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Four-layer Ocean Model

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Background

- Ocean circulations carry significant amounts of heat and carbon and play a crucial part in controlling the Earth's climate.
- Much of the complexity is attributed to energetic motions such as gyres, currents and eddies. The inclusion of these smaller-scale phenomena would inevitably require more advanced numerical simulations.
- Circulations are much larger in spatial scale and their existence is indicated by both fluid dynamics and hydrographical observations.
- Existence of water masses stratify the ocean into several layers.
- It is therefore noteworthy to study whether a simpler model can be used to describe these circulations without involving complicated dynamics.

Research Objectives

- Investigate the interactions between large-scale transport and their counterparts in smaller processes.
- Explore the effectiveness of layered models in large-scale circulations their ability in predicting ocean currents

Theory

Geostrophic Current

Steady horizontal flows on Earth(large-scale ocean currents and wind) is generally governed by the geostrophic approximation. It represents a balance between the horizontal pressure gradient and Coriolis forces:

$$\frac{1}{\rho}\frac{\partial p}{\partial x} = fv \qquad \frac{1}{\rho}\frac{\partial p}{\partial y} = -fu$$

The velocity, however, varies with depth due to the uneven distribution of density. For a stratified ocean, the anologue to "thermal wind" could be approximated as:

$$f\Delta_n u \approx -\gamma_n \frac{\partial H_n}{\partial y}$$

$$f\Delta_n v \approx \gamma_n \frac{\partial H_n}{\partial x}$$

where γ_n is the reduced gravity in the nth layer and H_n is the depth of the nth interface.
For the purpose of stratification, these interfaces are ideally surfaces of constant buoyancy.

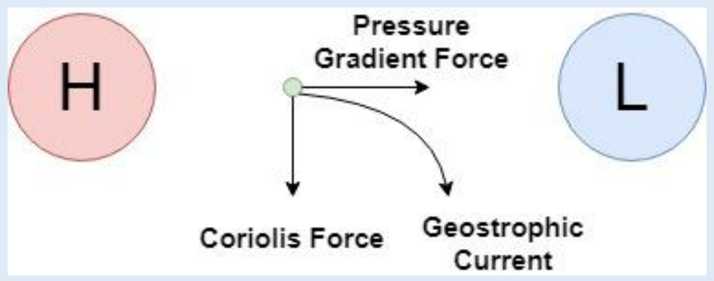

Fig.1: Illustrate of geostrophic balance. The approximation works well for steady-state currents away from boundaries, such that frictional forces are less significant.

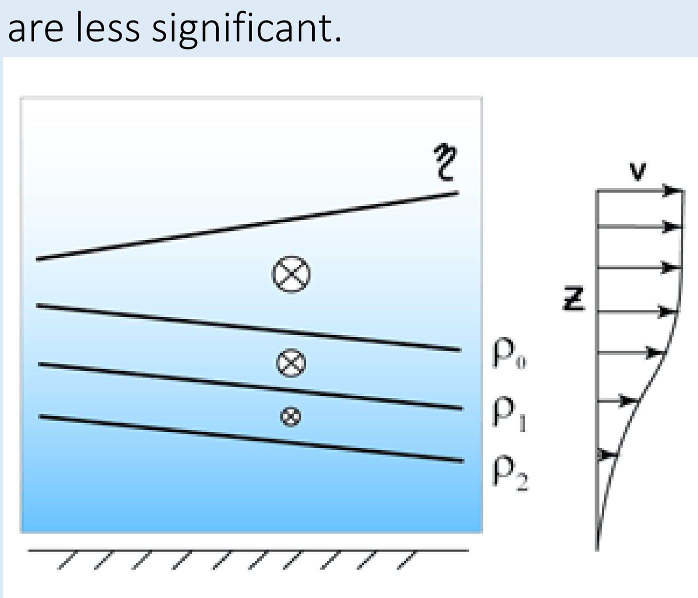

Fig.2: "Thermal wind" effect in the ocean.[1] Geostrophic velocity usually decreases with depth as horizontal pressure in deep ocean is generally lower.

Methodology

In this research, we constructed a four-layer model of the ocean with the following steps:

- Defining interfaces using σ_2 (density anomaly with a reference pressure of 2000 dbar) isopycnals to match the regions of cells(NADW, AABW).
- Computing the mean in-situ density of each resulting layer with the use of geometrical weighting.
- Applying numerical differentiation to compute the velocity. differences between each layer from the "thermal wind" relation.
- Formulating the key equations from the conservation of mass and potential vorticity.
- Solving the key equations in two classic scenarios:

  1. No cross-layer interaction (laminar)

  2. Diapycnal transport allowed through small scale motions, but with a stationary deep water (turbulent).

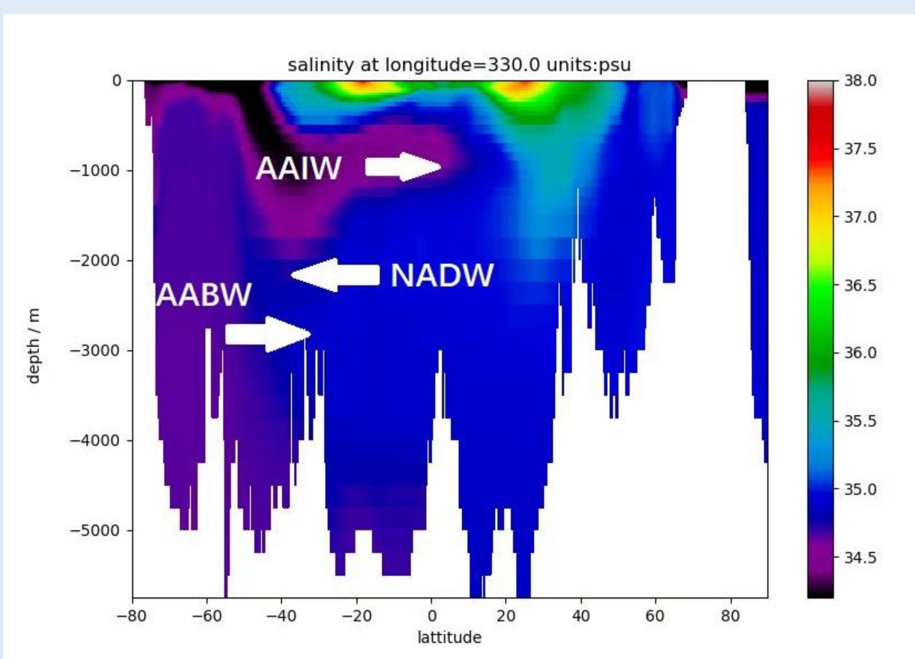

Fig. 3: Salinity profile at 330 degrees longitude. Major currents are indicated by arrows.

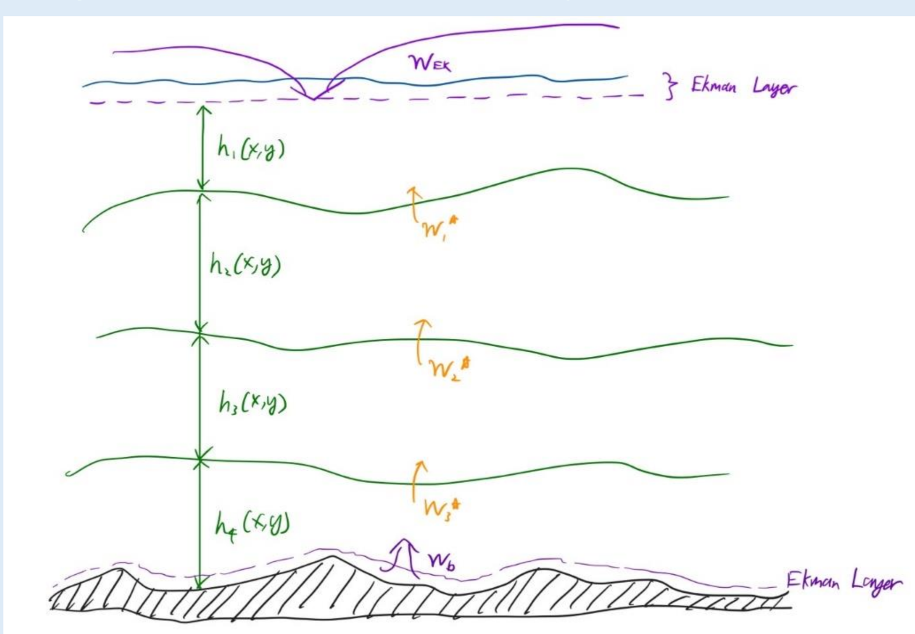

Fig. 4: Schematic diagram for the 4-layer model. Diapycnal transport is labelled by w_n* , with the uppermost layer contact with the air and experiences wind-driven Ekman Pumping.

Result

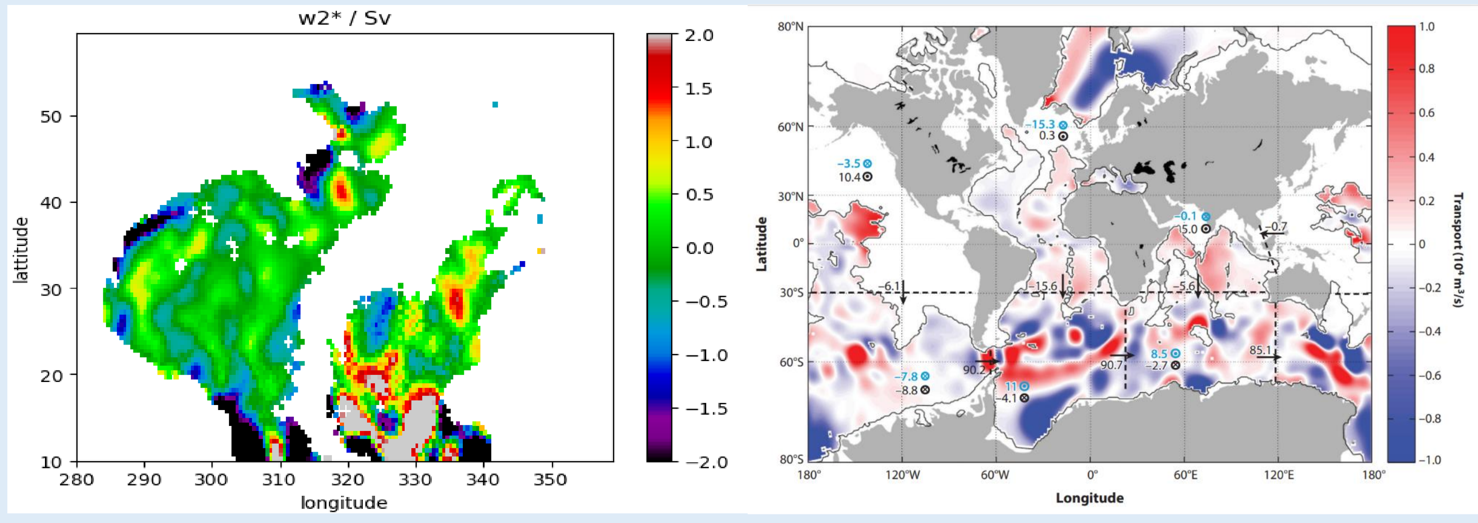

Fig. 5(a): Computed diapycnal transport across the σ_2 =36.9 interface in the North Atlantic. The missing region is due to the intersection of isopycnals with the seafloor. **(b)** Diapycnal transport across the σ2 =37.0 interface from Cessi et. Al(2019).[2]. Both isopycnals refer to a similar interface as different hydrography is used.

- The turbulent model provides a qualitative reflection of diapycnal transport with significantly larger values. It agrees with Luyten et.al. (1985)[3] to the same order of magnitude. However, results of this model differ from Cessi et.al.(2019)[2] despite the resemblance of pattern in some regions.

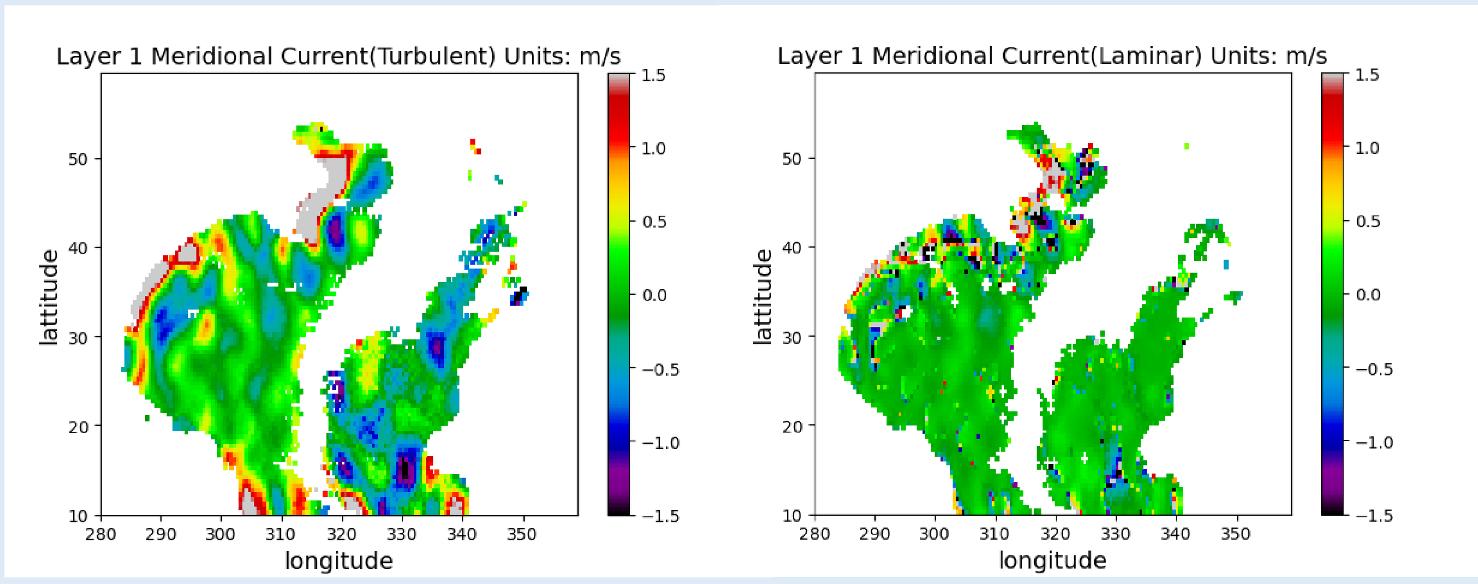

Fig. 6: Layer 1 meridional current in the North Atlantic predicted by both models.

- The laminar model predicts the North Atlantic currents more accurately. However, it is sensitive to bathymetry and overestimates the abyssal flows.

Conclusion

- Assuming that small scale motions are key to the circulation may not be realistic.
- Layer of no motion assumption is not applicable, especially in regions where strong currents exist.
- Both models work qualitatively. The turbulent model can predict the pattern of diapycnal mass transports, and the laminar model provides more reasonable current velocities values where there is no intense up/downwelling.
- Direct comparison with other study is difficult because of the difference in the hydrography of datasets.

Further Work

- Computational error control using natural units.
- Comparing current velocities between the two models as well as measurements.
- Testing the effectiveness of including more layers.
- Different physical constraints can be applied to the four-layer model.
- Code structure can be modularized to allow usage of other datasets.

References

[1]"OC2910: Physical Oceanography Basic Concepts", *Oc.nps.edu*, 2022. [Online]. Available: https://www.oc.nps.edu/nom/day1/partd.html. [Accessed: 02- Mar- 2022].
[2]P. Cessi, "The Global Overturning Circulation", *Annual Review of Marine Science*, vol. 11, no. 1, pp. 249-270, 2019. Available: 10.1146/annurev-marine-010318-095241.
[3]J. Luyten, H. Stommel and C. Wunsch, "A Diagnostic Study of the Northern Atlantic Subpolar Gyre", *Journal of Physical Oceanography*, vol. 15, no. 10, pp. 1344-1348, 1985. Available: 10.1175/1520-0485(1985)015<1344:adsotn>2.0.co;2.