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A Natural Convection Perspective on the Atlantic Meridional Overturning Circulation

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1. INTRODUCTION

The global meridional overturning circulation of the ocean is one of the Earth's largest natural convection systems, often conceptualized as a slow-moving "conveyor belt" that connects the major ocean basins. This basin scale overturing circulation redistributes heat, salt, and carbon on a global scale, thereby exerting a strong influence on climate and biogeochemical cycles [1]. Circulation combines a wide range of scales, from overturning cells and gyres spanning several thousand kilometers to boundary layers of a few meters, down to small-scale convection and turbulence, which form the fundamental building blocks of the circulation. Thus, understanding the convection mechanisms is critically important, yet many of the underlying physical processes remain poorly understood [2]. One challenge is that large-scale ocean models cannot directly resolve the fine-scale turbulent mixing and convection; instead, they rely on parameterized representations that can introduce systematic biases and reduce predictive skill in a changing climate.

Ocean circulation has long been studied through conventional numerical models, particularly those focused on the Atlantic Ocean, where large-scale overturning and gyre dynamics dominate [3]. Recent improvements in computational capacity now permit eddy-resolving simulations [4] that capture the influence of small-scale turbulence on global circulation. In parallel, laboratory analogues and direct numerical simulations [5, 6] guided by dynamical similarity principles are increasingly being used to explore these processes under controlled, yet physically realistic, conditions. Here, we extend this approach by developing the first direct numerical simulation framework capable of modelling hemisphere-scale overturning circulation in an idealized Atlantic Ocean. In this study, we examine the overturning circulation from a natural convection perspective by using state of the art direct numerical simulations.

2. APPROACH

We consider an idealized Atlantic Ocean basin with a prescribed meridional temperature profile imposed along the top boundary. This Dirichlet thermal boundary condition mimics the global sea surface temperature variation from the north pole to south pole which drives a horizontal convection current within the fluid domain. An open channel with periodic boundary conditions was incorporated near the southern boundary to represent the Southern Ocean's circumpolar pathway.

We solve the incompressible Navier–Stokes equations under the Boussinesq approximation, incorporating the Coriolis acceleration as a body force together with the thermal energy transport equation. We allow the flow to reach a thermodynamically equilibrated state when the net heat flux into and out of the top boundary of the domain becomes balanced, and the mean temperature within the domain shows no further drift.

3. RESULTS

The resulting instantaneous flow field successfully reproduces key dynamical features of the global ocean circulation, including the western boundary current, the North Atlantic Current, and the Antarc-

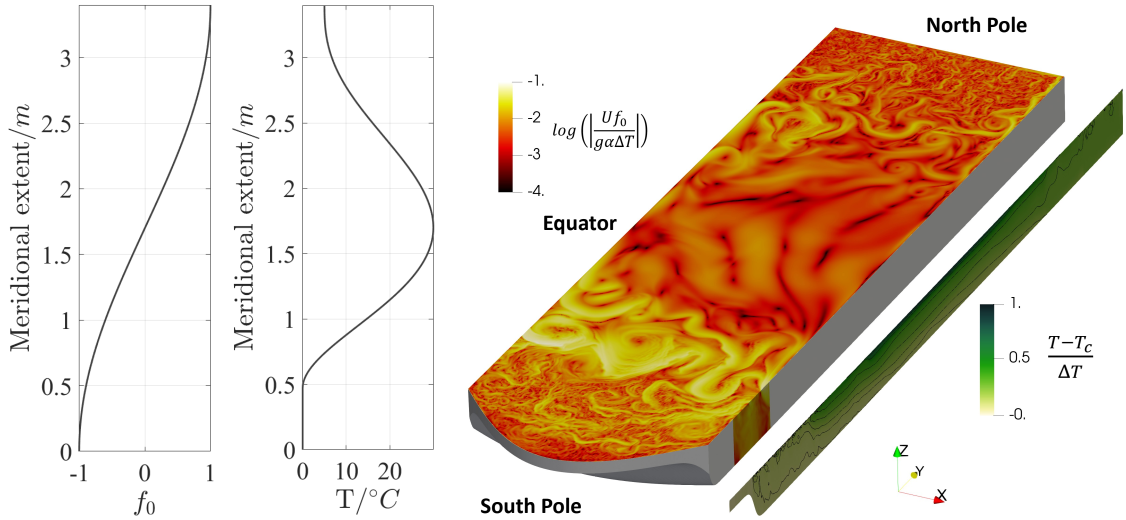

Figure 1. (a) The maximum Coriolis parameter, f_0, as a function of meridional extent, y, where, Coriolis acceleration $f = f_0 \cos(\pi y/L)$. (b) Imposed temperature, T, at the top boundary. (c) Resulting instantaneous flow field consists of western boundary current, North Atlantic current and Antarctic Circumpolar Current, mesoscale eddies and small-scale turbulence is shown by contours of normalized velocity magnitude in top plane. Vertical plane shows the normalized temperature at mid zonal width. Here, α, g, ΔT, and T_c are thermal expansion coefficient, gravity, characteristic temperature difference and the imposed minimum temperature, respectively.

tic Circumpolar Current, as well as the emergence of mesoscale eddies and small-scale turbulent structures, as illustrated in Figure 1. The model also captures additional dynamical processes such as the equatorward transport of Antarctic Bottom Water, and localized regions of boundary upwelling and downwelling, which contribute to the establishment of a realistic vertical density stratification that closely resembles the real ocean.

The time-averaged flow field reveals the large-scale structure of the meridional overturning circulation, characterized by two distinct overturning cells, one in each hemisphere. In the Southern Hemisphere, the Antarctic-origin cell extends from the surface to the ocean bottom. These circulation patterns demonstrate the model's ability to capture both the global-scale overturning and the small-scale dynamics that underpin natural convection in the ocean.

4. CONCLUSIONS

We demonstrate that convection resolving DNS setup, governed solely by temperature-driven density variations, can sustain a meridional overturning circulation in the absence of wind forcing. The setup also captures realistic density structures along with key ocean boundary currents and basin scale gyres.

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