Towards Realistically Modelling Southern Ocean Convection

Thesis Advisory Committee (TAC) Meeting #1

December 10, 2024

Rowan Brown

Prof. Dr. Alexander Haumann

Dr. Martin Losch

Professor Alberto Naveira Garabato

Dr. Cat Vreugdenhil

Outline

What is the role of the TAC?

Feel free to jump in at any point!

- Meet online every 6 months
- Review successes and roadblocks
- Advise on:
  - **Planned experiments, analyses, and publications**
  - **Degree timeline**
  - Opportunities for professional development (workshops, conferences, etc.)
- Opportunities for collaboration

Outline

Educational background

Bachelor of Engineering in Ocean and Naval Architectural Engineering, 2020
Memorial University of Newfoundland, St. John’s, Canada
Equivalent requirements for a Minor in Mathematics completed in 2021

Image from [1]

Master of Science in Earth and Atmospheric Sciences, 2024
University of Alberta, Edmonton, Canada
Supervisor: Dr. Paul Myers

Image from [3]

M.Sc. experience

Thesis project

Studying deep convection in the Labrador Sea using a 1/4° NEMO model, with a focus on the effects of tidal forcing and a parameterisation for mixed layer eddies

The Effects of Tides and Submesoscale Mixed Layer Eddies on Deep Convection in the Labrador Sea: Simulations at Resolutions Consistent with Coupled Climate Models

by

Rowan Brown

A thesis submitted in partial fulfilment of the requirements for the degree of

Master of Science

Department of Earth and Atmospheric Sciences

University of Alberta

Secondary project

Investigating the accuracy of tides in an O(100 m) nested NEMO model in support of a Fisheries and Oceans Canada operation to stop oil leaching from a WW2 shipwreck

Outline

The VERTEXSO project

VERTical **EX**change in the **S**outhern **O**cean

Part of the AWI-LMU joint research group for Southern Ocean-Climate Interactions (SO-CLIM)

VERTEXSO seeks to address the gap between observed and simulated changes in the Southern Ocean and thus reduce uncertainties in the ability of Earth System Models (ESMs) to accurately project future changes

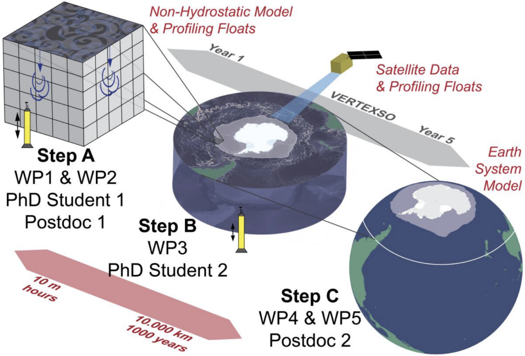


Figure from Haumann (personal communication)

Outline

The Southern Ocean and Antarctica by numbers

The Southern Ocean accounts for

- 75% of the ocean's anthropogenic heat uptake [8]
- 40% of the ocean's anthropogenic CO_2 uptake [8, 9]

The cryosphere

- 2023 set a record low minimum sea ice extent (36% below climatological values) [17]
- Loss of the West Antarctic Ice Sheet (containing 5.3 m of sea level rise) may now be unavoidable [16]

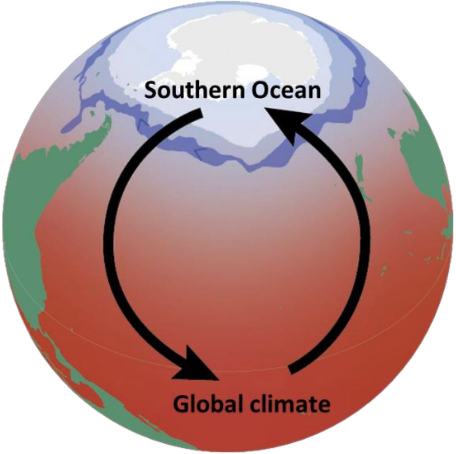


Figure from Haumann (personal communication)

The relevant circulation

Warm Circumpolar Deep Water (CDW) is upwelled [8]

- *Can* absorb anthropogenic CO_2 and heat
- *Can* bring up nutrients and CO_2

The upwelled CDW can take two paths

1. Southward, where it can melt ice sheets and sea ice before sinking to bottom [15, 22]
2. Northward, where it absorbs heat and CO_2 before being injected to intermediate depth [15]

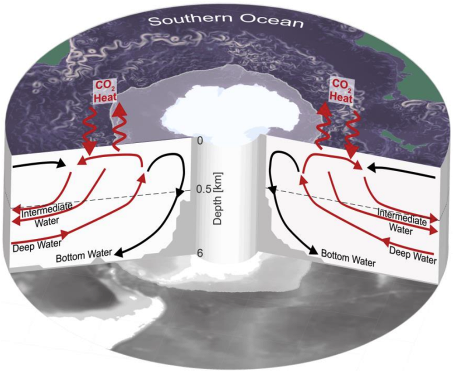


Figure from Haumann (personal communication)

The taxonomy of convection

1. Coastal
   - Cold katabatic winds → cools surface, opens polynyas
   - Brine rejection → salinifies surface
   - Produces Antarctic Bottom Water
2. Mixed layer
   - Characteristic of tropics/sub-tropics
   - Typically on a diurnal cycle
3. **Open ocean**
   - **Caused by atmospheric cooling**
   - **Does not necessarily extend to seafloor**

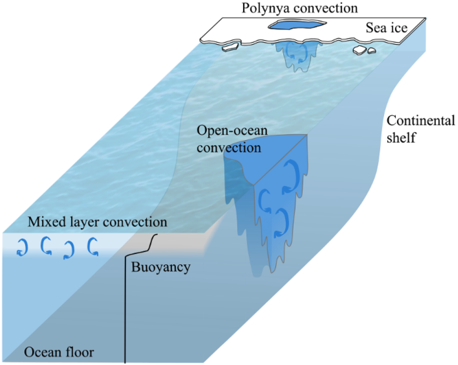


Figure from Vreugdenhil et al. [22]

Open-ocean convection

Three stages [14, 12]

- A Preconditioning (i.e., weak stratification; favoured by cyclonic circulation)
- B Violent convection in plumes of O(1 km)
- C Lateral exchange by baroclinic instabilities

Fundamentally **non-hydrostatic**

- Balance of vertical pressure gradient and buoyancy breaks down, i.e., $\frac{\partial p}{\partial z} \neq -\rho g$

$\therefore$ *Must be parameterized in global ESMs*

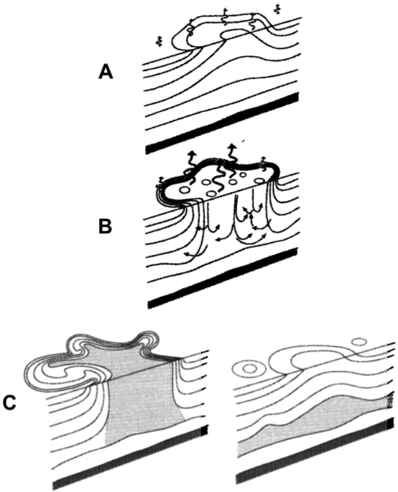


Figure from Marshall and Schott [14]

High-latitude considerations

High latitude

→ larger Coriolis ($f = 2\,\Omega\sin(\phi)$)

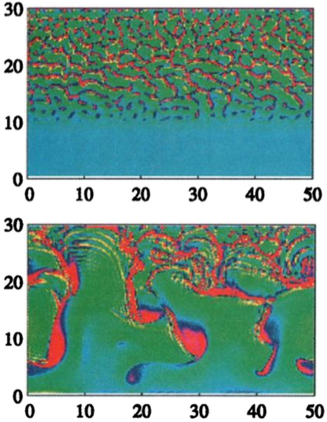
Weak stratification

→ low buoyancy frequency (N)

Rossby radius of deformation [14]:

- $L_\rho = NH/f \approx$ O(1–10 km)
- Rotation cannot be ignored
- Restratification occurs on geostrophic scales

High-latitude convection is a multi-scale process!



Convective plumes giving way to geostrophic mixing

Figure from Marshall et al. [13]

Water mass structure

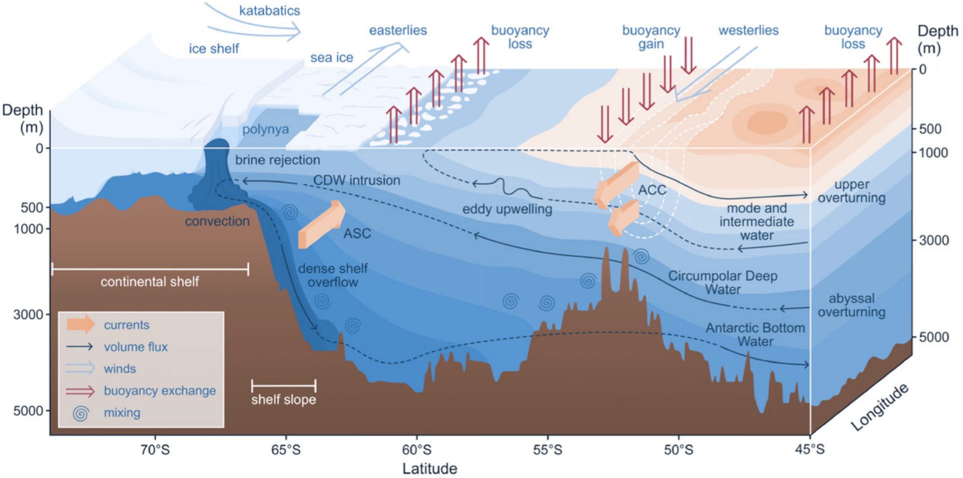
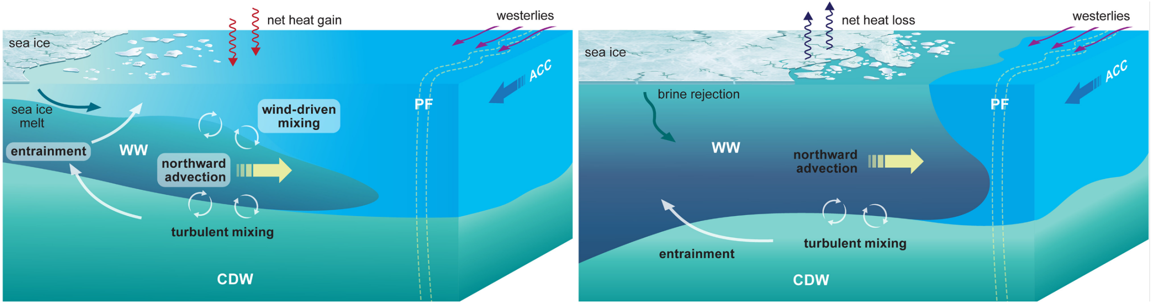


Figure from Bennetts et al. [5]

Winter Water (WW)

- Formed in the winter mixed layer by ice formation and air-sea heat flux
- Feedback: Mixes with CDW → increases heat content → inhibits ice grow
- Mixed layer shoals in summer from <200 m to 10s of m



Summer *Winter*

Figure from Spira et al., 2024 [19]

CDW transformations [7, 19]

What explains the CDW $\rightarrow$ WW pathway 1?

- Non-linear equation of state
- Double-diffusive convection
- Eddies, turbulence
- ...Shallow open-ocean convective plumes?

$\therefore$ ***I hypothesize that shallow open-ocean convective plumes connect the surface with the pycnocline and play an important role in setting the structure of heat and CO_2***

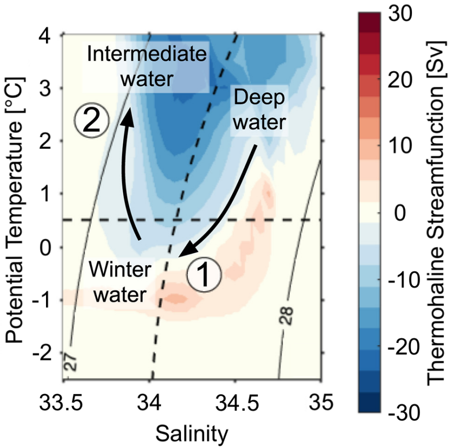


Figure from Evans et al. [7]

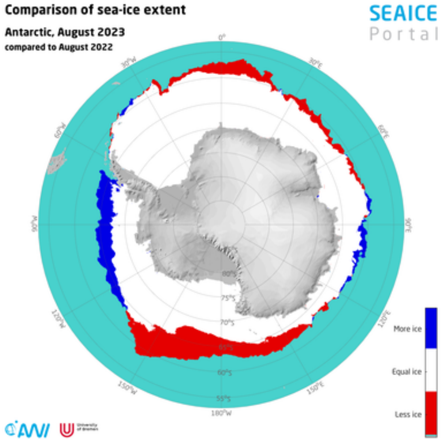
Convection in Earth System Models (ESMs)

ESMs' biggest problems

- Resolutions used are significantly too coarse to capture plumes
- Hydrostatic assumption $\rightarrow$ direct calculation of w is neglected

Many ESMs experience "too much" convection [10, 11, 20]

- i.e., overproduction of bottom waters via deep convection
- Yet, CMIP6 models don't produce the 2023 sea ice minimum [6]



Record sea ice low for Southern winter
Figure from AWI sea ice portal [2]

Hypothesis

Shallow open-ocean convective plumes are common throughout the surface of the Southern Ocean

- ESMs only capture wind-driven upwelling of CDW, not plume-driven entrainment into WW layer
- Small and short-lived plumes → easy to miss observationally
- *If* shallow open ocean plumes were included in ESMs, they might facilitate more accurate:
  - CO_2 sequestration/acidification;
  - heat transport and water mass structure; and
  - sea ice and glacial melt

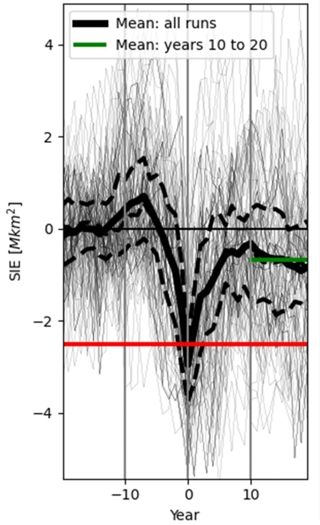
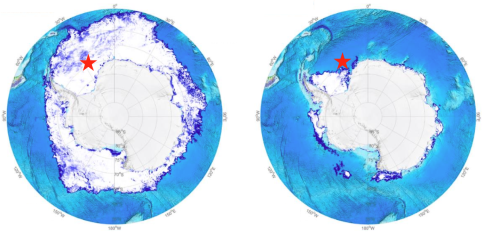


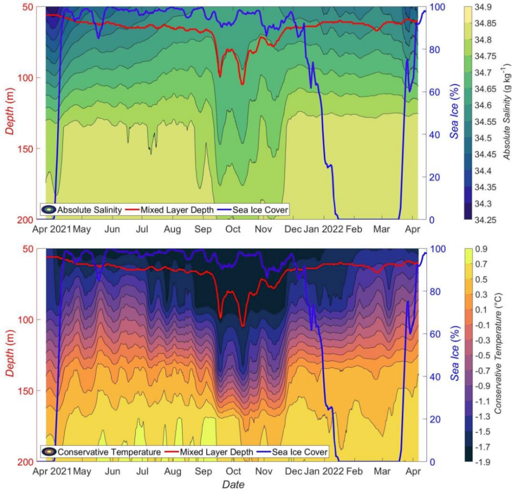
Figure from Diamond et al. [6]

Example 1/2: Plume over a Weddell Sea mooring?

- March 2021–April 2022
- 50 m (upper end)–4,600 m (water depth)
- Location shown by red star

Sudden deepening of the mixed layer seemingly driven by surface processes





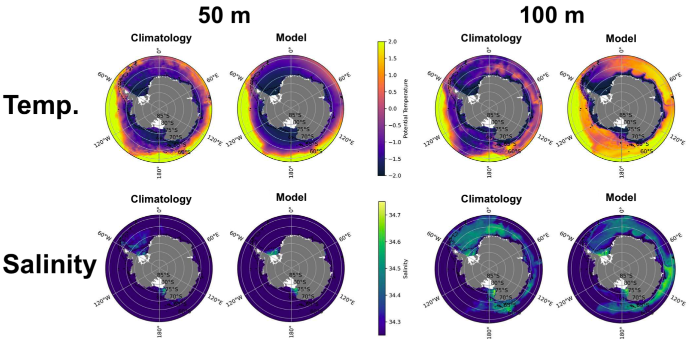
Figures from Rauch [18]

Example 2/2: Biases in recent model results

Compare Finite volumE Sea Ice-Ocean Model (FESOM2) with OCEAN:ICE climatology

Model exhibits strong subsurface biases (100 m) in both temperature and salinity

I hypothesize that a lack of plumes is leading to subsurface heat buildup and incorrect CDW-WW mixing



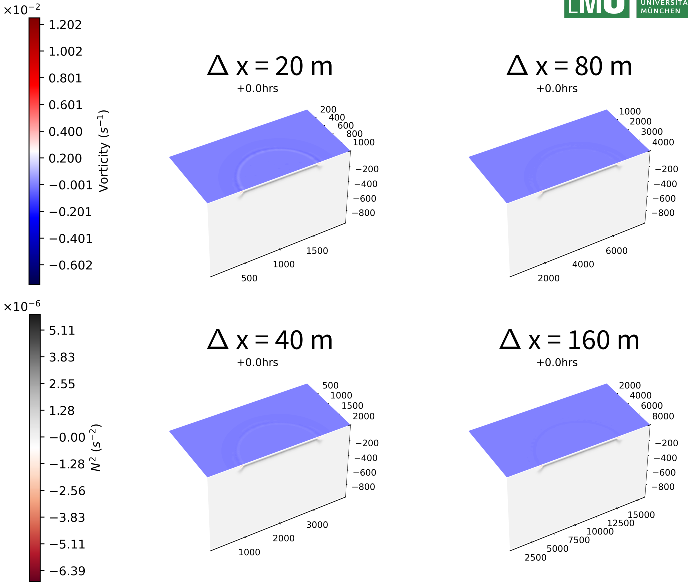
Figures from van Campos et al. [21]

Modelling overview

Use MITgcm [4], which permits **non-hydrostatic** and **very high-resolution** simulations

Run on Leibniz (LRZ) Supercomputing Centre systems (or AWI's Albedo when LRZ systems are down)

Implement increasing realism and a range of domains, from plume-scale to Southern Ocean-scale



Going forward

Questions

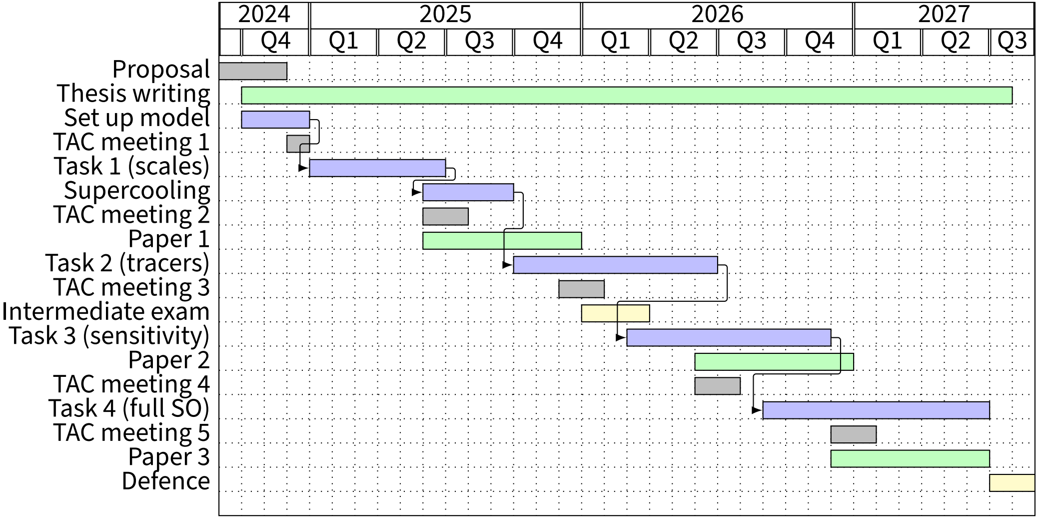
- How common are surface-to-pycnocline plumes?
- How do plumes' scales (time and space) vary with location, season, and other drivers of mixing?
- How does the hydrostatic approx. affect carbon, heat, and salinity?
- What is the role of plumes in setting the water mass structure and the exchange of heat and CO_2?

Tentative steps

0. Set up a test case and toolchains
1. Add realistic boundary and forcing cond.
2. Iterate over different domains
3. Model development ideas
   - Parameterisation for supercooled water?
   - New elliptic solver?
4. Effects of hydrostatic approx.
5. Sensitivity exp. on seasonality
6. Extend domain

Outline

Proposed timeline



Outline

Professional development

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

Past and ongoing:

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 Southern Ocean Freshwater Input from Antarctica (SOFIA) Initiative meetings

Future possibilities:

4. AWI courses, cruises, and quarterly visits
5. EGU General Assembly
   Vienna, Austria
   Apr. 27–May 2, 2025; 2026; 2027
6. AWI PhD days
   Spring 2025; 2026; 2027
7. AWI Science Week
   Bremerhaven
   Autumn 2025; 2026

6. The Ocean Sciences Meeting
   Glasgow, Scotland
   Feb. 22–27, 2026
7. Polarstern SWOS cruise
   Antarctic Peninsula
   Feb–Apr., 2026
8. 12th SCAR Open Science Conference
   Oslo, Norway
   Aug 8–18, 2026
9. Research visit(s)
   2026; 2027

Danke schön!

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