Towards Realistically Modelling Southern Ocean Convection

Ph.D. project summary
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1 Project outline

1.1 Oceanic climate change

The ocean is responsible for absorbing the large majority of excess heat in the climate system—91%—with the remainder being divided between land, the cryosphere, and the atmosphere (Lee et al., 2023). The Southern Ocean plays a central role in this process, serving as the gateway for roughly 75% of the global ocean's anthropogenic heat uptake (Frölicher et al., 2015) and 40% of its anthropogenic CO_2 uptake (Frölicher et al., 2015; Gruber et al., 2019). The Southern Ocean thus significantly slows the increase of the global surface air temperature, which during January–September 2024 exceeded 1.5°C above pre-industrial levels (World Meterological Organization, 2024).

The consequences of oceanic climate change are manifesting diversely and will directly or indirectly impact all people on Earth, although it is poor and marginalised communities who are most vulnerable (Pörtner et al., 2019). Around Antarctica, the minimum sea ice extent during the austral summer of 2023 serves as a portent of this change, setting a new record approximately 36% lower than climatological values, driven most likely by ocean warming (Purich & Doddridge, 2023). Ocean warming is also the main process controlling the loss of the West Antarctic Ice Sheet (Pörtner et al., 2019), which contains enough water to increase sea levels by up to 5.3 m and which may now be unavoidable (Naughten et al., 2023). It is likewise predicted that acidification will continue to parallel the ever-increasing concentration of atmospheric CO_2 (Lee et al., 2023), threatening polar ecosystems in particular with conditions that are antagonistic to calcifying organisms (Beaupré-Laperrière et al., 2020; Pörtner et al., 2019).

1.2 The Southern Ocean water mass structure

The Southern Ocean is characterised by vertical motion; namely, the upwelling of centuries-old, relatively warm ($\theta > 0.5$°C, Evans et al., 2018) Circumpolar Deep Water (CDW), linked to the aforementioned low summer sea ice extent and the melting of Antarctic ice shelves (Morrison et al., 2020), and its subsequent injection back into the interior and abyss of the global ocean (Frölicher et al., 2015; Meijers et al., 2023). In this capacity, vertical motion in the Southern Ocean is a key process closing the overturning circulation and modulating the global distribution of heat, carbon, and nutrients in the Earth system.

The processes controlling this vertical motion are not fully understood; the canonical view (illustrated in Figure 1) is that upwelling results from divergent flow at the surface, after which the newly ventilated CDW is converted to intermediate or deep water through a variety of processes (e.g., Marshall & Speer, 2012; Frölicher et al., 2015). The salient point is that CDW follows outcropping isopycnals to the surface in the vicinity of the sea ice edge. From here, it can continue southwards, driven by easterly winds and near-shore sinking, where its warmth can accelerate ice loss. Eventually, it loses buoyancy due to cold winds and sea ice formation processes, and it convectively sinks to join the northward-flowing slope currents which fill the global abyss (Vreugdenhil & Gayen, 2021; Meijers et al., 2023). The alternative pathway is northward across the Antarctic Circumpolar Current, along which it takes up heat and CO_2 from the atmosphere. Eventually, it is injected to intermediate depths, driven by wind and seasonal cooling (Meijers et al., 2023).

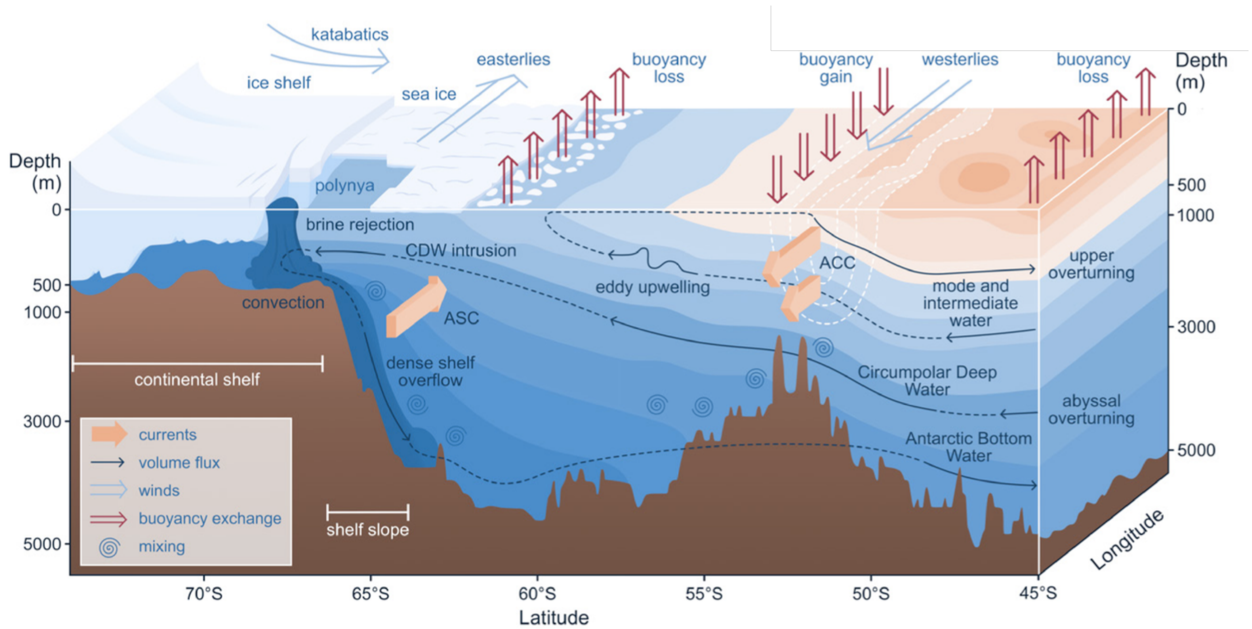

Figure 1: The water mass structure of the Southern Ocean. Circumpolar Deep Water (CDW) is upwelled before taking one of two pathways: southward, where it is converted to Antarctic Bottom Water via near-shore convection, or northward, where it is injected to intermediate depth at the northern side of the Antarctic Circumpolar Current (ACC). Density layers are indicated by the blue gradient. Reproduced from Bennetts et al. (2023).

1.3 Ocean surface convection

Convection occurs when the vertical gradient of potential density decreases with depth—in other words, dense water overlies light water, and the resultant static instability causes downward mixing within turbulent plumes approximately 1 km in the horizontal (Lab Sea Group, 1998; Marshall & Schott, 1999). Since the density of seawater is primarily set by temperature and salinity, it can be triggered by atmospheric cooling, evaporation, and/or salt rejection during sea ice formation processes.

The production of deep water by convection, illustrated as a dark-blue plume in Figure 1, is well-established by theory, observations, and models (e.g., Stommel, 1962; Killworth, 1983; Morrison et al., 2020). However, there has been limited focus on role of off-shelf convective plumes among the wide number of mixed layer processes that set the water mass structure. One confounding factor is the harshness and remoteness of the Southern Ocean, which severely limit the available observational data (Sarmiento et al., 2023; Tamsitt, 2023). There is nevertheless evidence of an extremely deep convective event occurring near Maud Rise in the Weddell Sea during the 1970s, which possibly extended to a depth of 4,000 m (Gordon, 1978), along with similar events possibly occurring in 2016 and 2017 (Campbell et al., 2019).

Evans et al. (2018) used an ocean state estimate and a seasonal climatology to find that the conversion of CDW into Antarctic Intermediate Water (AAIW) relies on both seasonal surface buoyancy loss and subsurface mixing, which work in concert to freshen and cool the water before it is warmed and subducted farther north. Figure 2 shows this process in temperature-salinity space, with Winter Water (WW) acting as a conduit between CDW and AAIW. The diabatic pathway 1 hints at the central line of inquiry of this proposal: Could buoyancy forcing in the form of shallow open-ocean convective plumes be responsible for the entrainment of CDW into the winter mixed layer (i.e., WW), especially in regions with a weak pycnocline? As a distinct process from the deep-water producing convection that occurs farther south, the comparative absence of such plumes from the observational record can plausibly be explained by their small—and thereby elusive—spatial and temporal scales. Basic questions thus emerge. For one example, since WW is related to seasonal sea ice formation (Spira et al., 2024), how might the intensity of these convective plumes, and hence WW production, vary with respect to the seasonal ice edge and the Polar Front of the Antarctic Circumpolar Current?

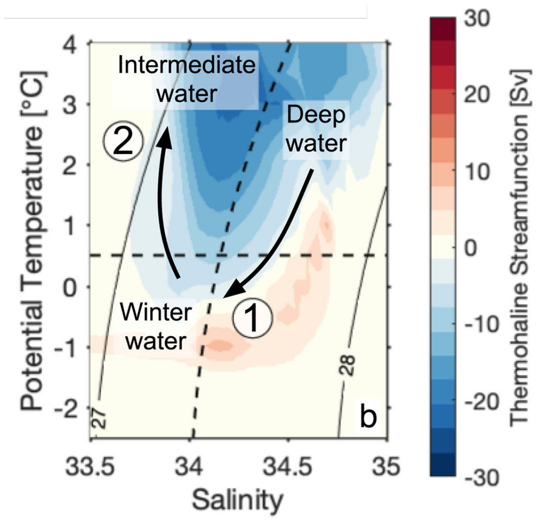

Figure 2: Estimate of the thermohaline streamfunction showing the pathway of deep to intermediate water in temperature-salinity space, with Winter Water (WW) serving as a conduit between the two water masses. I hypothesize that shallow open-ocean convective plumes could be an important player in pathway 1. Reproduced from Evans et al. (2018).

1.4 Earth System Models

In general, Earth System Models (ESMs) represent a partial solution to the lack of high-latitude observations in the climate sciences. However, their accuracy in the Southern Ocean is a particular challenge. For example, all ESMs used in the Intergovernmental Panel on Climate Change's (IPCC) recent Fifth and Sixth Assessment Reports failed to predict the low minimum sea ice extent of 2023, and most yield return periods over 1,000 years for sea ice loss anomalies of comparable magnitude (Diamond et al., 2024). Similarly, ESMs and observations often disagree on the rate of Southern Ocean CO_2 uptake, potentially illustrating biases in observational programs and/or model inaccuracies (Frölicher et al., 2015; Gruber et al., 2019; Dong et al., 2024).

Convection is a perennial difficulty for ESMs. First, due to the small extent of convective plumes, their true scale cannot be directly represented in ESMs. Even in the state-of-the-art models used within the IPCC's Sixth Assessment Report, the typical resolution of the ocean components was 1°, and the highest resolution models topped out at 1/10°, which yields grid spacings of more than 5 km throughout much of the Southern Ocean (Hewitt et al., 2020). Second, because global ESMs rely on the numerical recipes first described during the 1960s (within Bryan, 1969 and Manabe & Bryan, 1969), they commonly make the so-called "hydrostatic assumption". Consequently, the Navier-Stokes equations describing the fluid flow are reduced in the vertical to a balance of pressure and gravity, and the direct calculation of vertical velocity is neglected. The resultant equations are less onerous to solve numerically, and the hydrostatic assumption is valid for most of the global ocean. However, on scales and in regions relevant to ocean convection, hydrostatic balance breaks down (Marshall et al., 1997), and ESMs therefore need to rely on simplified parameterisations to capture its effects.

1.5 Hypothesis and objectives

I hypothesize that shallow, open-ocean convective plumes are common enough to have a major impact on the structure and transformations of water masses in the Southern Ocean, and on the exchange of heat and CO_2 between the atmosphere and the interior. However, due to the small scales and inherently non-hydrostatic nature of convective plumes, ESMs are only able to capture the wind-driven upwelling of deep water, and not the open-ocean convection.

Over recent decades, stratification around Antarctica has most likely been increasing (Stoessel et al., 2015; Li et al., 2020; Gunn et al., 2023), which would have a direct influence on the strength of convection and on the rate of sequestration of heat and CO_2. Under these conditions, if we are to accurately predict phenomena such as changing sea ice and glacial melt, acidification, sea level rise, global ocean heating, and more, we must equip ourselves with ESMs that can realistically forecast changes in vertical mixing within the Southern Ocean. The goal of the VERTEXSO (VERTical EXchange in the Southern Ocean) project is to address this need by improving how ESMs represent Southern Ocean convection.

As the first of five VERTEXSO work packages, my primary goal is to develop a comprehensive, mechanistic understanding of the role of convection in the Southern Ocean. To do this, I will use a suite of numerical simulations based on the Massachusetts Institute of Technology general circulation model (MITgcm) (Adcroft et al., 2018). One strength of MITgcm is its ability to solve non-hydrostatic flow, making it particularly adept at simulating convection.

Specifically, under realistic open-ocean forcing scenarios, I aim to investigate the following questions:

1. How common is the development of surface-to-pycnocline convective plumes? And how do their temporal and spatial scales vary with changes in:
   (a) Geographical location (e.g., relative to the sea ice edge and WW production, topography, and the strength of the halocline and thermocline)?

(b) Other factors known to control vertical mixing (e.g., internal tides, non-linear processes, vertical shear, supercooled water, eddies and more)?
(c) Seasonal surface forcing (e.g., buoyancy fluxes and wind shear, the latter of which controls the convergence/divergence of surface flows)?

2. What is the role of convective plumes in (a) the CDW $\rightarrow$ WW $\rightarrow$ surface water $\rightarrow$ AAIW pathway and (b) the exchange of heat and CO_2 between the atmosphere and the pycnocline?

Ultimately, I am optimistic that my novel simulations will provide unique insights into the true prevalence and behaviour of Southern Ocean convection. And it is my tentative hope that, within later stages of the VERTEXSO project, these insights are used to improve how ESMs represent Southern Ocean convection, thereby helping to close the gap between models and observations and reducing uncertainties about ESM projections of the future of the Southern Ocean and of the Earth.

1.6 Methodology

I am beginning my research with an idealised very high-resolution test case of deep convection, which I am in the process of setting up and validating on a parallel high-performance computer. I will then iteratively test various model domains to identify the best resolution for a trade-off of accuracy and computational cost (Task 1, Figure 3). Next, I will be able to implement increasing realism to explore the effects of summer, and later winter, conditions at the sea ice edge. In particular, I will focus on implementing a module for supercooled surface water, i.e., liquid water at or below the point of freezing, which was recently identified in much larger quantities than previously expected (Haumann et al., 2020). An important result of this early stage of work will be how readily shallow open-ocean convective plumes are generated under realistic forcing conditions. In the unexpected case that they are categorically never generated, I will refocus my studies on other potential causes of diapycnal mixing within the CDW $\rightarrow$ WW $\rightarrow$ surface water $\rightarrow$ AAIW pathway.

Once I have realistically tuned the model, I will conduct simulations in both hydrostatic and non-hydrostatic modes to elucidate the effects of the hydrostatic assumption on heat and CO_2 exchange (Task 2, Figure 3). I will also run sensitivity experiments to understand the responses of heat and CO_2 exchange to seasonal variability in wind and heat flux (Task 3, Figure 3). Finally, for a short period I will extend my model domain to the full Southern Ocean or a sector therein, depending upon the required computational expense and the available resources. At this stage, a significant risk will be if the supercomputer I intend to use (SuperMUC-NG) is unavailable. In this case, I will attempt to identify alternative systems and model domains to complete the desired simulations. I will then be able to evaluate variables such as heat, salt, and CO_2 against recent observational data, and I will study the role of convective plumes in the transformation of CDW to AAIW (Task 4, Figure 3).

2 Professional development

My current career goal is to work in the public sector on ocean and climate modelling. Over the next three years, it will therefore be crucial that I continue to develop both my communication abilities, because modelling is a community-driven field, and my technical skills, because models are complex programs. Through participation in the AWI graduate school POLMAR, I am eligible for many relevant short courses, which cover topics such as academic writing, high-performance computing, interview training, leadership skills, and more. For similar reasons, I also intend to make quarterly visits to AWI, where I can collaborate with, and learn from, AWI personnel, including Dr. Martin Losch and members of the SO-CLIM research group (Drs. Krissy Reeve, Léa Olivier, and Alexander Weinhart).

To strengthen my professional profile, it will also be invaluable that I demonstrate the ability to perform and complete research projects—in other words, to publish papers on my work. To this end, I intend to complete a "cumulative dissertation", in which three published or submitted papers constitute the majority of the manuscript. It will be similarly valuable to grow my professional network throughout my Ph.D. I therefore intend to present at several international conferences, participate in AWI cruises, potentially undertake research visits to other laboratories, and get involved in international working groups/meetings. Regarding the latter, an example of this is the monthly Southern Ocean Freshwater Input from Antarctica Initiative (SOFIA) meetings, which I have been attending to understand how community-driven science is organised.

In definitive terms, I have completed or am currently undertaking three professional development activities. They are:

1. *Parallel programming with MPI and OpenMP*, University of Bremen
   Sep 16–20, 2024
2. *Paper Writing Academy*, Tress Academic (online)
   Oct 7–Dec 16, 2024
3. Attend monthly SOFIA meetings

Potential future activities include the following:

4. *EGU General Assembly*, Vienna, Austria
   Apr 27–May 2, 2025; 2026; 2027
5. *AWI PhD days*, T.B.D. northern Germany
   Spring 2025; 2026; 2027
6. *AWI Science Week*, Bremerhaven, Germany
   Autumn 2025; 2026
7. *The Ocean Sciences Meeting*, Glasgow, Scotland
   Feb 22–27, 2026
8. *Polarstern SWOS cruise*, Antarctic Peninsula
   Feb–Apr 2026
9. The *12th SCAR Open Science Conference*, Oslo, Norway
   Aug 8–18, 2026
10. Research visit(s) to other lab(s)
    2026; 2027

3 Project timeline

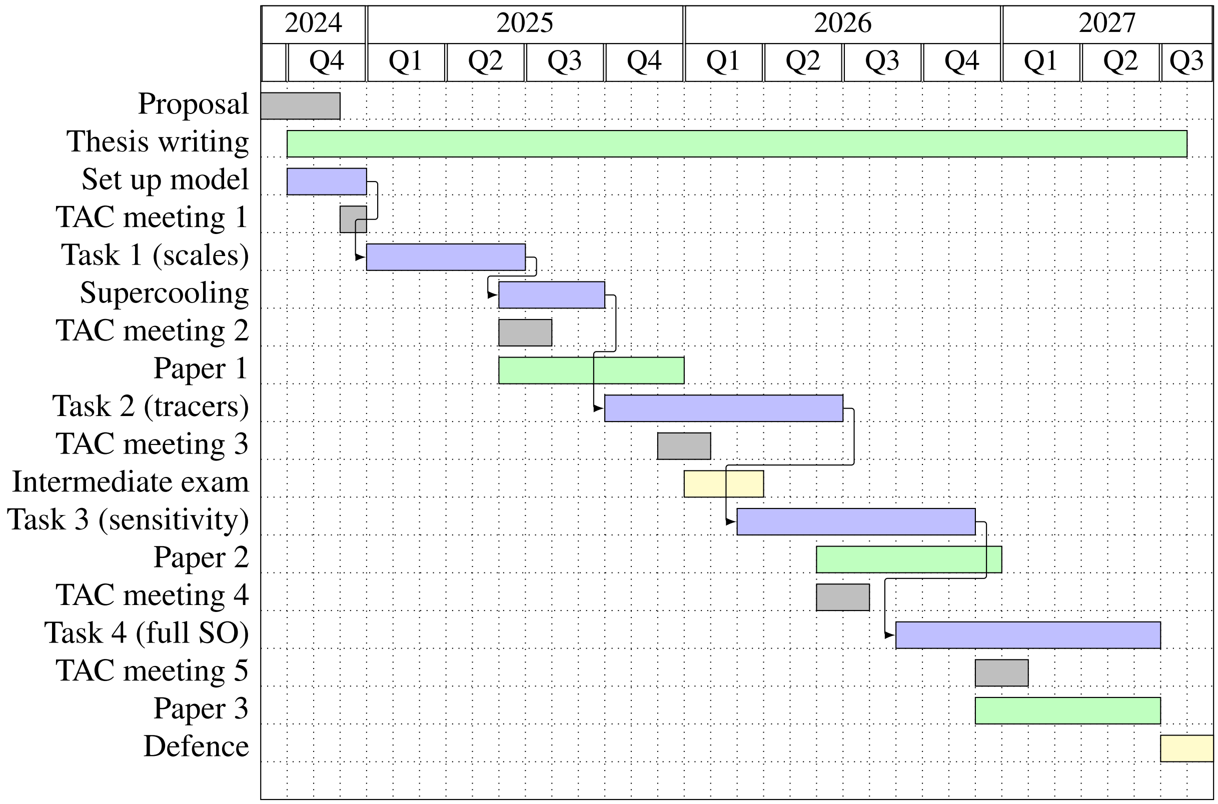

Figure 3: Gantt chart detailing my preliminary plan over 36-months. The critical path is denoted by arrows; slowdowns of these tasks will have delaying effects on downstream tasks and publications. SO: Southern Ocean.

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