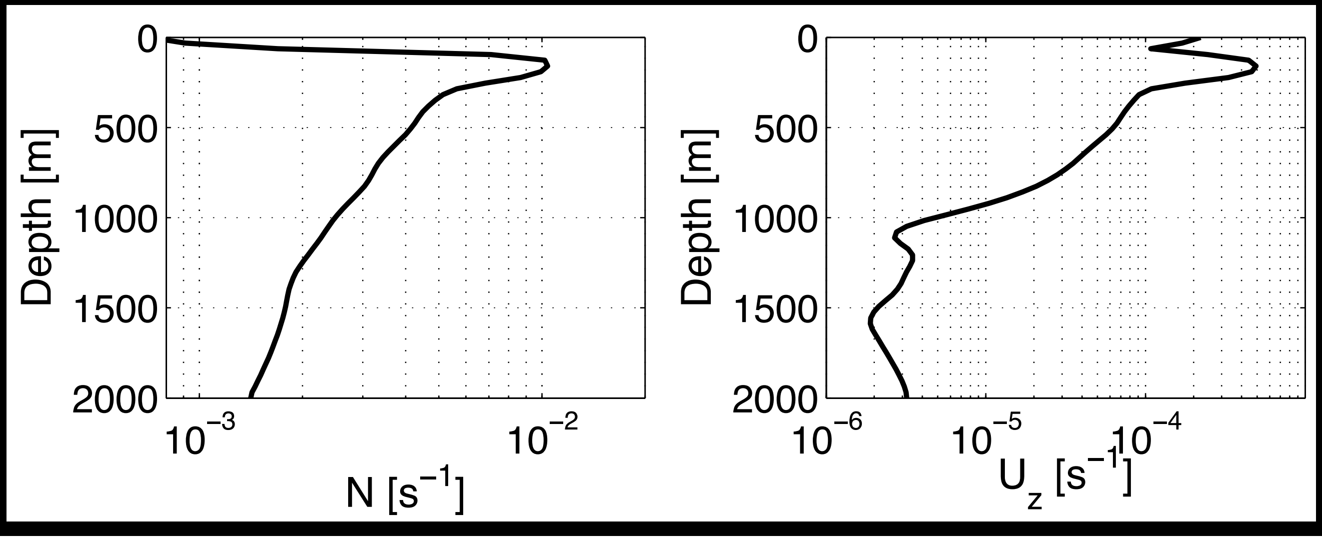


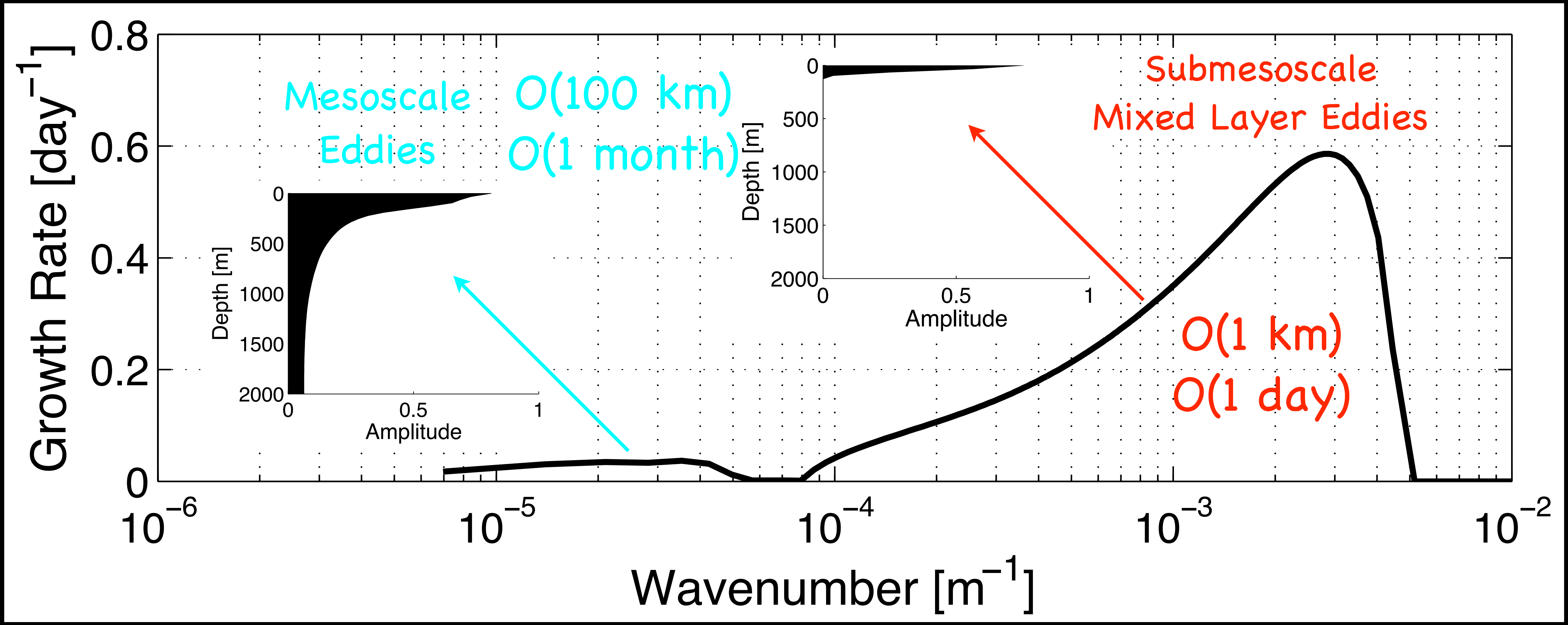
Surface QG model with ML and no deep shear: only submesoscale instabilities



Typical Ocean Stratification Permits
Two Types of Baroclinic Instability

Mesoscale and Submesoscale (Boccaletti et al., 2007)



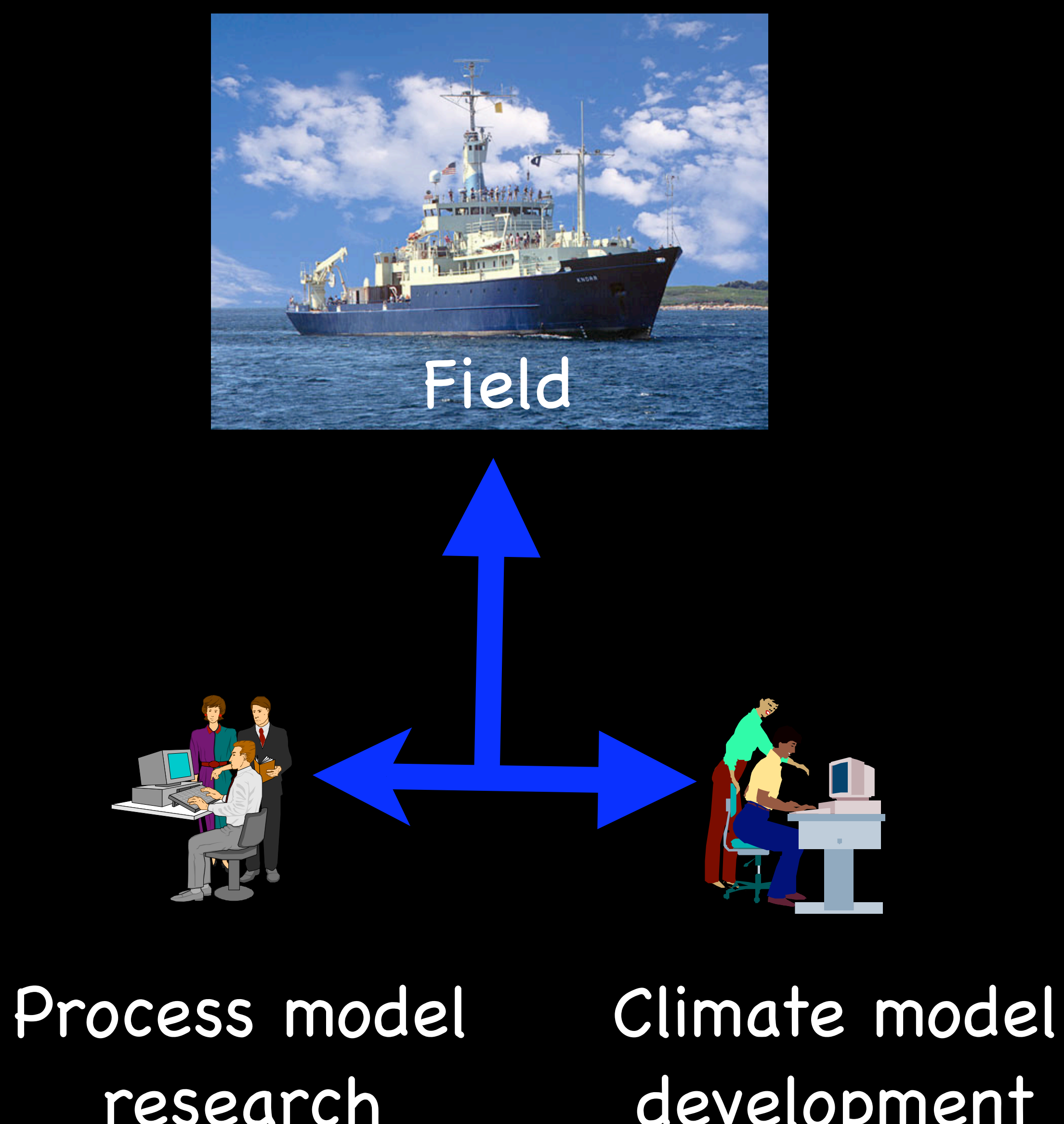


Climate Process Team on Eddy-MIxed Layer IntEractions

To what extent can uncertainties in model projections due to climate system feedbacks be reduced? (Climate Change Science Program)

- Imperfect or missing parameterizations of unresolved processes are a major source of model error and uncertainty

CPT Framework



- Focus
  - upper ocean dynamics
- Goal
  - develop parameterizations for key subgrid--scale processes
- Team members
  - PI: Raffaele Ferrari
  - Process modelers and theoreticians: Flierl, Fox-Kemper, Marshall, McWilliams, Tandon, Thomas, Vallis
  - Observationalists: Rudnick, Speer
  - Modeling centers: GFDL and NCAR

Upper ocean dynamics in climate models

- Large-scale ocean circulation
- Mesoscale turbulence (10 km - 100 km)
- Submesoscale turbulence (100 m - 10 km)
- Small-scale turbulent mixing (10 cm - 100 m)

Subgrid-scale processes in ocean climate models