Internal Waves and Mixing in the Coastal Ocean

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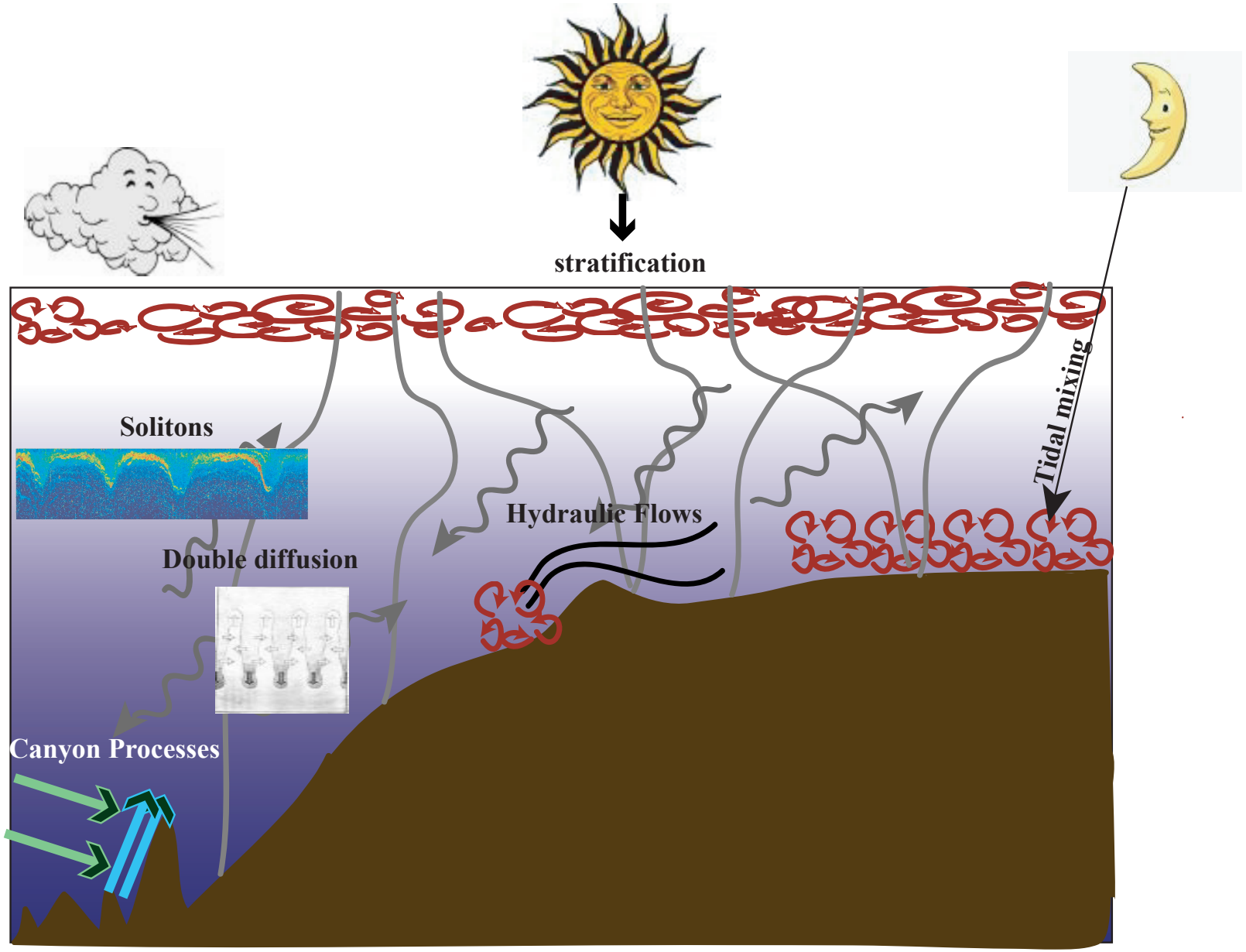
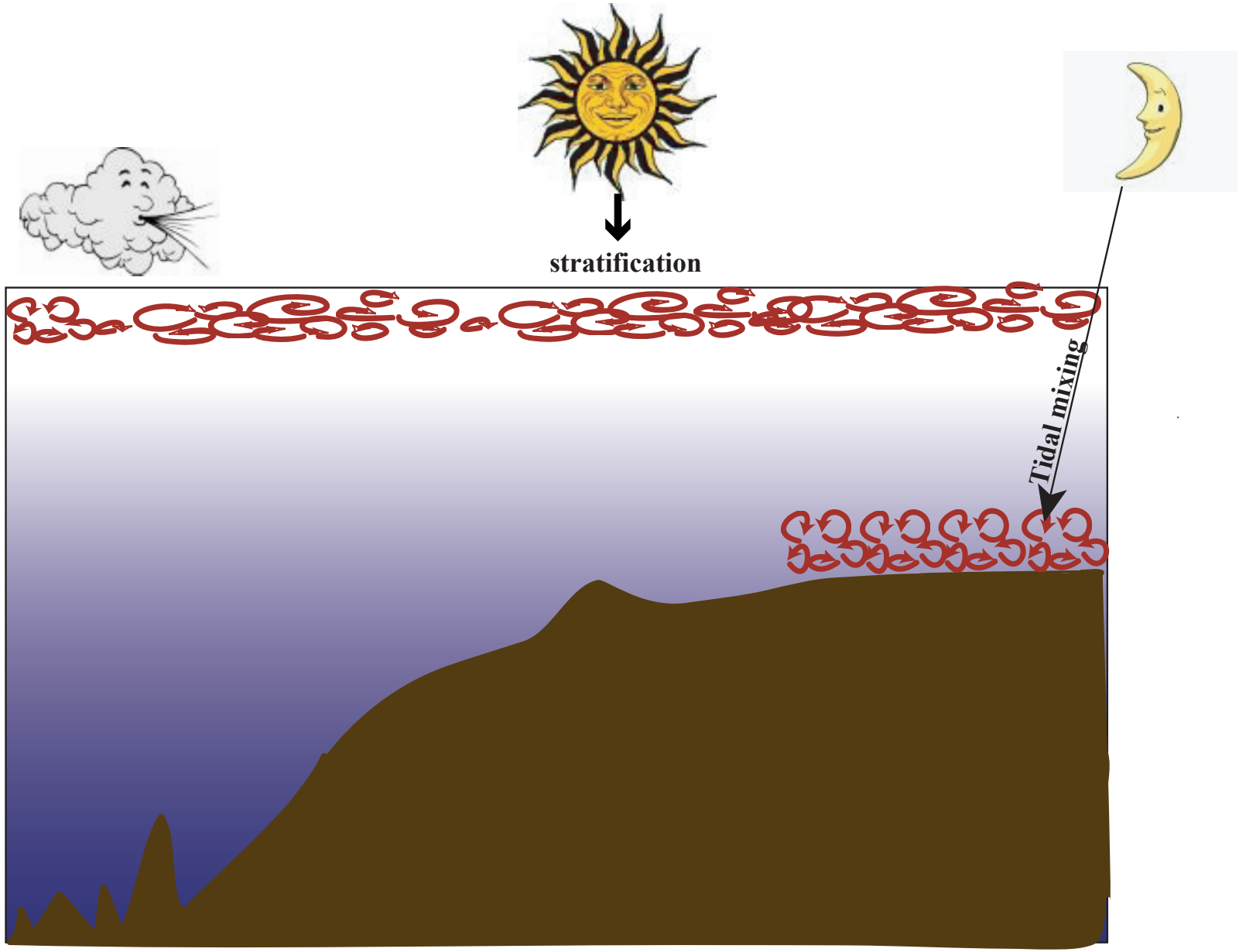
Coastal mixing mechanisms

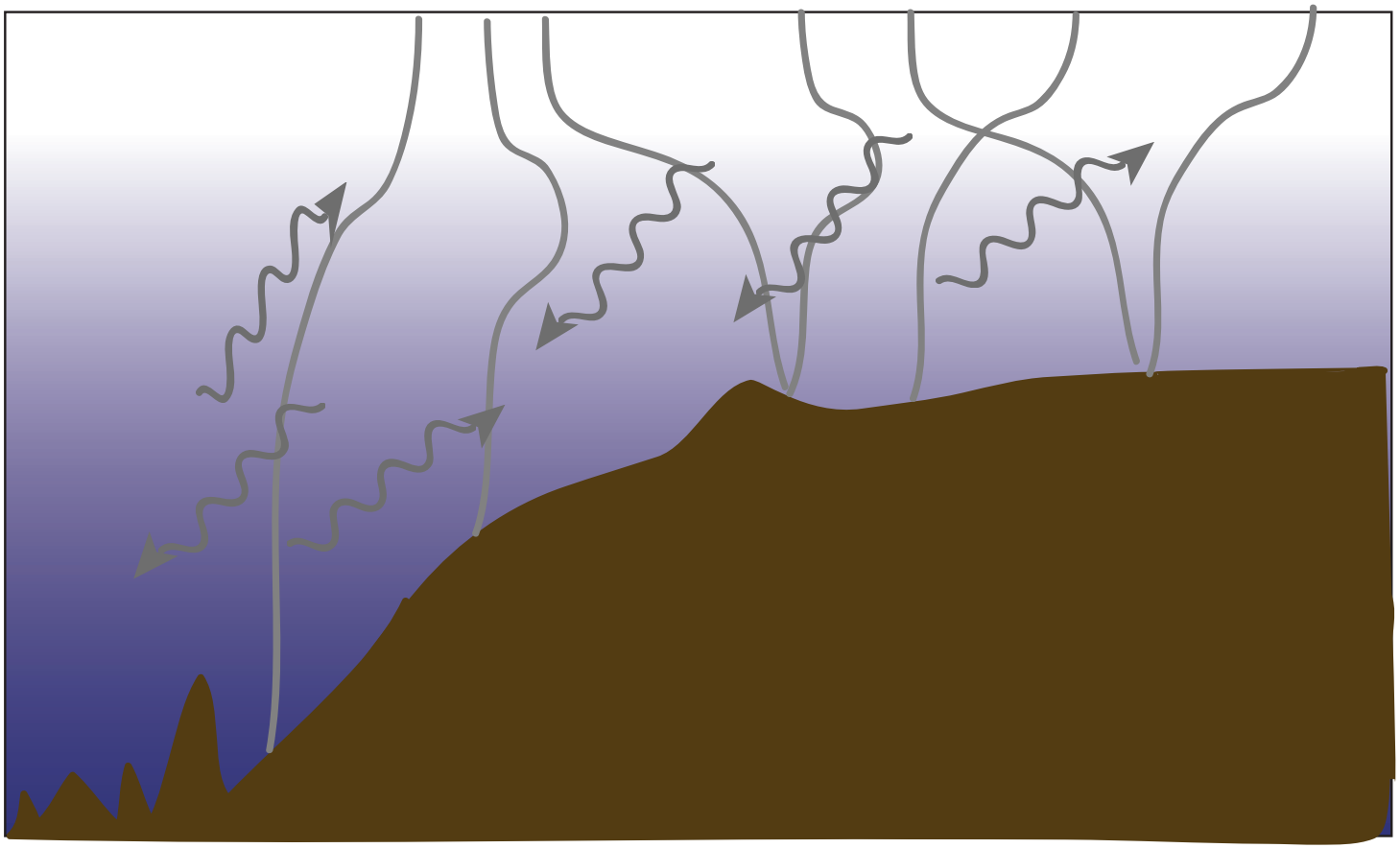


What mixing do models include?



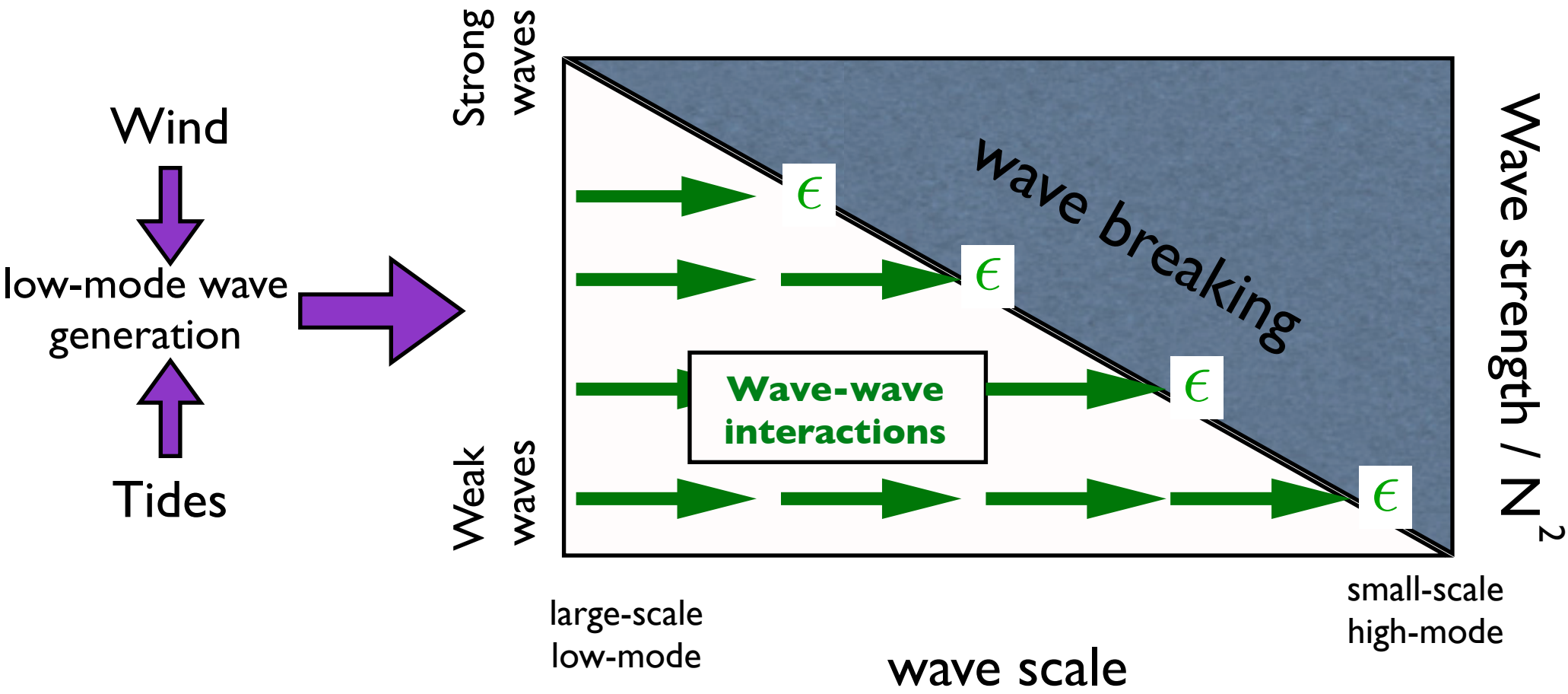
Internal-wave mixing as the next step

- models are or can resolve lowest-mode internal waves
- higher modes can be approached with statistical model
- similar dynamics from place to place



What makes internal-waves break?

- Simplistically, when shear overcomes stratification: $\mathrm{Ri}^{-1} \geq 4$
- If lowest modes are stable, energy transfers to smaller (vertical) scale waves until shear is large enough for wave to break

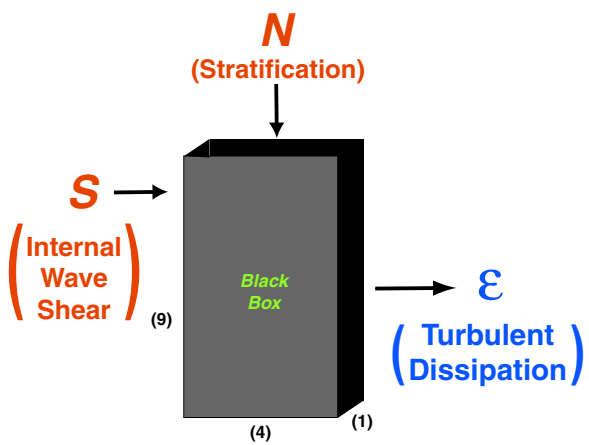


Outline

1. Descriptive look at internal waves, turbulence and mixing from the Coastal Mixing and Optics (CMO) experiment

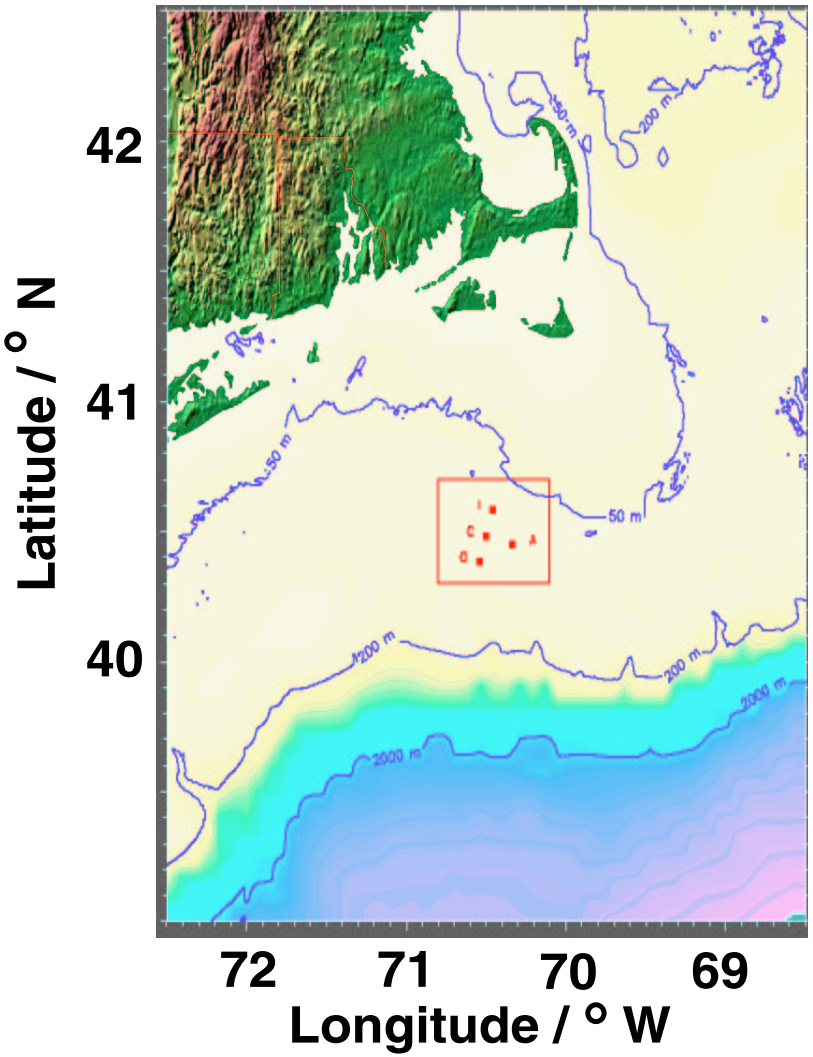
2. Quest for a physically-based parameterization of internal-wave mixing as a function of resolvable properties

$$K_\rho \approx \frac{0.2}{N^2} \quad \epsilon(S, N, f, ...?)$$

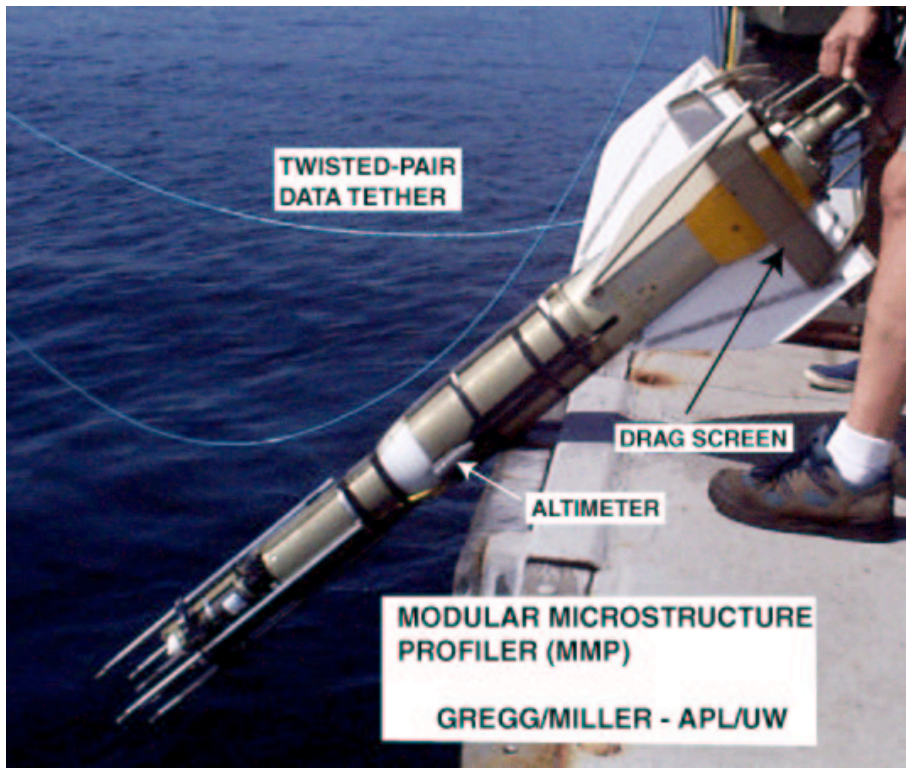


Coastal Mixing and Optics Experiment

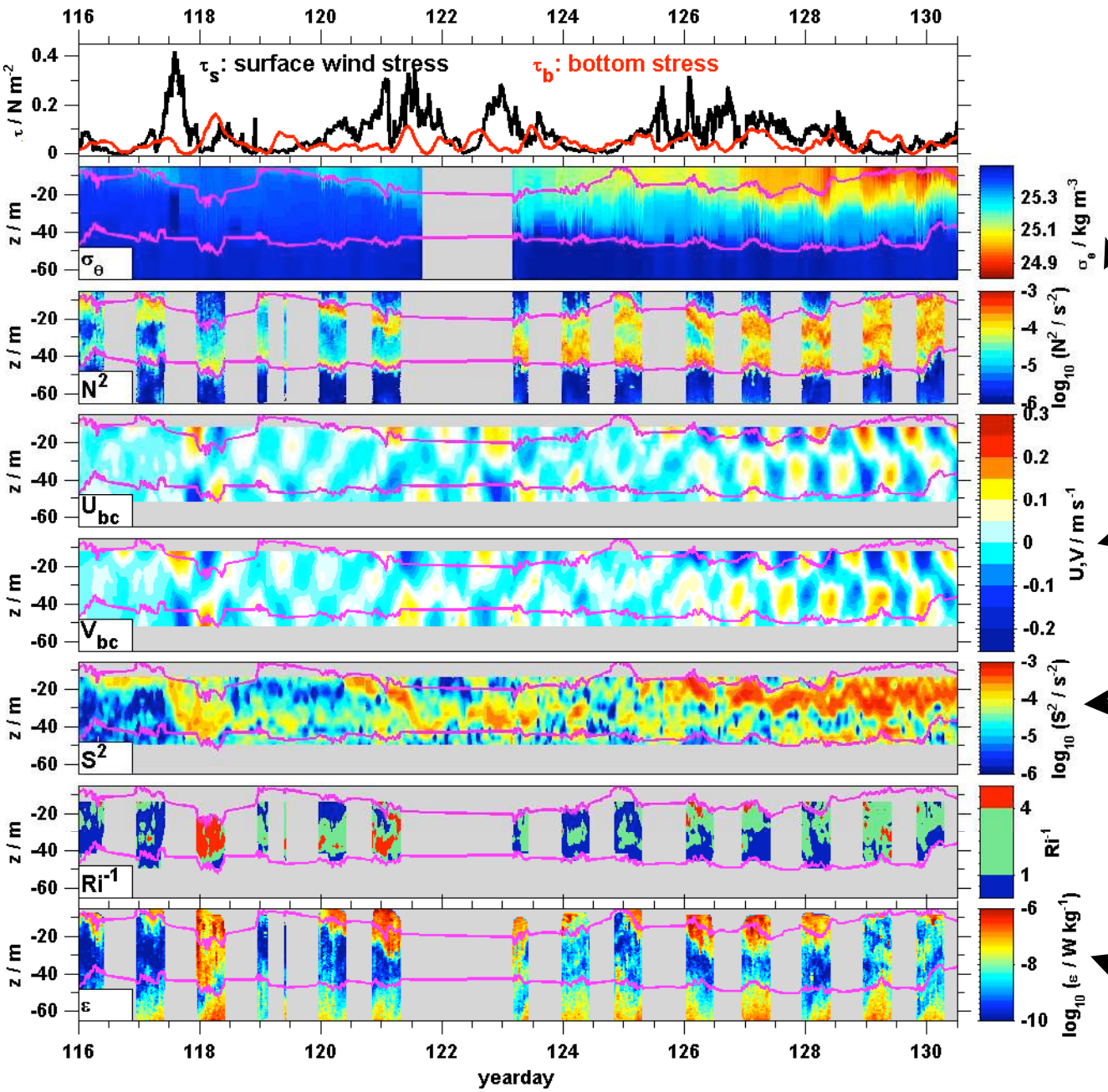
Summer 1996 and Spring 1997



- Modular Microstructure Profiler
- Shipboard ADCP

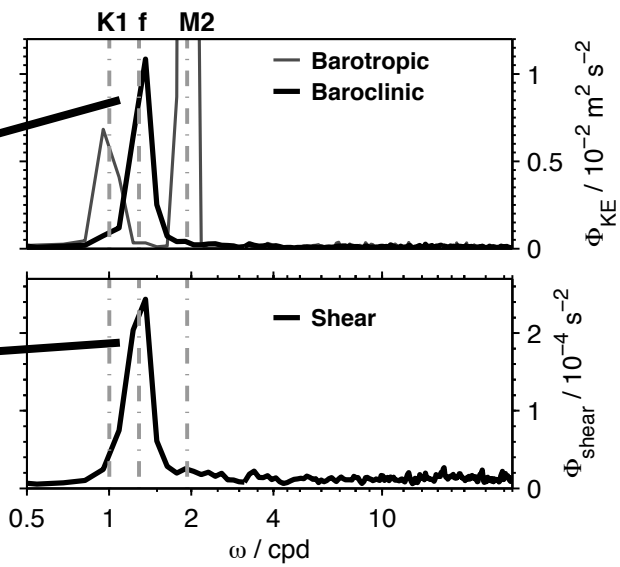


Waves and mixing during spring restratification



Growing stratification from surface heating

Near-inertial shear

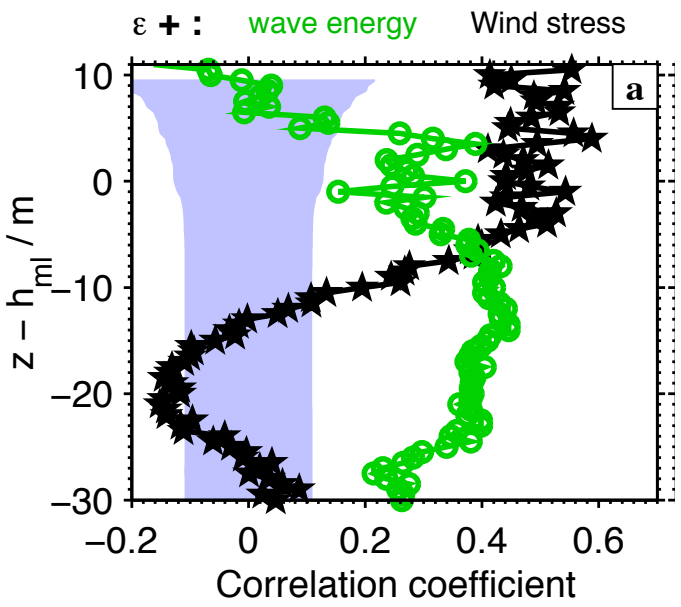


Strongest turbulence boundary-driven

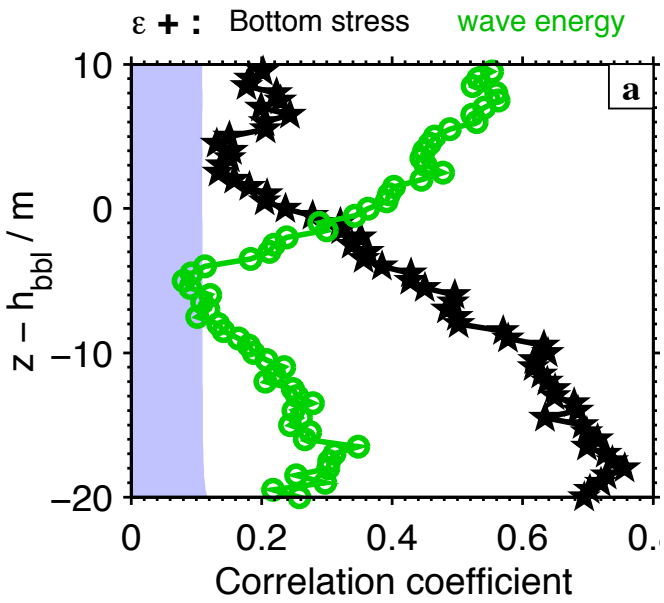
Mid-column turbulent mixing

What controls turbulent mixing in the thermocline? Though weaker, it's a chokepoint for transporting heat downwards and nutrients upwards.

below the surface boundary layer



above the bottom boundary layer



Turbulent dissipation away from boundary layers correlated with internal-wave energy.

Strong mixing during early spring storms

Rotating wind stress

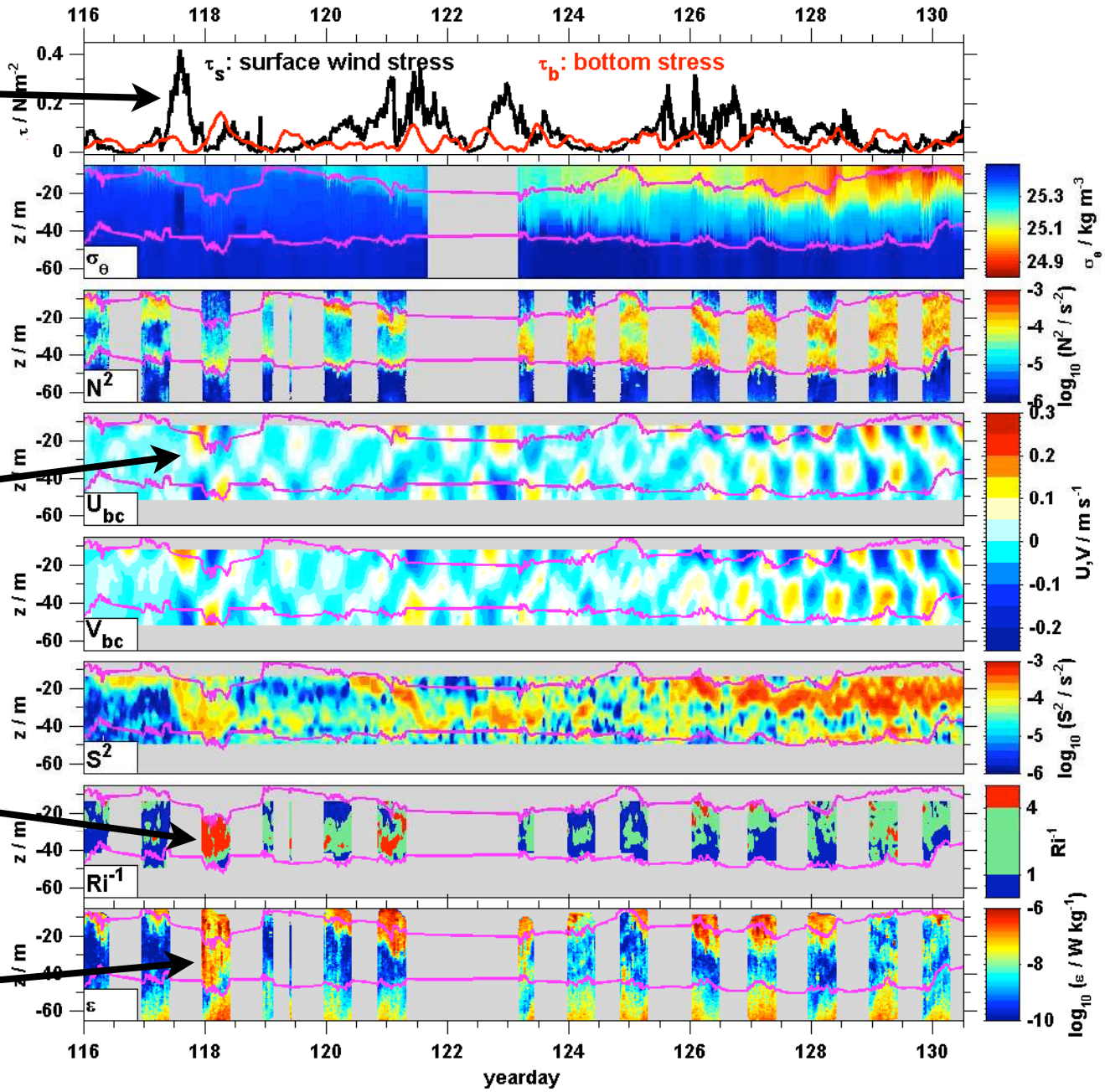
Near-inertial wave

(dies quickly)

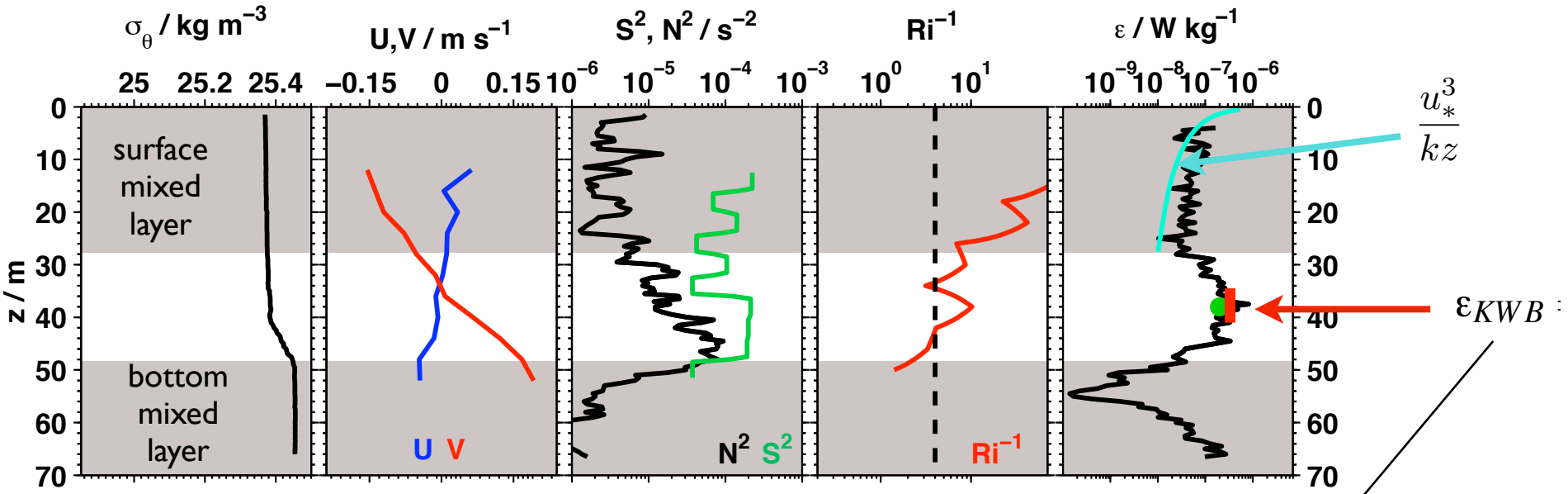
Super-critical

Richardson number

Strong turbulence



Early spring: "strong" mixing regime



Supercritical Richardson numbers

- Strong mixing ($K_\rho \geq 10^{-3}$ m s^{-2})
- Richardson-number base dissipation scalings acceptable

$$\varepsilon_{KWB} = (\Delta z)^2 \left\langle \left[\frac{S^2 - 4N^2}{24} \right] \left[\frac{S - 2N}{4} \right] \right\rangle \quad [\mathrm{W\,kg^{-1}}],$$

Mixing deepens stratification

Suface buoyancy flux from solar heating

$$6.8 \times 10^{-8} \ [\mathrm{W\ kg^{-1}}]$$

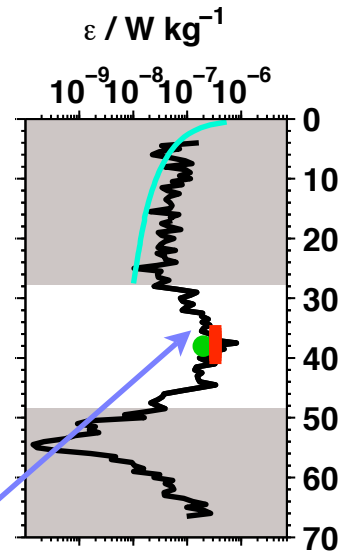
Carried downward by mid-column turbulent buoyancy fluxes

$$4 \times 10^{-8} \ [\mathrm{W\ kg^{-1}}] \approx 0.2 \times 2 \times 10^{-7} \ [\mathrm{W\ kg^{-1}}]$$

downward buoyancy flux

mixing efficiency

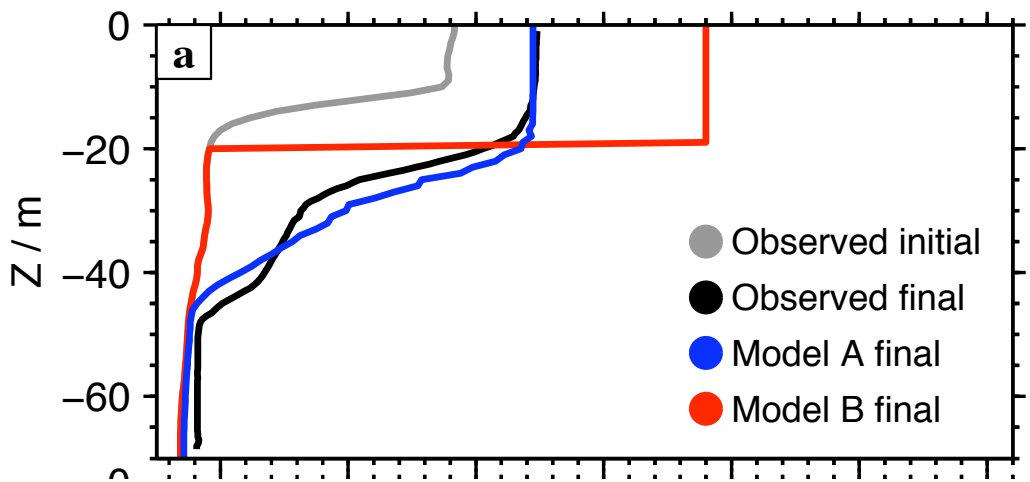
mid-colum dissipation rate



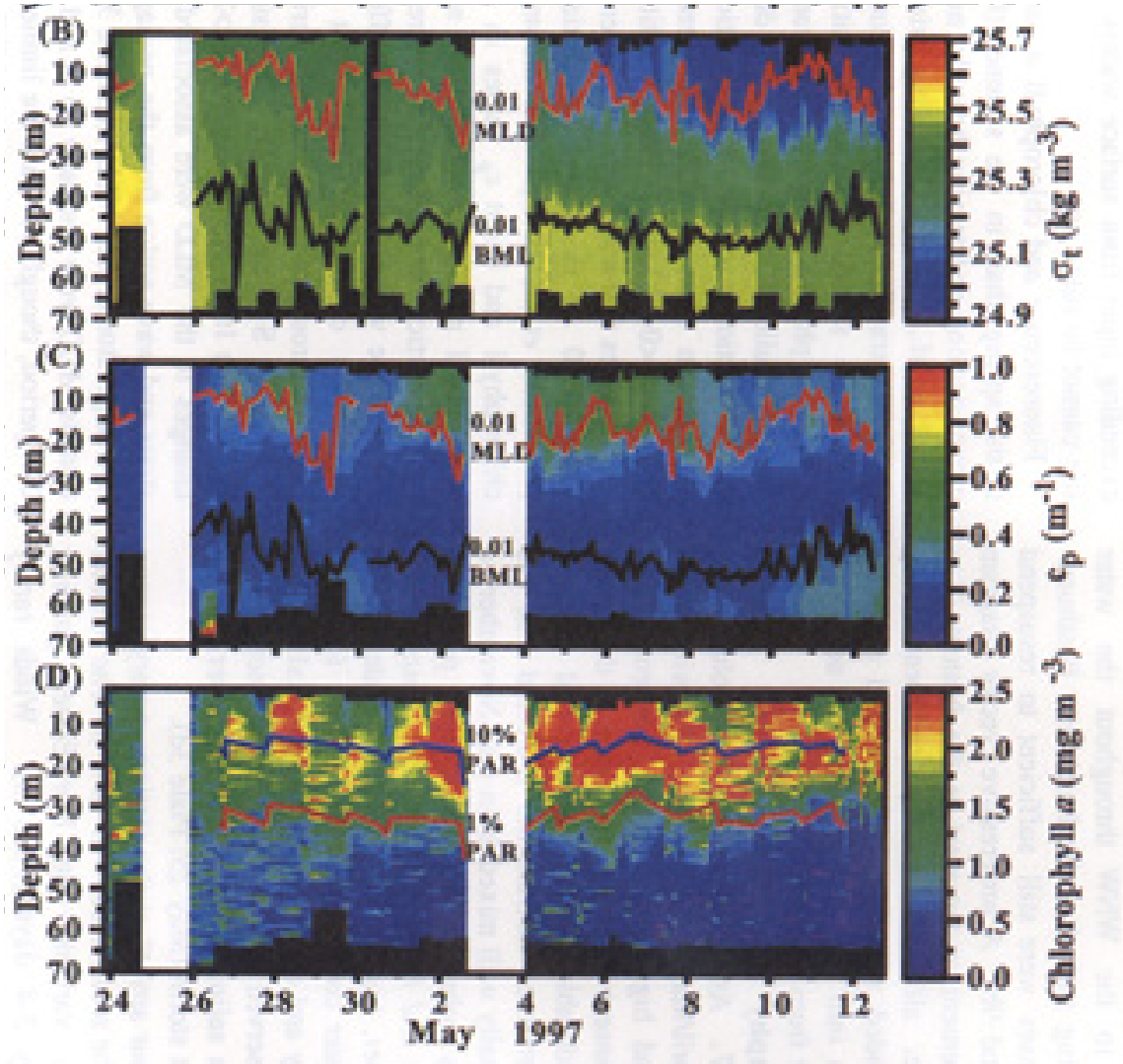
Need to include mid-column mixing to correctly model stratification growth

A) heat distributed downwards with observed turbulent fluxes

B) heat trapped in simple mixed-layer



Rising stratification => spring bloom!



Gardner et al 2001

Summary: part 1

1) Early spring: strong waves and weak stratification

Low-mode near-inertial waves

↓

large shear, subcritical Ri

↓

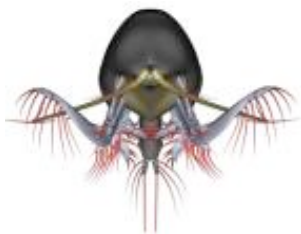
strong stratified turbulence → waves die quickly

↓

surface heat mixed to depth

↓

growing stratification → spring bloom



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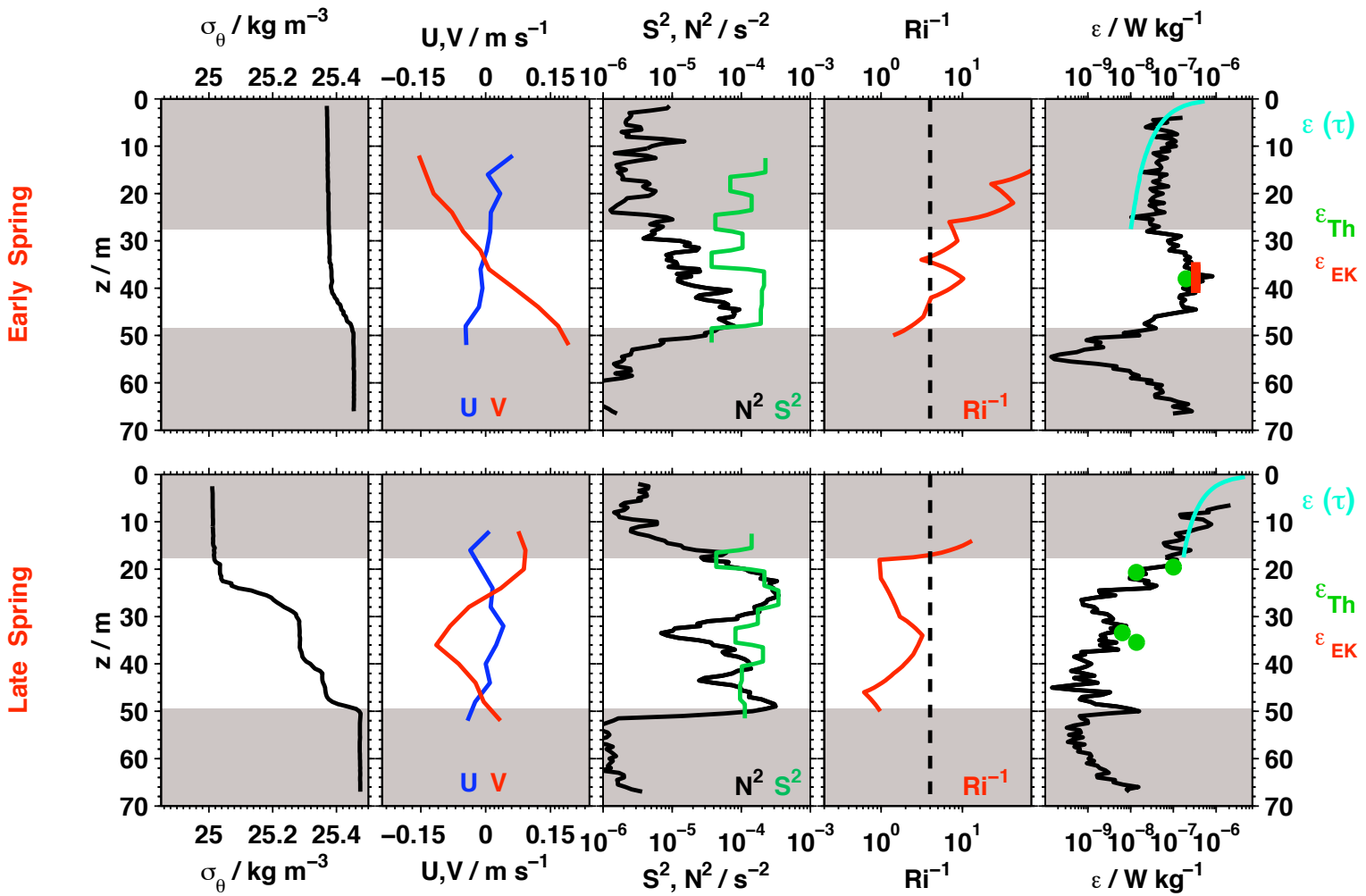
What happens to waves in stronger stratification?

Late spring: “weak” mixing

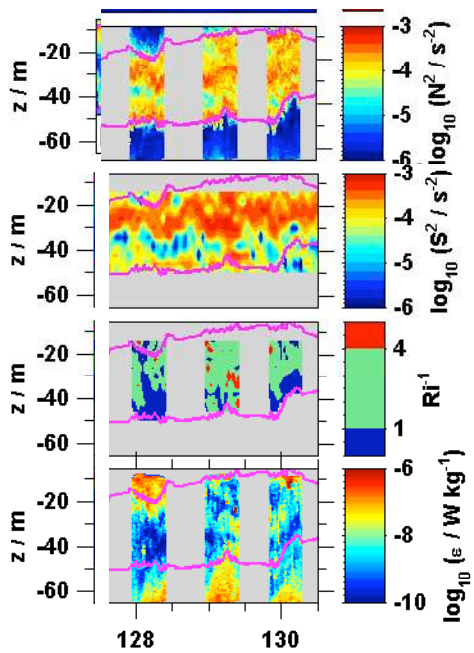


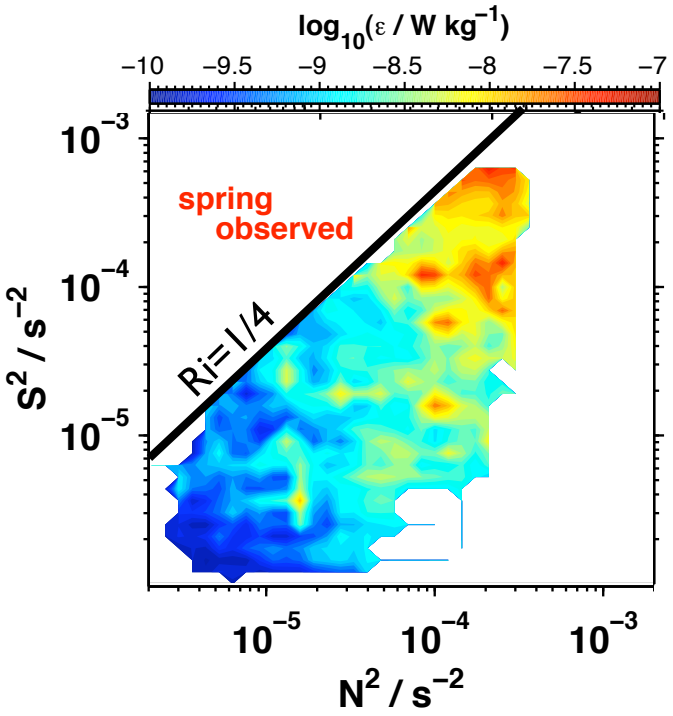
Sub-critical Richardson numbers

→ Traditional parameterizations not triggered (Sharples) because resolved shear not unstable

What's to be done?

Observe that there's still a relationship between S, N, and ϵ even when resolved low-mode wave isn't unstable.

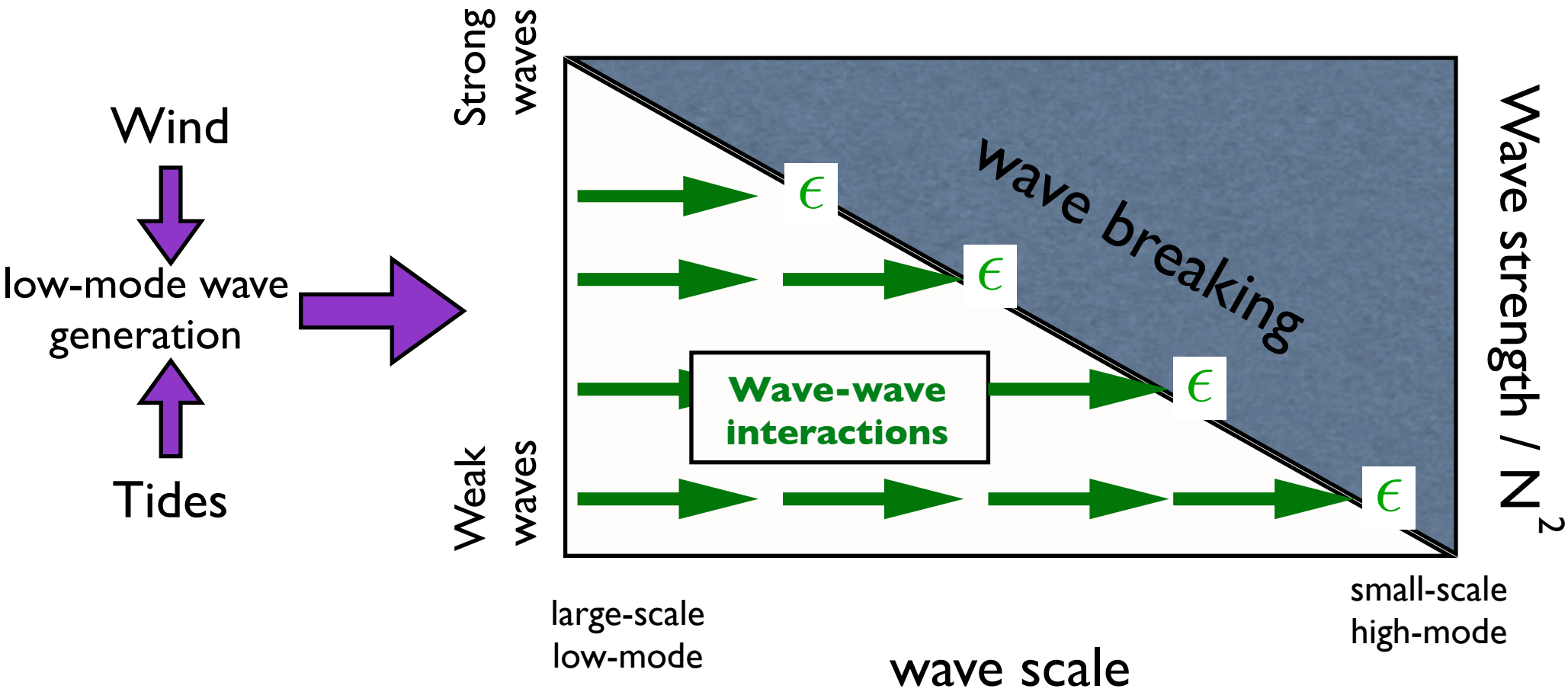




Dissipation rate increases with both shear and stratification

What controls turbulent dissipation?

RATE of wave breaking (ϵ) equal to the RATE energy is flowing from large to small-scale waves through wave-wave interactions



Wave-wave interactions

Gregg-Henyey Model (of open ocean success) assumes:

- Large vertical bandwidth for wave-interactions to occur (not too close to the wave-turbulence transition, or in too shallow water)
- Random phase waves (not a unidirectional tide)
- Statistical steady state (requires being 'far' from internal-wave sources).

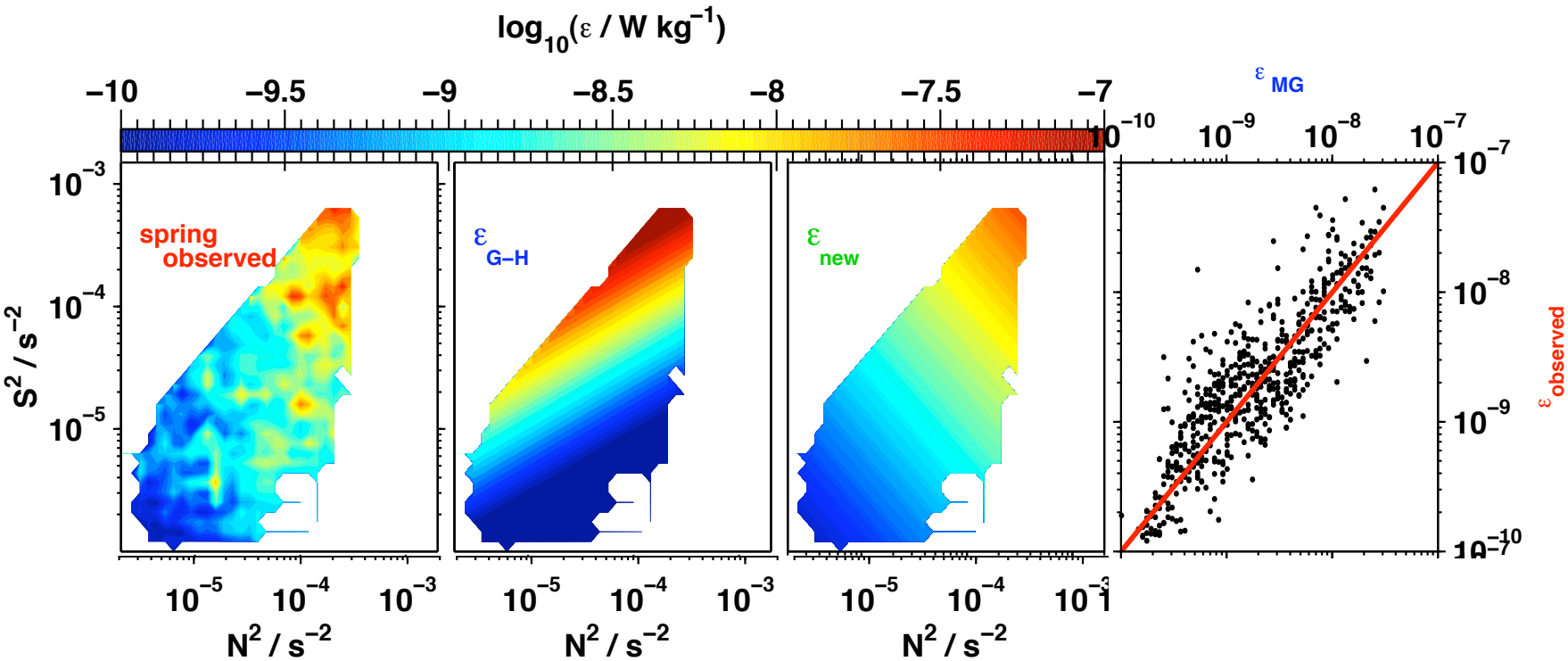
$$\epsilon_{GH} \propto S^4 N^2$$

Gregg 89
Henyey et al 96
Polzin 95

dimensionally correct version

$$\epsilon = 1.8 \times 10^{-6} \left[f \cosh^{-1}\left(\frac{N_0}{f}\right) \right] \left[\frac{S_{10}^4}{S_{GM}^4} \right] \left[\frac{N^2}{N_0^2} \right]$$

Need a new scaling for the coast



MacKinnon and Gregg 02 propose $\epsilon_{MG} \propto SN$

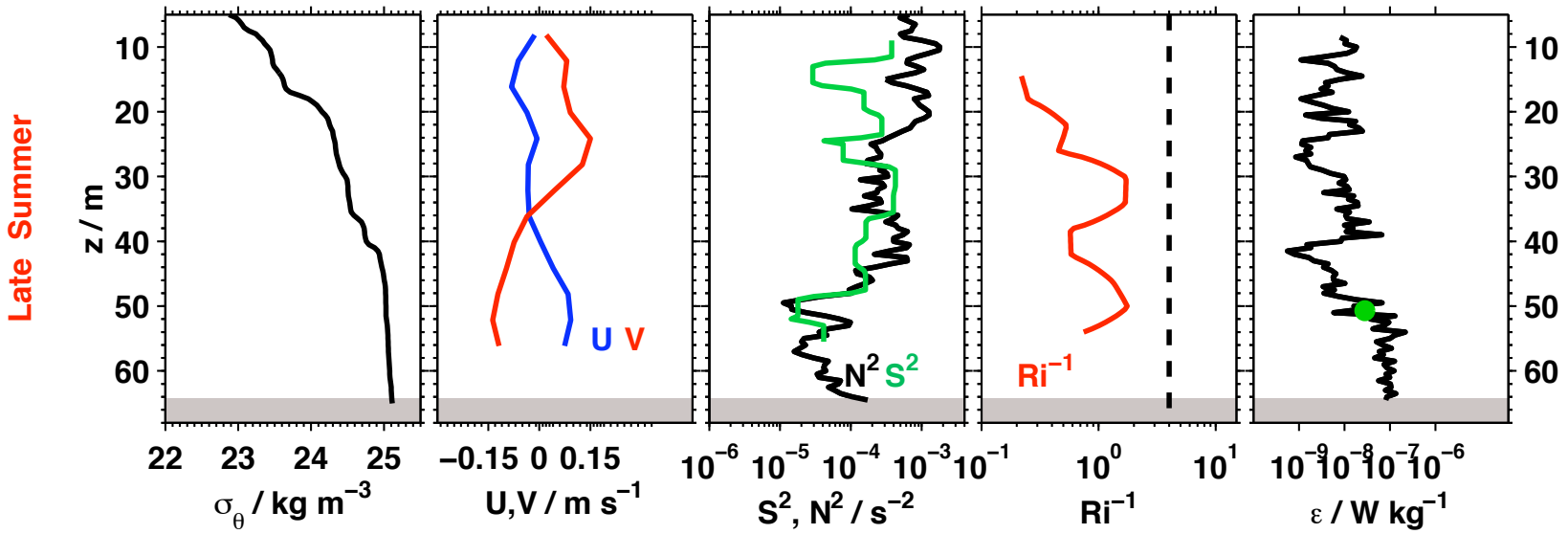
Partly empirical, partly based on rederivation of Gregg-Henyey results without statistical stationarity assumption

$$\epsilon_{MG} = \epsilon_0 \left(\frac{S}{S_0}\right)\left(\frac{N}{N_0}\right)$$

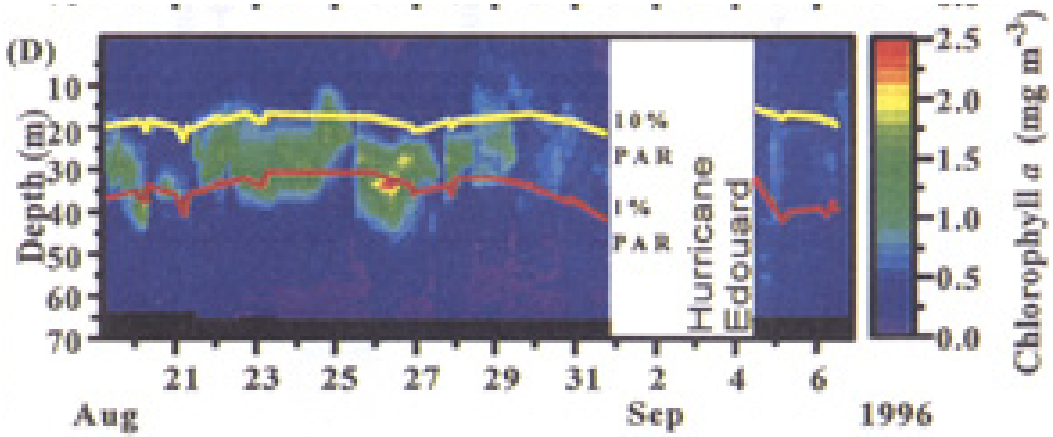
$\epsilon_0 = 2.4 \times 10^{-11}[\mathrm{Wkg}^{-1}]$ $\quad S_0 = N_0 = 3\mathrm{cph}$

Late-summer mixing

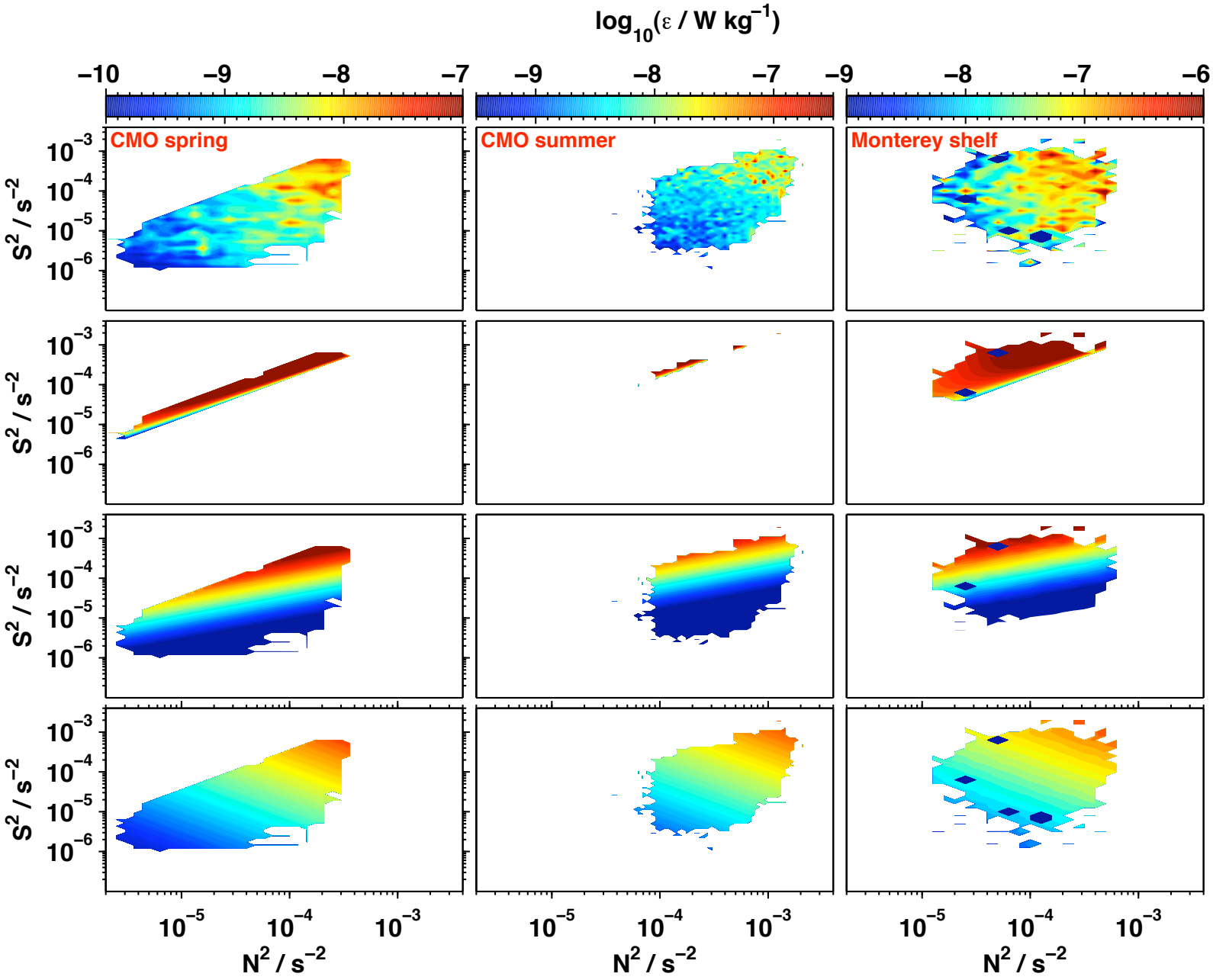
Strong stratification => relatively weak dissipation rates



Which is nevertheless important for maintaining the sub-surface chlorophyll maximum, amongst other things

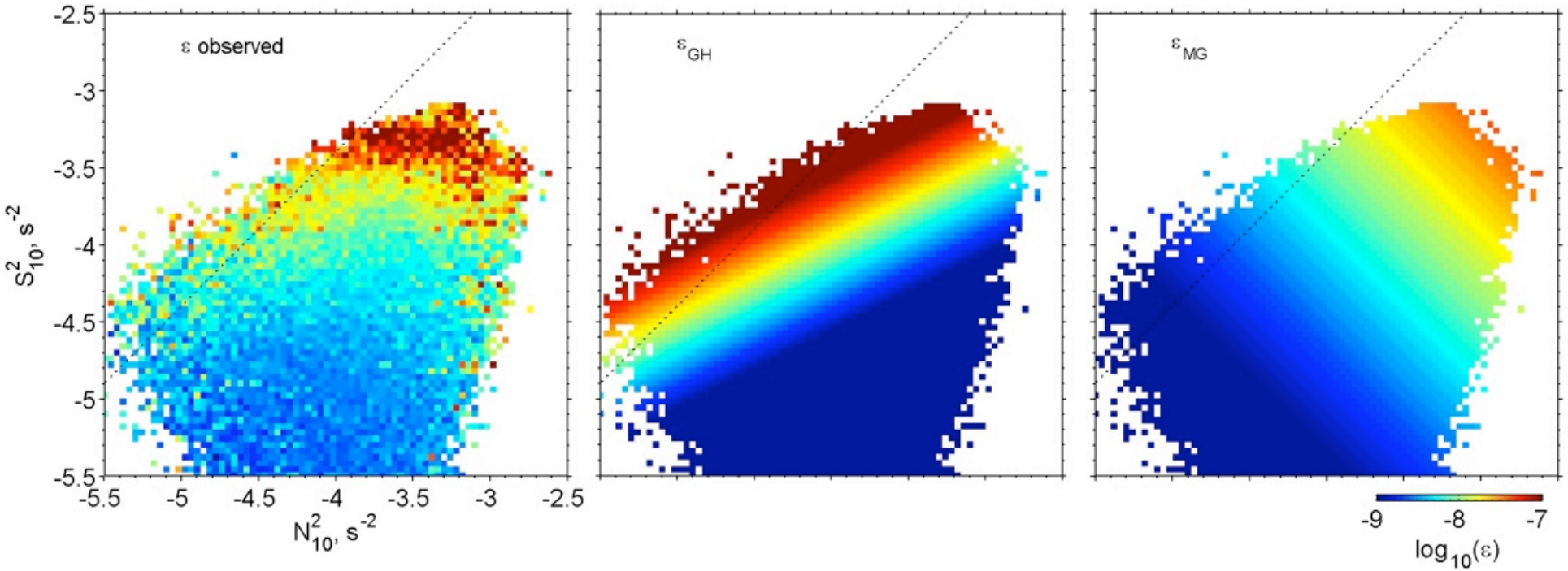


Similar dissipation scaling in Monterey



Monterey shelf data courtesy of Dr. Glenn Carter, UW

A bit different in Oregon?



courtesy of Greg Avicola, OSU

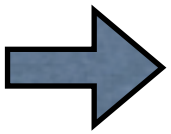
Our dynamical understanding (and hence parameterization) is not quite there yet...

AESOP

Numerical process studies of wave-wave interactions and turbulent mixing in a coastal environment to investigate dynamics of down-scale energy transport to dissipation. Hypothesis testing...

- Effect of shallow water (limited vertical bandwidth)
- Effect of coherency of low-mode waves
- Effect of variable forcing (low-mode waves not in a statistical steady state)

Low-mode internal tide or near-inertial wave input

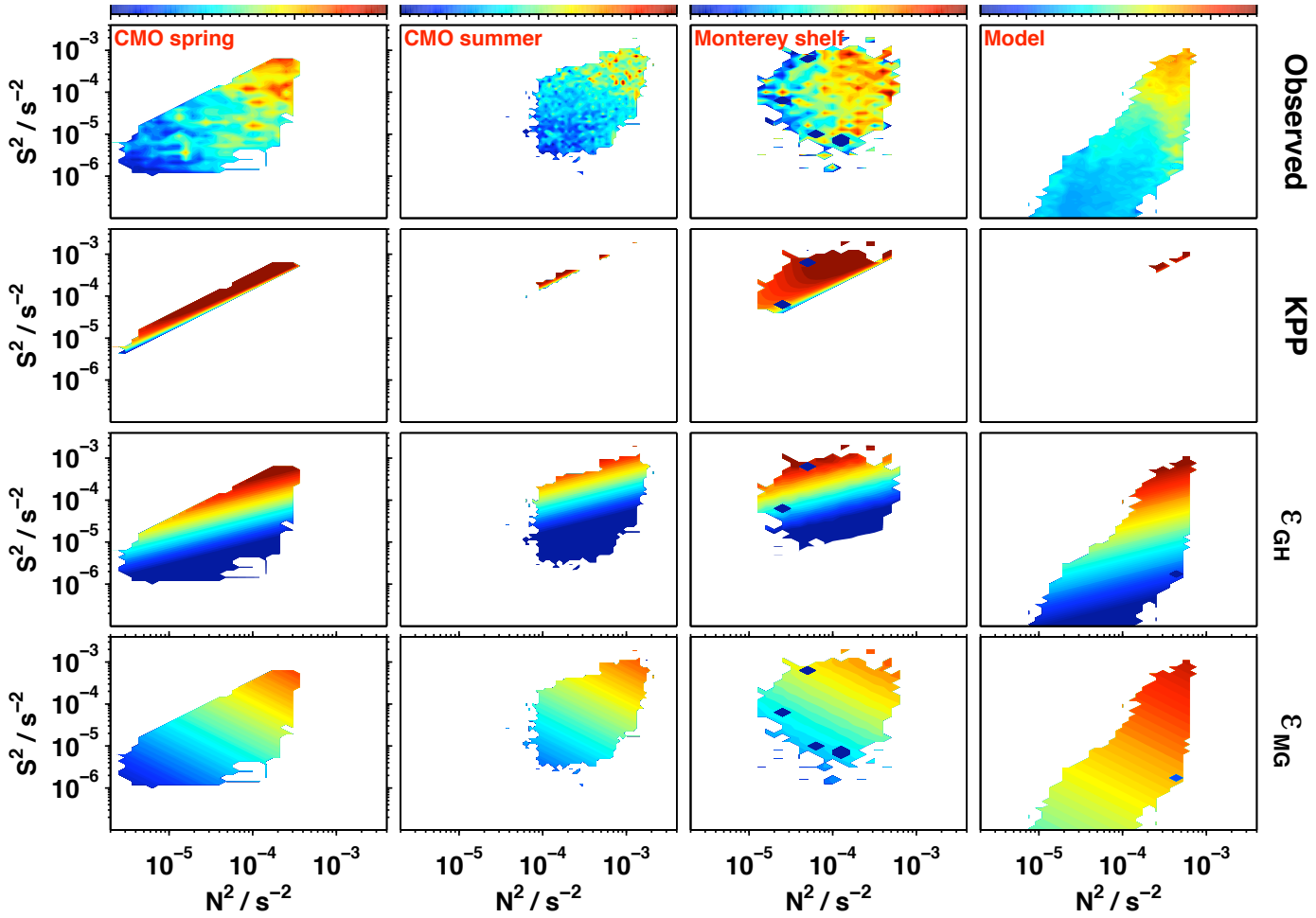


Pseudo-spectral, nonlinear, nonhydrostatic model (Winters et al 04)

small 'background' wave field

variable depth

model dissipation scaling



Similar scaling, but why?

Summary: part 2

1) Early spring: strong waves and weak stratification

Low-mode near-inertial waves

large shear, subcritical Ri

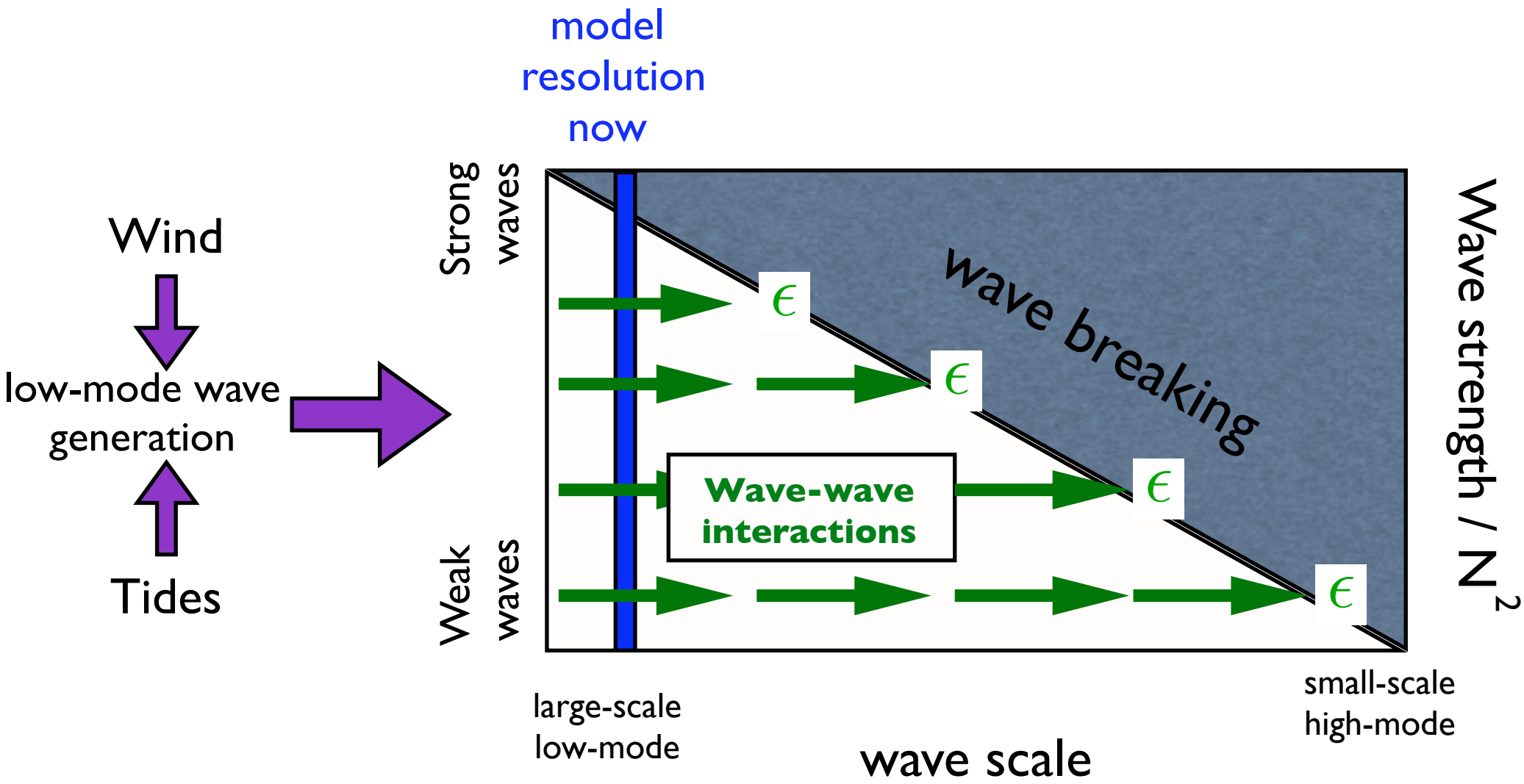
strong stratified turbulence

2) Late spring/summer:

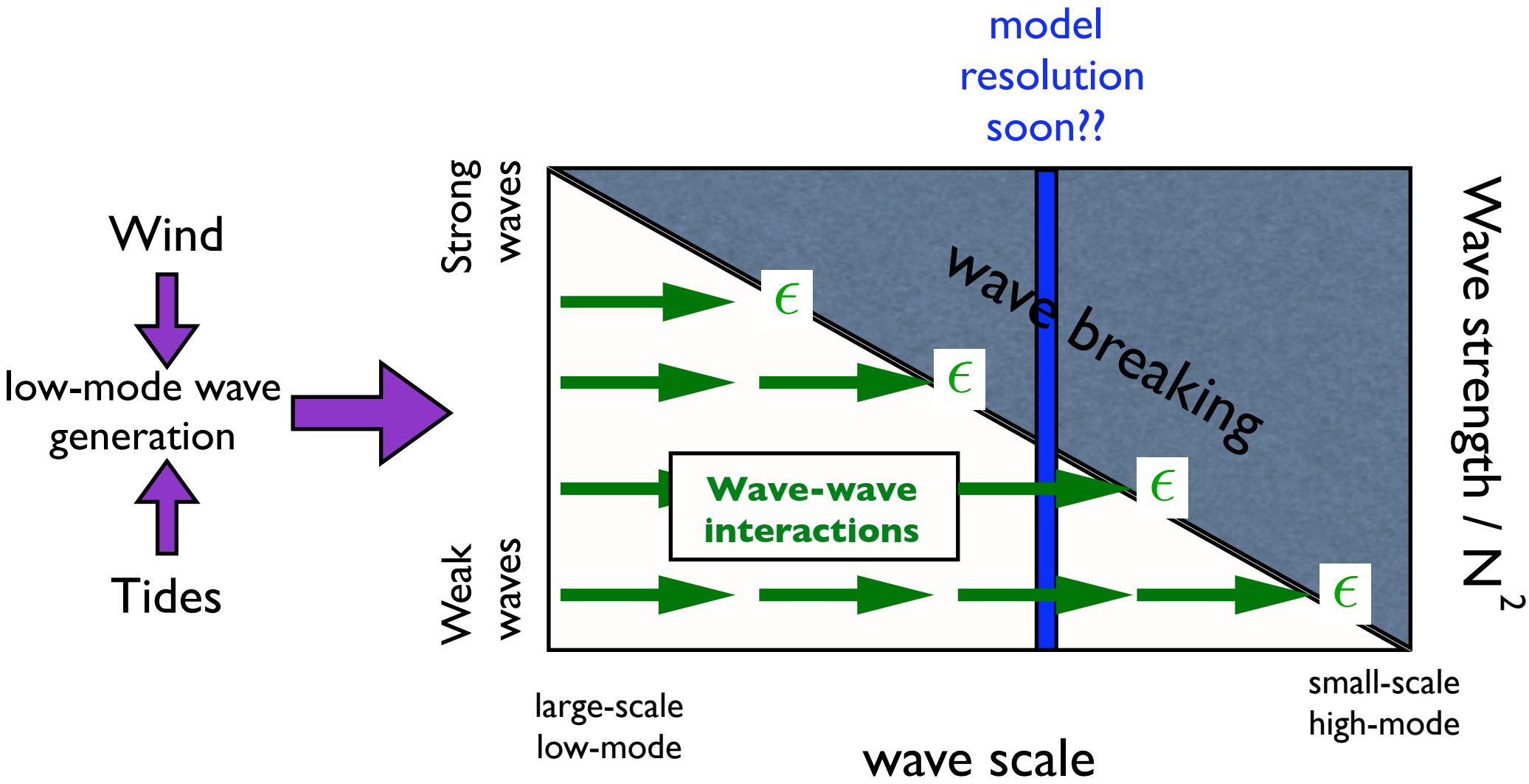
strong stratification and weak waves

- Dissipation rate controlled by rate of energy transport to smaller scales by wave-wave interactions
- Models generally not able to resolve the whole cascade, so need..
- Parameterizations that work well in the open ocean fail on the coast - either water is too shallow, low-mode waves are too variable, or wave phase is too coherent.
- Preliminary results show progress on new scalings, but stay tuned...

Eventual parameterizations need to be flexible



Eventual parameterizations need to be flexible



Prescription for mixing?

Am I in a boundary layer?
(surface or bottom)

Y → KPP
M-Y
k-e

N ↓

Do I resolve unstable shear/Ri?
* strong internal-waves
* solitons
* mixed-layer base
* jets?
* hydraulic jumps?

Y → Stratified turbulence
M-Y, k-e, etc

N ↓

Wave-wave interaction
controlled dissipation
e (S,N,...?)

Other mixing processes
* double diffusion?
* wave scattering / critical layers?
* bioturbation?

Breakout Session on Horizontal and Vertical Mixing
All Welcome! -- Thurs, 1:30 – 3:00 p.m.
(Contact Miles Sundermeyer and/or Jen MacKinnon for more info and/or suggested discussion topics)

Purpose: To bring together observationalists, modelers and other interested parties to discuss what are the major questions relating to mixing in the coastal ocean, and how we as a community might move address them. Possible topics of discussion may include, but are not limited to:

- What do observationalists and modelers each feel are the major outstanding issues relating to horizontal and vertical mixing in the coastal ocean?
- How well do we understand the energy pathways from large-scale to small, e.g. atmospheric and tidal forcing down to turbulent dissipation, kilometers to millimeters? What are the weak links?
- When/where does mixing matter? When/where does it not?
- How useful are existing mixing parameterizations? Can we better close the loop between process based observations, parameterizations, and numerical modeling?
- What processes are common between the outer and inner shelf, nearshore, and estuaries?
- Where do we need greater communication between small-scale observationalists, modelers, biologists, ecologists, engineers, etc.?
- What are the limits of existing observational and modeling capabilities, and how might we work together to take each to the next level?
- How might the small-scale community take advantage of new coastal observing system technologies?
- As numerical models move toward increasingly finer grid resolutions, should we be thinking more about “resolution flexible parameterizations?”