# Antarctic Winter Water

## Its role in Southern Ocean dynamics and sea ice variability

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Ph.D. Thesis

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# Contents

# Abstract

The Southern Ocean is central to the global climate system, connecting the world's major ocean basins and regulating intense exchange of carbon and heat between the atmosphere and deep ocean. Antarctic sea ice is a critical component to this system, influencing planetary albedo, modulating air–sea exchanges, and regulating the vertical structure of the upper ocean.

In recent years, Antarctic sea ice has undergone an unprecedented change, shifting from a multi-decadal state of gradual sea ice expansion to a regime of low, variable coverage—proposed as a new sea ice state. The processes driving this transition, particularly vertical ocean–ice interactions, remain poorly understood and models fail to reproduce observed conditions.

This thesis examines Antarctic Winter Water—the remnant cold wintertime mixed layer sandwiched between the warm and fresh summertime mixed layer and the warm and salty subsurface ocean interior. We investigate Winter Water's role in the overturning circulation system, how it modulates vertical fluxes, and its contribution to Antarctic sea ice variability, hypothesising that it acts as a stratification barrier and a cool, fresh reservoir within the upper water column.

I curated a circumpolar dataset of quality-controlled multi-platform *in-situ* observations spanning from 2004 to 2022. In combination with satellite records of sea ice concentration and re-analysis output, I characterised Winter Water properties, quantify their role in sea ice changes, and assess regional variations in ocean–ice coupling.

Four main studies underpin this thesis. First, I describe the seasonal cycle, spatial distribution, and highlight its role within the overturning circulation. Second, I show that from 2005–2015, Winter Water shoaled across much of the Southern Ocean, preconditioning the ocean for enhanced vertical heat fluxes that contributed to the 2015 transition to a new sea ice regime. Third, I reveal that this transition was not circumpolarly uniform: contrasting hydrographic structures across sectors led to opposing regional sea ice responses. Finally, I demonstrate that meltwater from giant icebergs in the Weddell Sea modifies Winter Water properties, increasing stratification and altering upper-ocean heat content.

The findings identify Winter Water as a critical component of the Southern Ocean system. By regulating vertical heat exchange, Winter Water regionally influences sea ice distribution and ocean density structure. Understanding the representation of Winter Water in climate models may prove essential for better projections of Antarctic sea ice and the Southern Ocean under continued climate change.

# Sammanfattning

Södra ishavet är centralt för det globala klimatsystemet. Det förbinder världens största havsbassänger och reglerar det intensiva utbytet av kol och värme mellan atmosfären och djuphavet. Den antarktiska havsisen är en avgörande komponent i detta system. Den påverkar planetens albedo, modulerar utbytet mellan luft och hav, samt reglerar den vertikala strukturen i det övre havet.

Under de senaste åren har den antarktiska havsisen genomgått en oöverträffad och snabb förändring, från ett decennielångt tillstånd av gradvis expansion till en ny regim med låg och variabel täckning. Denna förändring har föreslagits vara ett nytt havsistillstånd. Processerna som driver denna övergång, särskilt de vertikala interaktionerna mellan hav och is, är fortfarande dåligt förstådda, och klimatmodeller misslyckas med att reproducera det nya tillståndet för havsis.

Denna avhandling undersöker antarktiskt vintervatten, det kalla restlagret från vinterns blandningsskikt som ligger inklämt mellan sommarens varma och färska blandningsskikt, och det varma och salta djuphavet. Jag undersöker vintervattnets roll i den omvälvande cirkulationen, hur det modulerar vertikala flöden, och dess bidrag till att forma variationen i den antarktiska havsisen, med hypotesen att det förhindrar vertikal skiktning i havet.

Genom att använda ett cirkumpolärt dataset av kvalitetssäkrade observationer från olika plattformar (inklusive Argo, SOCCOM, MEOP-sensorsystem på sälar, profilerande havsrobotar, och fartygsbaserade CTD:er) från 2004 till 2022, kombinerat med satellitdata över havsisens distribution, och historisk dataanalys (med modellkombination) av diverse andra parametrar, karakteriserar jag vintervattnets egenskaper. Jag kvantifierar dess roll i de senaste havisförändringarna och utvärderar regionala variationer i kopplingen mellan hav och is.

Fyra huvudstudier utgör grunden för denna avhandling. I den första beskriver jag vintervattnets säsongscykel, rumsliga distribution och exportvägar, och belyser dess roll inom den omvälvande cirkulationen. Den andra studien påvisar att vintervattnet från 2005–2015 blev grundare över stora delar av Södra ishavet, vilket förberedde havet för ökade vertikala värmeflöden och bidrog till övergången till en ny havsisregim 2015. För det tredje avslöjar jag att denna övergång inte var enhetlig runt Antarktis: kontrasterande hydrografiska strukturer i olika sektorer ledde till motsatta regionala havsisresponser. Slutligen demonstrerar jag att smältande gigantiska isberg i Weddellhavet modifierar vintervattnets egenskaper, vilket ökar skiktningen och förändrar värmeinnehållet i de övre havsskikten. Resultaten identifierar vintervatten som en kritisk komponent i det Södra ishavets system. Genom att reglera det vertikala värmeutbytet påverkar vintervattnet regionalt havsisens distribution och havets densitetsstruktur. Att förbättra representationen av vintervatten i klimatmodeller är avgörande för bättre prognoser för antarktisk havsis och Södra ishavet under fortsatt klimatförändring.

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Reflecting on my PhD, the adage that "a PhD is a journey" has never felt more apt. Oftentimes, I feel like a ship sailing down a river – one I boarded without knowing how to sail (which is daunting and undisputably idiotic). So, unsurprisingly, my journey has been one filled with rapids, tides, abrupt meanders, gentle stretches and unexpected (U-)turns.

Fortunately, sailing my ship has not been a solo endeavour, and many have taught me the necessary skills to navigate the waters, how to stay afloat, and enjoy the many responsibilities in the life of a sailor.

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For those who are here for moral support; I am glad to have your presence. Please enjoy this small token of gratitude:

Are you listening to a multi-hour PhD defence? Do you have no idea what's going on? Are your eyelids heavy and you're battling with all your might to remain conscious? Try a thesis-themed word search to cure your boredom! Courtesy of www.puzzle-maker.com.

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ABYSS
ALPHA
ANTARCTIC
BETA
CLIMATE
FLOAT
FREEZING
GLIDER
HEAT
ICE
MIXING
OCEAN
PENGUIN
SALT
SEALS
WINTER

# Outline

This thesis is based on four scientific papers, which are referred to by the numbered Roman numerals listed below and are attached in the appendix.

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Papers this thesis is based on:

**I:** **T. Spira**, S. Swart, I. Giddy, and M. du Plessis, “The Observed Spatiotemporal Variability of Antarctic Winter Water,” *Journal of Geophysical Research: Oceans*, DOI: 10.1029/2024JC021017, 2024.

**II:** **T. Spira**, M. du Plessis, F. A. Haumann, I. Giddy, A. Narayanan, A. Silvano, and S. Swart, “Wind-triggered Antarctic sea-ice decline preconditioned by thinning Winter Water,” 2025 (Under Review for *Nature Climate Change*).

**III:** **T. Spira**, M. du Plessis, F. A. Haumann, A. Narayanan, and S. Swart, “Regional changes in ocean–ice coupling impact Antarctic sea-ice distribution,” 2025 (In Preparation for *The Cryosphere*).

**IV:** N. Lucas, J. Brearley, K. Hendry, **T. Spira**, A. Braakmann-Folgmann, E. P. Abrahamsen, M. Meredith, and G. Tarling, “Giant icebergs increase mixing and stratification in upper-ocean layers,” *Nature Geoscience*, DOI: 10.1038/s41561-025-01659-7, 2025.

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Published datasets and software:

**T. Spira**, S. Swart, and M. du Plessis (2023). *Processed hydrographic SO data, 2004–2021* [Dataset]. https://doi.org/10.5281/zenodo.10258138.

**T. Spira** (2024). *Antarctic Winter Water Climatology* [Software]. https://github.com/theospira/WW_climatology.

**T. Spira** (2025). *A68A iceberg and Winter Water observations* [Software]. https://github.com/theospira/2025-A68A_iceberg-WW.

**T. Spira** (2025). *WW–sea ice interactions* [Software]. https://github.com/theospira/WW-sea_ice.

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Other works not included in this thesis:

SO-CHIC Consortium, J. B. Sallée, ... , **T. Spira**, and others, "Southern Ocean carbon and heat impact on climate", *Philosophical Transactions of the Royal Society A*, DOI: 10.1098/rsta.2022.0056, 2023

A. Silvano, A. Narayanan, R. Catany, E. Olmedo, V. Gonzalez-Gambau, A. Turiel, R. Sabia, M. R. Mazloff, **T. Spira**, F. A. Haumann, and A. C. Naveira Garabato, "Rising surface salinity and declining sea ice: a new Southern Ocean state revealed by satellites", *Proceedings of the National Academy of Sciences*, DOI: 10.1073/pnas.2500440122, 2025

A. Narayanan, H. Ayres, M. H. England, F. A. Haumann, M. R. Mazloff, A. Silvano, **T. Spira**, S. Zhou, and A. C. Naveira Garabato, “Three-Phase Multiscale Drivers of Southern Ocean Sea Ice Loss,” Submitted to *Science Advances*, 2025.

Chapter 1

# Introduction

## 1.1 The Southern Ocean in the Planetary Climate System

The Earth receives more solar radiation at low latitudes than high latitudes. Consequently, the ocean and atmosphere at low latitudes are warmer than those at high latitudes, which leads to denser ocean surfaces at the poles compared to the equator and creates a density gradient. These density gradients, combined with the effects of the planet's rotation, drive a large-scale atmospheric and oceanic circulation that redistributes heat, carbon, and nutrients around the globe. This redistribution of heat and energy by the ocean is essential for maintaining a habitable planet. For example, in the Northern Hemisphere the transport of heat north-westward in the Atlantic Ocean helps to maintain relatively mild winters in Western Europe. Consequently, the average January temperature in London is 4°C, whilst Calgary (at the same latitude but located inland in central Canada) has average temperatures of -14°C.

In the North Atlantic, surface waters lose heat, become dense, and sink to form deep waters. These deep waters travel south and eventually upwell to re-emerge at the surface in the Southern Ocean (SO) hundreds to thousands of years later (Talley, 2013). This large-scale inter-basin exchange constitutes the ocean's global overturning circulation (Fig 1.1).

The SO is central to the global ocean circulation, directly connecting with three major ocean basins—the Atlantic, Pacific and Indian Oceans (Fig 1.1). This connection is facilitated by the Antarctic Circumpolar Current (ACC)—the world's strongest current, which flows eastward around Antarctica, unimpeded by land. The ACC is structured by several large-scale fronts (sharp boundaries of contrasting ocean temperature and salinity), which separate distinct oceanic regions and circulation processes (Orsi et al., 1995; Pollard et al., 2002). For example, the Subantarctic Front (SAF) marks the northern edge of the ACC's core. North of the SAF, ocean density is controlled by temperature (Roquet et al., 2022). In this region, deep mixed layers form (Caneill et al., 2024).

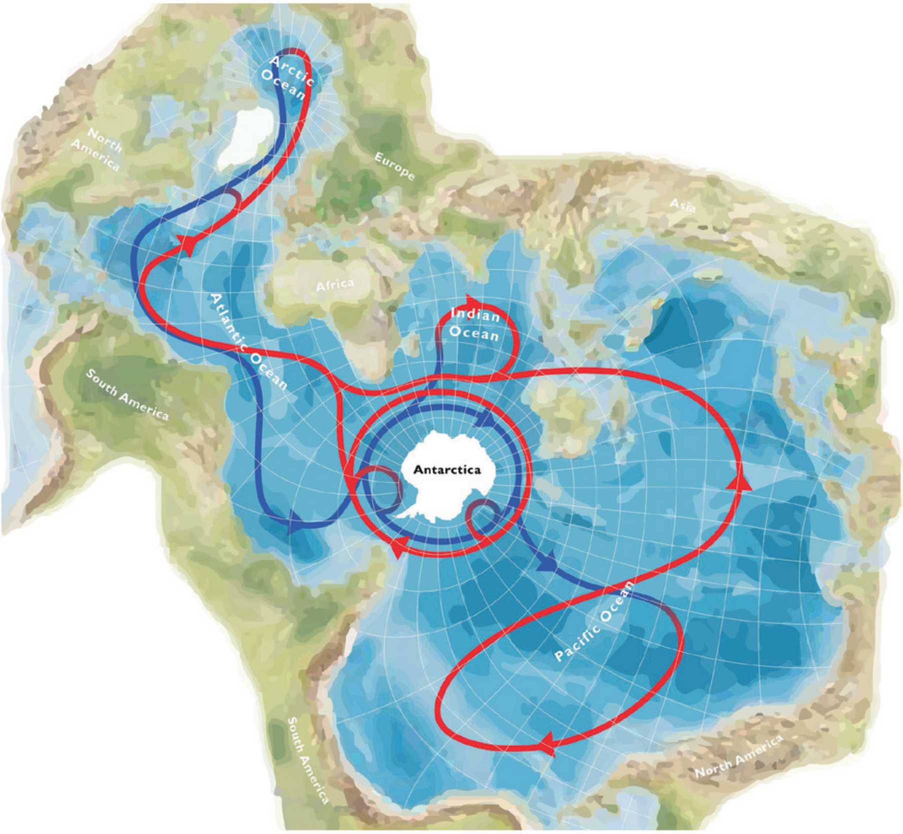

Figure 1.1: A Spilhaus projected map showing a singular, connected global ocean with arrows indicating an idealised overturning ocean circulation. The red arrows indicate surface flow (upper limb circulation) whilst the blue arrows indicate flow in the deep ocean (lower limb circulation). From Meredith, 2019.

Mixed layers are ocean surface layers in direct contact with the atmosphere, so are vigorously stirred (or mixed) such that temperature, salinity and density are almost vertically uniform (de Boyer Montégut, 2004). Water from these mixed layers eventually subduct to form Subantarctic Mode Water, an important water mass for the transport of heat and carbon into the ocean (Herraiz-Borreguero and Rintoul, 2011; Gao et al., 2018).

South of the SAF, the Polar Front (PF) marks where salinity, rather than temperature, controls density (Roquet et al., 2022). The PF is also the typical maximum sea ice extent (Goosse et al., 2025). Strong westerly winds around Antarctica, paired with the Earth's rotation, move surface waters northward via Ekman transport. When these surface waters (either mixed layer water or Antarctic Winter Water) encounter lighter waters, they sink below them and into the ocean, and eventually spread across the ocean at mid-depth to form

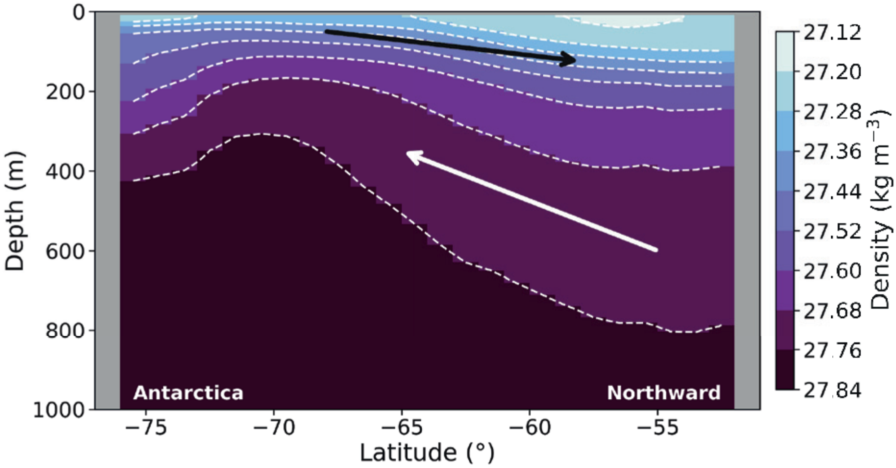

Figure 1.2: Southern Ocean density contours showing the region approximately within the red circle around Antarctica from Figure 1.1. The white arrow indicates where deep waters (Circumpolar Deep Water; CDW) rise to the surface and the black arrow indicates where surface waters (Antarctic Winter Water; WW) move northward.

intermediate waters north of the PF. This pathway transports surface waters into the ocean interior, and is commonly referred to as the upper limb of the SO overturning circulation (red arrows in Fig 1.1; Talley, 2013) At the same time, deep waters (such as Circumpolar Deep Water) are pulled to the surface south of the PF, following sloping density layers (Fig 1.2). These deep waters last interacted with the surface ocean hundreds to thousands of years prior (e.g., Toggweiler and Samuels, 1993). As a result, these waters are rich in heat, carbon and nutrient. When they reach the surface, they exchange properties with the atmosphere and act as a natural source of carbon release into the atmosphere (Lumpkin and Speer, 2007; Gray et al., 2018; Chen et al., 2022). The modified waters are then transported along the surface before sinking again. Some move northward and sink as intermediate waters; others travel southward and sink near the Antarctic shelf to form dense bottom waters—the lower limb of the SO overturning circulation (blue arrows in Fig 1.1). The amount of deep waters that upwell to the ocean surface varies naturally over millenial timescales. These changes affect atmospheric carbon dioxide concentrations and global temperatures, and are tightly tied to natural climate variability, including glacial–interglacial cycles (Toggweiler et al., 2006; Ferrari et al., 2014; Chandler and Langebroek, 2024). However, the rates of deep water upwelling can also vary on shorter timescales, which can directly impact ocean surface heat content (Dutrieux et al., 2014; Silvano et al., 2018), ice-shelf melt (Jenkins et al., 2010; Rignot et al., 2013a), and carbon dioxide outgassing (Chen et al., 2022; Gray et al., 2018; Nicholson et al., 2022).

Thus, this upwelling–transformation–subduction loop is a critical component of the Earth system that helps regulate the global climate. North of the PF, the formation of Subantarctic Mode Water in upper limb of the Southern Ocean overturning circulation plays an outsized role in sequestering heat and carbon. Since the 19th century, the SO has absorbed 60–90% of excess heat and ~40% of anthropogenic carbon dioxide (Frölicher et al., 2015; Meredith et al., 2019; Cheng et al., 2020).

In contrast, south of the PF, the SO is a natural source of heat and carbon to the atmosphere, as deep waters upwell to the ocean surface. The strength and extent of this upwelling vary on millennial timescales. However, shorter-term changes may also affect ocean heat content and increase outgassing of carbon dioxide into the atmosphere, with significant consequences for both the Antarctic and global climate. Hence, the Southern Ocean plays a complex role in the climate system: it acts as both a stabilising influence through its carbon and heat uptake, and a potential amplifier of climate change via natural variability, ocean warming, and carbon release.

## 1.2 Antarctic Sea Ice and Recent Changes

The SO is characterised by a stark seasonal cycle. Throughout austral (Southern Hemisphere) winter, the intensely cold atmosphere cools the ocean surface to its freezing point (~−1.8 °C), forming ice crystals that eventually consolidate into a layer of sea ice on the ocean surface (Talley et al., 2011). Sea ice is heavily influenced by winds, which redistribute sea ice around the SO (Kimura, 2004; P. R. Holland and Kwok, 2012). Consequently, wintertime sea ice typically accumulates to more than 16.5 million km$^2$ in area (Fig 1.3b and 1.3c; Massom and Stammerjohn, 2010)—that's roughly the same surface area as Russia or Pluto. Then, when solar radiation increases and the net heat flux is positive during summer, sea ice rapidly melts and decreases to ~2.5 million km$^2$ in area (Fig 1.3a). This huge variation in sea ice acts as the breath of the global climate, influencing the physical and biogeochemical ocean structure, as well as the planetary energy balance.

Antarctic sea ice is a crucial and multifaceted part of the Earth's planetary system. It regulates the surface albedo—a leading-order term in the global energy budget (Goosse et al., 2018); it caps the ocean to modulate air–sea exchanges of momentum, heat, water vapour, and carbon dioxide (Martinson and Wamser, 1990; Vichi et al., 2019; Droste et al., 2025); it is a habitat for a wide variety of animals, including many iconic species (Arrigo, 2017; Schofield et al., 2024); it acts to buffer ice shelves from the ocean, stymieing ice shelf collapse and subsequent sea level rise (Massom et al., 2018); it provides a vital contribution to the ocean circulation system through seasonally modifying freshwater content in the ocean surface (Haumann et al., 2016; Pellichero et al., 2018).

Understanding the relationship between Antarctic sea ice and ocean has become more pressing than ever. Whilst the top 2000 m of the global ocean, particularly in the SO, has consistently increased in temperature since ocean observation records began in the 1960s (Cheng et al., 2021), satellite-observations showed a

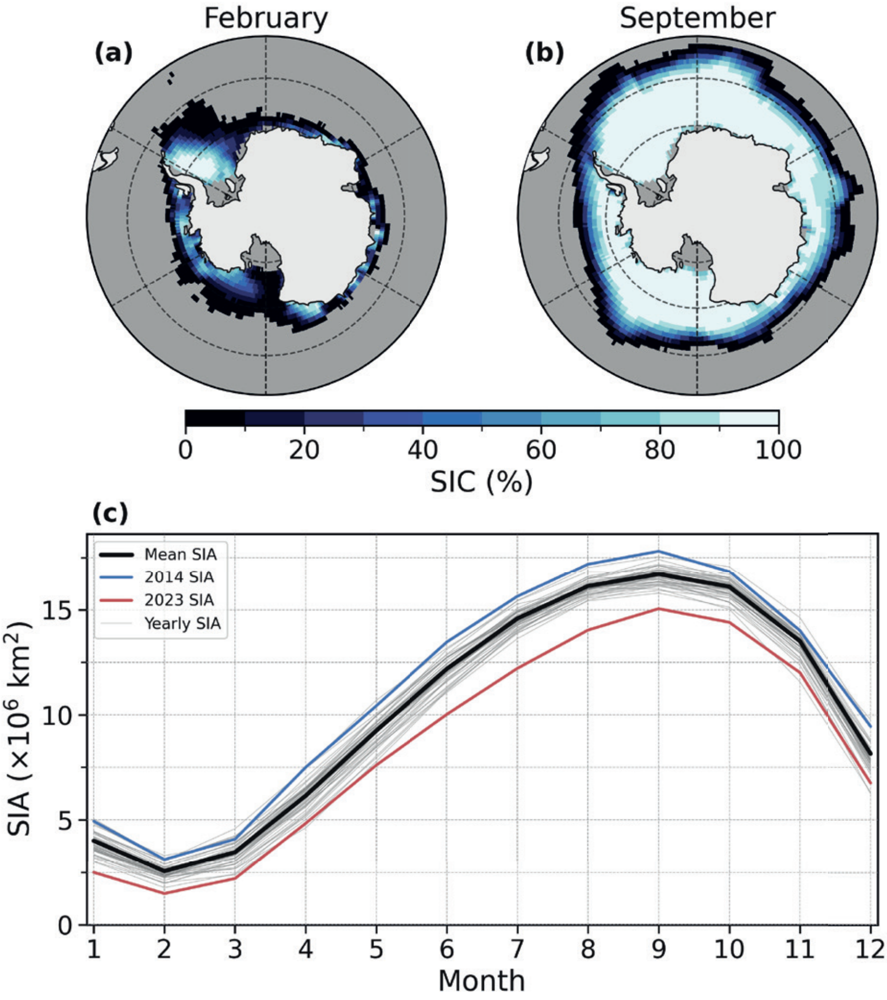

Figure 1.3: Mean sea ice concentration for (a) summer (February) and (b) winter (September) for November 1978–June 2024. (c) Monthly sea ice area: yearly (grey), climatological mean (black), and the years of satellite-record sea ice maximum in 2014 (blue) and minimum in 2023 (red).

counter-intuitive trend of sea ice expansion over a multi-decadal period (1978–2015; Fig 1.3c; Meehl et al., 2016; Turner et al., 2015). This sea ice expansion has been attributed to several different processes, including strong winds driven by various climate modes (P. R. Holland and Kwok, 2012; W. R. Hobbs et al., 2016) and ozone depletion (Ferreira et al., 2015) to increase the rate of sea ice distribution (Roach et al., 2023), as well as changes in ML freshwater content from elevated ice shelf meltwater input (Bintanja et al., 2013) and varying meltwater input from changes in sea ice distribution (Haumann et al., 2020).

These freshwater inputs strengthened stratification in the upper ocean, acting to prevent the mixing of the deeper and naturally warmer waters with the surface layer. This allowed an accumulation of heat and salt over multiple decades (Haumann et al., 2020).

Then, in August 2015, sea ice rapidly declined from satellite-record highs to satellite record-lows in summer (December–February) 2016/17 (Turner et al., 2017). Since then, sea ice has remained low, with increased year-to-year variability but weaker links to atmospheric climate modes (W. Hobbs et al., 2024). This culminated in year-round record lows throughout 2023 (Fig 1.3c; Josey et al., 2024). Consequently, it has been suggested that the sea ice system has entered into a new regime of lower, more variable sea ice coverage (Eayrs et al., 2021; Fogt et al., 2022; Raphael and Handcock, 2022; Purich and Doddridge, 2023).

However, climate models have largely failed to replicate satellite-observed changes in Antarctic sea ice and hydrographic-observed ocean structure. Most climate models in the Climate Model Intercomparison Project Phase 6 (CMIP6; Eyring et al., 2016) do not capture the observed sea ice expansion, ocean surface cooling, or ocean subsurface warming in recent decades (Beadling et al., 2020; Roach et al., 2020), and similarly struggle to reproduce the subsequent rapid decline in sea ice (Diamond et al., 2024). This model–observation mismatch leads to substantial uncertainty in the future projections of sea ice coverage and ocean properties, leading the IPCC to rate confidence in simulated Antarctic sea ice trends as "low" (Meredith et al., 2019; Masson-Delmotte et al., 2021). Furthermore, many models poorly misrepresent MLs in climate models (J.-B. Sallée et al., 2013), dense bottom waters (Heuzé, 2021), and meridional ocean transport (Beadling et al., 2020). These limitations suggest that key components of the SO circulation and water mass structure are likely not well resolved in current climate models. This mismatch of observed and modelled properties may stem from unresolved processes in the ice–ocean system, particularly those governing the vertical exchange of properties such as stratification.

## 1.3 Water Mass Structure and Antarctic Winter Water

Sea ice-driven freshwater changes in the mixed layer (ML) impact the vertical density structure, and play a role in the formation of various water masses in the SO, including Antarctic Winter Water (WW) (Abernathey et al., 2016; Pellichero et al., 2018). Wintertime MLs deepen through buoyancy loss via atmospheric cooling to form the cold WW (Figure 1.4a). Concurrently, sea ice formation increases salinity in the ML from brine rejection. This increases ML density, deepening the ML to entrain heat and salt from the underlying Circumpolar Deep Water (CDW) (Gordon and Huber, 1984; Pellichero et al., 2017). This entrainment can enhance sea ice melt, freshening the surface and limiting further deepening—a negative feedback (or self-regulating loop) that typically maintains sea ice thickness to 1–2 m (Bocquet et al., 2024) and the under-ice ML to less than 200 m depth (Martinson, 1990; Biddle and Swart, 2020; Wil-

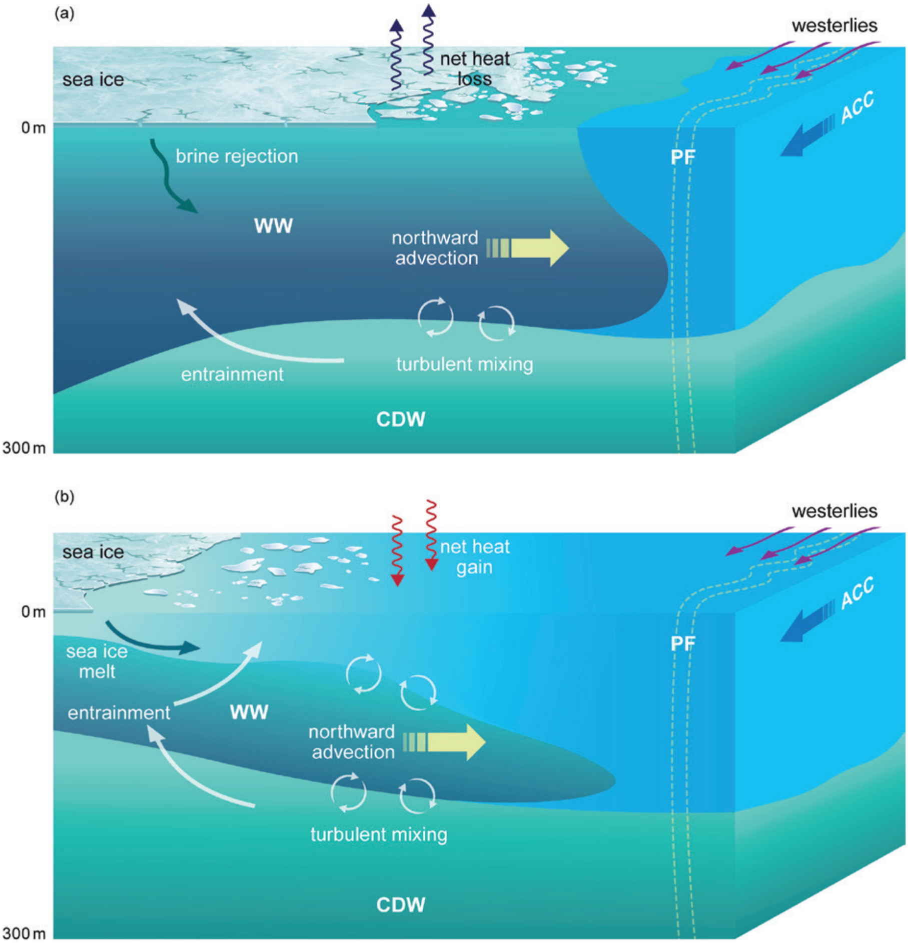

Figure 1.4: Conceptual view of Antarctic Winter Water. (a) $\mathrm{WW_{ML}}$ in wintertime and (b) $\mathrm{WW_{SS}}$ in summertime following summertime mixed layer restratification. Shown are the various physical mechanisms that impact the formation, distribution and erosion of WW. From **Paper I**.

son et al., 2019). With the progression from winter to summer, the atmosphere acts to warm the ocean. Consequently, the summertime ML shoals to become warm and fresh with a depth of only tens of meters (Pellichero et al., 2017). This leaves a residual cold layer beneath: the canonical (subsurface) WW (Figure 1.4b; Mosby, 1934; Toole, 1981; Sharma and Mathew, 1985; Hoppema et al., 1995), the remnant wintertime ML, and thus creates a warm–cold–warm layering of ML–WW–CDW.

WW acts as an intermediary between the ML and the ocean interior, residing on top of the relatively warm and salty CDW. Consequently, WW plays a critical role in the SO overturning circulation system. Through mixing, WW cools and freshens upwelled CDW, which is then advected northward in the upper ocean before it is subducting near the ACC to form Antarctic Intermediate Water (Fig 1.2; Evans et al., 2018; Klocker et al., 2023). Thus, WW facilitates the transformation of deep waters to intermediate waters, with its properties shaped through seasonal ocean–ice–atmosphere interactions (Evans et al., 2018; Giddy et al., 2023; Klocker et al., 2023; Sabu et al., 2020).

The vertical structure of the ocean controls its stratification, which is the difference in density between between layers of the ocean (e.g., Fig 1.2). These density differences indicate the amount of energy required to mix between layers. Stratification is often strongest at the interfaces between water masses, such as the ML–WW or WW–CDW boundaries (Giddy et al., 2023). These boundaries regulate the exchange of heat, salt and carbon between the deep ocean and the surface. Thus, the properties and thickness of WW can shape how much subsurface heat from CDW can access the surface to melt sea ice, and how ocean–ice feedbacks can influence the strength and structure of the global overturning ocean circulation system.

Yet, Winter Water has not been systematically described. There has been work providing regional descriptions from observations (Sabu et al., 2020) and glider-based process studies (Giddy et al., 2023). Model-based studies have shown the importance of stratification at the base of the Winter Water layer for season-to-season variability of sea ice (Libera et al., 2022)

## 1.4 Objectives

This thesis is guided by the central hypothesis that Antarctic Winter Water is a crucial stratification barrier that impacts the rate of heat and property exchange between the cool and fresh ML and the warm and salty CDW in the ocean interior. Through this role, WW modulates ocean–ice connectivity, and may have been integral in ocean-driven heat fluxes that contributed to recent changes in Antarctic sea ice. We address this hypothesis throughout this thesis in the following four hydrographic observation-based studies:

**Paper I:** Identify and characterise the spatial and temporal distribution of Antarctic Winter Water from a seasonal climatological perspective, and contextualise its role within the overturning ocean circulation system.

**Paper II:** Investigate the role of Antarctic Winter Water in the transition to the "new sea ice state", highlighting Winter Water as critical in regulating ocean heat exchange.

**Paper III:** Assess regional differences in ocean–ice coupling around the Southern Ocean based on spatial variations in water masses (WW and CDW) and sea ice structure.

**Paper IV:** Examine how iceberg melt modifies Antarctic Winter Water in the Weddell Sea, emphasising potential climate change implications.

I outline **Papers I–III** in Chapters 3–5, respectively. I synthesise the key findings and pose some open questions in Chapter 6, which includes a brief description of the importance of **Paper IV**'s findings under the context of climate change. I detail the data and methods used in Chapter 2. Lastly, I include some other experiences that have shaped my Ph.D. at Göteborgs universitet in Chapter 7.

Chapter 2

# Data and Methods

## 2.1 A Brief History of Hydrographic Data

Hydrographic data are notoriously difficult to obtain. The ocean interior is inaccessible to satellites and remote sensing, unlike the atmosphere or Earth surface. Harsh sea states and weather conditions, particularly in the Southern Ocean (SO), make ship-based research challenging—on top of the large monetary expense and carbon usage. Consequently, hydrographic data collected prior to the 2000s were sparse and limited to ship tracks in discrete locations, leaving vast areas of the ocean unobserved (Brett et al., 2020; Wunsch, 2016).

The first recorded water samples below the ocean surface were taken in the Southern Ocean in 1770s by James Cook (Cook, 2021; Abraham et al., 2013). Despite these early efforts, systematic data collection didn't begin until over 150 years later. In the 1950s, ship-based CTD (conductivity, temperature, depth) instrumentation was developed to provide continuous vertical profiles of salinity and temperature in the ocean. The widespread adoption of CTDs as onboard equipment on research vessels (e.g. Fig 2.1m) along with a growing recognition of the ocean's role in the climate system led to the launch of the World Ocean Circulation Experiment (WOCE) in 1990—the largest internationally coordinated oceanography experiment to date (Chapman, 1998). WOCE aimed to systematically observe the ocean, establishing and coordinating regularly repeated transects of CTD measurements as well as basin-scale measurements. These data revealed that subsurface ocean properties vary in time and space, providing a critical baseline for tracking long-term changes and often used as a benchmark for measuring climate change (Levitus et al., 2000). The WOCE programme inspired and grew in several directions to influence many other climate programmes and ocean observing system initiatives, including the Climate and Ocean: Variability, Predictability, and Change (CLIVAR), Global Ocean Observing System (GOOS), and SOCAT (Surface Ocean $CO_2$ Atlas).

WOCE was followed by the advent of the Argo programme in 1999, which revolutionised hydrographic data collection (Roemmich et al., 2009). Argo's autonomous profiling floats (Fig 2.1n ) are often deployed from ships and collect vertical profiles whilst they are steered by ocean currents. They sample on multi-day cycles for multiple years and return data via satellite. These floats can carry a suite of different sensors to measure temperature, salinity, pressure (CTD), biogeochemistry, and velocity. The Argo programme aims to have a 3° × 3° coverage of the global ocean with at least 3000 active floats at any one time (Roemmich et al., 2009). As such, Argo floats have dramatically increased the spatial and temporal coverage of ocean observations at a fraction of the cost of continuous ship-based campaigns.

In parallel, animal-borne sensing has extended observational reach in polar regions. Programmes such as Animal Borne Ocean Sensors (AniBOS; McMahon et al., 2021) and the Marine Mammals Exploring the Oceans Pole to Pole consortium (MEOP; Treasure et al., 2017) began in the early 2000s. MEOP uses small CTD loggers that are temporarily tagged onto marine mammals, particularly seals (Boehme et al., 2009). These animal-borne sensors collect data in ice-covered regions that are otherwise inaccessible to floats and ship-based measurements (Fig 2.1). The sensors transmit data via satellite and, when recovered, can provide high-resolution datasets, which offer unique insights into the under-ice ocean.

The SO remains particularly challenging to observe, with wintertime sea ice and weather hampering accessibility and data collection. It has been referred to as a "data desert" due to its sparse observational coverage (Meredith, 2019). Since 2004, autonomous floats have provided monthly observations from across the circumpolar SO, complemented by seasonal data coverage from MEOP seal tags (Fig 2.1). While seal-based data are more seasonal and regionally clustered due to their behaviour, they provide unique insight into under-ice ocean conditions in regions otherwise inaccessible to other platforms. Advancements in ice detection algorithms have likewise extended the life and capabilities of floats in high latitudes (Wong and Riser, 2011). Consequently, seasonal hydrographic data coverage has drastically improved across the SO since the early 2000s (Fig 2.1).

## 2.2 Southern Ocean Dataset Summary

To investigate hydrographic properties in the SO, we collated as much open-source data from 40 °S and poleward as feasibly possible, which comprises of Argo (Wong et al., 2020), MEOP (Treasure et al., 2017), SOCCOM (SOCCOM, 2019), as well as ship-based CTD and glider data from World Ocean Database (Boyer et al., 2018). We only use data flagged as "good" or "under sea-ice" for all data sources. Following Wilson et al. (2019), we further quality control the data such that each profile contains at least five measurements in the top 300 dbar with at least one data point in the top 25 dbar to ensure representation of the upper ocean, ensuring both the ML and majority of WW properties are captured. Profiles containing unrealistic values of potential temperature and

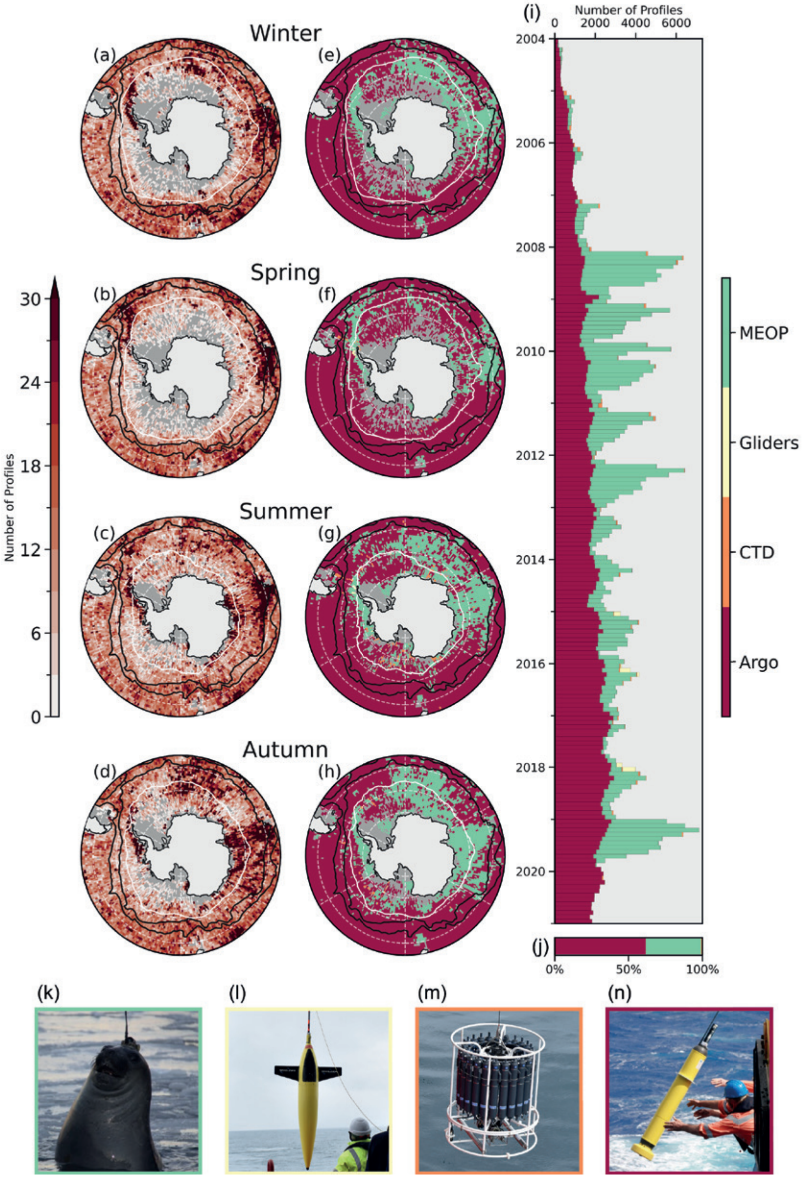

Figure 2.1: Hydrographic data distributions. (a–d) Spatial distribution of the total number of hydrographic profiles per season from winter through to autumn, respectively. (e–h) Spatial distribution of the most frequent data source per grid cell. The black contours indicate the Polar Front and Subantarctic Front, and the white lines are the mean 15% sea ice concentration for the relevant season in (a–h). (i) Monthly time series of data sources (stacked) across the Southern Ocean. (j) Total proportion of data per data source as a percentage. Examples of the instrumentation are shown: (k) a tagged seal (image from meop.net), (l) Seaglider, (m) rosette-mounted CTD, (n) Argo float (image from CSIRO). Note that Argo includes all floats—Argo and SOCCOM. Adapted from **Paper I**.

practical salinity are removed such that -2.5 < T < 16 °C and 30 < S < 36. These thresholds are obtained from the observed range of properties south of the Subantarctic Front. Consequently, there remain 620,293 quality-controlled CTD profiles—a dataset that is openly available (Spira et al., 2023).

We linearly interpolated these profiles for uniformity to a 2 dbar vertical gridding and smooth vertically using a Guassian fit in temperature and practical salinity before conducting analysis from 10–1000 dbar. We compute Conservative Temperature, Absolute Salinity and other oceanographic properties using the Gibbs SeaWater Oceanographic Toolbox of the Thermodynamic Equation Of Seawater - 2010 (TEOS-10; Ioc et al., 2010). The linearly interpolated MEOP data have an error of ±0.04 °C for temperature and ±0.03 g/kg for salinity (Siegelman et al., 2019), whilst float data after delayed mode post-processing have errors of ±0.002 °C in temperature and ±0.01 psu ~±0.01 g/kg in salinity (Wong et al., 2020).

All hydrographic properties, unless stated otherwise, are computed per hydrographic profile—for example, water mass properties.

## 2.3 Water Mass Identification

Throughout this thesis, we analyse various water masses, with a large focus on WW. Here, I outline the methods used for identification of the various water masses, including the development of a WW detection algorithm and the density-based criterion for mixed layer depth (MLD) and CDW identification.

We compute the MLD following a density difference criterion such that $\rho(z_{\mathrm{MLD}}) - \rho(10) = 0.03$ kg m$^{-3}$ (de Boyer Montégut, 2004).

We characterize WW into two classifications: mixed layer WW (WW$_{\mathrm{ML}}$, Fig 1.4a) and subsurface WW (WW$_{\mathrm{SS}}$, Fig 1.4b). WW$_{\mathrm{ML}}$ is defined as constrained to mixed layer (ML), taking the upper bound as the ocean surface and the lower bound as the MLD. We assume the ML is well-mixed, and therefore take the mid-depth of MLD as the WW core depth, whilst the core properties are defined as the mean properties across the ML. WW$_{\mathrm{SS}}$ only exists if there is a temperature inversion below the ML. That is, WW$_{\mathrm{SS}}$ only exists if there are at least 10 inversions, spanning 20 m, between the mean ML temperature and subsurface temperatures. We describe WW$_{\mathrm{SS}}$ through its core properties (the temperature minimum, the depth at which the temperature minimum occurs, as well as the salinity and density at that depth) and thickness (difference in depth between upper and lower boundary).

WW only exists if the core temperature is below 2 °C since this temperature denotes the boundary for the PF at 200 m depth (Belkin and Gordon, 1996; Morrow et al., 2008; Pollard et al., 2002). The PF is a baroclinic barrier to WW, marking the transition from saline- to thermally-dominating regimes in the upper ocean, which determines the existence of temperature inversions (Orsi et al., 1995; Stewart and Haine, 2016; Caneill et al., 2024). If the temperature at the lower bound is warmer than 2 °C, the 2 °C isotherm depth is used as

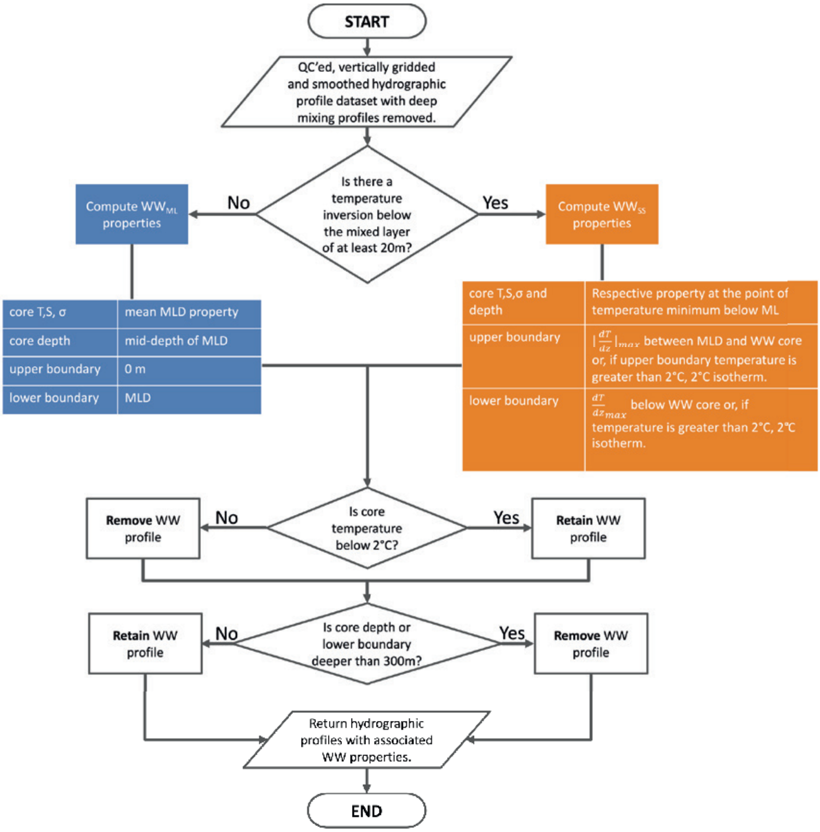

Figure 2.2: Flowchart summarising Antarctic Winter Water algorithm computation. From **Paper I**.

the WW lower boundary instead. Further, if the core depth is deeper than the lower bound depth, we conclude no WW exists in that profile. Similarly, if the core temperature is warmer than 2 °C then we conclude no WW exists in that profile. The lower boundary and, or core depth of WW can feasibly reach depths below 300 m, for example via deep convection cells as a result of polynya driven processes, which typically are found close to the Antarctic continent (Morales Maqueda et al., 2004; Tamura et al., 2008; Mohrmann et al., 2021; Whitworth et al., 1994). However, these processes are associated with deep water formation (Jacobs, 2004; Johnson, 2008; Kusahara et al., 2017; Meredith, 2013), and therefore associated with dynamics outside the scope of this study. WW is otherwise typically found in the bounds of 50–200 m (Lund et al., 2021; Sabu et al., 2020). Hence, WW profiles with a lower boundary deeper than 300 m are removed.

In total, 43% (266,856 profiles) of all profiles contain WW: 105,588 $WW_{ML}$ profiles and 161,268 $WW_{SS}$ profiles. We summarise the algorithm using the flowchart in Fig 2.2.

To identify CDW, we used potential density anomalies ($\sigma_0$). The upper CDW boundary and CDW core correspond to $\sigma_0 = 26.67$ kg m$^{-3}$ and $\sigma_0 = 26.74$ kg m$^{-3}$, respectively. These isopycnal surfaces correspond to the neutral density surfaces $\gamma^n = 28.00$ kg m$^{-3}$ and $\gamma^n = 28.10$ kg m$^{-3}$, respectively (Narayanan et al., 2023). If the upper CDW is shallower than the WW lower boundary, the CDW upper boundary is adjusted to match the WW lower boundary. We identify 212,845 profiles that contain CDW.

## 2.4 Gridding, Masking, and Anomalies

All hydrographic data are then gridded to 1° by 1° latitude–longitude median seasonal climatologies (**Paper I** and **II**) or monthly time series (**Paper II** and **III**). In **Paper I**, we base the seasons on annual sea ice evolution, thus representing austral summer as January to March, and so on (P. R. Holland, 2014; Goosse et al., 2023). In **Paper IV**, we grid instead to a 0.5° by 0.5° grid coverage for an extended summer climatology defined as the months January to April to include months of known iceberg activity, whilst removing years of known large iceberg proximity in the Weddell Sea (2004, 2015, 2021; Budge and Long, 2018). In **Paper II** and **III**, we mask data to the seasonally ice-covered SO (seasonal ice zone; SIZ) by: (i) taking hydrographic observations north of the 2000 m isobath to exclude regions of deep water formation and continental shelf processes (Orsi et al., 1999); and (ii) taking south of either the 0 °C WW core temperature or the Polar Front if it is further south than the 0 °C isotherm, which represents the northern boundary of the maximum sea ice extent (Goosse et al., 2025).

Following gridding, we compute anomalies such that $X' = X - \overline{X}$, where $\overline{X}$ is the annual mean in **Paper I** and the climatological monthly mean in **Paper II** and **III** for each grid cell and depth level. To account for meridional variation in grid cell size, weighted means are computed and reported in **Paper II** and **III**, using $\bar{X}_w = \frac{\sum_i w_i X_i}{\sum_i w_i}$.

## 2.5 Wind-driven Mixing

Vertical diffusion is a key mechanism that enables mixing between different ocean layers. It plays a critical role at the boundaries between water masses, where properties like heat and salt are exchanged (Osborn, 1980; Marshall et al., 1999; Thorpe, 2005; Groeskamp et al., 2016). At the ML base, rates of diffusion are particularly high due to a combination of factors, including wind-driven turbulence, strong air–sea exchange, tides, and other dynamic processes (Gregg et al., 2018). For mixed layer heat and salinity budgets, the vertical diffusion coefficient is often taken as a constant ($\kappa = 10^{-5}$ m$^2$ s$^{-1}$; Cisewski et al., 2005; Pellichero et al., 2017). However, this assumption oversimplifies the widely varying rates of diffusion across time and space in the SO (Ledwell et al., 2000; Thompson et al., 2007; Park et al., 2014; Laurent et al., 2012). Dissipation, a measure of how much energy is available for mixing in the water column, can be estimated theoretically from ocean surface stress (Osborn, 1980; Large et al., 1994). Theoretical dissipation rates strongly correlate with observed dissipation rates in the Southern Ocean in summertime (Nicholson et al., 2022; du Plessis et al., 2022; Giddy et al., 2023). Thus, turbulent mixing rates at the base of the mixed layer can be estimated using ocean surface stress data. In **Paper I** and **II**, we use wind stress re-analysis output to approximate dissipation following the law of the wall (von Kármán, 1931). Dissipation directly relates to diapycnal diffusivity—that is, diffusion rates across density gradients. Therefore, this relationship enables the estimation of vertical heat transfer (or other properties) at the mixed layer base.

Since measurements of dissipation are sparse in the global ocean and SO, we cannot validate these estimates. Similarly, the methodology does not account for other possible factors that contribute to mixing, such as convection or other sources of turbulence (Marshall and Schott, 1999; Fernandez Castro et al., 2022; Bisits et al., 2025). Whilst the methodology is novel and provides unique upscaling of a known relationship, the estimates of wind-driven mixing should be interpreted with caution.

## 2.6 Other Data

I used various other datasets throughout the works in this thesis to supplement the core dataset of hydrographic profiles for various purposes.

We used monthly 25 by 25 km sea ice concentration data from NSIDC (Meier et al., 2021). We compute sea ice area by multiplying sea ice concentration by grid cell area (Notz et al., 2016). We then interpolated to the respective time binning and 1° by 1° grid, which we used to compute any further analysis.

To identify the SAF and PF of the ACC at absolute dynamic topographies of $-0.1$ m and $-0.58$ m respectively (Park et al., 2019) from monthly AVISO altimetry data. We also use this altimetry data to transform from a latitude–longitude coordinate system to an ADT–longitude system. We use bathymetric data from the International Bathymetric Chart of the Southern Ocean (Dorschel et al., 2022). The components of the net surface heat flux ($Q_{SW}$, $Q_{LW}$, $Q_{lat}$, $Q_{sen}$), precipitation and evaporation, and the eastward and northward turbulent wind stresses for the computation of friction velocity are obtained at monthly and 0.25° resolution from ERA5 reanalysis of the European Centre for Medium-Range Weather Forecasts (Hersbach et al., 2023). These properties are interpolated onto a mean 1° by 1° resolution for co-location with hydrographic gridding.

## Chapter 3

# What is the Role of Antarctic Winter Water in the Overturning Circulation System?

Winter Water (WW) is a cold subsurface water mass formed in the Southern Ocean (SO) south of the Polar Front (PF), where salinity variations dominate changes in density (Roquet et al., 2022) and allow the existence of a vertically stable density profile to contain temperature inversions. It forms in the deep and cold wintertime ML and persists in summertime following ML restratification as a cold subsurface tongue. During this process of formation and subduction, WW mixes with subsurface Circumpolar Deep Water (CDW) (Evans et al., 2018; Groeskamp et al., 2016) and advects northward, eventually subducting around the PF to form Antarctic Intermediate Waters (Klocker et al., 2023; Gonzalez et al., 2025). However, WW had not previously been investigated from a circumpolar perspective. The mixing of WW with the subsurface was largely implied through mixing with the surface layer, but understanding WW as the conduit for connecting ocean circulation from observations was yet to be understood.

Here, I present a circumpolar, climatological characterisation of WW based on results from **Paper I**. We developed and applied a WW detection algorithm to individual hydrographic profiles, which distinguished WW into two classes: WW in the mixed layer ($\mathrm{WW_{ML}}$) and WW below the mixed layer (subsurface WW, $\mathrm{WW_{SS}}$; Fig 3.1). We then produce $1^\circ \times 1^\circ$ seasonal climatologies for various WW properties—see Chapter 2.3 for details. I describe its typical annual and spatial evolution in various properties (Fig 3.2), as well as determine regional overturning pathways that export WW properties northward, connecting the polar SO to the global ocean (Fig 3.3).

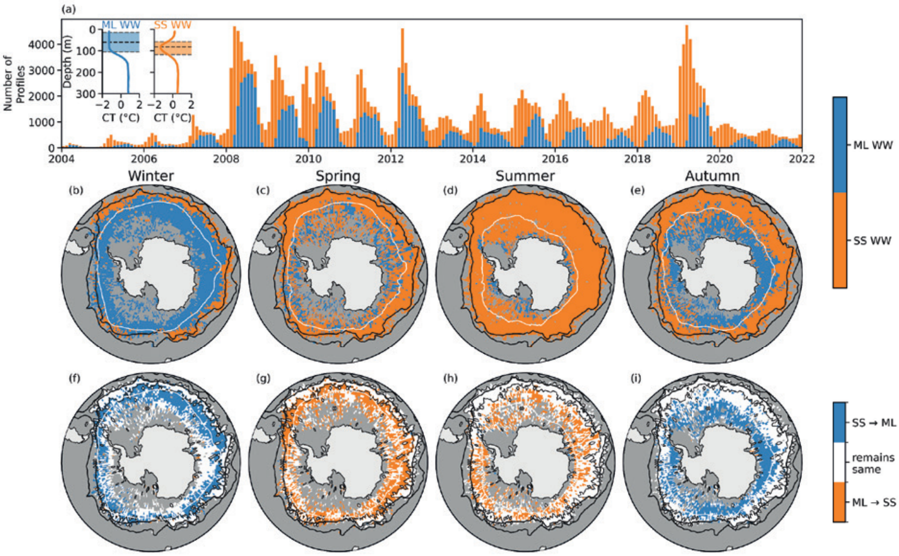

Figure 3.1: Classification of Antarctic Winter Water. (a) Monthly time series of WW classification (stacked) across the Southern Ocean. Inset in the top left of (a) are example profiles of detected mixed layer Winter Water (blue) and subsurface Winter Water (orange). (b–e) Spatial distribution of the modal average WW classification per season from winter through to autumn, respectively. (f–i) show the newly formed classification of WW for each season. The thin black contours around white areas show regions where the WW classification remains the same for all seasons. In (b–i), the thick black contours indicate the Polar Front and Subantarctic Front, and the white lines are the mean 15% sea ice concentration for the relevant season. Adapted and extended from **Paper I**.

## 3.1 Antarctic Winter Water Detection

We found that WW forms and erodes with the seasonal cycle, as expected (Fig 3.1). The number of WW profiles detected varies with the quantity of hydrographic profiles for that period; for example, far more WW was detected in the years 2008–2013 when there was a greater MEOP coverage than in other periods. The annual evolution of WW aligns with the sea ice cycle (Fig 3.1b-e): during winter, the ocean loses heat to the intensely cold atmosphere beyond the sea ice edge (Fig 3.1b). Consequently, the ML deepens through buoyancy loss from surface cooling and brine rejection from sea ice formation, forming a substantial portion of wintertime $\mathrm{WW_{ML}}$ (Fig 3.1f; Pellichero et al., 2017; Wilson et al., 2019). As sea ice melts in spring, the ML restratifies and shallows due to a positive net heat flux from the atmosphere and subsequent freshwater input from sea ice melt (Fig 3.1c), leaving a remnant cold layer below the ML and forming of the majority of the seasonal $\mathrm{WW_{SS}}$ (Fig 3.1g). Below sea ice (south of the 15% sea ice concentration contour), there is a patchy mixture of $\mathrm{WW_{SS}}$ and $\mathrm{WW_{ML}}$ as the summertime ML hasn't fully restratified. The SO becomes almost totally homogenous as $\mathrm{WW_{SS}}$ in summer, when sea ice melts to its lowest extent and the circumpolar ML shoals (Fig 3.1d)—only coastal regions associated with remaining high sea ice cover (Fig 1.3a) remain $\mathrm{WW_{ML}}$. This homogenous summertime season is important as it means all wintertime ML properties have been isolated from the ocean surface into the ocean interior. During autumn, the onset of atmospheric cooling and sea ice expansion drive a deepening of the ML and re-emergence of $\mathrm{WW_{ML}}$ below sea ice, while $\mathrm{WW_{SS}}$ is either eroded or re-entrained into the ML. Interestingly, there is a region on the circumpolar northern perimeter close to the PF (Fig 3.1f–3.1i) that does not form $\mathrm{WW_{ML}}$ yet remains $\mathrm{WW_{SS}}$ throughout the entire annual cycle; this is likely indicative of advective processes taking place to transport subsurface cold water northwards and thereby sustaining this region to contain only $\mathrm{WW_{SS}}$ (Morrison et al., 2016).

## 3.2 Antarctic Winter Water Seasonality

We summarise the seasonal cycle of WW from **Paper I** in Fig 3.2 by presenting the mean and the standard deviation of the seasonal climatologies, which represents the broad scale changes that take place across the annual cycle. Core properties are defined as properties at the temperature minimum for $\mathrm{WW_{SS}}$, whilst mean properties for $\mathrm{WW_{ML}}$. Core depth in $\mathrm{WW_{ML}}$ is taken as mid-depth.

Core temperature (Fig 3.2a) is largely homogenous below sea ice (south of 15% sea ice contour) since the atmosphere gets cold around the entire SO, and therefore the surface layer ubiquitously cools. The Weddell Gyre and Ross Gyre both sustain cold core temperatures to more northern extents as a result of topography sheltering the flow and enabling gyre circulation to redistribute cold water throughout the gyre regions (Jones et al., 2023; Patmore et al., 2019). There is a northward gradient of increasing temperature across the circumpolar SO. However, there are observed regions that remain cold and typically align with large topographic features. Core temperature largely varies around the annual cycle (Fig 3.2b) close to the sea ice edge since these are regions that experience the most change in exposure to atmosphere, and therefore experience most the variability of atmospheric forcing. The gyre regions, remain largely homogenous for similar arguments to previously: the gyre circulation sustains cold WW for the majority of the gyre regions and experience most variability at the gyre boundaries.

Core salinity (Fig 3.2c) is more saline below sea ice due to sea ice formation driving brine rejection into WW. The Weddell Gyre is greater in salinity due to producing a large quantity of sea ice, whilst the eastward limb of the Weddell Gyre has elevated salinity due to higher rates of mixing with the underlying CDW (Jones et al., 2023; Groeskamp et al., 2016). Sea ice production is also elevated along the coast of Eastern Antarctica resulting in the higher salinity signals (Timmermans et al., 2008) leading to higher core salinties. The Amundsen and Bellingshausen Seas (ABS) are far fresher than the rest of the under-ice SO. The proximity of the ABS to the energetic ACC and to the east-

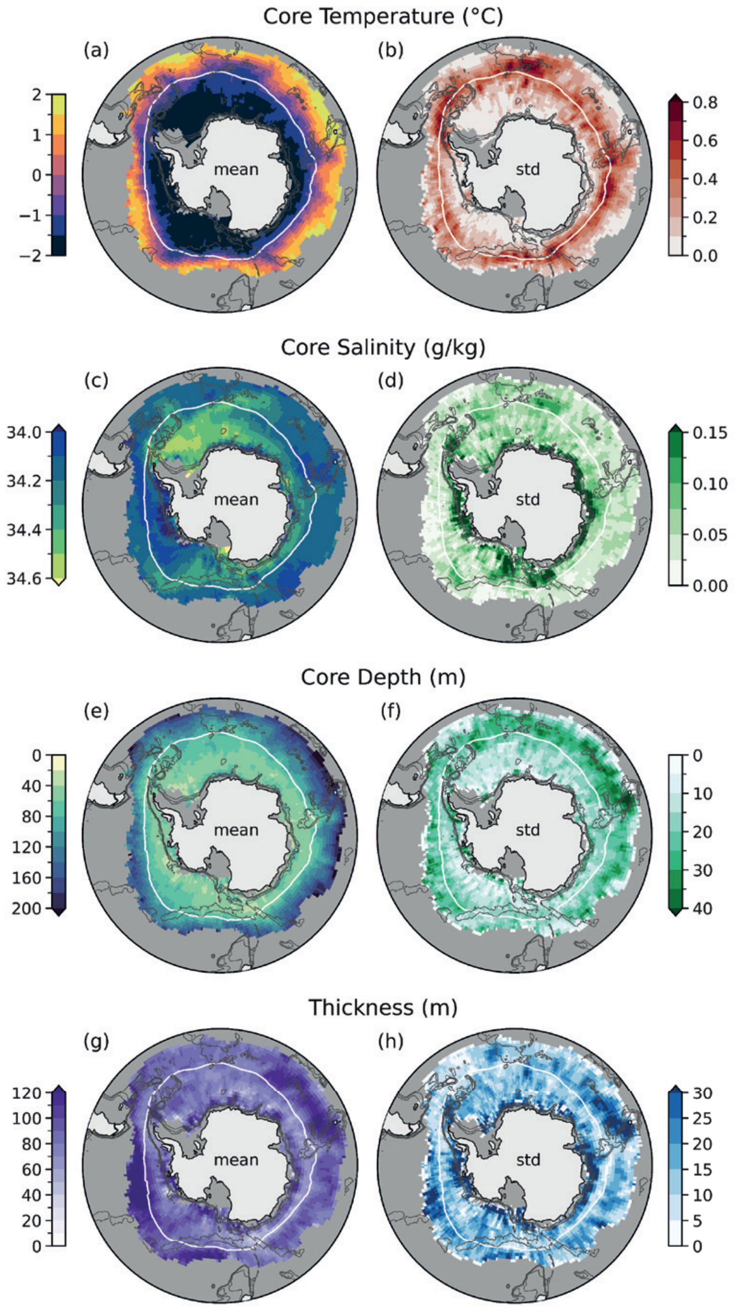

Figure 3.2: Summary of Seasonal Antarctic Winter Water Properties. Annual mean and standard deviation, respectively, of WW: (a,b) core temperature, (c,d) core salinity, (e,f) core depth, and (g,h) layer thickness. The white line indicates the annual mean 15% sea ice concentration, and the grey contours indicate the 1,2,3 km isobaths. Winter Water properties are smoothed using a 3°×3° latitude–longitude rolling mean and interpolated across a maximum gap of three missing grid cells to the maximum Winter Water extent. Adapted from **Paper I**.

ward limb of the Ross Gyre transports warm CDW southwards to maintain the ABS as a warm shelf region (Tamsitt et al., 2021; Narayanan et al., 2023; Prend et al., 2024). Consequently, there are high rates of sea ice melt (Haumann et al., 2016). Likewise, it is a region of high iceshelf meltwater input (Rignot et al., 2013b), which results in a region of fresh WW layers. Similar to core temperature, core salinity decreases in salinity (freshens) in the northward direction. Yet again, there are northward regions with salinity values that are typically associated with under-ice conditions—the most clearly of which being displayed as an outstretching limb from the Weddell Gyre. Lastly, core salinity varies most across the seasonal cycle along the shelf break of Antarctica, which is driven by the variability of sea ice production in coastal polynyas (Fig 3.2d; Tamura et al., 2008).

Similar to core temperature and core salinity, seasonal mean core depth (Fig 3.2e) displays homogeneity below sea ice, with a latitudinal gradient of deepening core depth in the northward direction in the open ocean (north of the 15% sea ice concentration contour). The largest seasonal variability (Fig 3.2f), on the other hand, is north of the sea ice edge in the open ocean region, where core depth varies most as a function of changing from $\mathrm{WW_{ML}}$ to $\mathrm{WW_{SS}}$. This happens to a greater extent in the northern regions where WW has a deeper lower boundary since CDW resides deeper in the water column (see **Paper III**).

WW thickness (Fig 3.2g) is thick close to the Antarctic continent due to coastal polynyas that drive deep convection in the surface layer (Tamura et al., 2008). Below sea ice, WW thickness is otherwise largely homogenous and relatively thin. North of the sea ice edge, in the open-ocean zone, there are regions that thicken northward. Downstream of large topographic features, eddy kinetic energy (EKE) is heightened (Dove et al., 2022; Rosso et al., 2014; Stappard et al., 2025), resulting in elevated mixing rates and vertical velocities (Vilela-Silva et al., 2024). Consequently, WW remains thin in these regions; this is clear when comparing upstream of the Kerguelen Plateau (in the Weddell Sea) and downstream of Kerguelen Plateau. Likewise, the largest seasonal variability of WW thickness is associated with regions of thick WW layers (Fig 3.2h).

## 3.3 Export Pathways of Antarctic Winter Water

Mean WW properties exhibit broadscale characteristics that are relatively consistent throughout all properties across the SO: in the under-ice zone WW properties are quasi-homogeneous, and have meridional gradients in the open-ocean zone that, typically, increase in the northward direction. Downstream of large topographic features, properties associated with under-ice conditions appear to be transported northward, towards the PF. In order to further investigate the spatial drivers of the large-scale properties of WW, we transform WW core density from latitude–longitude coordinate space to absolute dynamic topography (ADT)–longitude space (Fig 3.3c).

The distribution of WW is largely constrained to along-stream transport (referring to along-ADT streamlines). For example, east of the Pacific Antarctic

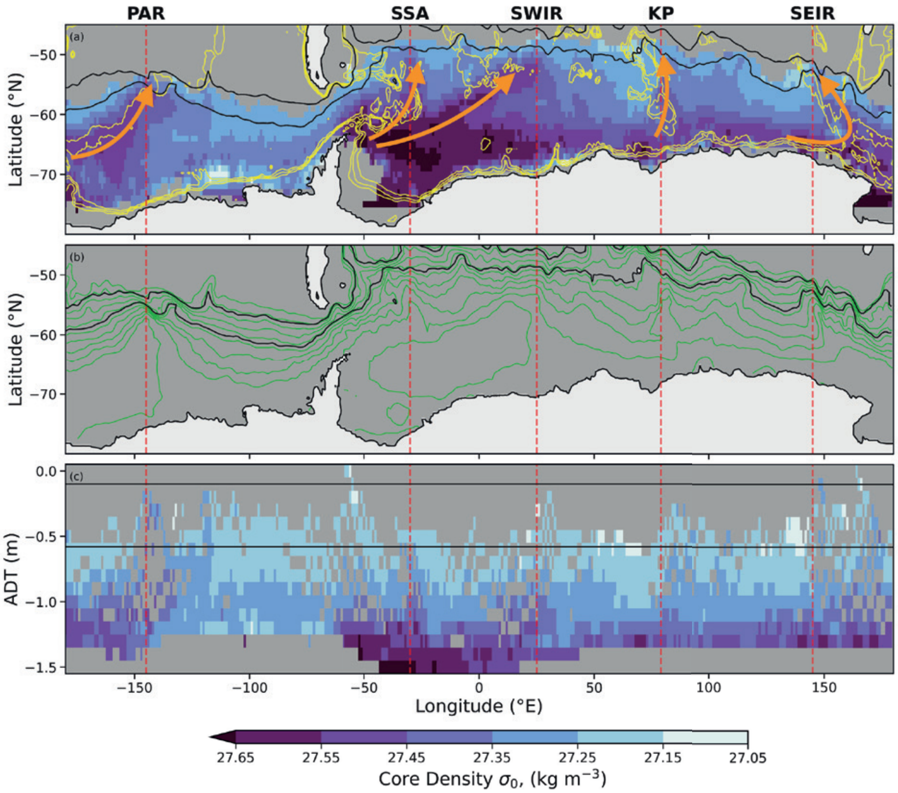

Figure 3.3: Antarctic Winter Water core density. (a) Annual mean WW core density. Yellow contours indicate 1km, 2km and 3km isobaths. Orange arrows indicate potential export pathways of Winter Water. (b) Absolute dynamic topography (ADT) streamlines are depicted in green. (c) Annual mean WW core density mapped onto ADT-Longitude coordinate space. (a–c) Black lines indicate the PF and SAF, and vertical dashed red lines show large topographic features. Adapted from **Paper I**.

Ridge to the Drake Passage, in the open ocean ABS, WW is lighter in density and tightly constrained to ADT contours. This is a region where there is deep ocean bathymetry and few topographic features (known as the Pacific Abyssal Plane), resulting in low interior mixing rates (Frants et al., 2013; Ledwell et al., 2011). Lower mixing rates reduces subsurface mixing with underlying CDW, maintaining lighter WW.

Locations of across-stream transport align with topographic features throughout the SO, with the strongest across-front signal observed at the Southwest Indian Ridge, which is a potential outflow region of the Weddell Gyre. The locations of elevated WW density extending equatorward reflect the pathways of northwards sea ice export (Haumann et al., 2016) and can potentially play a critical role in redistributing transformed CDW and sea ice-driven brine properties. Furthermore, WW core density reflects the northward advection of surface waters from the Weddell Sea where the South Sandwich Arch (SSA) is a region known for high rates of surface advection, as is reflected by iceberg pathways (so called 'iceberg alley', Budge and Long, 2018). Dense WW is transported northwards across the Pacific Antarctic Ridge, which is facilitated by the Ross Gyre; Zilberman et al., 2017 show similar findings of equatorward transport of ocean interior water masses such as Subantarctic Mode Water north of the ACC along large topographic features.

The regions of across-stream transport of WW coincide with the bathymetrically steered export pathways of Antarctic Bottom Water (Solodoch et al., 2022; Kusahara et al., 2017; Meredith, 2013; van Sebille et al., 2013). This also agrees with property transport preferentially facilitated by transient eddies, which are more likely present in regions of large bathymetric features and high EKE (Dove et al., 2022; Naveira Garabato et al., 2011; Wilson et al., 2022). In the ACC, eddies propagate and grow in regions where topographic features drive, split and destabilise the jets of the ACC (Thompson and Sallée, 2012). This drives stirring of the ocean, and facilitates the transport and locally elevated subduction of WW properties (Vilela-Silva et al., 2024; Gonzalez et al., 2025).

## 3.4 Summary

We compiled a substantial observational dataset to investigate the annual cycle of Antarctic Winter Water in **Paper I**. We propose several mechanisms to understand climatological variability in WW both at large scale (across circumpolar SO) as well as regionally by posing localised mechanisms to explain observed patterns.

We further support the seasonal transformation in the overturning system through a heat budget, which is presented in **Paper I**. The heat budget includes the development of the downward turbulent heat flux term's parameterisation—we apply the law of the wall for dissipation rates at the ML base (von Kármán, 1931) since theoretical and observed ML dissipation rates have been well correlated (Nicholson et al., 2022; du Plessis et al., 2022). This methodology is a development from previous approaches, which use a constant diffusion coefficient (e.g., Pellichero et al., 2017).

In this Chapter and in **Paper I**, we identify potential overturning pathways in localised regions to connect the polar SO to the global ocean, highlighting regions of elevated export of polar properties and the role of WW in the global ocean circulation system. This not only aids in addressing the IPCC Special Report on Cryosphere in a Changing Climate, which suggests a need for improving the understanding of the overturning circulation (Meredith, 2019), but develops the overturning system framework by providing further evidence to move away from the zonal, time-mean perspective (e.g., Fig 1.2).

**Paper I** is foundational in this thesis. The work identifies WW characteristics over the circumpolar extent of the SO, which provides context for the role of

WW in the SO system. This also sets the scene for investigating how WW has changed with time and how it impacts Antarctic sea ice.

Chapter 4

# Ocean–ice regime shift: a breakdown of the Winter Water barrier

## 4.1 A new sea ice regime?

Antarctic sea ice dynamics are in stark contrast to the Arctic. Often described as a litmus for climate change, Arctic sea ice has steadily decreased in sea ice cover since satellite records began, directly following carbon dioxide emissions (Stroeve and Notz, 2018; Notz and Stroeve, 2016). Antarctic sea ice, on the other hand, has shown a gradual net increase over multiple decades, reaching a satellite-record all-time high in 2014 (Fig 1.3c), along with monthly record highs in 2015. It then rapidly decreased to what was, at the time, a record-low coverage in summer 2016/17 (Fig 4.1). Sea ice cover has since remained in a low state, with year-round sea ice minima observed in 2023 (Fig 1.3c; Josey et al., 2024). This period of sustained low sea ice cover has been proposed as a new sea ice state (Eayrs et al., 2021; Purich and Doddridge, 2023; Raphael and Handcock, 2022), characterised by reduced duration of sea ice cover (Himmich et al., 2024), increased statistical variability, reduced connectivity with the atmospheric modes typically associated with Antarctic sea ice variability (W. Hobbs et al., 2024), and with sea ice anomalies more likely to persist from year-to-year rather than return to the climatological mean sea ice cover (Raphael et al., 2025).

This raises several puzzling questions: Why did sea ice around the Antarctic expand? Why did it then suddenly decrease? Why has it not recovered?

Indeed, in recent years these questions have received considerable attention. Sea ice expansion around Antarctica has been largely attributed to atmospheric anomalies, including shifts in atmospheric systems (P. R. Holland and Kwok, 2012; W. R. Hobbs et al., 2016), as well as changes in the Southern Annular Mode influenced by ozone depletion (Ferreira et al., 2015; Goosse et al., 2009) and anthropogenic forcing (Haumann et al., 2014). Meanwhile, long-term

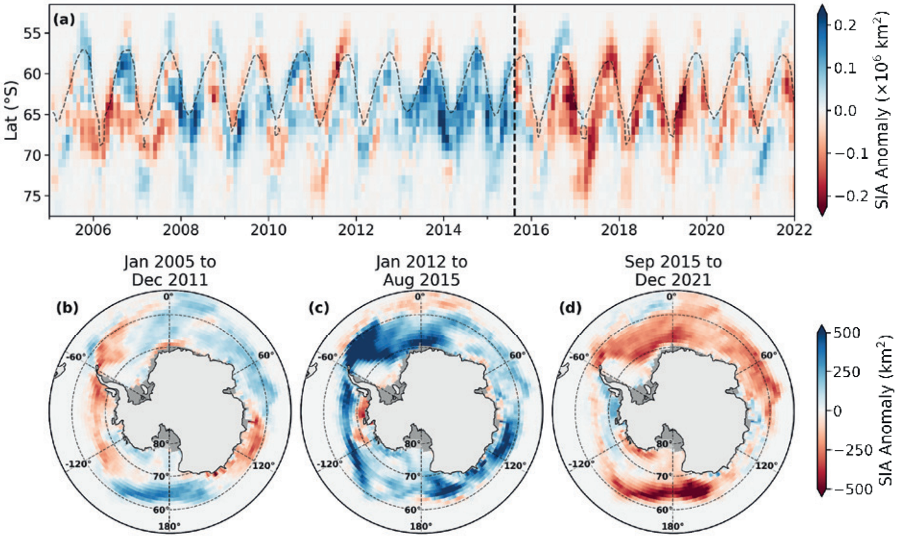

Figure 4.1: Changes in Antarctic sea ice cover. (a) Longitudinal-mean of Antarctic sea ice area anomalies. The dashed grey curve indicates the 15% sea ice concentration and the vertical deashed line denotes the transition from high sea ice cover to low sea ice cover (August 2015). (b–d) Mean sea ice area anomalies for the periods January 2005–December 2011, January 2012–August 2015, and September 2015–December 2021, respectively. From **Paper II**.

freshening and cooling of the ocean surface, alongside simultaneous heat and salt accumulation in the ocean subsurface, have been attributed to changes in near-surface winds and ocean surface freshwater content (Bintanja et al., 2013; Haumann et al., 2020; Roach et al., 2023). This change in vertical hydrographic structure elevated stratification and limited upward heat flux, while increasing the potential for future sea ice melt events (Silvano et al., 2025).

The initial sea ice minimum in 2016 has been linked to several atmospheric drivers, for example: a deep Amundsen Sea Low (Turner et al., 2017), a strong positive SAM phase (Stuecker et al., 2017; Schlosser et al., 2018; Schroeter et al., 2023), and various tropical influences (Meehl et al., 2019; Stuecker et al., 2017; Zhang et al., 2022). However, research into the persistence of the new low sea ice state has been less conclusive. The observed reduction in atmosphere–sea ice connectivity (W. Hobbs et al., 2024) suggests that the ocean is now playing a more prominent role. Indeed, coupled model simulations show that the ocean played a minor role in the initial sea ice low in 2016, but has been crucial for sustaining annual sea ice lows since (Zhang et al., 2022).

The release of the subsurface accumulated heat and salt to the ocean surface, and change in connectivity between ocean surface and deeper lying CDW may be critical to understanding recent Antarctic sea ice changes. In this section, we provide details on the role of Winter Water (WW) as a barrier between the cool and relatively fresh surface, and the warm and salty subsurface—where enhanced vertical gradients at the WW boundaries inhibit mixing (Giddy et al., 2023). Understanding upper ocean hydrographic changes and how WW evolved in the lead-up to and during the sea ice transition may provide essential insights into understanding the mechanisms underpinning this potential regime change.

Hence, in this section I outline key changes to observed hydrographic properties in the seasonal ice zone and their link to changes in sea ice area (SIA), summarising the findings from **Paper II**.

## 4.2 Hydrographic changes in the polar Southern Ocean

The change from high to low SIA was mirrored by changes in hydrographic properties (Fig 4.2). Between 2005 to 2012, the upper 300 m of the water column typically remained cooler than average (Fig 4.2c). Meanwhile, salinity showed more complex patterns, initially fresher than average throughout the water column, then saltier than average for the majority of the water column from 2007 to 2010 (Fig 4.2e). From 2010 to 2015, the ocean freshened in the WW layer and ML, while salinity increased below the WW layer. Consequently, stratification increased at the WW–CDW boundary (Fig 4.2g), and the strongest stratification was observed below WW in austral summer 2011/12. Similarly, from ~2012 to 2015, heat began to build up at a greater rate in the ocean interior, exhibiting a positive temperature anomaly below the WW layer.

Then, from 2015 onward, hydrographic properties within the upper ocean underwent drastic changes. WW warming was followed by rapid ML warming (Fig 4.2c), likely linked to reduced Ekman advection of cold polar waters and shallow MLs (Wilson et al., 2023). Beneath the WW layer, where CDW resides, initially decreased in temperature then remained warm for the majority of the 2017–2022 period. This is potentially linked to the subduction of warm surface layer properties (Doddridge et al., 2025; Goosse and Zunz, 2014; Doddridge et al., 2021; Lecomte et al., 2017). Salinity increased in the ML, agreeing with sea surface salinity products (Silvano et al., 2025). WW also increased in salinity, but it decreased in CDW, remaining anomalously fresh over the subsequent years (Fig 4.2e). These subsurface cooling and freshening trends, alongside concurrent surface salinification, suggest vertical exchange of properties between ocean surface and interior. Consequently, stratification was lower than average from late 2015 to 2022 (Fig 4.2g) with two major exceptions. The summers of 2017 and 2020 were periods of exceptionally warm ML temperatures that resulted in a thermally-stratified mixed layer (Fig S2i in **Paper II**; Wilson et al., 2023), acting to stabilise the water column and elevate stratification during those periods (Fig 4.2g).

The question remains: what caused the sudden shift in hydrographic properties? What does that mean for ocean–ice connectivity?

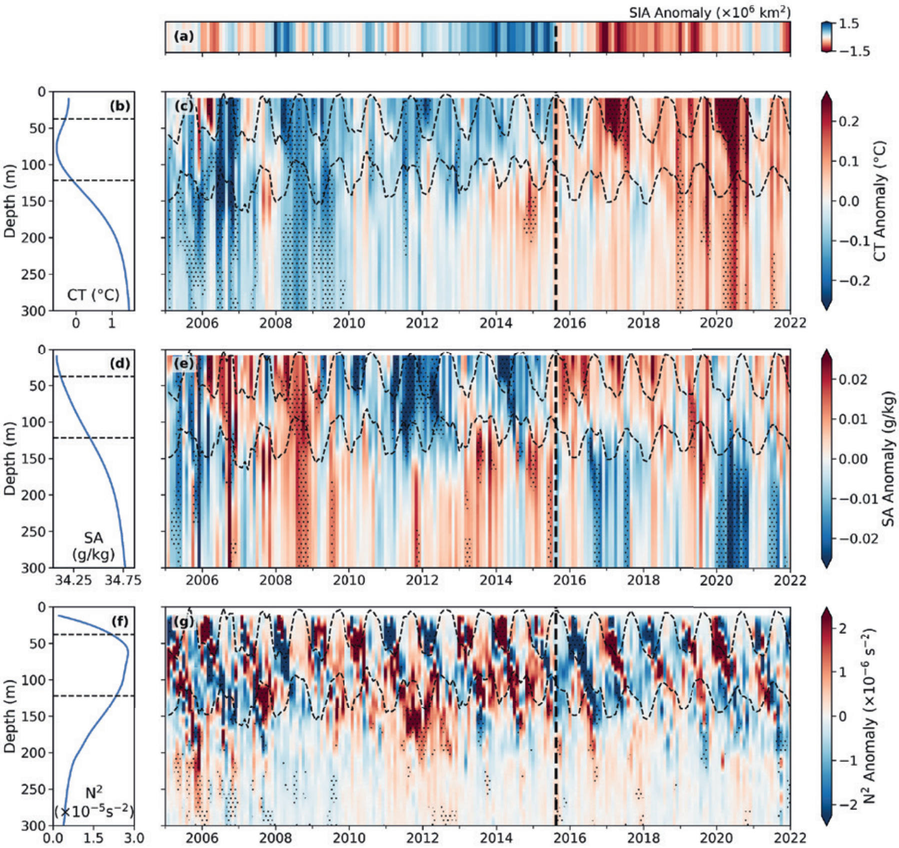

Figure 4.2: Changes in observed hydrographic properties in the upper ocean. (a) Monthly Southern Ocean sea ice area anomaly as climate stripes. (b,d,f) Spatially weighted mean and (c,e,g) monthly anomaly profiles of temperature, salinity and stratification in the seasonally ice-covered Southern Ocean, respectively. The vertical dashed black line in (a,c,e,g) denotes the start of the transition from high SIA to low SIA (August 2015). Stippling in (c,e,g) indicates regions where the anomaly is more than one standard deviation for each depth level. The dashed black horizontal lines in (b–g) denote the upper and lower Winter Water boundaries. From **Paper II**.

## 4.3 Regional reversals in ocean–ice coupling

The sudden change in upper ocean properties was driven by anomalous atmospheric circulation throughout 2015 (Zhang et al., 2022). Consequently, atmospheric stress on the ocean surface was on average 20% higher than the climatological mean (Fig 6 in **Paper II**). This elevated ocean stress paired with heightened temperature gradients between the ML and subsurface resulted in wintertime wind-driven heat fluxes that peaked at ~14 W m$^{-2}$, over double the 2005–2010 average, which entrained CDW into the ML. We further demonstrate the crucial role that WW plays as a barrier to upward heat transfer from

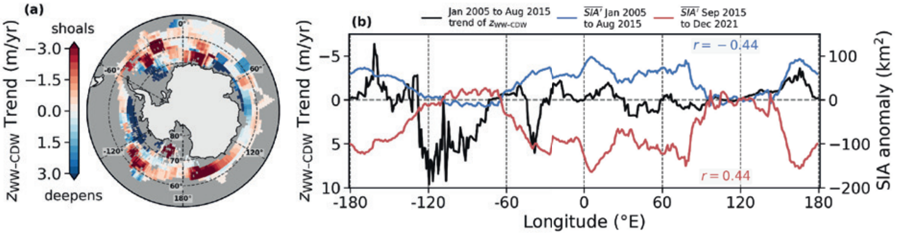

Figure 4.3: Reversal in the ocean–ice coupling. (a) Linear trend of the Winter Water–Circumpolar Deep Water interface depth ($z_{\text{WW–CDW}}$) between January 2005 to August 2015, smoothed with a centred rolling mean (10° in longitude, 5° in latitude). (b) Meridional mean of the smoothed linear trend of the Winter Water–Circumpolar Deep Water interface depth (black) and of the time-averaged sea ice area anomaly for the periods January 2005 to August 2015 (blue) and September 2015 to December 2021 (red). We correlate the two periods of mean sea ice area anomalies with the Jan 2005 to August 2015 trend of the Winter Water–Circumpolar Deep Water interface depth, and present the Pearson's $r$ correlation for each period in their respective colors. The p-value for each correlation, with adjusted degrees of freedom based on the 10° rolling mean, is ~$10^{-3}$. From **Paper II**.

the ocean interior to the ocean surface in **Paper II**. We show that, in the absence of WW, the mean heat flux is more than 5 times larger (Fig S4 in **Paper II**) and enough to substantially reduce sea ice cover.

Prior to 2015, CDW was more strongly insulated from the ocean surface by stratification. From 2005 to late 2015, the trend of the depth of the WW–CDW interface ($z_{\text{WW–CDW}}$) consistently shoaled with a linear trend of 2.8 m/year. This trend varied spatially: in some regions, $z_{\text{WW–CDW}}$ shoaled by up to 5 m/year while in others it deepened by nearly 10 m/year (Fig 4.3). The strongest trends were located in the Amundsen Bellingshausen Seas and the southern Weddell Sea (Fig 4.3a).

The trend of $z_{\text{WW–CDW}}$ negatively correlates with the average SIA anomaly for the same period ($r = -0.44$), suggesting that regions of high SIA anomaly align with regions of shoaling CDW and vice versa (Fig 4.3b). This finding suggests a disconnect between sea ice variability and oceanic trends, likely facilitated by the high stratification between ML and ocean interior. SIA anomaly for the period of September 2015 to December 2021 then changes in its correlation to the same $z_{\text{WW–CDW}}$ trend to become positively correlated ($r = 0.44$). This suggests that regions which experienced CDW shoaling between 2005 to 2015 saw decreased sea ice coverage after the 2015 transition to a low sea ice state. Therefore, there was likely an increase in connectivity between ocean surface and interior, enhancing vertical heat exchange and contributing to the melting of sea ice, as indicated by the reduced stratification state across the same time period (Fig 4.2g).

## 4.4 Summary

In this chapter, we highlight the role that the ocean has played in recent sea ice changes. We show that hydrographic properties have changed alongside the circumpolar sea ice changes, culminating in a persistently less stratified state. The initial elevated stratification resulted in a disconnect between the ocean surface and ocean interior, appearing as a negative correlation between SIA anomalies and trend of $z_{\mathrm{WW-CDW}}$ for the period January 2005 to August 2015. Then, in the period of low SIA coverage, sea ice become more connected to the subsurface CDW, as indicated by a reversal in correlation between SIA anomalies for the period September 2015 to December 2021 with the same $z_{\mathrm{WW-CDW}}$ trend. This shift from higher to lower than average SIA was brought about by a combination of long-term shoaling of the WW–CDW interface and anomalously large ocean stress in September 2015, which acted to increase mixing and connectivity between the ocean surface and deeper layers.

These findings support the hypothesis of a new sea ice state by proposing a structural shift in the upper ocean resulting in increased connectivity between ocean surface and interior since September 2015 to contribute toward sea ice melt.

Chapter 5

# Zonal Asymmetries in Ocean–Ice Coupling

## 5.1 Is the New Antarctic Sea Ice Regime Zonally Coherent?

Antarctic sea ice underwent a transition from a state of high sea ice coverage to persistently low and variable coverage—a shift proposed as a new sea ice regime (outlined in Chapter 4.1). Chapter 4 demonstrated that the transition began in August 2015, marked by a decline in net SIA, with Winter Water (WW) playing a crucial role in modulating vertical heat fluxes from Circumpolar Deep Water (CDW) into the mixed layer (ML). Anomalously strong surface winds intensified mechanical mixing, weakening upper ocean stratification. As a result, the WW stratification barrier weakened, allowing greater upward fluxes of heat and salt from CDW into the surface ocean.

However, it is unclear whether this circumpolar transition is regionally representative. Both model- and observation-based studies reveal zonally asymmetric and, in some cases, opposing trends in sea ice concentration (Stammerjohn and Maksym, 2017), sea ice thickness (P. R. Holland et al., 2014; Bocquet et al., 2024) and SIA (Fig 4.3b; Zhang et al., 2022; Espinosa et al., 2024). These differences are linked to regional variations in atmospheric forcing—such as wind strength, storm tracks, and air temperature (Raphael, 2007; P. R. Holland and Kwok, 2012; W. R. Hobbs et al., 2016; Comiso et al., 2017). Ocean hydrography, including stratification and water mass structure, has also been proposed as a key factor influencing sea ice variability (Meredith and King, 2005; Stammerjohn et al., 2012; Goosse and Zunz, 2014; Haumann et al., 2020; Saenz et al., 2023). Yet, observational studies directly linking offshore water mass structure to sea ice variability remain lacking.

Numerical studies show that the vertical oceanic structure is essential for interannual variability of sea ice (M. M. Holland et al., 2013; Marchi et al., 2019; Doddridge et al., 2021; Libera et al., 2022). W. Hobbs et al., 2024 indicate that the ocean potentially plays more of a role in sea ice variability under the new sea ice regime—reinforced by changes in surface properties and re-organisation of the vertical hydrographic structure (Silvano et al., 2025). Using observations, **Paper II** showed that the relationship between sea ice area and the ocean subsurface varied regionally (Fig 4.3b). While SIA generally decreased after 2015, some regions increased in SIA (Figs 4.1d and 5.1f). In sectors such as the ABS, where SIA anomaly was positive on average from 2016 onward, CDW exhibited a deepening trend (Fig 4.3b), reducing the availability of subsurface heat to the ocean surface (Fig 4.3a). Meanwhile, in other regions such as the Weddell and Ross Seas, the WW–CDW interface considerably shoaled, bringing warmer waters closer to the surface ocean and thereby increasing the potential for sea ice melt. These contrasting trends in CDW depth and SIA indicate zonally asymmetric ocean–ice coupling, shaped by region-specific changes in stratification and water mass structure.

In this chapter, we synthesise results from **Paper III** to explore sector-specific hydrographic structure and trends, especially WW and CDW interactions, to explain regionally varying sea ice coverage observed across the SO's seasonal ice zone.

## 5.2 Zonal Asymmetries in Sea Ice Changes

To investigate large-scale sea ice behaviour across regions, we use SIA anomalies ($\mathrm{SIA}'$) and its temporal derivative, $\left(\frac{\partial}{\partial t}\,\mathrm{SIA}\right)'$, which represent total sea ice coverage and how it has changed with time, respectively. We applied a change point detection algorithm to these timeseries (`KernelCPD` from the `ruptures` package; Truong et al., 2020), which identifies distributional changes in a multivariate time series using a kernel-based similarity metric. Thus, we interpret a change point as a transition in sea ice dynamics.

The change point analysis reveals that most SO sectors experienced shifts in SIA between 2005 and 2022 (Fig 5.1). Before the major decline detected in late 2015, sectors exhibited asynchronous SIA anomalies, alternating between elevated and reduced SIA. Although circumpolar sea ice expanded from March 2013 to August 2015 (Fig 5.1a), it was not spatially uniform. All sectors contributed to the circumpolar SIA increase to varying degrees, but downstream of Kerguelen Plateau (KP-d) was the only region to show a sustained period of elevated SIA in this time frame (Fig 5.1d). The largest contributions to SIA took place during summer 2013/14 (from WS, KP-d, ABS) and summer 2014/15 (WS, RS).

In August 2015, sea ice transitioned into a persistent low coverage state (Fig 5.1a). This decline in sea ice was circumpolar when viewed as a whole, but regionally staggered. Change points agreed or were within a month of overall sea ice decline in the upstream of Kerguelen Plateau (KP-u), KP-d and RS sectors. Meanwhile, the WS change point was detected more than a year later in October 2016 (Fig 5.1b) and, whilst it contributed to the 2016/17 summertime low, no change point was detected in ABS (Fig 5.1f). To examine why these differences occurred, we investigated the role of the connection between the

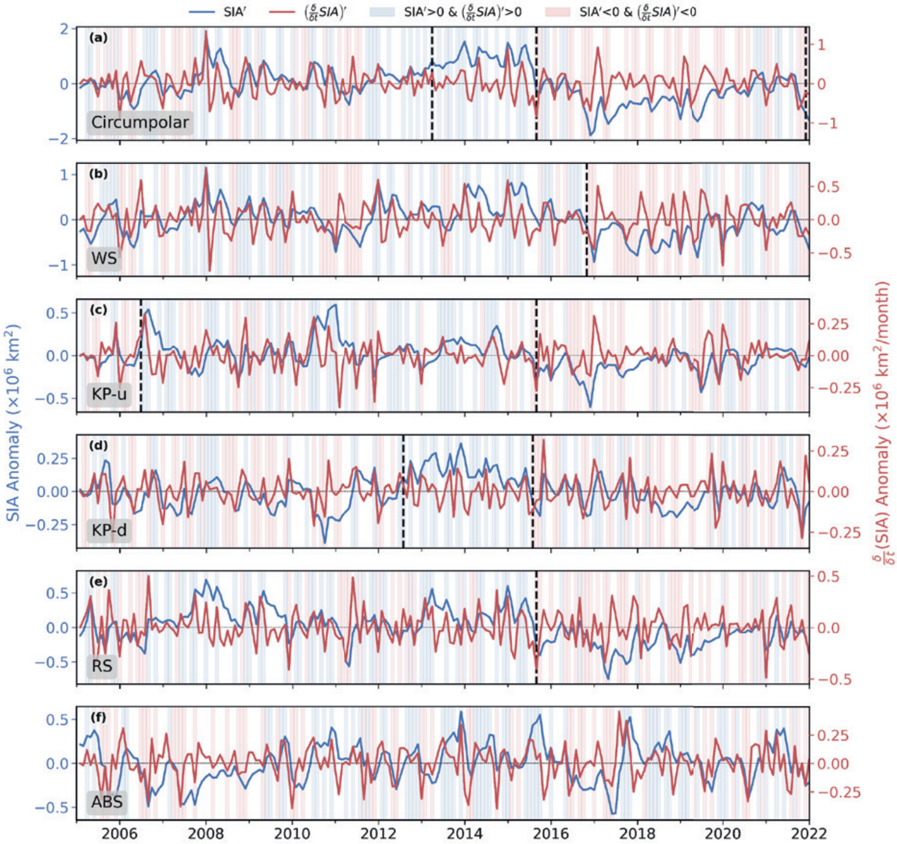

Figure 5.1: Change points of sea ice area. Net anomaly of sea ice area (blue) and the net anomaly of the rate of change of sea ice area (red) for (a) the circumpolar Southern Ocean and (b–f) zonal sections of the Southern Ocean. Background blue vertical bars indicate months of elevated sea ice cover where SIA$' > 0$ and $\left(\frac{\partial}{\partial t}\mathrm{SIA}\right)' > 0$ and background red vertical bars indicate months of lowered sea ice cover where SIA$' < 0$ and $\left(\frac{\partial}{\partial t}\mathrm{SIA}\right)' < 0$. Vertical dashed black line indicates the detected change points. If there is no vertical black dashed line, no change point has been detected. Note that these change points are detected using the full sea ice dataset (1979 to mid-2024) and we present here only the years aligning with the hydrographic dataset (2005 to 2022). From **Paper III**.

deeper and warmer water masses—namely, WW and CDW—and the sea ice anomalies.

## 5.3 Hydrographic Structure

The vertical hydrographic structure in the seasonal ice zone of the SO follows a consistent pattern: a relatively fresh and cold ML, which is underlain by colder and slightly saltier WW, and below that a warm and saline CDW layer.

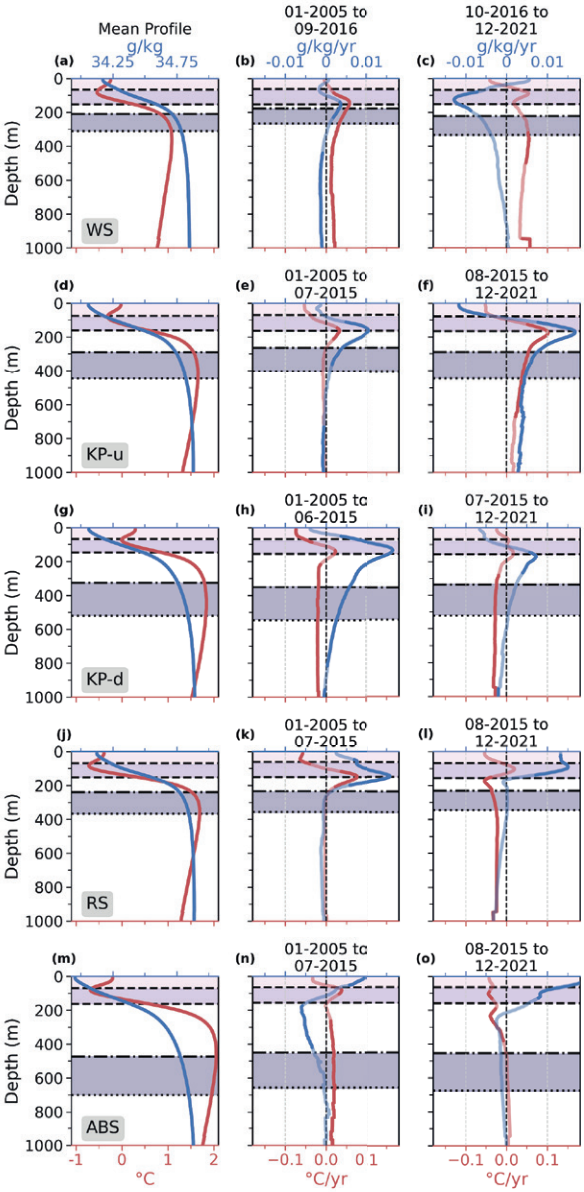

Figure 5.2: Hydrographic properties and trends of Southern Ocean sectors. Weighted mean profiles of regional hydrographic properties as well as trends for before and after detected sea ice change point associated with decline in sea ice cover. Properties shown are temperature (red) and salinity (blue) for the following regions: (a–c) the Weddell Sea, (d–f) upstream of the Kerguelen Plateau, (g–i) downstream of the Kerguelen Plateau, (j–l) the Ross Sea, (m–o) the Amundsen and Bellingshausen Seas. Average water masses for the respective period are shaded, showing the mixed layer (light pink), Winter Water (lavender) and Circumpolar Deep Water (grey-purple). Depths where trends are statistically significant ($p < 0.05$) are presented as opaque, whereas trends that are not statistically significant trends are translucent. Adapted from **Paper III**.

Although the structure is similar around the SO, the magnitudes and gradients of temperature and salinity vary considerably by region.

The RS and WS share similar hydrographic properties (Fig 5.2a and 5.2j)—the cold and salty MLs and WW layers reflect strong air–sea heat exchange (Pellichero et al., 2017; Wilson et al., 2023) and ocean–ice freshwater fluxes (Dong et al., 2009; Pellichero et al., 2017; Wilson et al., 2023). These are regions where CDW upwells via gyre circulation, resulting in shallower CDW layers, enhanced rates of mixing between surface and subsurface layers (Groeskamp et al., 2016; Tamsitt et al., 2017) and as a result, increased potential for upward heat fluxes. Consequently, elevated rates of mixing and transformation result in cold and fresh CDW layers (coldest and freshest in the WS; Narayanan et al., 2023). In KP-u and KP-d, CDW resides slightly deeper with a more gradual vertical structure. In contrast, the ABS has a very fresh ML, likely due to glacial meltwater input (Bintanja et al., 2013). Furthermore, the CDW layer is the warmest and saltiest, yet resides much deeper in the water column (~480–690 m; Fig 5.2m).

Temperature and salinity trends differ by region and water masses—note that only statistically significant trends are considered and reported. In KP-d and the RS, the ML statistically significantly cooled (Figs 5.2h and 5.2k). Meanwhile, only the ABS showed a significant ML salinity trend, showing a salinification trend (Fig 5.2n). All sectors exhibited a statistically significant warming trend for some portion of the WW layer, with the greatest magnitude at the WW lower boundary. Similarly, all sectors except the ABS exhibited a statistically significant salinification trend in the WW layer, with the strongest trend at the WW base. In the WS and ABS, a weak warming trend extended through the full depth below WW (Figs 5.2b and 5.2n). KP-d, on the other hand, exhibited a weak cooling trend below the WW layer (Fig 5.2h). Similarly, a salinification trend extended from WW into the CDW layer in WS, KP-u and KP-d. In contrast, the WW–CDW transition layer in the ABS exhibited a strong freshening trend (Fig 5.2n).

In the periods associated with sea ice loss (third column of Fig 5.2), statistically significant trends of temperature and salinity remained zonally asymmetric. There were no statistically significant trends in ML temperature. The ML freshened in KP-u, but salinified in the RS and ABS (Figs 5.2f, 5.2l, 5.2o). Subsurface warming trends were detected in the WS and KP-u, with a strong warming trend at the WW lower boundary in the KP-u (Fig 5.2f). Conversely, there were subsurface cooling trends in KP-d, RS, and ABS (Figs 5.2i, 5.2l, 5.2o). All sectors exhibited a salinification trend in the WW layer except in the WS, which freshened (Fig 5.2c). Of all sectors, only KP-u exhibited statistically significant trends in salinity below the WW layer, which was a moderately strong salinification trend (Fig 5.2f).

These regionally distinct temperature and salinity trends suggest that some sectors, particularly the RS and ABS, exhibit more similar hydrographic responses to sea ice loss. Increased salinity trends through the ML and/or WW likely indicate a reduction in stratification, increasing connectivity between the

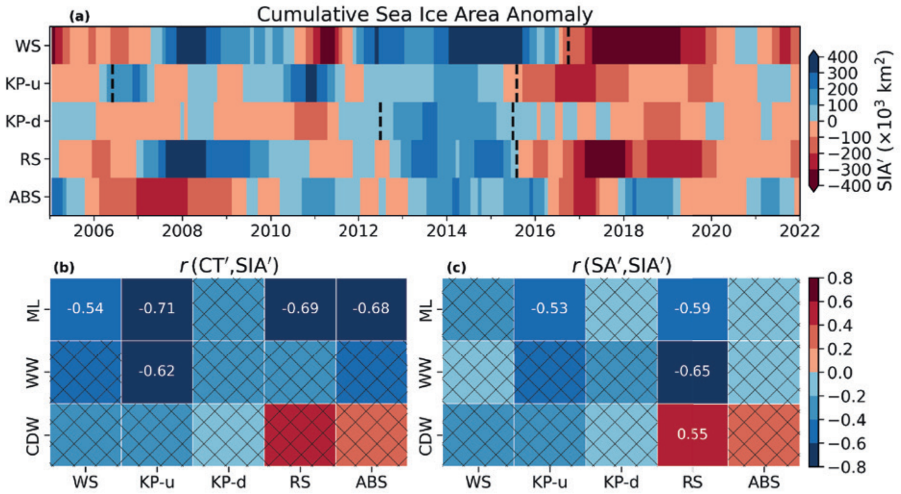

Figure 5.3: Monthly water mass–sea ice correlation. (a) Cumulative sea ice area anomaly for each region with respect to the 2005 to 2022 mean of the respective region. Vertical dashed black line indicates the detected change points. (b,c) Correlation matrices of sea ice area anomaly and anomaly of the mean (b) Conservative Temperature and (c) Absolute Salinity for different water masses. Hatching indicates regions that are not statistically significant, and annotated elements of the matrices show the $r$ value that are statistically significant ($p < 0.05$). From **Paper III**.

ocean surface and ocean interior. Meanwhile, the freshening ML trend with concurrent salinification trend in the WW layer in KP-u likely indicate an increase in stratification, as does the freshening trend in the WW layer in the WS. This increase in stratification may reduce the quantity of heat upwelled into the ML, potentially provides some insight into the slow recovery of sea ice in those regions (Figs 5.1b and 5.1c). These regionally differing trends highlight the need to assess whether changes in ocean–ice connectivity are directly connected to water mass structure across the SO.

## 5.4 Water Mass and Sea Ice Connectivity

To provide further insight into regional ocean–ice coupling, we examine the response of sea ice to changes in water mass characteristics. To do this, we correlate SIA anomalies with Conservative Temperature anomalies and Absolute Salinity anomalies for the different water masses of each ocean sector. These are Pearson correlations between sector-wide SIA anomalies and the monthly mean time series for each water mass (Fig 5.3). In other words, we ask the question: is there a direct response in the monthly net SIA anomalies that are driven by simultaneous changes in temperature and salinity?

We find that temperature anomalies in the ML strongly anti-correlate with SIA anomalies (Fig 5.3b) for all ocean sectors, with the exception of KP-d which shows an insignificant correlation. These anti-correlations reflect the pronounced seasonal cycle of sea ice growth and melt, driven primarily by solar radiation (Bitz et al., 2005; Roach et al., 2022) and ML heat content (Gordon, 1981; Libera et al., 2022; Himmich et al., 2023). In KP-u and the RS, ML salinity anomalies show strong negative correlations with SIA anomalies. These anti-correlations are likely driven by the strong seasonal cycle of sea ice and its impact on ML freshwater content (Haumann et al., 2016; Pellichero et al., 2017, 2018). Below the ML, WW temperature anomalies are negatively correlated to SIA anomalies in KP-u only (insignificant elsewhere), while WW salinity shows significant correlation only in the RS.

Below the WW layer, statistically significant correlations of CDW properties and SIA are limited to the RS, where CDW salinity anomalies are strongly and positively correlated with SIA anomalies (Fig 5.3b). This contrasts the strong negative correlations observed in the ML and WW salinity in the same region, which indicates that when SIA is high, ML and WW layers are fresh low whilst CDW layers are saline. Therefore, the water column is more strongly stratified during periods of elevated sea ice cover, as shown by previous studies (Lecomte et al., 2017; Haumann et al., 2020; Morioka et al., 2024). Conversely, in low sea ice states, the water column is weakly stratified, implying a reduction of salt from the CDW layer—a reduction in salinity likely indicates a transfer into the ML, which would be paired with heat transfer. This suggests that the accumulated heat and salt from CDW may have been more readily available from late 2015 onward in the RS, and contributed to the reduced sea ice state. These water mass correlations help explain the low predictability skill in RS winter sea ice predictions in studies that do not account for subsurface or CDW hydrographic properties (e.g., Bushuk et al., 2021).

The general lack of statistically significant correlations below the ML in most sectors of the SO may be related to a lagged delay in the response of SIA to changes in the properties of deeper waters. For example, the correlation computed in Chapter 4.3 (Fig 4.3b) showed a reversal in correlation between a long-term trend and long-term SIA anomalies, which may reflect lagged responses not captured in month-to-month co-variations. Time-lagged correlations of differing lengths may reveal varying time-dependent relationships not shown here, but investigated in other studies with both atmospheric and oceanic properties (e.g., Libera et al., 2022; Morioka et al., 2024; W. Hobbs et al., 2024). Alternatively, month-to-month connection between deeper waters and SIA may not be consistent enough to show up in a correlation analysis. For instance, a single season event (as shown in **Paper II**) is proposed to cause the mixing and connectivity between CDW and SIA. While still important, this single event will not show up in a multi-annual correlation analysis

## 5.5 Summary

In this chapter, we synthesise findings from **Paper III**. We demonstrate that sea ice changes are zonally asymmetric, varying between sectors. We show that only KP-d exhibits a change point associated with increased sea ice cover, whilst four out of five sectors exhibit change points linked to a decline in sea ice coverage (Fig 5.1). These change points are linked to the mixing of warmer and saltier CDW into the ML – and thereafter low SIA anomalies – by anomalously large winds in the winter of 2015. Of these sectors with declining sea ice, two change points agree with the circumpolar transition identified in **Paper II**, one occurs within a month, and another is more than a year later. Meanwhile, no change point was detected in the ABS for the entire 2005–2022 period, highlighting its unique dynamical system.

Similarly, we find that hydrographic structure and its evolution vary substantially by region (Fig 5.2). These findings are important to demonstrate that when it is important to be specific about the region of interest when discussing Southern Ocean SIA anomalies and change, especially in the context of a change in sea ice state. Furthermore, we show that regional asymmetries in ocean–ice coupling (Fig 5.3) are critical to understanding and predicting Antarctic sea ice behaviour, and that a deeper understanding of the role of the ocean on the longer term sea ice state is worth investigating further.

Chapter 6

# Outlook and Conclusions – Antarctic Winter Water in a Changing Climate

## 6.1 Summary of Key Findings

This thesis demonstrates that Antarctic Winter Water (WW) plays a central role in regulating vertical exchange of heat and salt between the mixed layer (ML) and Circumpolar Deep Water (CDW) in the Southern Ocean (SO) climate system, with implications for overturning ocean circulation, ocean stratification, and sea ice variability. Across multiple studies, I investigated the structure, evolution and climatic relevance of WW using a large observational dataset that I constructed.

In **Paper I**, we developed a robust algorithm to identify WW from hydrographic profiles that can be efficiently implemented on a multi-hundred thousand profile dataset to output WW properties. We characterised the seasonal structure of WW to describe its annual cycle, which we show aligns with sea ice in that WW is largely located in the polar SO and that the WW seasonal cycle is mirrored with the sea ice seasonal cycle. Critically, we identify bathymetrically steered pathways that export WW equatorward, connecting the polar SO to the subpolar ocean. This provides evidence of localised overturning pathways to further develop from the canonical zonal-mean overturning circulation framework.

In **Paper II**, we examined the role of WW as a stratification barrier during the lead-up to the major sea ice decline in 2015/16. We showed that, between 2005–2015, WW slowly eroded from below over multiple years, bringing the warm and salty subsurface CDW closer to the ocean surface and increasing vertical stratification. This preconditioned the ocean for an abrupt change: a strong wind event tapped through the ML to entrain CDW, elevating vertical fluxes of heat and salt. Increased salinity in the ocean surface changed the density structure to reduce stratification in the upper ocean and increase connectivity between ocean surface and subsurface, reversing ocean–ice coupling.

In **Paper III**, we reveal that the changes in ocean–ice coupling were zonally asymmetric—only some ocean sectors exhibited coupled shifts in ocean structure and sea ice, whilst others diverged from the circumpolar signal. We linked these differences to regional variations in water mass structure and ocean–ice connectivity, showing that sea ice processes cannot be fully understood from large-scale averages alone. This reinforces the importance of regional hydrography in shaping sea ice variability.

This thesis underscores the importance of sustained *in-situ* observations in the Southern Ocean. Programmes such as Argo, SOCCOM, MEOP, and others provide the multi-year, circumpolar data coverage necessary to reveal the physical processes shaping Antarctic Winter Water. These data are rich in detail and act as a key tool for identifying and constraining missing processes in climate models, improving projections of future climate change scenarios.

## 6.2 Other Winter Water Studies

Within the period of this doctoral thesis, there has been a growing importance of for understanding WW, both as a direct result of the papers within this thesis and elsewhere. For example, the understanding of WW beyond its role as a barrier to sea ice variability, including its modification by freshwater inputs from giant icebergs and the role it plays in biogeochemical cycling.

**Paper IV** demonstrates the impact of meltwater input from giant icebergs on the upper ocean water column, using high-resolution glider observations in close proximity to the iceberg A-68A. Substantial meltwater input was observed at the iceberg base, reducing salinity to ~26 g kg$^{-1}$ at the WW base and enhancing vertical stratification. This meltwater upwelled through the thermocline and into the ML, promoting upwelling of warm, salty and nutrient-rich CDW into the ML. Along with meltwater input, the iceberg discharge also carried nutrient-rich land-sourced material. Thus, upwelled mixtures of CDW–iceberg discharge have the potential to create favourable conditions for phytoplankton blooms in the wake of the icebergs. My contribution to this work was by analysing coincident hydrographic profiles and satellite-derived iceberg tracks to provide a broader understanding of the impact of icebergs on hydrographic properties. My analysis helped to understand how WW profiles, in the wake of icebergs, were fresher and elevated in stratification at the ML–WW interface compared to climatological WW properties. The calving of large-draft icebergs is projected to increase under climate change with the melting of ice shelves. Thus, understanding the ramifications of episodic stratification anomalies and ocean nutrients injections as outlined in **Paper IV** may prove a critical in understanding physical and biological changes to the ocean carbon pump.

A recent study by Gonzalez et al., 2025 explores the role of biogeochemical properties of $\mathrm{WW}_{\mathrm{SS}}$ using BGC-Argo, providing a seasonal and spatiotemporal description (similar to **Paper I**) of properties including nitrate, carbon, AOU and chlorophyll-*a*. They show that $\mathrm{WW_{SS}}$ biogeochemical properties are subducted near the Polar Front into the ocean interior via eddy subduction, and preferentially occurring in regions aligning with high eddy kinetic energy (Vilela-Silva et al., 2024)—approximately agreeing with the export pathways identified in **Paper I**. The alignment of physical and biogeochemical pathways suggest that WW may link surface properties to the ocean interior and ultimately feed into the formation of Antarctic Intermediate Water properties (Evans et al., 2018; Klocker et al., 2023). This study provides further context to the role of WW in the ocean system.

## 6.3 Emerging Questions

This thesis has detailed that WW is central to upper ocean stratification and sea ice variability. These findings raise several outstanding questions about the role of WW in future climate and biogeochemical systems, many of which extend beyond the immediate scope of this thesis.

- How will Winter Water change under climate change?

WW forms where salinity dominates variations in ocean density (i.e., beta ocean), such that a cold subsurface tongue can form while remaining stable in density. Caneill et al., 2022 artificially tested changes in the thermal expansion coefficient to show that a larger thermal expansion coefficient reduces the extent of beta ocean, which would potentially shrinking WW volume. Furthermore, the present-day new sea ice regime reduces sea ice insulation as well as drives changes in ocean freshwater cycling. This may alter the buoyancy forcing that governs WW formation. Whether WW persists, shoals or erodes under these changing conditions remains an open and important question.

- What role does Winter Water have on biogeochemical cycling?

WW is a low stratification water mass formed in the mixed layer, later subducting into the ocean interior, and almost vertically homogenous in properties—analogous to a mode water (Masuzawa, 1969; Hanawa and D.Talley, 2001; Portela et al., 2020). Mode waters are pathways of heat, oxygen and nutrients, with up to 50% of subducted oxygen eventually mixed into surrounding water masses (Jutras et al., 2025). Gonzalez et al., 2025 showed that WW carries biologically relevant tracers like nitrate, AOU and carbon into the ocean interior, with eddy subduction hotspots near the PF. Meanwhile, Portela et al., 2020 demonstrated a decadal trend of reduced Antarctic Intermediate Water volume via increased transformation into WW, and subsequently obducted into the ML, indicating a shifting role in water mass transformation and nutrient cycling. Olivier and Haumann, 2025 used long-term repeat ship transects of CTD and biogeochemical sampling in the SO to show that WW thinned so that CDW—which is rich in carbon dioxide—resided closer to the ocean surface. Concurrently, surface freshening increased stratification, suppressing vertical mixing and limiting CDW-sourced carbon dioxide outgassing. These trends agree with the shoaling and stratification changes described in **Paper II**. However, a lack of recent repeat transects leaves open the question of whether the decoupling of ocean surface–subsurface will persist and the impact it has on carbon outgassing.

These findings raise questions about how WW influences nutrient and carbon distributions, and how such processes may respond to the evolving hydrographic structure described in **Papers II** and **III**.

- What drove the decadal thinning of Antarctic Winter Water?

**Paper II** showed that WW thinned from below across much of the SO from 2005–2015, coinciding with a shoaling of CDW—and reflected by regional anomalies in **Paper III** (supplementary figures). One hypothesis suggested is that increased heat content in the CDW layer enhanced vertical diffusive mixing, eroding the WW layer from below. Conceptual models suggest that turbulent mixing across boundaries can oscillate the boundary depth on long timescale due to differing adjustments rates of temperature and salinity (Welander, 1982). However, mixing rates may not be the sole mechanism that contributed to WW thinning. Increased atmospheric cyclonicity has been proposed to increase gyre cyclonicity, elevating rates of Ekman pumping of CDW (Schmidtko et al., 2014; Meehl et al., 2019). de Jager and Vichi, 2025 showed multi-decadal increases in sea ice vorticity and cyclonicity, potentially enhancing energy transfer of atmosphere–ice–ocean stresses and further elevate rates of upwelling. Subantarctic Mode Waters exhibits multi-decadal variability linked to shifts in atmospheric modes that modulate air–sea buoyancy fluxes during formation (Cerovečki and Haumann, 2023). Given WW shares similarities with mode water, it is plausible that large-scale tropical teleconnections and atmospheric circulation shifts also modulate WW volume.

- Is Winter Water represented in coupled climate models?

Coupled climate models (e.g., CMIP6) struggle to reproduce observed Antarctic sea ice and SO hydrographic changes, including ocean surface cooling (Beadling et al., 2020; Roach et al., 2020), water mass properties (J.-B. Sallée et al., 2013; Heuzé, 2021), polynyas (Mohrmann et al., 2021), and sea ice extremes (Diamond et al., 2024). These discrepancies result in low confidence in future Antarctic and Southern Ocean projections (Masson-Delmotte et al., 2021). Given the role of WW in regulating vertical property exchange and sea ice stability, its absence or poor representation in these models may contribute to persistent model biases. A key open question is whether improved representation of WW structure and variability would lead to more accurate sea ice and climate predictions.

These questions underscore the emerging relevance of Winter Water as more than a passive product of seasonal sea ice processes. Instead, WW appears to act as a dynamic regulator of upper ocean stratification, a tracer of air–sea exchange, and a conduit linking surface forcing to interior ocean variability. As the Southern Ocean continues to warm, freshen, and lose sea ice, the persistence, transformation, and climatic role of WW remain open and consequential areas of investigation. Addressing these questions will require sustained observations, improved model fidelity, and a deeper understanding of the coupled atmosphere–ice–ocean system in the Antarctic.

Chapter 7

# Other Academic Activities and Training

A PhD is not only about academic output, and mine has involved more than the papers outlined in this thesis. Here, I highlight some personal experiences that contributed to the development of my PhD.

## 7.1 Working Environment

My PhD journey has been relatively smooth, but not without its hiccups. My working environment has certainly helped to navigate those challenges. I have supervisors who encourage autonomy, as well as the resources to support and enable professional development. I have been fortunate enough to be a member of a supportive research group, Polar Gliders, who study a diverse range of topics largely focused on finescale observations, and who regularly meet to discuss a variety of subjects to aid in navigating academia. I have also been an external member of Alex Haumann's LMU/AWI SO-CLIM group, who welcomed me in and provided an avenue to learn about different facets of Southern Ocean science. I have shared space in a working environment surrounded by a range of disciplines within marine sciences at Gothenburg University's Department of Marine Sciences. These communities are special—each is unique and shaped my scientific perspective. I am extremely privileged to have been a member of these communities and I am endlessly grateful for the support I have received.

## 7.2 SO-CHIC

Involvement in the EU Horizon project SO-CHIC (Southern Ocean Carbon and Heat Impact on Climate; J. B. Sallée et al., 2023) has been an important aspect of my PhD. It immediately placed me into a network of Southern Ocean physical oceanographers, and together we organised regular virtual meetups for Early Career Researchers, which involved research presentations and a journal club. This was extremely important to my personal development and understanding of the field, particularly given my background in fluid dynamics and theoretical oceanography. I attended two SO-CHIC annual general meetings, which allowed me to learn of new and exciting science and connect face-to-face with the fellow ECRs and senior scientists—a friendly and encouraging community that I am grateful to have been part of.

I was fortunate to join the SO-CHIC 2022 research cruise focused on data collection around Maud Rise in the Weddell Sea. As part of the GU team, I contributed to the deployment of two Seagliders and one Sailbuoy, among our additional responsibilities. My role included troubleshooting Sailbuoy sensors for correct calibration and settings in collaboration with the GU land-based team—often with views like that in Fig 7.1d. The entire SO-CHIC ship-based team helped with CTD operations, which included sampling for dissolved inorganic carbon, phytoplankton and oxygen isotopes. Part of the GU Team's responsibilities included running the analysis of phytoplankton samples. I also assisted with the deployment of several other instruments including APEX floats, UP-TempO buoys, moorings, and a CARIOCA buoy (Naëck et al., 2025). The experience of fieldwork and data collection was a whirlwind. There was constant suspense and uncertainty of whether the cruise would go ahead, with problems encountered at every attempt to travel to Antarctica (from the COVID-Omicron breakouts to polar storms). The time, effort and resources to deploy a singular instrument in the Southern Ocean, let alone an entire array of platforms, were enormous and gave me a deep appreciation of the difficulty in oceanographic data collection. The intense conditions that those who travel south and/or to sea must endure are stark—both from nature (swells, storms, sea ice) and the working environment (long days, discrimination, inequality). My appreciation for oceanographic data and the people behind it grew substantially. This experience has helped me to understand the importance of open-access data in making science equitable and collaborative.

## 7.3 Teaching, Conferences and Courses

I have acted as a Teaching Assistant on multiple courses as a PhD student. This was challenging but rewarding, giving me an insight into different approaches to teaching. A key challenge was to tailor teaching style and content to the students' needs. The most significant challenge was the rapid adoption of AI tools such as ChatGPT, particularly in coding-focused classes.

I have attended several courses and conferences during my PhD. The courses have covered an array of topics, including data analysis, data visualisation, a glider crash course, climatological statistics, and professional development. The diverse range of topics has equipped me with practical tools and exposed me to different scientific perspectives through both course material and engaging with researchers from different disciplines. Most courses have allowed me to keep up-to-date with cutting edge research, often inspiring new lines of analysis.

I often come away from conferences and courses feeling scientifically energised

Figure 7.1: Images from the SO-CHIC 2022 expedition: (a) The S.A. Agulhas II moored alongside Penguin Bukta ice shelf, (b) Sailbuoy deployment, (c) CTD cast, (d) on-board Seaglider tests.

(and physically exhausted). One of the most valuable of these events was SOOS Symposium 2023; I was able to engage with a scientific community that I often don't get exposure to, which was novel and very valuable. Since the Symposium was smaller in attendance capacity, the organic exposure to people was greater, resulting in a stronger fostering of connection. It was also my first conference oral presentation, which I am sure positively biased my experience. Similarly, the School and Workshop on Polar Climates: Theoretical, Observational and Modelling Advances was another stand out event—the school took a broad yet deep dive into many different aspects of the polar climate system, bringing together scientists of different climate disciplines at all career stages. Entering with an understanding of the ocean physics component, I was in an environment where I could pick out important nuances from many different aspects of the climate system. Notably, it was the first time that I was graced with seeing one of my own published figures presented by someone else! Importantly, these opportunities have also enabled the development of my scientific network, leading to collaborations and research visits that have been central to this thesis.

A different yet stand-out course was Jonathan Lily's year long mentorship programme, Life Skills for Young Scientists (LiSYS). The world of academia can be emotionally draining and extremely blurry, but LiSYS has started me on a journey to develop the necessary tools and resources to navigate with "ease and poise".

## 7.4 Final Reflections

Undertaking a PhD in Sweden is a huge privilege—a country where PhDs are hired researchers in a system designed to protect workers. This means earning a salary and a pension, having insurance, holiday and sick leave, union support, and working in a doctoral programme geared towards producing research. Such conditions are far from universal, with many researchers worldwide underpaid and working under vulnerable conditions. These inequalities are compounded by systemic inequity for women and marginalised groups in academia and oceanography, including pay gaps, underrepresentation across career stages, and disproportionate harassment and bias (UNESCO, 2019; Berhe et al., 2022; Kozlowski et al., 2022; Legg et al., 2023). Systemic inequality translates to climate change impact. Low- and middle-income countries that contribute least to climate change are disproportionately affected, and have already seen the largest declines in economic growth as a result (Callahan and Mankin, 2022). Likewise, most of the world's coastlines border low- and middle-income countries, yet representation both in science and global policy remains low, and integration with local communities is often minimal (de Vos, 2020; Spalding et al., 2023; National Academies of Sciences, Medicine, et al., 2025). These patterns reflect cognitive biases and barriers of dominant societal systems, shaped by colonial histories. Structural change is essential to make scientific development accessible and inclusive, irrespective of identity, and to enable meaningful policy-making.

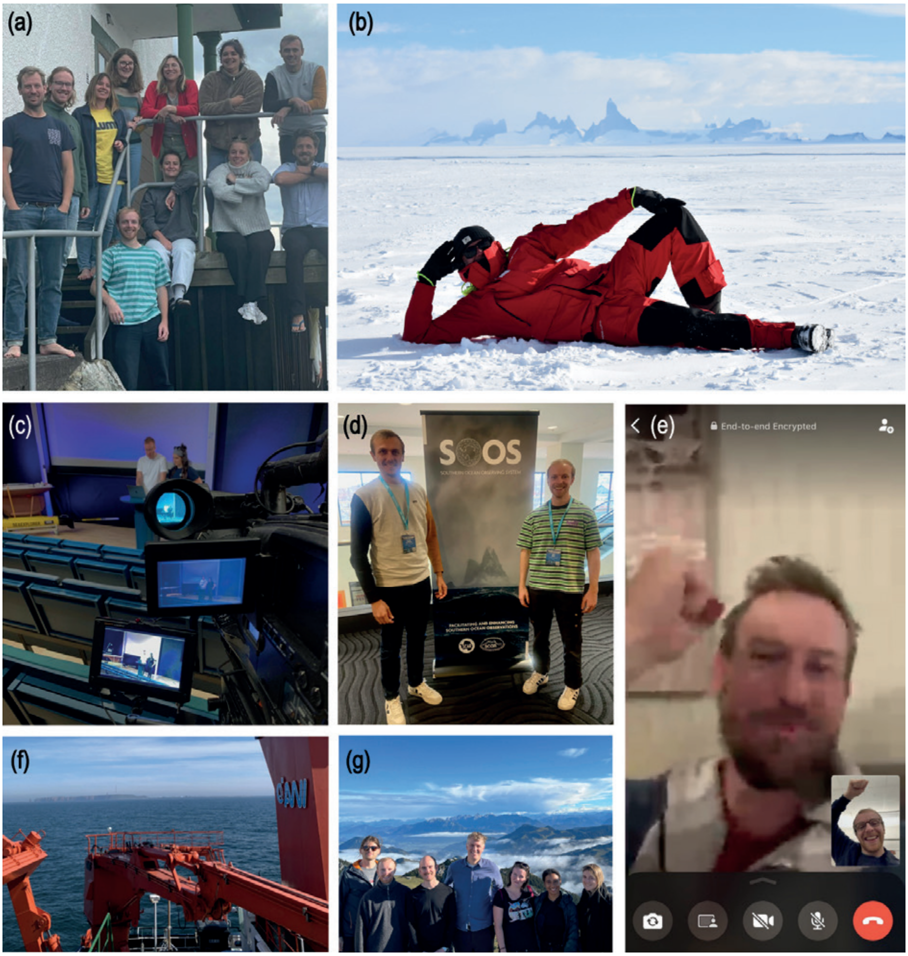

Figure 7.2: A collection of photographs capturing various moments throughout the PhD. (a) Polar Gliders group retreat on Bornö (September 2023), (b) Marcel du Plessis in front of Wolf's Fang of the Drygalski Mountains during the SO-CHIC expedition (New Years eve, 2021), (c) Johan Edholm and Estel Font at Vetenskapsfestivalen (May 2022), (d) coupla legends at SOOS Symposium (August 2023), (e) video call during my first paper submission with Seb Swart (February 2024), (f) AWI teaching excursion on the Heincke (May 2024), (g) SO-CLIM group retreat in the Bavarian Alps (October 2024).

# Bibliography

Abernathey, R. P., Cerovecki, I., Holland, P. R., Newsom, E., Mazloff, M., & Talley, L. D. (2016). Water-mass transformation by sea ice in the upper branch of the Southern Ocean overturning. *Nature Geoscience*, *9*(8). DOI: 10.1038/ngeo2749.

Abraham, J. P., Baringer, M., Bindoff, N. L., Boyer, T., Cheng, L. J., Church, J. A., Conroy, J. L., Domingues, C. M., Fasullo, J. T., Gilson, J., Goni, G., Good, S. A., Gorman, J. M., Gouretski, V., Ishii, M., Johnson, G. C., Kizu, S., Lyman, J. M., Macdonald, A. M., … Willis, J. K. (2013). A review of global ocean temperature observations: Implications for ocean heat content estimates and climate change. *Reviews of Geophysics*, *51*(3). DOI: 10.1002/rog.20022.

Arrigo, K. R. (2017). Sea ice as a habitat for primary producers. In *Sea Ice*. DOI: 10.1002/9781118778371.ch14.

Beadling, R. L., Russell, J. L., Stouffer, R. J., Mazloff, M., Talley, L. D., Goodman, P. J., Sallée, J. B., Hewitt, H. T., Hyder, P., & Pandde, A. (2020). Representation of Southern Ocean Properties across Coupled Model Intercomparison Project Generations: CMIP3 to CMIP6. *Journal of Climate*, *33*(15). DOI: 10.1175/JCLI-D-19-0970.1.

Belkin, I. M., & Gordon, A. L. (1996). Southern Ocean fronts from the Greenwich meridian to Tasmania. *Journal of Geophysical Research: Oceans*, *101*(C2). DOI: 10.1029/95JC02750.

Berhe, A. A., Barnes, R. T., Hastings, M. G., Mattheis, A., Schneider, B., Williams, B. M., & Marín-Spiotta, E. (2022). Scientists from historically excluded groups face a hostile obstacle course. *Nature Geoscience*, *15*(1). DOI: 10.1038/s41561-021-00868-0.

Biddle, L. C., & Swart, S. (2020). The Observed Seasonal Cycle of Submesoscale Processes in the Antarctic Marginal Ice Zone. *Journal of Geophysical Research: Oceans*, *125*(6). DOI: 10.1029/2019JC015587.

Bintanja, R., van Oldenborgh, G. J., Drijfhout, S. S., Wouters, B., & Katsman, C. A. (2013). Important role for ocean warming and increased ice-shelf melt in Antarctic sea-ice expansion. *Nature Geoscience*, *6*(5). DOI: 10.1038/ngeo1767.

Bisits, J. I., Zika, J. D., & Sohail, T. (2025). Cabbeling as a catalyst and driver of turbulent mixing. *Journal of Fluid Mechanics*, *1011*. DOI: 10.1017/jfm.2025.349.

Bitz, C. M., Holland, M. M., Hunke, E. C., & Moritz, R. E. (2005). Maintenance of the Sea-Ice Edge. *Journal of Climate*, *18*(15). DOI: 10.1175/JCLI3428.1.

Bocquet, M., Fleury, S., Rémy, F., & Piras, F. (2024). Arctic and Antarctic Sea Ice Thickness and Volume Changes From Observations Between 1994 and 2023. *Journal of Geophysical Research: Oceans*, *129*(11). DOI: 10.1029/2023JC020848.

Boehme, L., Lovell, P., Biuw, M., Roquet, F., Nicholson, J., Thorpe, S. E., Meredith, M. P., & Fedak, M. (2009). Technical Note: Animal-borne CTD-Satellite Relay Data Loggers for real-time oceanographic data collection. *Ocean Sci.*

Boyer, T., Baranova, C., Coleman, H. E., Garcia, A., Grodsky, R. A., Locarnini, A. V., Mishonov, C. R., Paver, J. R., Reagan, D., Seidov, I. V., Smolyar, K. W., Weathers, M. M., & Zweng. (2018). World Ocean Database 2018.

Brett, A., Leape, J., Abbott, M., Sakaguchi, H., Cao, L., Chand, K., Golbuu, Y., Martin, T. J., Mayorga, J., & Myksvoll, M. S. (2020). Ocean data need a sea change to help navigate the warming world. *Nature*, *582*(7811). DOI: 10.1038/d41586-020-01668-z.

Budge, J. S., & Long, D. G. (2018). A Comprehensive Database for Antarctic Iceberg Tracking Using Scatterometer Data. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *11*(2). DOI: 10.1109/JSTARS.2017.2784186.

Bushuk, M., Winton, M., Haumann, F. A., Delworth, T., Lu, F., Zhang, Y., Jia, L., Zhang, L., Cooke, W., Harrison, M., Hurlin, B., Johnson, N. C., Kapnick, S. B., McHugh, C., Murakami, H., Rosati, A., Tseng, K.-C., Wittenberg, A. T., Yang, X., & Zeng, F. (2021). Seasonal Prediction and Predictability of Regional Antarctic Sea Ice. *Journal of Climate*, *34*(15). DOI: 10.1175/JCLI-D-20-0965.1.

Callahan, C. W., & Mankin, J. S. (2022). Globally unequal effect of extreme heat on economic growth. *Science Advances*, *8*(43). DOI: 10.1126/sciadv.add3726.

Caneill, R., Roquet, F., Madec, G., & Nycander, J. (2022). The Polar Transition from Alpha to Beta Regions Set by a Surface Buoyancy Flux Inversion. *Journal of Physical Oceanography*, *52*(8). DOI: 10.1175/JPO-D-21-0295.1.

Caneill, R., Roquet, F., & Nycander, J. (2024). The Southern Ocean deep mixing band emerges from a competition between winter buoyancy loss and upper stratification strength. *Ocean Science*, *20*(2). DOI: 10.5194/os-20-601-2024.

Cerovečki, I., & Haumann, F. A. (2023). Decadal Reorganization of Subantarctic Mode Water. *Geophysical Research Letters*, *50*(14). DOI: 10.1029/2022GL102148.

Chandler, D. M., & Langebroek, P. M. (2024). Glacial–interglacial Circumpolar Deep Water temperatures during the last 800&thinsp;000 years: Estimates from a synthesis of bottom water temperature reconstructions. *Climate of the Past*, *20*(9). DOI: 10.5194/cp-20-2055-2024.

Chapman, P. (1998). The world ocean circulation experiment (woce). *Marine Technology Society Journal*, *32*(3), 23–36.

Chen, H., Haumann, F. A., Talley, L. D., Johnson, K. S., & Sarmiento, J. L. (2022). The Deep Ocean's Carbon Exhaust. *Global Biogeochemical Cycles*, *36*(7). DOI: 10.1029/2021GB007156.

Cheng, L., Abraham, J., Trenberth, K. E., Fasullo, J., Boyer, T., Locarnini, R., Zhang, B., Yu, F., Wan, L., Chen, X., Song, X., Liu, Y., Mann, M. E., Reseghetti, F., Simoncelli, S., Gouretski, V., Chen, G., Mishonov, A., Reagan, J., & Zhu, J. (2021). Upper Ocean Temperatures Hit Record High in 2020. *Advances in Atmospheric Sciences*, *38*(4). DOI: 10.1007/s00376-021-0447-x.

Cheng, L., Trenberth, K. E., Gruber, N., Abraham, J. P., Fasullo, J. T., Li, G., Mann, M. E., Zhao, X., & Zhu, J. (2020). Improved Estimates of Changes in Upper Ocean Salinity and the Hydrological Cycle. *Journal of Climate*, *33*(23). DOI: 10.1175/JCLI-D-20-0366.1.

Cisewski, B., Strass, V. H., & Prandke, H. (2005). Upper-ocean vertical mixing in the antarctic polar front zone. *Deep Sea Research Part II: Topical Studies in Oceanography*, *52*(9-10), 1087–1108.

Comiso, J. C., Gersten, R. A., Stock, L. V., Turner, J., Perez, G. J., & Cho, K. (2017). Positive Trend in the Antarctic Sea Ice Cover and Associated Changes in Surface Temperature. *Journal of Climate*, *30*(6). DOI: 10.1175/JCLI-D-16-0408.1.

Cook, J. (2021). Voyage towards the south pole. In *Travels, explorations and empires, 1770-1835, part i vol 3* (pp. 17–40). Routledge.

de Boyer Montégut, C. (2004). Mixed layer depth over the global ocean: An examination of profile data and a profile-based climatology. *Journal of Geophysical Research*, *109*(C12). DOI: 10.1029/2004JC002378.

de Jager, W., & Vichi, M. (2025). Increased Rotational Coupling Between Antarctic Sea Ice and the Atmosphere Over the Last 30 Years. *Journal of Geophysical Research: Oceans*, *130*(2). DOI: 10.1029/2024JC021239.

de Vos, A. (2020). The problem of 'Colonial Science' [Accessed: 2025-08-11].

Diamond, R., Sime, L. C., Holmes, C. R., & Schroeder, D. (2024). CMIP6 Models Rarely Simulate Antarctic Winter Sea-Ice Anomalies as Large as Observed in 2023. *Geophysical Research Letters*, *51*(10). DOI: 10.1029/2024GL109265.

Doddridge, E. W., Hobbs, W. R., Auger, M., Boyd, P. W., Chua, S. M. T., Cook, S., Corney, S., Emmerson, L., Fraser, A. D., Heil, P., Kelly, N., Lannuzel, D., Li, X., Liniger, G., Massom, R. A., Meyer, A., Reid, P., Southwell, C., Spence, P., . . . Yamazaki, K. (2025). Impacts of Antarctic summer sea-ice extremes. *PNAS Nexus*, *4*(7). DOI: 10.1093/pnasnexus/pgaf164.

Doddridge, E. W., Marshall, J., Song, H., Campin, J.-M., & Kelley, M. (2021). Southern Ocean Heat Storage, Reemergence, and Winter Sea Ice Decline Induced by Summertime Winds. *Journal of Climate*, *34*(4). DOI: 10.1175/JCLI-D-20-0322.1.

Dong, S., Garzoli, S. L., & Baringer, M. (2009). An assessment of the seasonal mixed layer salinity budget in the Southern Ocean. *Journal of Geophysical Research: Oceans*, *114*(C12). DOI: 10.1029/2008JC005258.

Dorschel, B., Hehemann, L., Viquerat, S., Warnke, F., Dreutter, S., Tenberge, Y. S., Accettella, D., An, L., Barrios, F., Bazhenova, E., Black, J., Bohoyo, F., Davey, C., De Santis, L., Dotti, C. E., Fremand, A. C., Fretwell, P. T., Gales, J. A., Gao, J., . . . Arndt, J. E. (2022). The International Bathymetric Chart of the Southern Ocean Version 2. *Scientific Data*, *9*(1). DOI: 10.1038/s41597-022-01366-7.

Dove, L. A., Balwada, D., Thompson, A. F., & Gray, A. R. (2022). Enhanced Ventilation in Energetic Regions of the Antarctic Circumpolar Current. *Geophysical Research Letters*, *49*(13). DOI: 10.1029/2021GL097574.

Droste, E. S., Bakker, D. C. E., Venables, H. J., Jones, E. M., Meredith, M. P., Dall'Olmo, G., Hoppema, M., Legge, O. J., Lee, G. A., & Queste, B. Y. (2025). Sea ice controls net ocean uptake of carbon dioxide by regulating wintertime stratification. *Communications Earth & Environment*, *6*(1). DOI: 10.1038/s43247-025-02395-x.

du Plessis, M. D., Swart, S., Biddle, L. C., Giddy, I. S., Monteiro, P. M. S., Reason, C. J. C., Thompson, A. F., & Nicholson, S.-A. (2022). The Daily-Resolved Southern Ocean Mixed Layer: Regional Contrasts Assessed Using

Glider Observations. *Journal of Geophysical Research: Oceans*, *127*(4). DOI: 10.1029/2021JC017760.

Dutrieux, P., De Rydt, J., Jenkins, A., Holland, P. R., Ha, H. K., Lee, S. H., Steig, E. J., Ding, Q., Abrahamsen, E. P., & Schröder, M. (2014). Strong Sensitivity of Pine Island Ice-Shelf Melting to Climatic Variability. *Science*, *343*(6167). DOI: 10.1126/science.1244341.

Eayrs, C., Li, X., Raphael, M. N., & Holland, D. M. (2021). Rapid decline in Antarctic sea ice in recent years hints at future change. *Nature Geoscience*, *14*(7). DOI: 10.1038/s41561-021-00768-3.

Espinosa, Z. I., Blanchard-Wrigglesworth, E., & Bitz, C. M. (2024). Understanding the drivers and predictability of record low Antarctic sea ice in austral winter 2023. *Communications Earth & Environment*, *5*(1). DOI: 10.1038/s43247-024-01772-2.

Evans, D. G., Zika, J. D., Naveira Garabato, A. C., & Nurser, A. J. G. (2018). The Cold Transit of Southern Ocean Upwelling. *Geophysical Research Letters*, *45*(24). DOI: 10.1029/2018GL079986.

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016). Overview of the coupled model intercomparison project phase 6 (cmip6) experimental design and organization. *Geoscientific Model Development*, *9*(5), 1937–1958.

Fernandez Castro, B., Peña, M., Nogueira, E., Gilcoto, M., Broullón, E., Comesaña, A., Bouffard, D., Naveira Garabato, A. C., & Mouriño-Carballido, B. (2022). Intense upper ocean mixing due to large aggregations of spawning fish. *Nature Geoscience*, *15*(4).

Ferrari, R., Jansen, M. F., Adkins, J. F., Burke, A., Stewart, A. L., & Thompson, A. F. (2014). Antarctic sea ice control on ocean circulation in present and glacial climates. *Proceedings of the National Academy of Sciences*, *111*(24). DOI: 10.1073/pnas.1323922111.

Ferreira, D., Marshall, J., Bitz, C. M., Solomon, S., & Plumb, A. (2015). Antarctic Ocean and Sea Ice Response to Ozone Depletion: A Two-Time-Scale Problem. *Journal of Climate*, *28*(3). DOI: 10.1175/JCLI-D-14-00313.1.

Fogt, R. L., Sleinkofer, A. M., Raphael, M. N., & Handcock, M. S. (2022). A regime shift in seasonal total Antarctic sea ice extent in the twentieth century. *Nature Climate Change*, *12*(1). DOI: 10.1038/s41558-021-01254-9.

Frants, M., Damerell, G. M., Gille, S. T., Heywood, K. J., MacKinnon, J., & Sprintall, J. (2013). An Assessment of Density-Based Finescale Methods for Estimating Diapycnal Diffusivity in the Southern Ocean. *Journal of Atmospheric and Oceanic Technology*, *30*(11). DOI: 10.1175/JTECH-D-12-00241.1.

Frölicher, T. L., Sarmiento, J. L., Paynter, D. J., Dunne, J. P., Krasting, J. P., & Winton, M. (2015). Dominance of the Southern Ocean in Anthropogenic Carbon and Heat Uptake in CMIP5 Models. *Journal of Climate*, *28*(2). DOI: 10.1175/JCLI-D-14-00117.1.

Gao, L., Rintoul, S. R., & Yu, W. (2018). Recent wind-driven change in Subantarctic Mode Water and its impact on ocean heat storage. *Nature Climate Change*, *8*(1). DOI: 10.1038/s41558-017-0022-8.

Giddy, I. S., Fer, I., Swart, S., & Nicholson, S.-A. (2023). Vertical Convergence of Turbulent and Double-Diffusive Heat Flux Drives Warming and Erosion of

Antarctic Winter Water in Summer. *Journal of Physical Oceanography*, *53*(8). DOI: 10.1175/JPO-D-22-0259.1.

Gonzalez, M., Dove, L. A., & Freilich, M. A. (2025). Distribution and Transport of Antarctic Winter Water Biogeochemical Properties. *Geophysical Research Letters*, *52*(8). DOI: 10.1029/2025GL114950.

Goosse, H., & Zunz, V. (2014). Decadal trends in the Antarctic sea ice extent ultimately controlled by ice–ocean feedback. *The Cryosphere*, *8*(2). DOI: 10.5194/tc-8-453-2014.

Goosse, H., Allende Contador, S., Bitz, C. M., Blanchard-Wrigglesworth, E., Eayrs, C., Fichefet, T., Himmich, K., Huot, P.-V., Klein, F., Marchi, S., Massonnet, F., Mezzina, B., Pelletier, C., Roach, L., Vancoppenolle, M., & van Lipzig, N. P. M. (2023). Modulation of the seasonal cycle of the Antarctic sea ice extent by sea ice processes and feedbacks with the ocean and the atmosphere. *The Cryosphere*, *17*(1). DOI: 10.5194/tc-17-407-2023.

Goosse, H., Kay, J. E., Armour, K. C., Bodas-Salcedo, A., Chepfer, H., Docquier, D., Jonko, A., Kushner, P. J., Lecomte, O., Massonnet, F., Park, H.-S., Pithan, F., Svensson, G., & Vancoppenolle, M. (2018). Quantifying climate feedbacks in polar regions. *Nature Communications*, *9*(1). DOI: 10.1038/s41467-018-04173-0.

Goosse, H., Lefebvre, W., de Montety, A., Crespin, E., & Orsi, A. H. (2009). Consistent past half-century trends in the atmosphere, the sea ice and the ocean at high southern latitudes. *Climate Dynamics*, *33*(7). DOI: 10.1007/s00382-008-0500-9.

Goosse, H., Libera, S., Naveira Garabato, A. C., Richaud, B., Silvano, A., & Vancoppenolle, M. (2025). On the control of the position of the winter sea ice edge by the antarctic circumpolar current. *EGUsphere*, *2025*, 1–27.

Gordon, A. L. (1981). Seasonality of Southern Ocean sea ice. *Journal of Geophysical Research: Oceans*, *86*(C5). DOI: 10.1029/JC086iC05p04193.

Gordon, A. L., & Huber, B. A. (1984). Thermohaline stratification below the southern ocean sea ice. *Journal of Geophysical Research: Oceans*, *89*(C1), 641–648.

Gray, A. R., Johnson, K. S., Bushinsky, S. M., Riser, S. C., Russell, J. L., Talley, L. D., Wanninkhof, R., Williams, N. L., & Sarmiento, J. L. (2018). Autonomous Biogeochemical Floats Detect Significant Carbon Dioxide Outgassing in the High-Latitude Southern Ocean. *Geophysical Research Letters*, *45*(17). DOI: 10.1029/2018GL078013.

Gregg, M., D'Asaro, E., Riley, J., & Kunze, E. (2018). Mixing Efficiency in the Ocean. *Annual Review of Marine Science*, *10*(1). DOI: 10.1146/annurev-marine-121916-063643.

Groeskamp, S., Abernathey, R. P., & Klocker, A. (2016). Water mass transformation by cabbeling and thermobaricity. *Geophysical Research Letters*, *43*(20). DOI: 10.1002/2016GL070860.

Hanawa, K., & D.Talley, L. (2001). Chapter 5.4 Mode waters. In G. Siedler, J. Church, & J. Gould (Eds.), *International Geophysics* (Vol. 77). DOI: 10.1016/S0074-6142(01)80129-7.

Haumann, F. A., Gruber, N., & Münnich, M. (2020). Sea-Ice Induced Southern Ocean Subsurface Warming and Surface Cooling in a Warming Climate. *AGU Advances*, *1*(2). DOI: 10.1029/2019AV000132.

Haumann, F. A., Gruber, N., Münnich, M., Frenger, I., & Kern, S. (2016). Sea-ice transport driving Southern Ocean salinity and its recent trends. *Nature*, *537*(7618). DOI: 10.1038/nature19101.

Haumann, F. A., Notz, D., & Schmidt, H. (2014). Anthropogenic influence on recent circulation-driven Antarctic sea ice changes. *Geophysical Research Letters*, *41*(23). DOI: 10.1002/2014GL061659.

Herraiz-Borreguero, L., & Rintoul, S. R. (2011). Subantarctic mode water: Distribution and circulation. *Ocean Dynamics*, *61*(1). DOI: 10.1007/s10236-010-0352-9.

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., & Thépaut, J.-N. (2023). Era5 monthly averaged data on single levels from 1940 to present [Accessed on 01-06-2023]. *Copernicus Climate Change Service (C3S) Climate Data Store (CDS)*. DOI: 10.24381/cds.f17050d7.

Heuzé, C. (2021). Antarctic Bottom Water and North Atlantic Deep Water in CMIP6 models. *Ocean Science*, *17*(1). DOI: 10.5194/os-17-59-2021.

Himmich, K., Vancoppenolle, M., Madec, G., Sallée, J.-B., Holland, P. R., & Lebrun, M. (2023). Drivers of Antarctic sea ice advance. *Nature Communications*, *14*(1). DOI: 10.1038/s41467-023-41962-8.

Himmich, K., Vancoppenolle, M., Stammerjohn, S., Bocquet, M., Madec, G., Sallée, J.-B., & Fleury, S. (2024). Thermodynamics Drive Post-2016 Changes in the Antarctic Sea Ice Seasonal Cycle. *Journal of Geophysical Research: Oceans*, *129*(8). DOI: 10.1029/2024JC021112.

Hobbs, W., Spence, P., Meyer, A., Schroeter, S., Fraser, A. D., Reid, P., Tian, T. R., Wang, Z., Liniger, G., Doddridge, E. W., & Boyd, P. W. (2024). Observational Evidence for a Regime Shift in Summer Antarctic Sea Ice. *Journal of Climate*, *37*(7). DOI: 10.1175/JCLI-D-23-0479.1.

Hobbs, W. R., Massom, R., Stammerjohn, S., Reid, P., Williams, G., & Meier, W. (2016). A review of recent changes in Southern Ocean sea ice, their drivers and forcings. *Global and Planetary Change*, *143*. DOI: 10.1016/j.gloplacha.2016.06.008.

Holland, M. M., Blanchard-Wrigglesworth, E., Kay, J., & Vavrus, S. (2013). Initial-value predictability of Antarctic sea ice in the Community Climate System Model 3. *Geophysical Research Letters*, *40*(10). DOI: 10.1002/grl.50410.

Holland, P. R. (2014). The seasonality of Antarctic sea ice trends. *Geophysical Research Letters*, *41*(12). DOI: 10.1002/2014GL060172.

Holland, P. R., Bruneau, N., Enright, C., Losch, M., Kurtz, N. T., & Kwok, R. (2014). Modeled Trends in Antarctic Sea Ice Thickness. *Journal of Climate*, *27*(10). DOI: 10.1175/JCLI-D-13-00301.1.

Holland, P. R., & Kwok, R. (2012). Wind-driven trends in Antarctic sea-ice drift. *Nature Geoscience*, *5*(12). DOI: 10.1038/ngeo1627.

Hoppema, M., Fahrbach, E., Schröder, M., Wisotzki, A., & de Baar, H. J. W. (1995). Winter-summer differences of carbon dioxide and oxygen in the Weddell Sea surface layer. *Marine Chemistry*, *51*(3). DOI: 10.1016/0304-4203(95)00065-8.

Ioc, S., et al. (2010). The international thermodynamic equation of seawater–2010: Calculation and use of thermodynamic properties. *Intergovernmental Oceanographic Commission, UNESCO Manuals and Guides No*, *56*(203), 196.

Jacobs, S. S. (2004). Bottom water production and its links with the thermohaline circulation. *Antarctic Science*, *16*(4). DOI: 10.1017/S095410200400224X.

Jenkins, A., Dutrieux, P., Jacobs, S. S., McPhail, S. D., Perrett, J. R., Webb, A. T., & White, D. (2010). Observations beneath Pine Island Glacier in West Antarctica and implications for its retreat. *Nature Geoscience*, *3*(7). DOI: 10.1038/ngeo890.

Johnson, G. C. (2008). Quantifying Antarctic Bottom Water and North Atlantic Deep Water volumes. *Journal of Geophysical Research: Oceans*, *113*(C5). DOI: 10.1029/2007JC004477.

Jones, D. C., Sonnewald, M., Zhou, S., Hausmann, U., Meijers, A. J. S., Rosso, I., Boehme, L., Meredith, M. P., & Naveira Garabato, A. C. (2023). Unsupervised classification identifies coherent thermohaline structures in the Weddell Gyre region. *Ocean Science*, *19*(3). DOI: 10.5194/os-19-857-2023.

Josey, S. A., Meijers, A. J. S., Blaker, A. T., Grist, J. P., Mecking, J., & Ayres, H. C. (2024). Record-low Antarctic sea ice in 2023 increased ocean heat loss and storms. *Nature*, *636*(8043). DOI: 10.1038/s41586-024-08368-y.

Jutras, M., Bushinsky, S. M., Cerovečki, I., & Briggs, N. (2025). Mixing Accounts for More Than Half of Biogeochemical Changes Along Mode Water Ventilation Pathways. *Geophysical Research Letters*, *52*(7). DOI: 10.1029/2024GL113789.

Kimura, N. (2004). Sea ice motion in response to surface wind and ocean current in the southern ocean. *Journal of the Meteorological Society of Japan. Ser. II*, *82*(4), 1223–1231.

Klocker, A., Naveira Garabato, A. C., Roquet, F., de Lavergne, C., & Rintoul, S. R. (2023). Generation of the Internal Pycnocline in the Subpolar Southern Ocean by Wintertime Sea Ice Melting. *Journal of Geophysical Research: Oceans*, *128*(3). DOI: 10.1029/2022JC019113.

Kozlowski, D., Larivière, V., Sugimoto, C. R., & Monroe-White, T. (2022). Intersectional inequalities in science [Publisher: Proceedings of the National Academy of Sciences]. *Proceedings of the National Academy of Sciences*, *119*(2), e2113067119. DOI: 10.1073/pnas.2113067119.

Kusahara, K., Williams, G. D., Tamura, T., Massom, R., & Hasumi, H. (2017). Dense shelf water spreading from Antarctic coastal polynyas to the deep Southern Ocean: A regional circumpolar model study. *Journal of Geophysical Research: Oceans*, *122*(8). DOI: 10.1002/2017JC012911.

Large, W. G., McWilliams, J. C., & Doney, S. C. (1994). Oceanic vertical mixing: A review and a model with a nonlocal boundary layer parameterization. *Reviews of Geophysics*, *32*(4). DOI: 10.1029/94RG01872.

Laurent, L. S., Garabato, A. C. N., Ledwell, J. R., Thurnherr, A. M., Toole, J. M., & Watson, A. J. (2012). Turbulence and Diapycnal Mixing in Drake Passage [Publisher: American Meteorological Society Section: Journal of Physical Oceanography]. *Journal of Physical Oceanography*, *42*(12), 2143–2152. DOI: 10.1175/JPO-D-12-027.1.

Lecomte, O., Goosse, H., Fichefet, T., de Lavergne, C., Barthélemy, A., & Zunz, V. (2017). Vertical ocean heat redistribution sustaining sea-ice concentration trends in the Ross Sea. *Nature Communications*, *8*(1). DOI: 10.1038/s41467-017-00347-4.

Ledwell, J. R., Laurent, L. C. S., Girton, J. B., & Toole, J. M. (2011). Diapycnal Mixing in the Antarctic Circumpolar Current. *Journal of Physical Oceanography*, *41*(1). DOI: 10.1175/2010JPO4557.1.

Ledwell, J. R., Montgomery, E. T., Polzin, K. L., St. Laurent, L. C., Schmitt, R. W., & Toole, J. M. (2000). Evidence for enhanced mixing over rough topography in the abyssal ocean. *Nature*, *403*(6766). DOI: 10.1038/35003164.

Legg, S., Wang, C., Kappel, E., & Thompson, L. (2023). Gender Equity in Oceanography. *Annual Review of Marine Science*, *15*(Volume 15, 2023). DOI: 10.1146/annurev-marine-032322-100357.

Levitus, S., Antonov, J. I., Boyer, T. P., & Stephens, C. (2000). Warming of the World Ocean. *Science*, *287*(5461). DOI: 10.1126/science.287.5461.2225.

Libera, S., Hobbs, W., Klocker, A., Meyer, A., & Matear, R. (2022). Ocean-Sea Ice Processes and Their Role in Multi-Month Predictability of Antarctic Sea Ice. *Geophysical Research Letters*, *49*(8). DOI: 10.1029/2021GL097047.

Lumpkin, R., & Speer, K. (2007). Global Ocean Meridional Overturning. *Journal of Physical Oceanography*, *37*(10). DOI: 10.1175/JPO3130.1.

Lund, D. C., Chase, Z., Kohfeld, K. E., & Wilson, E. A. (2021). Tracking Southern Ocean Sea Ice Extent With Winter Water: A New Method Based on the Oxygen Isotopic Signature of Foraminifera. *Paleoceanography and Paleoclimatology*, *36*(6). DOI: 10.1029/2020PA004095.

Marchi, S., Fichefet, T., Goosse, H., Zunz, V., Tietsche, S., Day, J. J., & Hawkins, E. (2019). Reemergence of Antarctic sea ice predictability and its link to deep ocean mixing in global climate models. *Climate Dynamics*, *52*(5). DOI: 10.1007/s00382-018-4292-2.

Marshall, J., Jamous, D., & Nilsson, J. (1999). Reconciling thermodynamic and dynamic methods of computation of water-mass transformation rates. *Deep Sea Research Part I: Oceanographic Research Papers*, *46*(4), 545–572.

Marshall, J., & Schott, F. (1999). Open-ocean convection: Observations, theory, and models. *Reviews of Geophysics*, *37*(1). DOI: 10.1029/98RG02739.

Martinson, D. G. (1990). Evolution of the southern ocean winter mixed layer and sea ice: Open ocean deepwater formation and ventilation. *Journal of Geophysical Research: Oceans*, *95*(C7). DOI: 10.1029/JC095iC07p11641.

Martinson, D. G., & Wamser, C. (1990). Ice drift and momentum exchange in winter Antarctic pack ice. *Journal of Geophysical Research: Oceans*, *95*(C2). DOI: 10.1029/JC095iC02p01741.

Massom, R. A., Scambos, T. A., Bennetts, L. G., Reid, P., Squire, V. A., & Stammerjohn, S. E. (2018). Antarctic ice shelf disintegration triggered by sea ice loss and ocean swell. *Nature*, *558*(7710). DOI: 10.1038/s41586-018-0212-1.

Massom, R. A., & Stammerjohn, S. E. (2010). Antarctic sea ice change and variability – Physical and ecological implications. *Polar Science*, *4*(2). DOI: 10.1016/j.polar.2010.05.001.

Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M., et al. (2021). Climate change 2021: The physical science basis. *Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change*, *2*(1), 2391.

Masuzawa, J. (1969). Subtropical mode water. *Deep Sea Research and Oceanographic Abstracts*, *16*(5). DOI: 10.1016/0011-7471(69)90034-5.

McMahon, C. R., Roquet, F., Baudel, S., Belbeoch, M., Bestley, S., Blight, C., Boehme, L., Carse, F., Costa, D. P., Fedak, M. A., Guinet, C., Harcourt, R., Heslop, E., Hindell, M. A., Hoenner, X., Holland, K., Holland, M., Jaine, F. R. A., Jeanniard du Dot, T., . . . Woodward, B. (2021). Animal Borne Ocean

Sensors – AniBOS – An Essential Component of the Global Ocean Observing System. *Frontiers in Marine Science*, *8*. DOI: 10.3389/fmars.2021.751840.

Meehl, G. A., Arblaster, J. M., Bitz, C. M., Chung, C. T. Y., & Teng, H. (2016). Antarctic sea-ice expansion between 2000 and 2014 driven by tropical Pacific decadal climate variability. *Nature Geoscience*, *9*(8). DOI: 10.1038/ngeo2751.

Meehl, G. A., Arblaster, J. M., Chung, C. T. Y., Holland, M. M., DuVivier, A., Thompson, L., Yang, D., & Bitz, C. M. (2019). Sustained ocean changes contributed to sudden Antarctic sea ice retreat in late 2016. *Nature Communications*, *10*(1). DOI: 10.1038/s41467-018-07865-9.

Meredith, M. P. (2013). Replenishing the abyss. *Nature Geoscience*, *6*(3). DOI: 10.1038/ngeo1743.

Meredith, M. P. (2019). The global importance of the Southern Ocean, and the key role of its freshwater cycle.

Meredith, M. P., & King, J. C. (2005). Rapid climate change in the ocean west of the Antarctic Peninsula during the second half of the 20th century. *Geophysical Research Letters*, *32*(19). DOI: 10.1029/2005GL024042.

Meredith, M. P., Sommerkorn, M., Cassotta, S., Derksen, C., Ekaykin, A., Hollowed, A., Kofinas, G., Mackintosh, A., Melbourne-Thomas, J., Muelbert, M., et al. (2019). Polar regions. chapter 3, ipcc special report on the ocean and cryosphere in a changing climate.

Mohrmann, M., Heuzé, C., & Swart, S. (2021). Southern Ocean polynyas in CMIP6 models. *The Cryosphere*, *15*(9). DOI: 10.5194/tc-15-4281-2021.

Morales Maqueda, M. A., Willmott, A. J., & Biggs, N. R. T. (2004). Polynya Dynamics: A Review of Observations and Modeling. *Reviews of Geophysics*, *42*(1). DOI: 10.1029/2002RG000116.

Morioka, Y., Manabe, S., Zhang, L., Delworth, T. L., Cooke, W., Nonaka, M., & Behera, S. K. (2024). Antarctic sea ice multidecadal variability triggered by Southern Annular Mode and deep convection. *Communications Earth & Environment*, *5*(1). DOI: 10.1038/s43247-024-01783-z.

Morrison, A. K., Griffies, S. M., Winton, M., Anderson, W. G., & Sarmiento, J. L. (2016). Mechanisms of Southern Ocean Heat Uptake and Transport in a Global Eddying Climate Model. *Journal of Climate*, *29*(6). DOI: 10.1175/JCLI-D-15-0579.1.

Morrow, R., Valladeau, G., & Sallee, J.-B. (2008). Observed subsurface signature of Southern Ocean sea level rise. *Progress in Oceanography*, *77*(4). DOI: 10.1016/j.pocean.2007.03.002.

Mosby, H. (1934). The waters of the Atlantic Antarctic ocean. *Scientific Research Norwegian Expedition 1927-28*, *1*(1), 1–131.

Naëck, K., Boutin, J., Swart, S., du Plessis, M., Merlivat, L., Beaumont, L., Lourenco, A., d'Ovidio, F., Rousselet, L., Ward, B., & Sallée, J.-B. (2025). Anomalous summertime $CO_2$ sink in the subpolar Southern Ocean promoted by early 2021 sea ice retreat. *Biogeosciences*, *22*(8). DOI: 10.5194/bg-22-1947-2025.

Narayanan, A., Gille, S. T., Mazloff, M. R., du Plessis, M. D., Murali, K., & Roquet, F. (2023). Zonal Distribution of Circumpolar Deep Water Transformation Rates and Its Relation to Heat Content on Antarctic Shelves. *Journal of Geophysical Research: Oceans*, *128*(6). DOI: 10.1029/2022JC019310.

National Academies of Sciences, E., Medicine et al. (2025). *Forecasting the ocean: The 2025–2035 decade of ocean science.*

Naveira Garabato, A. C., Ferrari, R., & Polzin, K. L. (2011). Eddy stirring in the Southern Ocean. *Journal of Geophysical Research: Oceans*, *116*(C9). DOI: 10.1029/2010JC006818.

Nicholson, S.-A., Whitt, D. B., Fer, I., du Plessis, M. D., Lebéhot, A. D., Swart, S., Sutton, A. J., & Monteiro, P. M. S. (2022). Storms drive outgassing of CO2 in the subpolar Southern Ocean. *Nature Communications*, *13*(1). DOI: 10.1038/s41467-021-27780-w.

Notz, D., & Stroeve, J. (2016). Observed Arctic sea-ice loss directly follows anthropogenic CO2 emission [Publisher: American Association for the Advancement of Science]. *Science*, *354*(6313), 747–750. DOI: 10.1126/science.aag2345.

Olivier, L., & Haumann, F. A. (2025). Southern Ocean freshening stalls deep ocean CO2 release in a changing climate. DOI: 10.21203/rs.3.rs-6530488/v1.

Orsi, A. H., Johnson, G. C., & Bullister, J. L. (1999). Circulation, mixing, and production of antarctic bottom water. *Progress in Oceanography*, *43*(1), 55–109.

Orsi, A. H., Whitworth, T., & Nowlin, W. D. (1995). On the meridional extent and fronts of the Antarctic Circumpolar Current. *Deep Sea Research Part I: Oceanographic Research Papers*, *42*(5). DOI: 10.1016/0967-0637(95)00021-W.

Osborn, T. R. (1980). Estimates of the Local Rate of Vertical Diffusion from Dissipation Measurements. *Journal of Physical Oceanography*, *10*(1). DOI: 10.1175/1520-0485(1980)010<0083:EOTLRO>2.0.CO;2.

Park, Y.-H., Lee, J.-H., Durand, I., & Hong, C.-S. (2014). Validation of Thorpe-scale-derived vertical diffusivities against microstructure measurements in the Kerguelen region. *Biogeosciences*, *11*(23). DOI: 10.5194/bg-11-6927-2014.

Park, Y.-H., Park, T., Kim, T.-W., Lee, S.-H., Hong, C.-S., Lee, J.-H., Rio, M.-H., Pujol, M.-I., Ballarotta, M., Durand, I., & Provost, C. (2019). Observations of the Antarctic Circumpolar Current Over the Udintsev Fracture Zone, the Narrowest Choke Point in the Southern Ocean. *Journal of Geophysical Research: Oceans*, *124*(7). DOI: 10.1029/2019JC015024.

Patmore, R. D., Holland, P. R., Munday, D. R., Garabato, A. C. N., Stevens, D. P., & Meredith, M. P. (2019). Topographic Control of Southern Ocean Gyres and the Antarctic Circumpolar Current: A Barotropic Perspective. *Journal of Physical Oceanography*, *49*(12). DOI: 10.1175/JPO-D-19-0083.1.

Pellichero, V., Sallée, J.-B., Chapman, C. C., & Downes, S. M. (2018). The southern ocean meridional overturning in the sea-ice sector is driven by freshwater fluxes. *Nature Communications*, *9*(1). DOI: 10.1038/s41467-018-04101-2.

Pellichero, V., Sallée, J.-B., Schmidtko, S., Roquet, F., & Charrassin, J.-B. (2017). The ocean mixed layer under Southern Ocean sea-ice: Seasonal cycle and forcing: OCEAN MIXED LAYER UNDER SOUTHERN SEA-ICE. *Journal of Geophysical Research: Oceans*, *122*(2). DOI: 10.1002/2016JC011970.

Pollard, R. T., Lucas, M. I., & Read, J. F. (2002). Physical controls on biogeochemical zonation in the Southern Ocean. *Deep Sea Research Part II: Topical Studies in Oceanography*, *49*(16). DOI: 10.1016/S0967-0645(02)00084-X.

Portela, E., Kolodziejczyk, N., Maes, C., & Thierry, V. (2020). Interior Water-Mass Variability in the Southern Hemisphere Oceans during the Last Decade. *Journal of Physical Oceanography*, *50*(2). DOI: 10.1175/JPO-D-19-0128.1.

Prend, C. J., MacGilchrist, G. A., Manucharyan, G. E., Pang, R. Q., Moorman, R., Thompson, A. F., Griffies, S. M., Mazloff, M. R., Talley, L. D., & Gille, S. T. (2024). Ross Gyre variability modulates oceanic heat supply toward the West

Antarctic continental shelf. *Communications Earth & Environment*, *5*(1). DOI: 10.1038/s43247-024-01207-y.

Purich, A., & Doddridge, E. W. (2023). Record low Antarctic sea ice coverage indicates a new sea ice state. *Communications Earth & Environment*, *4*(1). DOI: 10.1038/s43247-023-00961-9.

Raphael, M. N. (2007). The influence of atmospheric zonal wave three on Antarctic sea ice variability. *Journal of Geophysical Research: Atmospheres*, *112*(D12). DOI: 10.1029/2006JD007852.

Raphael, M. N., & Handcock, M. S. (2022). A new record minimum for antarctic sea ice. *Nature Reviews Earth & Environment*, *3*(4), 215–216.

Raphael, M. N., Maierhofer, T. J., Fogt, R. L., Hobbs, W. R., & Handcock, M. S. (2025). A twenty-first century structural change in Antarctica's sea ice system. *Communications Earth & Environment*, *6*(1). DOI: 10.1038/s43247-025-02107-5.

Rignot, E., Jacobs, S., Mouginot, J., & Scheuchl, B. (2013a). Ice-Shelf Melting Around Antarctica. *Science*, *341*(6143). DOI: 10.1126/science.1235798.

Rignot, E., Jacobs, S., Mouginot, J., & Scheuchl, B. (2013b). Ice-shelf melting around antarctica. *Science*, *341*(6143), 266–270.

Roach, L. A., Eisenman, I., Wagner, T. J. W., Blanchard-Wrigglesworth, E., & Bitz, C. M. (2022). Asymmetry in the seasonal cycle of Antarctic sea ice driven by insolation. *Nature Geoscience*, *15*(4). DOI: 10.1038/s41561-022-00913-6.

Roach, L. A., Dörr, J., Holmes, C. R., Massonnet, F., Blockley, E. W., Notz, D., Rackow, T., Raphael, M. N., O'Farrell, S. P., Bailey, D. A., & Bitz, C. M. (2020). Antarctic Sea Ice Area in CMIP6. *Geophysical Research Letters*, *47*(9). DOI: 10.1029/2019GL086729.

Roach, L. A., Mankoff, K. D., Romanou, A., Blanchard-Wrigglesworth, E., Haine, T. W. N., & Schmidt, G. A. (2023). Winds and Meltwater Together Lead to Southern Ocean Surface Cooling and Sea Ice Expansion. *Geophysical Research Letters*, *50*(24). DOI: 10.1029/2023GL105948.

Roemmich, D., Johnson, G., Riser, S., Davis, R., Gilson, J., Owens, W. B., Garzoli, S., Schmid, C., & Ignaszewski, M. (2009). The Argo Program: Observing the Global Oceans with Profiling Floats. *Oceanography*, *22*(2). DOI: 10.5670/oceanog.2009.36.

Roquet, F., Ferreira, D., Caneill, R., Schlesinger, D., & Madec, G. (2022). Unique thermal expansion properties of water key to the formation of sea ice on Earth. *Science Advances*, *8*(46). DOI: 10.1126/sciadv.abq0793.

Rosso, I., Hogg, A. M., Strutton, P. G., Kiss, A. E., Matear, R., Klocker, A., & Van Sebille, E. (2014). Vertical transport in the ocean due to sub-mesoscale structures: Impacts in the Kerguelen region. *Ocean Modelling*, *80*. DOI: 10.1016/j.ocemod.2014.05.001.

Sabu, P., Libera, S. A., Chacko, R., Anilkumar, N., Subeesh, M., & Thomas, A. P. (2020). Winter water variability in the Indian Ocean sector of Southern Ocean during austral summer. *Deep Sea Research Part II: Topical Studies in Oceanography*, *178*, 104852. DOI: 10.1016/j.dsr2.2020.104852.

Saenz, B. T., McKee, D. C., Doney, S. C., Martinson, D. G., & Stammerjohn, S. E. (2023). Influence of seasonally varying sea-ice concentration and subsurface ocean heat on sea-ice thickness and sea-ice seasonality for a 'warm-shelf' region in Antarctica. *Journal of Glaciology*, *69*(277). DOI: 10.1017/jog.2023.36.

Sallée, J. B., Abrahamsen, E. P., Allaigre, C., Auger, M., Ayres, H., Badhe, R., Boutin, J., Brearley, J. A., de Lavergne, C., ten Doeschate, A. M. M., Droste, E. S., du Plessis, M. D., Ferreira, D., Giddy, I. S., Gülk, B., Gruber, N., Hague, M., Hoppema, M., Josey, S. A., … Zhou, S. (2023). Southern ocean carbon and heat impact on climate. *Royal Society*, *381*(2249), 20220056. DOI: 10.1098/rsta.2022.0056.

Sallée, J.-B., Shuckburgh, E., Bruneau, N., Meijers, A. J. S., Bracegirdle, T. J., & Wang, Z. (2013). Assessment of Southern Ocean mixed-layer depths in CMIP5 models: Historical bias and forcing response. *Journal of Geophysical Research: Oceans*, *118*(4). DOI: 10.1002/jgrc.20157.

Schlosser, E., Haumann, F. A., & Raphael, M. N. (2018). Atmospheric influences on the anomalous 2016 Antarctic sea ice decay. *The Cryosphere*, *12*(3). DOI: 10.5194/tc-12-1103-2018.

Schmidtko, S., Heywood, K. J., Thompson, A. F., & Aoki, S. (2014). Multidecadal warming of Antarctic waters. *Science*, *346*(6214). DOI: 10.1126/science.1256117.

Schofield, O., Cimino, M., Doney, S., Friedlaender, A., Meredith, M., Moffat, C., Stammerjohn, S., Mooy, B. V., & Steinberg, D. (2024). Antarctic pelagic ecosystems on a warming planet. *Trends in Ecology & Evolution*, *0*(0). DOI: 10.1016/j.tree.2024.08.007.

Schroeter, S., O'Kane, T. J., & Sandery, P. A. (2023). Antarctic sea ice regime shift associated with decreasing zonal symmetry in the Southern Annular Mode. *The Cryosphere*, *17*(2). DOI: 10.5194/tc-17-701-2023.

Sharma, G. S., & Mathew, B. (1985). Hydrography and circulation off the Antarctica in the Indian Ocean region. *Journal of Earth System Science*, *94*(1). DOI: 10.1007/BF02863405.

Siegelman, L., Roquet, F., Mensah, V., Rivière, P., Pauthenet, E., Picard, B., & Guinet, C. (2019). Correction and Accuracy of High- and Low-Resolution CTD Data from Animal-Borne Instruments. *Journal of Atmospheric and Oceanic Technology*, *36*(5). DOI: 10.1175/JTECH-D-18-0170.1.

Silvano, A., Narayanan, A., Catany, R., Olmedo, E., González-Gambau, V., Turiel, A., Sabia, R., Mazloff, M. R., Spira, T., Haumann, F. A., & Naveira Garabato, A. C. (2025). Rising surface salinity and declining sea ice: A new Southern Ocean state revealed by satellites. *Proceedings of the National Academy of Sciences*, *122*(27). DOI: 10.1073/pnas.2500440122.

Silvano, A., Rintoul, S. R., Peña-Molino, B., Hobbs, W. R., van Wijk, E., Aoki, S., Tamura, T., & Williams, G. D. (2018). Freshening by glacial meltwater enhances melting of ice shelves and reduces formation of Antarctic Bottom Water. *Science Advances*, *4*(4). DOI: 10.1126/sciadv.aap9467.

SOCCOM. (2019). Southern ocean carbon and climate observations and modelling. [Retrieved from https://soccom.princeton.edu/]. *(SOCCOM)*.

Solodoch, A., Stewart, A. L., Hogg, A. M., Morrison, A. K., Kiss, A. E., Thompson, A. F., Purkey, S. G., & Cimoli, L. (2022). How Does Antarctic Bottom Water Cross the Southern Ocean? *Geophysical Research Letters*, *49*(7). DOI: 10.1029/2021GL097211.

Spalding, A. K., Grorud-Colvert, K., Allison, E. H., Amon, D. J., Collin, R., de Vos, A., Friedlander, A. M., Johnson, S. M., Mayorga, J., Paris, C. B., Scott, C., Suman, D. O., Cisneros-Montemayor, A. M., Estradivari, Giron-Nava, A., Gurney, G. G., Harris, J. M., Hicks, C., Mangubhai, S., . . . Thurber, R. V. (2023). Engaging the tropical majority to make ocean governance and science more equitable and effective. *npj Ocean Sustainability*, *2*(1). DOI: 10.1038/s44183-023-00015-9.

Spira, T., Swart, S., & du Plessis, M. (2023). Processed hydrographic SO data, 2004-2021 [Dataset]. DOI: 10.5281/zenodo.10258138.

Stammerjohn, S., & Maksym, T. (2017). Gaining (and losing) Antarctic sea ice: Variability, trends and mechanisms. In *Sea Ice*. DOI: 10.1002/9781118778371.ch10.

Stammerjohn, S., Massom, R., Rind, D., & Martinson, D. (2012). Regions of rapid sea ice change: An inter-hemispheric seasonal comparison. *Geophysical Research Letters*, *39*(6). DOI: 10.1029/2012GL050874.

Stappard, D., Fernández Castro, B., Naveira Garabato, A., & Tyrrell, T. (2025). Identification of southern ocean upwelling from biogeochemical-argo floats. *Journal of Geophysical Research: Oceans*, *130*(6), e2023JC020597.

Stewart, K. D., & Haine, T. W. N. (2016). Thermobaricity in the Transition Zones between Alpha and Beta Oceans. *Journal of Physical Oceanography*, *46*(6). DOI: 10.1175/JPO-D-16-0017.1.

Stroeve, J., & Notz, D. (2018). Changing state of Arctic sea ice across all seasons. *Environmental Research Letters*, *13*(10). DOI: 10.1088/1748-9326/aade56.

Stuecker, M. F., Bitz, C. M., & Armour, K. C. (2017). Conditions leading to the unprecedented low Antarctic sea ice extent during the 2016 austral spring season. *Geophysical Research Letters*, *44*(17). DOI: 10.1002/2017GL074691.

Talley, L. (2013). Closure of the Global Overturning Circulation Through the Indian, Pacific, and Southern Oceans: Schematics and Transports. *Oceanography*, *26*(1). DOI: 10.5670/oceanog.2013.07.

Talley, L., Pickard, G. L., Emery, W. J., & Swift, J. H. (2011). Physical properties of seawater. *Descriptive physical oceanography*, *6*, 29–65.

Tamsitt, V., England, M. H., Rintoul, S. R., & Morrison, A. K. (2021). Residence Time and Transformation of Warm Circumpolar Deep Water on the Antarctic Continental Shelf. *Geophysical Research Letters*, *48*(20). DOI: 10.1029/2021GL096092.

Tamsitt, V., Drake, H. F., Morrison, A. K., Talley, L. D., Dufour, C. O., Gray, A. R., Griffies, S. M., Mazloff, M. R., Sarmiento, J. L., Wang, J., & Weijer, W. (2017). Spiraling pathways of global deep waters to the surface of the Southern Ocean. *Nature Communications*, *8*(1). DOI: 10.1038/s41467-017-00197-0.

Tamura, T., Ohshima, K. I., & Nihashi, S. (2008). Mapping of sea ice production for Antarctic coastal polynyas. *Geophysical Research Letters*, *35*(7). DOI: 10.1029/2007GL032903.

Thompson, A. F., Gille, S. T., MacKinnon, J. A., & Sprintall, J. (2007). Spatial and Temporal Patterns of Small-Scale Mixing in Drake Passage. *Journal of Physical Oceanography*, *37*(3). DOI: 10.1175/JPO3021.1.

Thompson, A. F., & Sallée, J.-B. (2012). Jets and Topography: Jet Transitions and the Impact on Transport in the Antarctic Circumpolar Current. *Journal of Physical Oceanography*, *42*(6). DOI: 10.1175/JPO-D-11-0135.1.

Thorpe, S. A. (2005). *The turbulent ocean*. Cambridge university press.

Timmermans, M.-L., Toole, J., Krishfield, R., & Winsor, P. (2008). Ice-Tethered Profiler observations of the double-diffusive staircase in the Canada Basin thermocline. *Journal of Geophysical Research: Oceans*, *113*(C1). DOI: 10.1029/2008JC004829.

Toggweiler, J. R., Russell, J. L., & Carson, S. R. (2006). Midlatitude westerlies, atmospheric CO2, and climate change during the ice ages. *Paleoceanography*, *21*(2). DOI: 10.1029/2005PA001154.

Toggweiler, J., & Samuels, B. (1993). New radiocarbon constraints on the upwelling of abyssal water to the ocean's surface. In *The global carbon cycle* (pp. 333–366). Springer.

Toole, J. M. (1981). Sea ice, winter convection, and the temperature minimum layer in the Southern Ocean. *Journal of Geophysical Research: Oceans*, *86*(C9). DOI: 10.1029/JC086iC09p08037.

Treasure, A. M., Roquet, F., Ansorge, I. J., Bester, M. N., Boehme, L., Bornemann, H., Charrassin, J.-B., Chevallier, D., Costa, D. P., Fedak, M. A., Guinet, C., Hammill, M. O., Harcourt, R. G., Hindell, M. A., Kovacs, K. M., Lea, M.-A., Lovell, P., Lowther, A. D., Lydersen, C., … de Bruyn, P. N. (2017). Marine Mammals Exploring the Oceans Pole to Pole: A Review of the MEOP Consortium. *Oceanography*, *30*(2).

Truong, C., Oudre, L., & Vayatis, N. (2020). Selective review of offline change point detection methods. *Signal Processing*, *167*. DOI: 10.1016/j.sigpro.2019.107299.

Turner, J., Hosking, J. S., Bracegirdle, T. J., Marshall, G. J., & Phillips, T. (2015). Recent changes in Antarctic Sea Ice. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *373*(2045). DOI: 10.1098/rsta.2014.0163.

Turner, J., Phillips, T., Marshall, G. J., Hosking, J. S., Pope, J. O., Bracegirdle, T. J., & Deb, P. (2017). Unprecedented springtime retreat of Antarctic sea ice in 2016. *Geophysical Research Letters*, *44*(13). DOI: 10.1002/2017GL073656.

UNESCO. (2019). *Women in science* (tech. rep. No. Fact Sheet No. 55) (Accessed: 2025-08-11). UNESCO Institute for Statistics.

van Sebille, E., Spence, P., Mazloff, M. R., England, M. H., Rintoul, S. R., & Saenko, O. A. (2013). Abyssal connections of Antarctic Bottom Water in a Southern Ocean State Estimate. *Geophysical Research Letters*, *40*(10). DOI: 10.1002/grl.50483.

Vichi, M., Eayrs, C., Alberello, A., Bekker, A., Bennetts, L., Holland, D., de Jong, E., Joubert, W., MacHutchon, K., Messori, G., Mojica, J. F., Onorato, M., Saunders, C., Skatulla, S., & Toffoli, A. (2019). Effects of an Explosive Polar Cyclone Crossing the Antarctic Marginal Ice Zone. *Geophysical Research Letters*, *46*(11). DOI: 10.1029/2019GL082457.

Vilela-Silva, F., Bindoff, N. L., Phillips, H. E., Rintoul, S. R., & Nikurashin, M. (2024). The Impact of an Antarctic Circumpolar Current Meander on Air-Sea Interaction and Water Subduction. *Journal of Geophysical Research: Oceans*, *129*(7). DOI: 10.1029/2023JC020701.

von Kármán, T. (1931). Mechanische ähnlichkeit und turbulenz [Publisher: Sveriges Litografiska Tryckerier]. *Proceedings of the Third International Congress on Applied Mechanics*, *1*, 85–93.

Welander, P. (1982). A simple heat-salt oscillator. *Dynamics of Atmospheres and Oceans*, *6*(4). DOI: 10.1016/0377-0265(82)90030-6.

Whitworth, T., Nowlin, W. D., Orsi, A. H., Locarnini, R. A., & Smith, S. G. (1994). Weddell Sea shelf water in the Bransfield Strait and Weddell-Scotia Confluence. *Deep Sea Research Part I: Oceanographic Research Papers*, *41*(4). DOI: 10.1016/0967-0637(94)90046-9.

Wilson, E. A., Bonan, D. B., Thompson, A. F., Armstrong, N., & Riser, S. C. (2023). Mechanisms for Abrupt Summertime Circumpolar Surface Warming in the Southern Ocean. *Journal of Climate*, *36*(20). DOI: 10.1175/JCLI-D-22-0501.1.

Wilson, E. A., Riser, S. C., Campbell, E. C., & Wong, A. P. S. (2019). Winter Upper-Ocean Stability and Ice–Ocean Feedbacks in the Sea Ice–Covered Southern Ocean. *Journal of Physical Oceanography*, *49*(4). DOI: 10.1175/JPO-D-18-0184.1.

Wilson, E. A., Thompson, A. F., Stewart, A. L., & Sun, S. (2022). Bathymetric Control of Subpolar Gyres and the Overturning Circulation in the Southern Ocean. *Journal of Physical Oceanography*, *52*(2). DOI: 10.1175/JPO-D-21-0136.1.

Wong, A. P. S., & Riser, S. C. (2011). Profiling Float Observations of the Upper Ocean under Sea Ice off the Wilkes Land Coast of Antarctica. *Journal of Physical Oceanography*, *41*(6). DOI: 10.1175/2011JPO4516.1.

Wong, A. P. S., Wijffels, S. E., Riser, S. C., Pouliquen, S., Hosoda, S., Roemmich, D., Gilson, J., Johnson, G. C., Martini, K., Murphy, D. J., Scanderbeg, M., Bhaskar, T. V. S. U., Buck, J. J. H., Merceur, F., Carval, T., Maze, G., Cabanes, C., André, X., Poffa, N., … Park, H.-M. (2020). Argo Data 1999–2019: Two Million Temperature-Salinity Profiles and Subsurface Velocity Observations From a Global Array of Profiling Floats. *Frontiers in Marine Science*, *7*.

Wunsch, C. (2016). Global Ocean Integrals and Means, with Trend Implications. *Annual Review of Marine Science*, *8*(1). DOI: 10.1146/annurev-marine-122414-034040.

Zhang, L., Delworth, T. L., Yang, X., Zeng, F., Lu, F., Morioka, Y., & Bushuk, M. (2022). The relative role of the subsurface Southern Ocean in driving negative Antarctic Sea ice extent anomalies in 2016–2021. *Communications Earth & Environment*, *3*(1). DOI: 10.1038/s43247-022-00624-1.

Zilberman, N. V., Roemmich, D. H., & Gille, S. T. (2017). The East Pacific Rise current: Topographic enhancement of the interior flow in the South Pacific Ocean. *Geophysical Research Letters*, *44*(1). DOI: 10.1002/2016GL069039.