



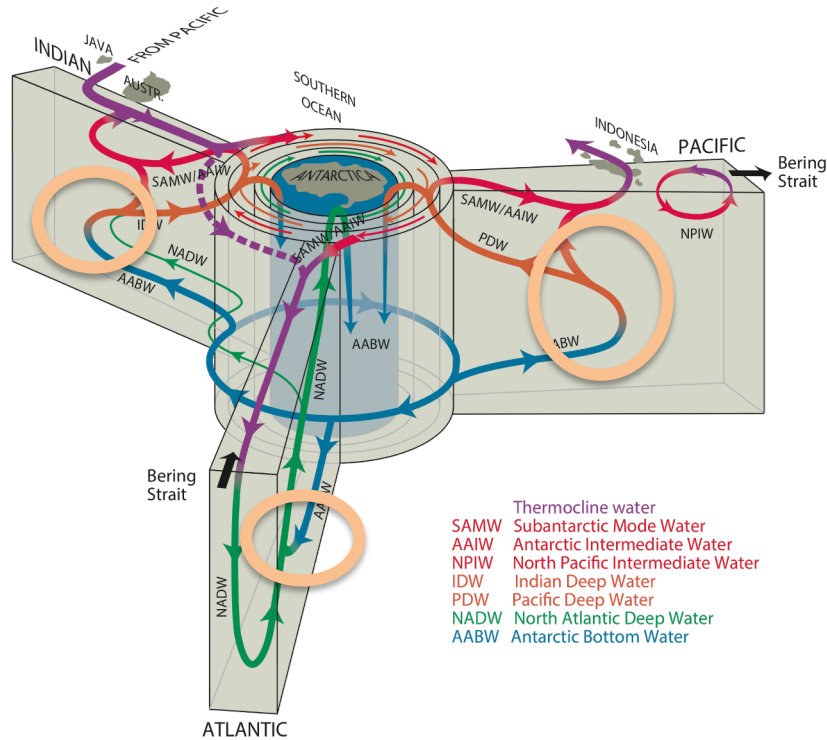
# Abyssal equatorial mixing and the overturning circulation

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ICTP 7<sup>th</sup> summer school July 8, 2026

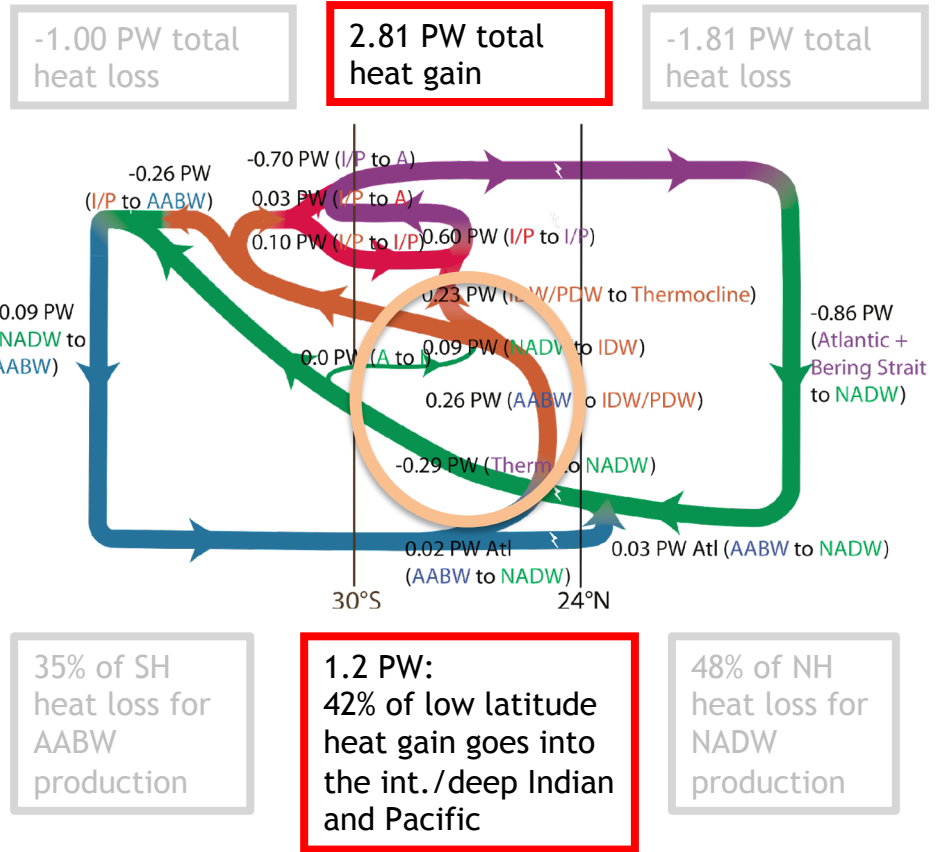
*Special thanks to Caitlin Whalen, Amy Waterhouse, Gunnar Voet*



# Low latitude heat flux from surface into the deep ocean is critical for GMOC



Bottom Waters upwell diffusively into Deep Waters



35% of SH heat loss for AABW production

1.2 PW: 42% of low latitude heat gain goes into the int./deep Indian and Pacific

48% of NH heat loss for NADW production

Based on Talley (Oceanography, 2013)  
 Transports adjusted from Reid (1994, 1997, 2003)

# Diapycnal diffusivities required for low latitude upwelling branch of deep GMOC

Pacific overturning streamfunction:  
upwelling at low latitudes, southward return beneath 1500 m

If upwelling occurs uniformly from 28°S to 24°N:  $\kappa \sim 1 \times 10^{-4} \text{ m}^2\text{s}^{-1}$

If upwelling is predominantly near-equatorial:  $\kappa \sim 4 \text{ to } 7 \times 10^{-4} \text{ m}^2\text{s}^{-1}$

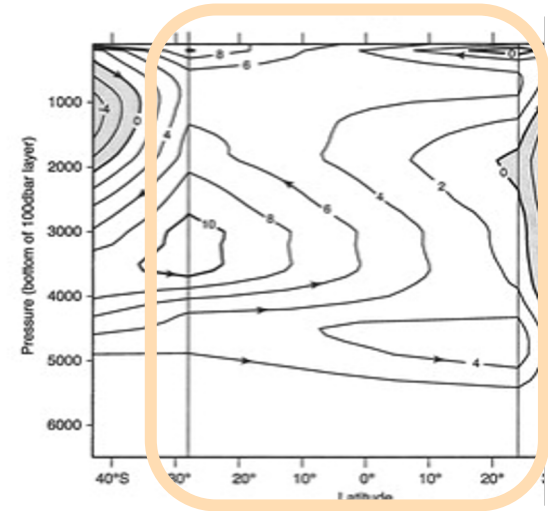
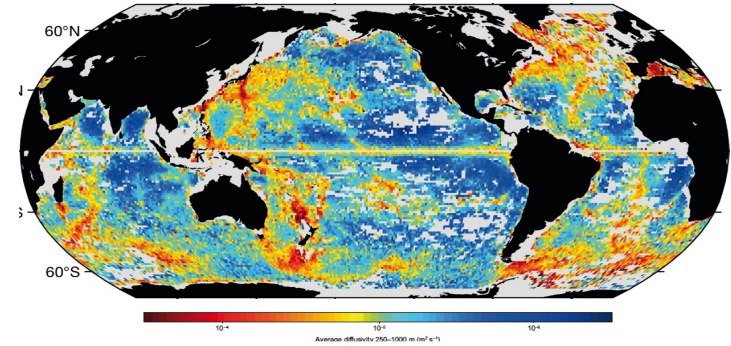


TABLE 2. Estimated tropical upwelling rates, areas, velocities, and diapycnal diffusivities.

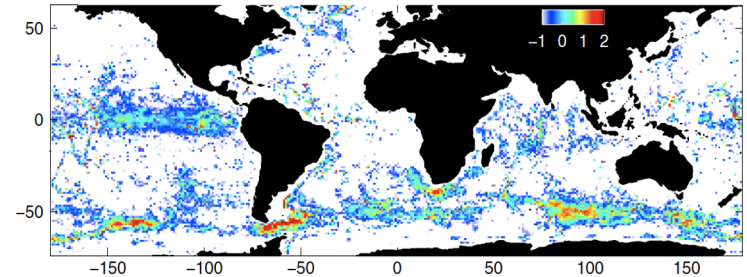
Ocean (lat band for calculation)	Upwelling transport ( $1 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ )	Surface area 2000 m* ( $\text{m}^2$ )	Avg vertical velocity ( $\text{cm s}^{-1}$ )	Diapycnal diffusivity ( $\text{cm}^2 \text{ s}^{-1}$ )
Atlantic (10.5°S–10.5°N)	8	$1.20 \times 10^{13}$	$7 \times 10^{-5}$	1.5
Atlantic (2.5°S–2.5°N)	8	$0.32 \times 10^{13}$	$25 \times 10^{-5}$	5.5
Pacific (10.5°S–10.5°N)	14	$3.70 \times 10^{13}$	$4 \times 10^{-5}$	0.8
Pacific (2.5°S–2.5°N)	14	$0.88 \times 10^{13}$	$16 \times 10^{-5}$	3.5
Indian (10.5°S–10.5°N)	10	$1.34 \times 10^{13}$	$7 \times 10^{-5}$	1.7
Indian (2.5°S–2.5°N)	10	$0.33 \times 10^{13}$	$31 \times 10^{-5}$	6.8
Indian (north of 8.5°N)	8	$0.45 \times 10^{13}$	$18 \times 10^{-5}$	3.9

# PREVIOUS EXAMPLES: Vertical mixing enhancement at the equator

**Upper ocean:** Vertical diffusivity at 250-1000 m estimated from Argo  $N^2$  profiles, after Whalen et al. (2012) (IPCC SROCC, 2019)



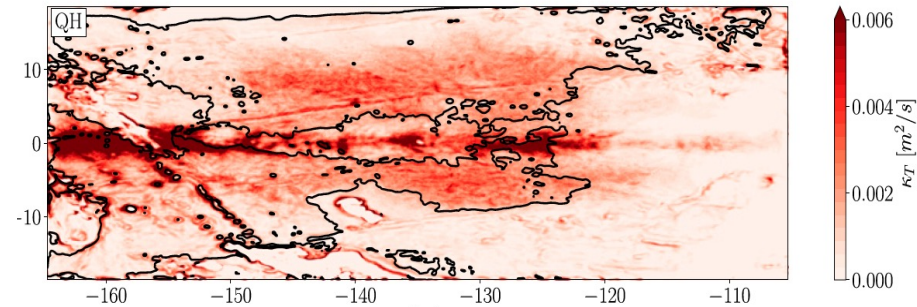
**Abyssal ocean:** Modeled energy conversion to mixing by generation of lee waves generated by abyssal flow over topography (Nikurashin and Ferrari, 2013, 2011)



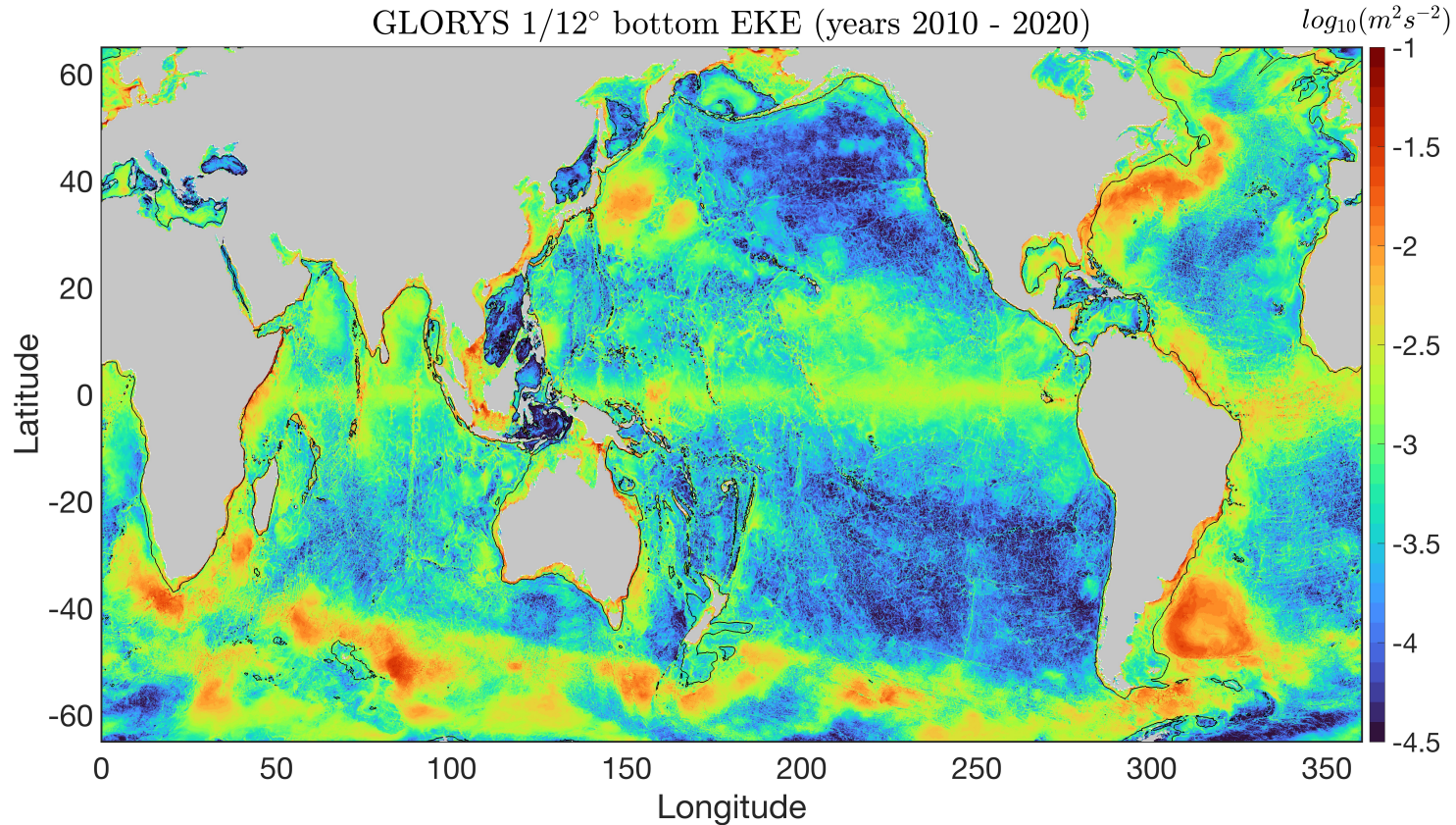
**Abyssal ocean:** Modeled diffusivity due to critical reflection of equatorially trapped waves  
Delorme et al. (JPO, 2019, 2021)

Non-traditional Coriolis terms included (important near equator)

$$K > 40 \times 10^{-4} \text{ m}^2\text{s}^{-1}$$



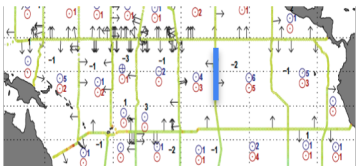
# NEW: From Jim McWilliams, Kaushik Srinivasan, Pierre Damien (April 2026)



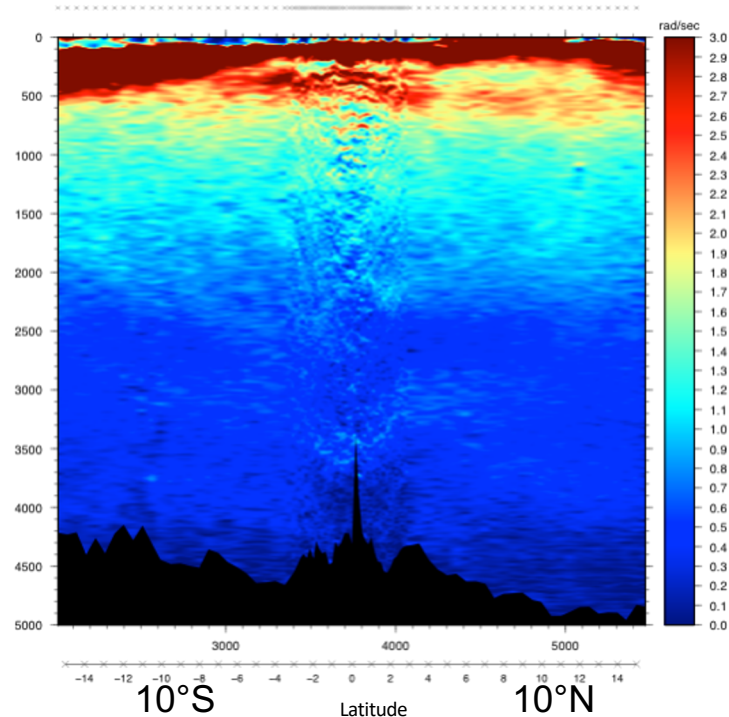
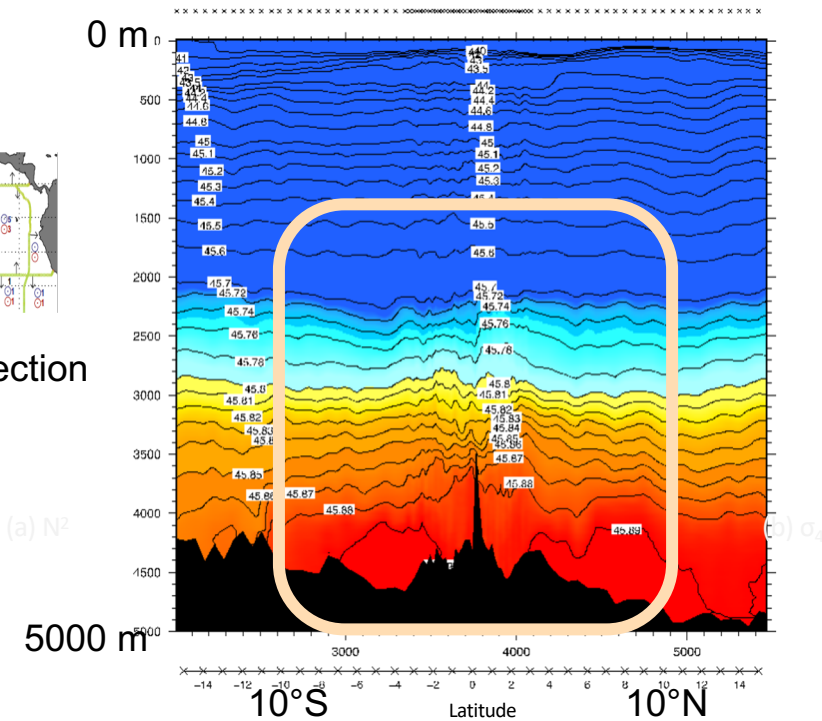
# CTD RESULTS: Bottom layer potential density structure suggests enhanced mixing

Potential density  $\sigma_4$

Brunt Vaisala frequency

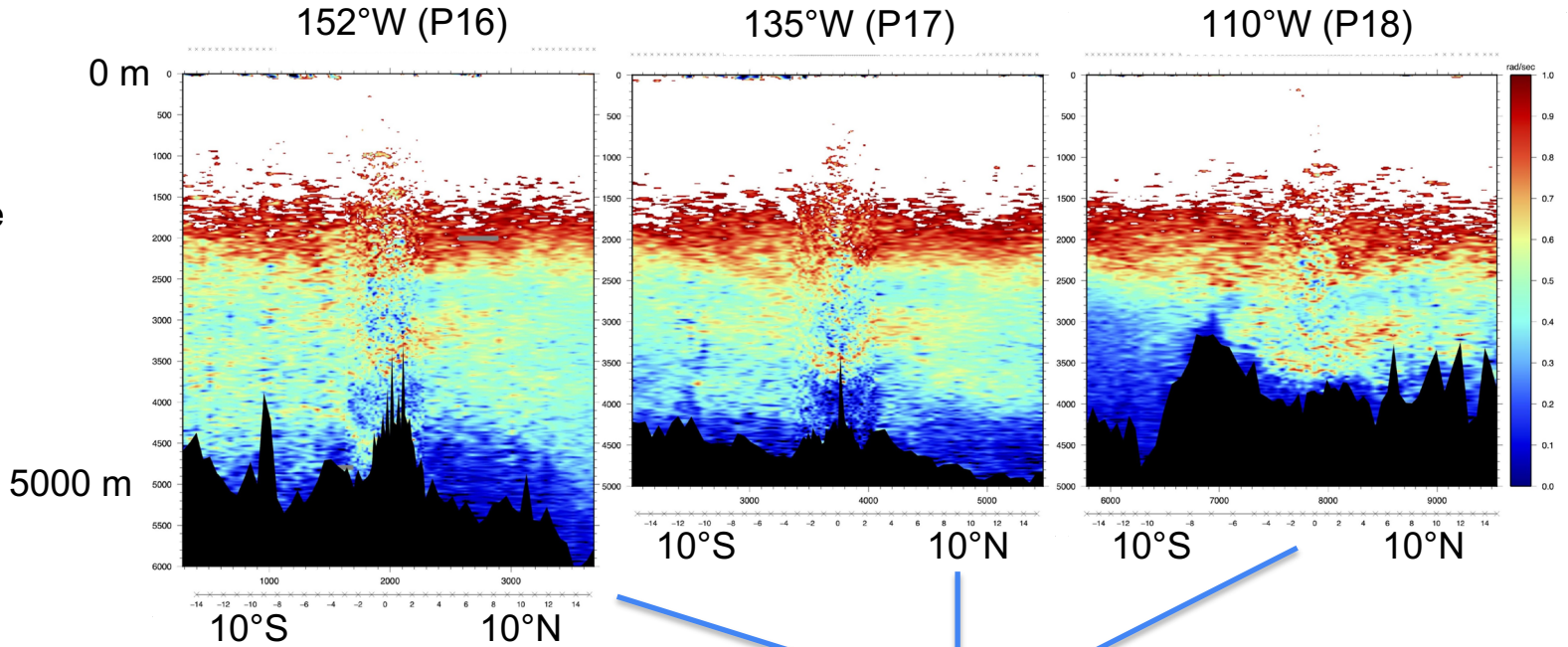


Meridional CTD section  
in central Pacific



135°W (WOCE P17)

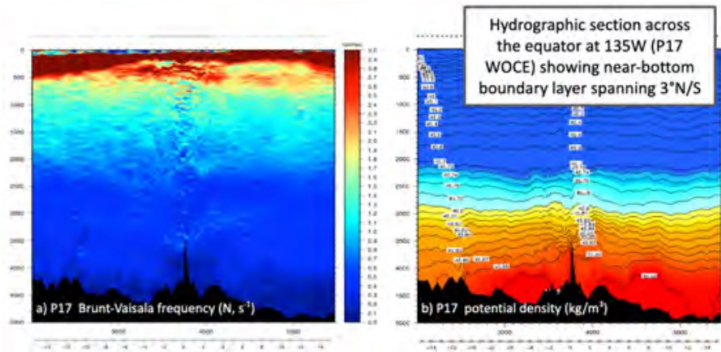
# CTD RESULTS: Stratification (Brunt-Vaisala frequency) suggests enhanced vertical mixing



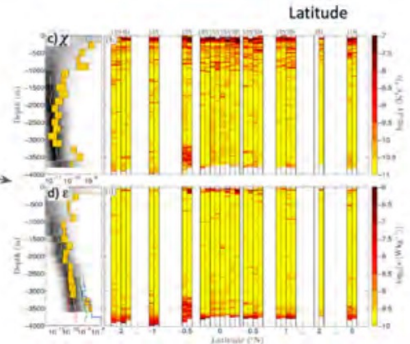
Inverse model with 16 Sv upwelling out of AABW Macdonald et al (PiO 2009)

# Direct measurements bottom boundary layer in equatorial Pacific

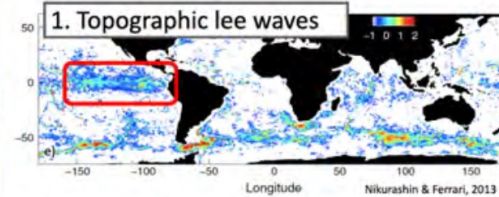
MOTIVE experiment 2024-2025: mixing under Tropical Instability Waves (Whalen, Waterhouse, Voet)  
Abyssal turbulence? Added deep thermistors to 1.75°N mooring.  
Very little bottom topography or roughness here.



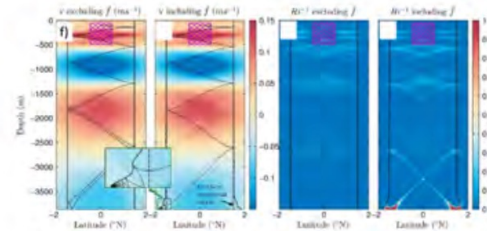
Enhanced near-bottom dissipation rate ( $\epsilon$ ) and thermal variance ( $\chi$ ) at the equator at 110W from Holmes et al (2016)



Proposed Mechanisms:



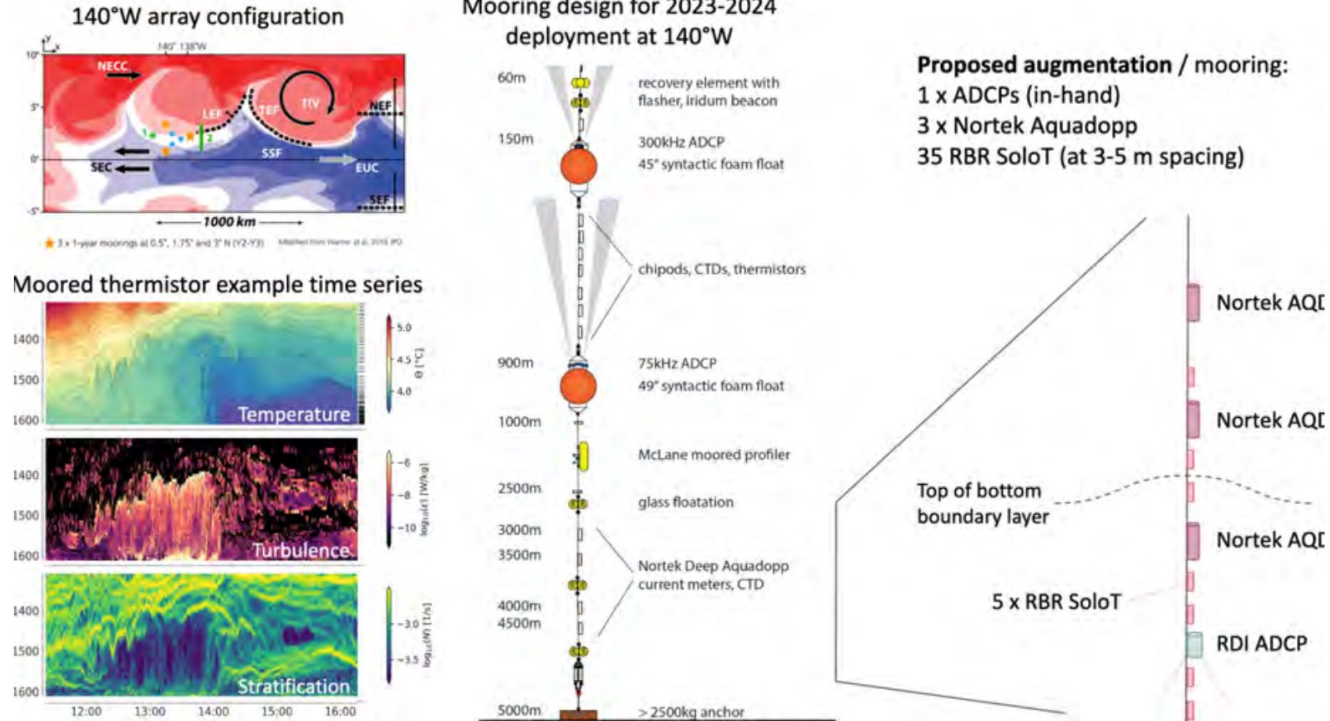
2. Trapped equatorial waves, including non-traditional Coriolis



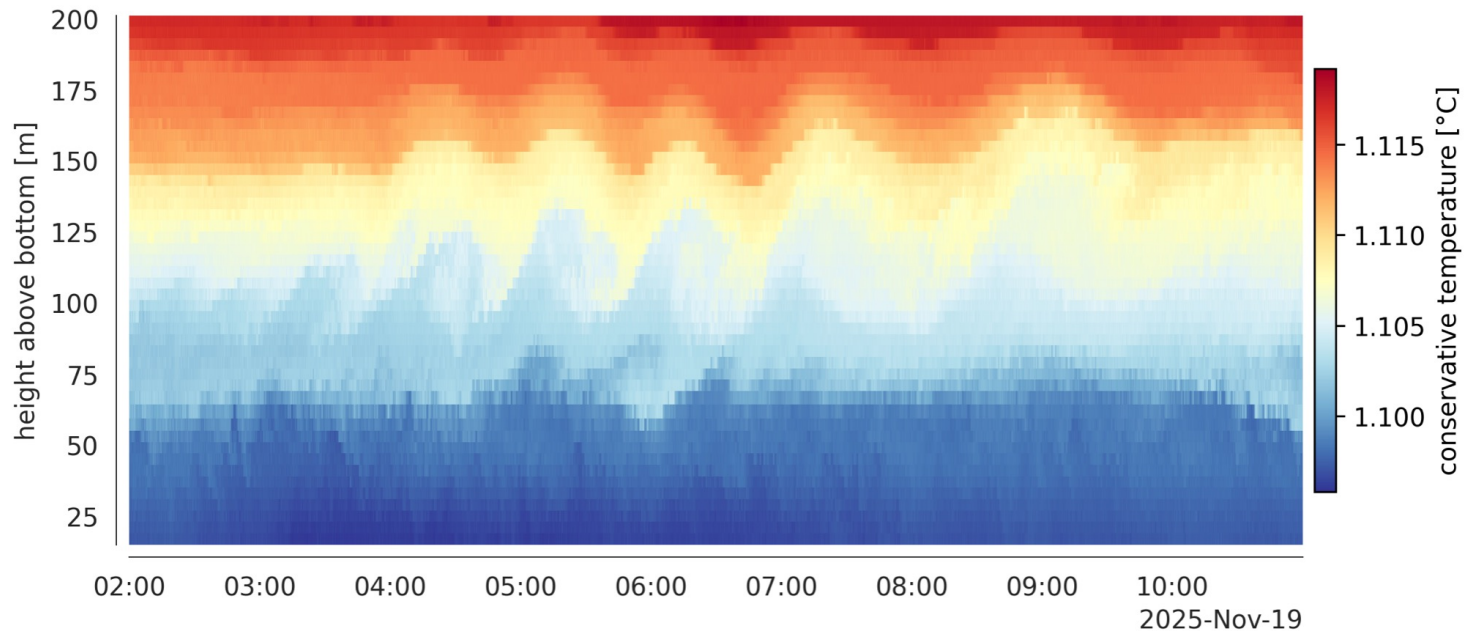
3. Inertial instability

# Direct measurements in bottom boundary layer in equatorial Pacific

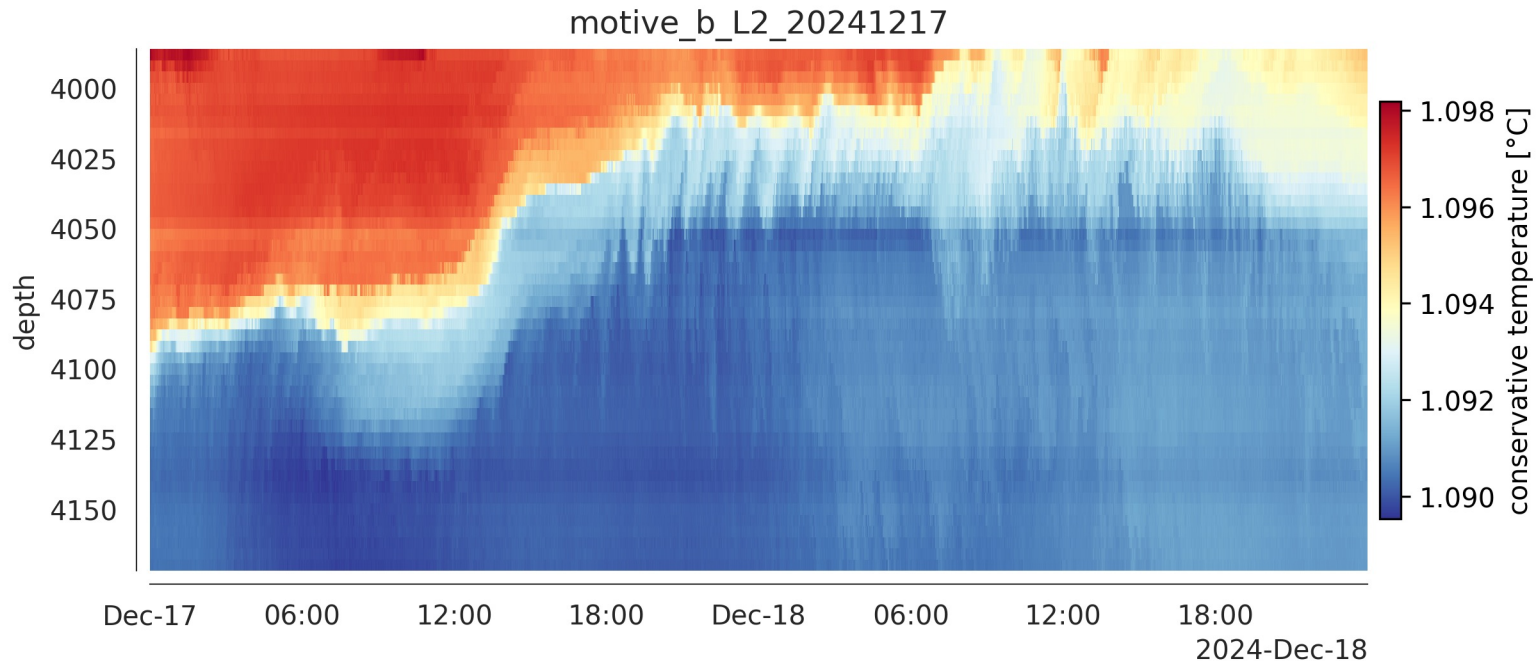
MOTIVE experiment: mixing under Tropical Instability Waves (Whalen, Waterhouse, Voet)  
Abyssal turbulence? Added deep thermistors to 1.75°N mooring (same PIs plus Talley).  
Very little bottom topography or roughness here.



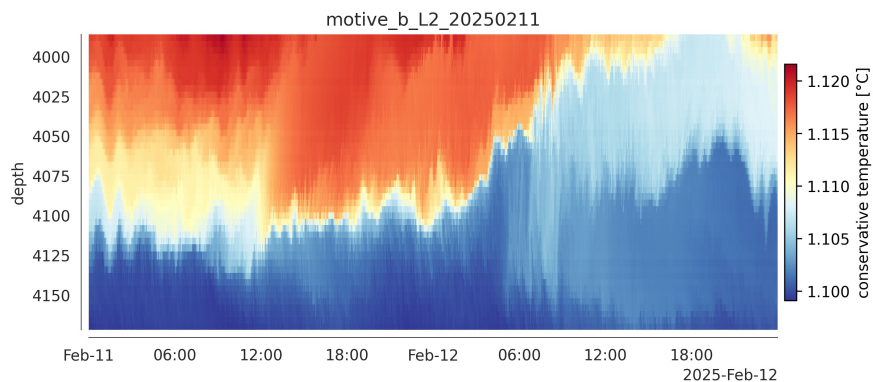
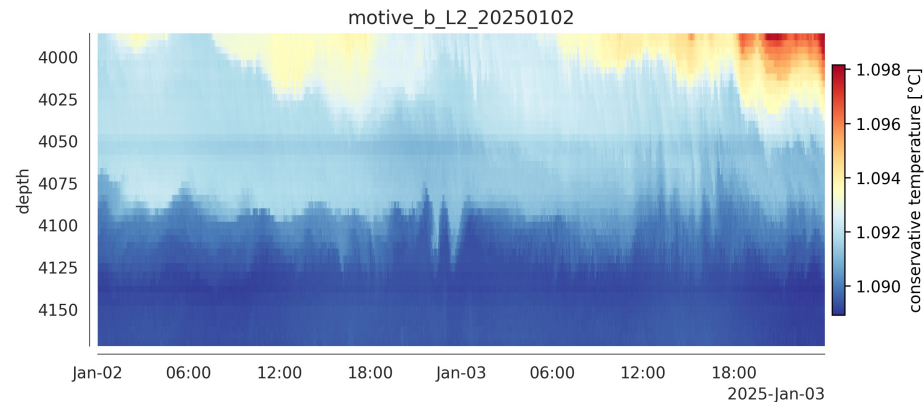
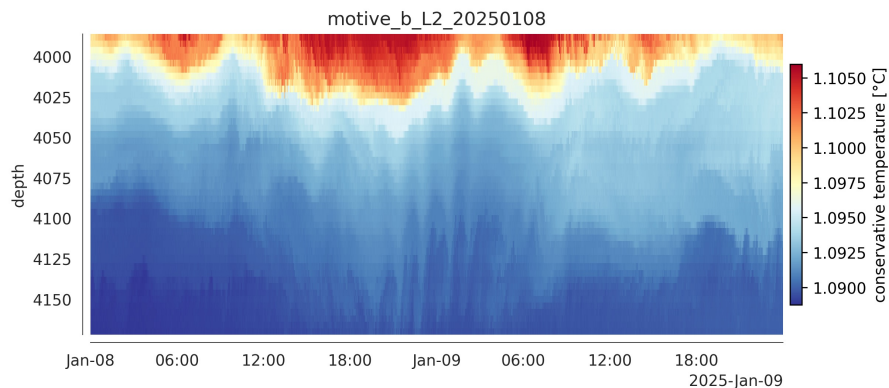
# Preliminary analysis shows **KU** instabilities, indicative of shear-driven turbulent mixing



# Preliminary analysis shows $K\Omega$ instabilities, indicative of shear-driven turbulent mixing



# Direct measurements bottom boundary layer in equatorial Pacific



LOTS TO DO!  
Hot off the press

- Look at the full year of data
- Characterize time and length scales, apparent types of turbulence – relationship to Tropical Instability Waves, etc
- Relate to possible forcings – we have instruments on the full mooring, can look at propagation of waves, including Yanai waves

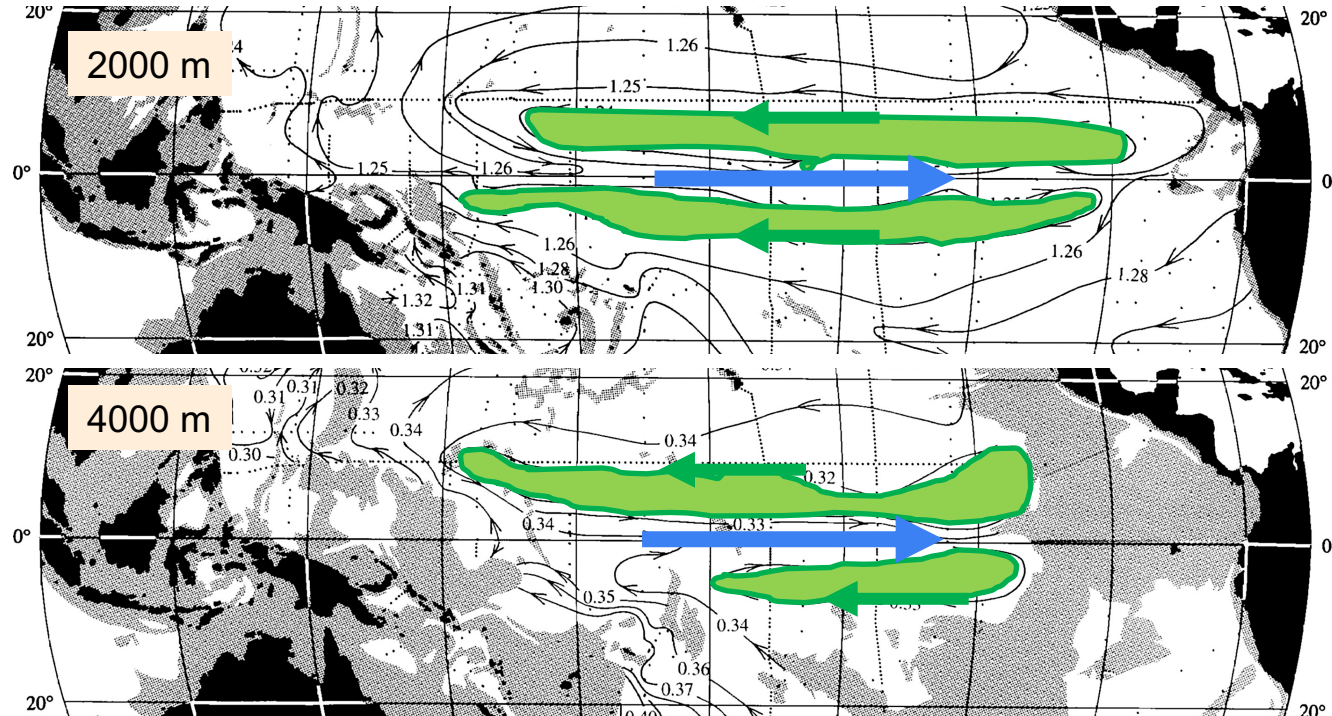
# IMPACT: Equatorial upwelling forcing abyssal lateral circulation?

## Pacific equator:

Mean streamfunctions at  
2000 and 4000 m  
(hydrographic data)

Eastward flow at equator  
Westward flow poleward of 5°

Hence: **cyclonic gyres**  
flanking equator  
(planetary PV balance, next  
slide)



## Atlantic equator:

Eastward AABW below 3000 m upwelling into NADW  
(Friedrichs, McCartney & Hall, JGR 1994)

Reid (PiO, 1997)  
Reproduced in Talley et al. (DPO, 2011)

# IMPACT: Abyssal dynamics creating elongated equatorial gyres

1-D buoyancy

$$w = (1/\rho_z) (\kappa \rho_z)_z$$

$$\kappa = \kappa(y, z)$$

Planetary potential vorticity off equator

$$\beta v = f w_z$$

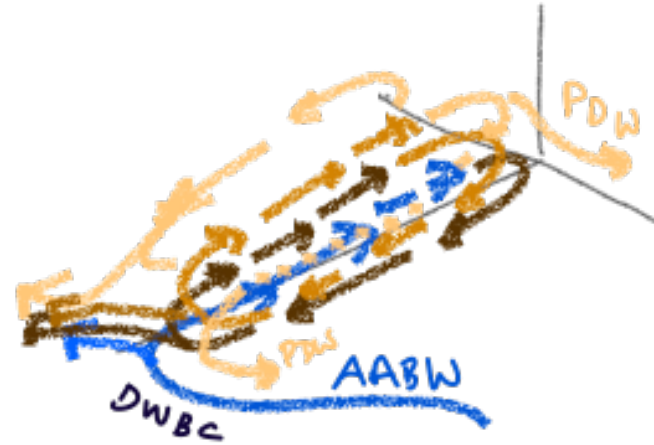
$$f = 2\Omega \sin \theta$$

$$\beta = (2\Omega \cos \theta)/a = \tilde{f}/a$$

Planetary potential vorticity close to equator

$$\beta v = f w_z + \tilde{f} w_y = \beta y w_z + \tilde{f} w_y = \beta(y w_z + a w_y)$$

$$\tilde{f} = 2\Omega \cos \theta$$



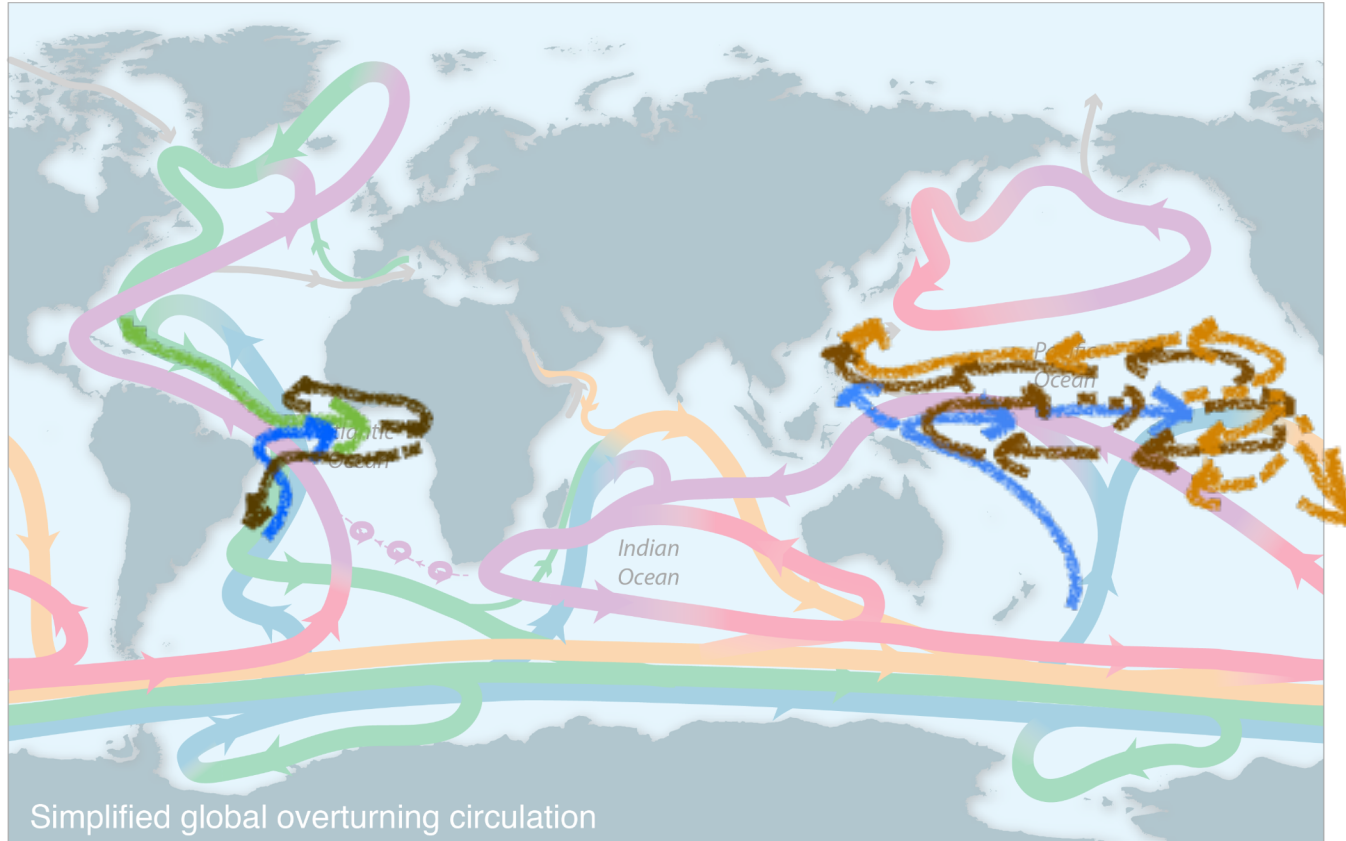
Play with simple examples

$w_z > 0$  (with max localized at equator upwelling increasing upwards) -> poleward motion -> elongated cyclonic gyres

-> eastward flow along equator to feed upwelling and gyres, fed from the Deep Western Boundary Current, diverting flow from crossing equator.

$w_y$  (with max  $w$  at equator) -> equatorward motion, as does  $w$  decreasing upwards. Resulting gyres would be within the deformation radius, could feed westward equatorial flow (as in Friederichs et al's MNADW layer above the LNADW, which flows eastward).

# SCHEMATIC: Abyssal equatorial upwelling and the GMOC



# SUMMARY: Importance of abyssal equatorial upwelling for the GMOC

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1 Diffusivities within equatorial band are high enough to perform most of the downward buoyancy flux required for the low latitude diffusive upwelling limb of the GMOC.

Enhanced  $N^2$  structure that suggests enhanced diffusivity occurs all along the equator.

2 Enhanced equatorial upwelling can drive the observed mean flow, diverting DWBC waters eastward along equator and into recirculating gyres

-> Increases residence time in the equatorial zone and hence longer exposure to downward buoyancy flux.

## Recommendations:

- Full analysis (just starting!) of our mooring measurements
- Incorporation of enhanced equatorial mixing in high resolution ESMs

