# Abyssal Ocean Circulation

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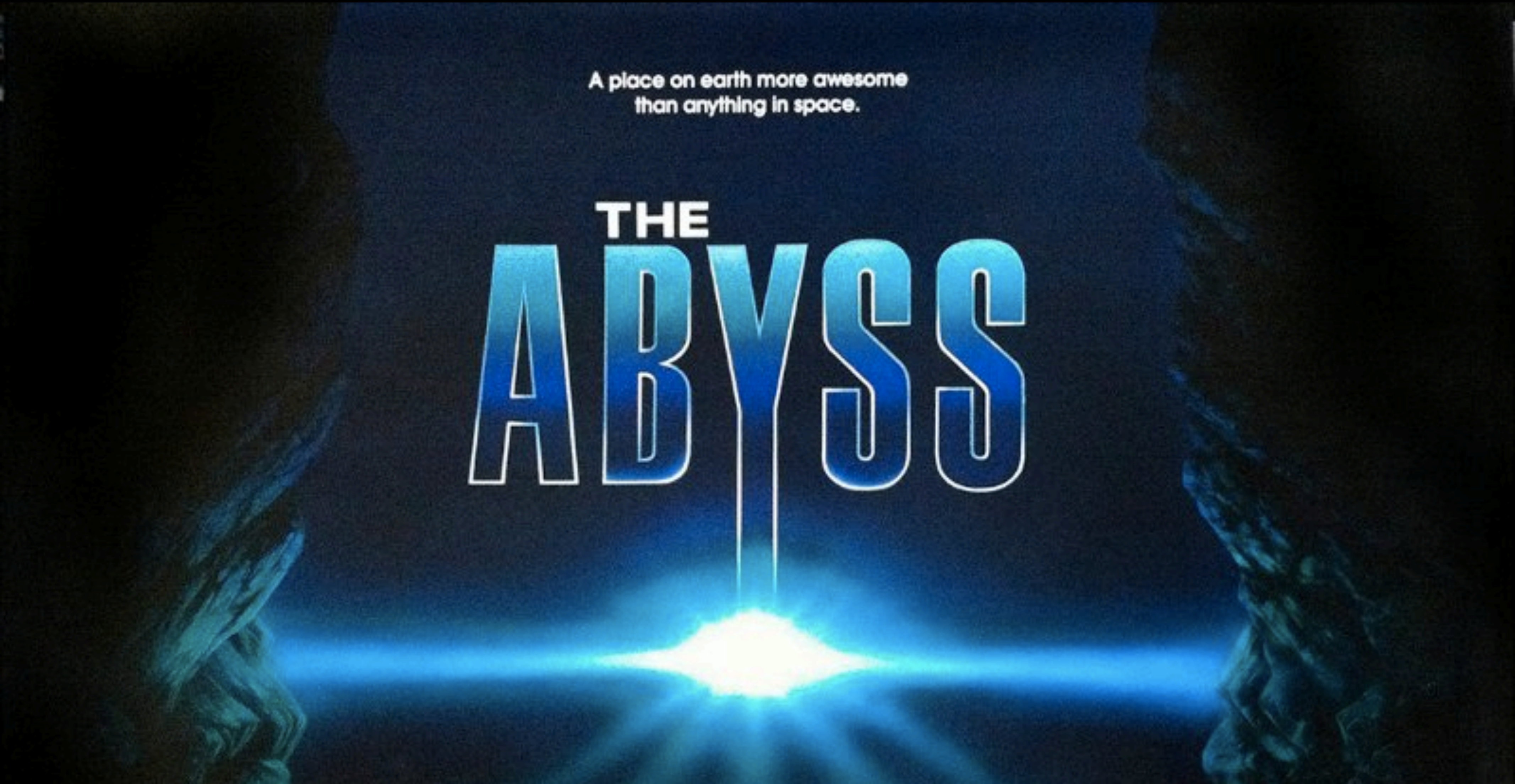
Les Houches, August 2017

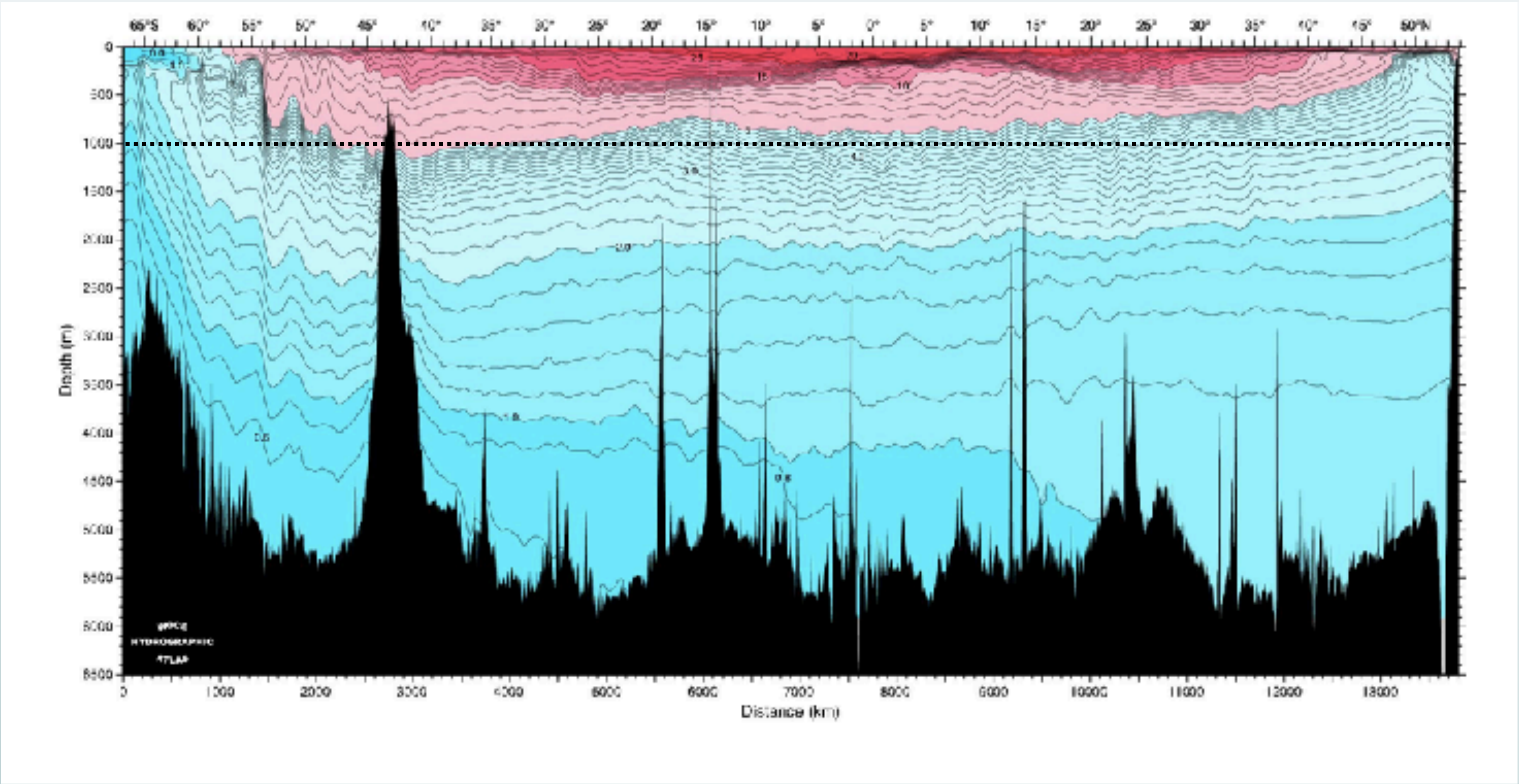


# Outline

- The deep ocean
- The deep circulation
- The sinking branch: deep convection
- The upwelling branch: Stommel-Arons theory
- The upwelling branch: Munk's "Abyssal Recipes"
- The deep and abyssal ocean circulations

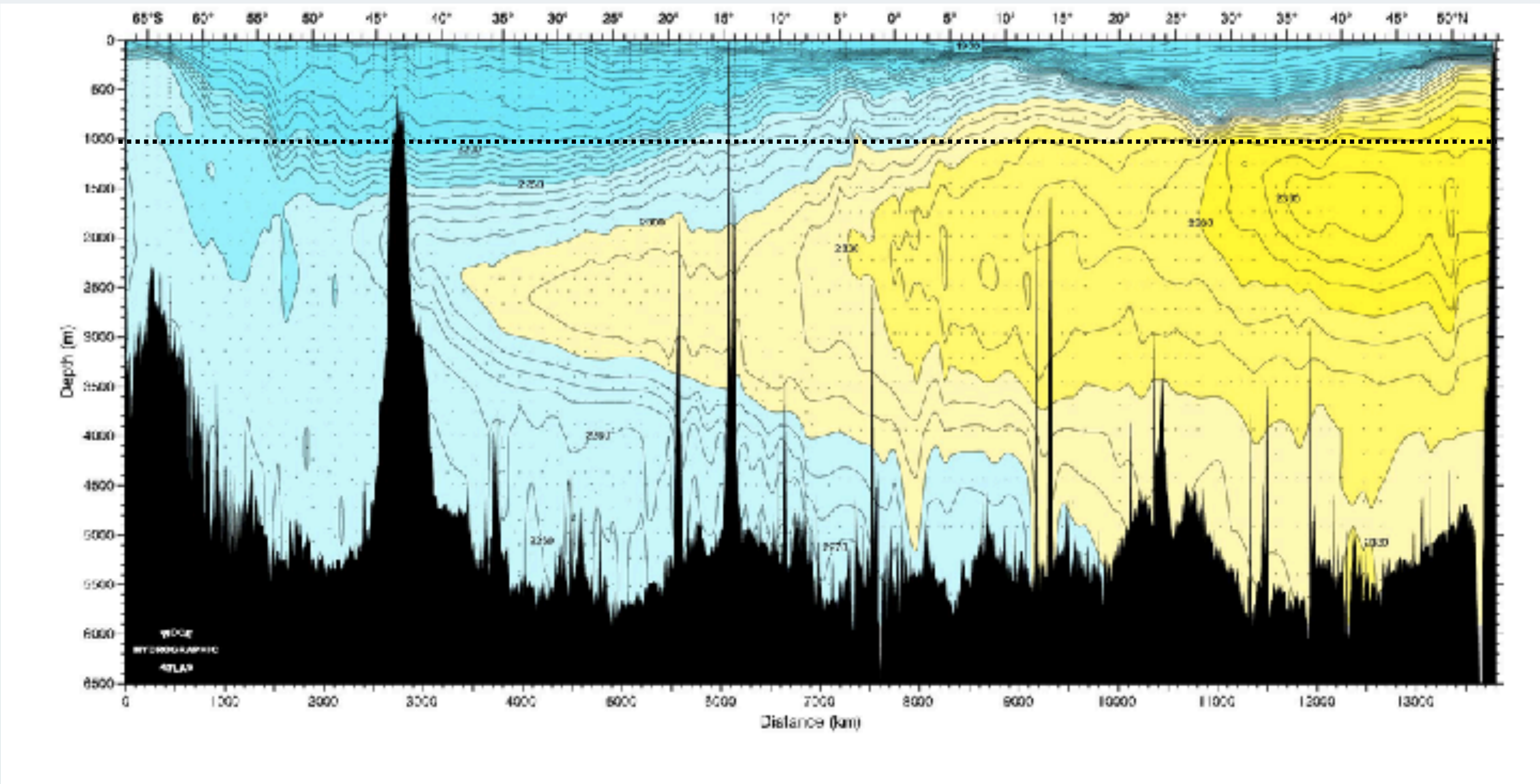
# The deep ocean

# Ocean temperature




Potential temperature — WOCE section P15, 165 W

# Ocean dissolved carbon




Dissolved inorganic carbon — WOCE section P15, 165 W

# The deep circulation

# Deep circulation

Henri Ellis (1751)

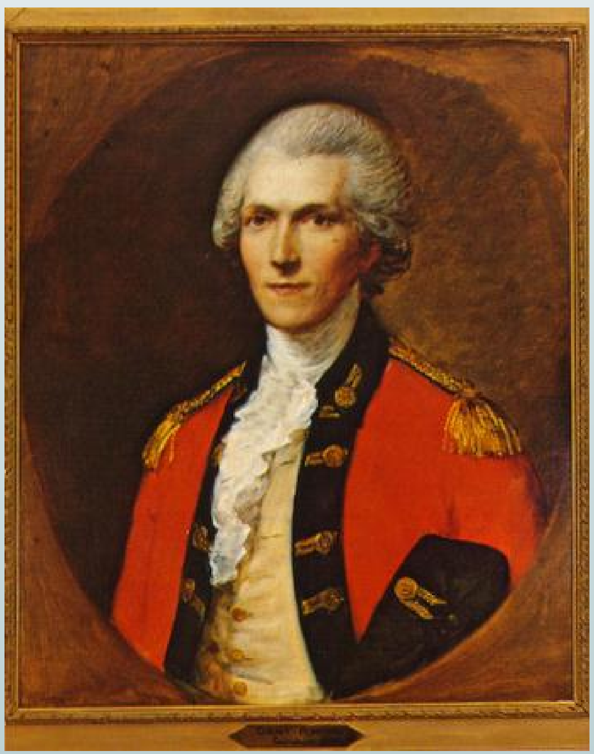
*"The cold increased regularly, in proportion to the depths, till it descended to 3900 feet: from whence the mercury in the thermometer came up at 53 degrees Fahrenheit (11 degrees Celsius); and tho' I afterwards sunk it to the depth of 5346 feet, that is a mile and 66 feet, it came up no lower."*

*This experiment, which seemed at first but mere food for curiosity, became in the interim very useful to us. By its means we supplied our cold bath, and cooled our wines or water at pleasure; which is vastly agreeable to us in this burning climate."*

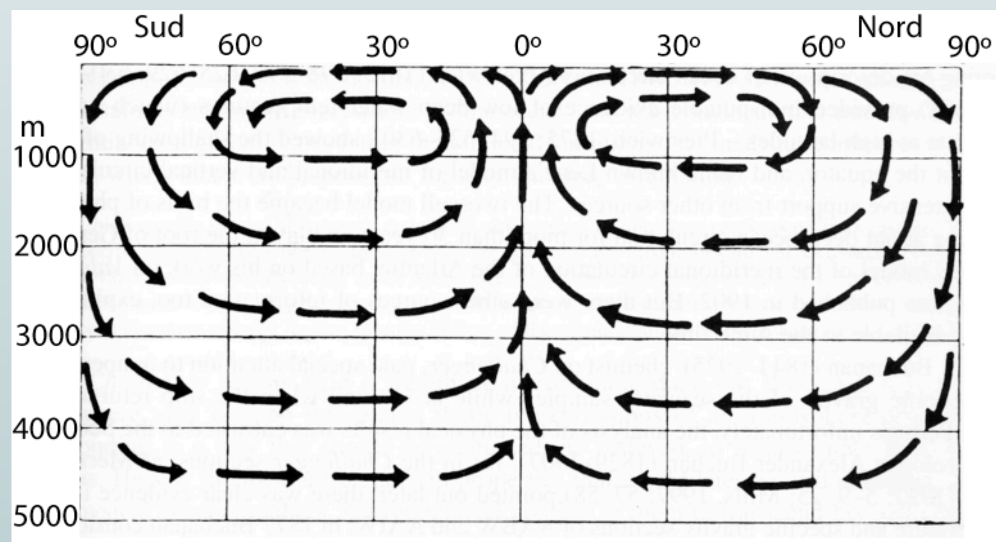
# Deep circulation

Benjamin Thomson
Count Rumford of the Holy Roman Empire
(1753-1814)

*On the Propagation of Heat in Fluids*

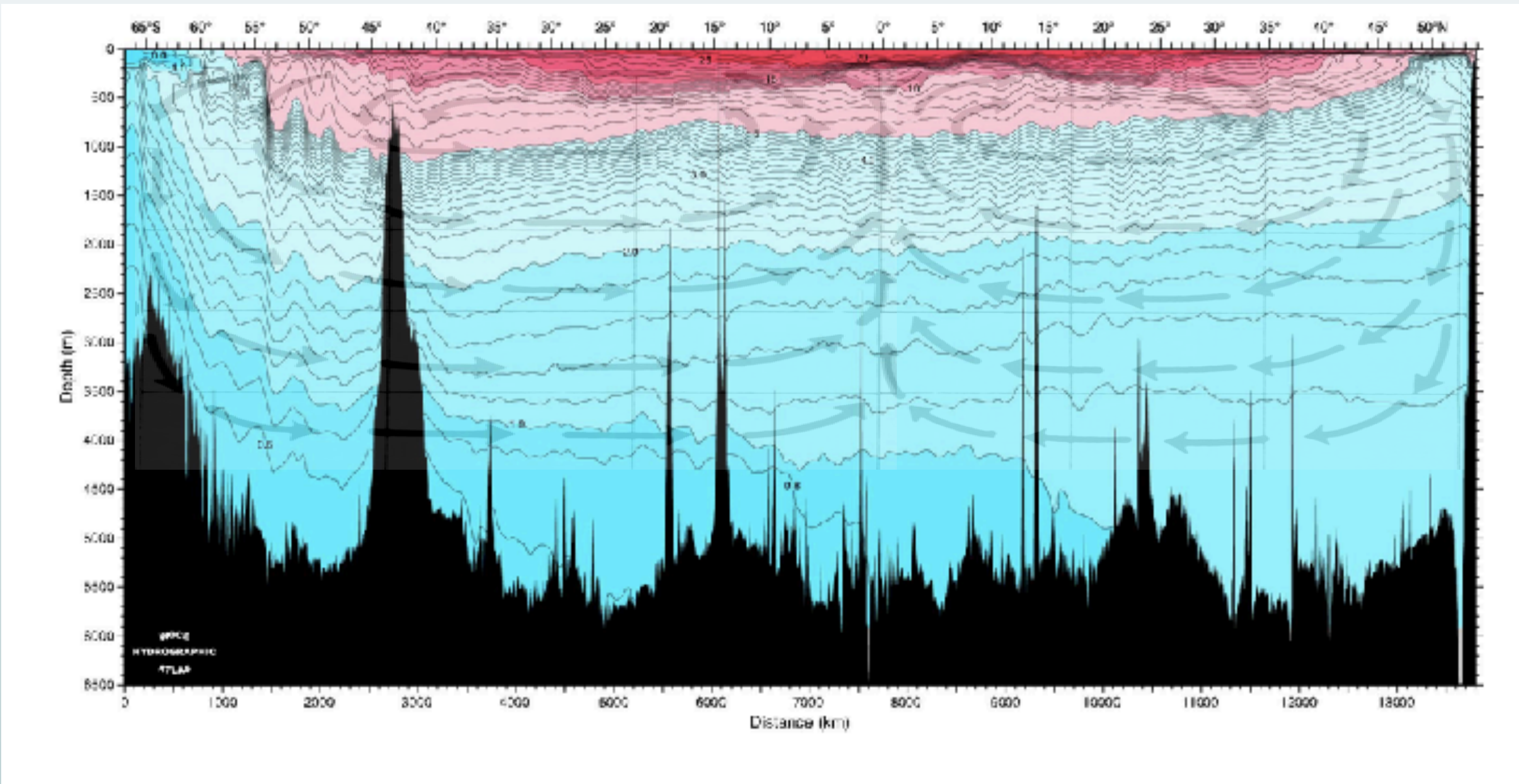


Cooling Heating Cooling



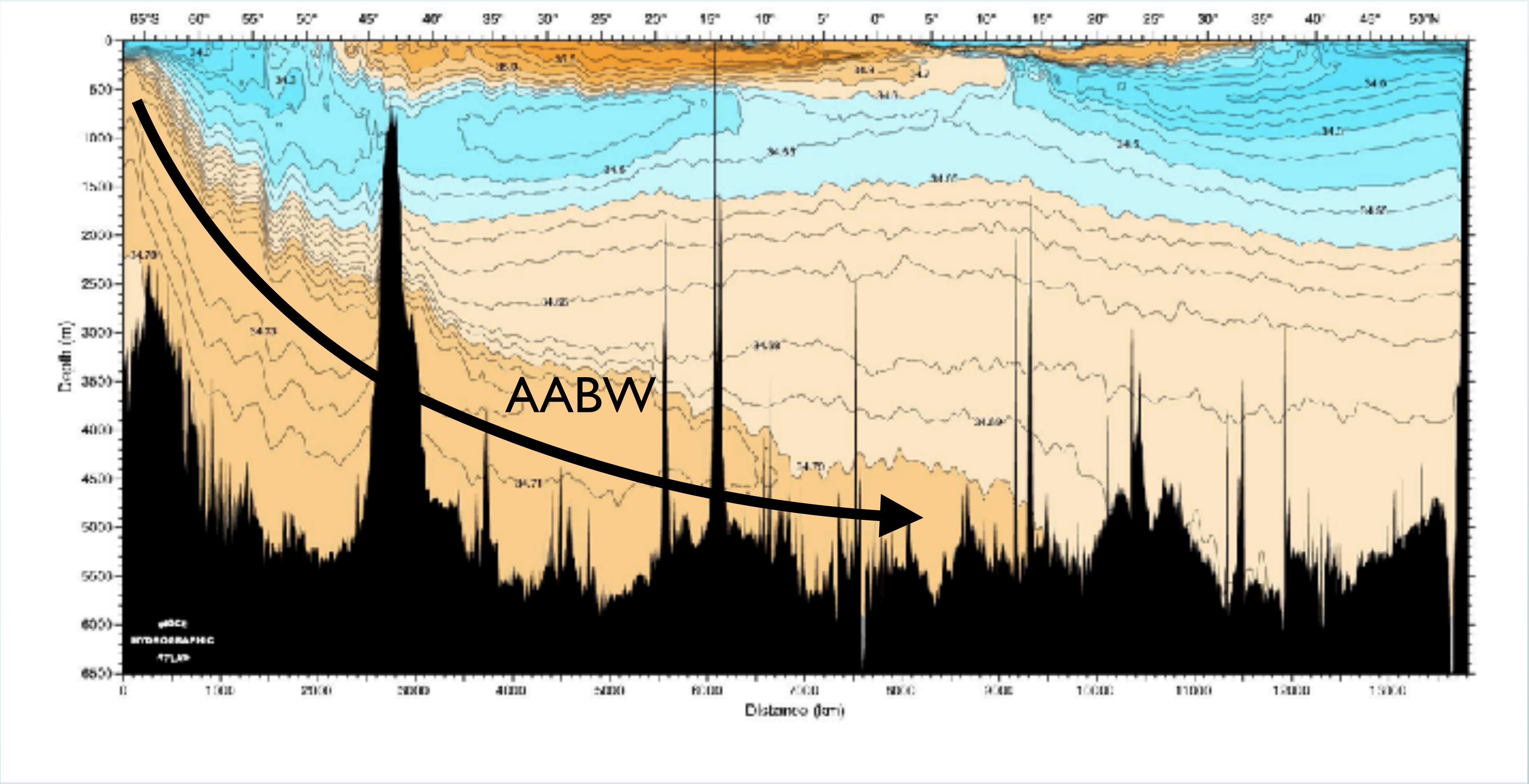

Lenz, 1845

# Deep circulation



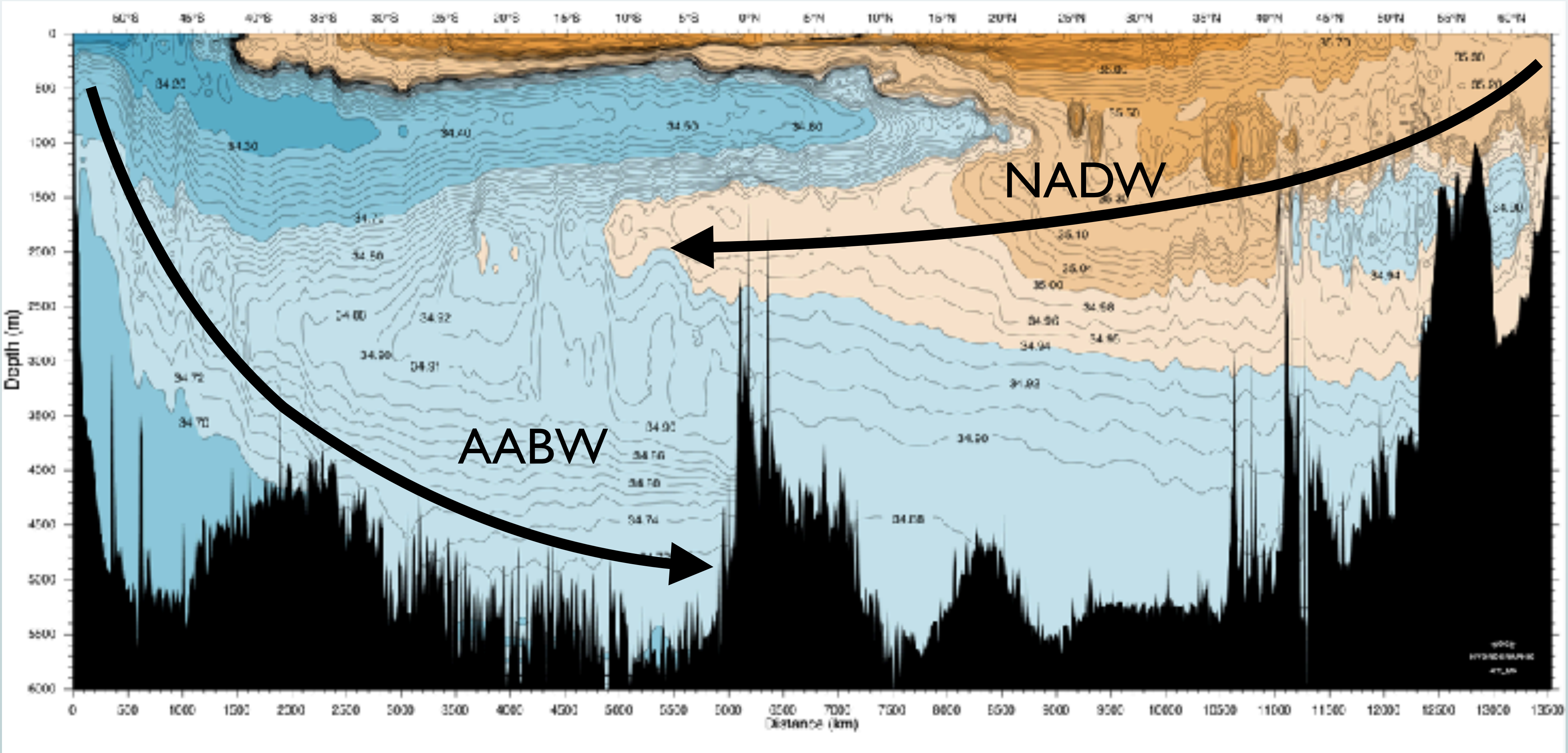

Potential temperature — WOCE section P15, 165 W

# Pacific deep circulation



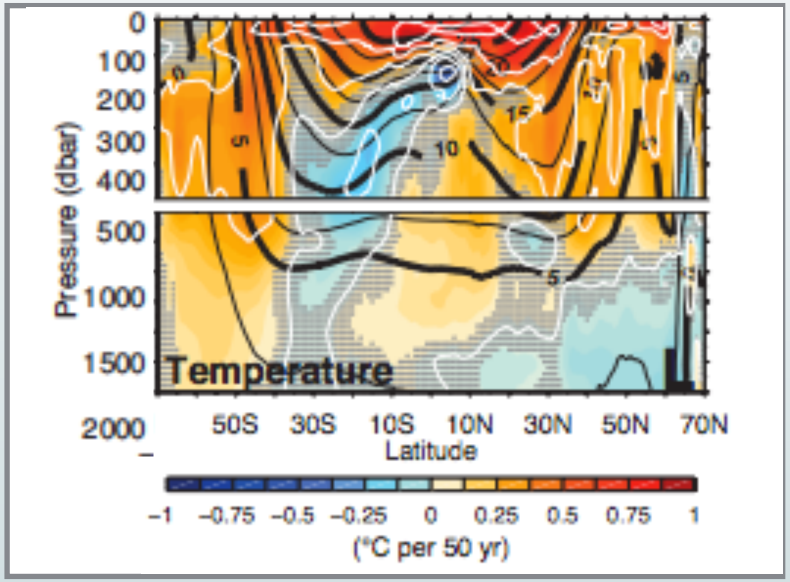

Salinity — WOCE section P15, 165 W

# Atlantic deep circulation



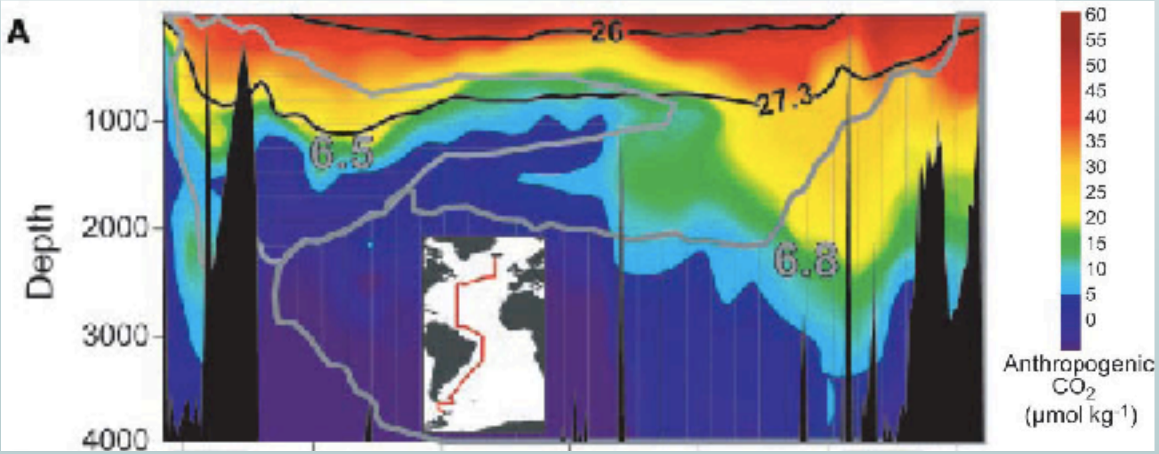

Salinity — WOCE section A16, 25 W

# Ocean Heat & Carbon Uptake




Observed temperature trends

Durack and Wijffels (2010)




Anthropogenic carbon

Sabine et al. (2004)

# Where does water sink?

# Deep convection

Deep convection in the ocean occurs

- when the air-sea fluxes act to increase surface density
- when the ocean stratification is weak

These conditions are realized in sub polar gyres

- Nordic Seas of the North Atlantic
- Weddell and Ross Sea around Antarctica

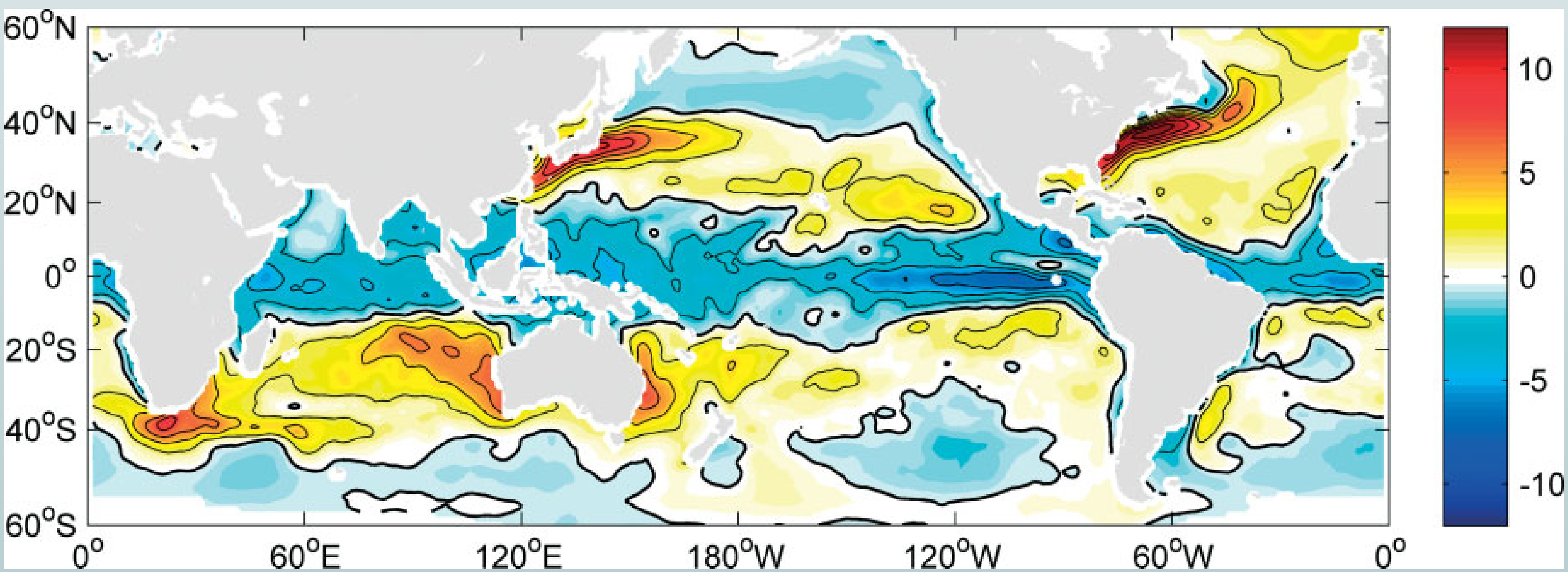



*Figure 4. Annual air-sea density fluxes, contour interval 2 × $10^{-6}$ kg $m^{-2}$ $s^{-1}$.*

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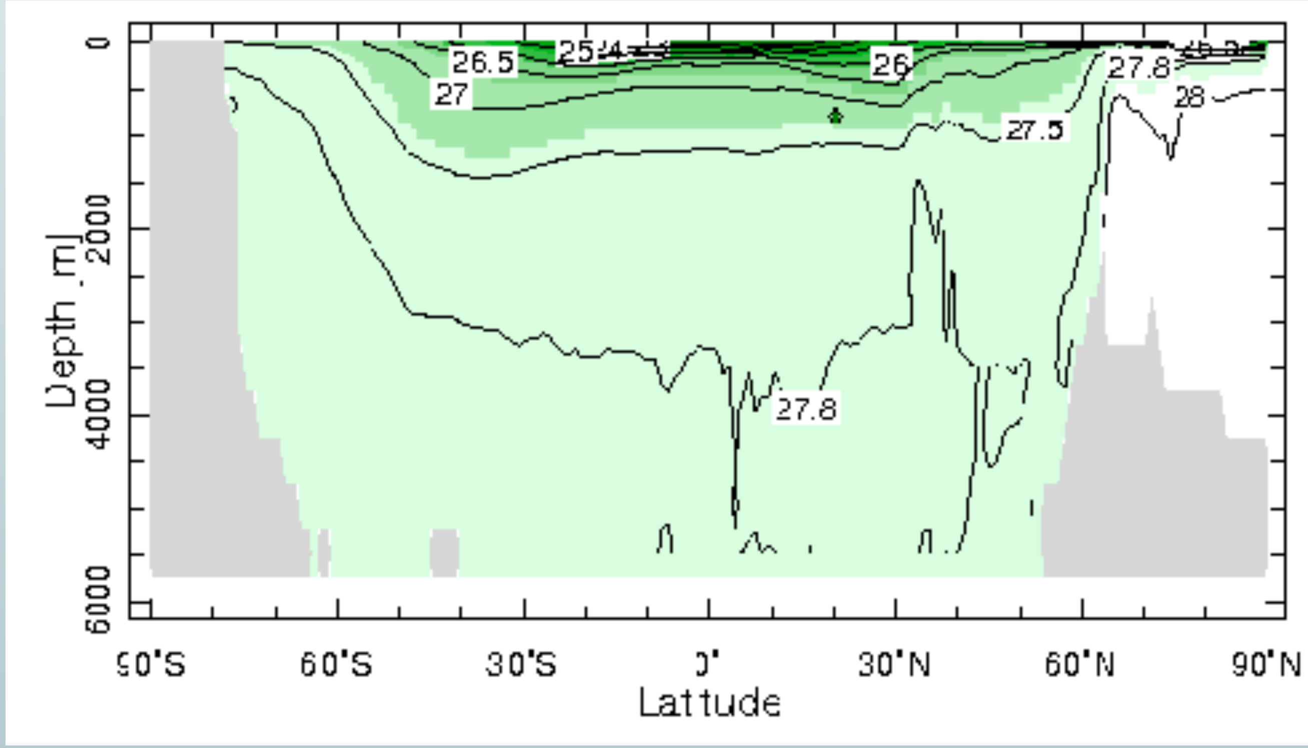

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- Greenland and Labrador Seas in the North Atlantic
- Weddell and Ross Sea around Antarctica

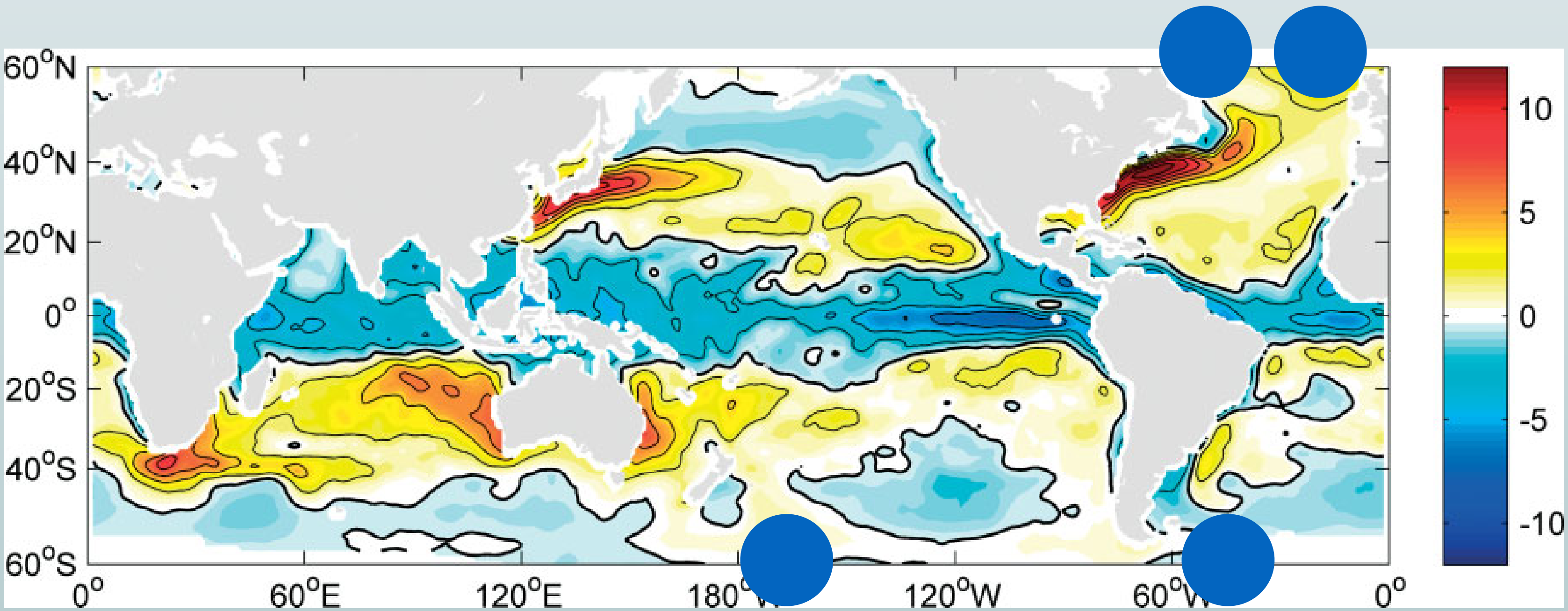



*Figure 4. Annual air-sea density fluxes, contour interval 2 × $10^{-6}$ kg $m^{-2}$ $s^{-1}$.*

# Where does water rise?
# Stommel-Arons theory

# Uniform upwelling

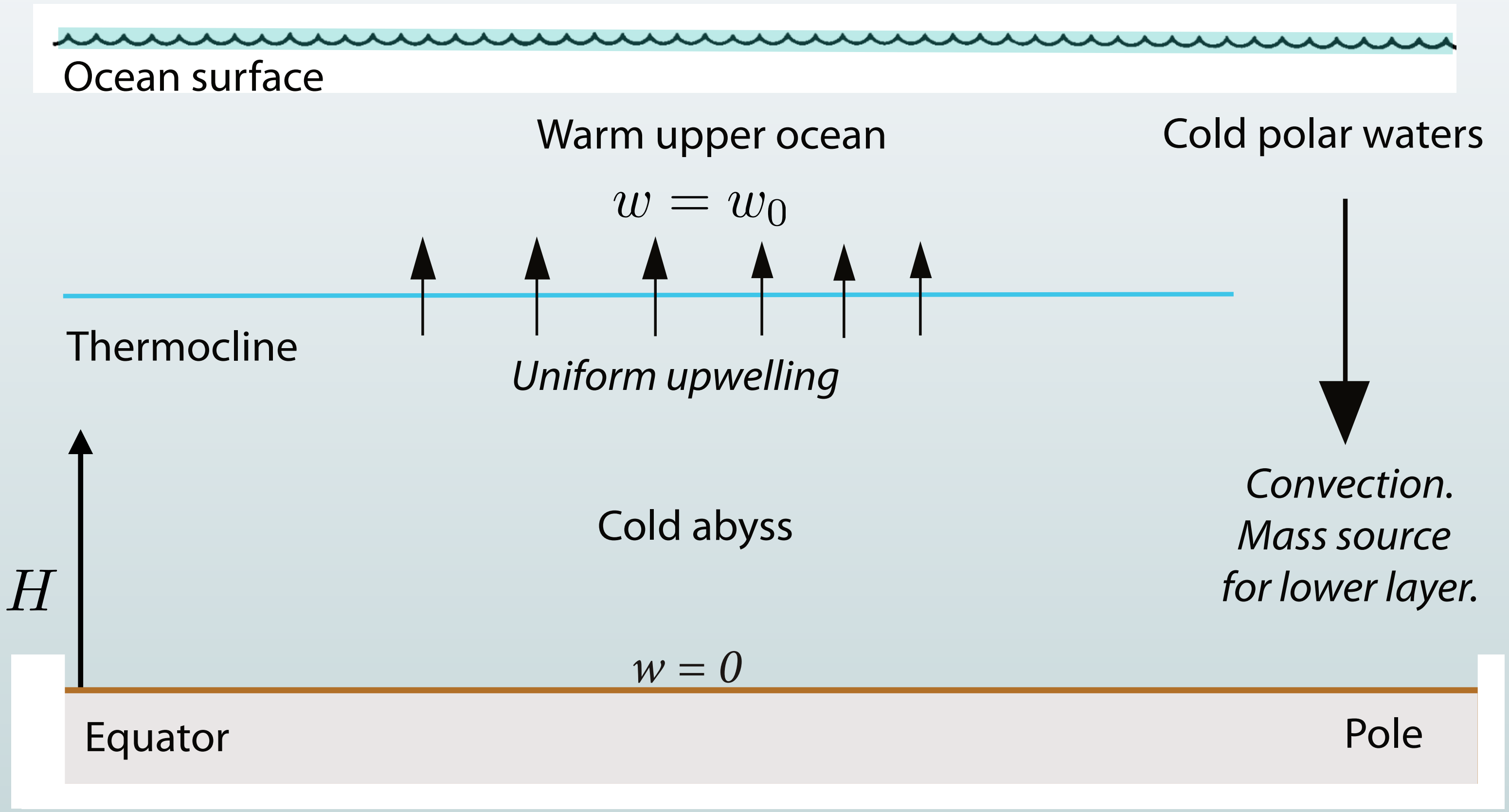



Fig. 21.12 (Vallis, 2017)

Upwelling in Pacific: $w_0 = \frac{S_0}{A} = \frac{15 \times 10^6 \text{m}^3\text{s}^{-1}}{1.6 \times 10^{14}\text{m}^2} \simeq 10^{-7}\text{m s}^{-1} \simeq 3\text{m year}^{-1}$

# Vorticity equation

- Planetary geostrophic equations
    - geostrophic balance

$$-fv = -\partial_x p$$

$$+fu = -\partial_y p$$

with $f = f_0 + \beta y$

    - mass conservation

$$\partial_x u + \partial_x v + \partial_z w = 0$$

- Vorticity equation

$$\beta v + f(\partial_x u + \partial_y v) = 0$$

$$\beta v = f\partial_z w$$

- Taking the vertical integral

$$\beta v H = f w_0 \quad \Longrightarrow \quad v = \frac{f}{\beta}\frac{w_0}{H} \simeq 2 \times 10^{-4} \mathrm{m\ s}^{-1}$$

# Vertically integrated circulation

Fig. 21.14 (Vallis, 2017)

Meridional transport

$$T_I \equiv vHL_x = \frac{f}{\beta} w_0 L_x$$

Upwelling

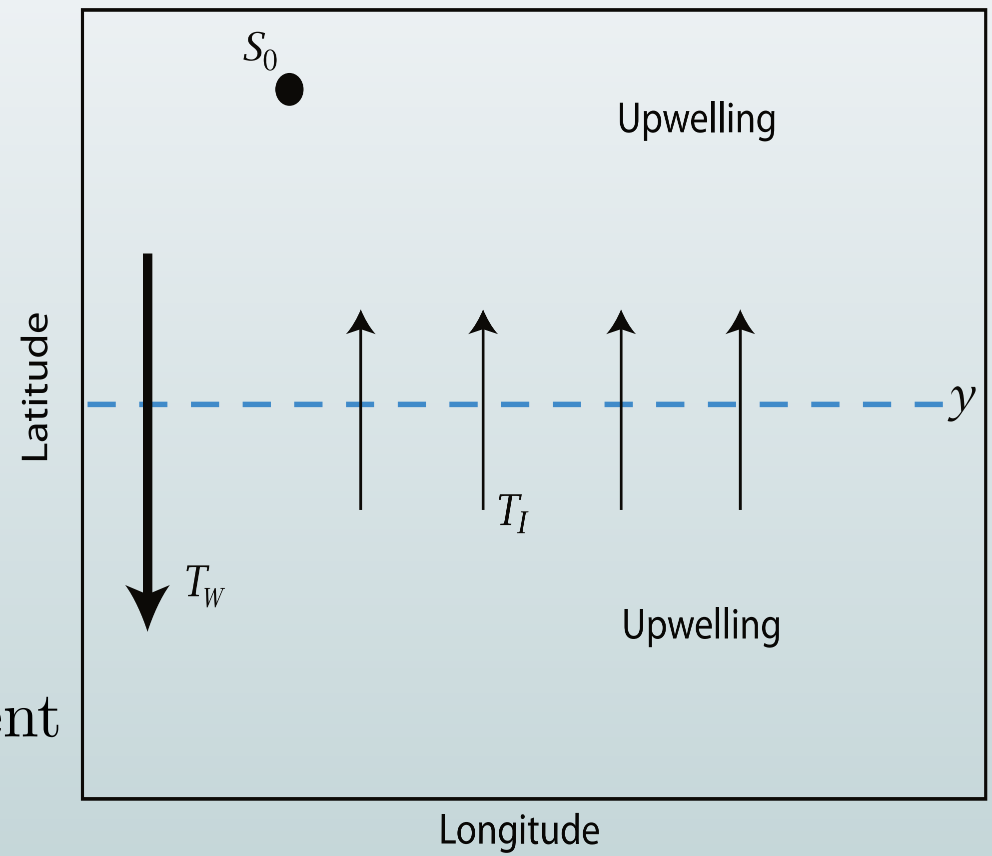
$$T_U = w_0 L_x (L_y - y)$$

Western boundary current

$$T_W = S_0 + T_I - T_U$$

$$T_W|_{y>0} = S_0 + T_I - T_U \geq T_I$$

$$v_W \geq v \frac{L_x}{L_W} \simeq 2 \times 10^{-2} \mathrm{m\ s^{-1}}$$



# Vertically integrated circulation

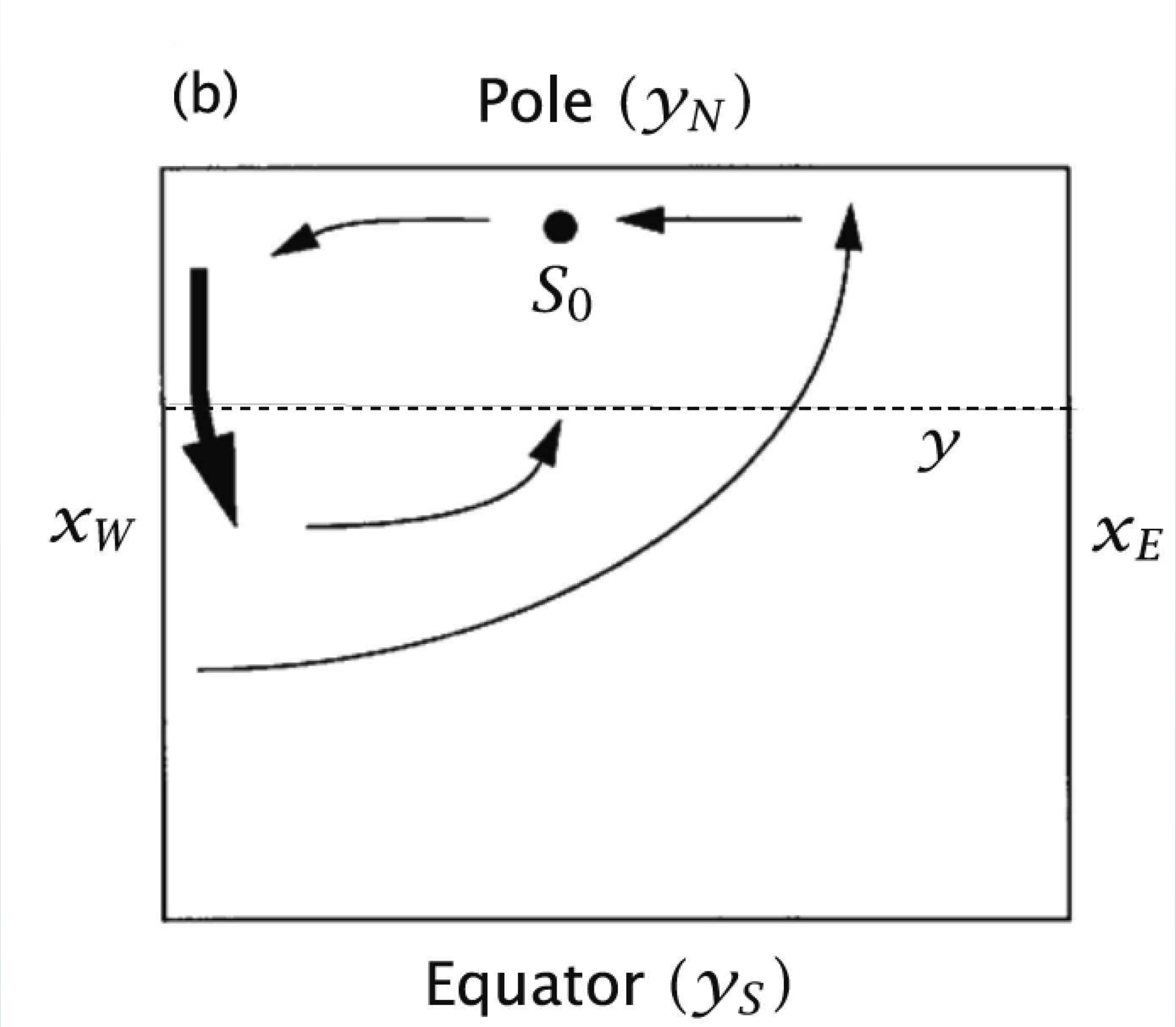
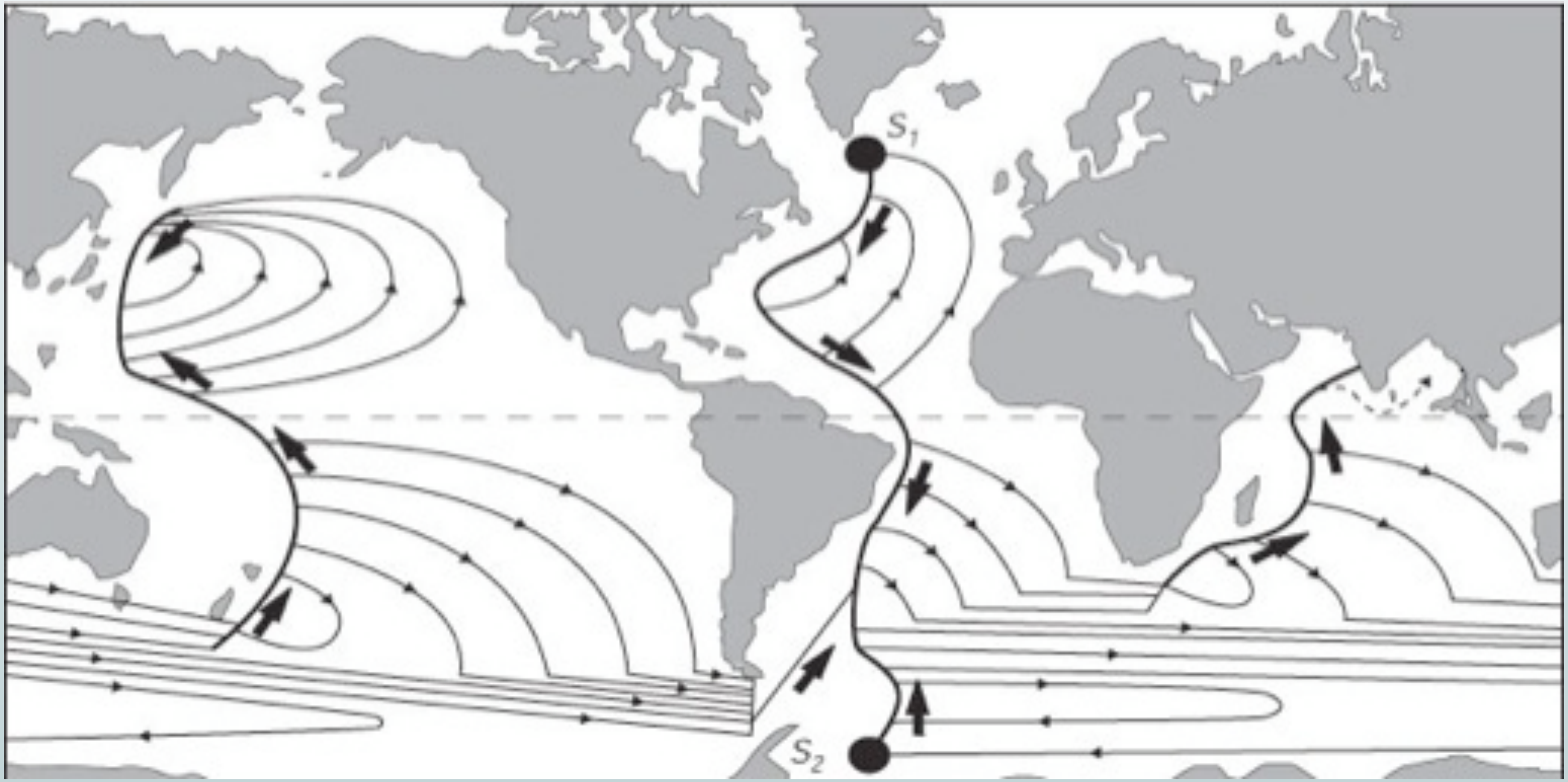



Fig. 21.13 (Vallis, 2017)

# Global deep circulation




Stommel Arons (1958-1960)

# Western Boundary Current found below Gulf Stream!

No. 4571 June 8, 1957 NATURE

LETTERS TO THE EDITORS

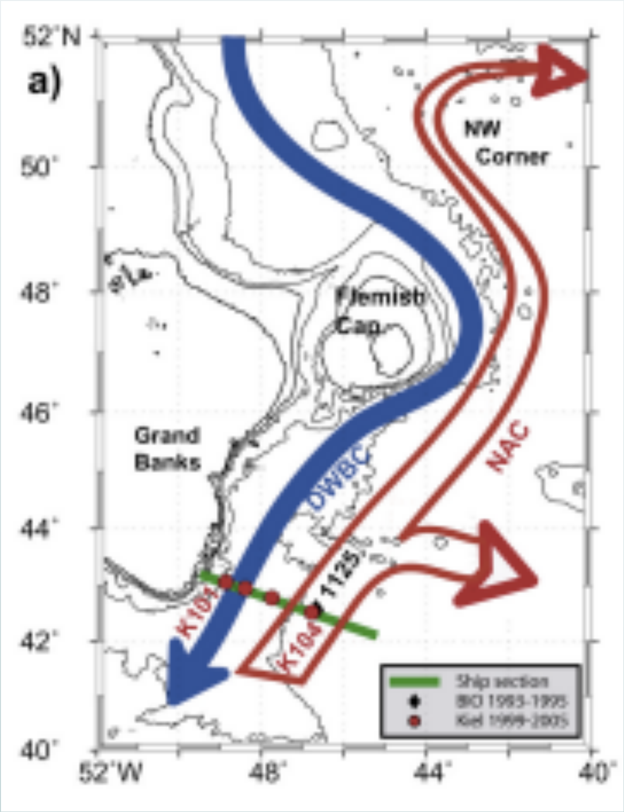
J. C. Swallow
National Institute of Oceanography,
Wormley, Godalming,
Surrey.
L. V. Worthington
Woods Hole Oceanographic Institution,
Woods Hole, Mass.
May 13.

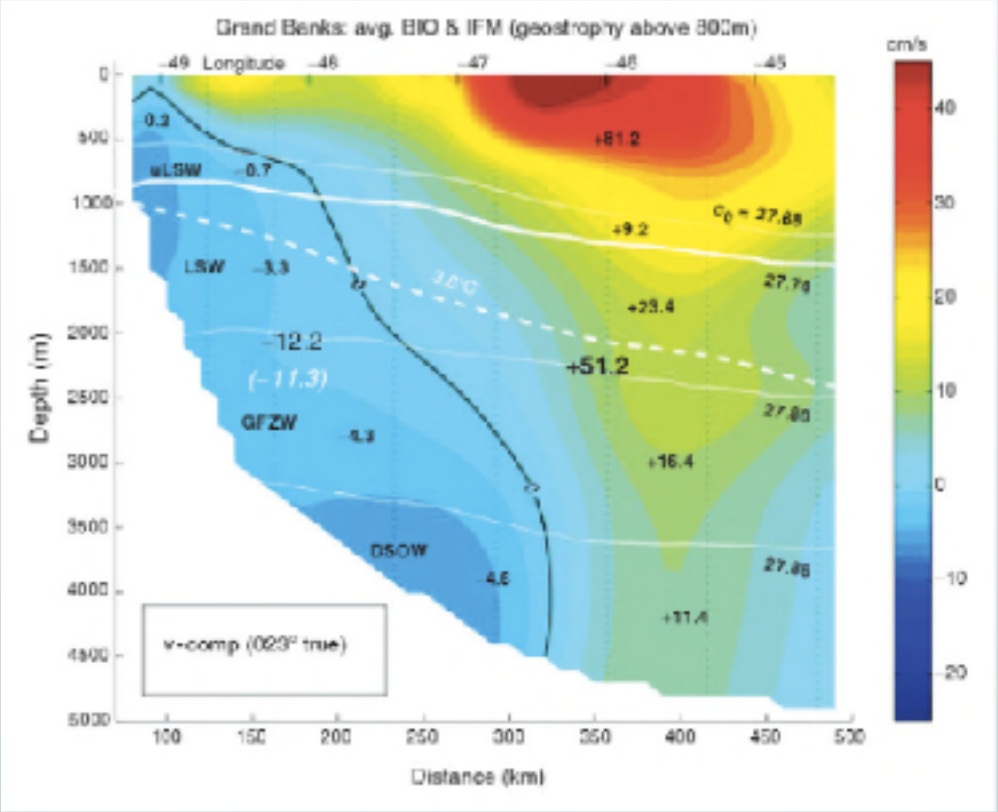
## Measurements of Deep Currents in the Western North Atlantic

The depth of the level of no motion has been a controversial matter among oceanographers for many years. In calculating currents from observed pressure distributions, it has often been assumed that the motion of the deep water must be so slow as to be negligible[1,2]. On the other hand, Defant[3] and Wüst[4] have arrived at consistent pictures of the circulation in the Atlantic using a surface of no motion at intermediate depths. More recently, Stommel[5] has suggested that there should be a deep current along the western boundary of the Atlantic, associated with an internal thermohaline mode of circulation, in the opposite direction to the Gulf Stream.

Nine floats were followed, of which seven were in deep south-going water. The measurements lasted for periods of 1–4 days, with some overlaps when more than one float was being followed. Three floats at 2,500 metres moved in directions between south and south-west with mean velocities between 2·6 and 9·5 cm./sec., and four floats at 2,800 metres depth moved almost due south with velocities of 9·7–17·4 cm./sec. Additional evidence for a south-going deep current was obtained by A. S. Laughton, who took underwater photographs[7] of the deflexion of a ball suspended on a string, only 50 cm. above the sea floor, in a depth of 3,200 metres. A southward movement of about 5 cm./sec. was found at that depth.

# Western Boundary Current found below Gulf Stream!

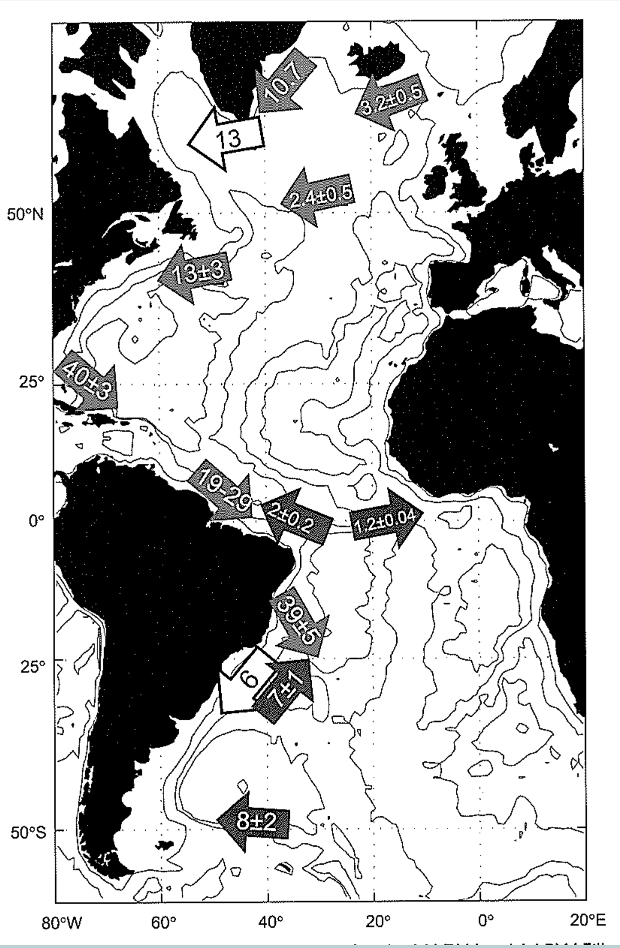


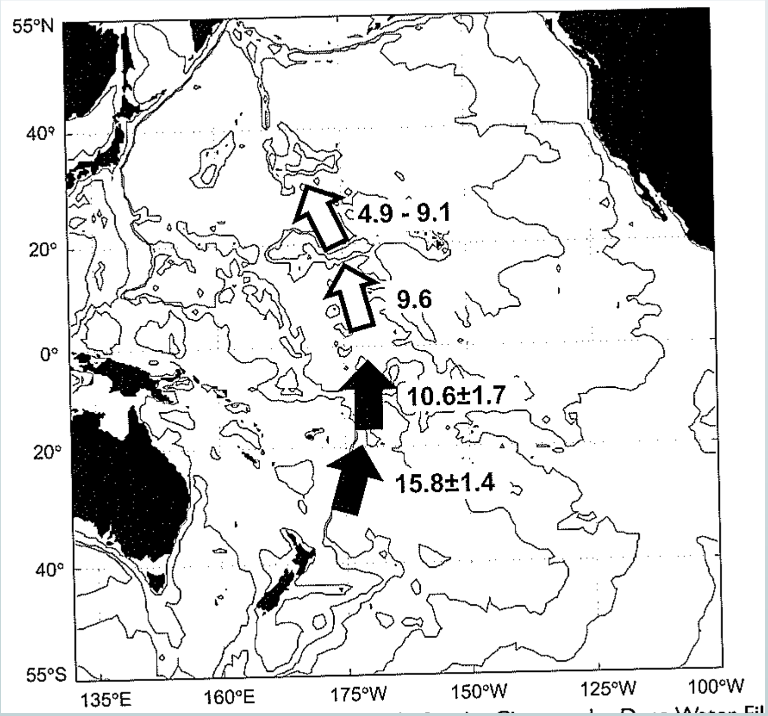

North Atlantic WOCE section 42-43 N (Schott et al. 2004)

# Deep WBC

Atlantic



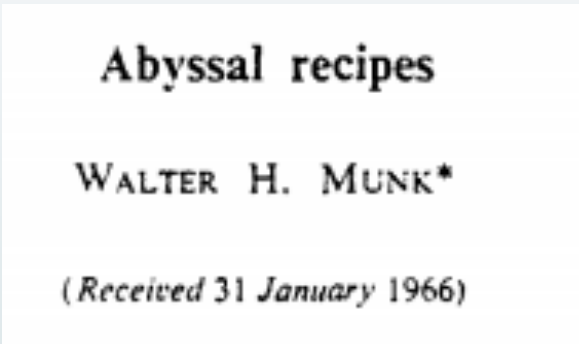

Pacific




Hogg (2001)

# Where does water rise?
# Munk’s Abyssal Recipes

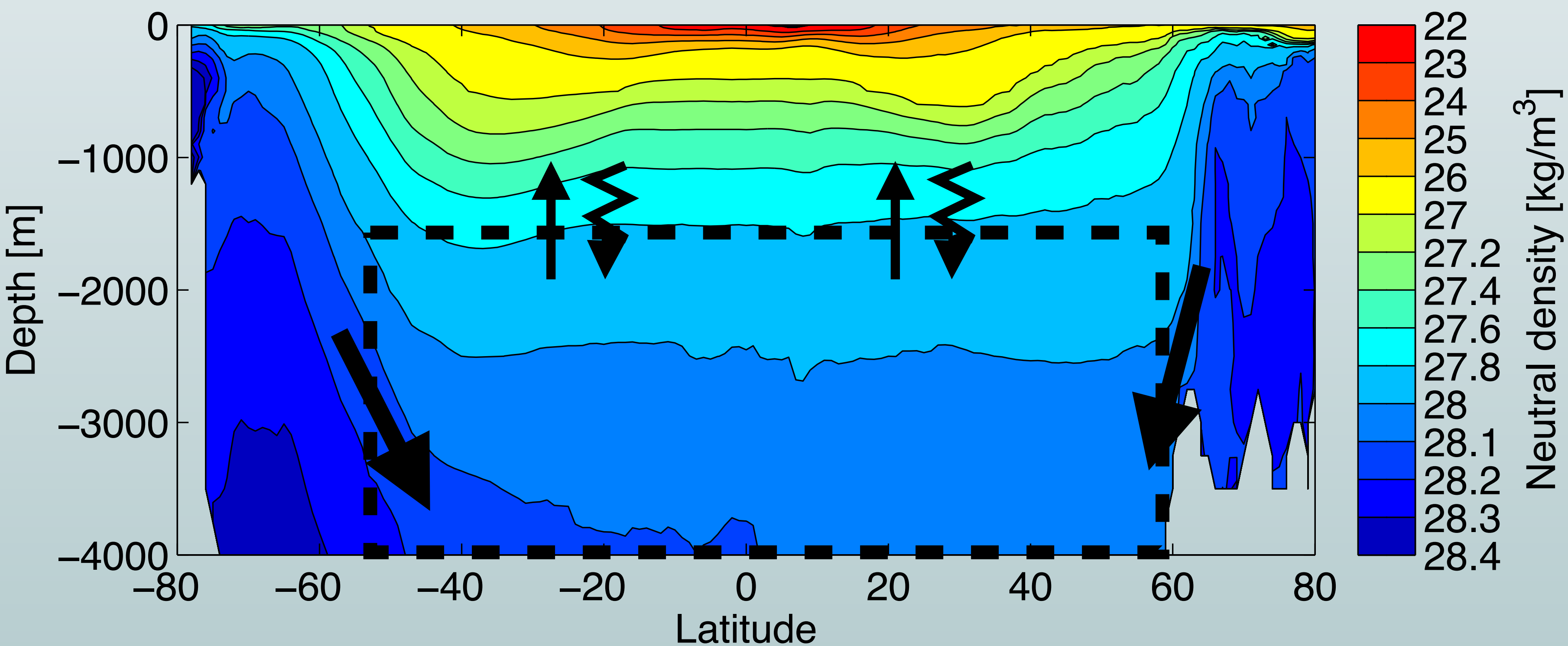
# Abyssal Recipes


**Abyssal recipes**

Walter H. Munk*

(*Received* 31 *January* 1966)

$$\mathbf{u} \cdot \nabla \rho = \partial_z \left( \kappa_T \partial_z \rho \right)$$



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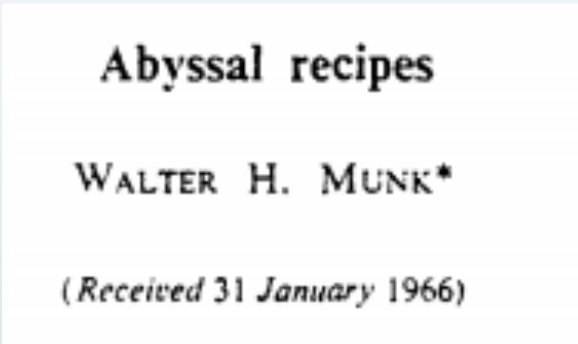
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WALTER H. MUNK*

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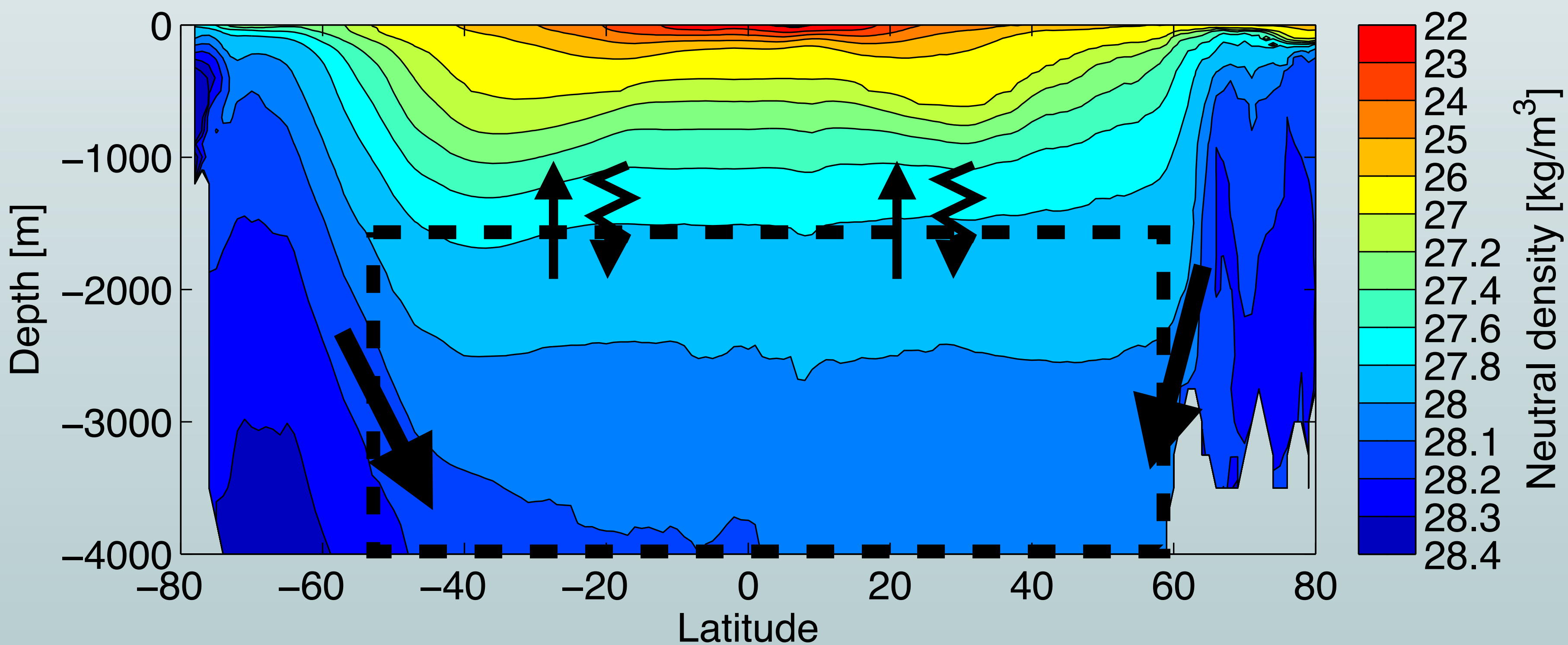
$$\iint w \frac{\partial \rho}{\partial z} \, \mathrm{d}A = \iint \frac{\partial}{\partial z} \left( \kappa_T \frac{\partial \rho}{\partial z} \right) \mathrm{d}A$$



# Abyssal Recipes

- Munk found that vertical profiles of density and $^{14}C$ in abyssal Pacific are consistent with 1-D balance

$$w_0 \frac{\partial \rho}{\partial z} = \kappa_T \frac{\partial^2 \rho}{\partial z^2}$$

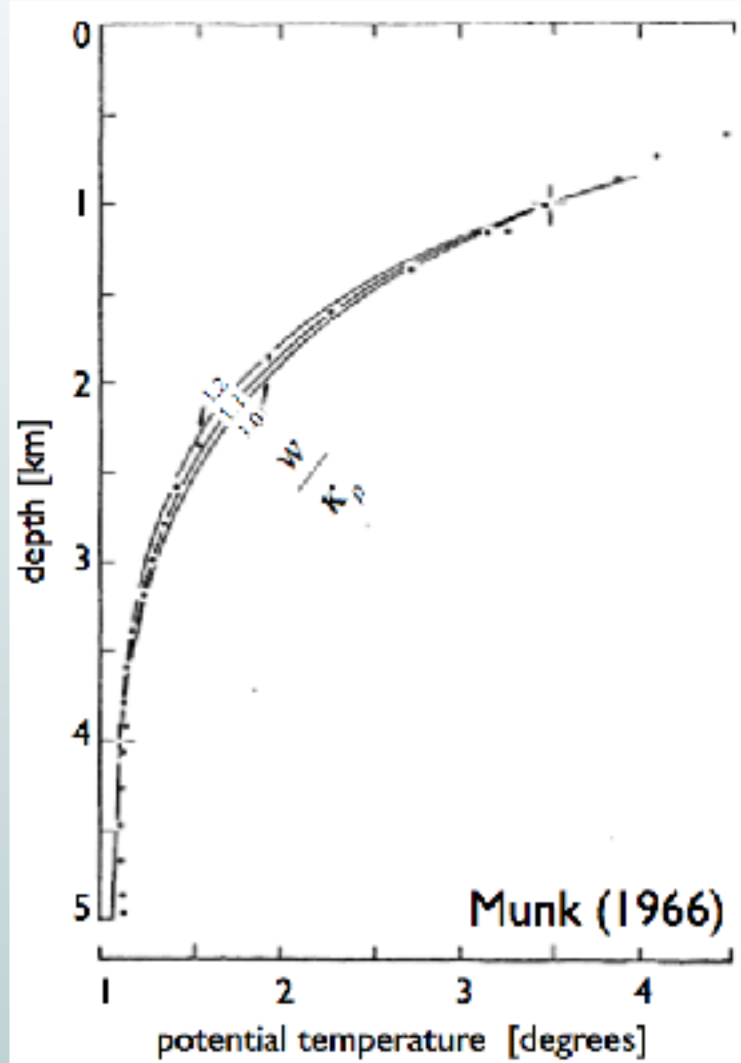
$$\rho(z) \propto \exp\left(\frac{w_0}{\kappa_T} z\right)$$

- Least-square curve field yield

$$\frac{w_0}{\kappa_T} \simeq 1.2 \text{ km}^{-1}$$

- Upwelling in Pacific

$$w_0 = \frac{S_0}{A} = \frac{15 \times 10^6 \text{m}^3\text{s}^{-1}}{1.6 \times 10^{14} \text{m}^2} \simeq 10^{-7} \text{ms}^{-1}$$



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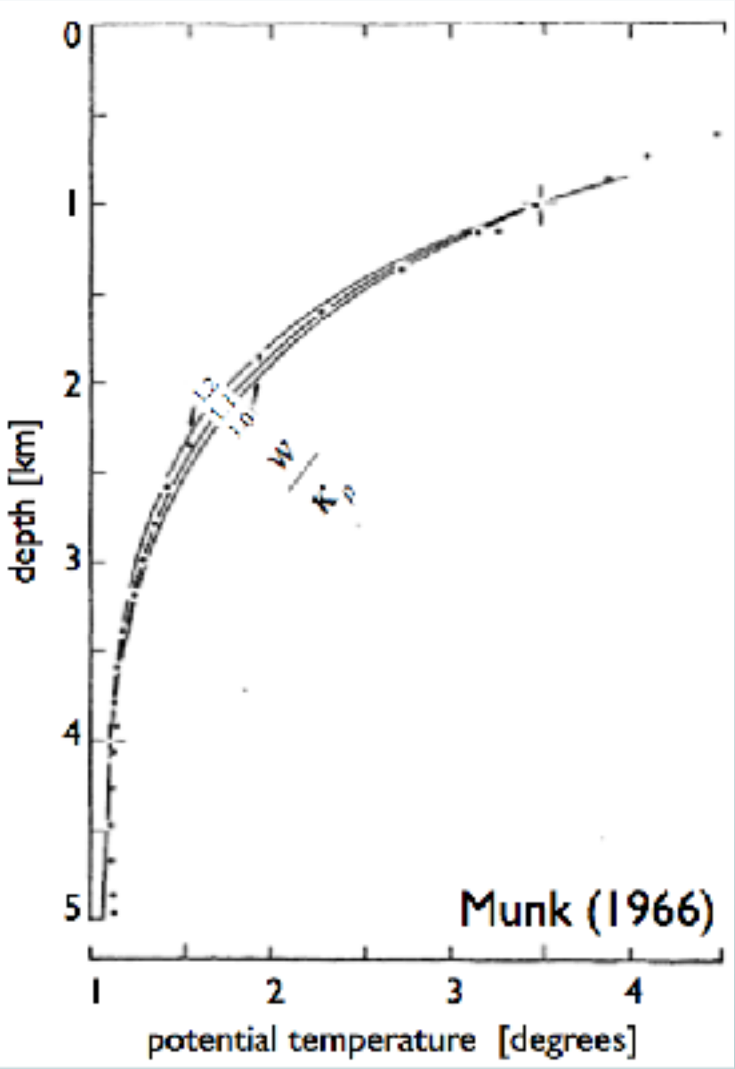
- Least-square curve field yield

$$\frac{w_0}{\kappa_T} \simeq 1.2 \text{ km}^{-1}$$

- Turbulent diffusivity

$$\kappa_T \simeq \frac{10^{-7}\,\text{ms}^{-1}}{1.2 \times 10^{-3}\,\text{m}^{-1}} \simeq 10^{-4}\,\text{m}^2\text{s}^{-1}$$



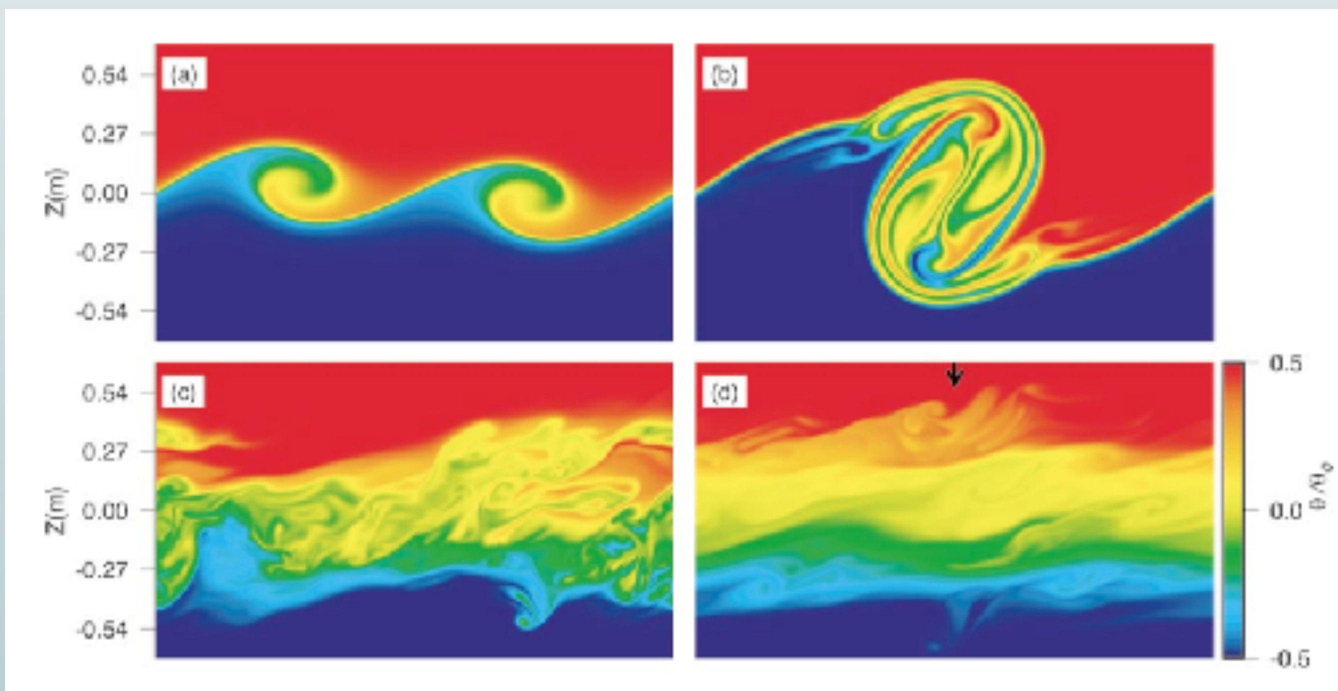
# Turbulent mixing

- Mixing in the deep ocean below1000 m is turbulent

$$\kappa_T \sim 10^{-4}\ \mathrm{m^2 s^{-1}} \qquad \gg \text{molecular diffusion}$$

- Turbulent mixing is typically associated with breaking internal waves

$$Ri \equiv \frac{N^2}{|\partial_z \mathbf{u}|^2} = \begin{cases} \text{large for geostrophic motions} \\ O(1) \text{ for internal waves} \end{cases}$$




Smyth et al. (2001)

# Abyssal circulation and $\kappa_T$

**Parameter Sensitivity of Primitive Equation Ocean General Circulation Models**

FRANK BRYAN

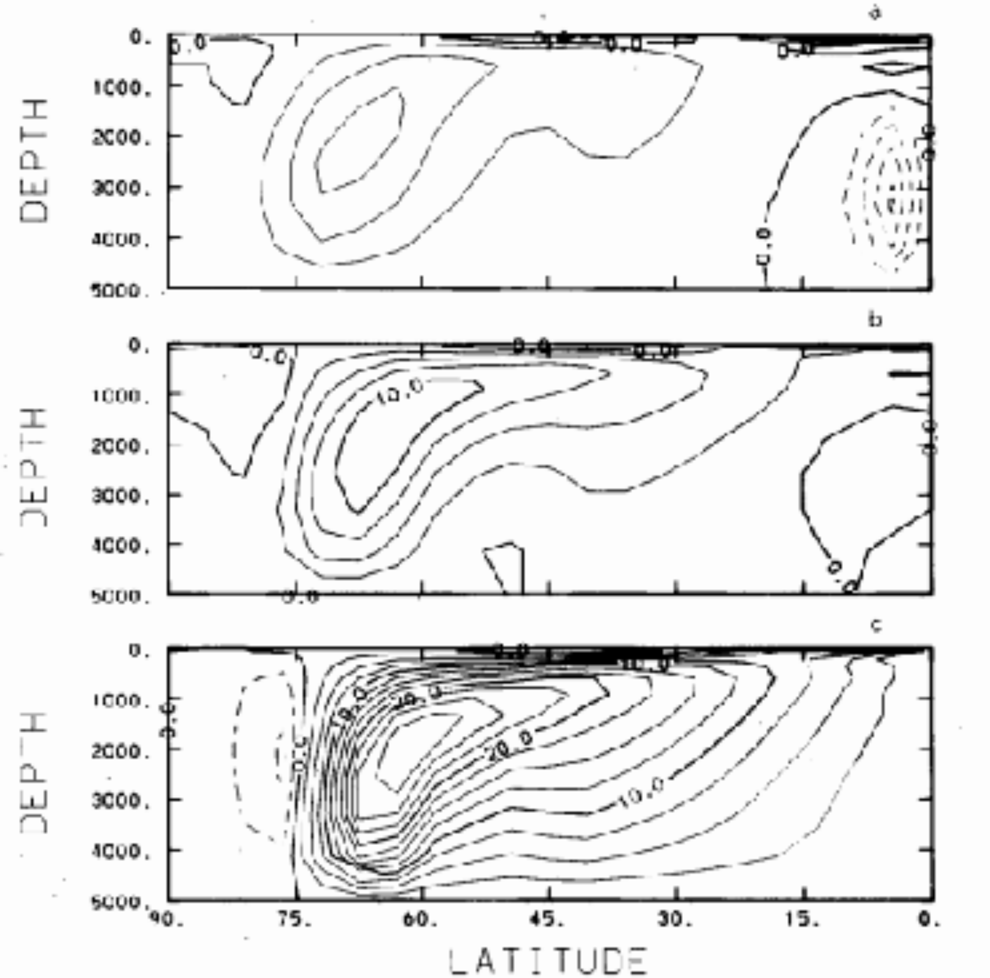



FIG. 7. Meridional overturning streamfunction for (a) $A_{HV}$ = 0.1, (b) $A_{HV}$ = 0.5, (c) $A_{HV}$ = 2.5 (c.i. = 2.5 × $10^6$ $m^3$ $s^{-1}$, solid contours indicate counterclockwise circulation).

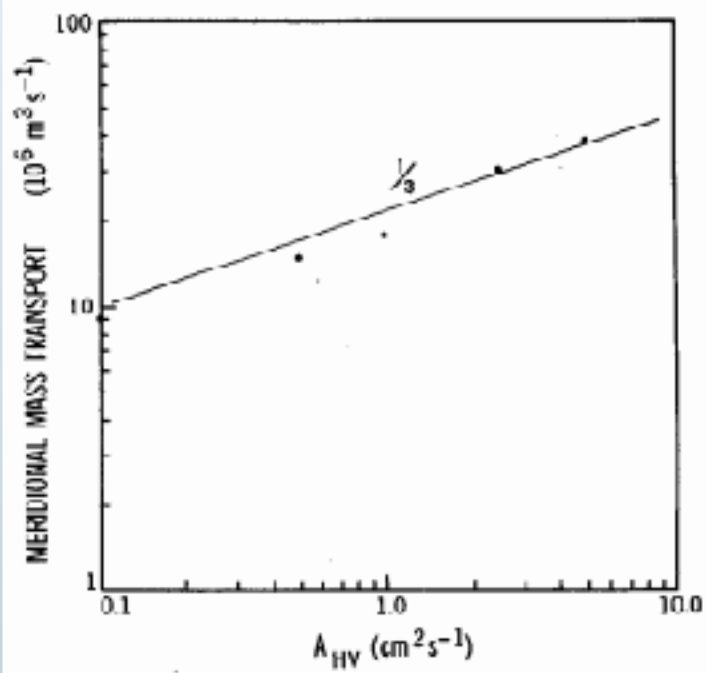
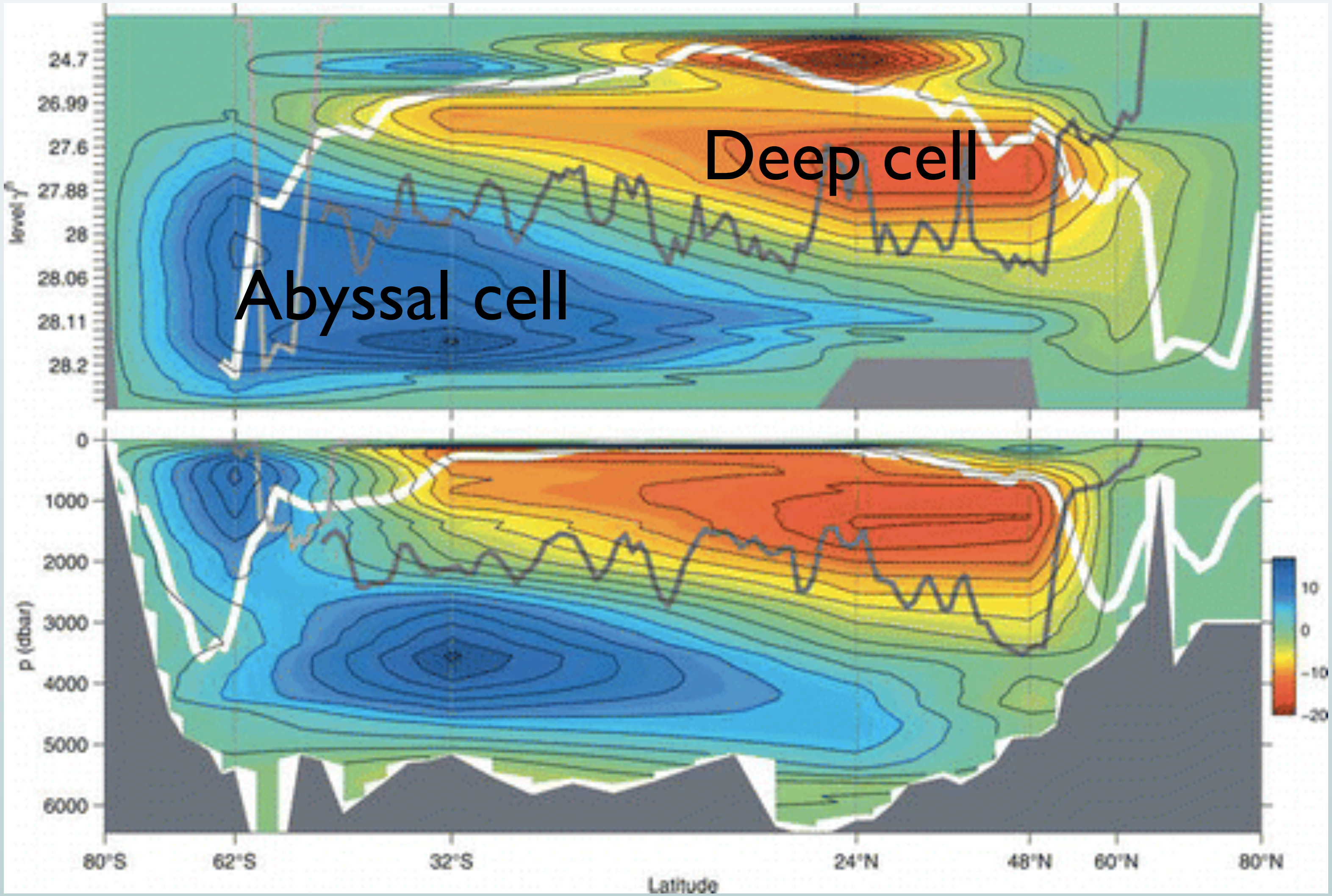



FIG. 8. Dependence of meridional overturning streamfunction on vertical diffusivity.

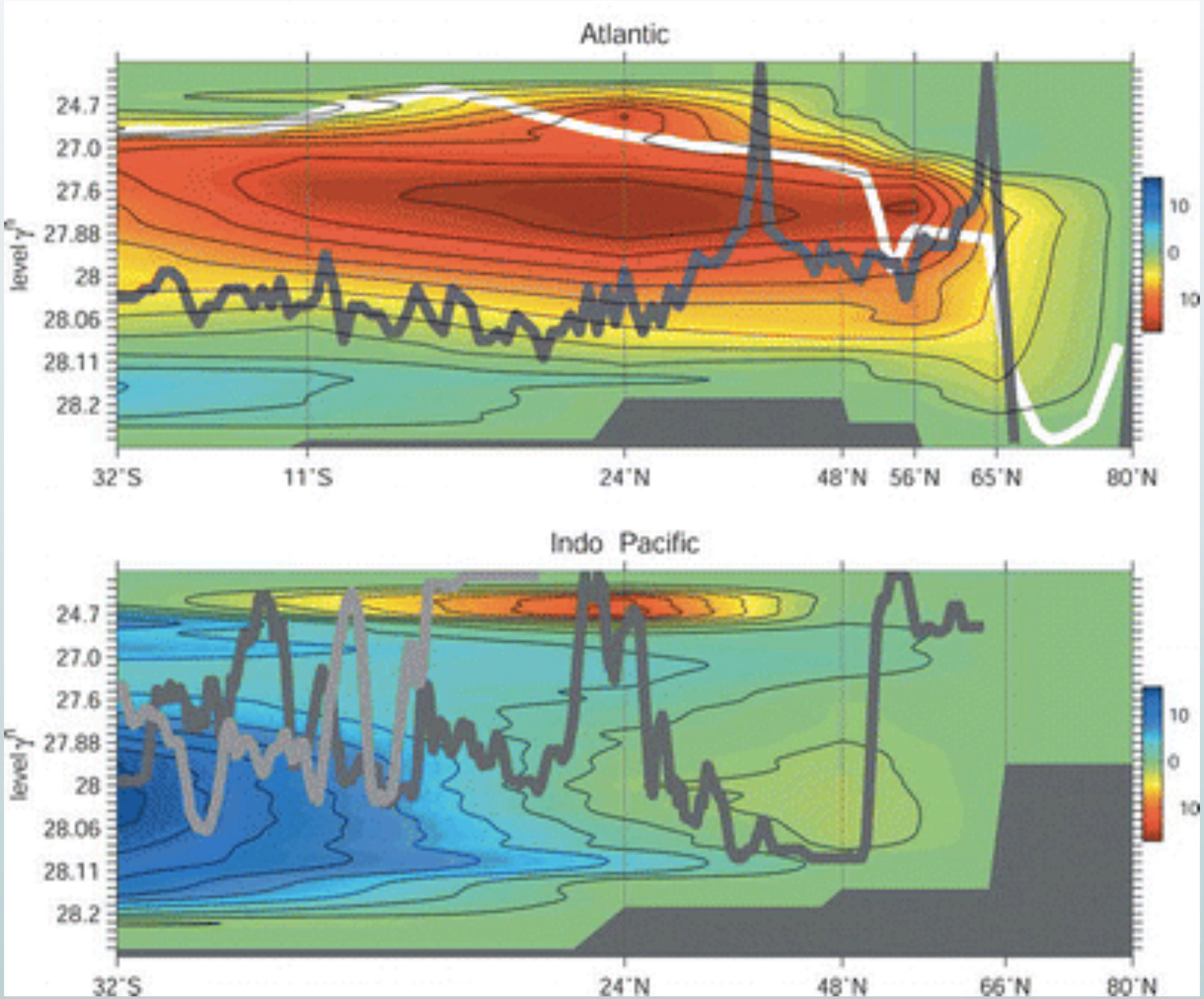
# Observations of abyssal circulation: WOCE era

# Abyssal overturning circulation




Lumpkin and Speer (2007)

# Abyssal overturning circulation

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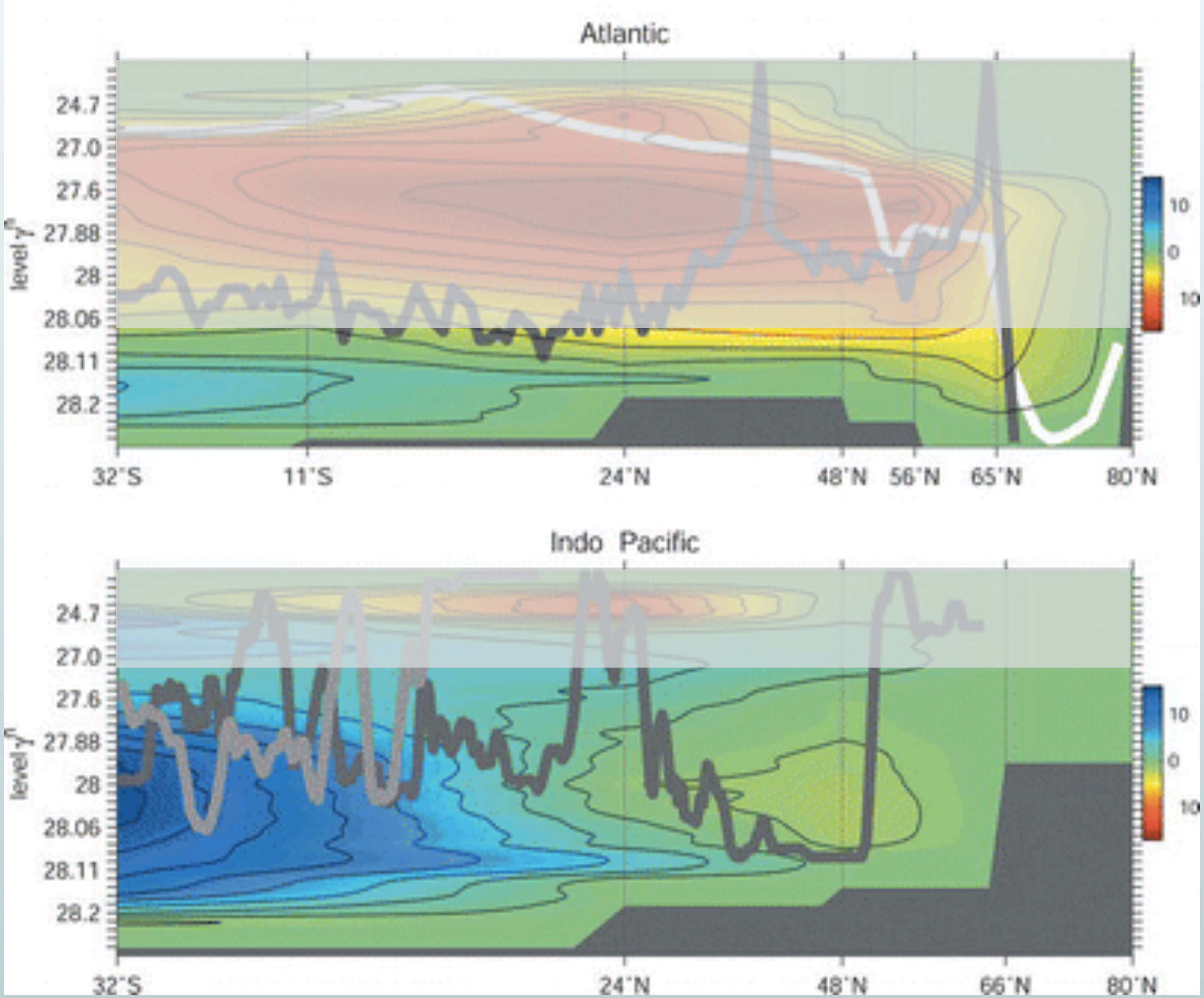
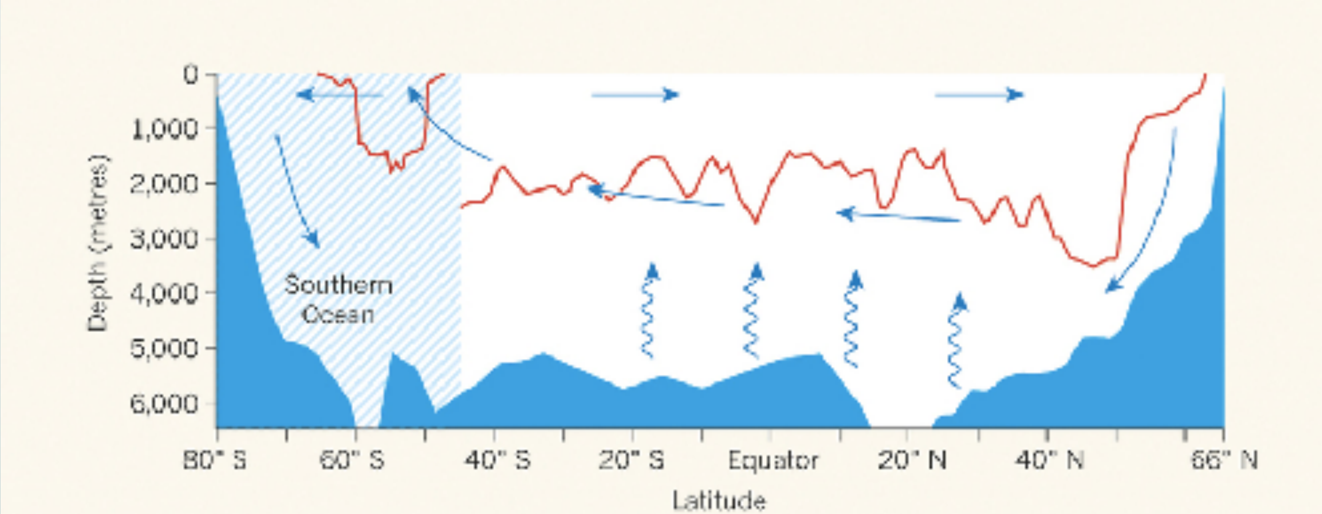



Lumpkin and Speer (2007)

# Conclusions

- The deep ocean circulation is fed by deep convection
  - in the North Atlantic
  - around Antarctica

- The deep waters return to the surface
  - pulled by winds above 2000m the Southern Ocean
  - through mixing in the abyssal Atlantic, Indian and Pacific Oceans




Ferrari (2014)