13th Australasian Natural Convection Workshop (13ANCW)
Canberra, Australia, 1st and 2nd December 2025

The Influence of Convection and Rotation on Downslope Flow over a Continental Shelf

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1. Introduction

On the Antarctic margins, buoyancy losses at the sea surface generate dense water convective plumes that descend and subsequently leave the shelf break, flowing over the continental slope. As the water flows along the slope, it is influenced by a combination of gravitational and Coriolis forces, leading to the geostrophic adjustment, formation of boundary layers, baroclinic eddies, and other dynamical features. The downward flow of dense water masses gradually mixes at various depths and eventually reaches the abyss, forming Antarctic Bottom Water, which contributes to the ocean's meridional overturning circulation. When wind blows over the continental sea surface, it can affect the uptake of surface buoyancy and transfer momentum to the ocean. The combination of wind stress and rotational effects creates Ekman transport, which drives surface waters toward the continent, impacting water mass properties. The combined effects of flow dynamics around Antarctica significantly influence the transport of heat, nutrients, and dissolved gases across the shelf and into deeper ocean layers [1]. However, current numerical ocean models are relatively coarse and rely on parameterization of convection, meaning that these models often fail to capture small-scale turbulence mechanisms. Observations of these ocean processes are highly valuable, however, they are limited in resolution by the difficulty in taking measurements in extreme Antarctic environments. These limitations motivate the need for high-resolution studies to better understand this complex system. Therefore, this study investigates how convection and Earth's rotation modify flow patterns and the overall stability of the slope current system using high-resolution techniques.

2.Approach

This study utilizes the computational fluid dynamics solver employing the Boussinesq approximation. The model setup, as illustrated in Figure 1(a), includes a sloping bottom boundary designed to replicate the Antarctic continental slope. Buoyancy forcing is applied as a Dirichlet condition over the top surface of the domain, with buoyancy gain occurring away from the continent (northern region) and buoyancy loss on the continental shelf (southern region). A constant Coriolis parameter is integrated into the model to account for rotational effects. The top surface is subjected to a free-slip velocity condition, while the bottom topography and the northern and southern boundaries are treated as no-slip boundaries. To maintain continuity, the along-slope boundaries (front and back) are treated with periodic boundary conditions. The simulations are performed as a Large Eddy Simulation. The continuity, momentum, and temperature equations used in this setup are:

$$\nabla \cdot \mathbf{u} = 0 \tag{1}$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u} = -\frac{1}{\rho}\nabla p + \nu\nabla^2\mathbf{u} + \nabla\cdot\tau^{sgs} - f\,\hat{z}\times\mathbf{u} + g\,\mathbf{k} \tag{2}$$

$$\frac{\partial T}{\partial t} + \mathbf{u}\cdot\nabla T = \kappa\nabla^2 T + \nabla\cdot(\kappa_{sgs}\nabla T) \tag{3}$$

3.Results

Convective plumes, generated over the shallow continental region, initiate a downslope flow of dense water, as illustrated in Figure 1(a). However, under the influence of rotation, this flow undergoes geostrophic adjustment, wherein the horizontal pressure gradient is balanced by the Coriolis force. The pressure gradient in the x-direction is significantly amplified due to density variations. This amplification results in a surface-intensified flow in the positive z-direction away from the slope and a velocity component in the negative z-direction over the slope, as illustrated in Figure 1(b). Conversely, the pressure gradient in the z-direction is comparatively small, leading to weaker flow in the x-direction, except within the bottom Ekman boundary layer. The normalized turbulent kinetic energy field, presented in Figure 1(c), highlights the presence of large-scale baroclinic eddies within the system, indicating turbulent and complex flow structures.

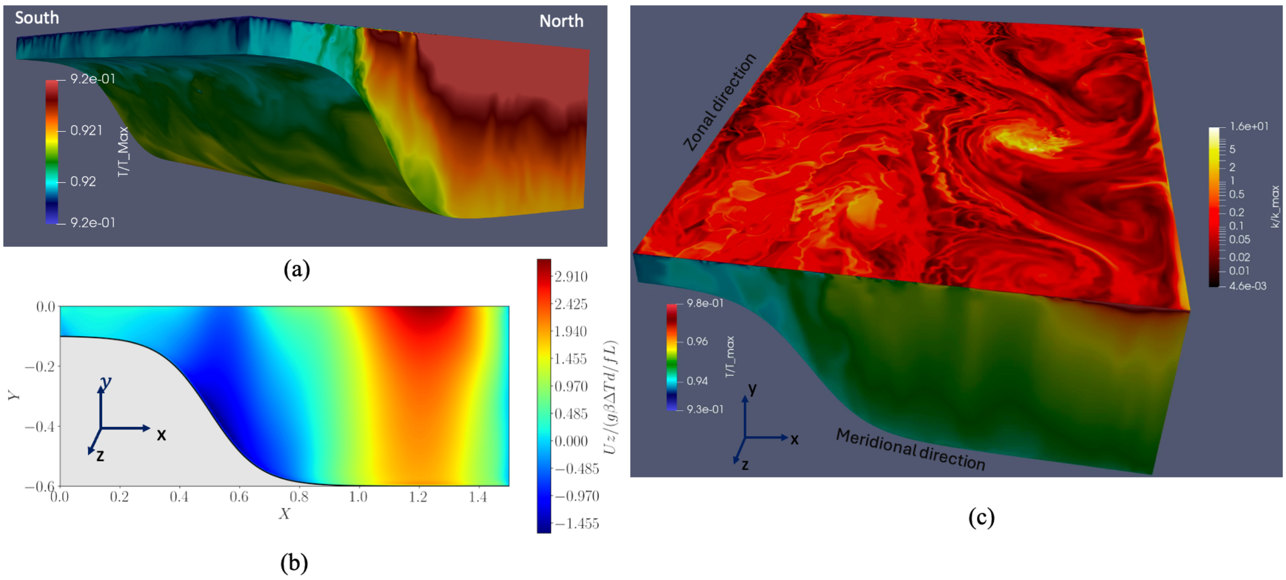

Figure 1. Downslope flow along the Antarctic continental shelf modeled using LES. (a) The side view of the flow domain shows the buoyancy field, where red indicates more buoyant water and blue indicates denser water. Convection plumes form near the surface and feed into a downslope flow that propagates off the shelf. Also shown are (b) the bottom-intensified current (blue) and the surface-intensified current (red), and (c) the normalized kinetic energy field highlighting the presence of large eddies.

4.Conclusions

This study demonstrates the significance of geostrophic adjustment, highlighting the balance between Coriolis forces and pressure gradients. Our findings on dense flow and the slope current system enhance our understanding of ocean dynamics in the Antarctic margin. Future research will integrate wind stress over the surface into our model to better understand the flow dynamics of the slope current system in the presence of wind.

Acknowledgments

We gratefully acknowledge the computational resources provided by the National Computational Infrastructure NCI-Gadi for conducting my simulations.

REFERENCES

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