Basin-scale overturning circulation and the role of small-scale processes (lessons learned from the Baltic Sea)

Lars Umlauf

Peter Holtermann, Hans Burchard, Toste Tanhua, Jim Ledwell, Oliver Schmale

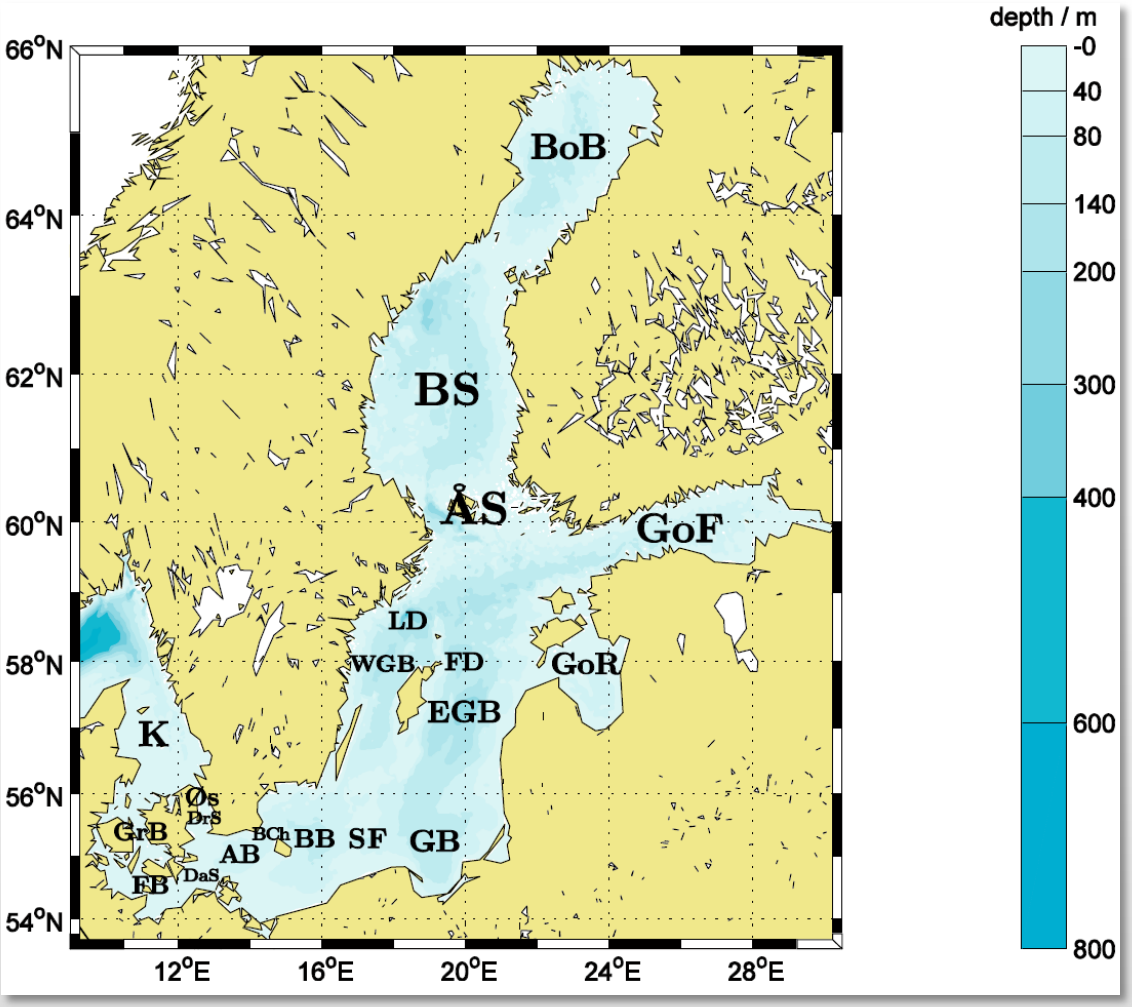
Leibniz Institute for Baltic Sea Research Warnemünde

Woods Hole Oceanographic Institution 1930

GEOMAR

DFG Deutsche Forschungsgemeinschaft

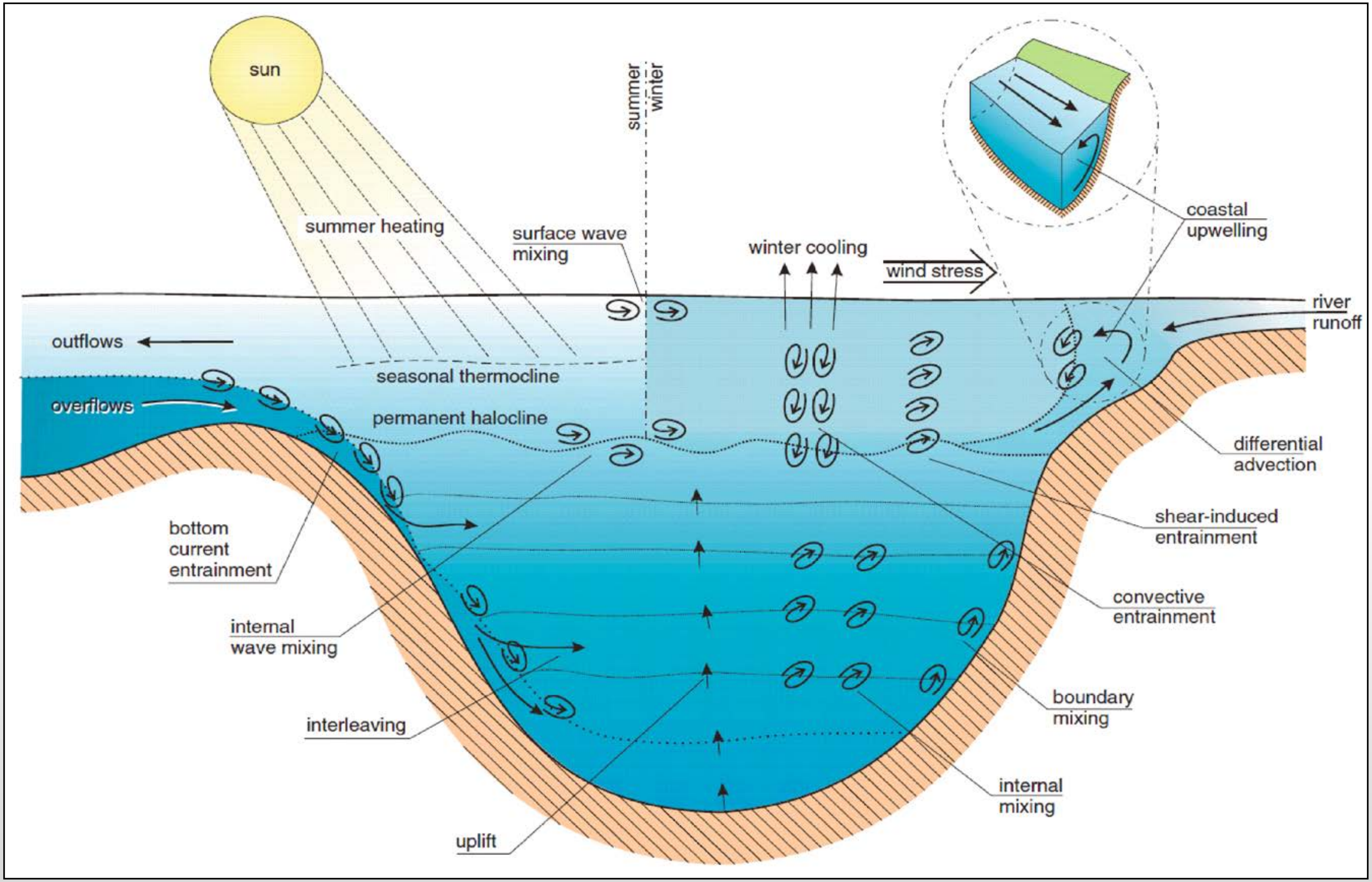
Baltic Sea - Overview



Reissmann et al. (2009)

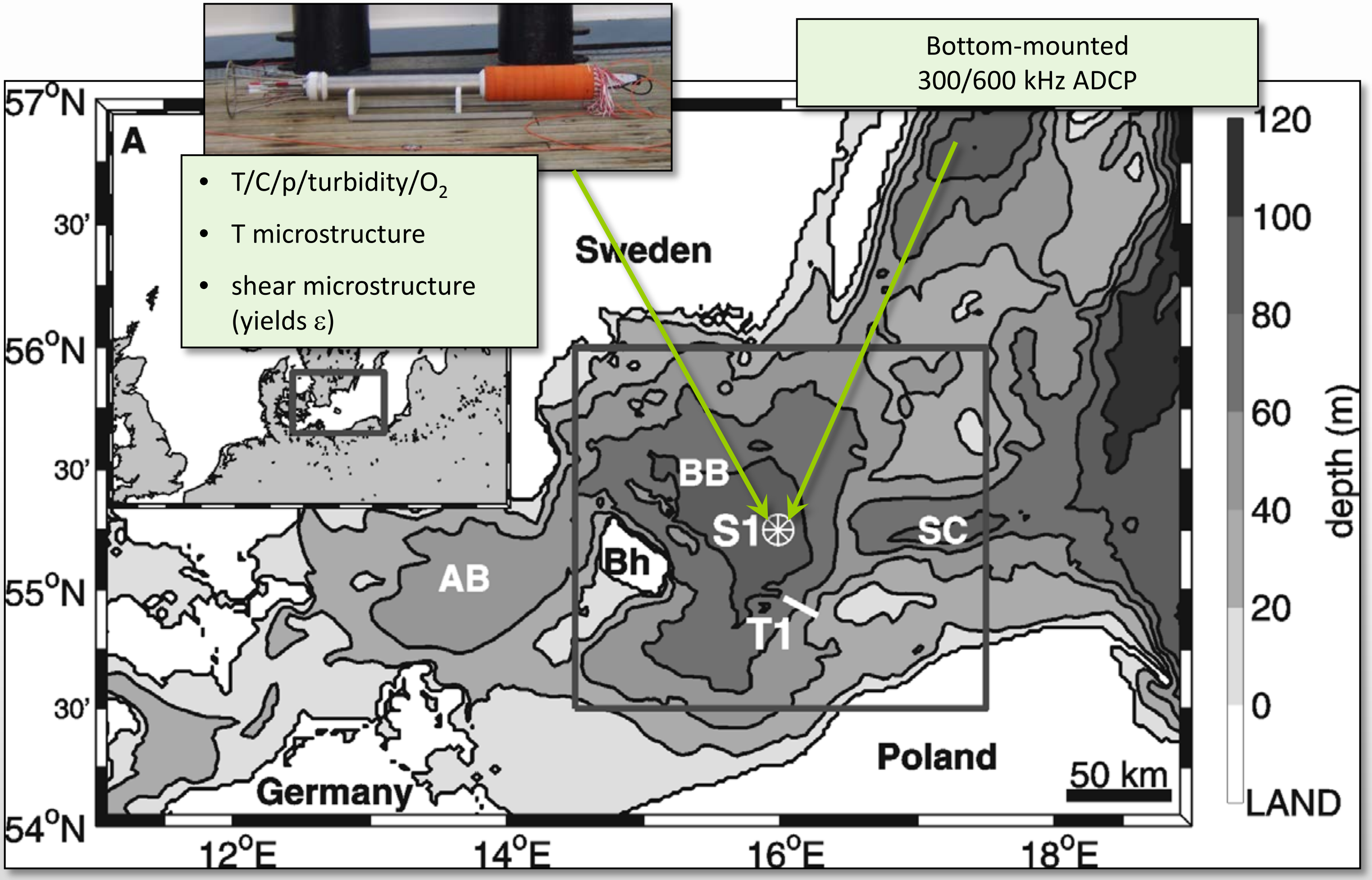
- lateral scale: 1000 km
- depth scale: 100 m
- no tides
- connection to North Sea
- strong salinity gradients (0-20 g/kg)
- deep-water renewal by dense bottom currents
- inertial period ~14 hours
- 1st mode Rossby radius 3-10 km

The role of mixing



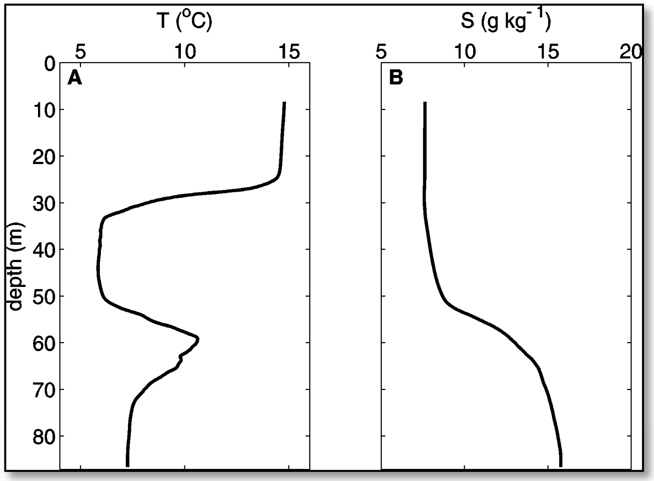
Reissmann et al. (2009)

Internal-Wave Mixing
(Bornholm Basin)



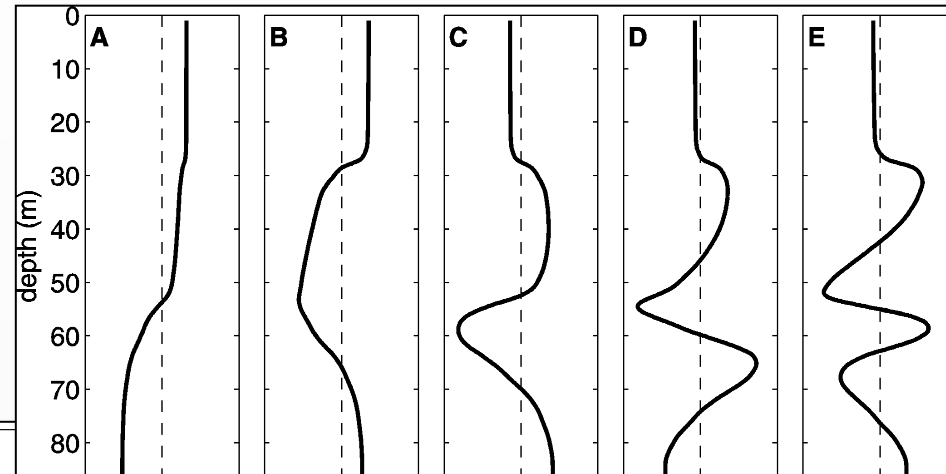
van der Lee and Umlauf (2011)

Late-Summer Conditions (September 2008)

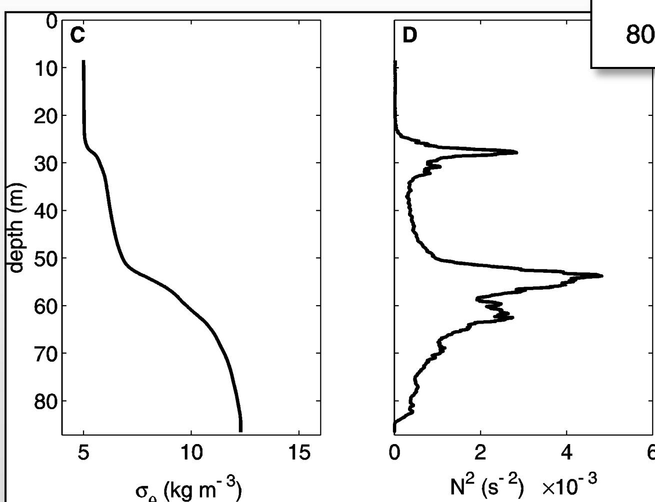


$$\frac{d}{dz}\left(\frac{1}{N^2}\frac{d\Psi_m}{dz}\right)+\frac{1}{c_m^2}\Psi_m=0$$

Low-mode structure



van der Lee and Umlauf 2011)

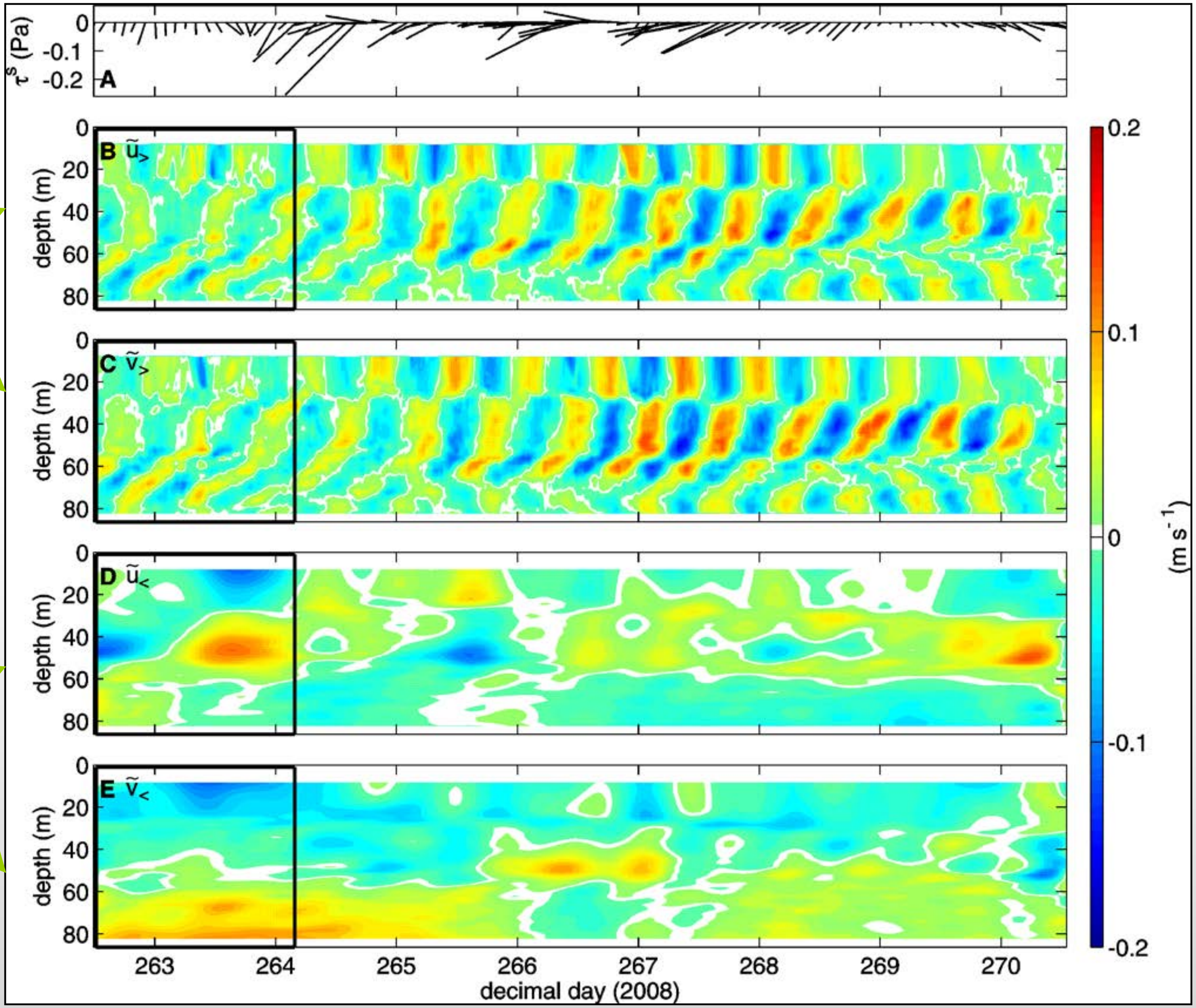


Near-Inertial Motions

Super-inertial

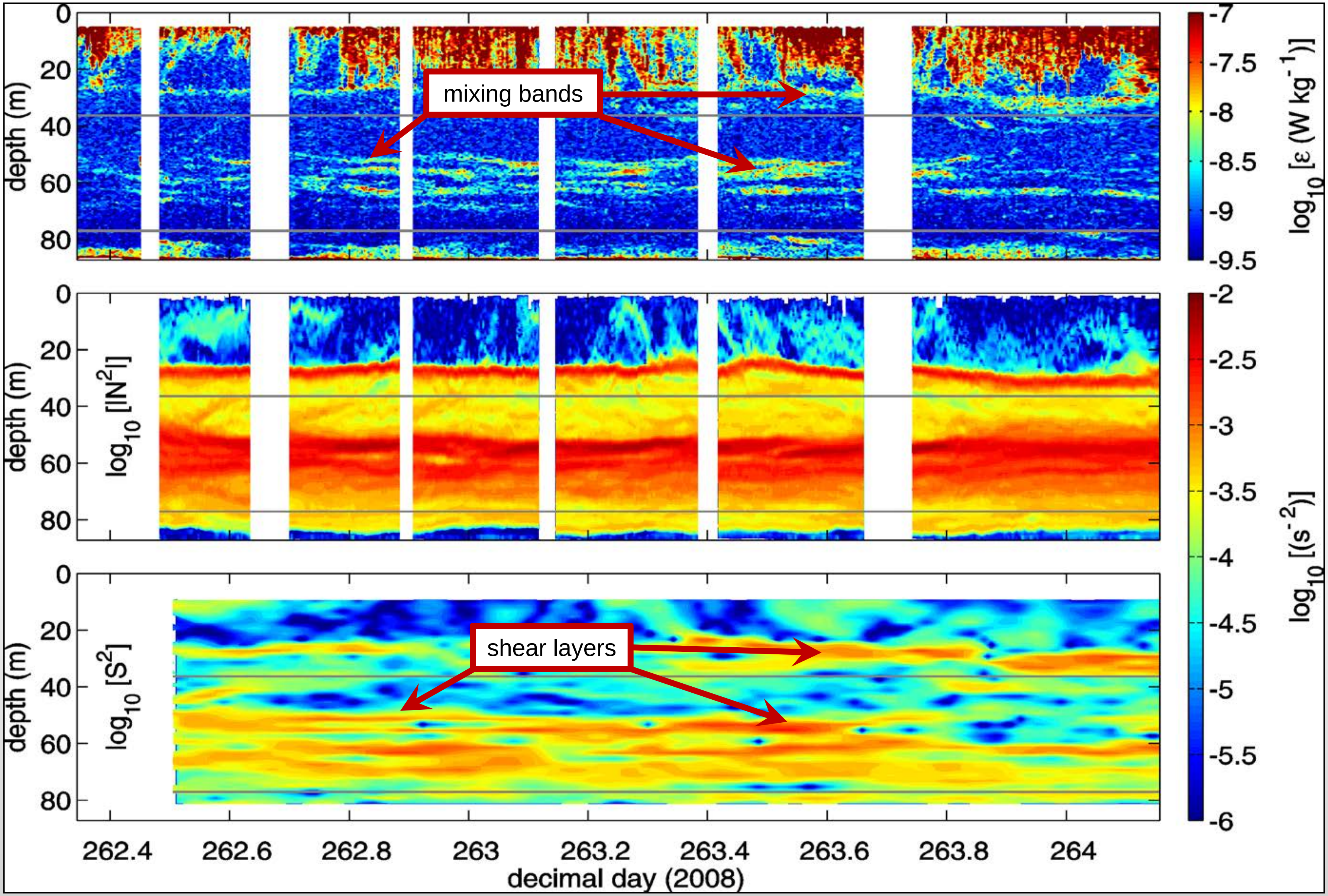
$T_f = 14.5\,\text{hours}$

sub-inertial

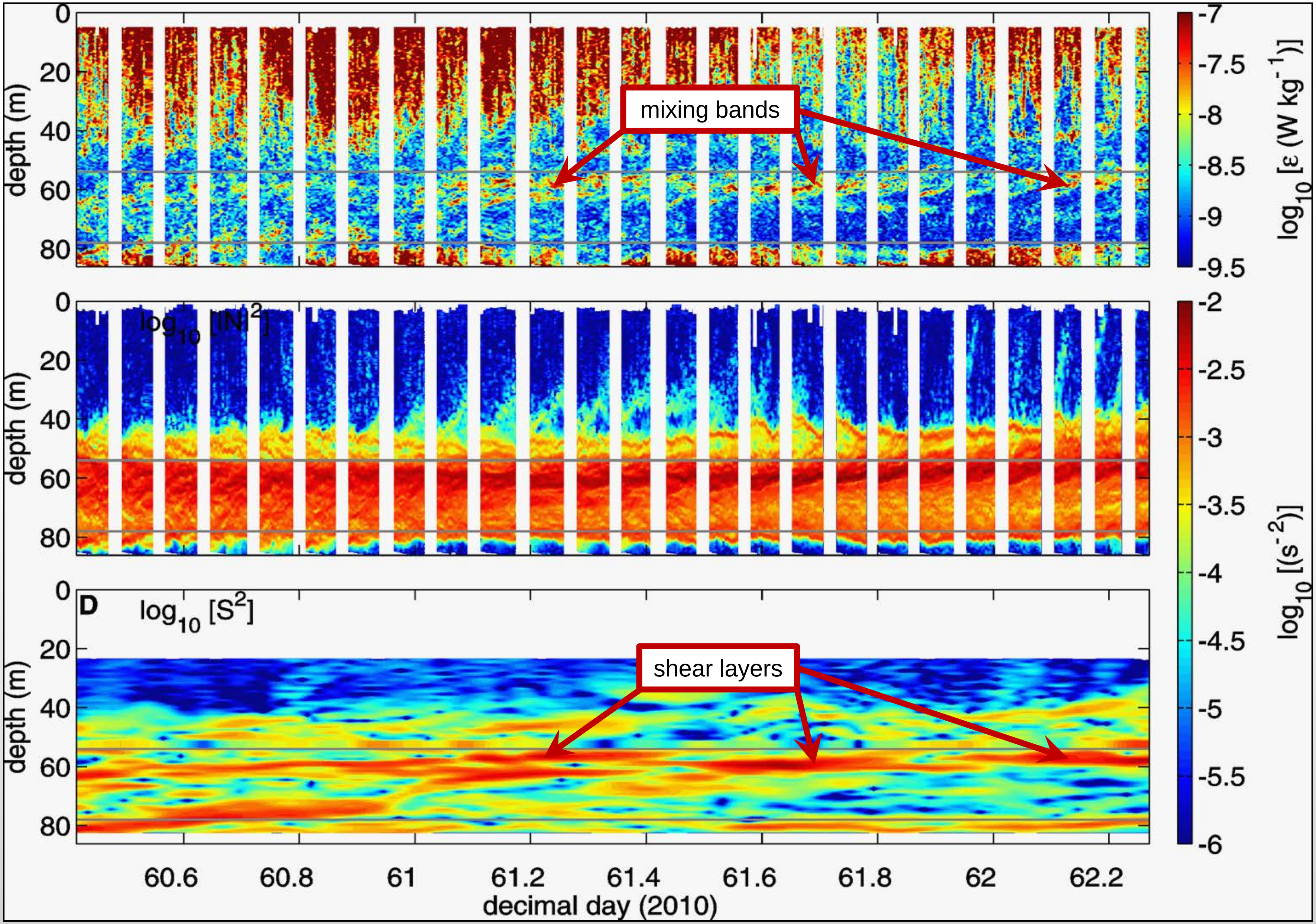


van der Lee and Umlauf (2011)

Summer Mixing (September 2008)

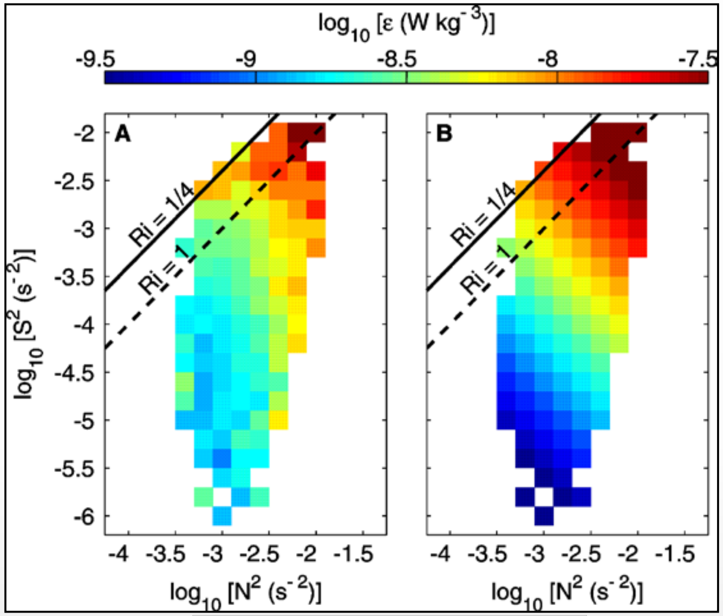


Winter Mixing (February 2010)



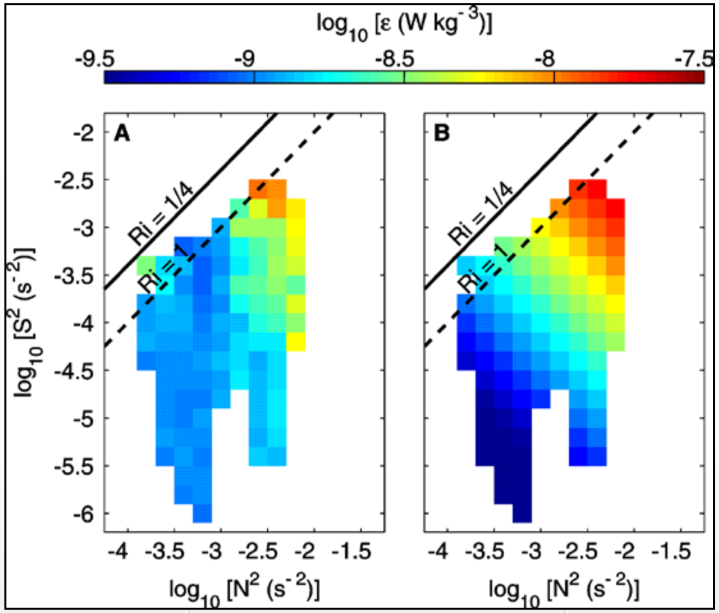
Scaling Internal-Wave Mixing

February 2010



$$\varepsilon_0 = 1.7\times10^{-10}\ \mathrm{W\ kg^{-1}}$$

September 2008



$$\varepsilon_0 = 1.5\times10^{-10}\ \mathrm{W\ kg^{-1}}$$

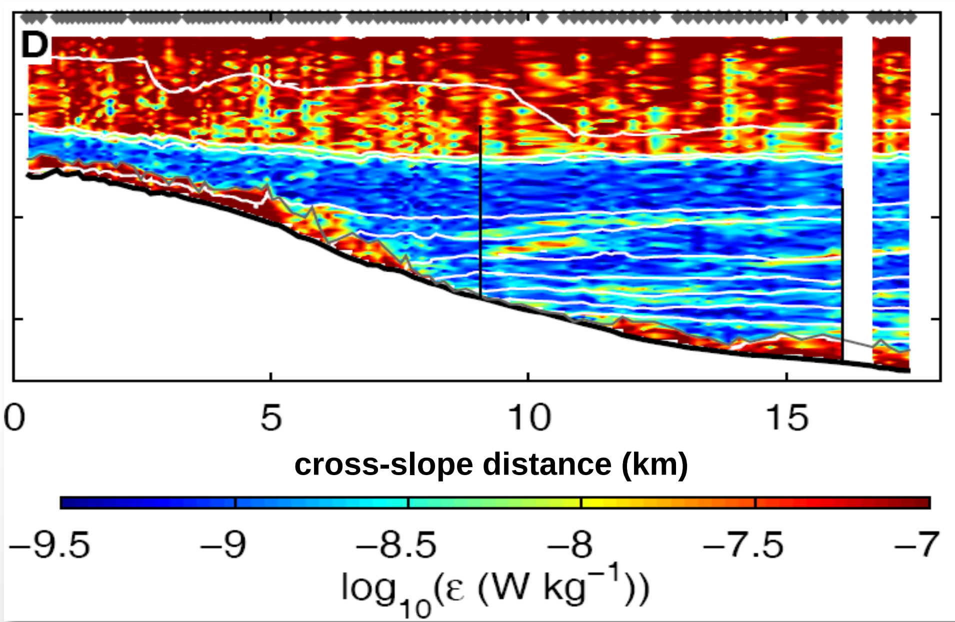
$$\varepsilon = \varepsilon_0 \frac{N}{N_0}\frac{S}{S_0}$$

$$N_0 = S_0 = 3\ \mathrm{cph}$$

(van der Lee and Umlauf, 2011
MacKinnon and Gregg, 2003)

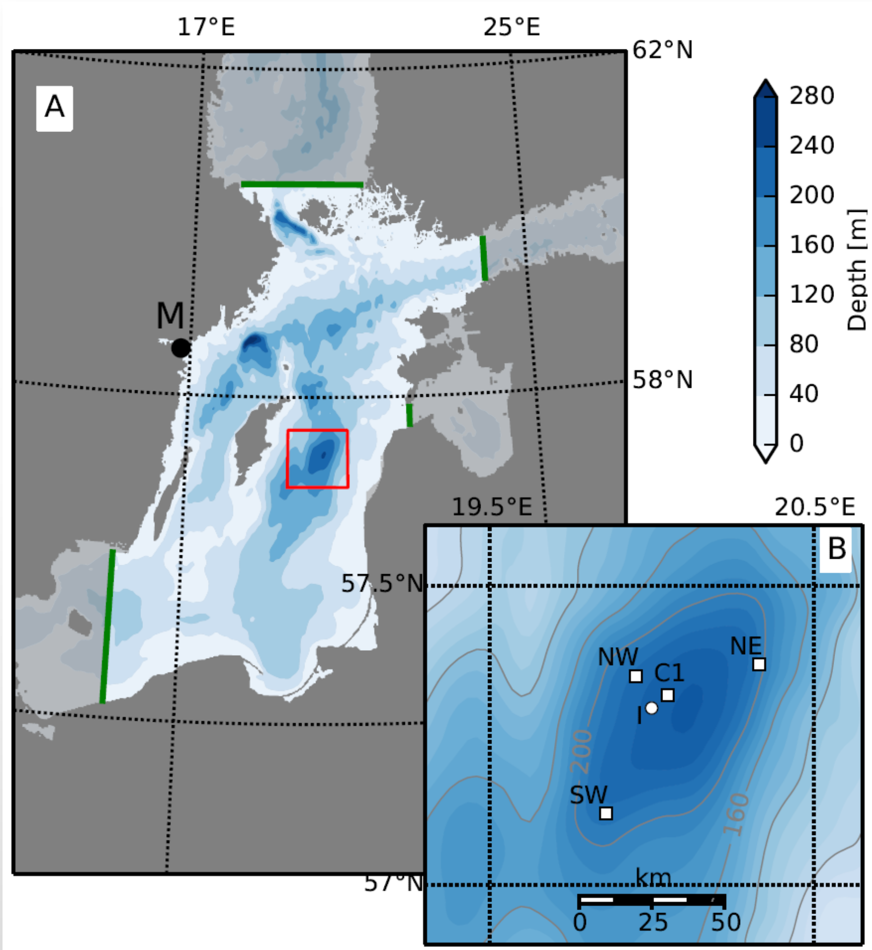
- Part of the shear is **sub-inertial**. Is this really an **internal-wave model**?
- Which motions cause the instability? Large-scale **near-inertial waves** or **short internal waves**?
- Is there an **internal-wave energy cascade** on the continental shelf?

Role of Boundary Mixing



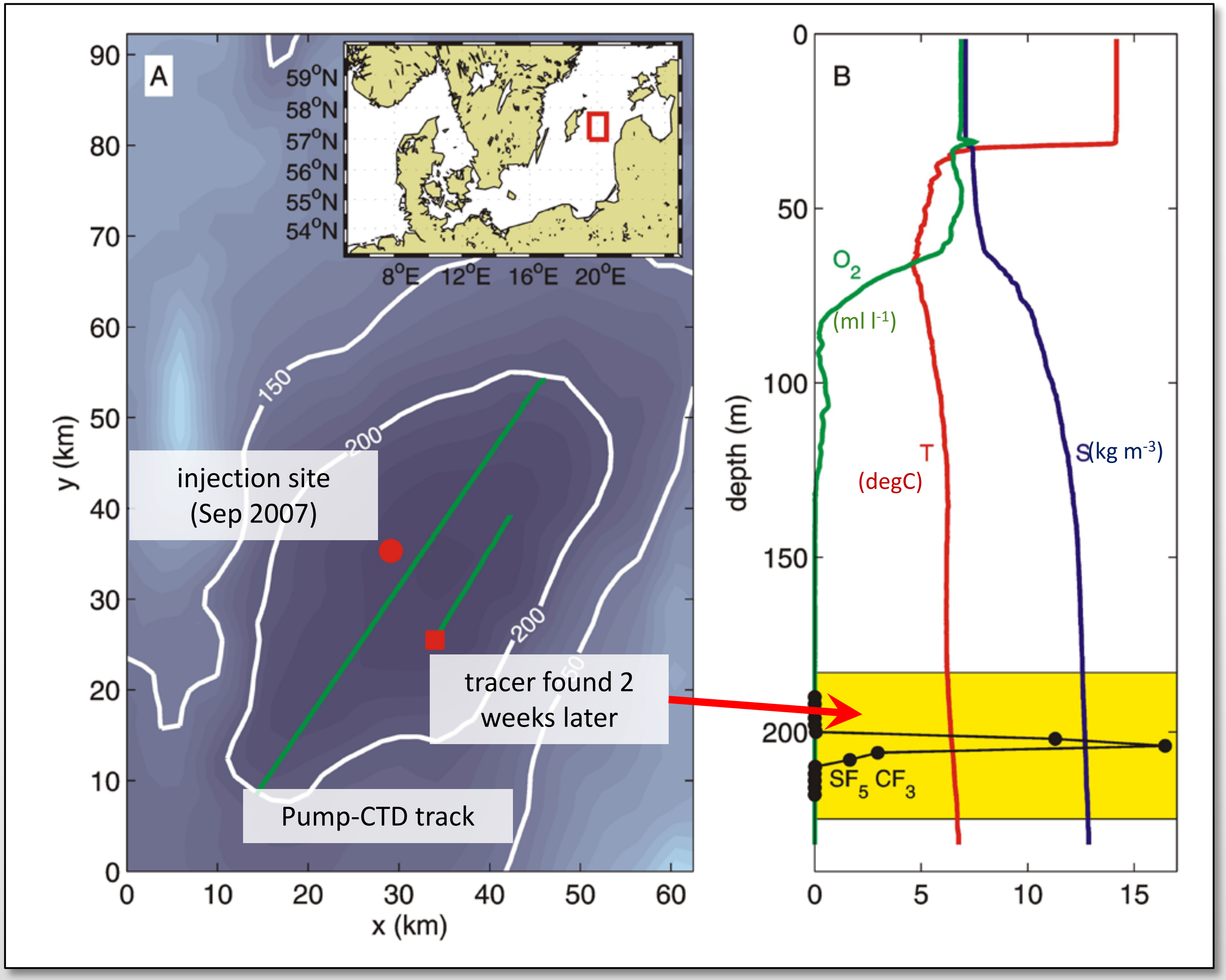
- Observed **interior mixing is too small** to explain basin-scale mixing
- There is direct evidence for **boundary mixing**.
- So where does the mixing actually occur?

Deep-water mixing processes

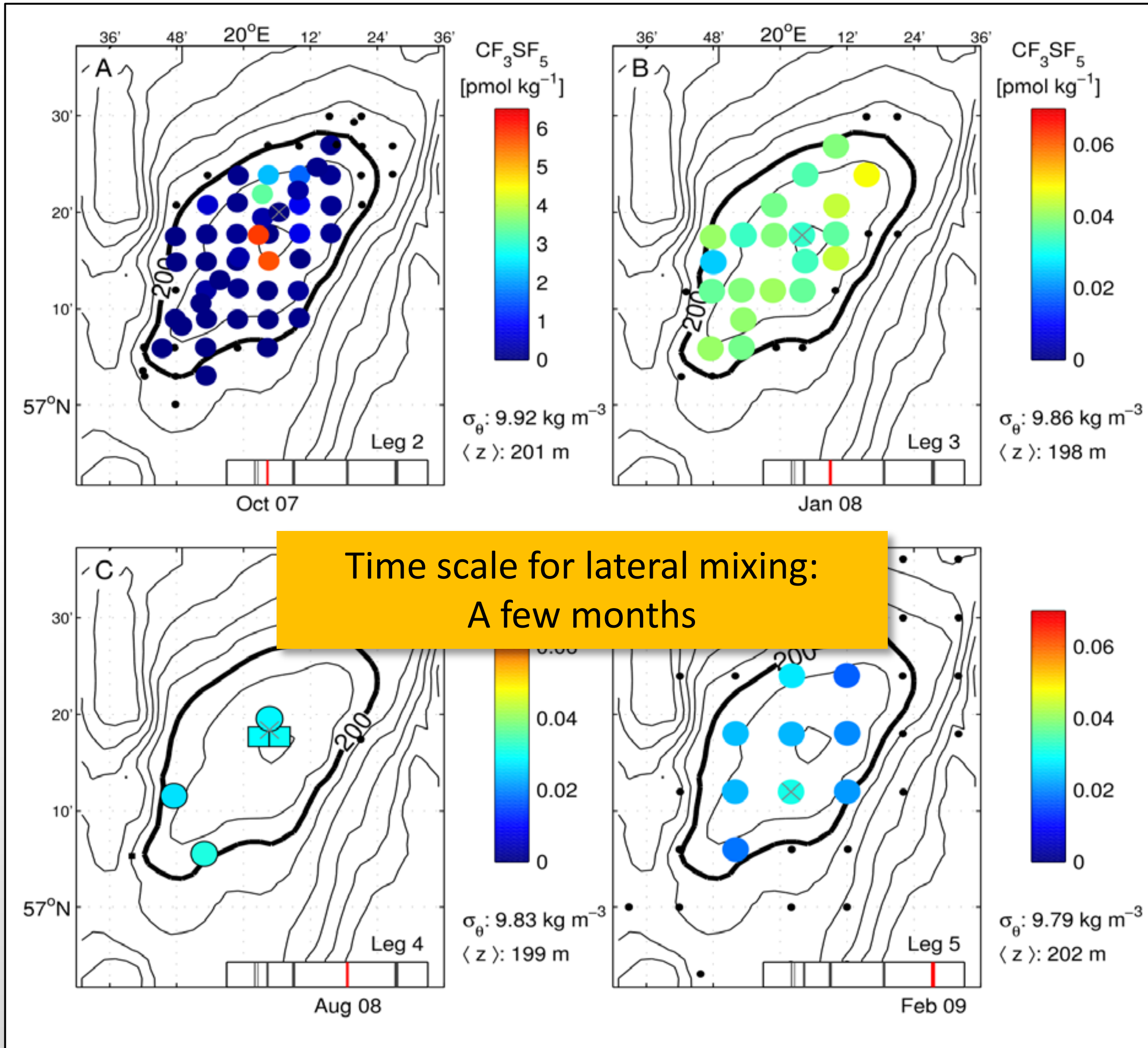


- Goal: **quantify and understand deep-water mixing** in the central Baltic Sea
- **Tracer experiment**, turbulence measurements, moorings, modeling
- **Mooring arrays** and turbulence measurements
- **High-resolution nested 3-D model (GETM)**
  - 600 m lateral resolution
  - vertically adaptive grid (Hofmeister et al. 2010)
  - Second-moment turbulence closure model

Location and Hydrography



Lateral Tracer Spreading



Time scale for lateral mixing:
A few months

Holtermann et al. (2012)

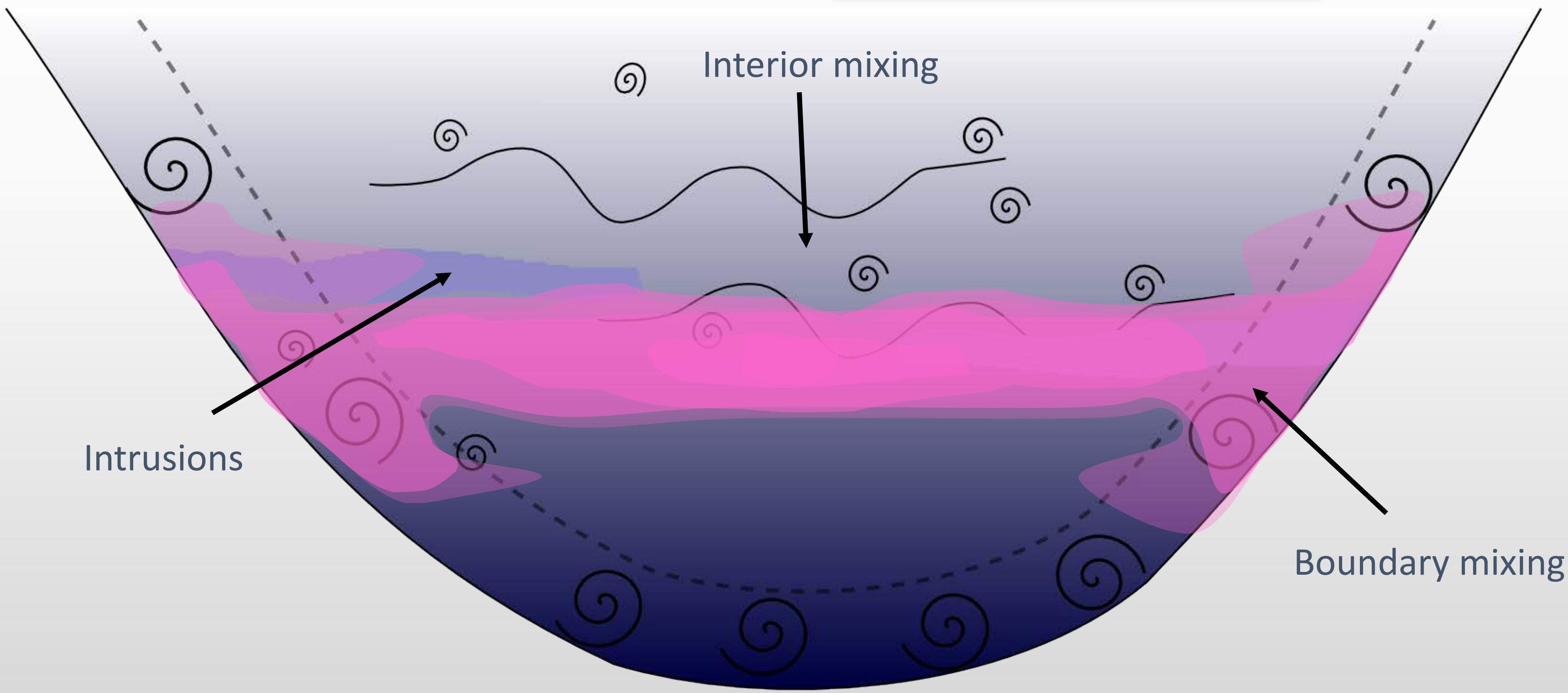
Vertical Mixing Rates

Initial stage
(before boundary contact):
$\kappa \sim 10^{-6}\ m^2\ s^{-1}$

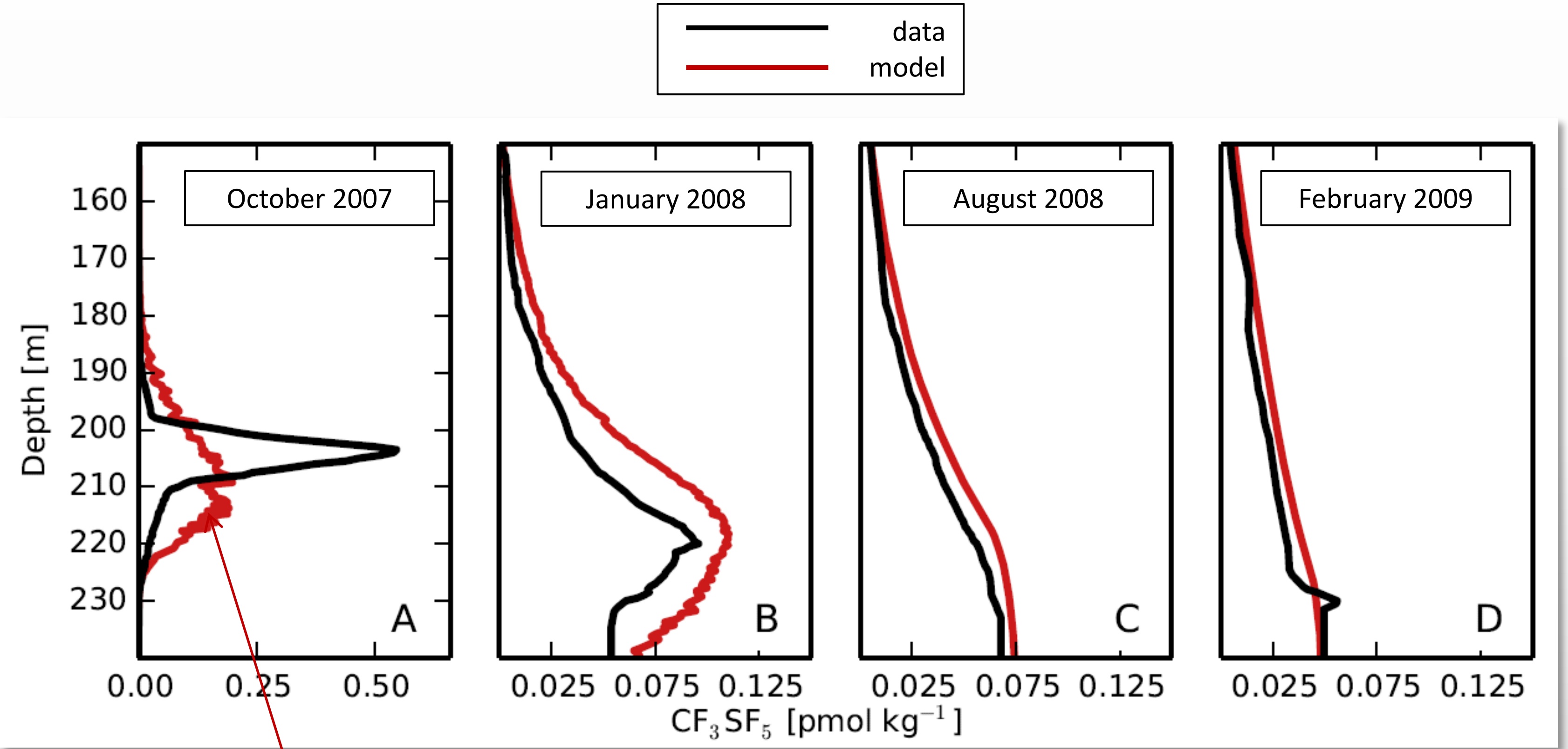
Late stage
(after boundary contact):
$\kappa \sim 10^{-5}\ m^2\ s^{-1}$

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial z}\left[\kappa_I \frac{\partial c}{\partial z}\right]$$

$$\frac{\partial c}{\partial t} = \frac{1}{A}\left[\frac{\partial}{\partial z}\left(A\kappa \frac{\partial c}{\partial z}\right)\right]$$



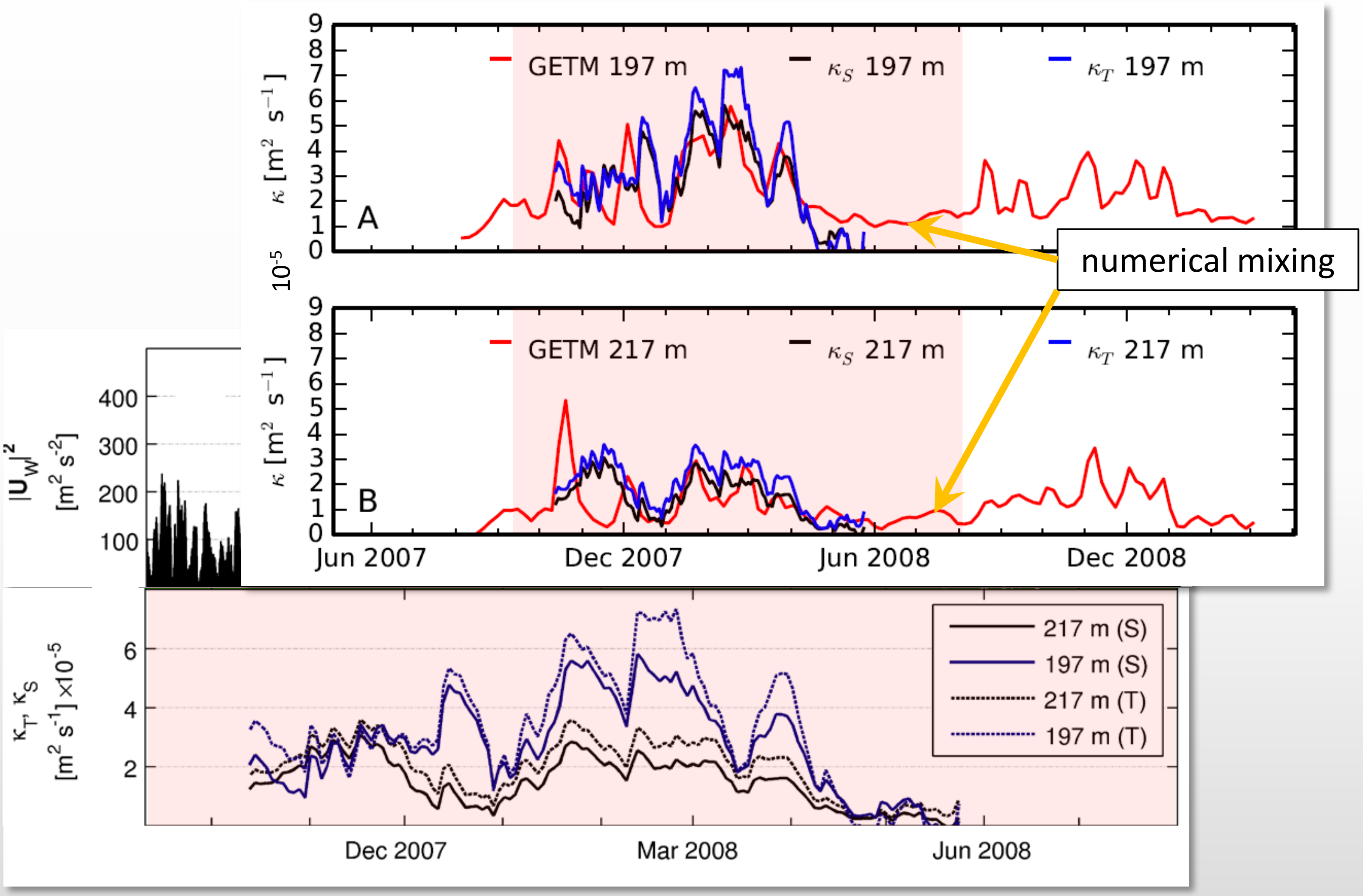
Numerical Model Results



Holtermann et al. (2014)

- model feels **boundary mixing** too early
- **numerical mixing** important during initial period of the experiment

Seasonal Variability of Mixing

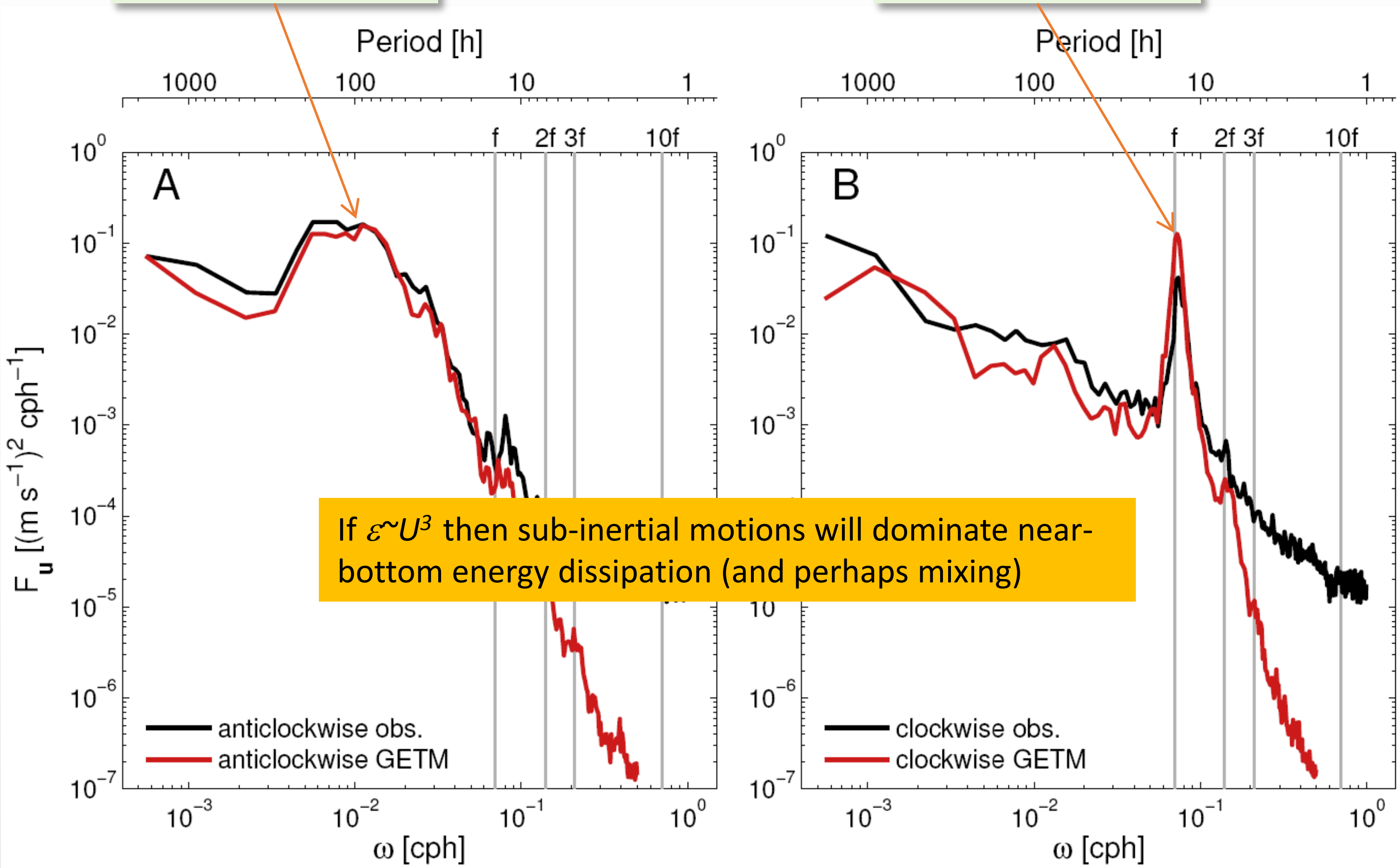


Holtermann and Umlauf (2012)

Deep-Water Dynamics

sub-inertial motions (anti-clockwise)

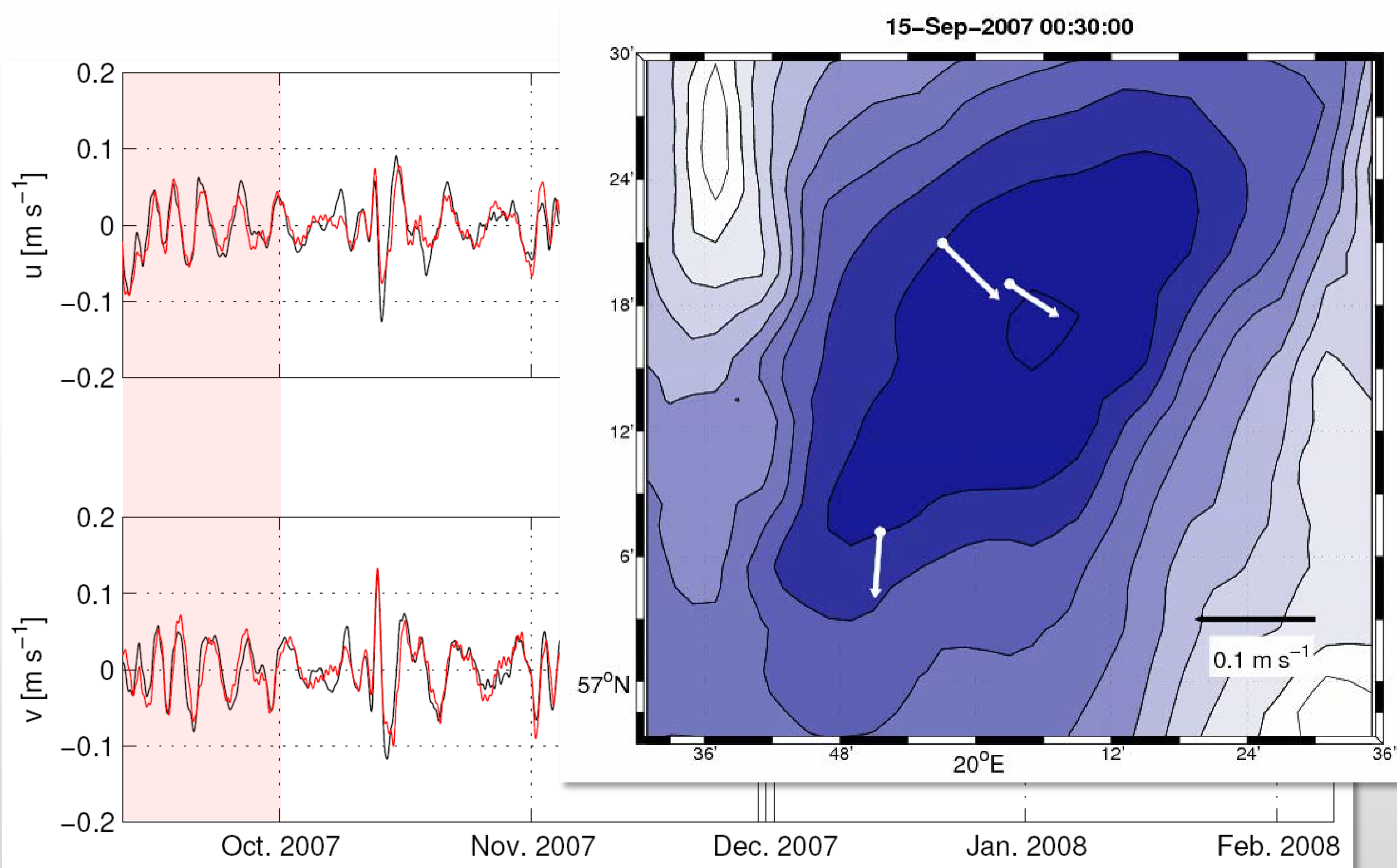
near-inertial waves (clockwise)



If $\varepsilon \sim U^3$ then sub-inertial motions will dominate near-bottom energy dissipation (and perhaps mixing)

Holtermann and Umlauf (2012)
Holtermann et al. (2014)

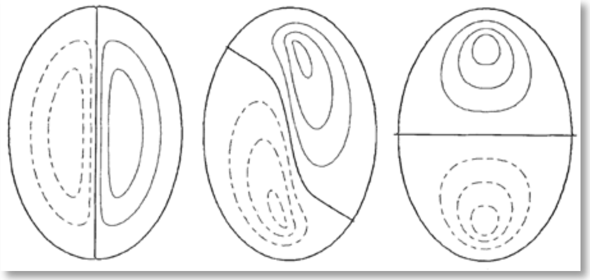
Sub-Inertial Variability



Holtermann et al. (2014)

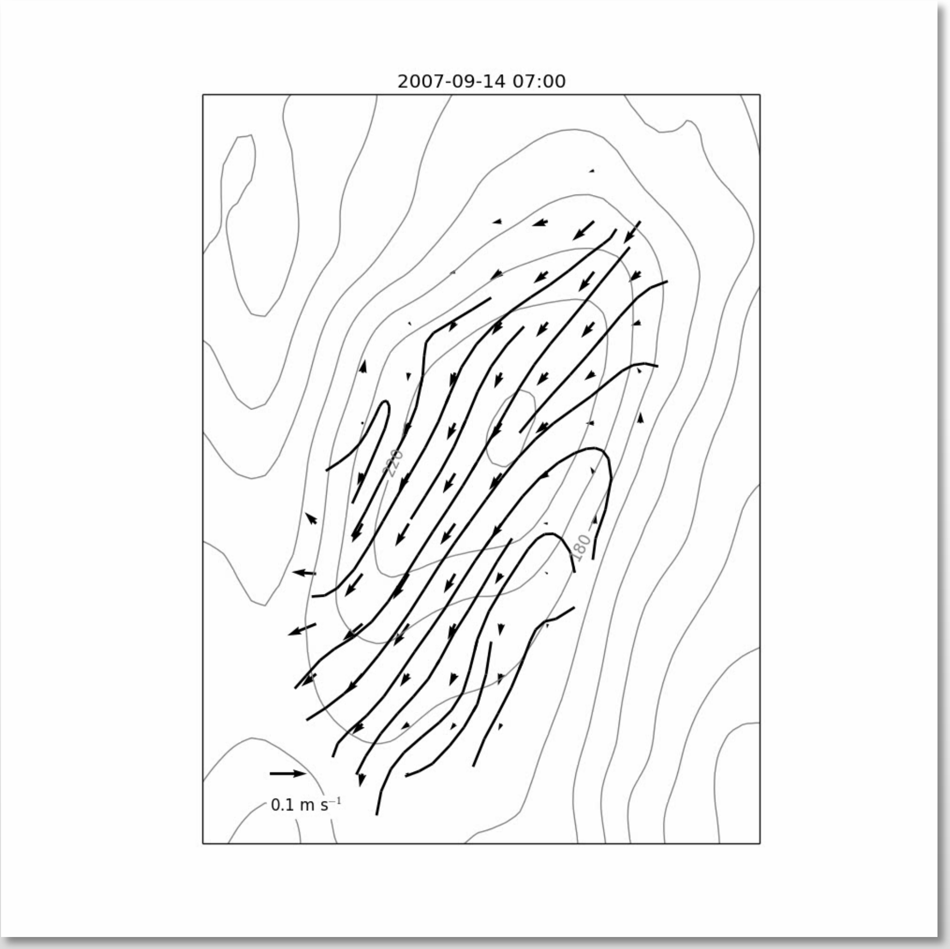
Basin-Scale Topographic Waves

The „Ball“ Mode (Ball 1965)

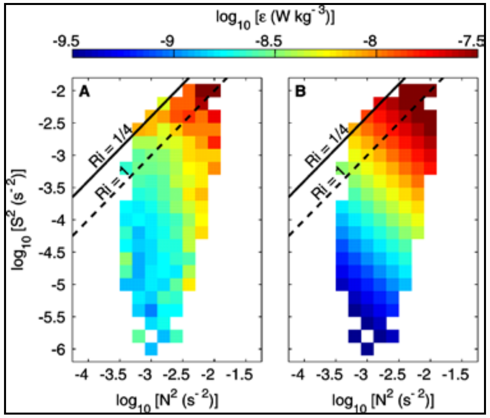


Johnson (1986)

3-5 day topographic wave mode (mixed barotropic-baroclinic)

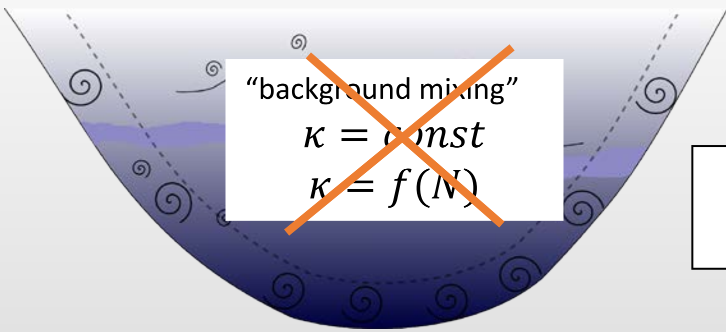


Conclusions



- **Near-inertial waves** dominate internal-wave band
- **Dissipation rates scale with N and S**, similar to the shelf.
- **Energetics and mechanisms** of internal-wave mixing unclear
- **Energy-consistent implementation** unclear

Numerical Models



BATRE