

Drivers of Southern Ocean as Revealed by Convection-Resolving Direct Numerical Simulations

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1. INTRODUCTION

The Southern Ocean occupies a unique position on the planet, a vast encircling conduit where waters from all major ocean basins converge through an intricate web of currents. This singular setting makes it the beating heart of the global ocean, mediating the exchange of heat, carbon and momentum between the atmosphere and the ocean interior. Although it spans barely a third of the global ocean's surface, it has absorbed over 90% of the excess heat accumulated since the 1970s and accounts for more than 40% of the global oceanic uptake of carbon dioxide. In terms of climate, this region plays a chief and regulating role in Earth's response to ongoing global warming [1].

The dynamics of the Southern Ocean encompasses a range of scales of interconnected systems, from the larger-scaled Antarctic Circumpolar Current, Slope Current, Subpolar Gyres and Antarctic Bottom Water formation to the finer-scale processes of convection and turbulence. However, the exact nature of the interactions between these systems and how they evolve under climate change remains unexplored. This is primarily owing to limitations existing in the current conventional methods of numerical oceanography. Most ocean models, even those derived from the Navier-Stokes framework, rely primarily on hydrostatic approximations that do not resolve the very scales where turbulence and convection thrive. The parameterizations employed there suffice for capturing the broader scales of ocean circulation but miss the small, energetic motions that often drive it [2].

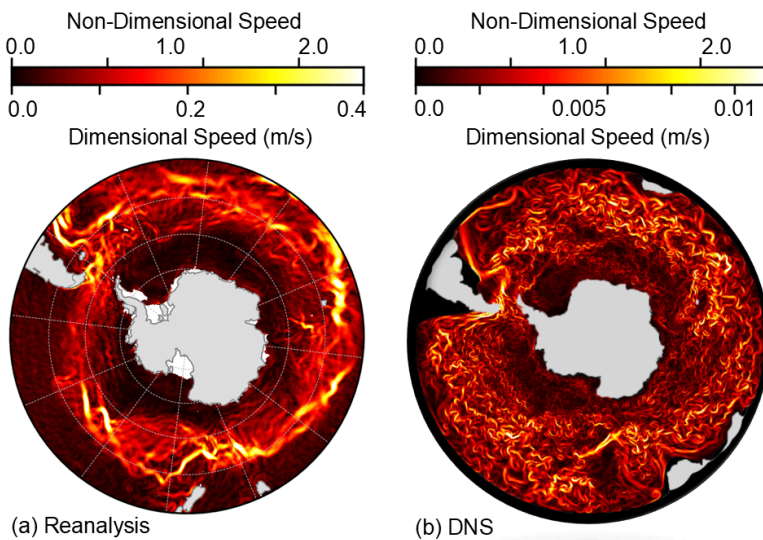


Figure 1. Flow velocity fields compared between DNS and Reanalysis, both are non-dimensionalized by geostrophic scaling.

In this study, we bridge that gap through high-fidelity Direct Numerical Simulations (DNS) performed under a fully non-hydrostatic framework. By directly solving the incompressible Navier-Stokes equations under the Boussinesq approximation, DNS resolves all dynamically active scales of the system, from basin-scale flows to the finest Kolmogorov-scales, allowing us to capture the whole picture of the physics of motion in the Southern Ocean.

2. METHODS

Nek5000, a highly scaled spectral-element Navier-Stokes solver, is utilized as the core framework for the DNS [3]. The simulations are carried out in a domain that represents the subpolar Southern Ocean in semi-realistic form, capturing the essential bathymetry and geometry of the Antarctic coastline. The flow is driven by a Coriolis term that accounts for planetary rotation, while the surface is forced with a meridionally asymmetric, zonally varying density field constructed to resemble the observed sea surface density. The simulations are also carried out with multiple magnitudes of surface wind stress fields, enabling the comparative study of the relevance of surface wind in Southern Ocean circulation. The resulting flow fields are then interpreted through the principle of dynamic scale similarity, which links the simulated system to the real ocean by matching key non-dimensional parameters and preserving the dynamical equivalence (e.g. [4]).

3. RESULTS

Resolving convection enables the transport of mass both vertically and horizontally. In this density-forced pan-Antarctic DNS, this triggers a cascade of physical processes that collectively give rise to the major oceanographic features of the subpolar Southern hemisphere. Beyond the emergence of geostrophic currents, the simulations reveal convective activity along the Antarctic margins where the masses of waters are transported into the abyss at locations similar to previous studies [5]. This forms Antarctic Bottom Water, the densest water mass in the global ocean, which then contributes to the lower limb of the Meridional Overturning Circulation. This process complements the branching of the warmer Circumpolar Deep Water from the Antarctic Circumpolar Current, forming cyclonic circulations, or gyres, within Weddell, Ross and Kerguelen basins. These simulated gyres closely mirror their observed counterparts [6]. Surface winds, although not required to form the gyres, act to make the systems more energetic. Analyzing the various terms of the vorticity budget within the gyre system across different wind forcings reveal the relative importance of Bottom Pressure Torque and how it shifts from being a vorticity source to a sink for the gyres when the surface winds are gradually amplified.

4. CONCLUSIONS

The preliminary results and analyses aim to advance the comprehensive understanding of the relative roles of wind and buoyancy forcings in shaping the Southern Ocean circulation by resolving all scales of motions, primarily convection. When integrated with existing observations and ocean models, these efforts have the potential to refine our understanding of the subpolar Southern hemispheric oceanography and its influence on the global climate system.

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