Is the abyssal overturning driven by breaking internal waves?

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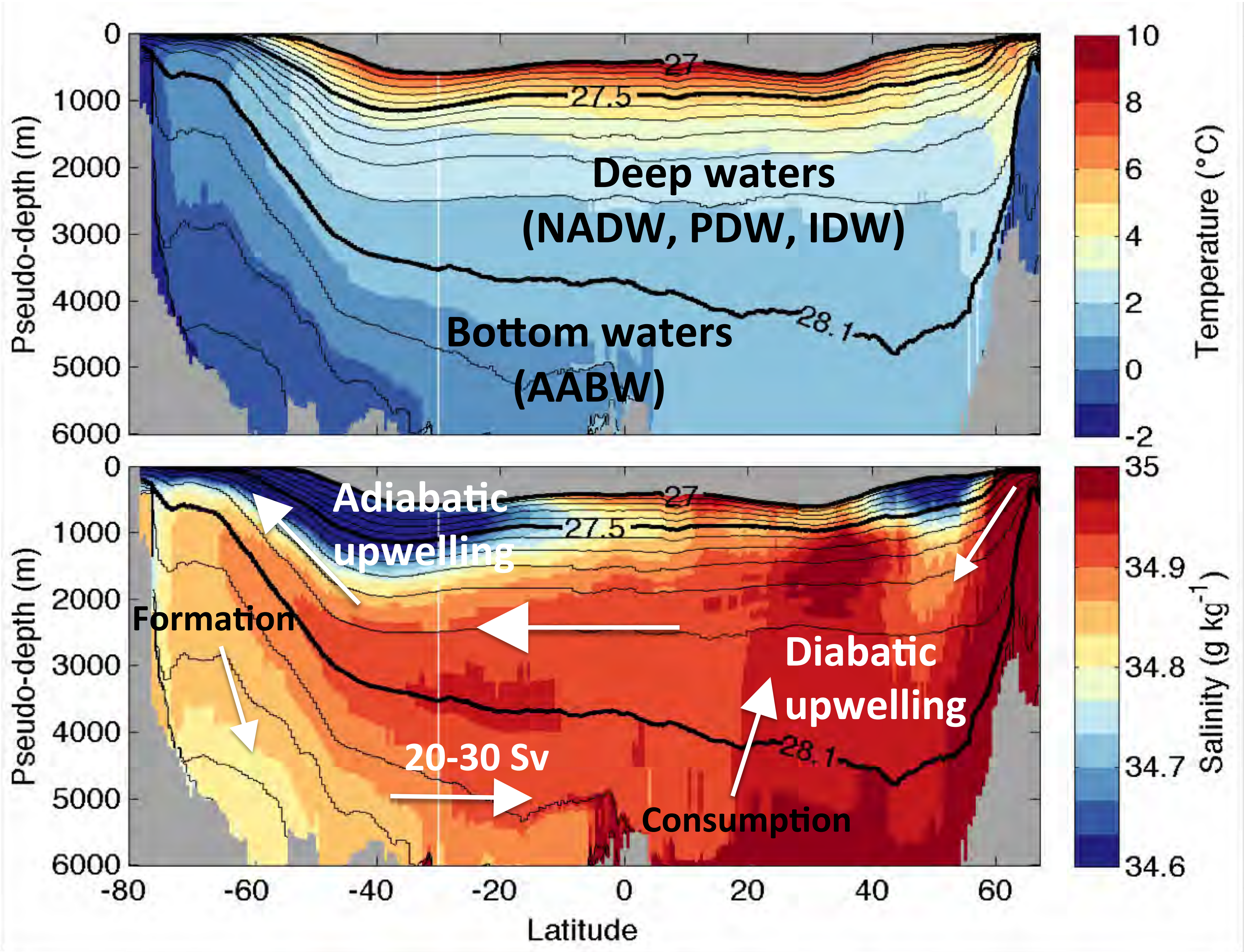
Introduction - The diabatic overturning circulation



Methods (1/3) - Water mass transformation

Balance between advection and diffusion:

Dia-neutral advection = Divergence of buoyancy flux

$$\omega \partial_z \rho = \partial_z (K_\perp \partial_z \rho)$$

Or accounting for non-linearity:

$$\omega \partial_z \rho = \rho \alpha \; \partial_z (K_\perp \partial_z \theta) + \rho \beta \; \partial_z (K_\perp \partial_z S)$$

To obtain ω, we need a 3-D map of $K_\perp$.

Methods (2/3) - Parameterization of internal wave-driven mixing

$$K_\perp N^2 = R_f \, \varepsilon_T$$

Wave-breaking energy [W kg^{-1}]

$$\text{Mixing efficiency} = \begin{cases} 1/6 \\ f\left(\dfrac{\varepsilon_T}{\nu N^2}\right) \xrightarrow[N^2 \to 0]{} 0 \end{cases}$$

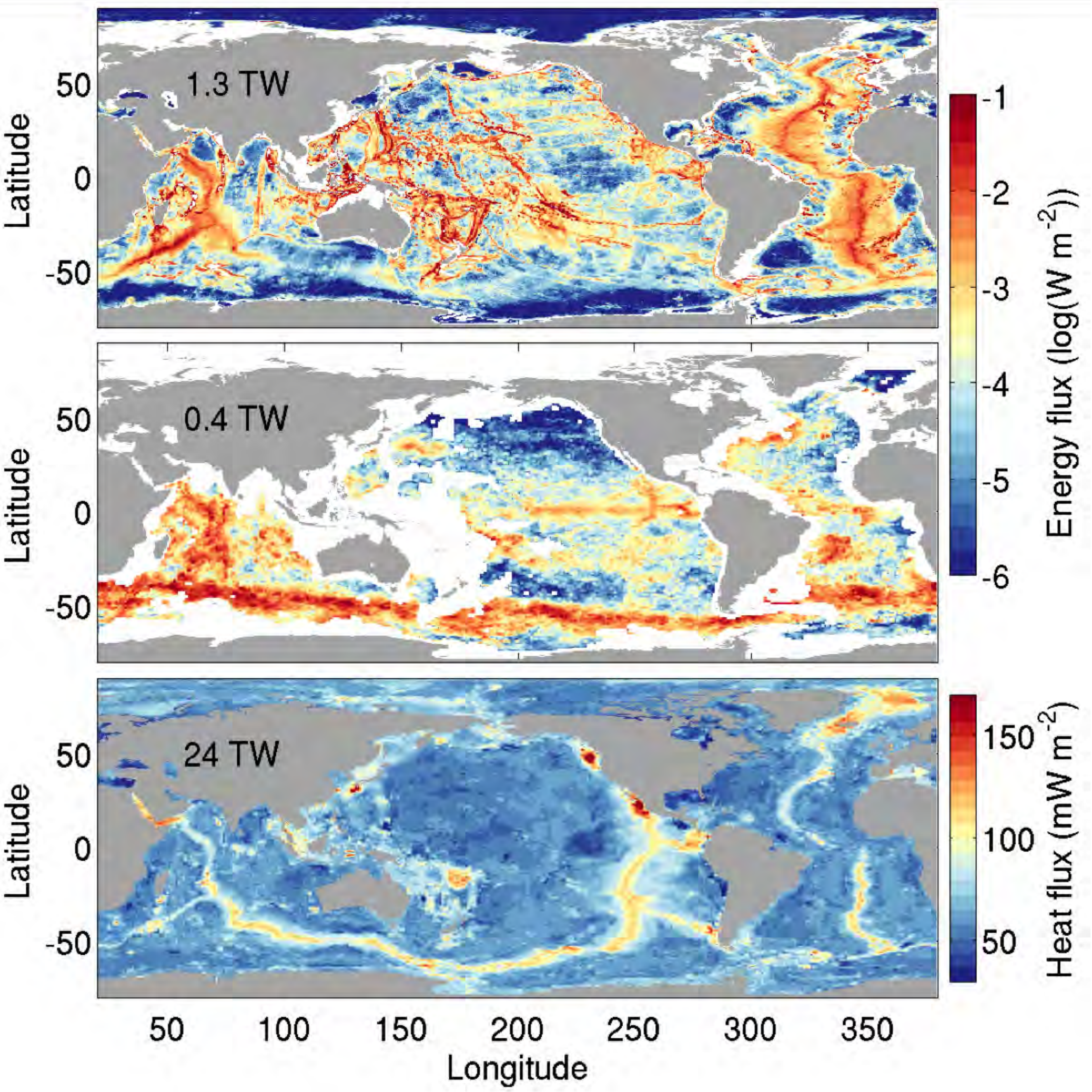
$1/6$	Constant R_f	Osborn 1980
$f\left(\frac{\varepsilon_T}{\nu N^2}\right) \xrightarrow[N^2 \to 0]{} 0$	Variable R_f	Shih et al. 2005

St Laurent et al. 2002:

$$\varepsilon_T(x,y,z) = \frac{1}{\rho}\,\boxed{q}\,\boxed{E(x,y)}\,\boxed{F(z)}$$

	Fraction of energy dissipation	Column-integrated energy dissipation [W m^{-2}]	Vertical structure of energy dissipation [m^{-1}]
Near-field	1/3	Internal tide generation rate	Exponential decay from seafloor
Far-field	2/3	Spread around generation sites	4 tested structures

Methods (3/3) – Bottom energy fluxes *E*(*x*,*y*)

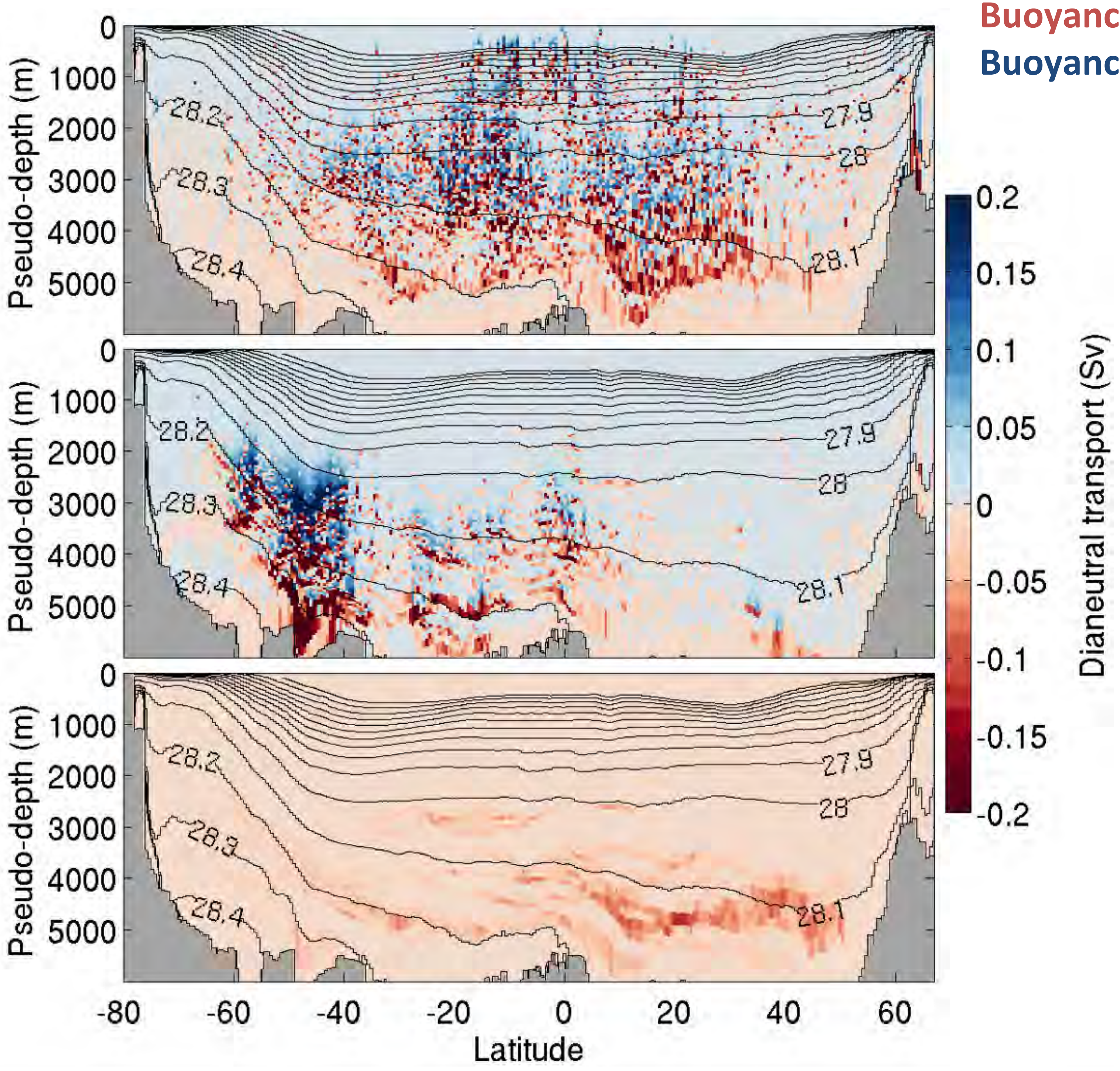


Internal tides
Nycander 2005
+
Melet et al. 2013

Lee waves
Scott et al. 2011

Geothermal heating
Goutorbe et al. 2011

Dianeutral transports: zonal view



Buoyancy gain = upwelling

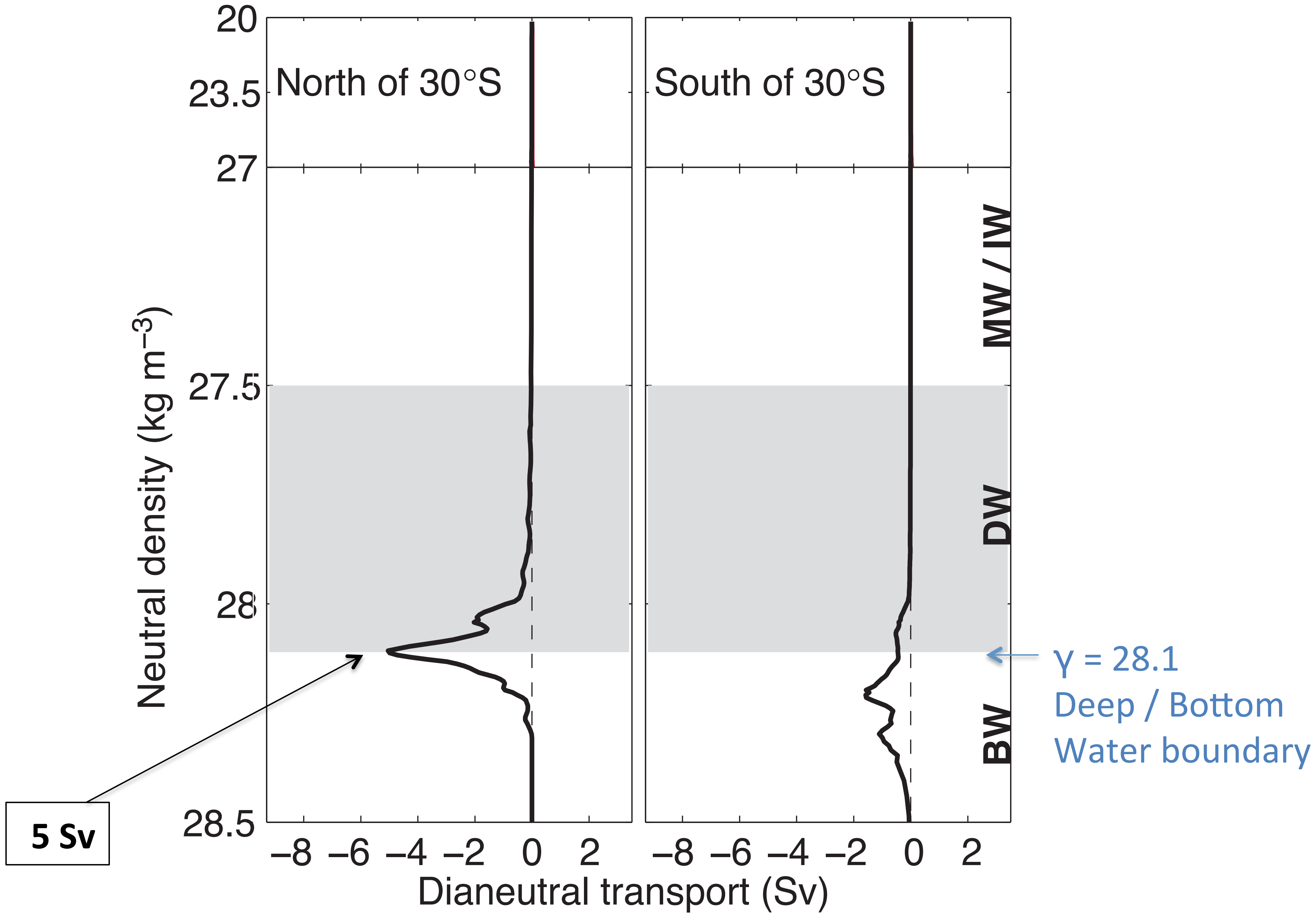
Buoyancy loss = downwelling

Internal tides (near-field)

Lee waves

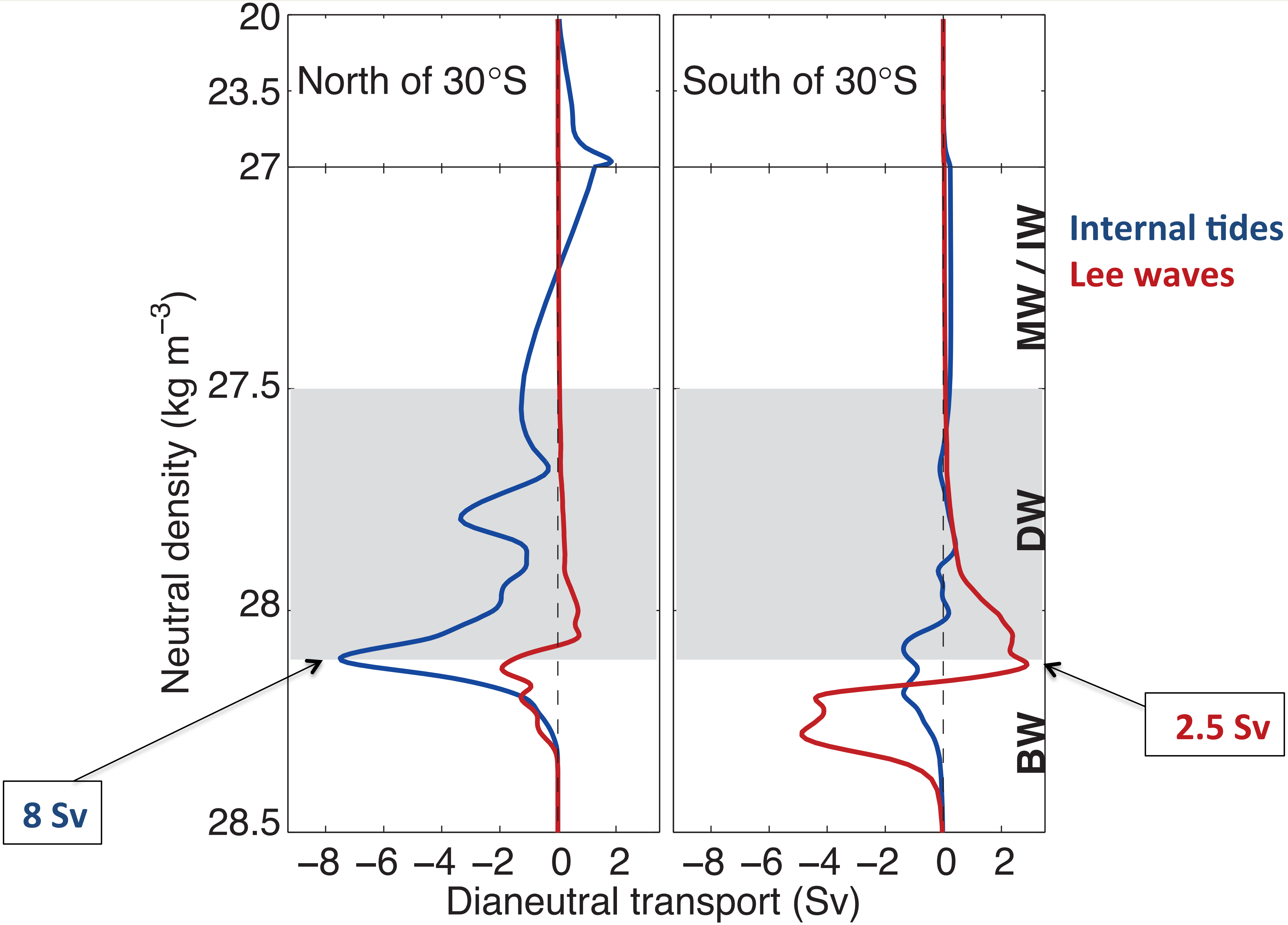
Geothermal heating

Dianeutral transports: geothermal heating



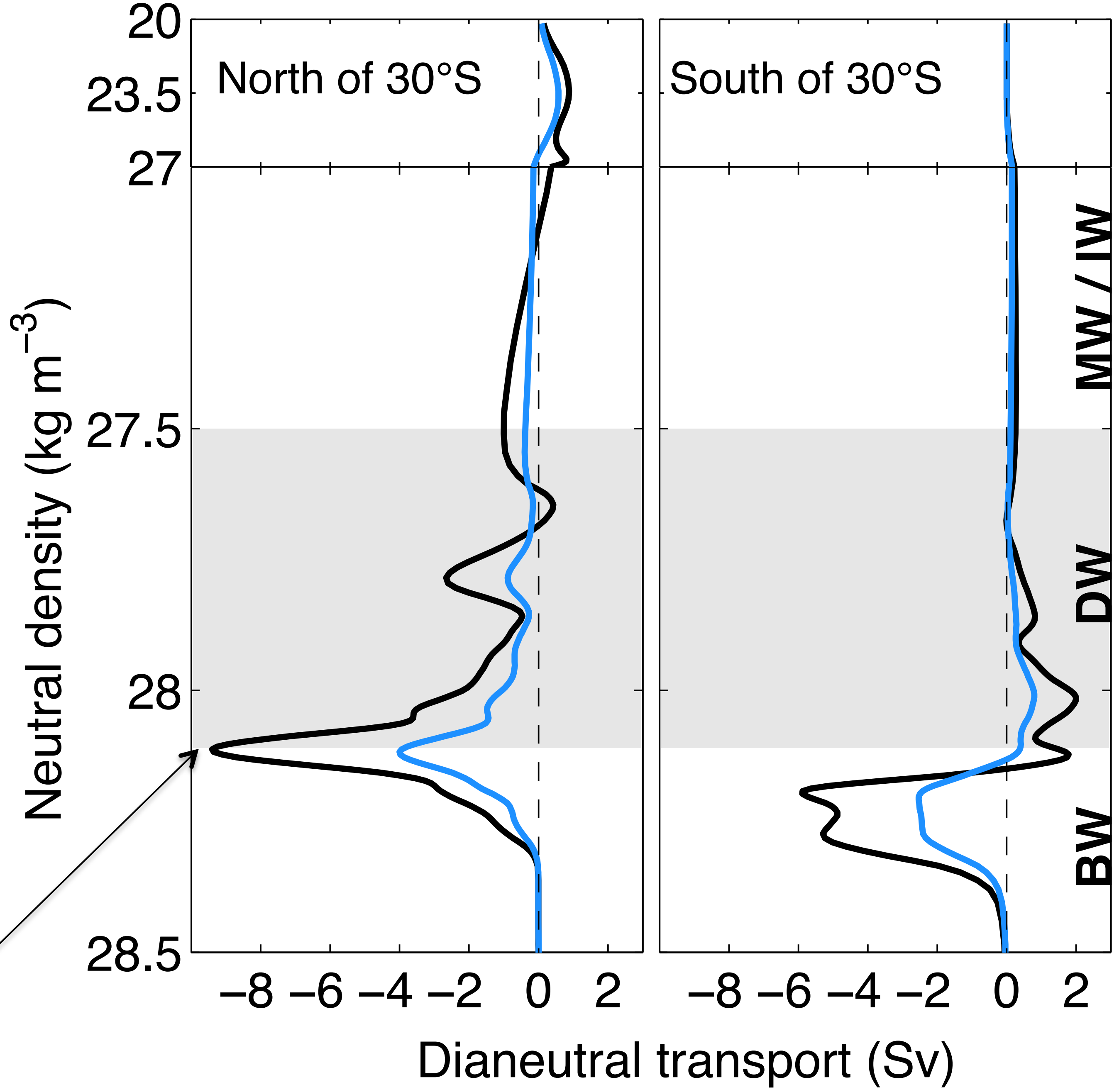
Consistent with results of Emile-Geay & Madec (2009)

Dianeutral transports: near-field mixing, constant R_f



Consistent with OGCM simulations of Saenko & Merryfield (2005) and Melet et al. (2014)

Dianeutral transports: total near-field, sensitivity to R_f



Constant R_f

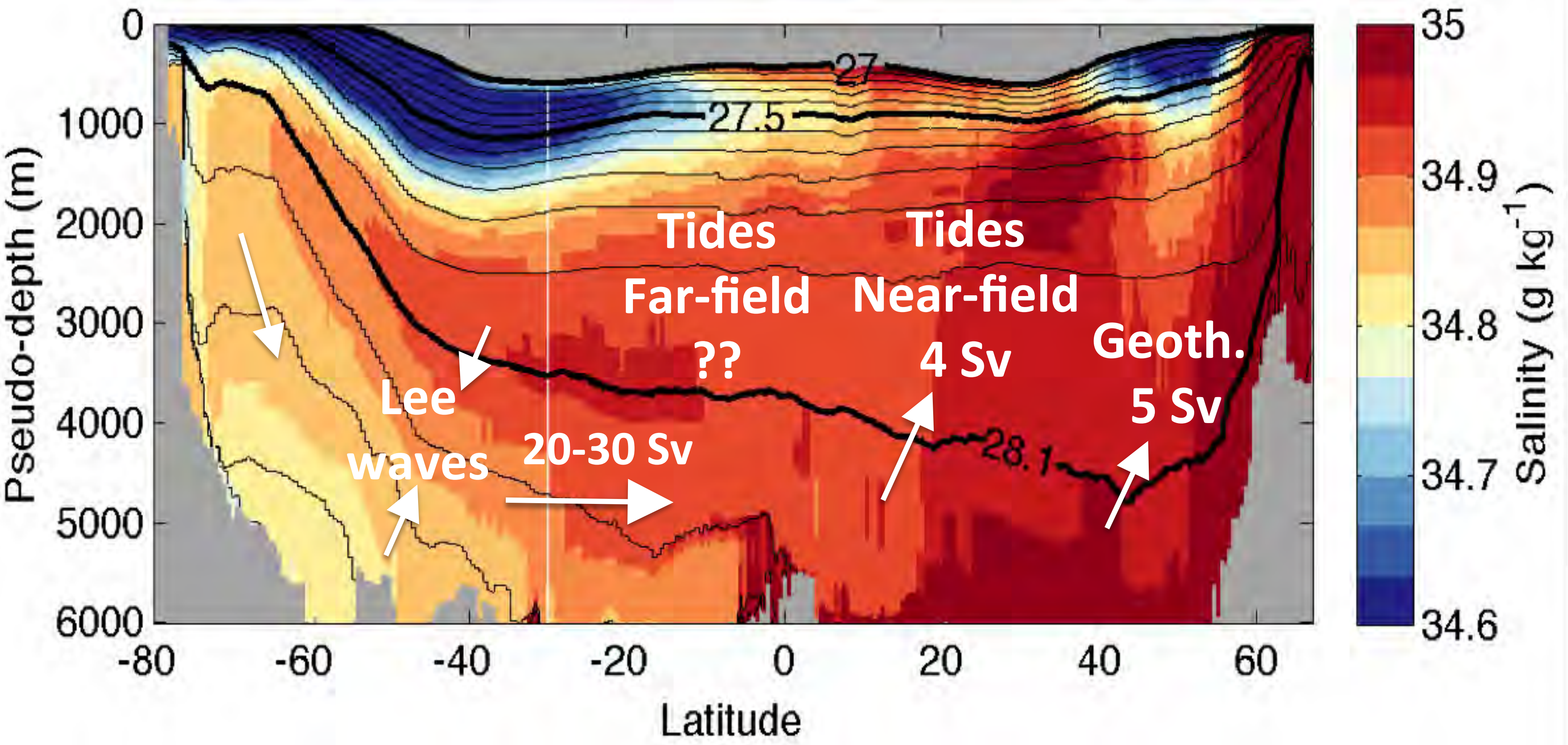
Variable R_f

9 Sv

4 Sv

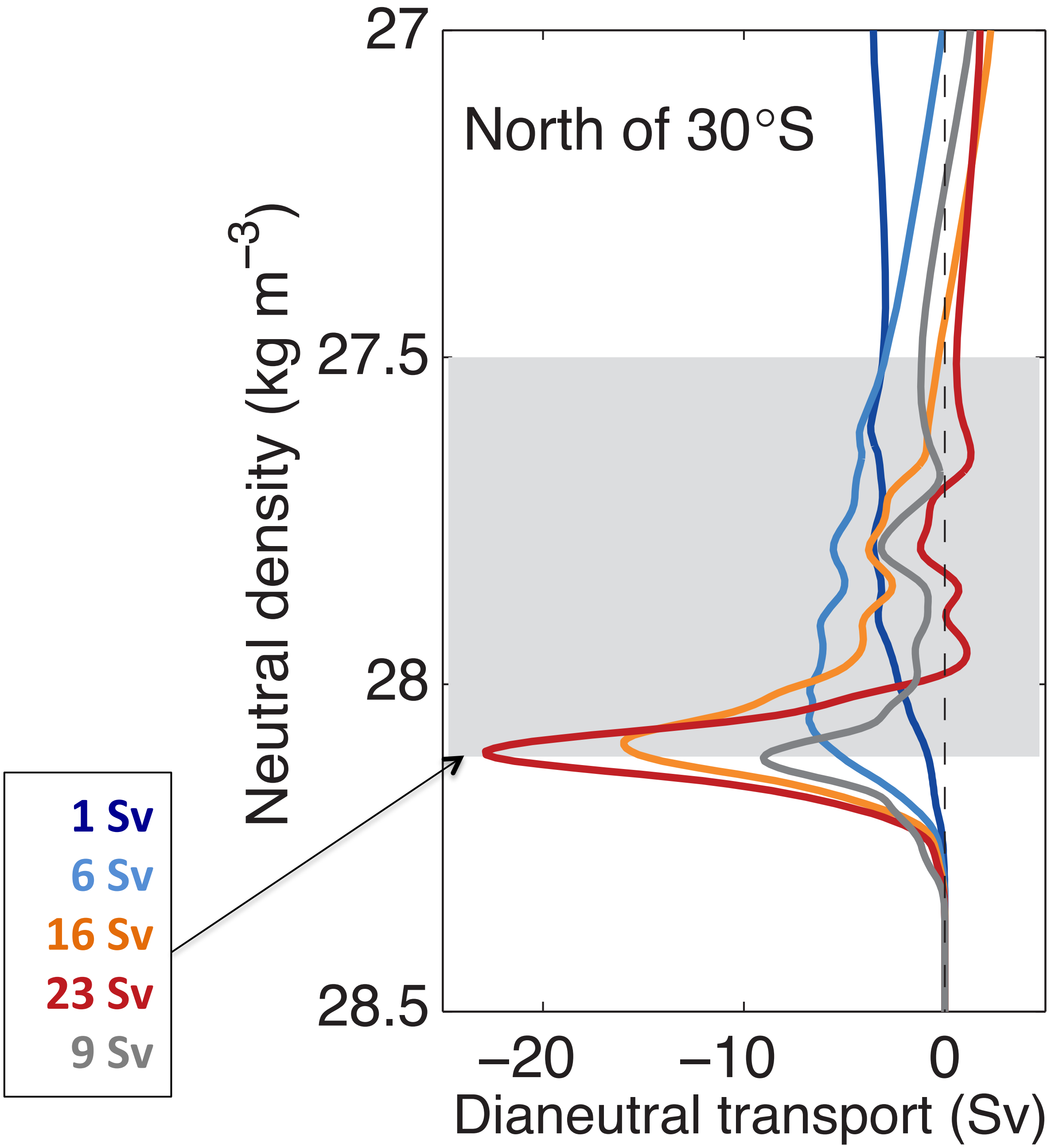
Total near-field = lee waves + locally-dissipating internal tides

What about remotely-dissipating internal tides?



Dianeutral transports: far-field tidal mixing, constant R_f

$E_{far\text{-}field}(x,y)$ = energy spread around generation sites over a 1,000 km radius



$F(z) \propto N^2$ --> $K_z \propto 1$
Koch-Larrouy et al. 2007

$F(z) \propto N$ --> $K_z \propto 1/N$
Gargett 1984, Melet et al. subm.

$F(z) \propto 1$ --> $K_z \propto 1/N^2$
Oka & Niwa 2013

$F(z) \propto 1/N$ --> $K_z \propto 1/N^3$

Near-field (lee + tides)

Dianeutral transports: far-field tidal mixing, sensitivity to R_f

$E_{far\text{-}field}(x,y)$ = energy spread around generation sites over a 1,000 km radius

	Constant R_f	Variable R_f	Vertical structure
AABW upwelling rate (Sv)	1	1	**$F(z) \propto N^2$** Koch-Larrouy et al. 2007
	6	4	**$F(z) \propto N$** Gargett 1984, Melet et al. subm.
	16	9	**$F(z) \propto 1$** Oka & Niwa 2013
	23	11	**$F(z) \propto 1/N$**
	9	4	**Near-field (lee + tides)**

=> Impact of variable R_f depends on vertical structure of dissipation

Conclusions

- **Bottom-intensified mixing by breaking internal waves: small contributor to AABW upwelling.**

- **Concentrated mixing quickly saturates**.

  → Unless strong density gradients can be maintained, such as in deep overflows.

- **Remotely-dissipating internal tides: vertical structure is key**.

- **More work is needed to**
  - **Constrain the horizontal and vertical distributions of internal wave-driven turbulence from observations and theory.**
  - **Improve model parameterizations of deep mixing accordingly.**

de Lavergne, Madec, Le Sommer, Nurser & Naveira Garabato, *JPO:*

On the consumption of Antarctic Bottom Water in the abyssal ocean (in revision)

The impact of a variable mixing efficiency on the abyssal overturning (in press)

Is it reasonable to assume a constant mixing efficiency?

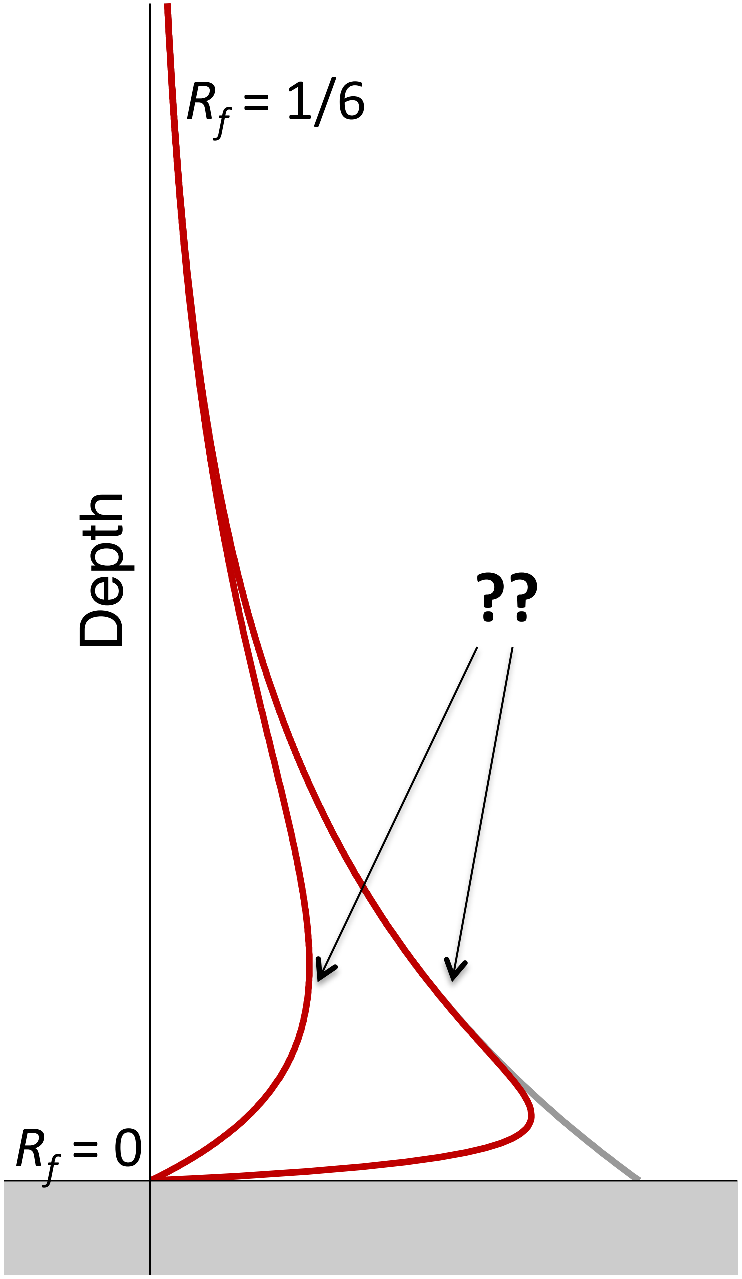
The no-flux bottom boundary condition implies that mixing efficiency is zero at the seafloor.

Physically, the buoyancy flux must vanish together with the stratification:

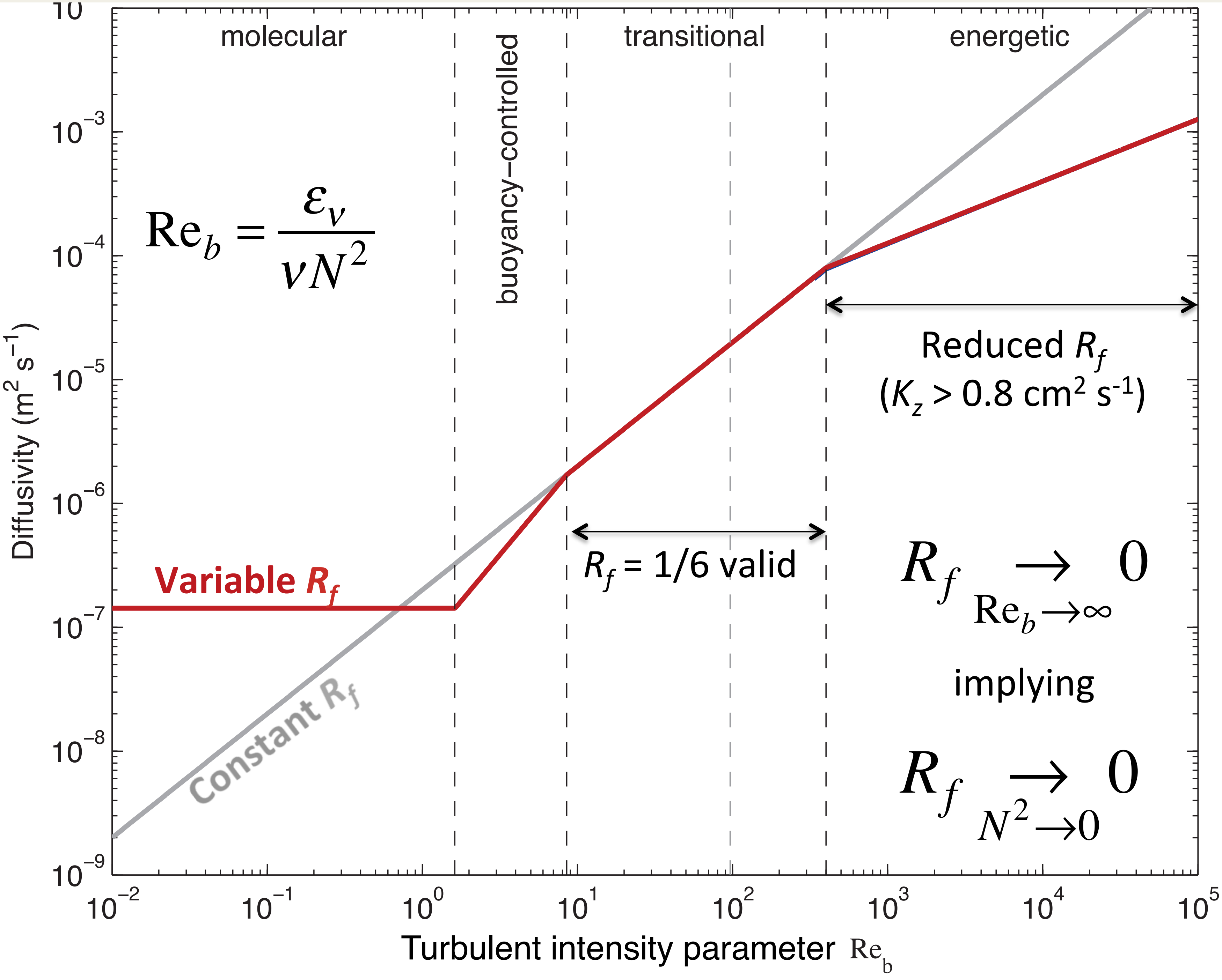
$$K_{\perp} N^2 = R_f \varepsilon_T \underset{N^2 \to 0}{\longrightarrow} 0$$

(In the limit of a homogenous fluid, mixing cannot drive a buoyancy flux.)

=> How can we account for reduced mixing efficiency in weak stratification?



The Re_b-dependent model (Shih et al. 2005, Bouffard & Boegman 2013)



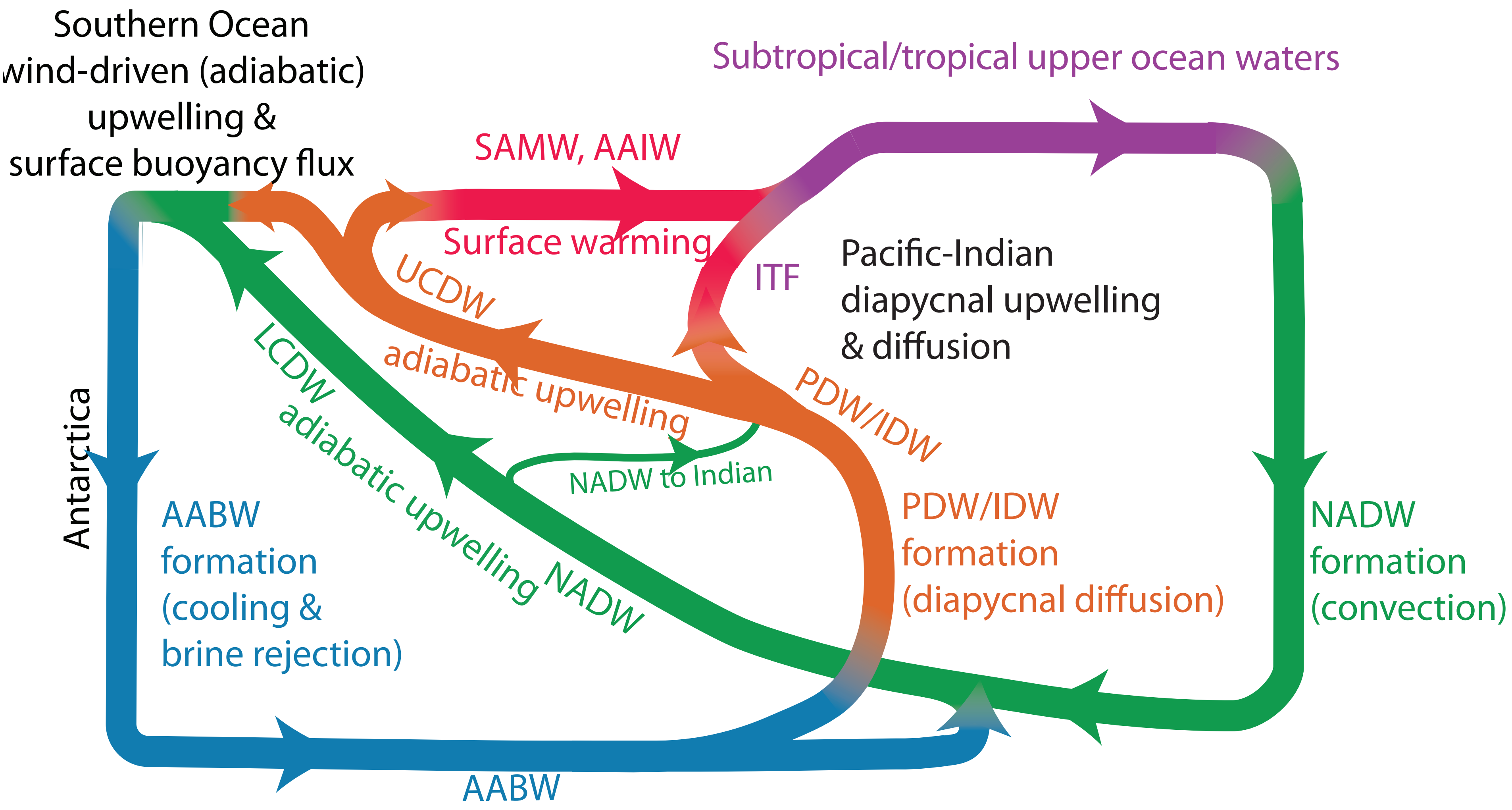
$$Re_b = \frac{\varepsilon_v}{\nu N^2}$$

$$R_f \xrightarrow[Re_b \to \infty]{} 0$$

implying

$$R_f \xrightarrow[N^2 \to 0]{} 0$$

The meridional overturning circulation: diabatic and adiabatic pathways



Southern Ocean
wind-driven (adiabatic)
upwelling &
surface buoyancy flux

Subtropical/tropical upper ocean waters

SAMW, AAIW

Surface warming

ITF

Pacific-Indian
diapycnal upwelling
& diffusion

UCDW

adiabatic upwelling

LCDW

adiabatic upwelling NADW

NADW to Indian

PDW/IDW

PDW/IDW
formation
(diapycnal diffusion)

NADW
formation
(convection)

Antarctica

AABW
formation
(cooling &
brine rejection)

AABW

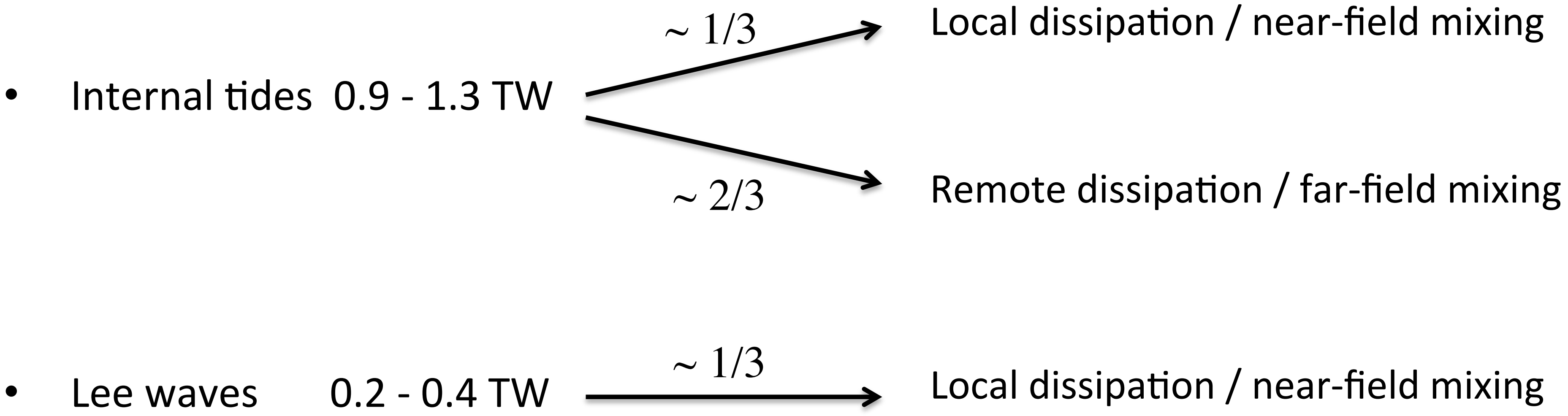
20-30 Sv

Talley, 2013

Candidate buoyancy sources for AABW

1. **Turbulent mixing**, thought to be primarily driven by internal wave breaking.

Quantified deep ocean internal wave energy sources include:



- Internal tides 0.9 - 1.3 TW

~ 1/3 → Local dissipation / near-field mixing

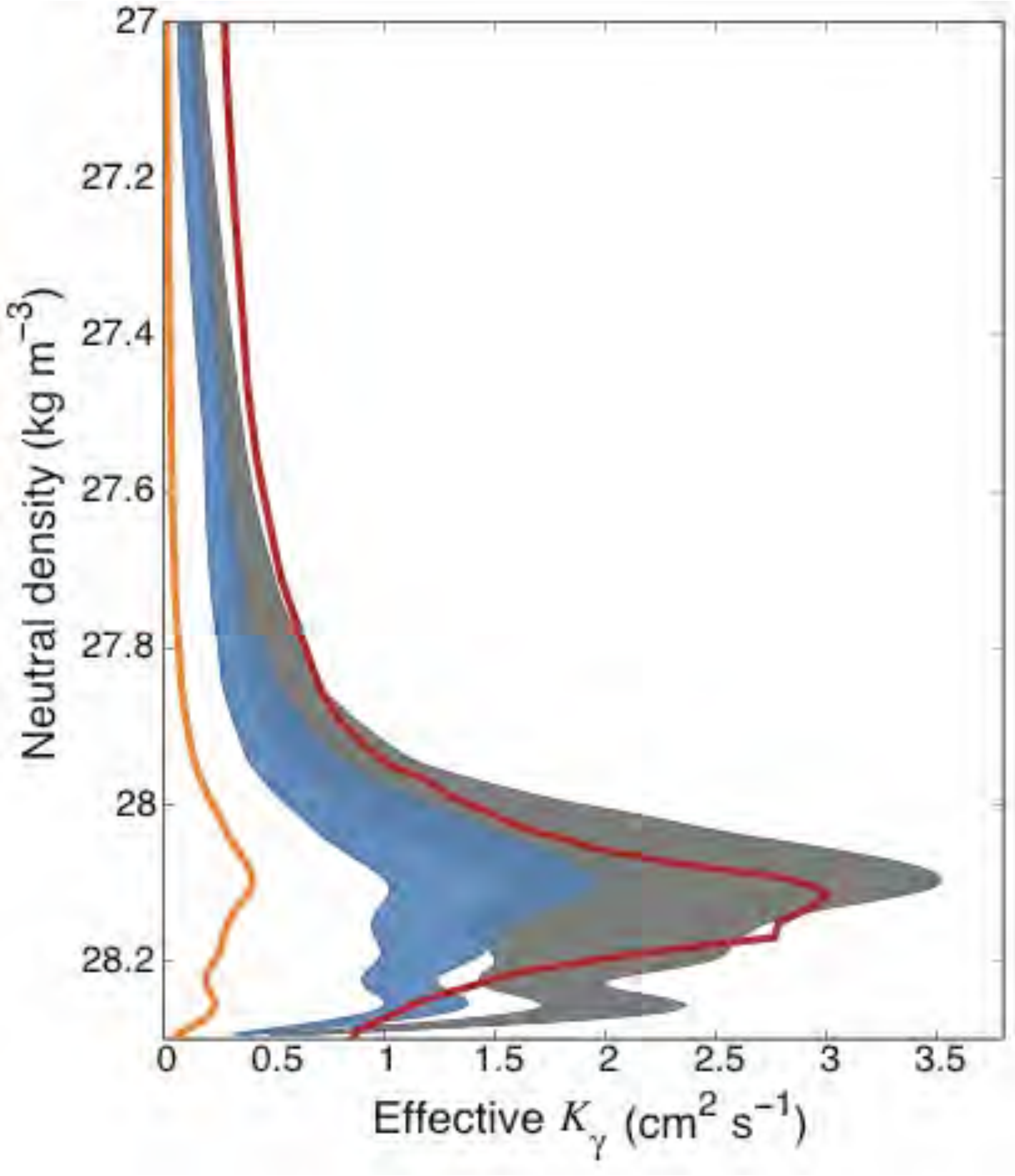
~ 2/3 → Remote dissipation / far-field mixing

- Lee waves 0.2 - 0.4 TW

~ 1/3 → Local dissipation / near-field mixing

2. **Geothermal heating**.
   - Global ocean heat flux of about 30 TW.
   - Potential energy source of about 0.05 TW => often assumed to be negligible.

Effective diffusivity: near-field + far-field + geothermal



Profile of effective diffusivity for the 32°S-48°N region.

Envelope corresponds to the four tested vertical structures of remote tidal dissipation.

Inverse model (Lumpkin & Speer 2007)

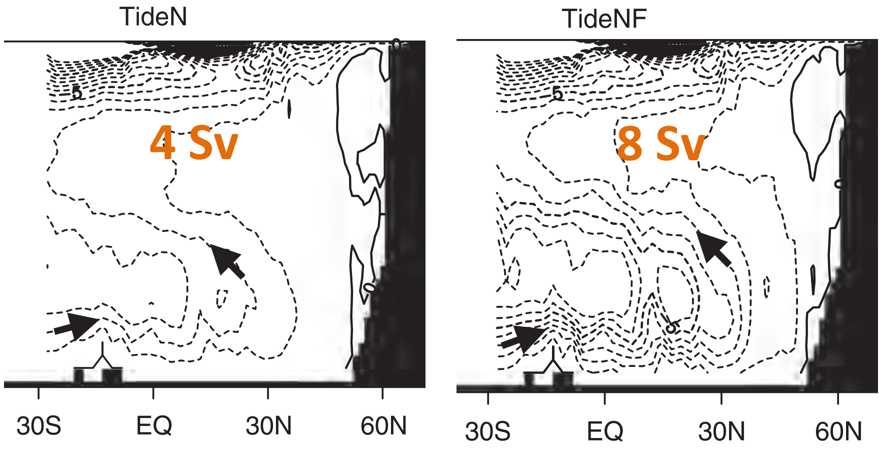
Geothermal

Geothermal + Variable R_f

Geothermal + Fixed R_f

Recent results

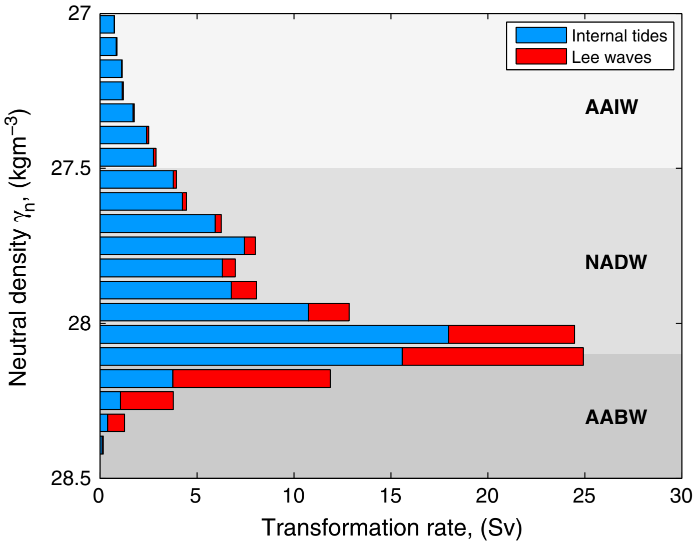
- **Oka & Niwa (2013):**
  Internal tides
  Near-field + Far-field
  Sufficient to simulate 8 Sv Pacific deep MOC
  (in agreement with observations: 7-10 Sv)



Near field

Near + Far field

- **Nikurashin & Ferrari (2013):**
  Lee waves + Internal tides
  Near-field
  Sufficient to upwell 25 Sv of AABW

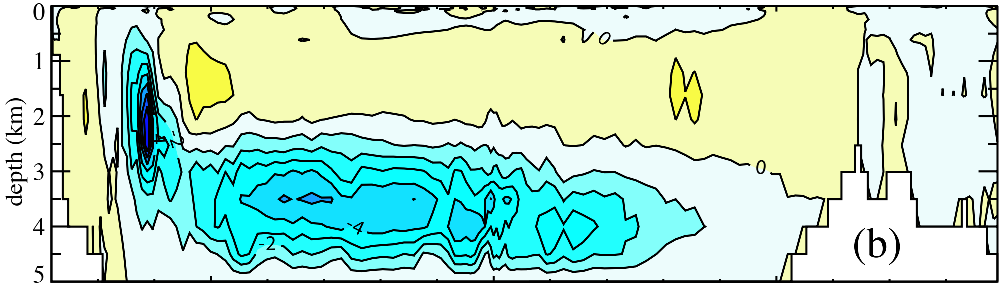


Tides

Lee

16 + 9
= 25 Sv

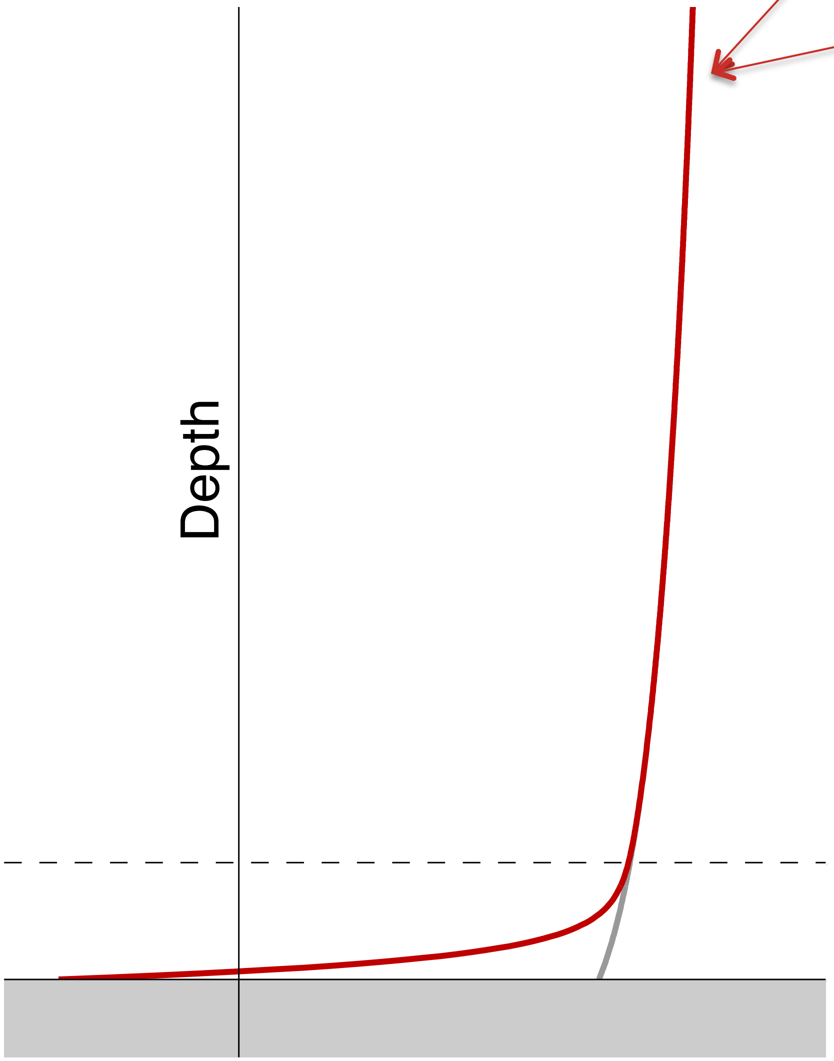
- **Emile-Geay & Madec (2009):**
  Geothermal heating
  5 Sv of AABW upwelling

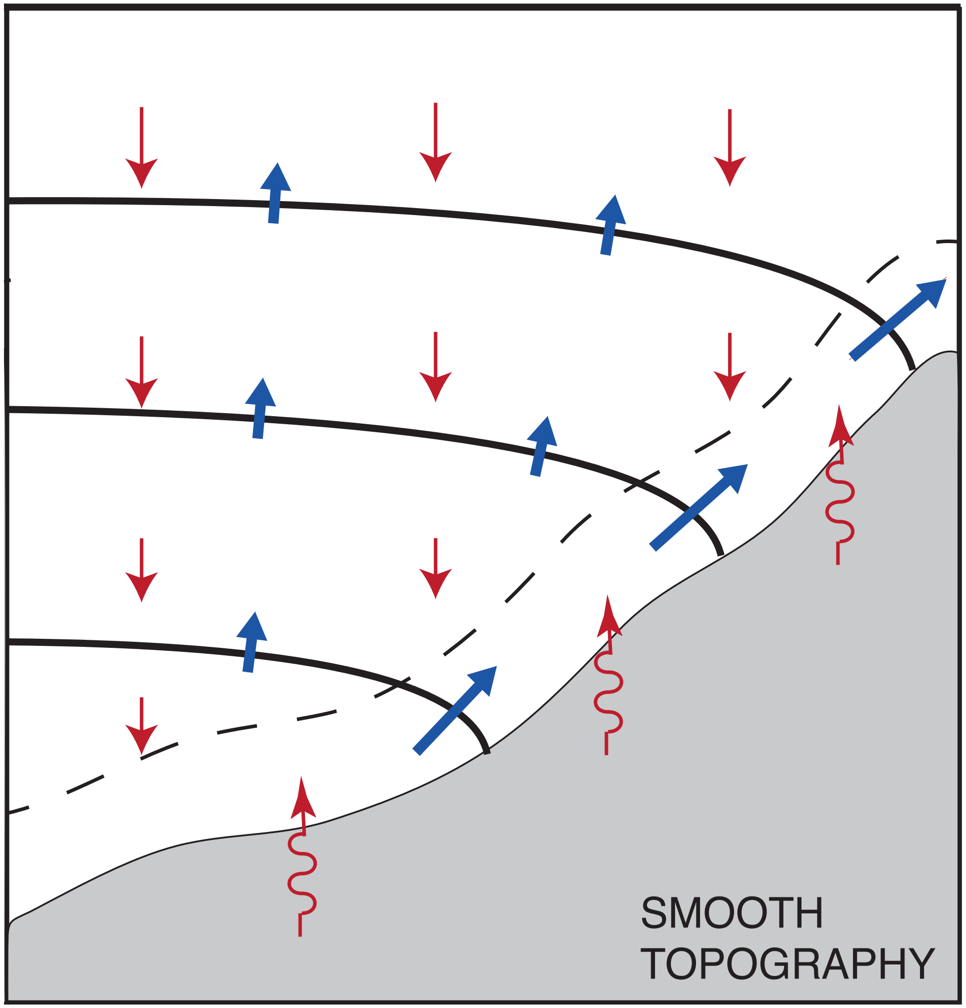


Preliminary remarks: depth-decreasing dissipation

Dia-neutral advection = Divergence of buoyancy flux

$$\boxed{\omega} = \frac{1}{N^2}\partial_z\left(\boxed{K_\perp N^2}\right) = \frac{1}{N^2}\partial_z\left(\boxed{R_f \varepsilon_T}\right)$$





Preliminary remarks: depth-increasing dissipation

Dia-neutral advection = Divergence of buoyancy fluxes

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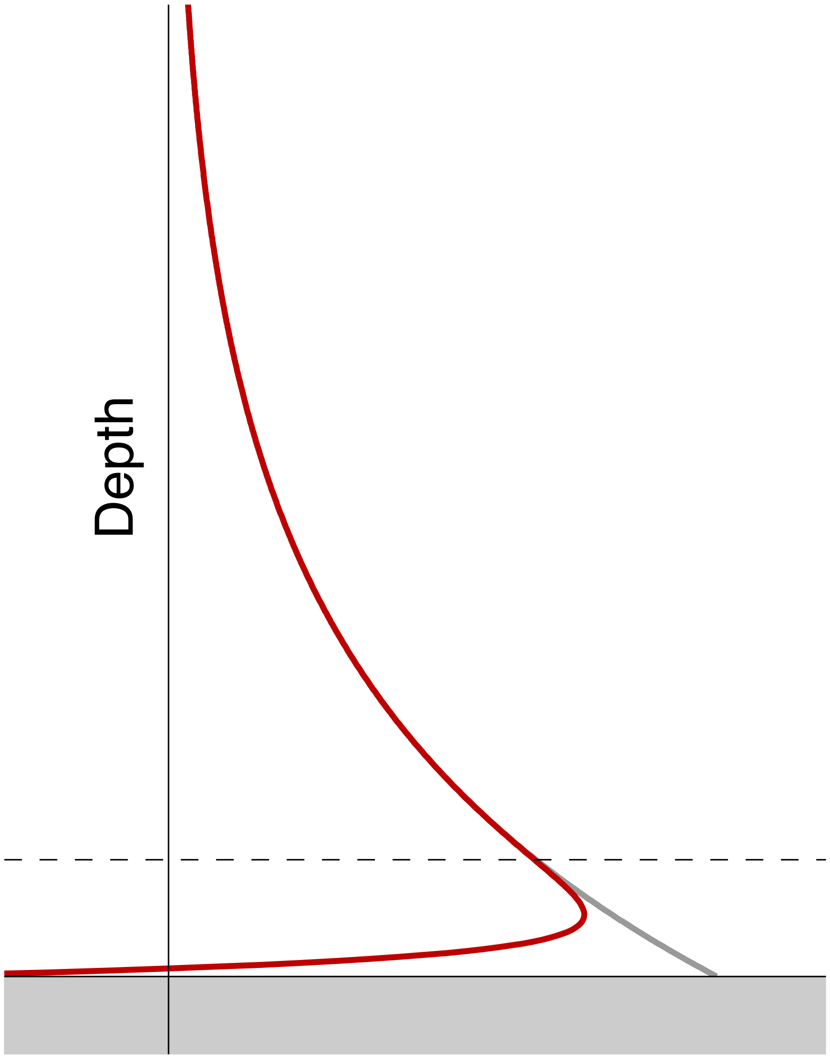
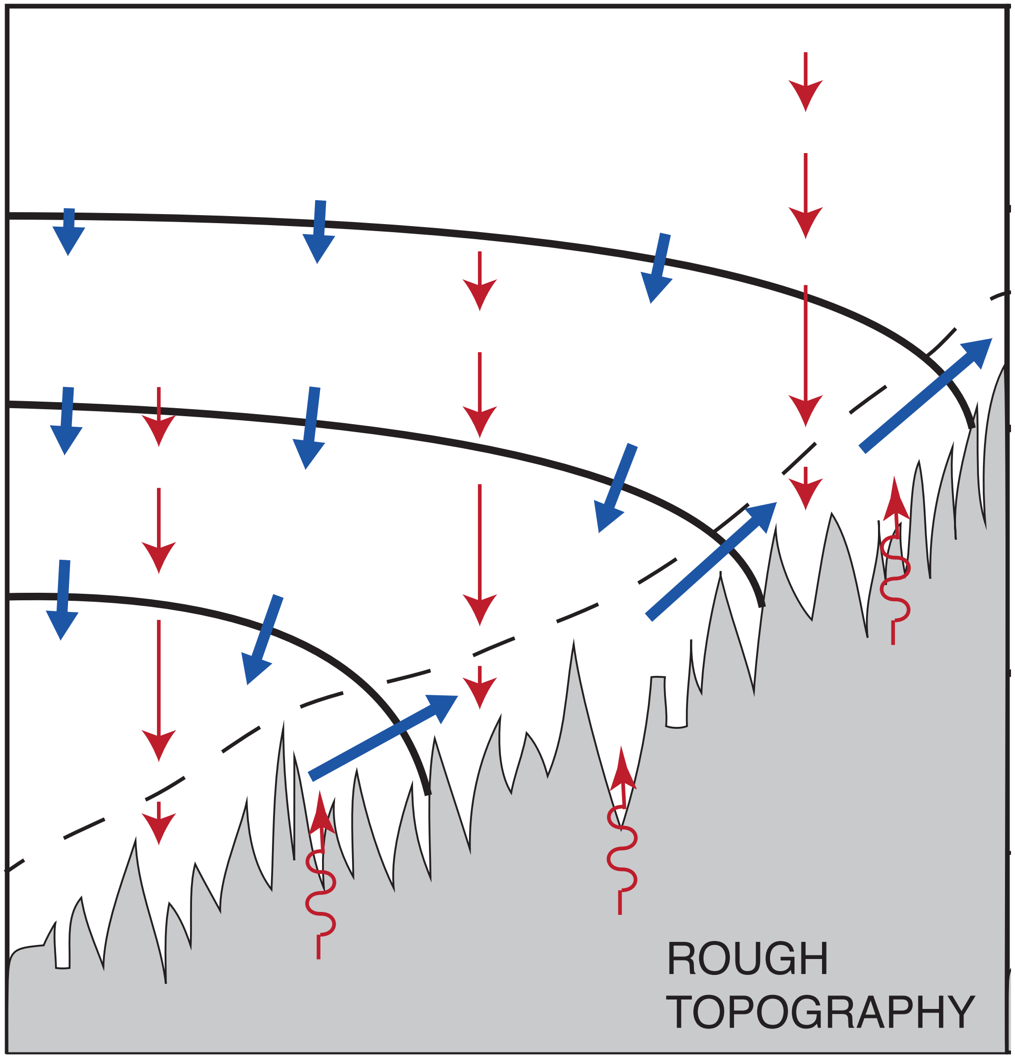
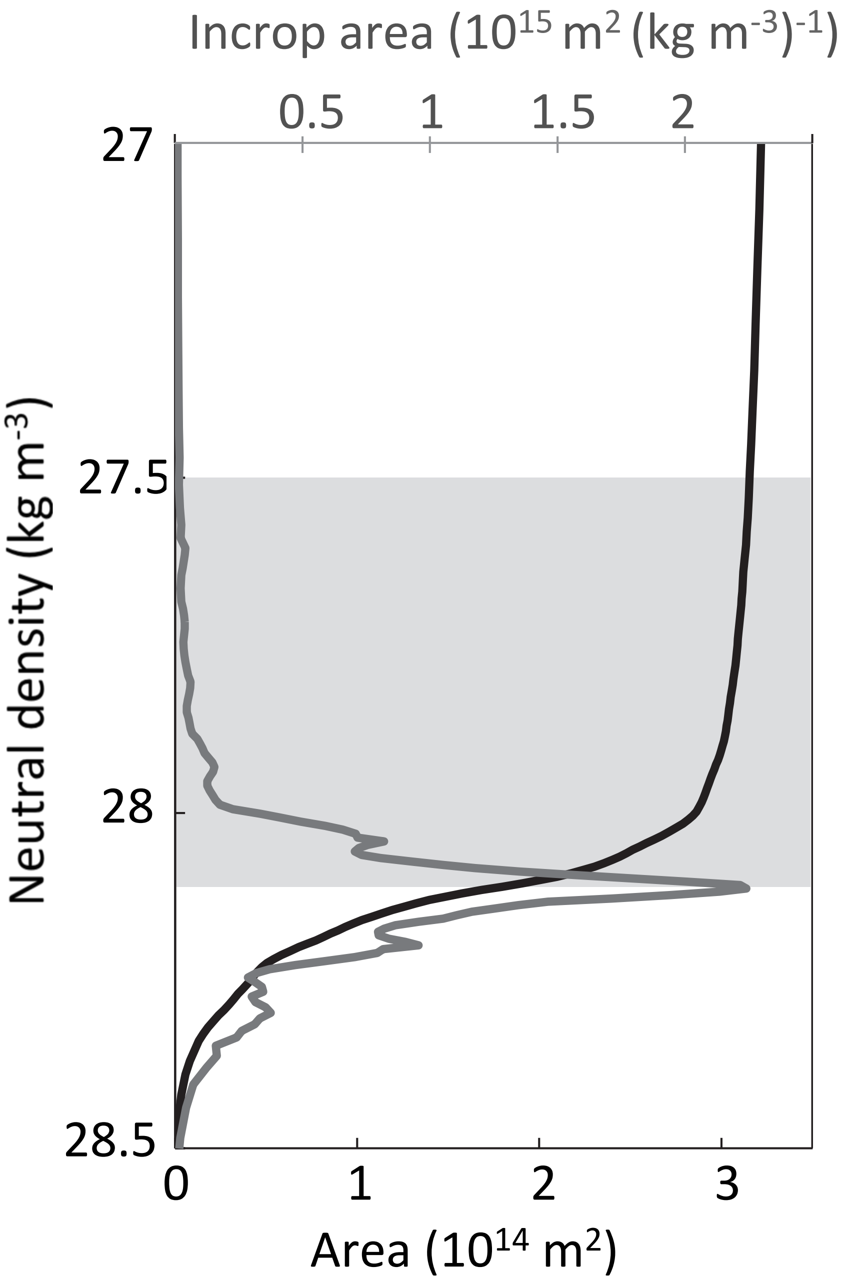
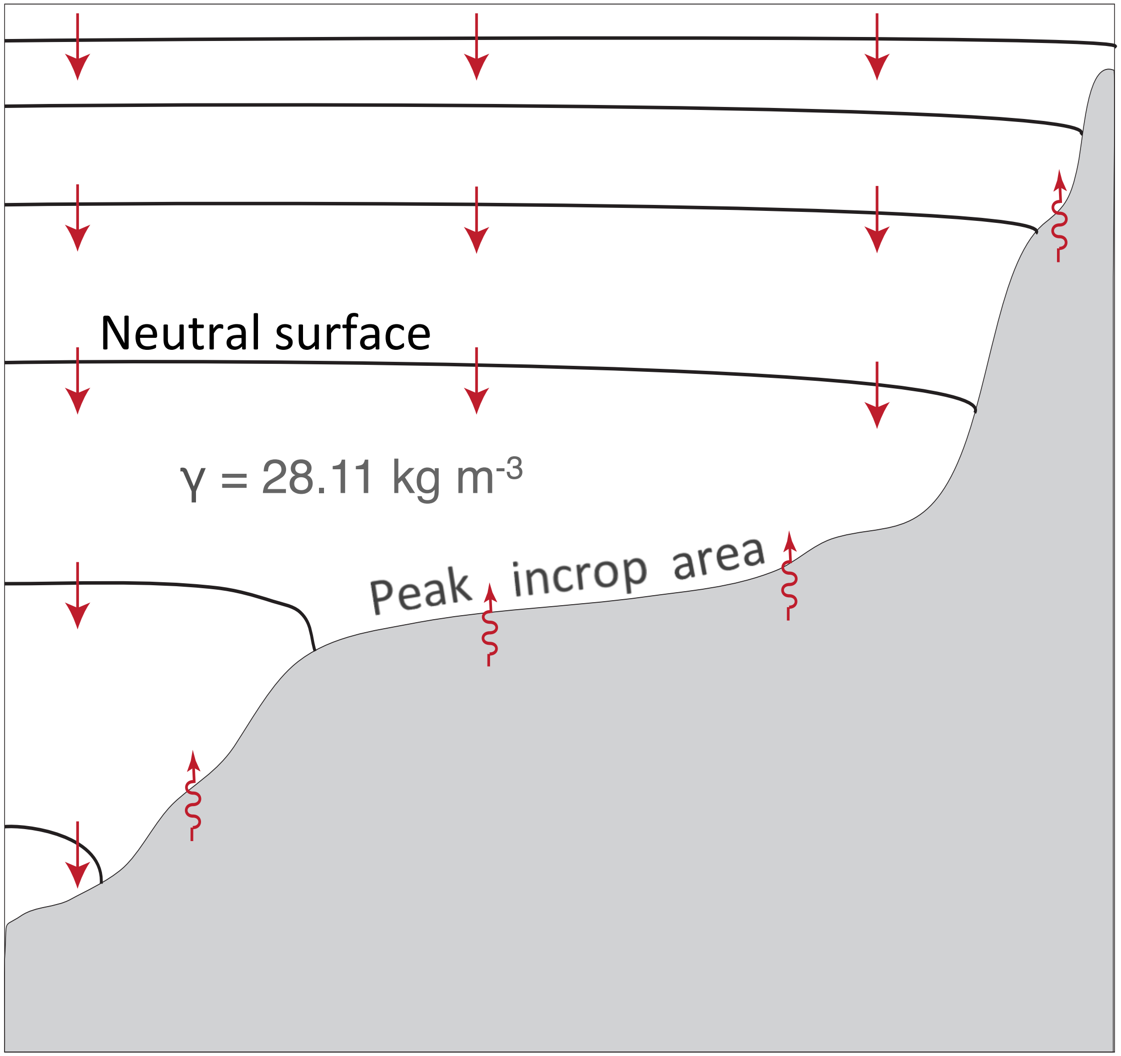




The key role of incrop areas





Geothermal transformation vs. incrop area