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OCES 2003 : Descriptive Physical Oceanography

(a.k.a. physical oceanography by drawing pictures)

Lecture 14: MOC

Thur 25th Mar

Outline

- Meridional Overturning Circulation (MOC)
  $\rightarrow$ role and structure
- watermasses
  $\rightarrow$ watermass properties
- where does water go down?
  $\rightarrow$ watermass transformation
  $\rightarrow$ deep/abyssal water formation
- where does water come up?
  $\rightarrow$ broad diffusive picture, diapycnal mixing
  $\rightarrow$ more updated picture: boundary layers

Key terms: MOC, watermasses, diapycnal mixing

Recap: Southern Ocean

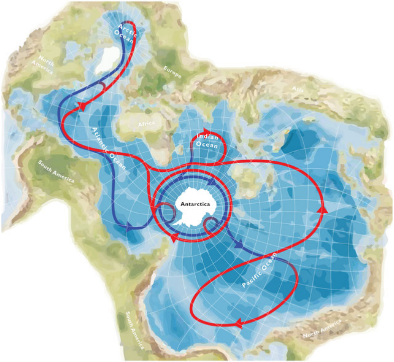


Figure: Spillhaus projection with a focus on the oceans and, in particular, of the Southern Ocean, with a schematic of the MOC put on (red = warm surface waters, blue = cold deep/abyssal waters). From Mike Meredith (BAS), from his Challenger Medal ceremony talk in 2018.

- Southern Ocean the "center" of the global ocean
- **Antarctic Circumpolar Current** (ACC)

  → world's largest current, transport of ≈ 130 Sv (1 Sv $= 10^6$ m^3 s^{-1})

  → tilting isopycnals, thermal wind relation

  → very turbulent/unstable region (see Lec. 17)

Recap: Southern Ocean

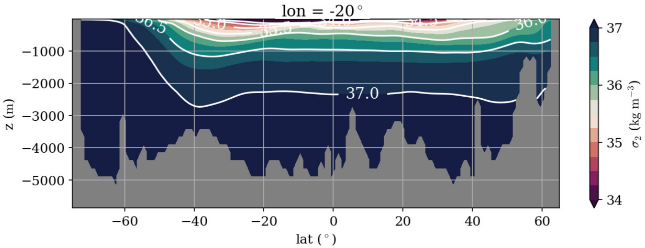
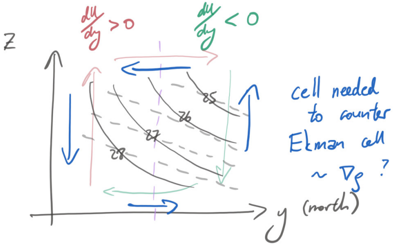


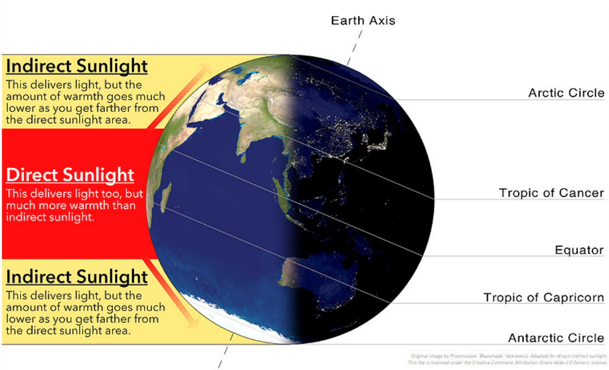
Figure: Meridional section in the Atlantic of σ_2. See `plot_eos.ipynb`. Strongly tilting isopycnals present in the Southern Ocean, in contrast to relatively flat isopycnals in the basins.



- Ekman vs. eddy overturning cell, residual affecting overall stratification

$\rightarrow$ can have **global** effect via isopycnal connectivity

Recap: thermodynamic forcing



- tilted 23.26° (does change, see OCES 4001)
- uneven solar heating

  → gradient in forcing / energy, expectation for diffusion + transport (Lec. 10)

Transport of energy (PW $= 10^{15}$W)

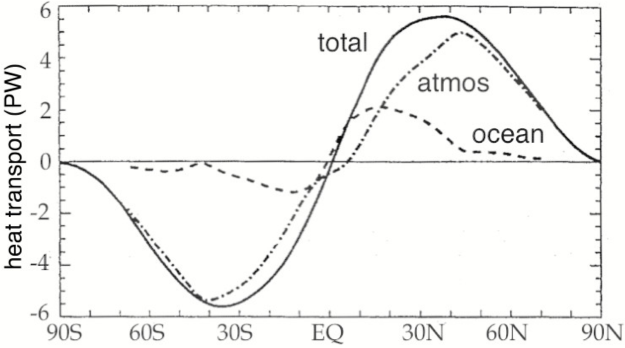


Figure: Total transport of energy to the **north** as a function of latitude. Reworked from Trenberth & Caron, 2001, *J. Climate*.

- atmospheric transport larger in magnitude and fairly symmetric about EQ
- ocean transport not negligible, but asymmetric?

MOC

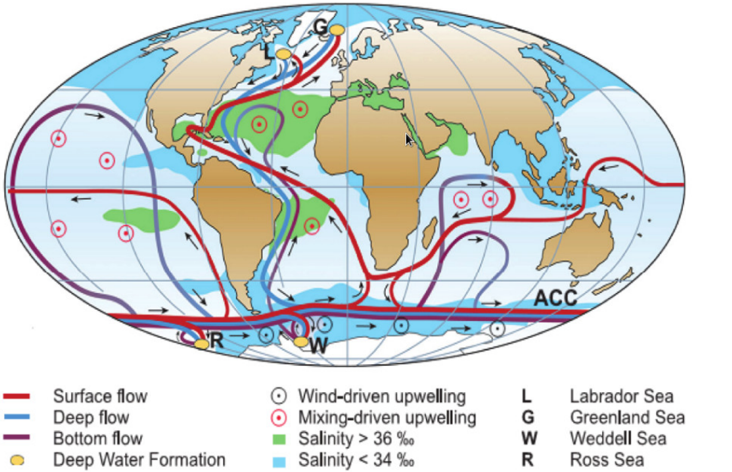


Figure: Schematic of the global MOC (red: surface warmer waters; blue: deeper colder waters; purple: abyssal cold waters). From Rahmstorf (2002), *Nature*, figure in Box 1.

MOC

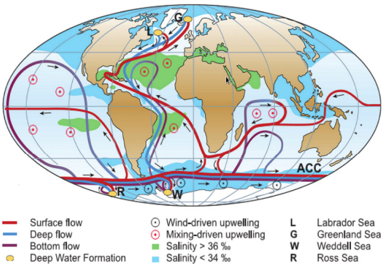


Figure: Schematic of the global MOC (red: surface warmer waters; blue: deeper colder waters; purple: abyssal cold waters). From Rahmstorf (2002), *Nature*, figure in Box 1.

- conveyor belt like schematic (more on this later)
- surface warmer water goes poleward largely via WBC (cf. Lec. 2)

  → energy transport polewards, warming of Western Europe predominantly
- goes to depth and returns via DWBC (Lec. 12)
- sinking at isolated places

  → e.g. Lab sea, Weddell sea (see later)

  → **where** and **how** does water come up?
- notice that there is an AMOC but not really a PMOC

MOC

The preferred terminology here is the **Meridional Overturning Circulation** (MOC)

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- sometimes global ocean conveyor belt (cf. Wally Broecker, 1931 - 2019)

✓ implies global connectivity

× implies transport isolated to certain regions

MOC

The preferred terminology here is the **Meridional Overturning Circulation** (MOC)

- meridional motion + up and down motion

- sometimes global ocean conveyor belt (cf. Wally Broecker, 1931 - 2019)
- ✓ implies global connectivity
- × implies transport isolated to certain regions

- sometimes thermohaline circulation
- ✓ T and S certainly play an important role
- × wind, tides etc. also contribute

Watermasses: overview

How to identify connectivity? Want to identify **origins** of water

Use tracer properties?

- "stuff" gets mixed into the water parcel (Lec. 10)

  $\rightarrow$ usually near sea surface of certain regions, κ_z large

Watermasses: overview

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  $\rightarrow$ in interior κ_z much smaller (what about κ_h?)

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identify water origin by watermass properties

- can do via observations as well as numerical models (can do "better" in numerical models)
- strictly speaking we should be considering κ_d (diapycnal) rather than κ_z (vertical)

Watermasses: e.g. NADW via S

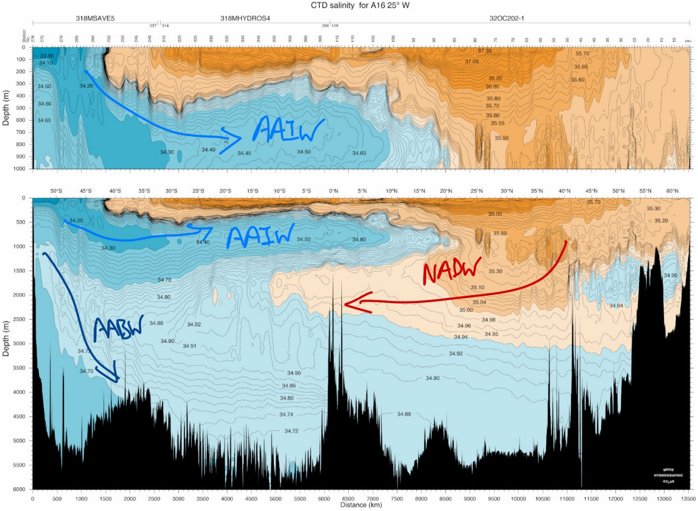


Figure: Salinity profile at 25° W, highlighting the **North Atlantic Deep Water** (NADW). "Warm"-ish salty water from Gulf Stream reaches higher latitudes, gets intensely cooled at Lab sea, sinks, but keeps the S signature. Can also see the Antarctic Intermediate Water (AAIW, the cold fresh tongue coming from the South). From WOCE.

Watermasses: e.g. AABW via T

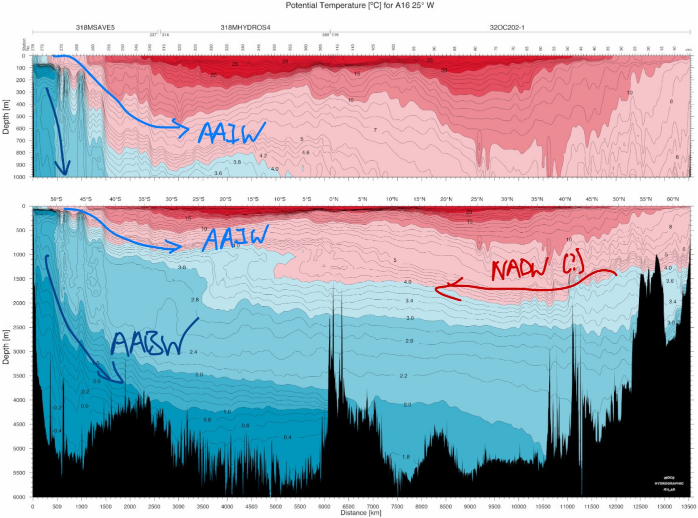


Figure: Potential temperature profile at 25°W, highlighting the Antarctic Bottom Water (AABW), the coldest tongue of water coming from the South and spreading along the abyssal plain. Intense cooling of waters reaching the Antarctic makes water extremely dense, sinking all the way to the bottom and spreads. From WOCE.

Watermasses: e.g. AAIW via Oxygen

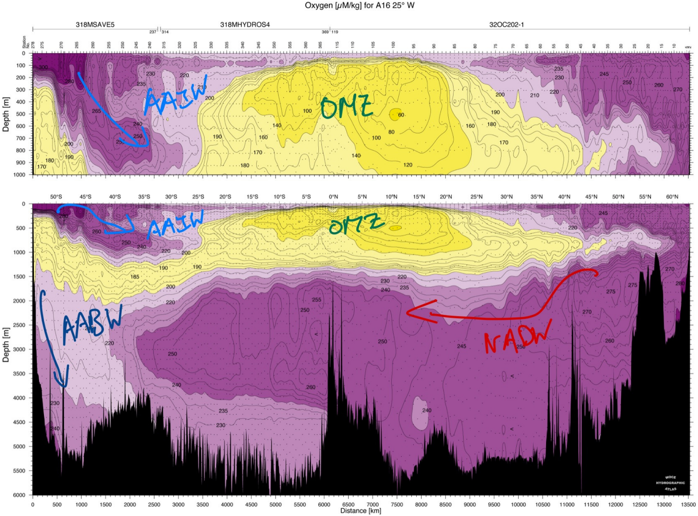


Figure: Dissolved oxygen concentration profile at 25° W, highlighting the Antarctic Intermediate Water (AAIW) high oxygen tongue at intermediate depths in the South. Downwelling via **Ekman pumping** (recall Lec. 13) of water recently in contact with atmosphere brings down water with high oxygen concentration. From WOCE.

Watermasses: e.g. AABW via γ^n

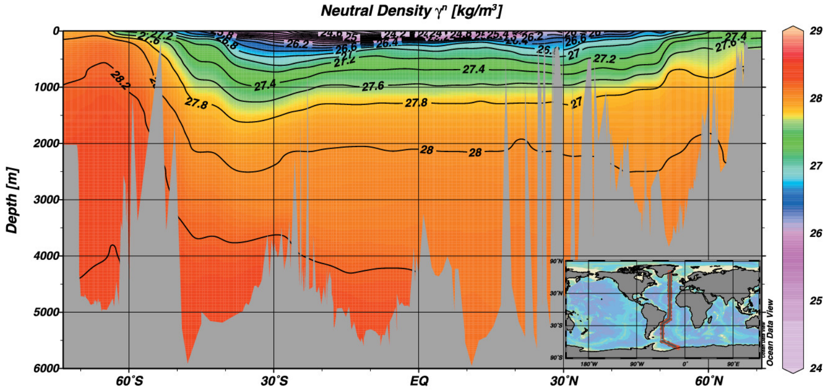


Figure: Neutral density profile at 25° W. AABW roughly corresponds to waters below 28.1 isopycnal, and 27.9 corresponds to the isopycnal extended roughly around the ice edge in the Antarctic. From WOCE data, diagram taken from Kuhlbrodt *et al.*, 2007, *Review of Geophyisics*.

a key point: transport predominantly along isopycnals

Watermasses

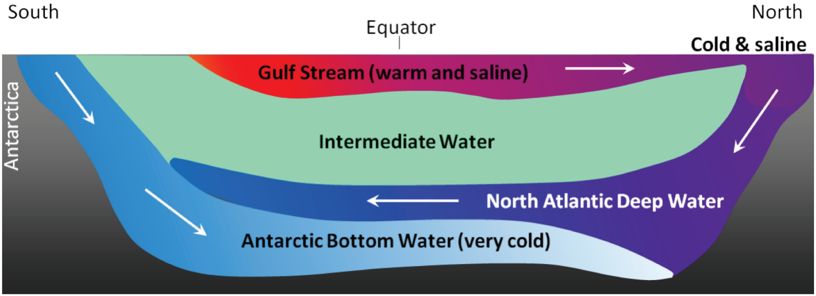


Figure: Schematic of the MOC and watermasses in the Atlantic. From Stephen Earle's open source textbook, Figure 18.17.

- many more different types of watermasses (not doing all of them...)
- more WOCE meridional sections at `https://www.ewoce.org/gallery/index.html`

Deep/abyssal water formation

Given observations that water does **sink** and **rise**:

- **where** and **how**?
- Ekman pumping in SO could do some of it (AAIW above) $\rightarrow$ forming **intermediate** class ($\approx$ 1000m depth), want **deep/abyssal** classes ($>$ 1500m depth)

Deep/abyssal water formation

Given observations that water does **sink** and **rise**:

- **where** and **how**?
- Ekman pumping in SO could do some of it (AAIW above) $\rightarrow$ forming **intermediate** class ($\approx$ 1000m depth), want **deep/abyssal** classes ($>$ 1500m depth)
- recall motion largely follow isopycnals $\rightarrow$ otherwise do a lot of work against buoyancy

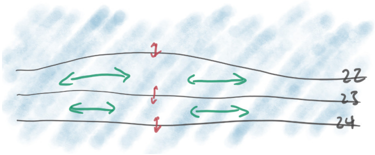


Figure: Flow likes to go along isopycnals (green) and less across isopycnals, for energetic reasons.

need watermass transformation + changes in density classes

Deep/abyssal water formation

convection is one way

- convection mostly **shallow** over the ocean

  → top-down heating is not efficient

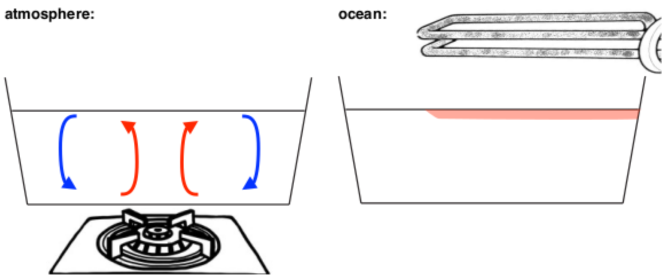


Figure: Schematic of principal sources of thermal forcing between atmosphere and ocean. Courtesy of David Marshall (Oxford).

Deep/abyssal water formation

deep convection

- intense **cooling** can make water very dense
  - → limited to high latitudes
  - → cabbeling effects also (nonlinear EOS, not elaborated here)
- places that can hold water back helps
  - → marginal seas + sills would do it (Lec. 2 + 3)

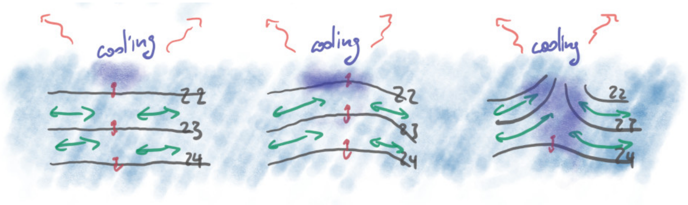


Figure: Watermass transformation by decreasing temperature.

Deep/abyssal water formation

- intense **evaporation** + sudden cold burst can do it
  - → limited to tropics (just the Med sea really)
  - → dramatic increase in salinty + cold water
- places that can hold water back helps
  - → marginal seas + sills would do it (Lec. 2 + 3)

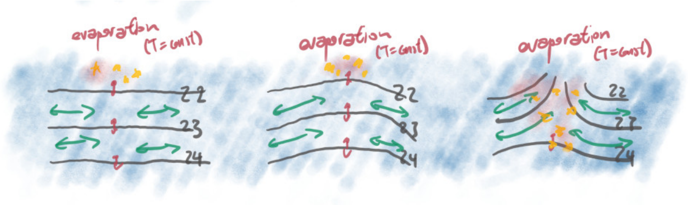


Figure: Watermass transformation by increase in salinity.

Deep/abyssal water formation

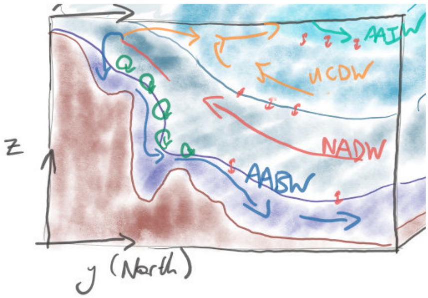


Figure: Schematic of watermass movement in the Southern Ocean.

Weddell sea example:

- very cold air, water gets cooled, sinks
- held back by sills
- spills over as overflows, some mixing

  $\rightarrow$ cf. **waterfalls**

- similar things going on in

  $\rightarrow$ Weddell sea, Ross sea (AABW), Labrador sea (NADW)

  $\rightarrow$ Mediterranean sea (contributes to NADW)

Deep/abyssal water upwelling

What goes **down** must come **up**

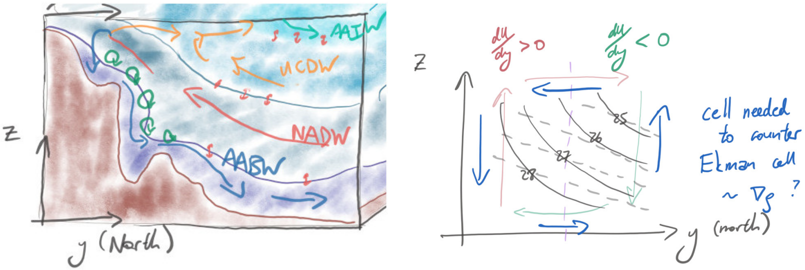


Figure: Schematic of watermass transformation in the Southern Ocean.

- NADW is probably mostly by Ekman upwelling in the Southern Ocean

what about the abyssal waters though?

Deep/abyssal water upwelling

"Classical" picture: broad diffusive upwelling (Munk, 1966, Abyssal Recipes)

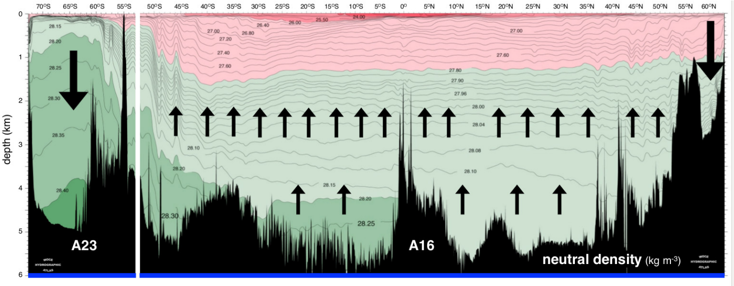


Figure: Schematic of the broad diffusive upwelling picture. Modified from WOCE diagrams.

- transformation of bottom/abyssal waters on a **diffusive** millemnia time-scale

  $\rightarrow$ dependent on diapycnal diffusivity κ_d (Lec. 10 + few slides ago)

Deep/abyssal water upwelling

- we know how much water is going down roughly from observations

Q. how big does κ_d need to be to bring the water back up?

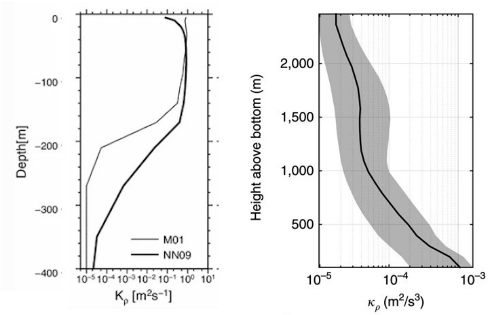
$\rightarrow$ broad diffusive picture, large ocean area/volume!

Deep/abyssal water upwelling

- we know how much water is going down roughly from observations

Q. how big does κ_d need to be to bring the water back up?
$\rightarrow$ broad diffusive picture, large ocean area/volume!

- average of around $\kappa_d = O(10^{-4}\ \mathrm{m}^2\ \mathrm{s}^{-1})$ (Abyssal Recipes, Munk, 1966, *Deep Sea Res.*)



- agrees well with observations, but diffusivity larger in upper and lower boundary layers

Figure: Observed κ_d in the upper ocean (left) and deep ocean (right). Figure taken from Watanabe & Hibiya (2013), *J. Phys. Oceanogr.* (left, their Fig. 5*d*) and Mashayek *et al.* (2017), *Nature Comms.* (right, their Fig. 2*c*).

Deep/abyssal water upwelling: schematic

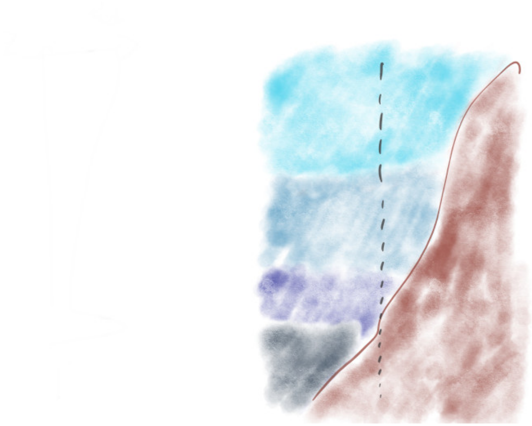
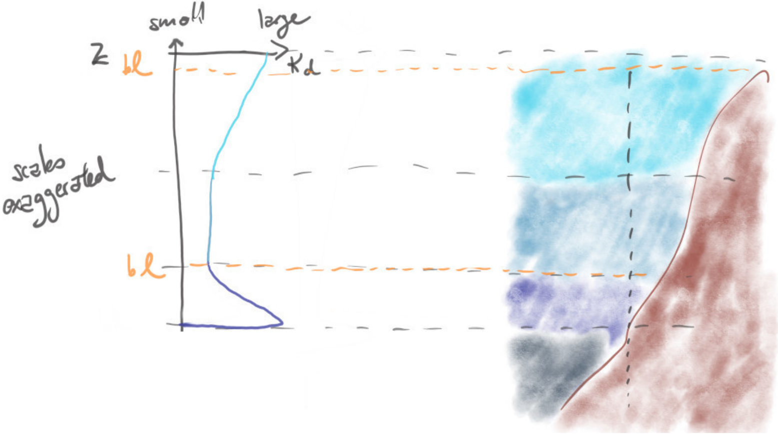


Figure: Schematic of the diffusive upwelling.

Deep/abyssal water upwelling: schematic



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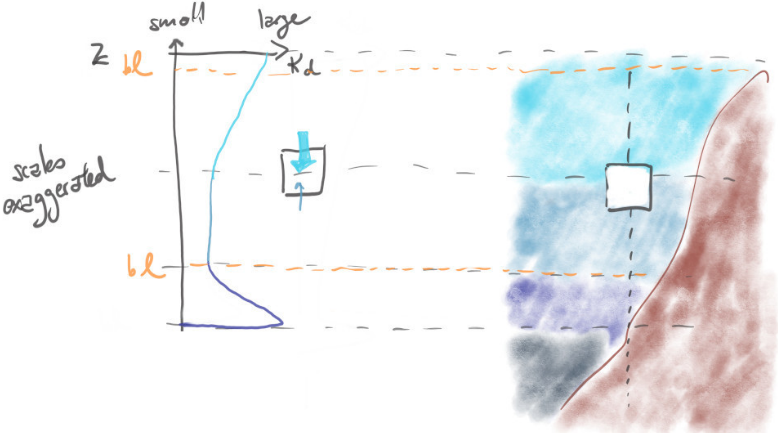

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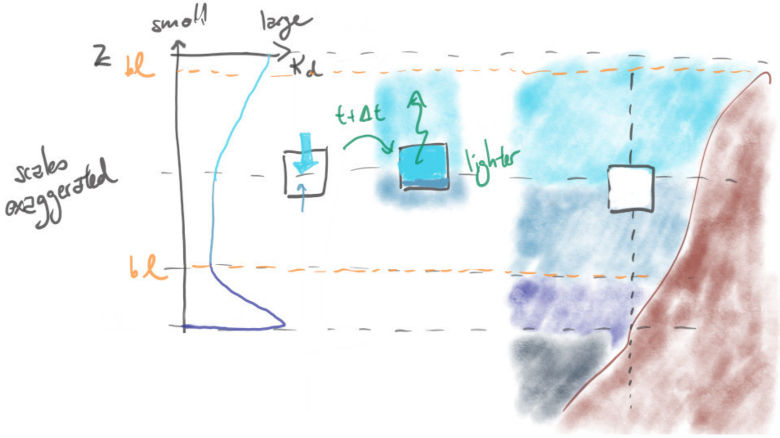

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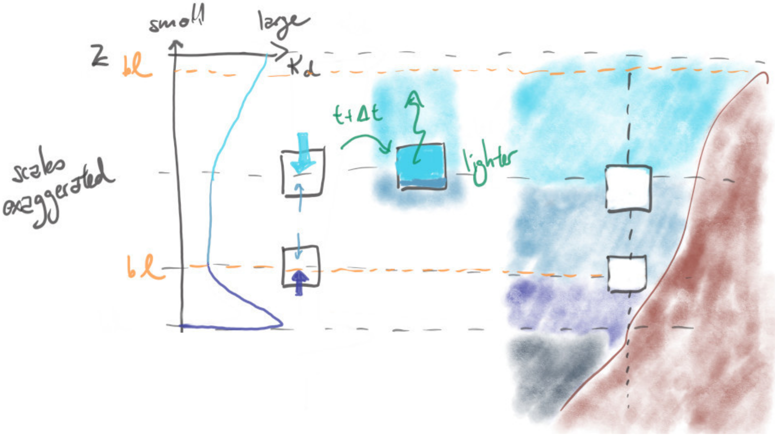
Deep/abyssal water upwelling: schematic



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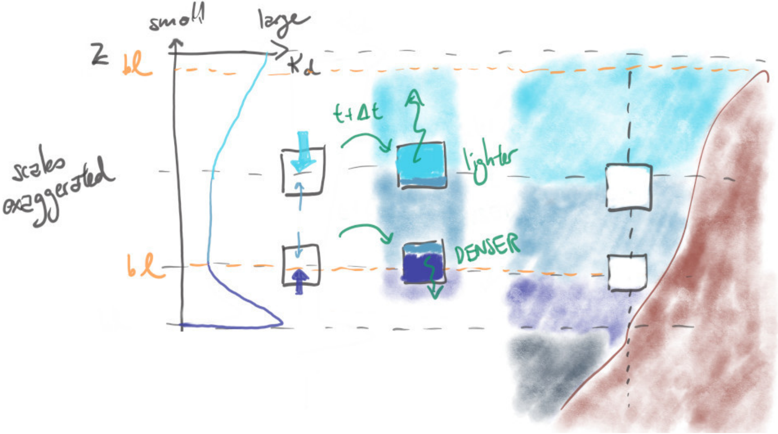
Deep/abyssal water upwelling: schematic



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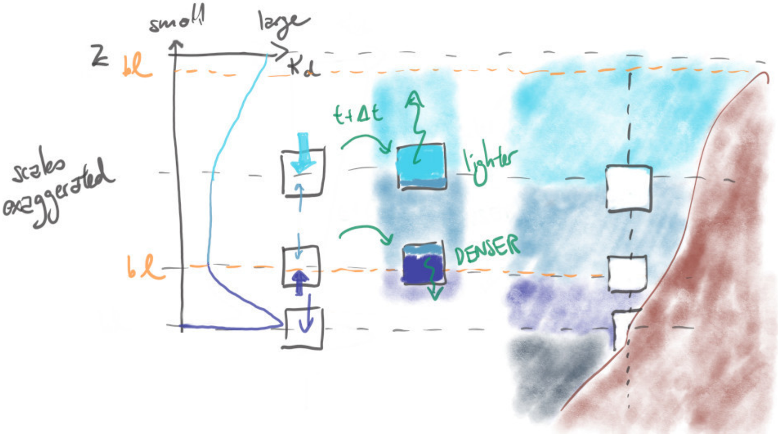
Deep/abyssal water upwelling: schematic



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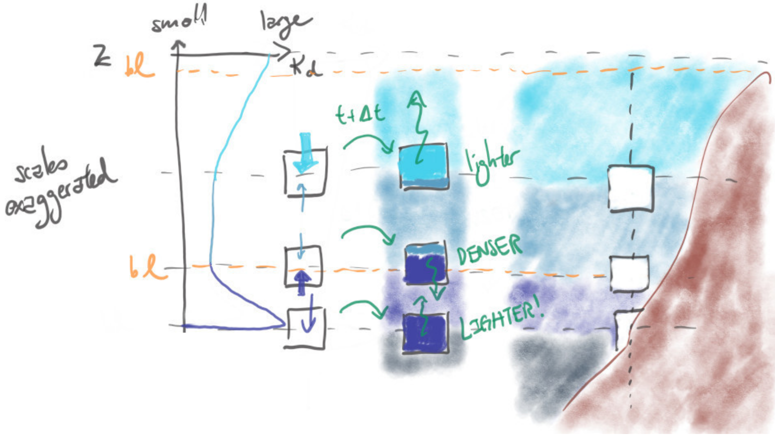
Deep/abyssal water upwelling: schematic



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Deep/abyssal water upwelling: schematic

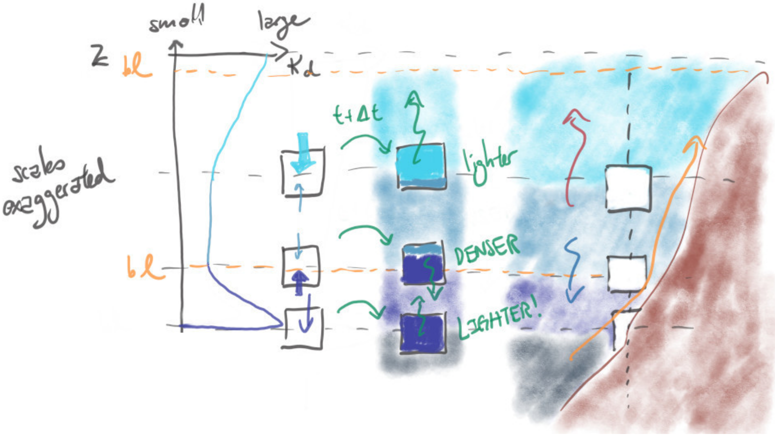

Figure: Schematic of the diffusive upwelling.

More updated view

- upwelling of **abyssal** waters preferentially over bottom boundary layers
  $\rightarrow$ depends on $\partial\kappa_d/\partial z$ and sea floor geometry

(e.g. Ferrari *et al.*, 2016, *J. Phys. Oceanogr.*; de Lavergne *et al.*, 2016*a*, *b*, *J. Phys. Oceanogr.*)

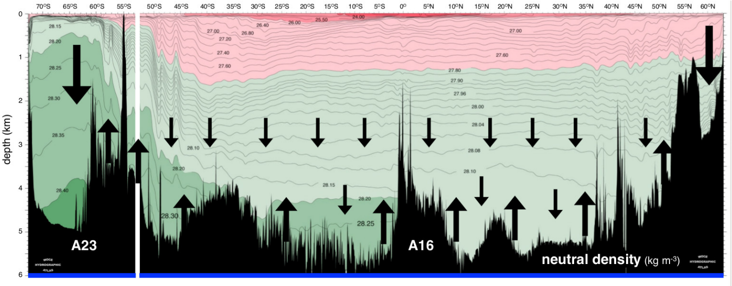

Figure: Schematic of the boundary intensified picture. Modified from WOCE diagrams.

More updated view

- observational evidence for the boundary intensified picture through radiocarbon Δ^{14}C content

  $\rightarrow$ proxy (see e.g. OCES 4001) for **water age** since the ^{14}C isotope is radioactive with known half-life (e.g. OCES 2002)

  $\rightarrow$ isolated in interior with no renewal

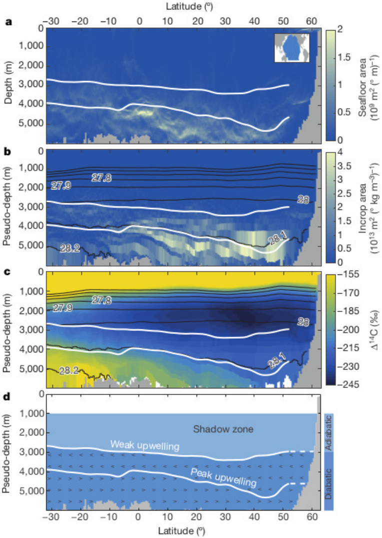

Figure: Observational evidence for shadow zones and boundary intensified upwelling. Taken from de Lavergne *et al.* (2017), *Nature* (their Fig. 3).

Summary

- MOC important for global climate

  $\rightarrow$ e.g. energy transport, atmosphere-ocean coupling, biogeochemistry, carbon storage...
- **conveyor belt** picture useful for intuition can be misleading

  $\rightarrow$ MOC is probably the most "accurate" term (deliberately vague?)

  $\rightarrow$ includes gyre + WBCs, ACC, up/downwelling etc.
- water origin can be identified through tracer properties

  $\rightarrow$ $S, T, \sigma, \gamma^n, [^{16}\mathrm{O}], \Delta^{14}\mathrm{C}, \ldots$

  $\rightarrow$ assumes mixing is weak ($\kappa_d \ll 1$)
- downwelling + upwelling via diapycnal transport

  $\rightarrow$ isolated locations for deep/abyssal water formation

  $\rightarrow$ boundary intensified upwelling

Summary

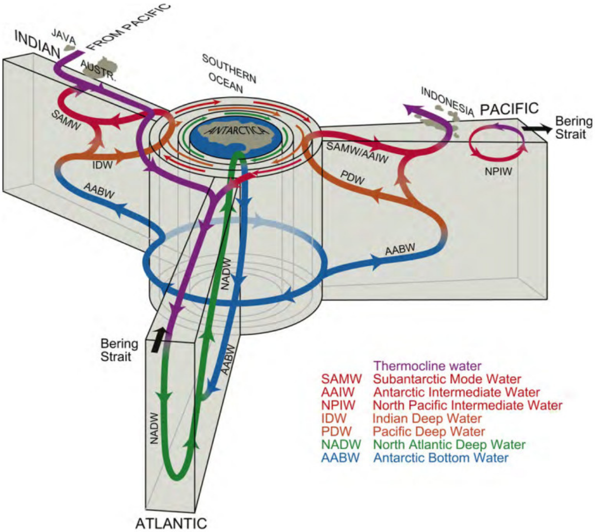

Figure: Schematic of the 3d MOC with watermass distributions. From Talley *et al.* (2011), *Descriptive Physical Oceanography*; see more in their Fig. 14.11. Format after Arnold Gordon (1991).

Summary

- again, theory is continually challenged and updated
  $\rightarrow$ ~~broad diffusive~~ boundary intensified upwelling
- ongoing areas of research:
  $\rightarrow$ how does it change?
  $\rightarrow$ what controls the MOC?
  $\rightarrow$ Southern Ocean control?
  $\rightarrow$ how to model changes?
  $\rightarrow$ parameterisation of small-scale processes?
  $\rightarrow$ ...

large-scale $\Rightarrow$ **small-scales** (e.g. instabilities) see Lec. 15-18

<u>**BUT**</u> **small-scale** $\Rightarrow$ **large-scales!** (eddy/wave-mean interaction)