A three-dimensional theory for the descending branch of the AMOC:

idealized solutions with buoyancy forcing and winds

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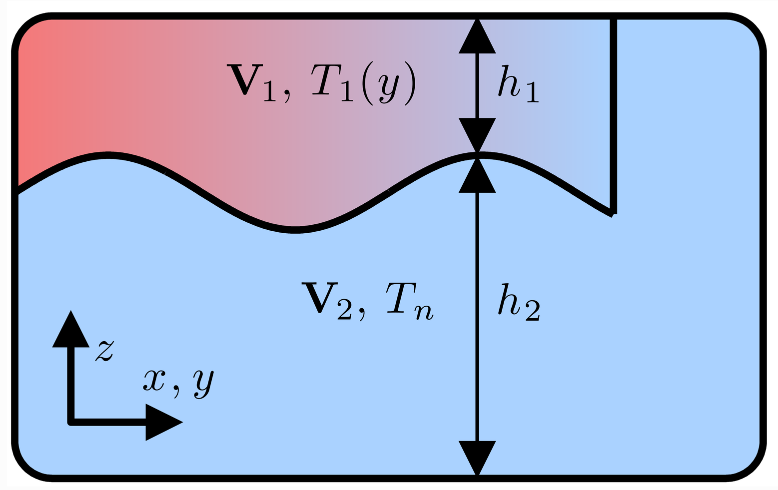
(I) Overview

To develop a three-dimensional theory for the Atlantic meridional overturning circulation (AMOC), we derive and analyze analytical solutions to a variable-density layer model (VLOM), and compare them to solutions to an ocean general circulation model (MITgcm). Here, we present solutions with zonal winds and buoyancy forcing and discuss how **the strength and structure of the descending branch is related to the tropical thermocline depth H, the large-scale meridional surface density gradient, the wind-driven gyre circulation and mixing processes**. Our results provide a novel perspective on how large-scale mass convergence is generated in response to buoyancy forcing and winds.

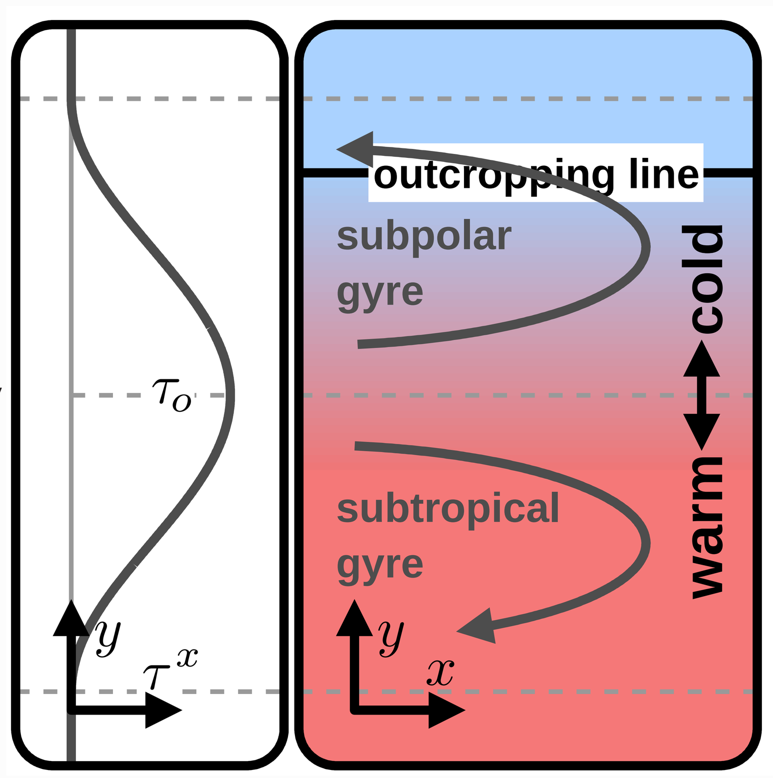
(II) The variable-density layer model (VLOM)

- Temperature (density) varies meridionally in the upper layer.
- Linear density equation; no consideration of salinity.
- Geostrophic flow plus Ekman transports in the interior ocean.
- A frictional western boundary layer.
- The layer interface outcrops at the latitude where the surface temperature becomes equal to the deep-layer temperature, and VLOM reduces to a 1-layer system to the north.
- A "mixed-layer" entrainment velocity maintains a minimum upper-layer thickness in regions where the surface temperature is warmer than the deep-layer temperature (Region B in Box *IV*).
- Mixing processes generate detrainment by raising the layer interface when it is deeper than a prescribed "mixing depth" [1].



(III) Forcing and model domain

- The model is forced by a westerly wind stress (left panel) that drives a subpolar and a subtropical gyre (right panel).
- The surface temperature is prescribed (right panel, shading) and the ocean is homogeneous to the north of the outcropping line; advection is balanced by a surface heat flux.
- The closed ocean basin is 40° wide and extends from the Equator to 60°N.
- The tropical thermocline depth H is prescribed in a sponge layer near the southern boundary of the domain.



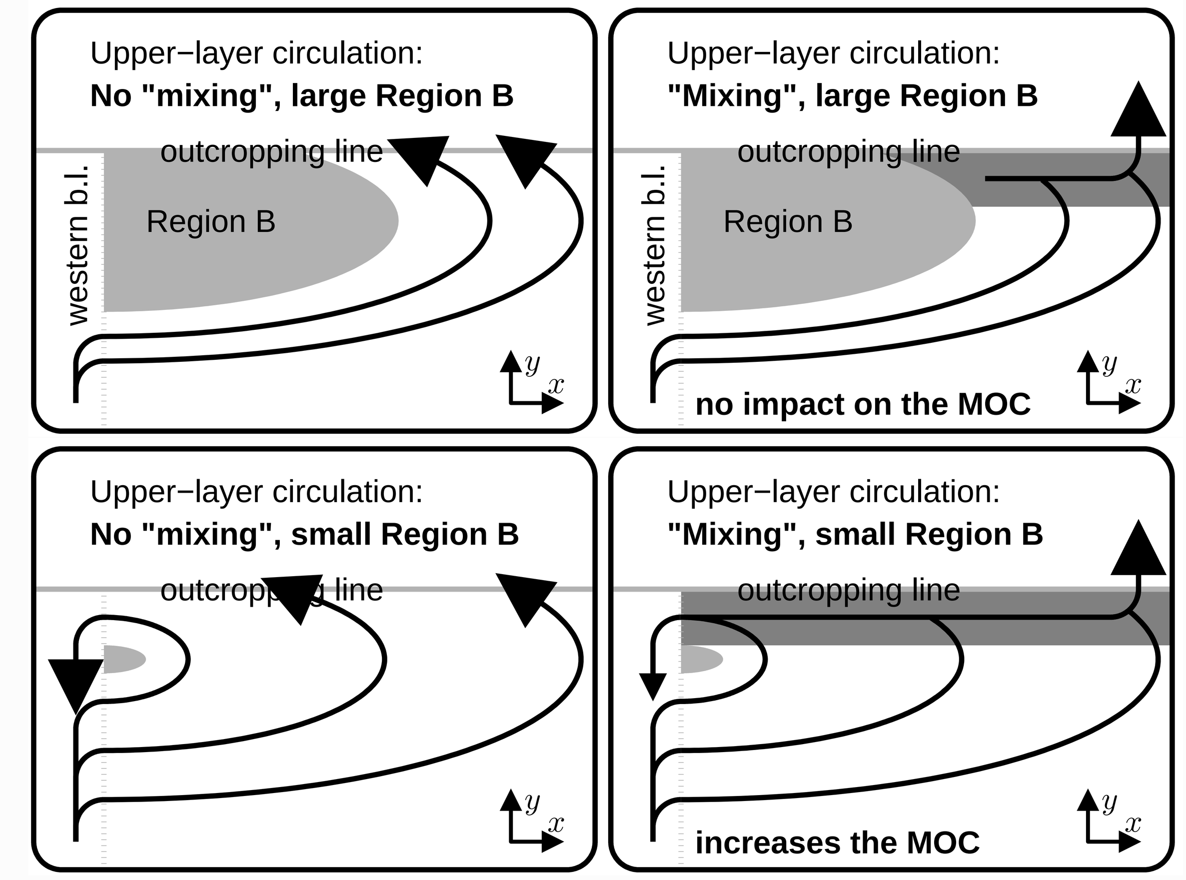
(IV) Thermocline depth and circulation

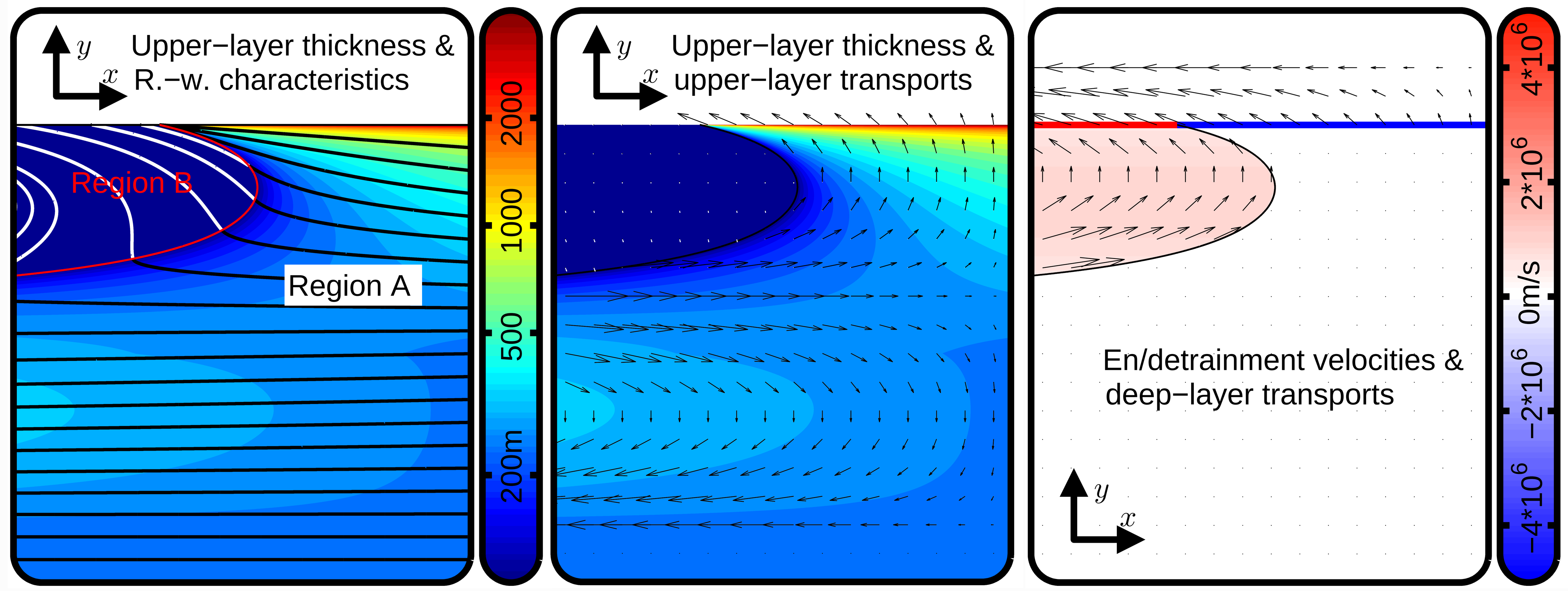
Solution without mixing:

The eastern-boundary layer thickness is derived from a "no-flow" condition normal to the wall. As a result, the upper layer thickens poleward in response to the surface density gradient. Then, the interior-ocean layer thickness is derived by integration along Rossby wave characteristics (left panel, Region A). When the upper-layer thickness approaches zero in the center of the subpolar gyre, a "mixed-layer" entrainment velocity maintains a minimum upper-layer thickness and balances the Ekman pumping (right panel, Region B). The upper-layer transport is equal to the Sverdrup transport in Region A, and is small in the outcropping region (Region B). The deep layer is at rest, except for the interior outcropping region and to the north of the outcropping line, where the upper layer vanishes (right panel). Water detrains by flowing across the northern outcropping line to the east of the interior outcropping region. Subpolar-ocean upwelling occurs in Region B (right panel) and in the western boundary layer; the MOC is closed in the sponge layer near the southern boundary (not shown).

The effect of mixing:

[1] show that mixing processes in OGCM solutions without wind forcing thin the upper layer in a boundary layer along the northern outcropping line, where the upper-layer is extremely thick, and thereby maintain a northeastward, converging upper-layer flow. These processes are included in VLOM in form of a detrainment velocity in a northern boundary layer.

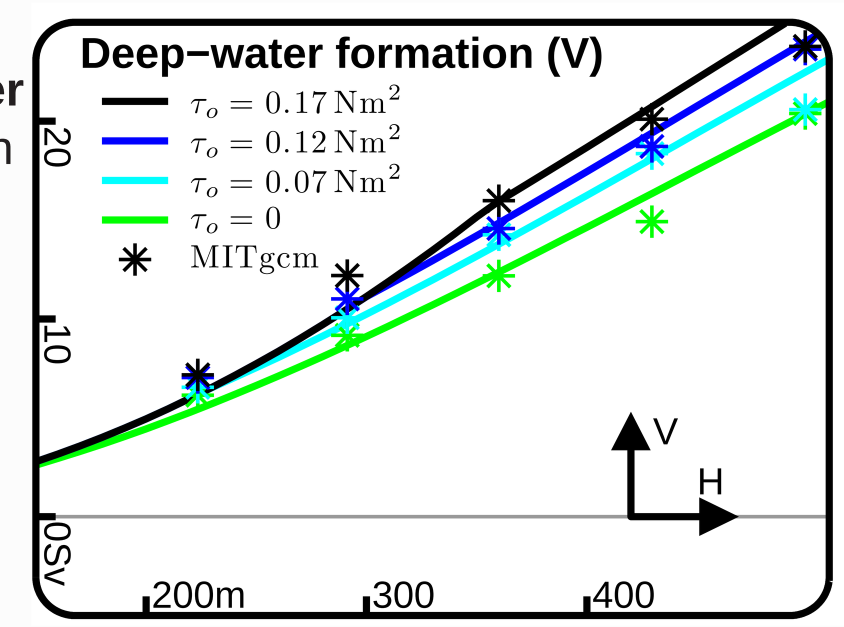


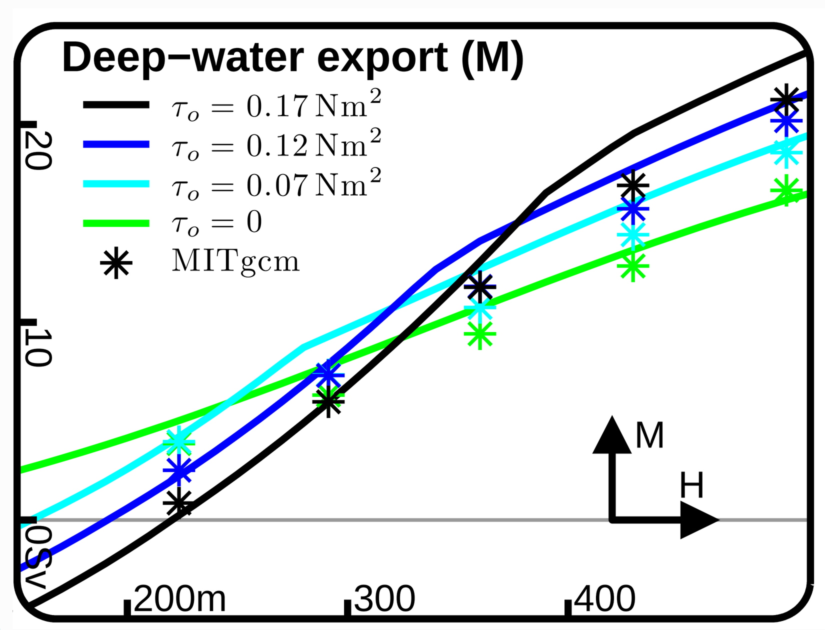


The schematics above illustrate, how such a northern boundary layer (dark shading in the right panels) affects the upper-layer circulation with winds. When Region B intersects the northern outcropping line (upper panels), the detrainment across the northern outcropping line is equal to the Sverdrup flow to the east of the interior outcropping line. Mixing processes modify the structure of the flow locally, but do not impact the large-scale MOC (upper-right panel). When Region B does not intersect the northern outcropping line (lower panels), the northern boundary layer extends to the western boundary layer, weakens the recirculation in the western boundary current, and hence strengthens the MOC (lower-right panel).

(V) Strength of the MOC

- In case of a shallow tropical thermocline H (large Region B, see Box *IV*), the **deep-water formation** rate is independent of the strength of the winds τ_o and mixing in the northern boundary layer; for larger H, it depends on mixing processes and is proportional to τ_o.
- The **deep-water export** is given by the formation rate minus upwelling in the subpolar ocean.
- When H is small and Region B is large (see Box *IV*), subpolar-ocean upwelling is strong and proportional to τ_o; consequently the deep-water export is inversely proportional to τ_o.
- The subpolar-ocean upwelling is weak when H is large, and the deep-water export is proportional to its formation rate and τ_o.





(VI) Conclusions

- A simple model (VLOM) reproduces the thermocline depth and many features of the three-dimensional circulation in ocean general circulation models.
- We have developed an analytical theory for the descending branch of the AMOC, which recovers previous scaling laws, and relates the overturning transport to the thermocline depth, surface densities, Rossby-wave damping and zonal wind forcing.
- The deep-water export from the subpolar gyre is inversely proportional to the strength of the wind forcing when upwelling is strong in the subpolar ocean, and proportional to the winds in case of weak upwelling.
- The deep-water formation rate is proportional to the strength of the wind forcing τ_o when Region B intersects the northern outcropping line, and independent of τ_o when it does not.

(VII) Notes

[1] F. Schloesser, R. Furue, J. McCreary and A. Timmermann, 2011. Dynamics of the Atlantic meridional overturning circulation. Part 1: Buoyancy forced response. *Progress in Oceanography, Submitted*.

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