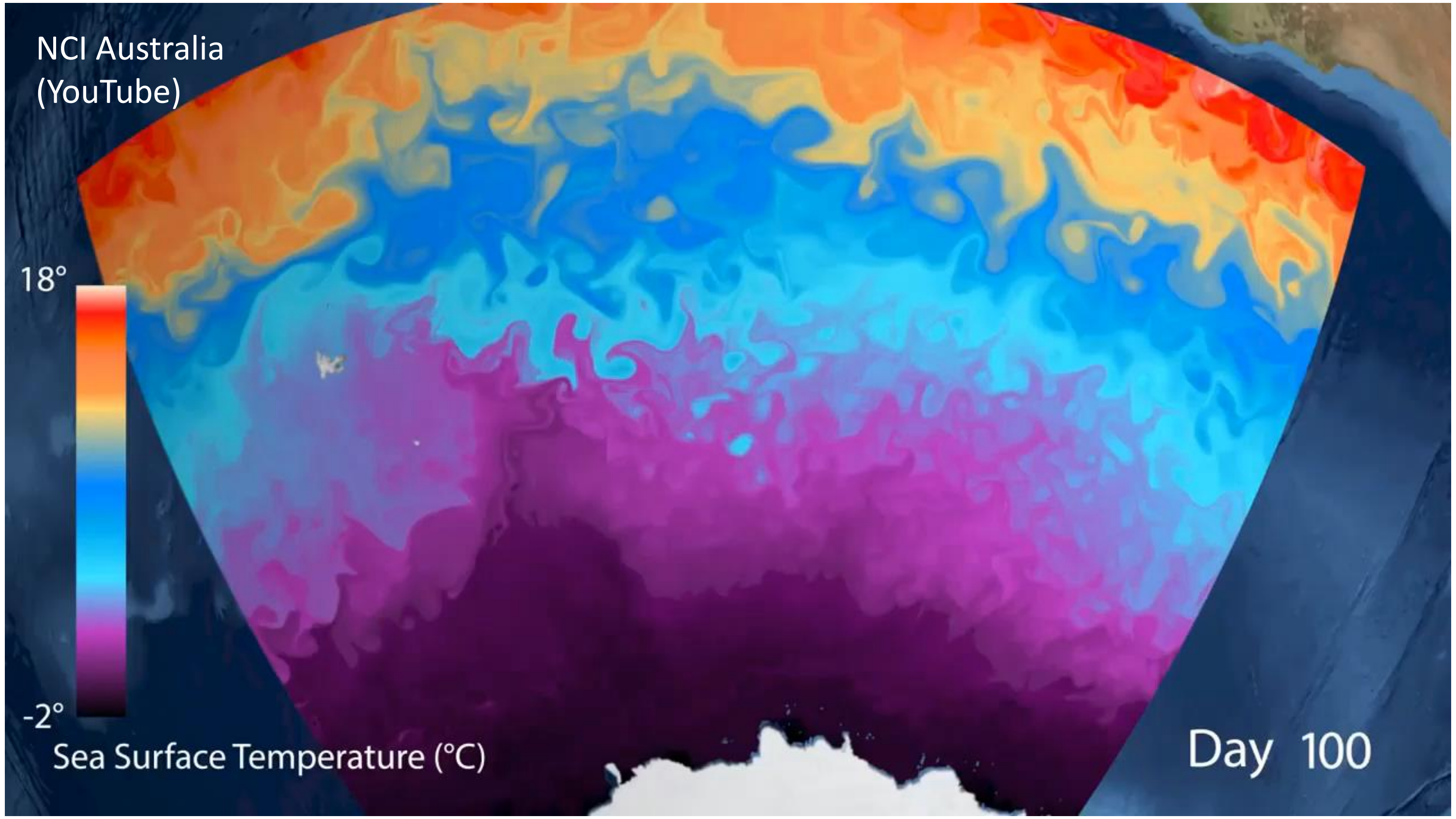
OS1.10 The Southern Ocean in a changing climate: open-ocean physical and biogeochemical processes
EGU22-1404 → entry to OSPP Award

Onshore Diffusion of Circumpolar Deep Water



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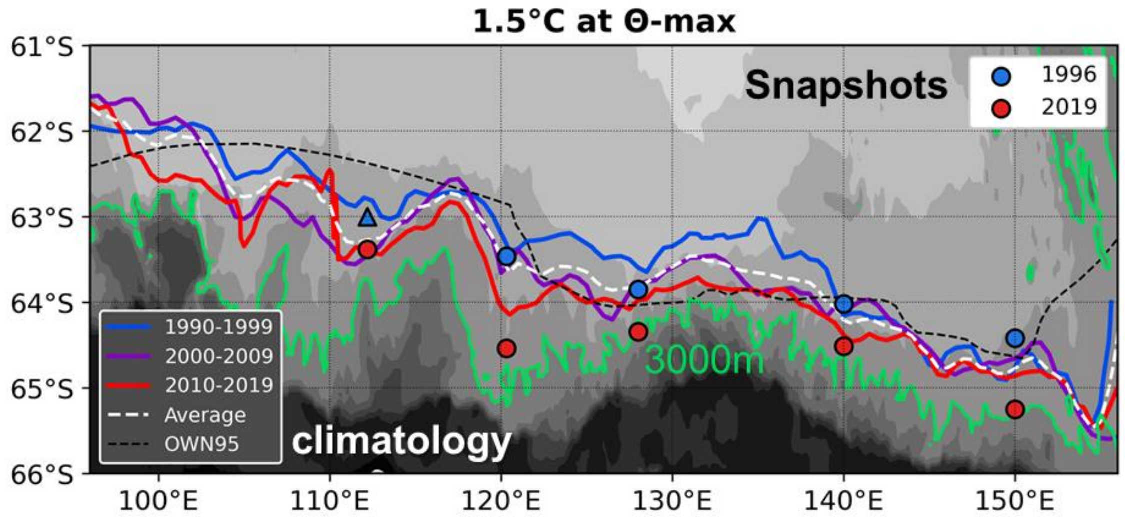
2. Graduate School of Environmental Science, Hokkaido University,
3. National Institute of Polar Research Japan (JSPS Postdoctoral Fellow),
4. Tokyo University of Marine Science and Technology

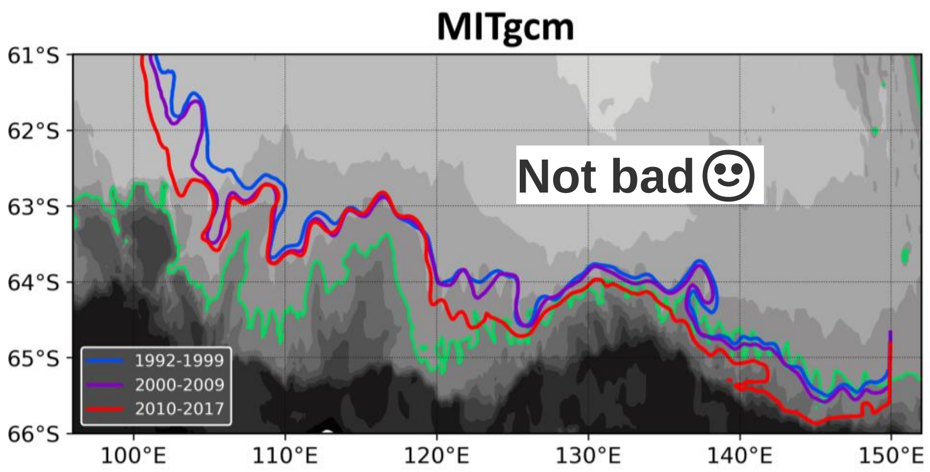
Motivation

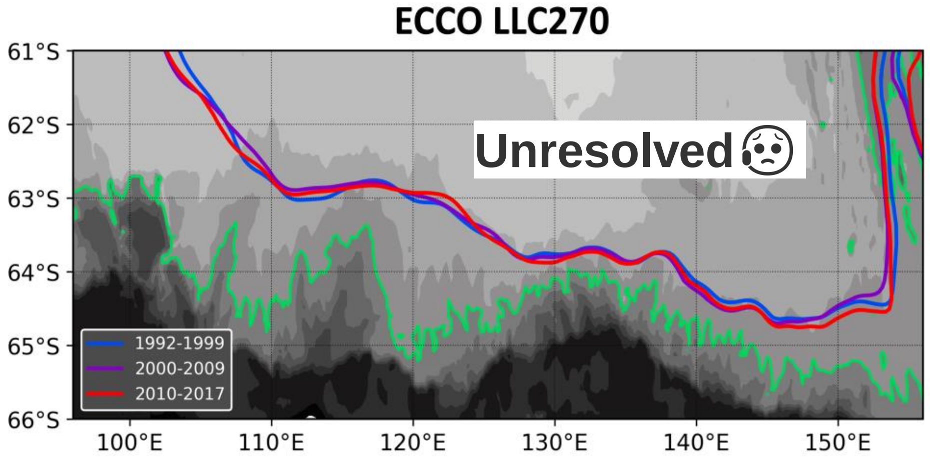


Multidecadal poleward shift of the ACC's SB
(Yamazaki+ 2021)

Eddy-resolving
1/30°

Eddy-permitting
1/4°





Can we estimate eddy diffusivity and onshore CDW flux purely based on observational data?

Yamazaki, K., Aoki, S., Katsumata, K., Hirano, D., & Nakayama, Y. (2021). Multidecadal poleward shift of the southern boundary of the Antarctic Circumpolar Current off East Antarctica. Science Advances, 7(24), eabf8755.

Measure: mixing length framework

isopycnal tracer conservation

$$\frac{\partial\bar{\theta}}{\partial t} + \bar{u}\cdot\nabla\bar{\theta} = -\nabla\cdot(\overline{u'\theta'})$$

Fickian diffusion

$$F_{\theta} = \overline{u'\theta'} \stackrel{def}{=} -K\nabla\bar{\theta}$$

divide by $\nabla\bar{\theta}$*

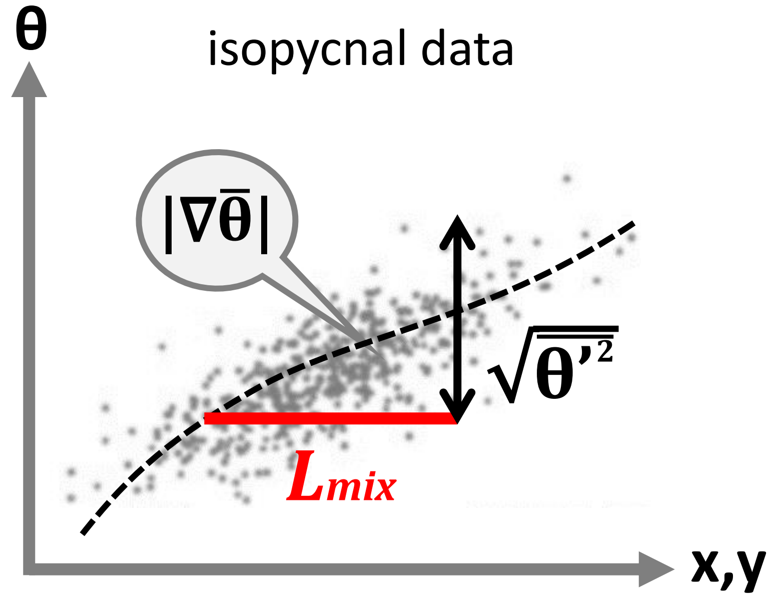
eddy diffusivity

$$K = \frac{\overline{u'\theta'}}{|\nabla\bar{\theta}|} = \frac{\overline{u'\theta'}}{\sqrt{\overline{u'^2}\,\overline{\theta'^2}}}\sqrt{\overline{u'^2}}\,\frac{\sqrt{\overline{\theta'^2}}}{|\nabla\bar{\theta}|}$$

Γ — mixing efficiency

u_{eddy} — eddy velocity

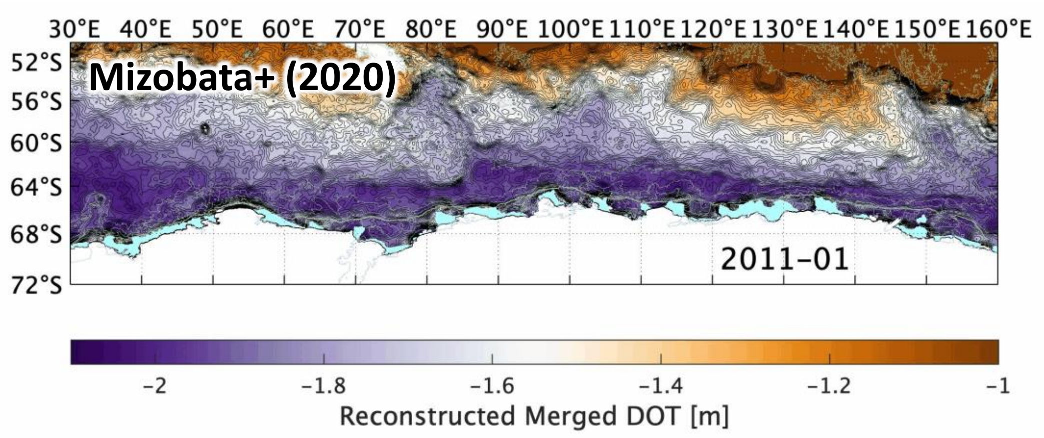
L_{mix} — mixing length



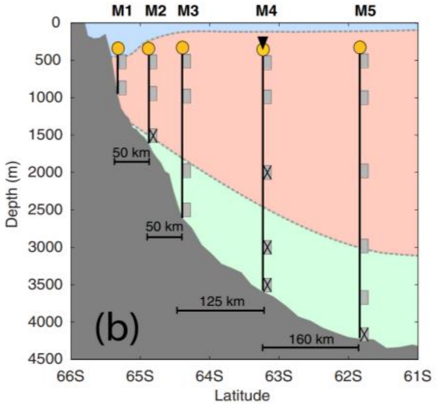
Hydrographic diffusivities in SO

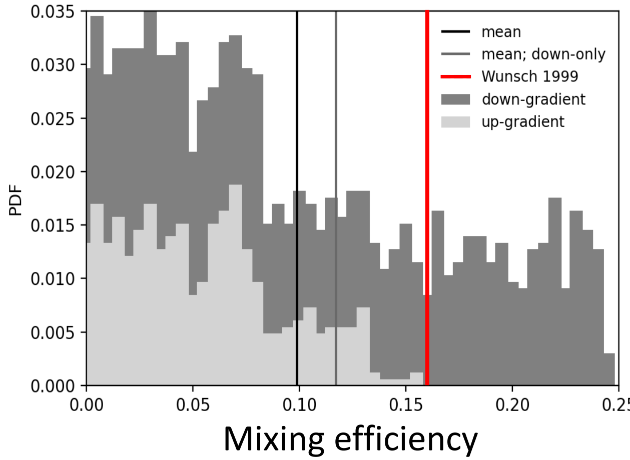
$$K = \frac{\overline{u'\theta'}}{|\nabla\bar{\theta}|} = \underbrace{\frac{\overline{u'\theta'}}{\sqrt{\overline{u'^2}\,\overline{\theta'^2}}}}_{\Gamma}\ \underbrace{\sqrt{\overline{u'^2}}}_{u_{eddy}}\ \underbrace{\frac{\sqrt{\overline{\theta'^2}}}{|\nabla\bar{\theta}|}}_{L_{mix}}$$

	Location	CTD for L_{mix}	Tracer θ	u_{eddy}	Mixing efficiency Γ
Garabato+ (2011)	north of SACCF	ship	temperature	AVISO	N/A (suggesting 0.01-0.4)
Foppert+ (2019)	SB to ASF	biologging	spiciness	N/A	N/A (implicitly 1.0)
This study	PF to ASF	ship + float + biologging	spiciness + thickness	CryoSat-2 synthesis	0.16 (Wunsch, 1999)



Pena-Molino+ (2016)





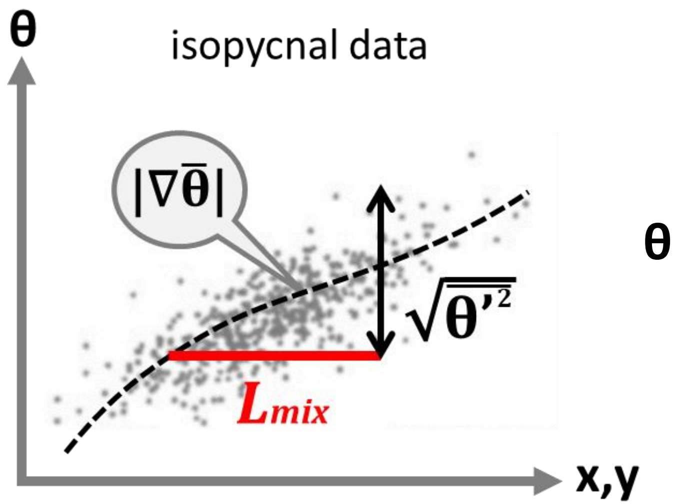
Naveira Garabato, A. C., Ferrari, R., & Polzin, K. L. (2011). Eddy stirring in the Southern Ocean. Journal of Geophysical Research: Oceans, 116(C9).
Foppert, A., Rintoul, S. R., & England, M. H. (2019). Along-slope variability of cross-slope Eddy transport in East Antarctica. Geophysical Research Letters, 46(14), 8224-8233.

Mixing length calculation

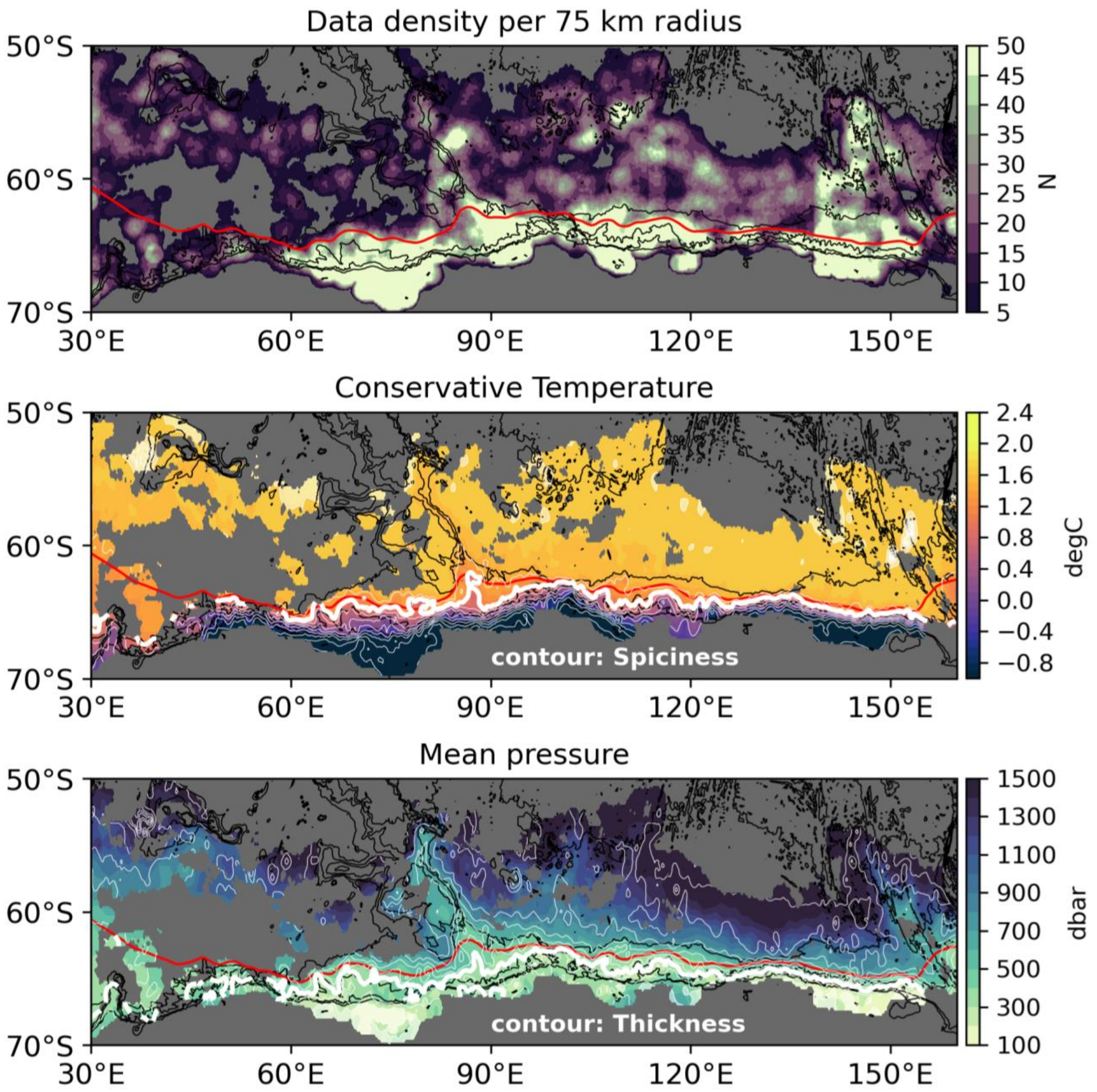
- **Ship, Argo, biologging CTD data, post 1990 Dec-Mar**
- **Isopycnally averaged after 1db Akima interpolation**

  (γn: 27.9-28.0 for ASW; γn: 28.0-28.1 for CDW)
- **1/4° grids with > 10 pts within 75 km radius**

  (the criterion is based on Garabato+ 2011 and the scale of slope)



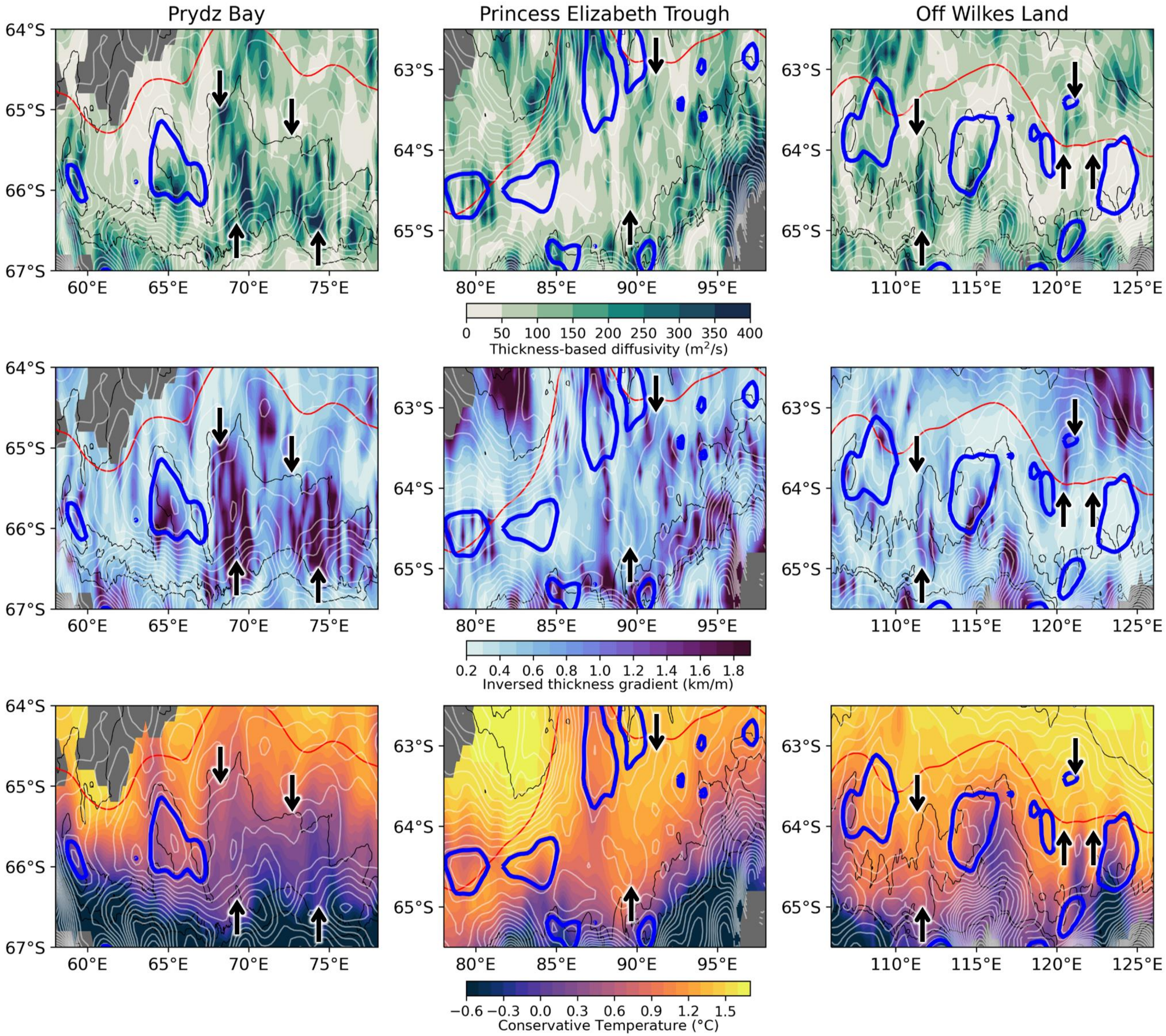
θ is { spiciness, thickness



Naveira Garabato, A. C., Ferrari, R., & Polzin, K. L. (2011). Eddy stirring in the Southern Ocean. Journal of Geophysical Research: Oceans, 116(C9).

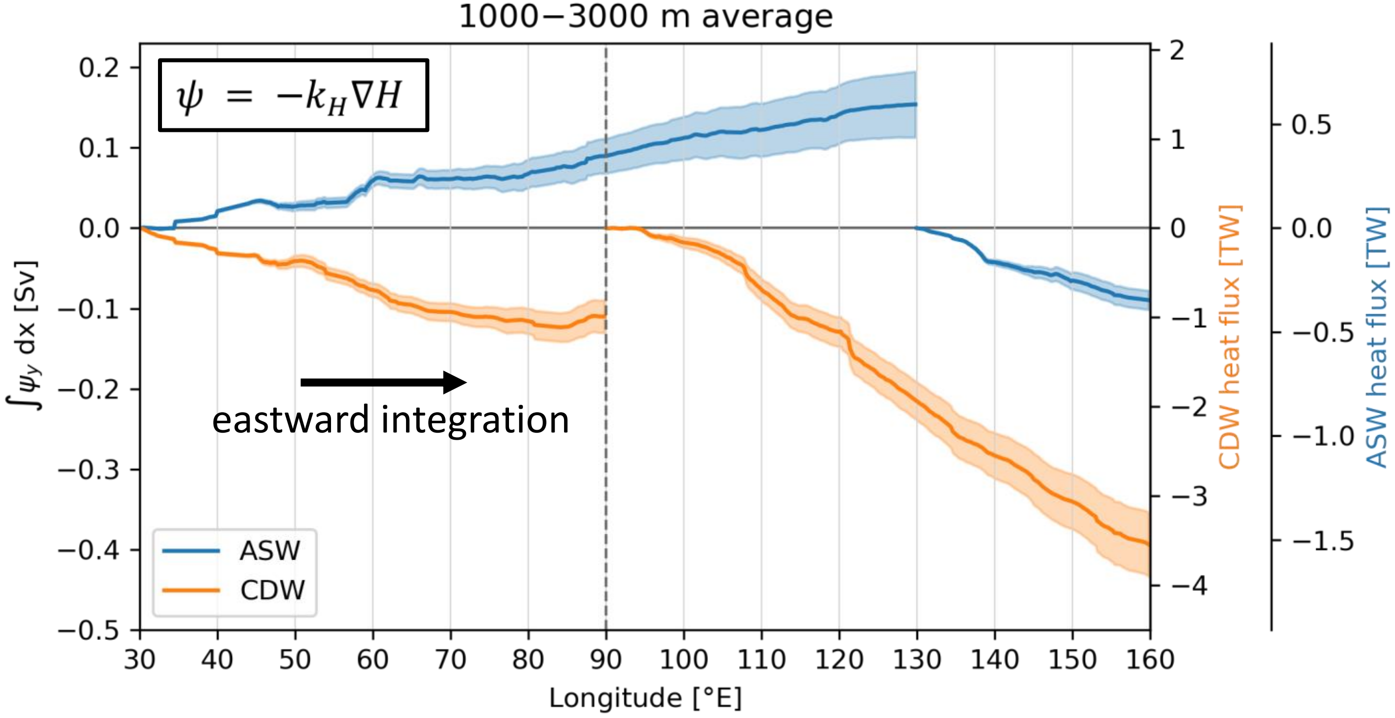
Results

- **Typically 100-500 m²/s in the Antarctic margin**
- **K, 1/∇H ∝ CDW intrusion**
- **Choice of tracer does not affect qualitatively**

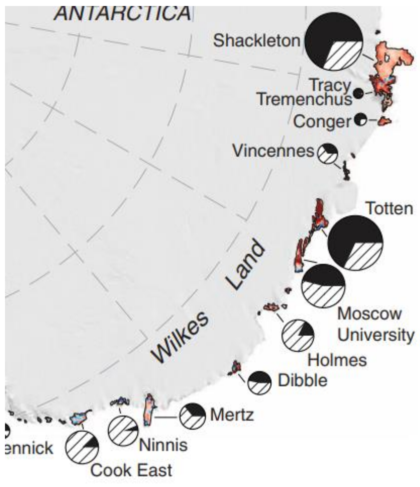


red curve: SB
white: dynamic topography
(blue: subgyre)

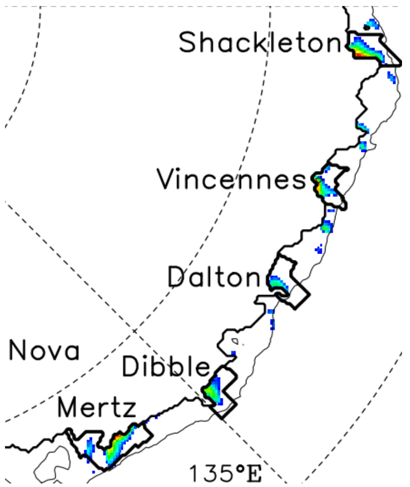
Cross-slope heat flux



Rignot+ (2013)



Tamura+ (2011, 2016)



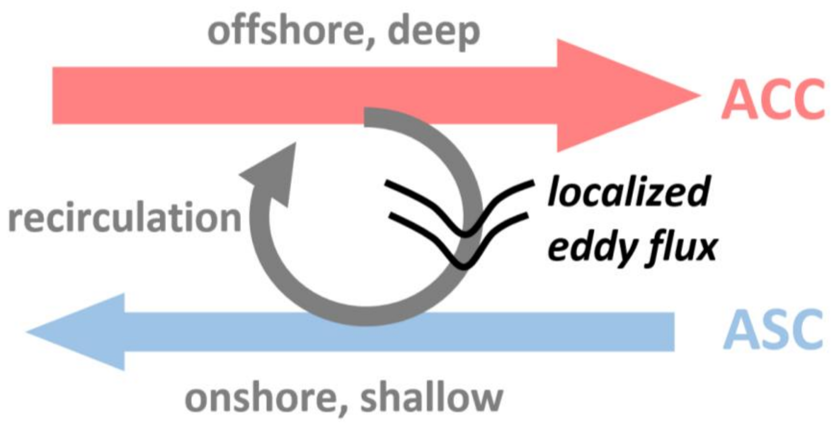
★Climatological heat budget (90-160E)

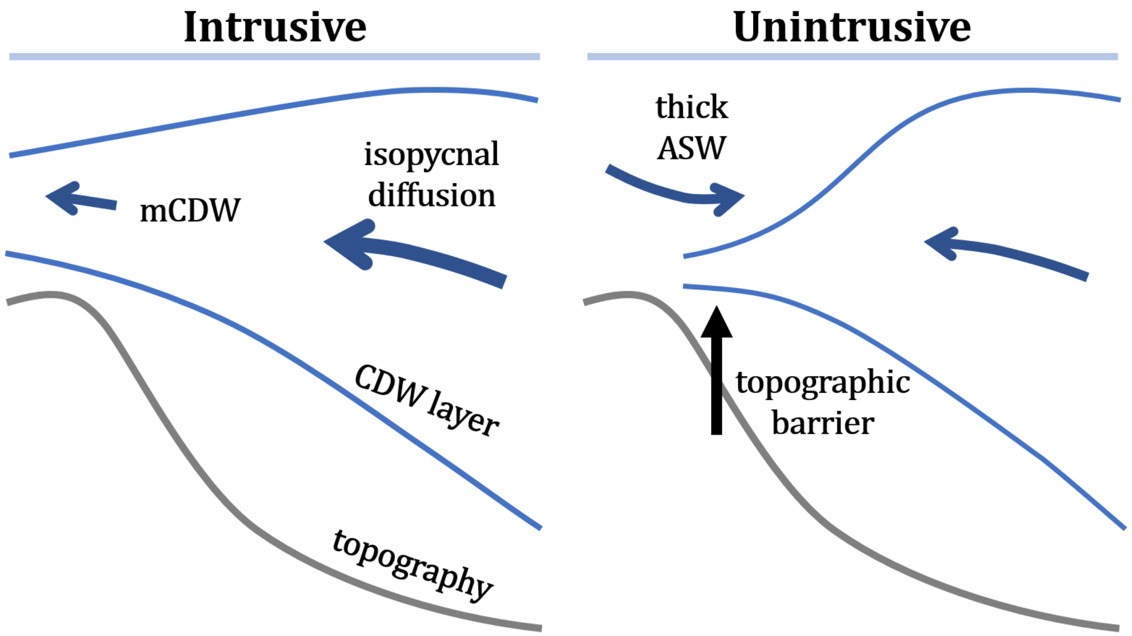
- Sea ice production: **−4.2- −5.6 TW**
- Basal melt rate: **−1.7- −2.5 TW**
- Solar heating: **+5 TW** (inshore 100 km)

- **Onshore CDW flux supplies +3.2-3.9 TW** (cumulative of 90-160E)
- **[CDW flux] + [solar heating] ~ [basal melt] + [sea ice production]**

Rignot, E., Jacobs, S., Mouginot, J., & Scheuchl, B. (2013). Ice-shelf melting around Antarctica. Science, 341(6143), 266-270.
Tamura, T., Ohshima, K. I., Fraser, A. D., & Williams, G. D. (2016). Sea ice production variability in Antarctic coastal polynyas. Journal of Geophysical Research: Oceans, 121(5), 2967-2979.
Tamura, T., Ohshima, K. I., Nihashi, S., & Hasumi, H. (2011). Estimation of surface heat/salt fluxes associated with sea ice growth/melt in the Southern Ocean. SOLA, 7, 17-20.

Summary





- **Eddy diffusivity is 100-500 m^2/s in the Antarctic margin**
- **Onshore CDW intrusion with enhanced diffusivity**
- **Closure of the coastal heat budget by eddy CDW flux**

★This work is currently *in revision* to JGR-Oceans. **Preprint:**

Appendix

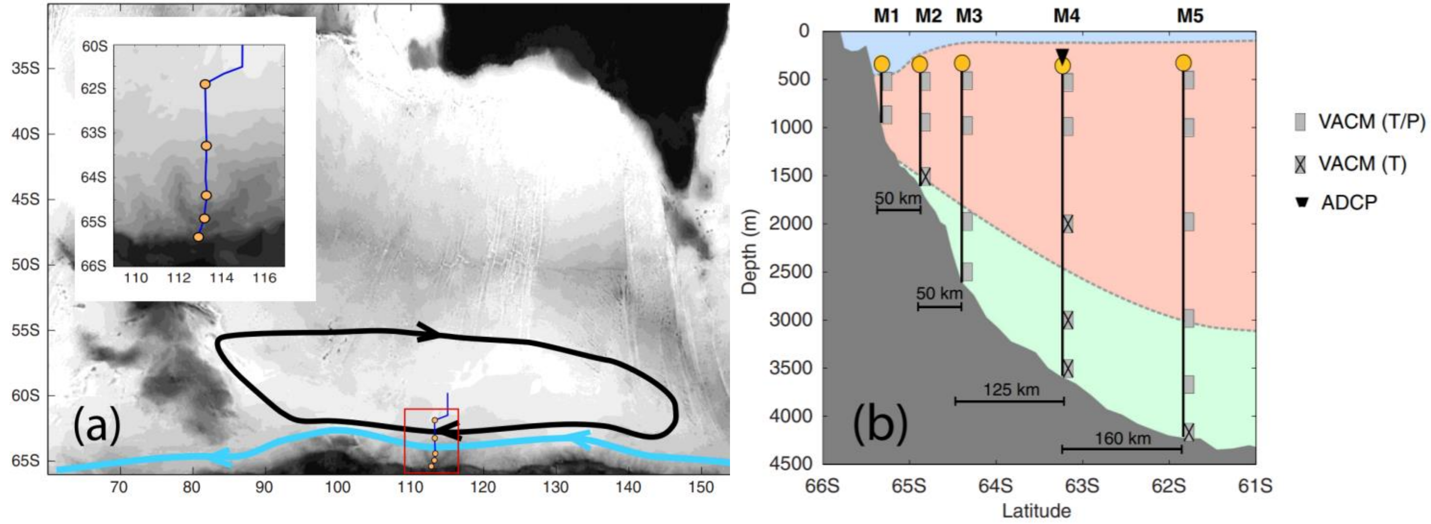
Choosing mixing efficiency Γ

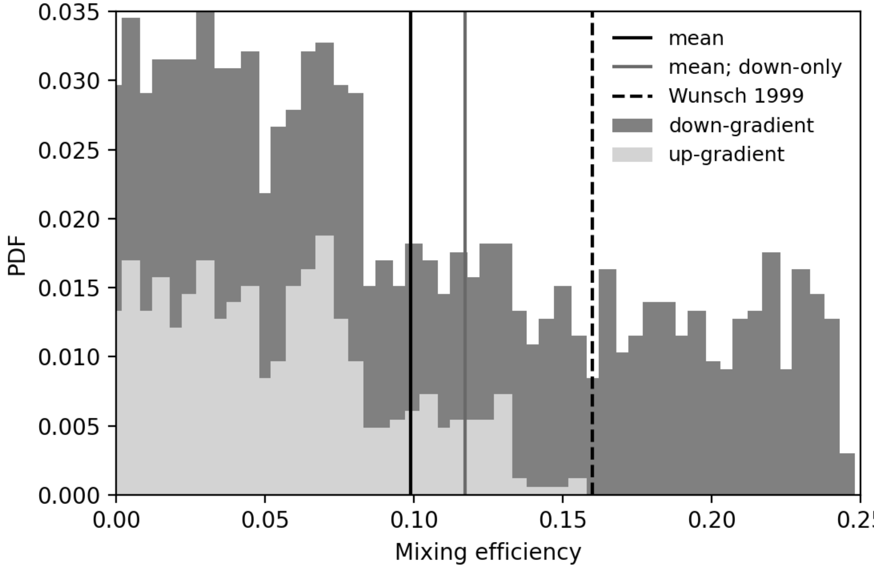
$$K = \frac{\overline{u'\theta'}}{|\nabla\overline{\theta}|} = \frac{\overline{u'\theta'}}{\sqrt{\overline{u'^2}\,\overline{\theta'^2}}}\sqrt{\overline{u'^2}}\frac{\sqrt{\overline{\theta'^2}}}{|\nabla\overline{\theta}|}$$

Γ u_{eddy} L_{mix}

Γ is correlation coefficient of tracer density and cross-frontal velocity

Cross-slope mooring section at I9S (Peña-Molino+ 2016)



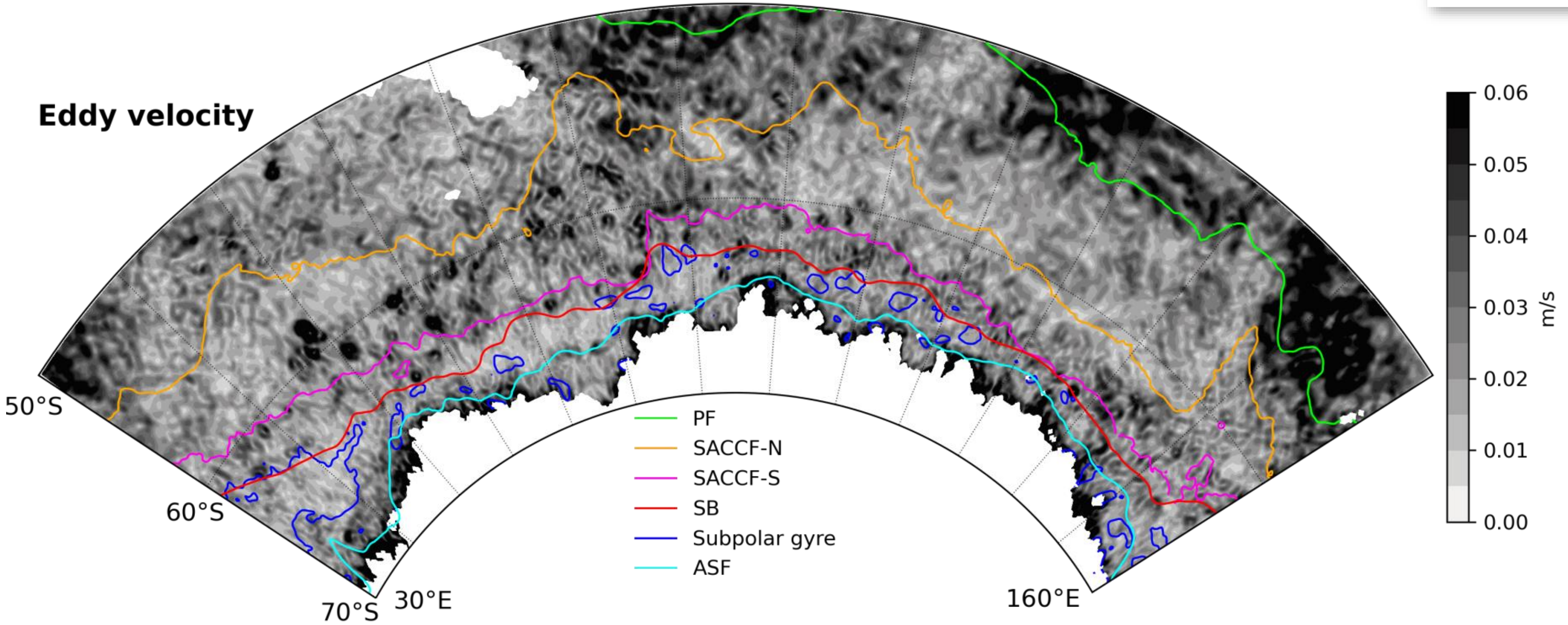


Global estimate by Wunsch (1999; Γ=0.16) seems acceptable

Wunsch, C. (1999). Where do ocean eddy heat fluxes matter?. Journal of Geophysical Research: Oceans, 104(C6), 13235-13249.
Peña-Molino, B., McCartney, M. S., & Rintoul, S. R. (2016). Direct observations of the A ntarctic S lope Current transport at 113° E. Journal of Geophysical Research: Oceans, 121(10), 7390-7407.

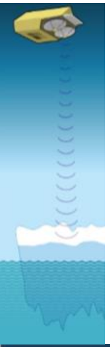
Altimetric eddy velocity $u_{eddy} = \sqrt{\overline{u'^2}}$

$$K = \frac{\overline{u'\theta'}}{|\nabla\theta|} = \underbrace{\frac{\overline{u'\theta'}}{\sqrt{\overline{u'^2}}\sqrt{\overline{\theta'^2}}}}_{\Gamma}\ \underbrace{\sqrt{\overline{u'^2}}}_{u_{eddy}}\ \underbrace{\frac{\sqrt{\overline{\theta'^2}}}{|\nabla\theta|}}_{L_{mix}}$$



Agree with the mooring data

(0.04-0.06 m/s)



Monthly dynamic topography in 0.2° grids (Mizobata+, 2020)

- Synthesized with radar altimetry of sea ice freeboard
- Noise removal with EOF-filters

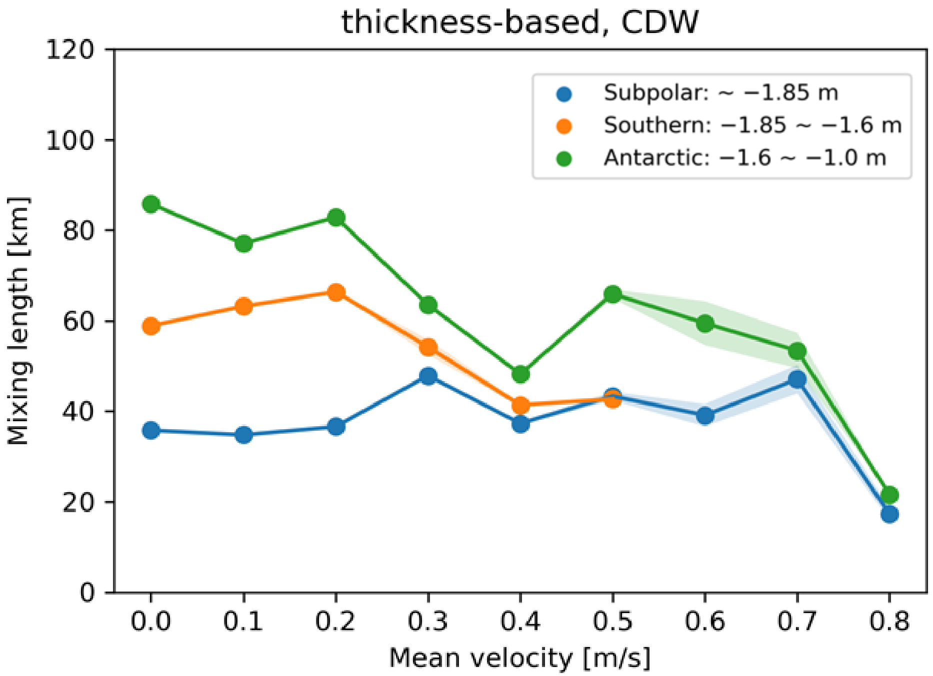
Table 1

Observational Platform for Sea Surface Height

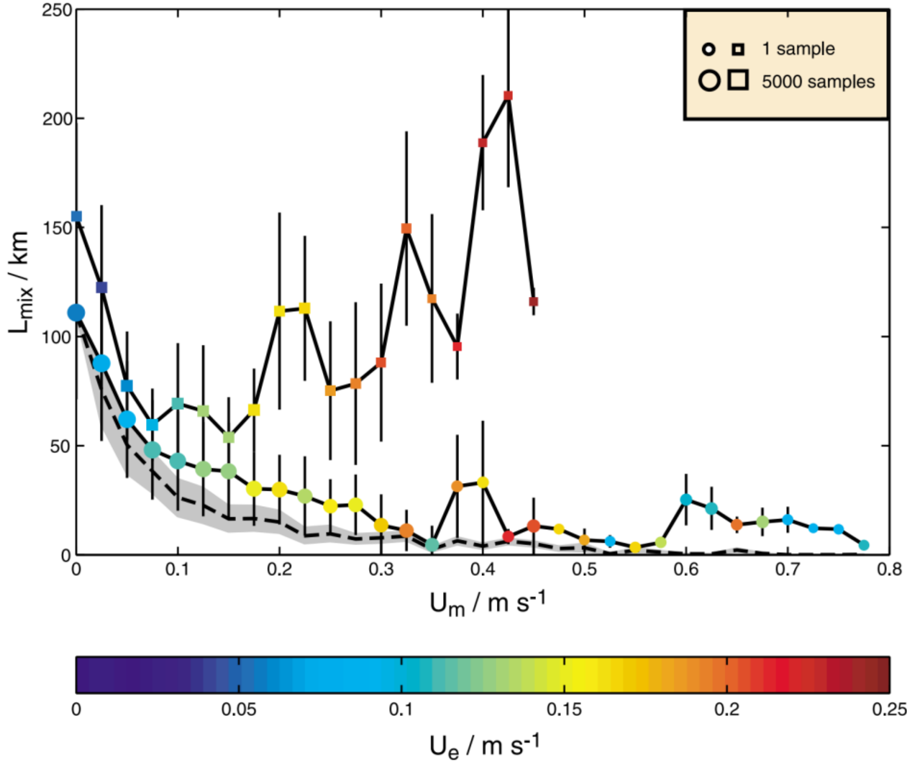
Open water area	Ice-covered area
Jason-2/Poseidon-3	CryoSat-2/SIRAL (SAR mode)
Jason-3/Poseidon-3B	CryoSat-2/SIRAL (SARin mode)
Sentinel-3A/SAR radar altimeter	
CryoSat-2/SIRAL (low-resolution mode)	

Mizobata, K., Shimada, K., Aoki, S., & Kitade, Y. (2020). The cyclonic eddy train in the Indian Ocean sector of the Southern Ocean as revealed by satellite radar altimeters... Journal of Geophysical Research: Oceans, 125(6), e2019JC015994.
Peña-Molino, B., McCartney, M. S., & Rintoul, S. R. (2016). Direct observations of the A ntarctic S lope Current transport at 113° E. Journal of Geophysical Research: Oceans, 121(10), 7390-7407.

Dependency on mean flow



Garabato+ (2011)



As moving poleward, L_{mix} becomes less dependent on mean flow

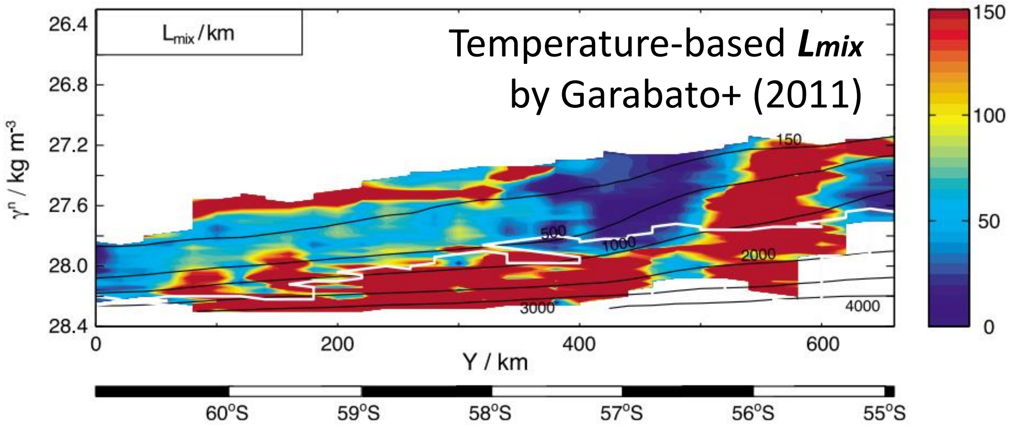
→ jet-induced mixing suppression likely ceases in the south

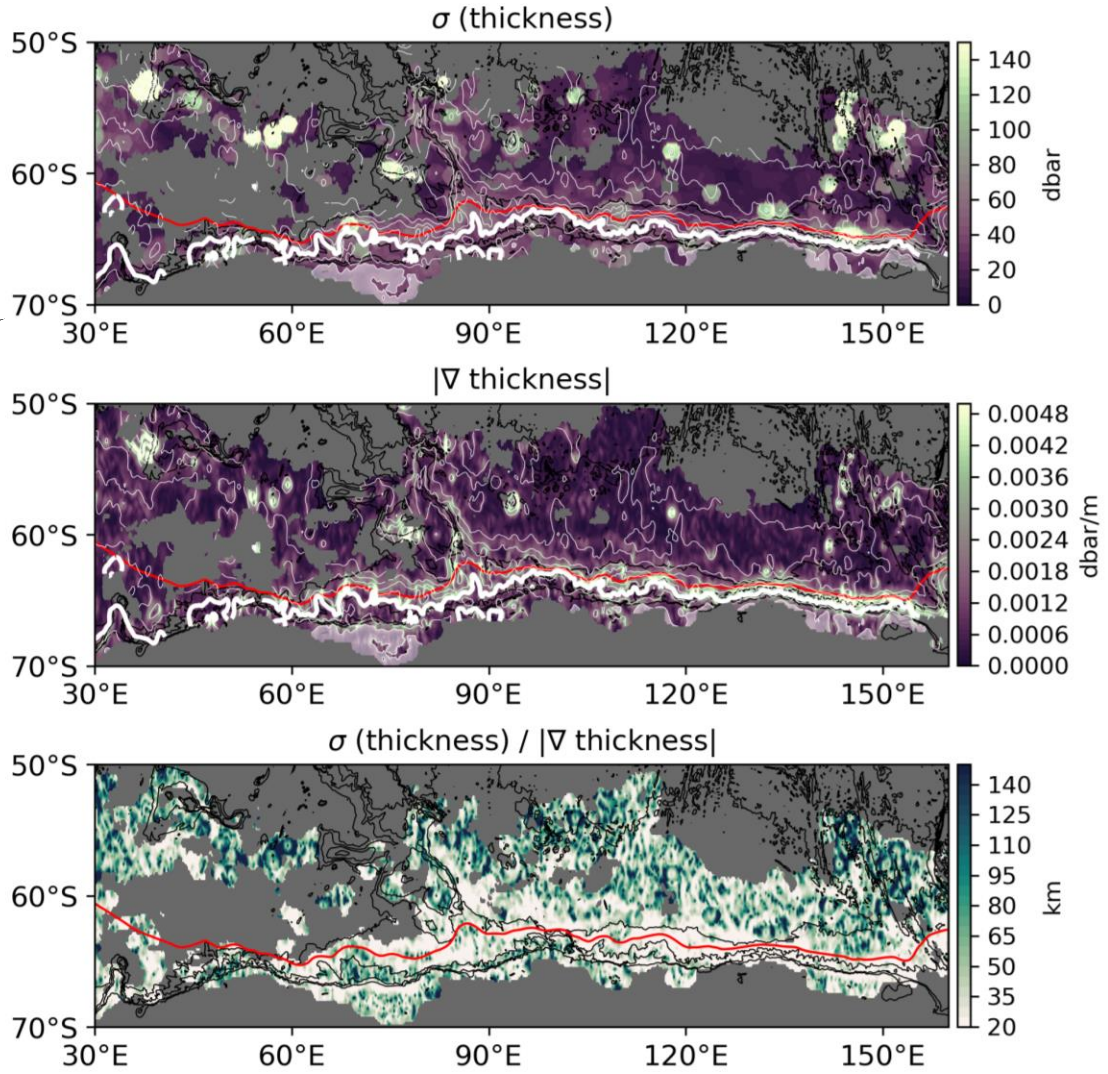
Naveira Garabato, A. C., Ferrari, R., & Polzin, K. L. (2011). Eddy stirring in the Southern Ocean. Journal of Geophysical Research: Oceans, 116(C9).

Thickness-based L_{mix} for CDW

σ (θ) = σ (θ original − θ interpolated, r=75km)

spatial variation



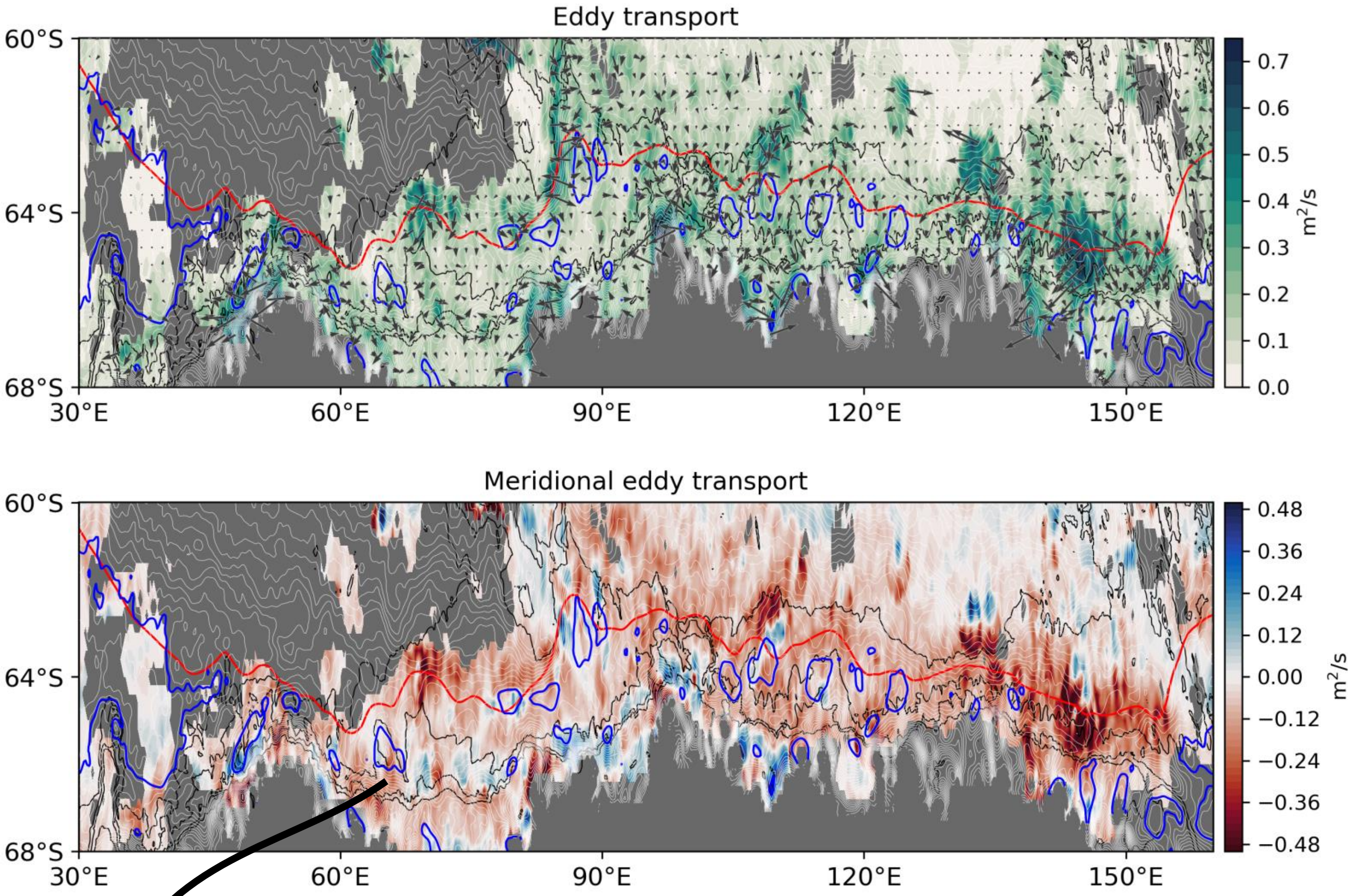


O(100km) **with shoreward suppression, broadly consistent with previous estimates**

Naveira Garabato, A. C., Ferrari, R., & Polzin, K. L. (2011). Eddy stirring in the Southern Ocean. Journal of Geophysical Research: Oceans, 116(C9).

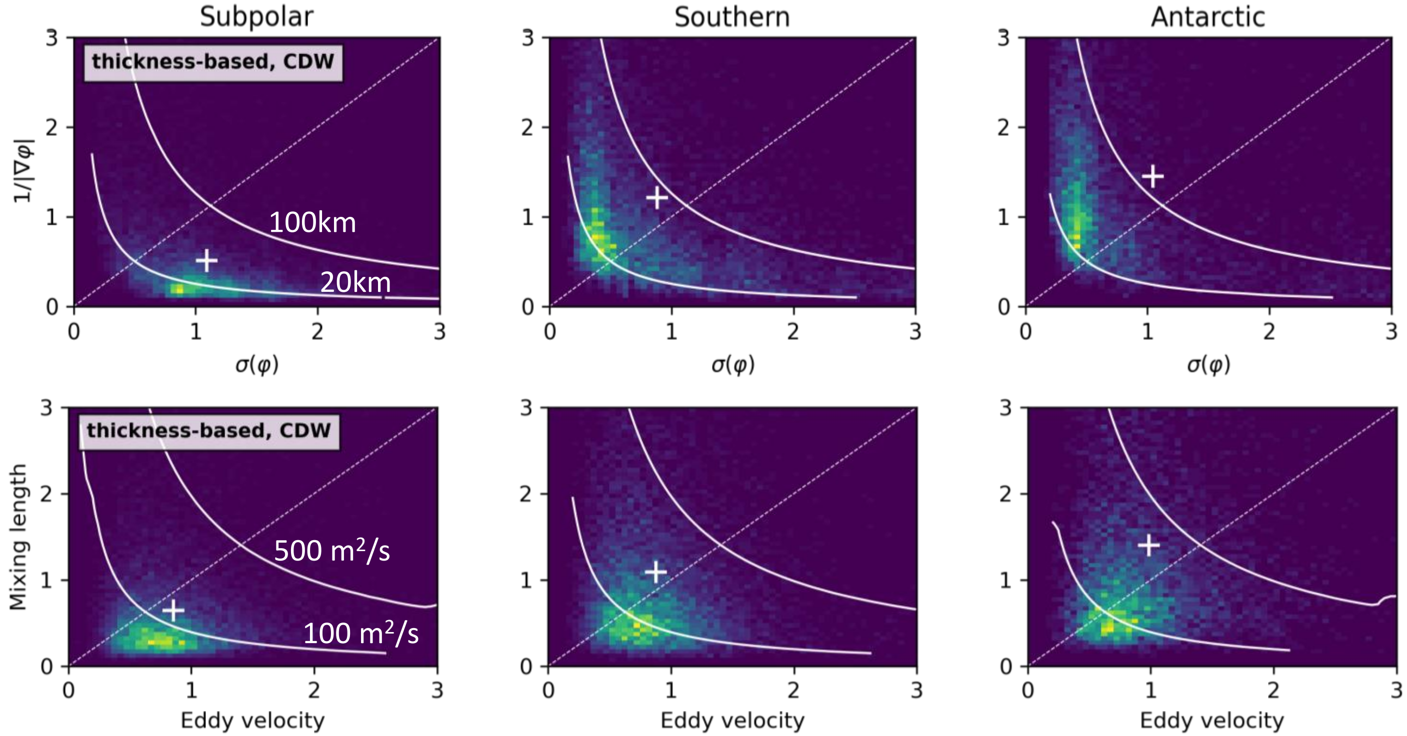
Eddy volume transport

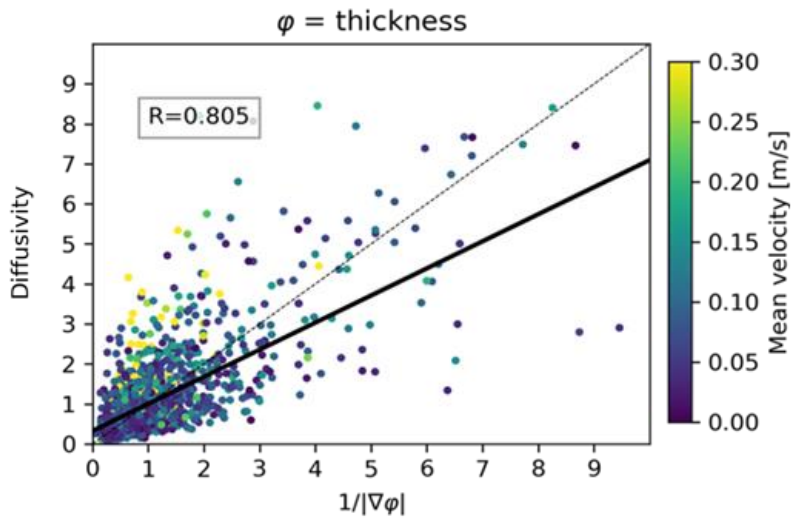
$$\Psi_{\mathbf{eddy}} = -\,K\nabla\mathrm{H}$$
$$\propto\ \Gamma\, u_{eddy}\, \sigma(\mathrm{H})$$



Extract for the continental slope (1000-3000 m)…

Controlling factor of K

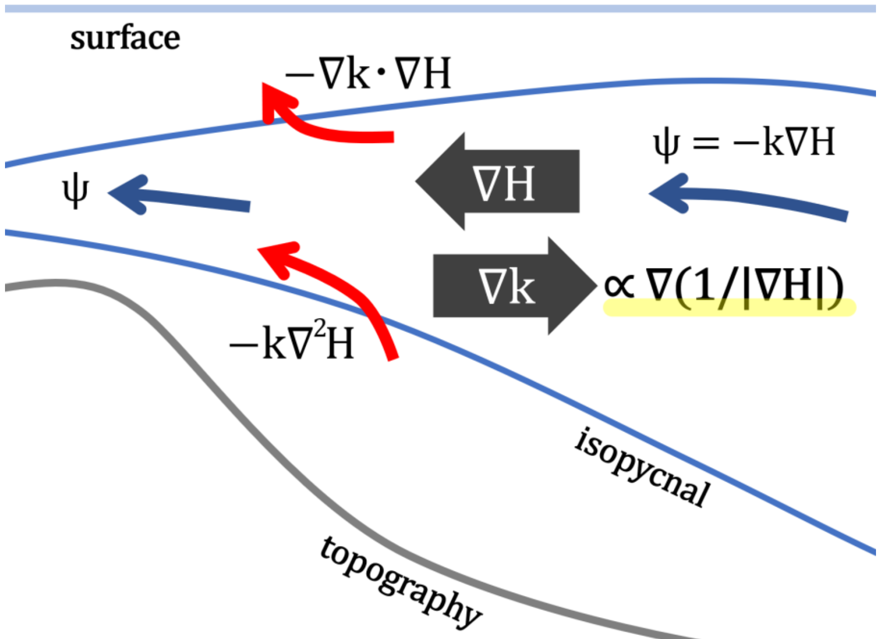


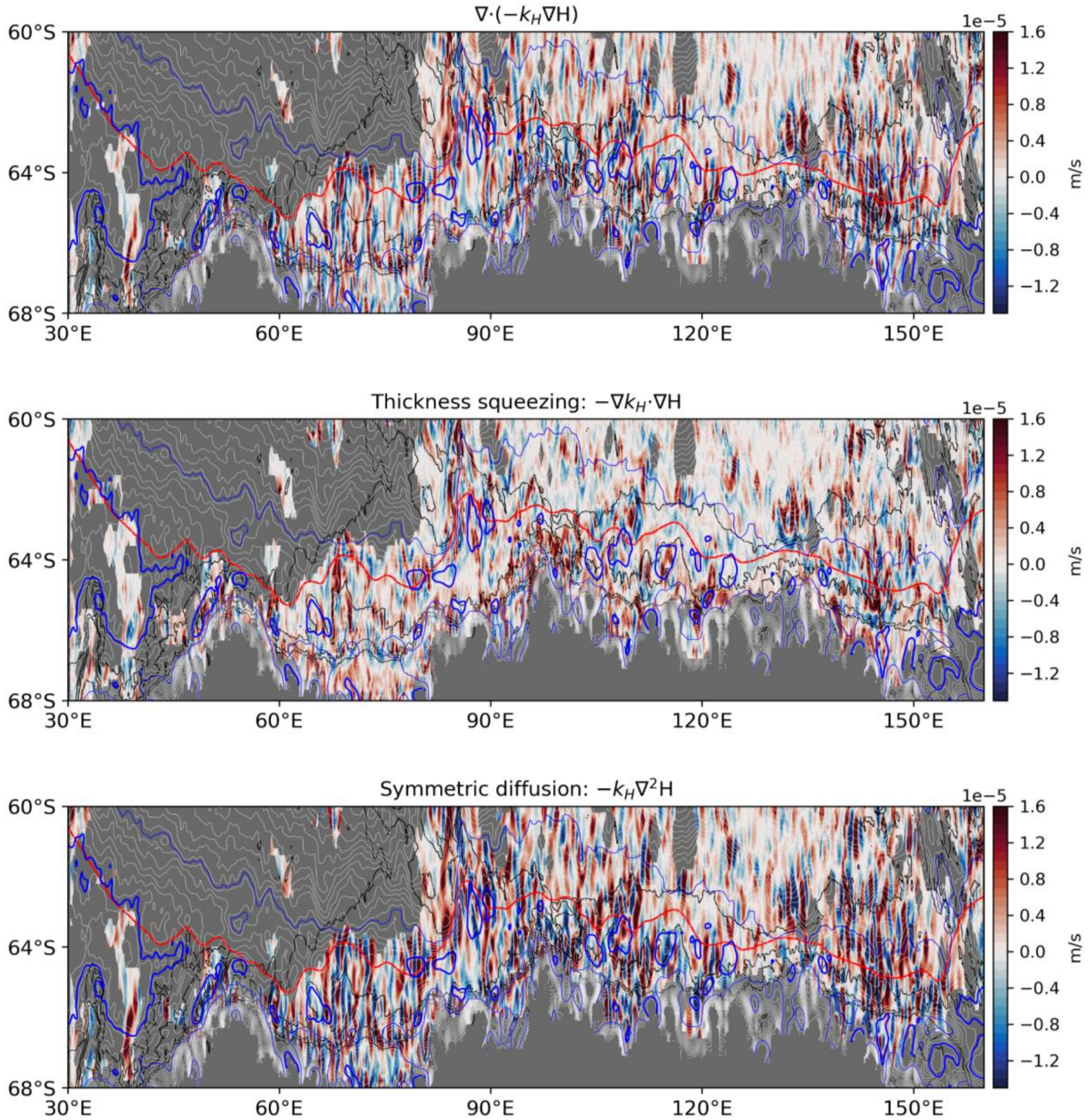


2D histograms of L_{mix} and K for each frontal zone

- **Moving poleward, L_{mix} and $|\nabla\theta|$ becomes more influential than u_{eddy} and $\sqrt{\theta'^2}$**
- **"Thickness gradient" is the primary factor in the Subpolar** (R~0.8)

Implication for diapycnal flux





The mean upward diapycnal velocity is comparable to Ekman upwelling

(2±10 μm/s in the subpolar zone)