Ocean-ice interaction in the subpolar Southern Ocean generates the ocean's internal pycnocline

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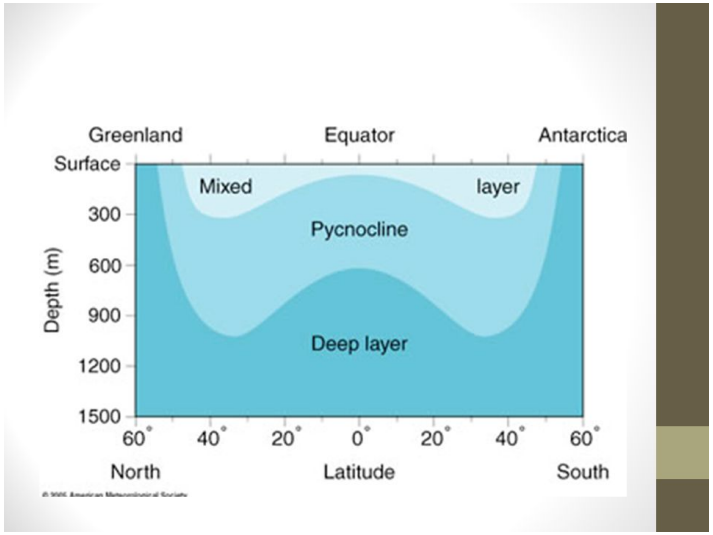
What is the permanent pycnocline?



- By definition, a pycnocline is a thin layer where the vertical gradient of density is a local maximum.
- The (permanent) pycnocline is a major organizing feature of the global ocean circulation, separating the relatively fast-ventilated waters of the upper ocean from the more slowly-renewed deepwaters.

What is the internal pycnocline?

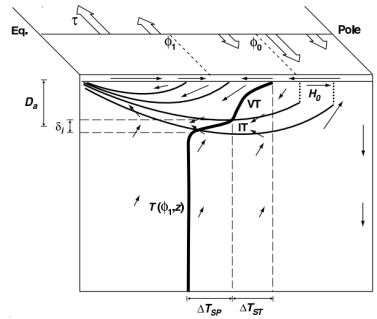
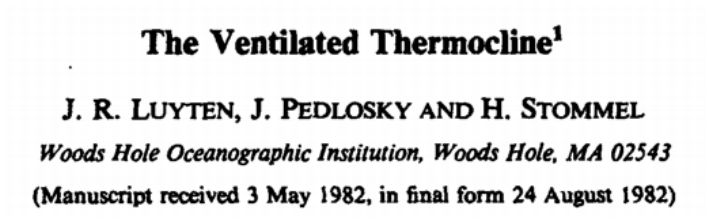


Figure 3. A schematic of the structure of the classical wind- and buoyancy-driven thermocline, according to SV. The medium-weight lines are isopycnals, 'IT' denotes the advective-diffusive internal thermocline, 'VT' denotes the advective ventilated thermocline, and the thick solid line is a temperature profile through the middle of the subtropical gyre. The single arrows represent the meridional circulation, and the double arrows the overlying windstress. Buoyancy forcing may be considered to be low-latitude surface warming and high-latitude surface cooling.

- In the **ventilated** pycnocline, the wind-driven motion of water parcels directed along sloping isopycnals connects the isopycnals' surface outcrops in subtropical regions to the ocean interior.
- In contrast, the underlying **internal** pycnocline develops as an internal boundary between the warm upper-ocean waters of the ventilated pycnocline and the colder deep waters in the abyss.

Caveats of thermocline theories



The Ventilated Thermocline[1]

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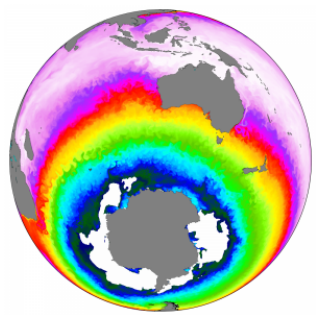
Classical thermocline theories suffer from at least two key limitations that challenge their relevance to the real world:

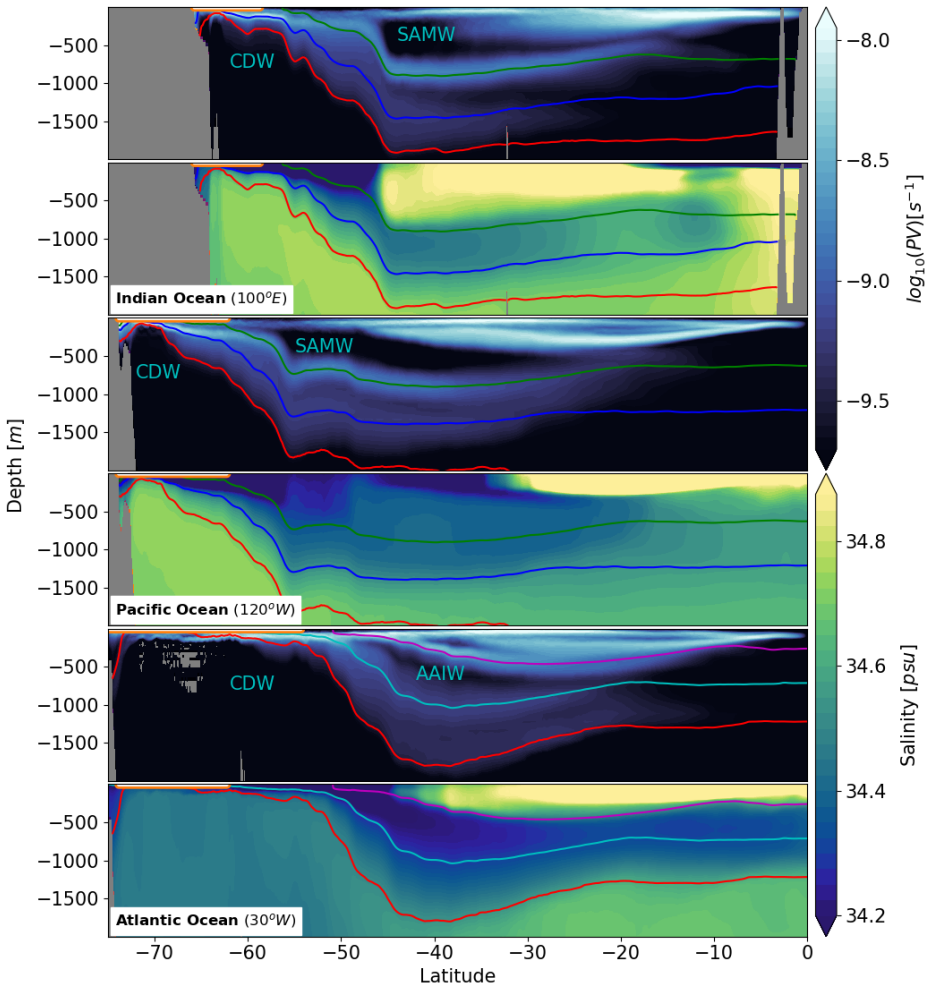
- First, they omit the impact of the Southern Ocean's zonal channel, thought to lead to a markedly different pycnocline structure as well as the emergence of a vigorous inter-hemispheric overturning circulation.
- Second, classical thermocline theories regularly assume, through their focus on temperature stratification, that density is a conservative quantity.

An eddy-rich global ocean-sea ice model

- Two-way coupled ocean-sea ice model.
- The ocean model component is the Modular Ocean Model (MOM) version 5.1, and the sea ice component is a fork from the Los Alamos sea ice model (CICE) version 5.1.2.
- These components are forced by prescribed atmospheric conditions taken from the 55-year Japanese Reanalysis.
- This model configuration is run at 1/10 degree horizontal resolution with 75 vertical layers.
- Consortium for Ocean-Sea Ice Modelling in Australia (www.cosima.org.au)

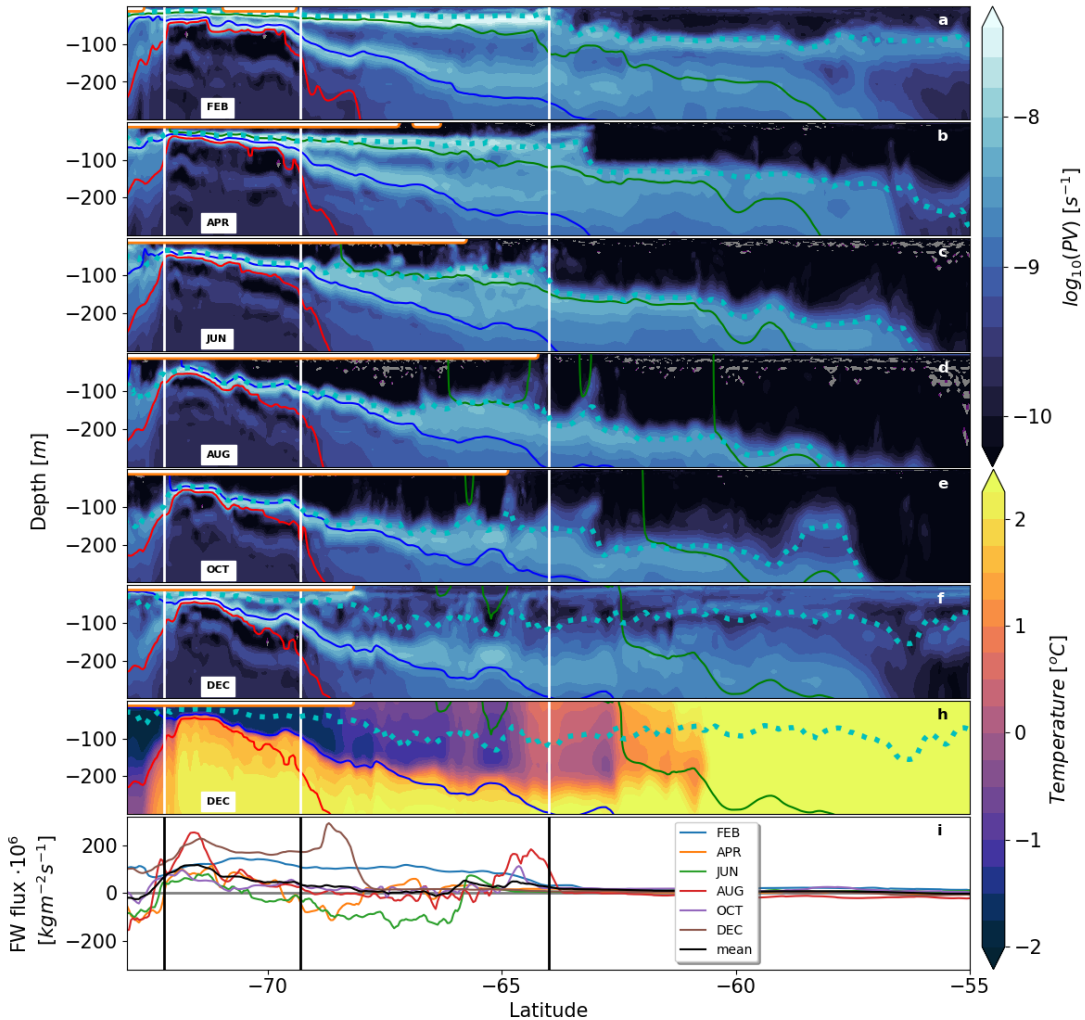


PV distribution as organising framework for the large-scale water mass structure

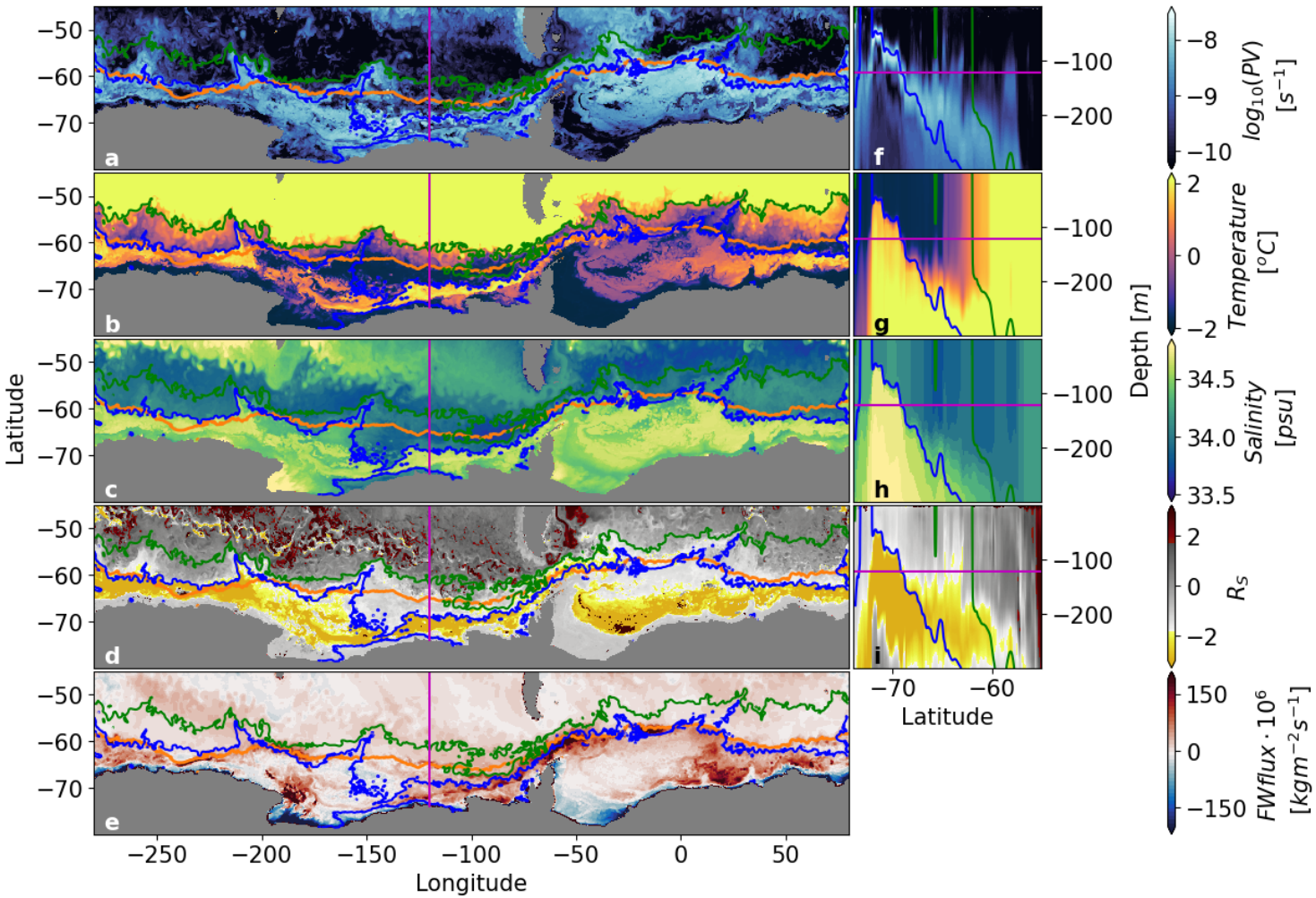


- $PV = f \cdot N^2$.
- $\sigma_0 = 26.85 kgm^{-3}$ (magenta)
- $\sigma_0 = 27.15 kgm^{-3}$ (green)
- $\sigma_0 = 27.3 kgm^{-3}$ (cyan)
- $\sigma_0 = 27.5 kgm^{-3}$ (blue)
- $\sigma_0 = 27.7 kgm^{-3}$ (red)
- maximum ice extent (orange)

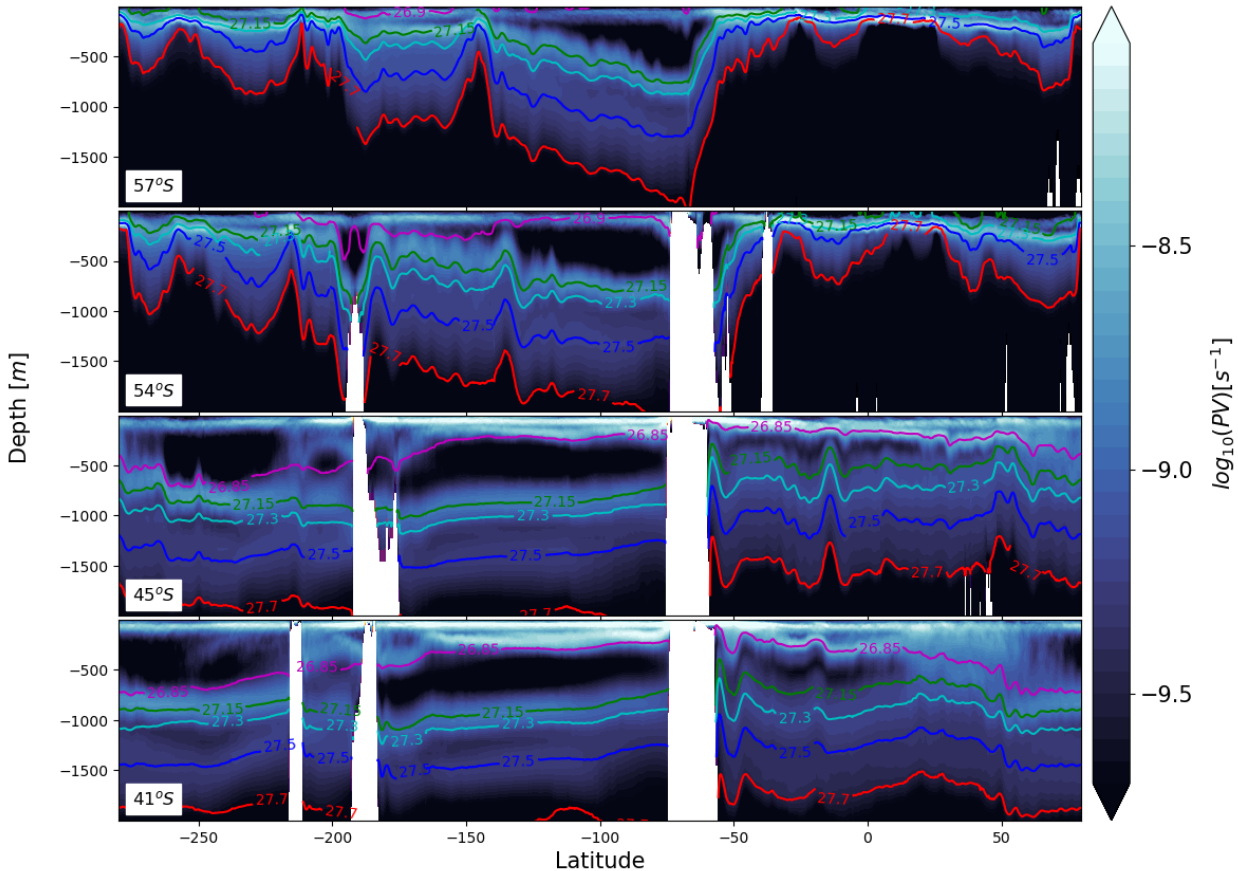
PV generation in the subpolar Southern Ocean



PV generation in the subpolar Southern Ocean

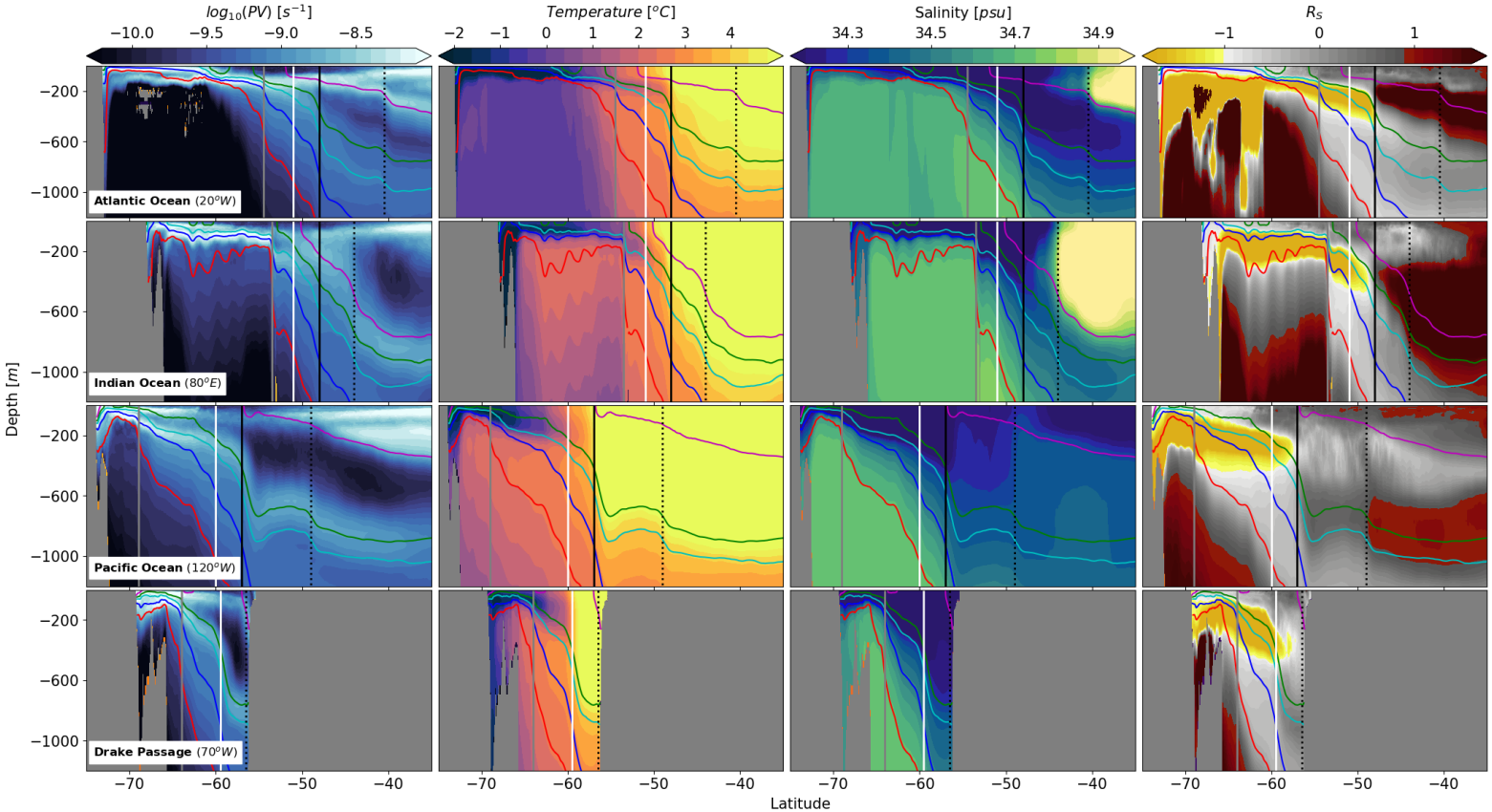


Zonal evolution of PV distribution



- There is a difference between the isopycnals associated with the internal pycnocline in the Indo-Pacific and the Atlantic.

ACC fronts and the internal pycnocline



- ACC fronts are associated with particular isopycnals leaving the base of the permanent pycncocline, e.g. the cyan isopycnal is always associated with the Polar Front.

Take-home message

- The **internal pycnocline** originates in the subpolar Southern Ocean as a vertical density gradient at the base of the winter mixed layer. This distinguishes the internal pycnocline from the ventilated pycnocline. In the **ventilated pycnocline**, interior stratification comes from the isopycnal projection of near-surface horizontal (rather than vertical) density gradients.
- The two ingredients missing from classical thermocline theories—a southern channel and non-linear two-component stratification—turn out to be pivotal for understanding the generation of the internal pycnocline.