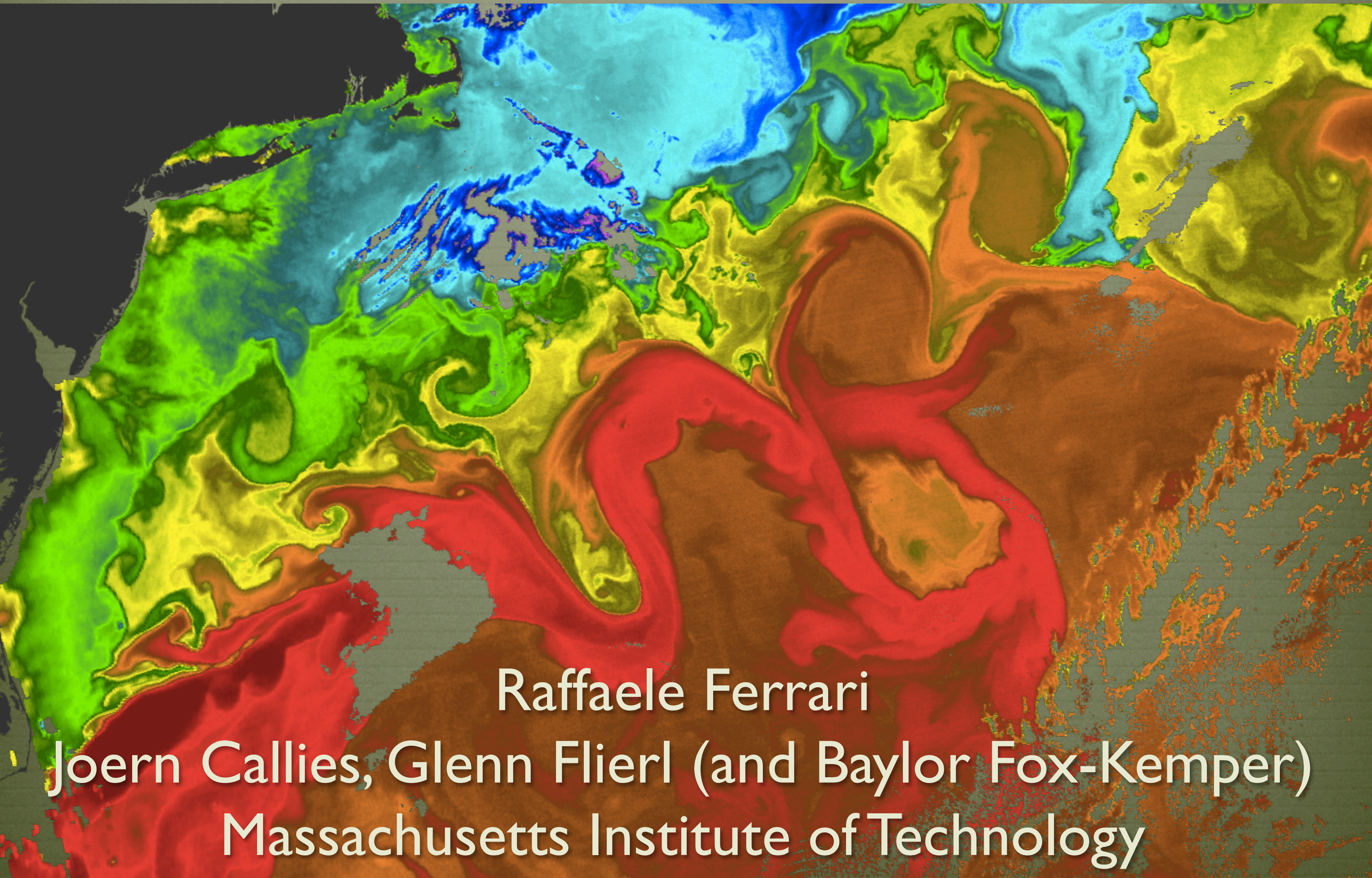
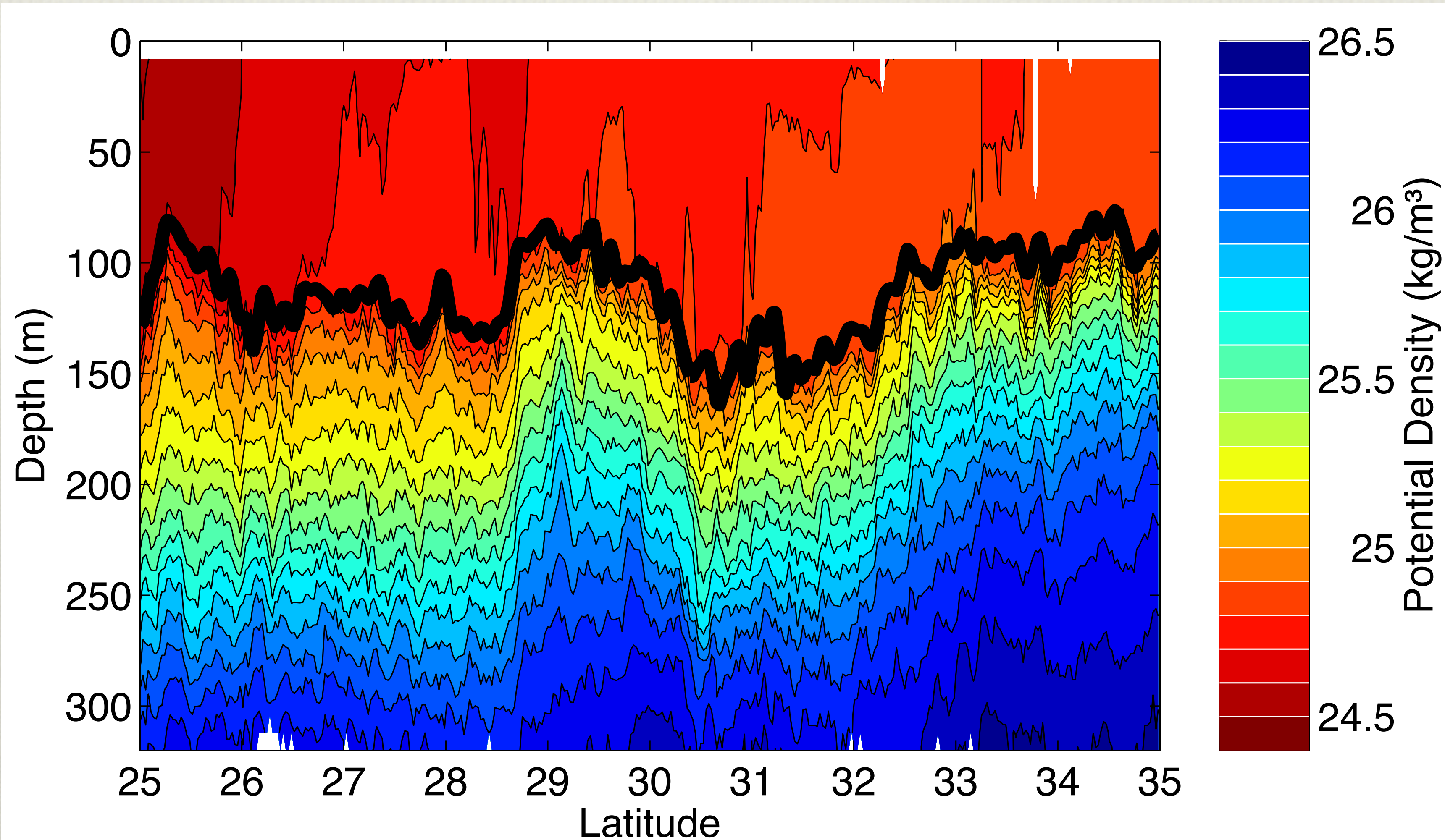
Upper Ocean Turbulence



Raffaele Ferrari
Joern Callies, Glenn Flierl (and Baylor Fox-Kemper)
Massachusetts Institute of Technology

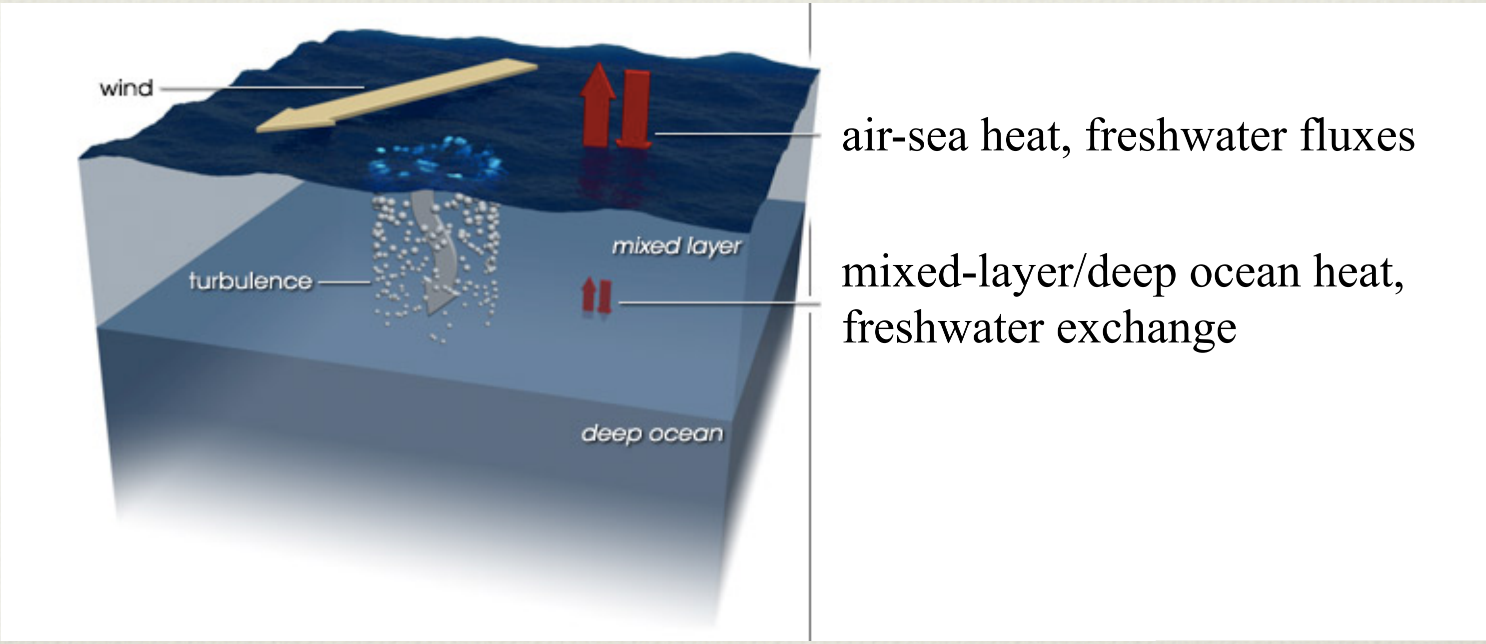
Ocean Mixed Layer

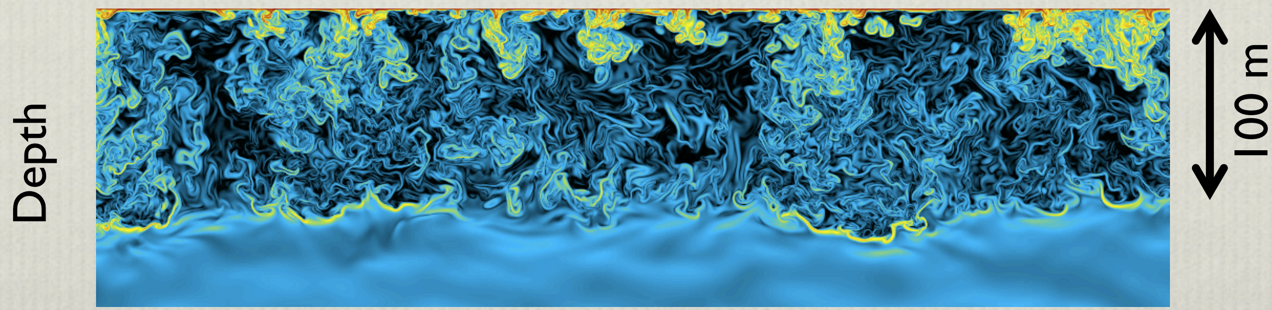


Ferrari and Rudnick (JGR, 2000)

Mixed Layer 3D turbulence

Air-sea fluxes trigger 3D turbulence and “mix” the mixed-layer

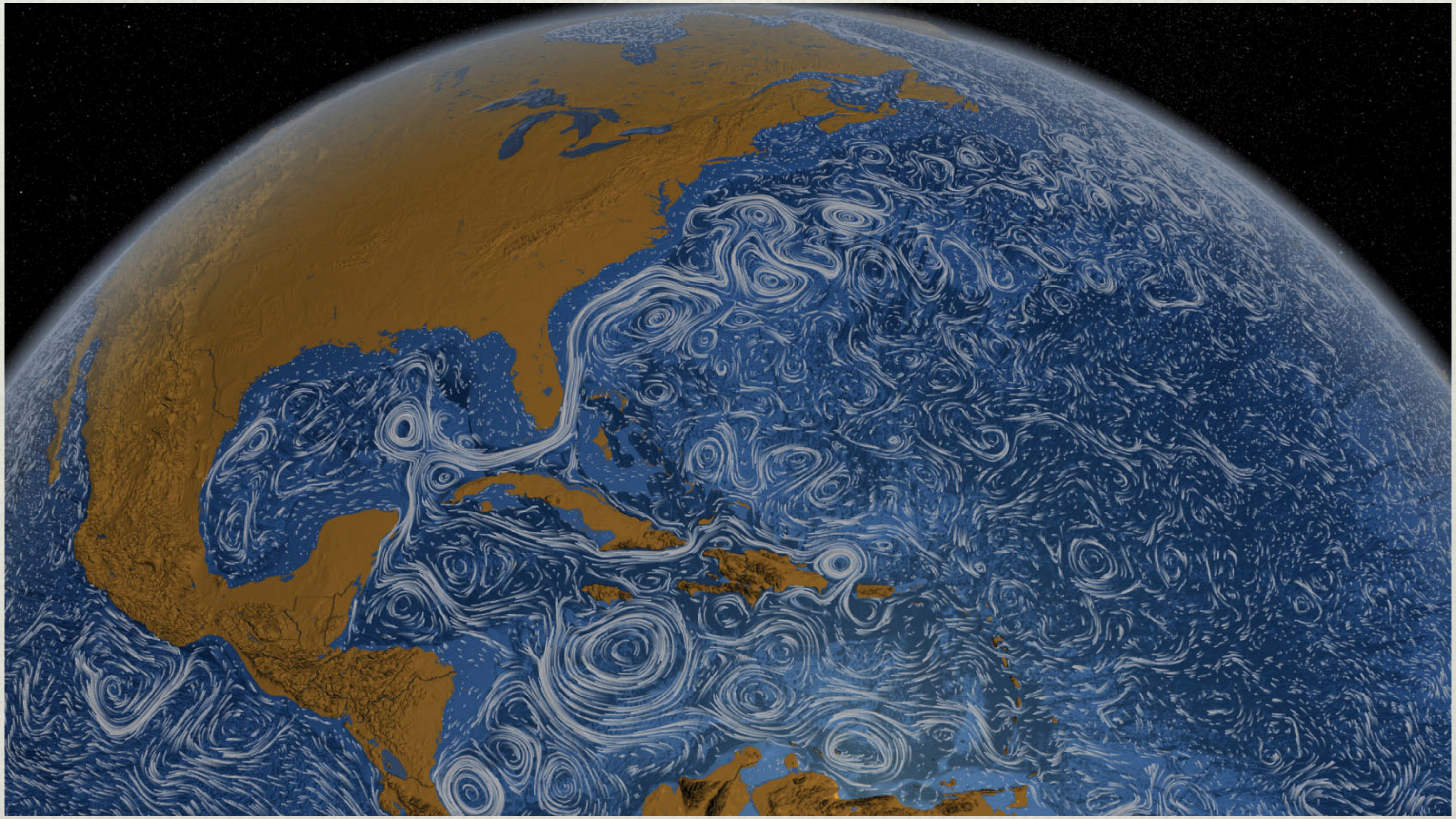




3D turbulent eddies (scales < 100m)

Mixed layer mesoscale turbulence

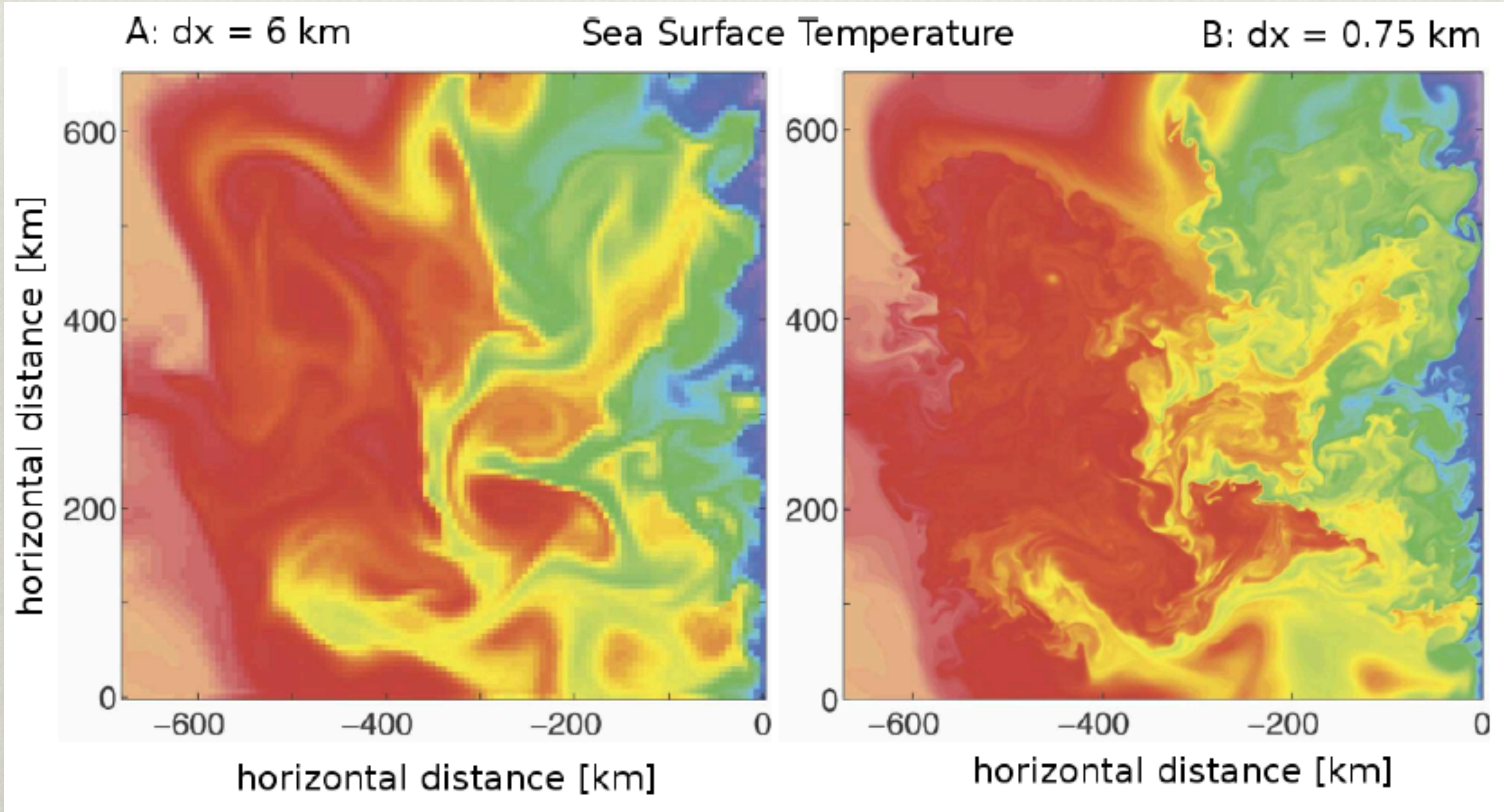
Mesoscale eddies stir and mix lateral density gradients



Mesoscale turbulent eddies (scales > 10 km)

Submesoscale mixed layer turbulence

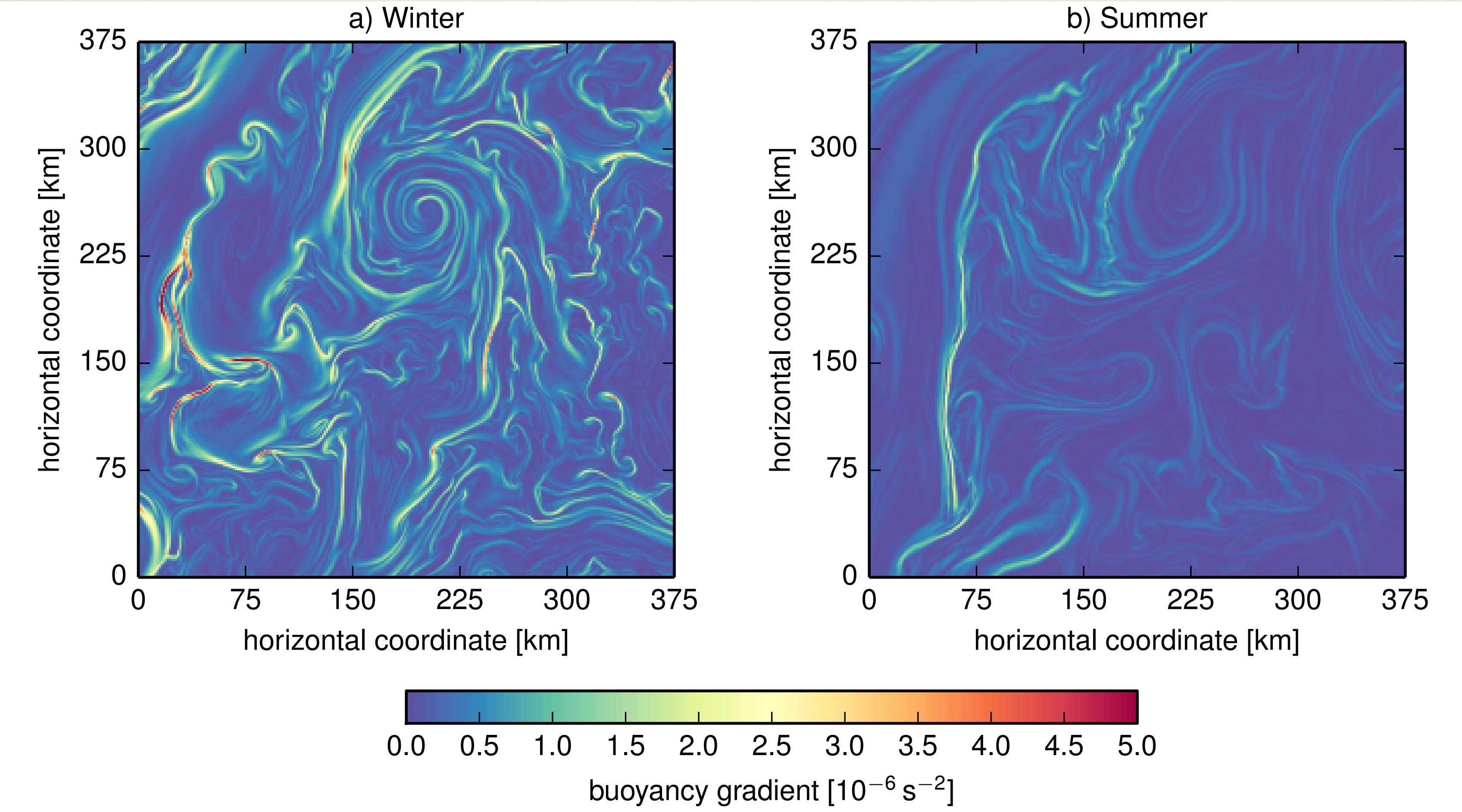
Turbulence emerges on scales smaller than the mesoscale eddies



Capet et al. (JPO, 2008)

Seasonality of mixed layer instabilities

- Submesoscale turbulence enhanced in winter
- Consistent with in-situ observations

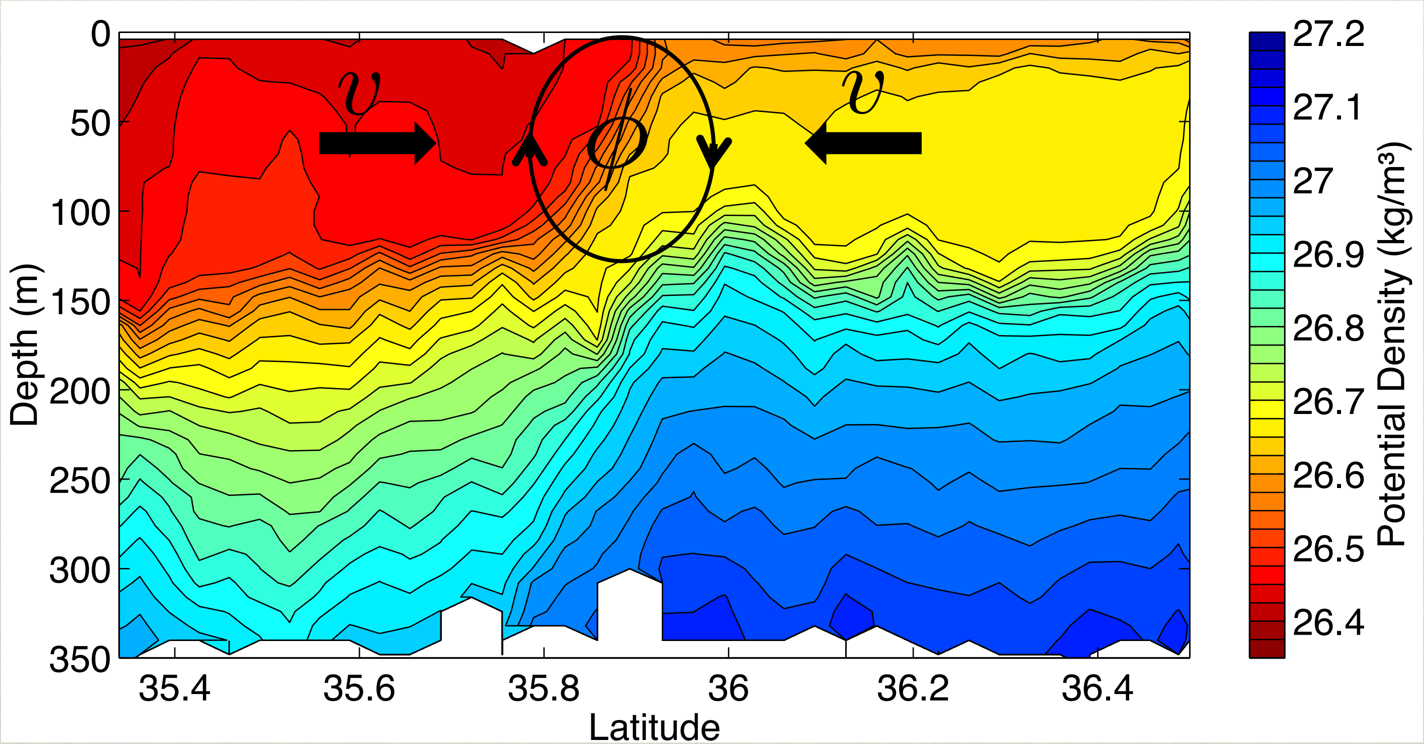


Molemaker et al. (personal communication)

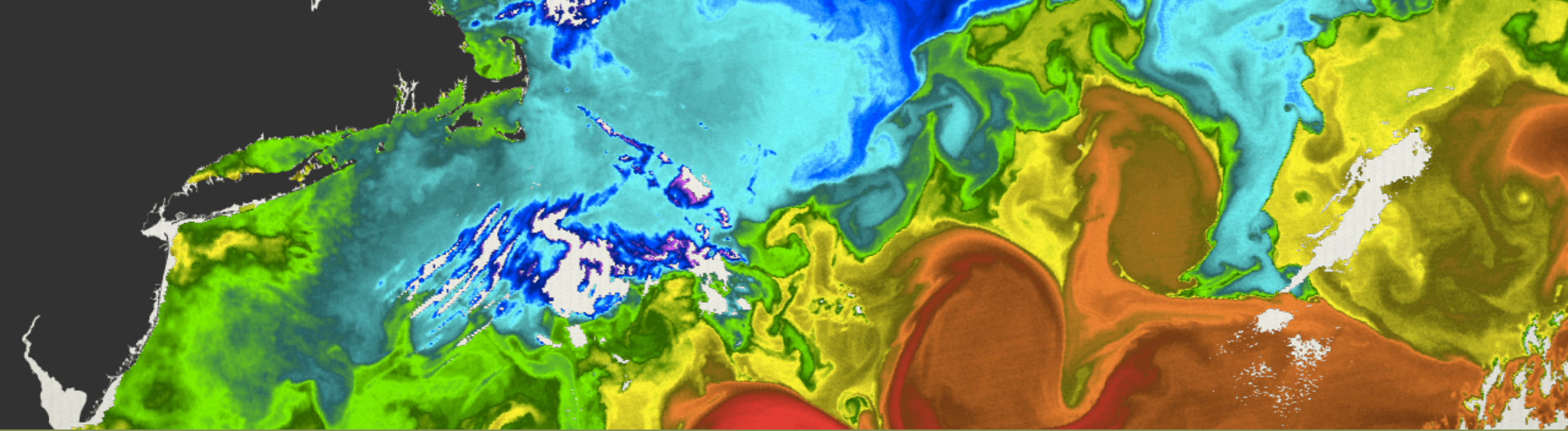
Ocean Fronts

Submesoscale turbulence accelerates vertical exchange with deep ocean

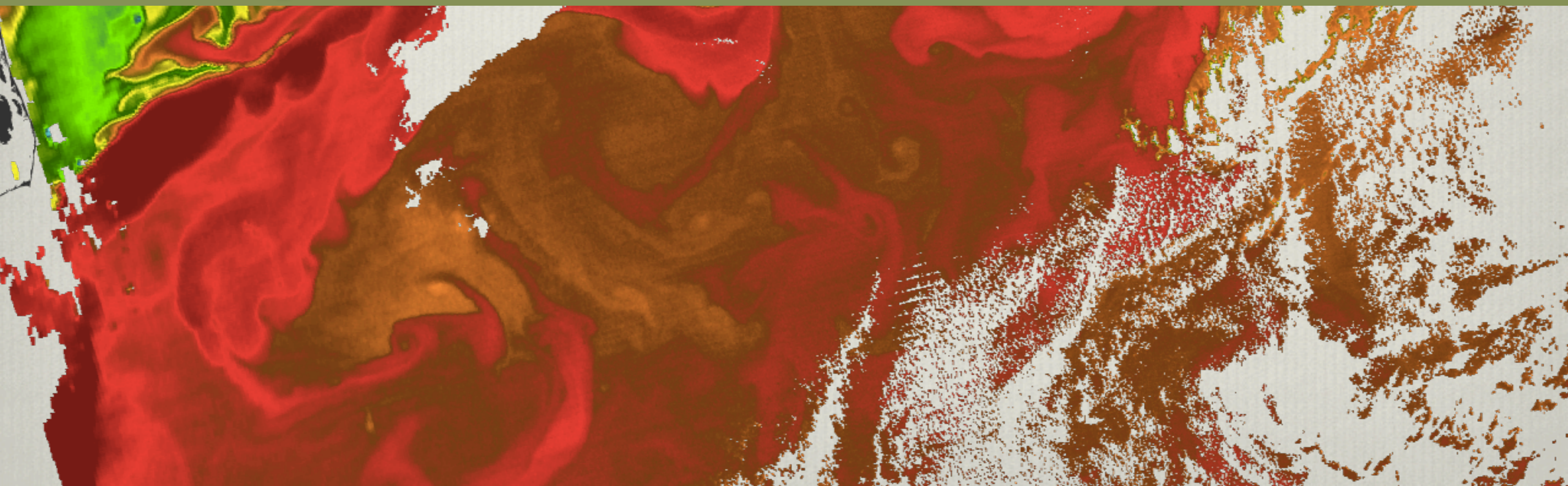
$$f^2\partial_{zz}\phi + N^2\partial_{yy}\phi = -2\,\partial_y v\,\partial_y b$$



Rudnick and Luyten (JGR, 1996)

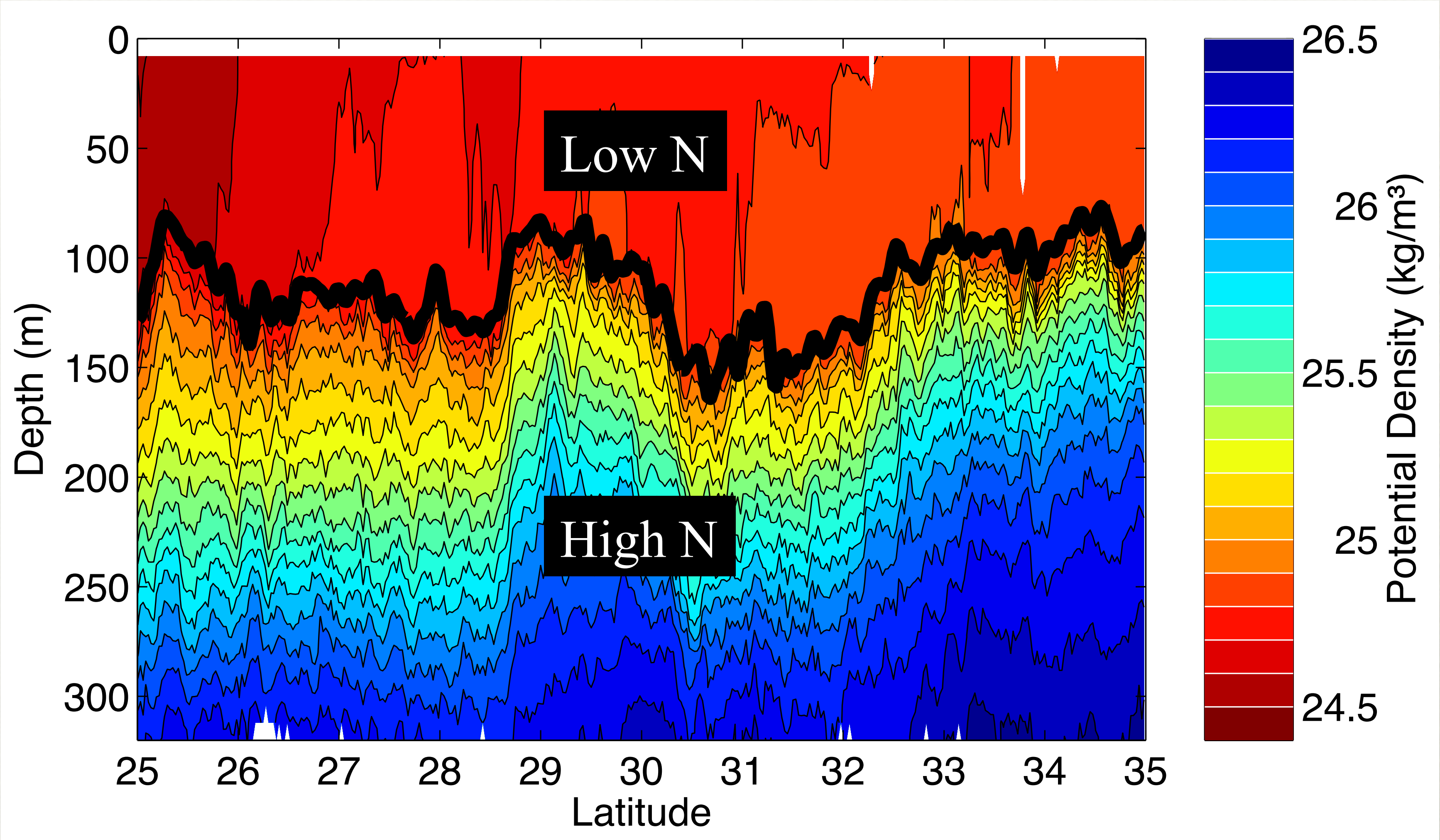


A quasi-geostrophic model to study submesoscale turbulence



Mixed layer instabilities

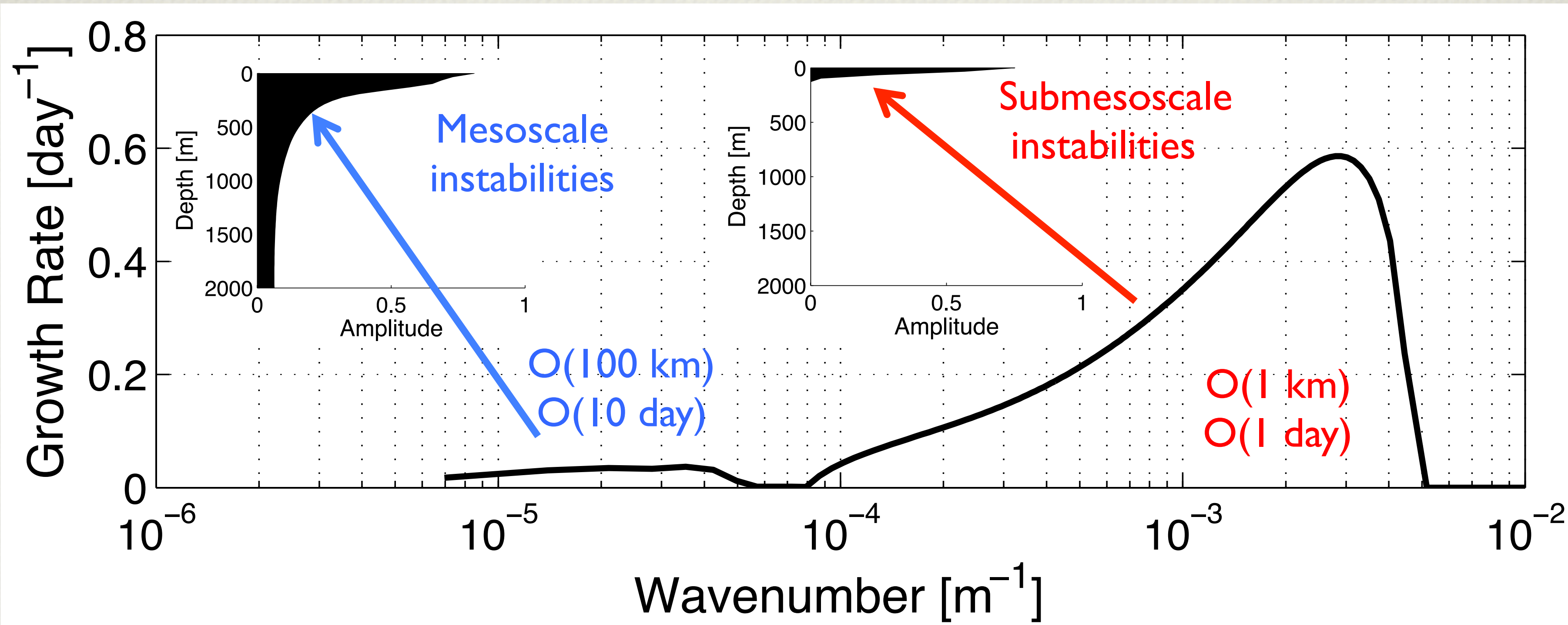
Sharp PV contrast between mixed layer and thermocline



Boccaletti, Ferrari and Fox-Kemper (JPO, 2007)

Mixed layer instabilities

- Sharp PV contrast between mixed layer and thermocline
- Submesoscale baroclinic instability in the mixed layer

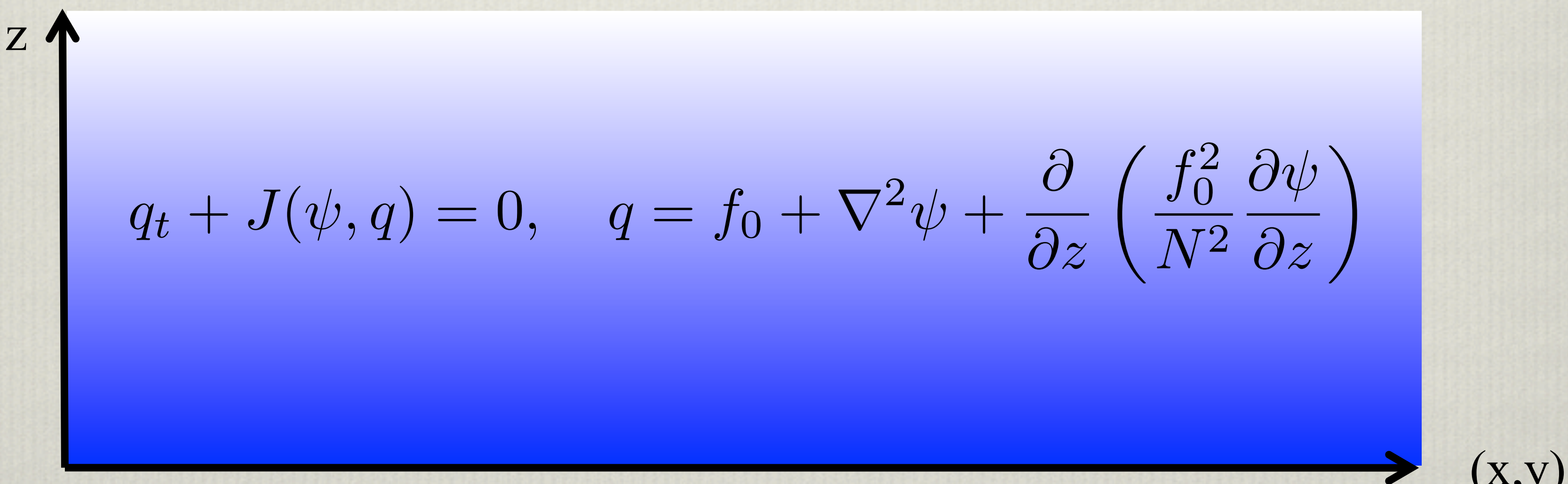


Boccaletti, Ferrari and Fox-Kemper (JPO, 2007)

Quasi-geostrophic (QG) dynamics

- Quasi-geostrophic approximation
  - small Rossby number, $Ro \equiv \dfrac{U}{fL} \ll 1$
  - motions with scales close to deformation radius, $L \approx f^{-1}NH$
  - vertical stratification in only a function of depth, $N^2 = -\dfrac{g}{\rho_0}\dfrac{\partial \rho}{\partial z}$

$$w = 0 \quad \Rightarrow \quad b_t^T + J(\psi, b^T) = 0, \quad b^T = f_0 \psi_z, \quad z = 0$$

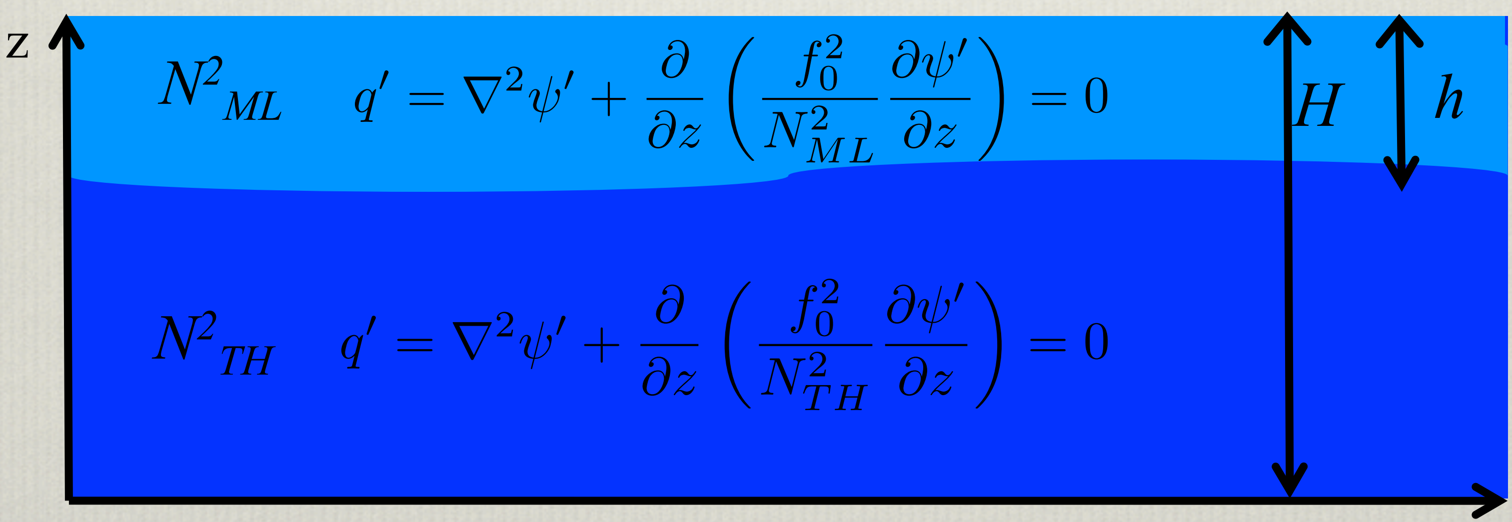


$$q_t + J(\psi, q) = 0, \quad q = f_0 + \nabla^2 \psi + \frac{\partial}{\partial z}\left(\frac{f_0^2}{N^2}\frac{\partial \psi}{\partial z}\right)$$

$$w = 0 \quad \Rightarrow \quad b_t^B + J(\psi, b^B) = 0, \quad b^B = f_0 \psi_z, \quad z = -H$$

QG submesoscale model

- Two layers of uniform PV (constant stratification)
  - Mixed layer of depth *h*
  - Thermocline of depth *H*-*h*



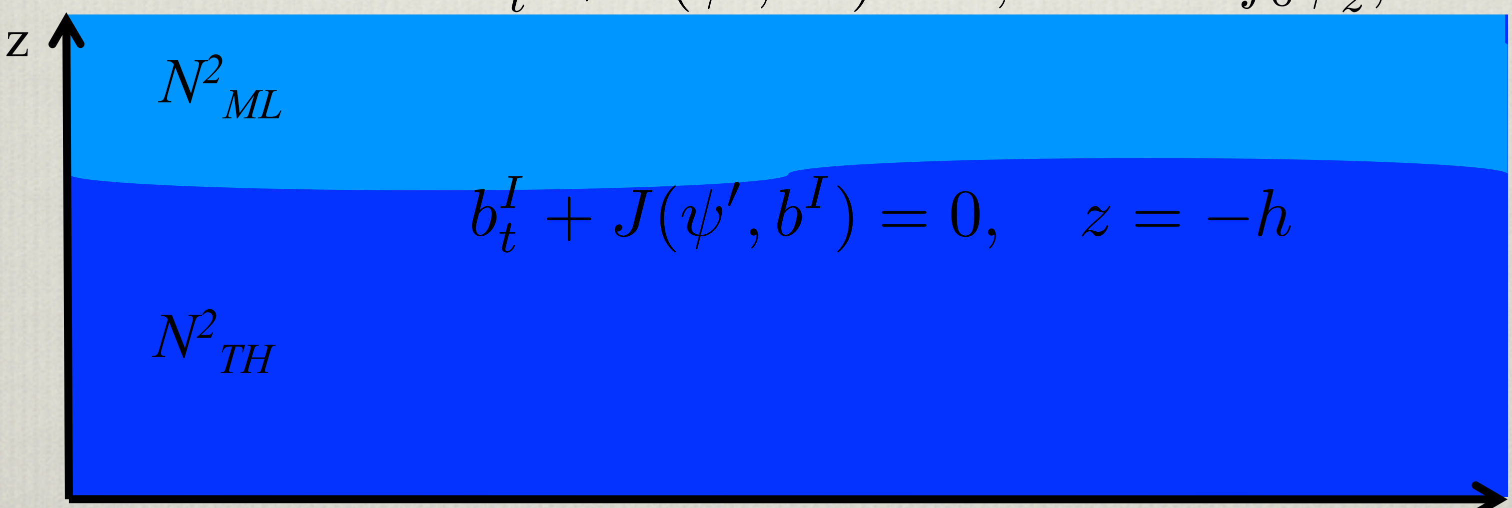
QG submesoscale model

- Two layers of uniform PV (constant stratification)
- Dynamics at the interface

$$b_t^+ + J(\psi', b^+) + wN_{ML}^2 = 0, \qquad b_t^- + J(\psi', b^-) + wN_{TH}^2 = 0,$$

$$\Rightarrow b_t^I + J(\psi', b^I) = 0, \qquad b^I = f_0^2\left(\frac{b^+}{N_{ML}^2} - \frac{b^-}{N_{TH}^2}\right)$$

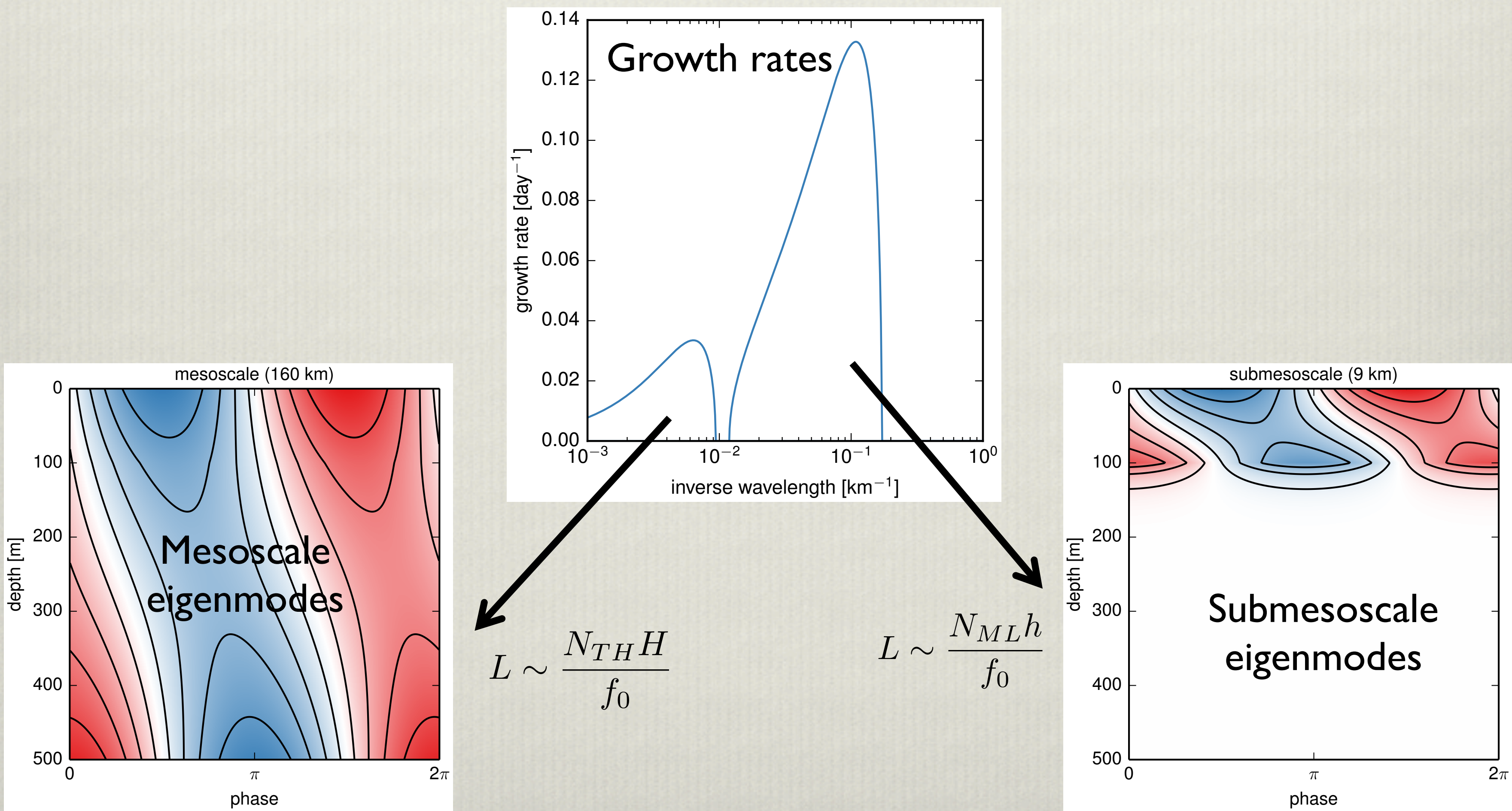
$$w = 0 \quad \Rightarrow \quad b_t^T + J(\psi', b^T) = 0, \quad b^T = f_0\psi'_z, \quad z = 0$$



$$w = 0 \quad \Rightarrow \quad b_t^B + J(\psi', b^B) = 0, \quad b^B = f_0\psi'_z, \quad z = -H$$

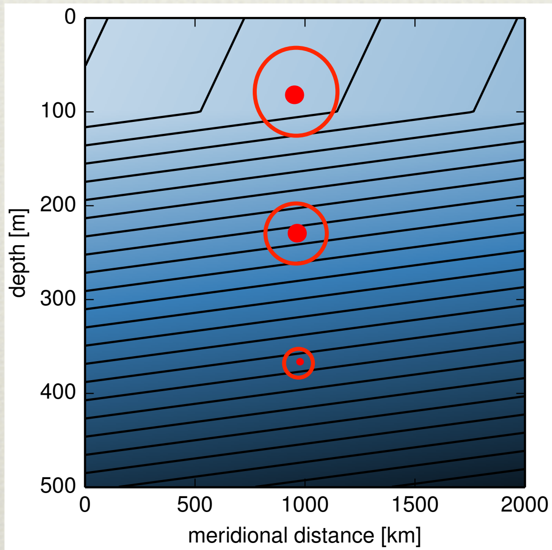
Linear stability analysis

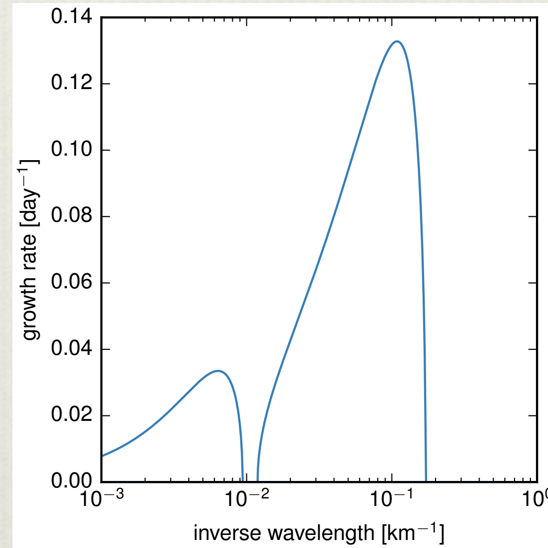
- Consider a basic state with constant mean shear in geostrophic balance with lateral buoyancy gradient
- Two modes of instability (two deformation radii)



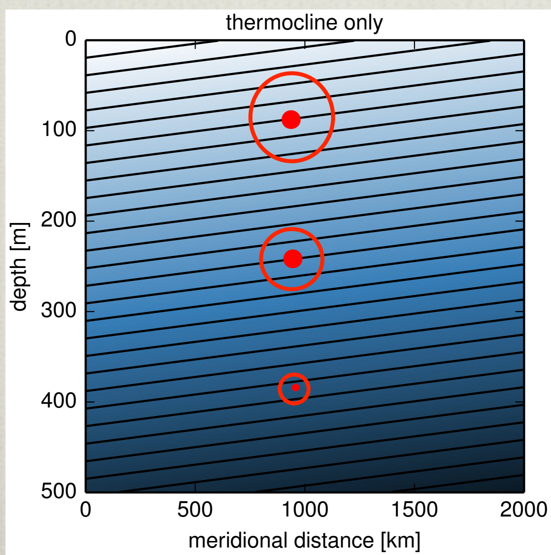
Two model configurations

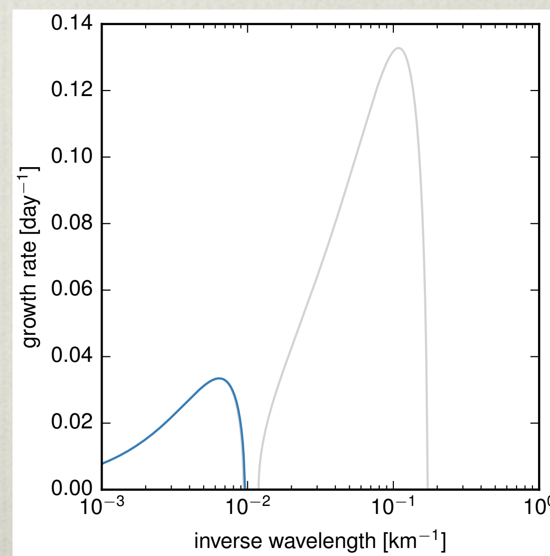
Full model





No ML





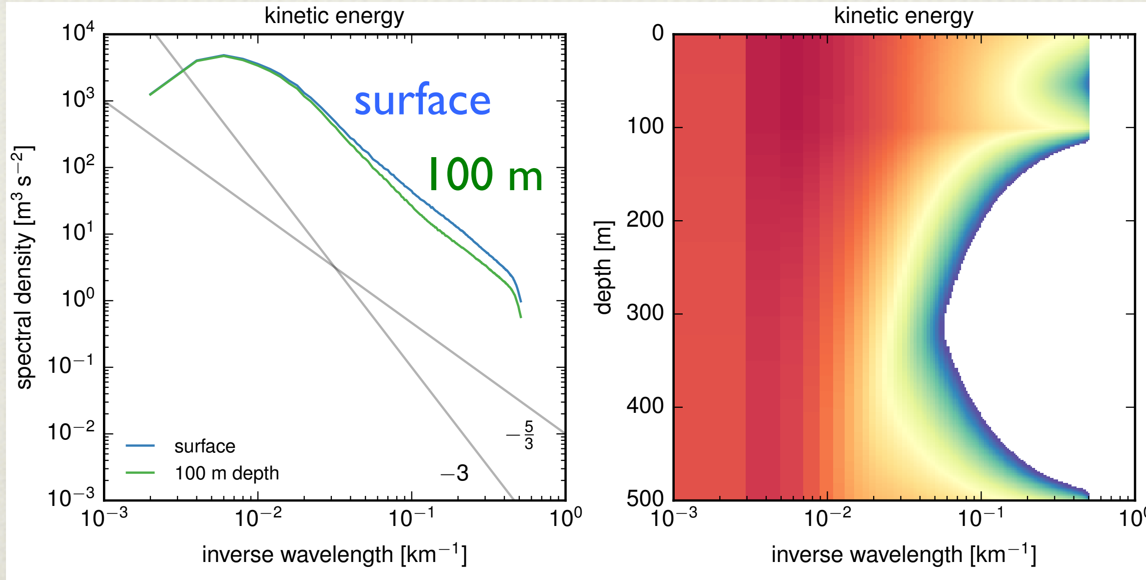
Nonlinear simulations

Full model

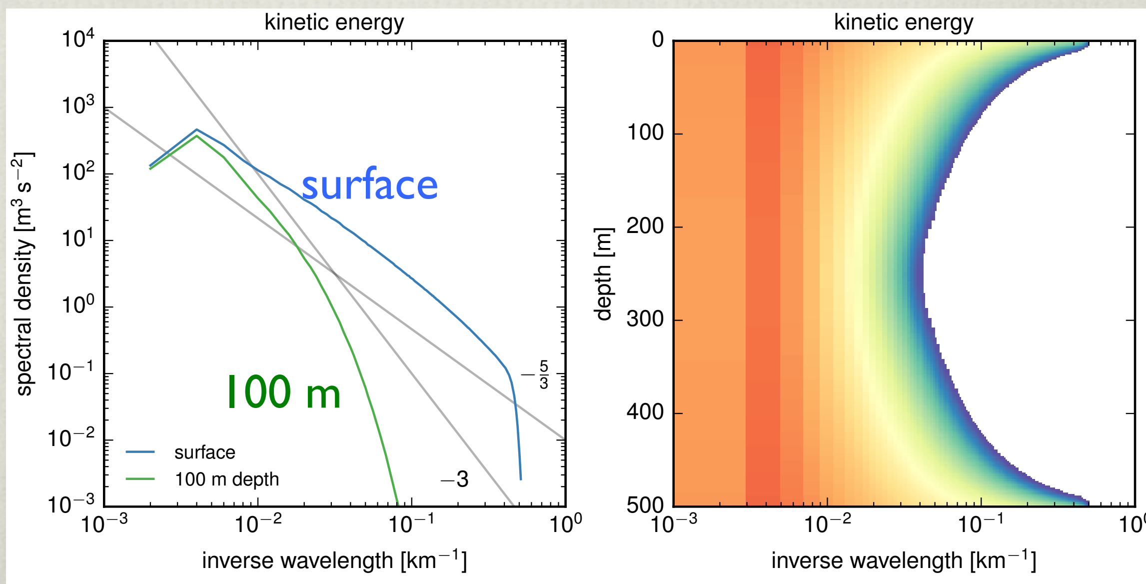
No ML

Kinetic energy spectra

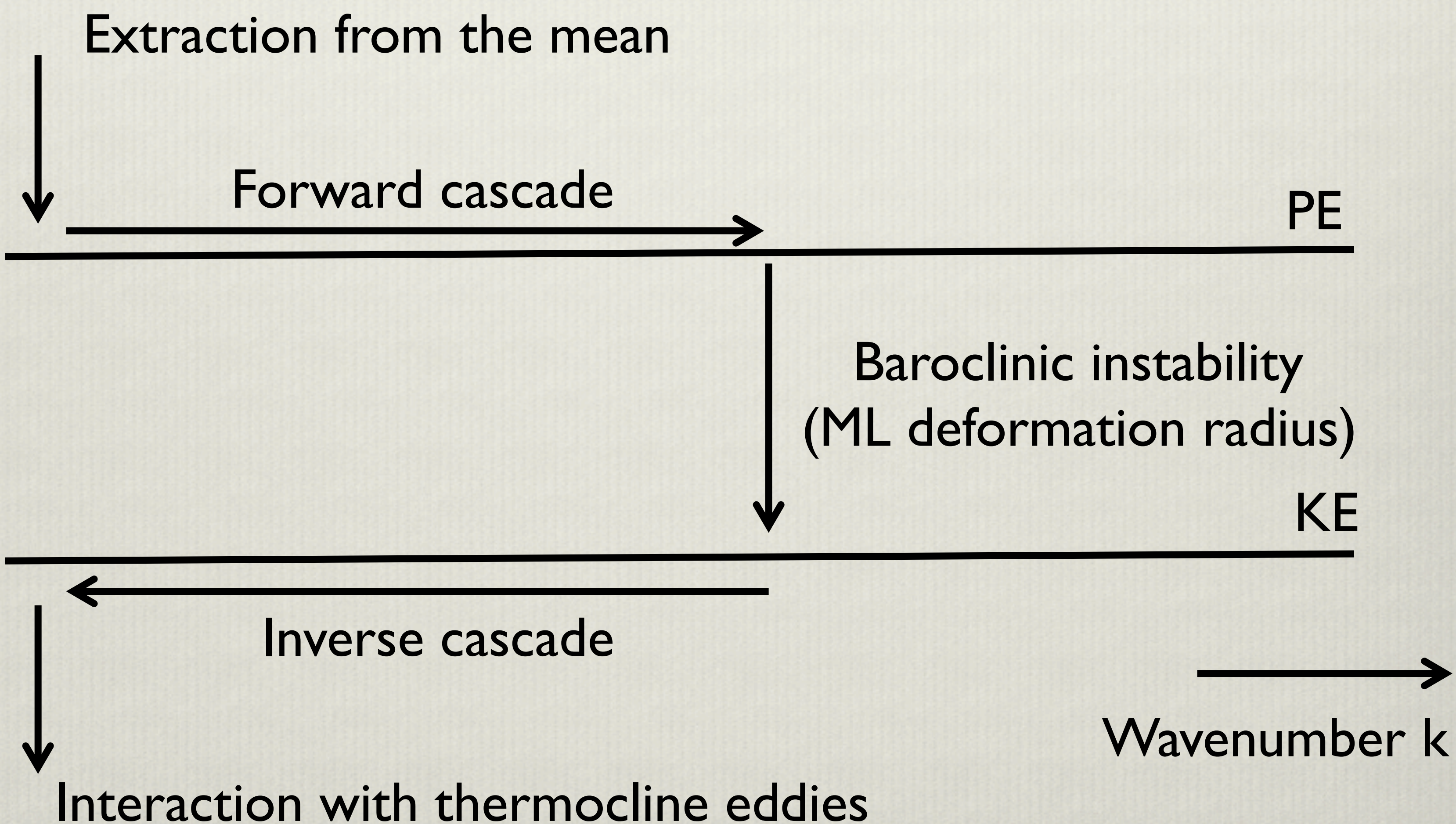
Full model



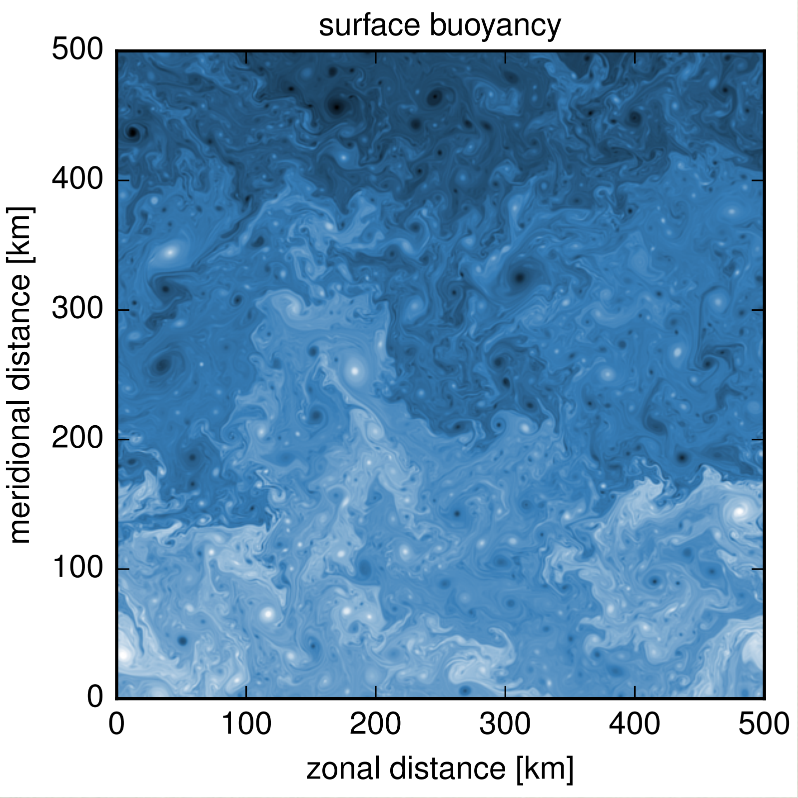
No ML

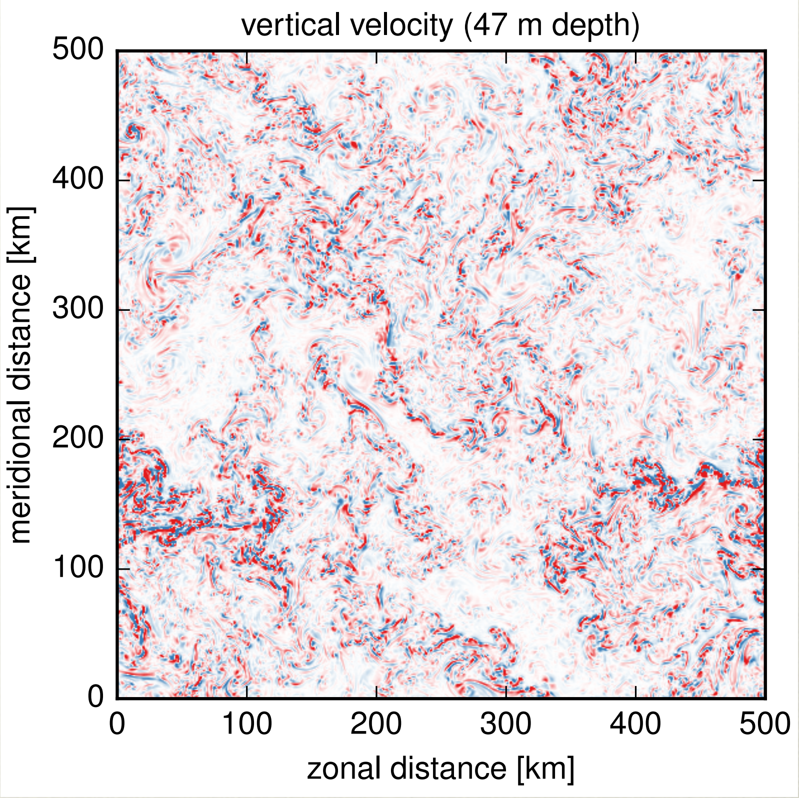


Phenomenology of mixed layer submesoscale turbulence



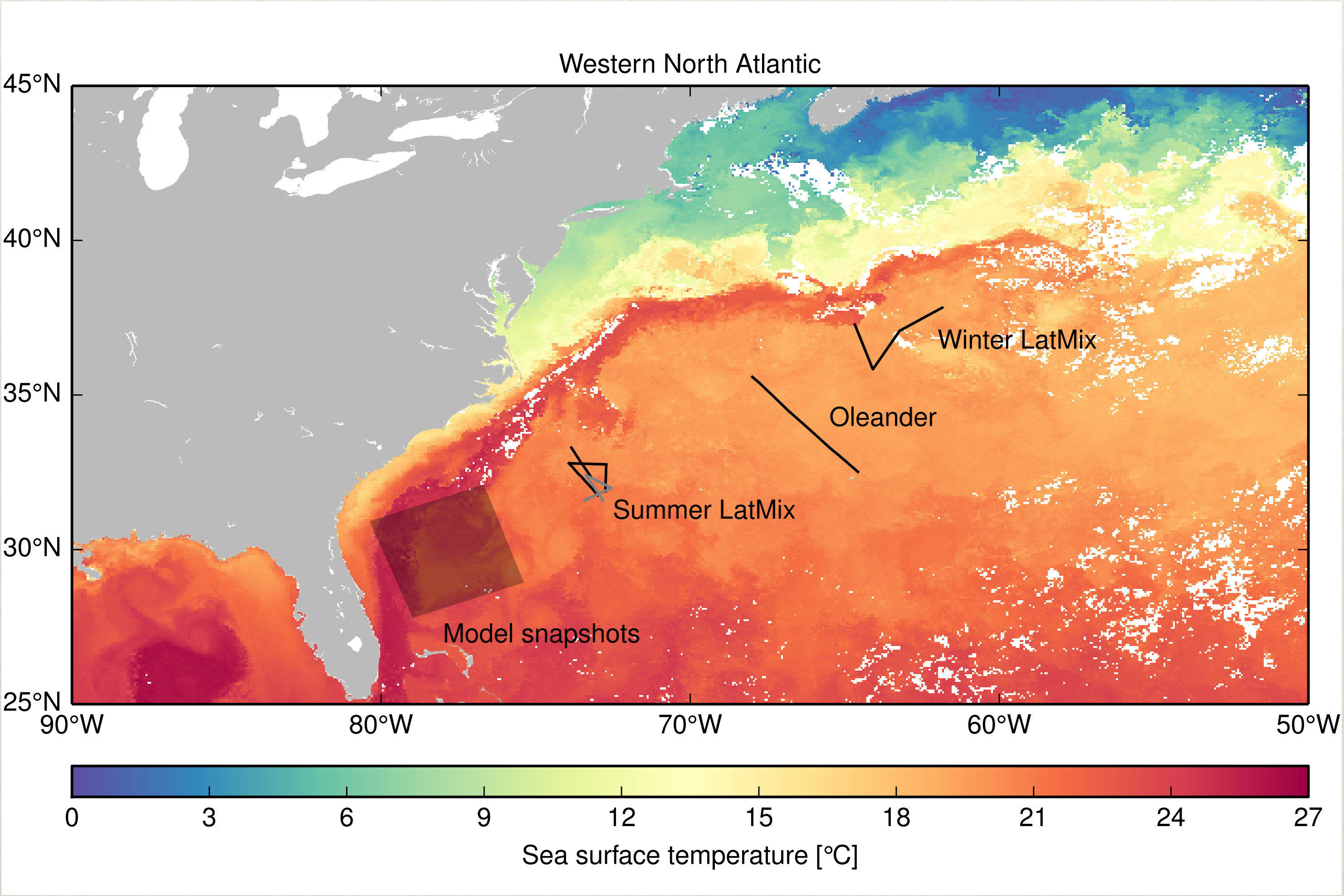
Vertical velocities





- Vertical velocities are dominated by submesoscales
- Largest in frontal regions, not in coherent vortices
- Vertical velocities are ten times larger with ML

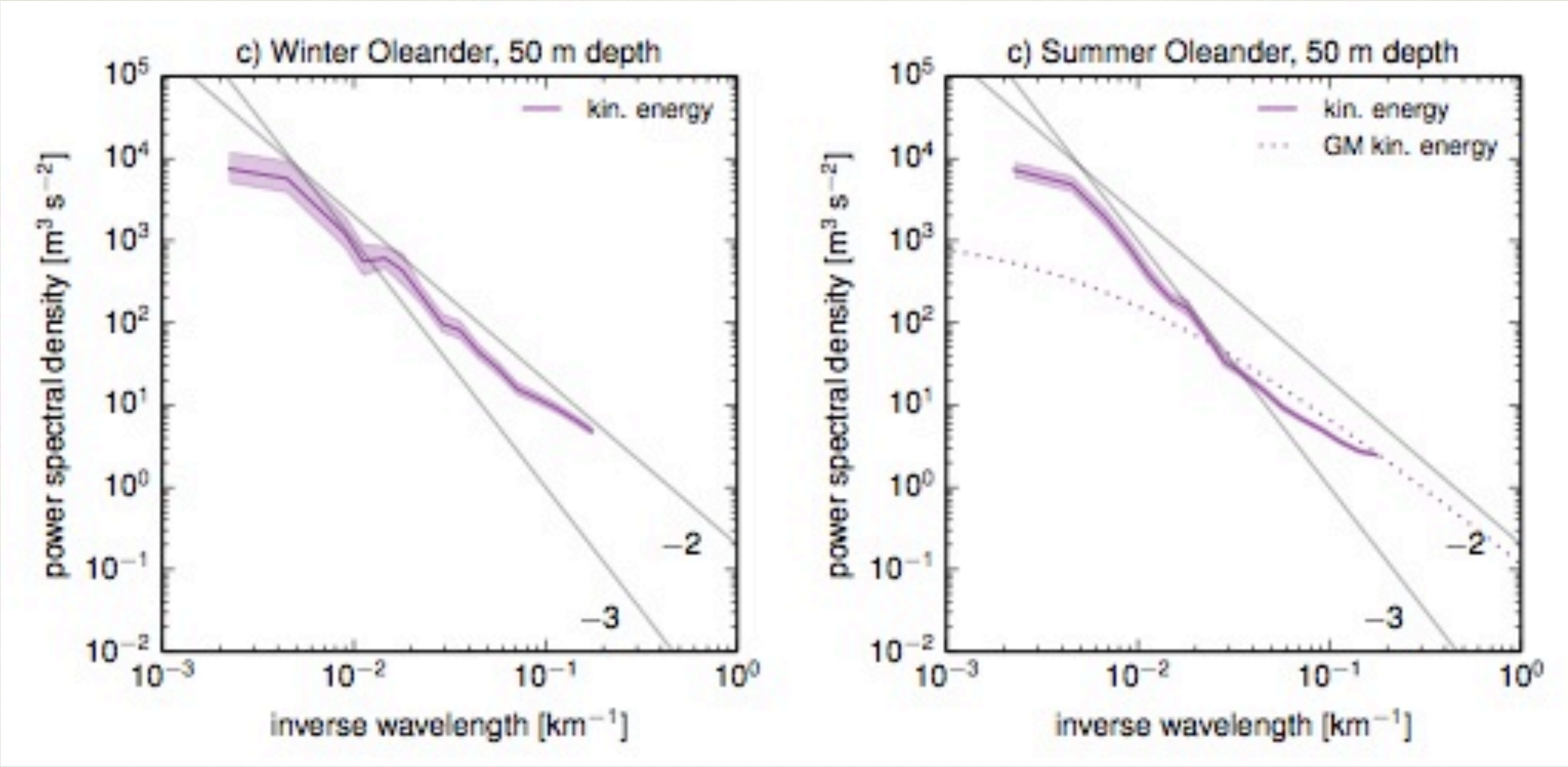
Observations



Seasonality of submesoscales

Seasonality consistent with dynamics driven by mixed layer instabilities

Winter (full model) Summer (no ML model)



Callies, Ferrari, Klymak and Molemaker (submitted)

Seasonality of submesoscales

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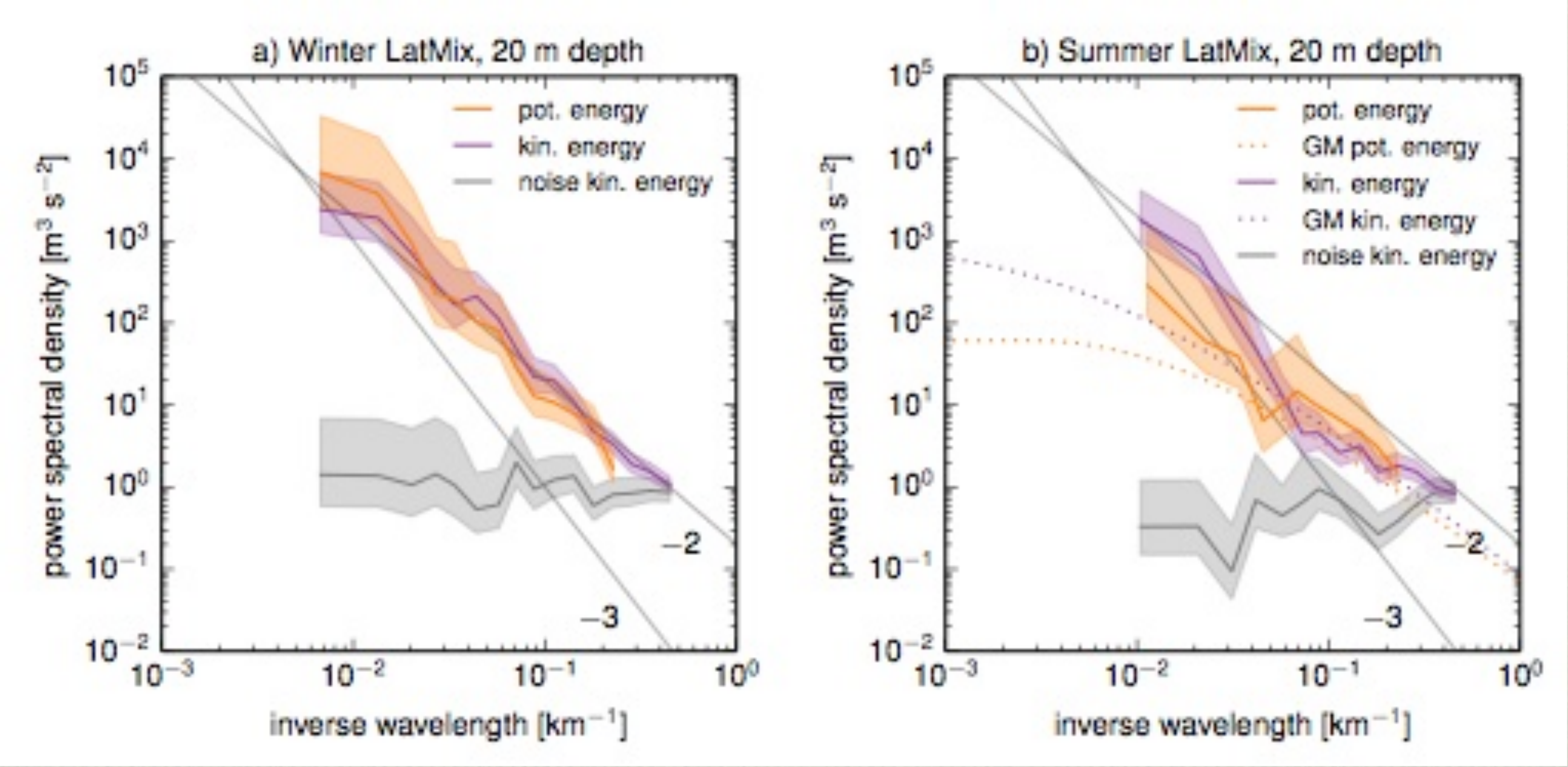
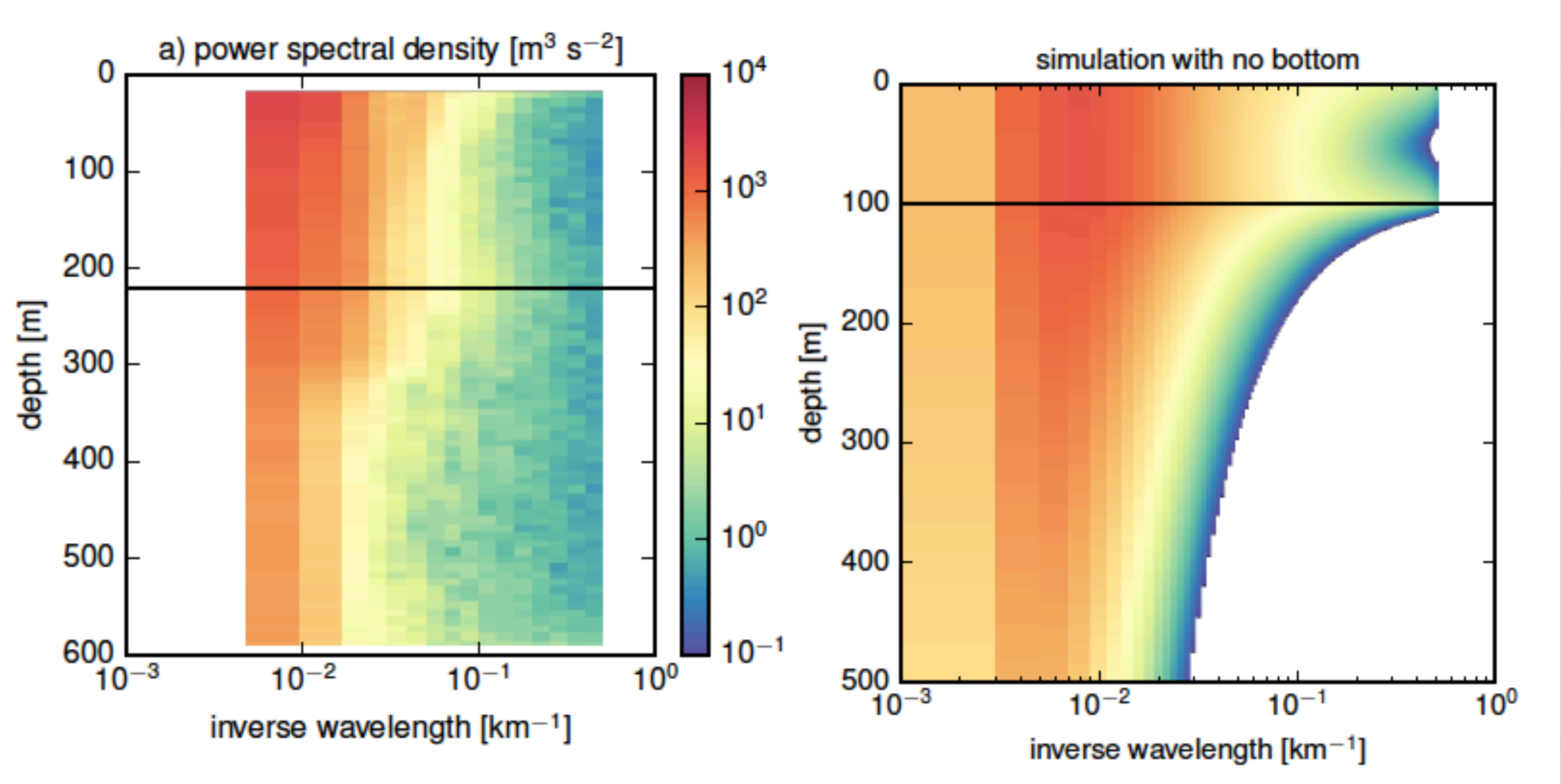


Callies, Ferrari, Klymak and Molemaker (submitted)

Vertical structure of submesoscales

Vertical structure of kinetic energy spectra consistent between observations and simulations



Callies, Ferrari, Klymak and Molemaker (submitted)

Conclusions

- A “novel” three layer QG model captures key aspects of submesoscale turbulence in the upper ocean
- The enhancement of submesoscale fronts by mixed layer instabilities is consistent with observations
- Vertical velocities are dramatically enhanced at fronts
- Submesoscale fronts drive strong exchange of tracers between mixed layer and deep ocean in winter