Ocean mixing and polynyas at Maud Rise, Weddell Sea

Doctoral Thesis

Martin Mohrmann

UNIVERSITY OF GOTHENBURG
Department of Marine Sciences
University of Gothenburg
2022

UNIVERSITY OF GOTHENBURG

Dissertation for the Degree of Doctor of Philosophy, Ph.D., in Natural Sciences, specialising in Oceanography
University of Gothenburg, 2022

Ocean mixing and polynyas at Maud Rise, Weddell Sea

ISBN 978-91-8009-751-2 (printed)
ISBN 978-91-8009-752-9 (pdf)

This book was typeset by the author using LaTeX.

Cover image: Image of the Maud Rise Polynya, observed on the 23 September 2017. Data from the MODIS 500 m Calbrated Radiance Product (MODIS Characterization Support Team, 2017).

Back cover photo: The author in front of Gothenburg's archipelago

Printed by: Stema Specialtryck AB, Borås, 2022

Keywords: Maud Rise, frontal mixing, Weddell Sea, Lazarev Sea, sea-ice, profiling floats, convection, Southern Ocean.

Acknowledgements

I thank all the people that supported me throughout my PhD project.

First, I would like to express my gratitude to my supervisors Sebastiaan Swart and Céline Heuzé. Their enthusiasm about polynya research convinced me instantly to dedicate several years of my life to a natural phenomenon that I had never heard of before. I do not regret it, even though the promised 2018 polynya never appeared.

I also thank my examiner Göran Broström for his guidance through the formalities of the PhD program, the opponent of my defense Laura de Steur and the thesis committee members Torge Martin, Carolina Dufour, Lars Arneborg, and Heather Reese for reading my work and joining my defense.

During my PhD project, additional people at the University of Gothenburg started to focus on the Maud Rise Polynya. This resulted in an inspirational small and focused working group, and I thank Lu Zhou, Aditya Narayanan and Birte Gülk for exciting discussions and proof reading of my manuscripts. More proofreading of my manuscript was done by Hannah Joy-Warren, Theo Spira and Salar Karam. I enjoyed to be part of the group "Polar Gliders" under the lead of Sebastiaan Swart - it was great to work with all of you!

Even though it is easy to forget in the final weeks of thesis writing: There is a life away from the (home-)office. I would like to thank my mum and dad for always supporting my ideas and for travelling many times to visit me in Gothenburg. Also a big thanks to Emma, who is the the best company and kept my sanity up during dark and isolated pandemic days.

Finally, I would like to acknowledge my funding: Most notably, my PhD position was made possible due to the Oceanography Marks Foundation at the Department of Marine Sciences. Two novel profiling floats that provided a core part of my data were purchased with funds from the Climate Fund at the University of Gothenburg and the Wallenberg Academy Fellowship of S. Swart (WAF 2015.0186). The mobility to travel to South Africa and partake on the voyage to Antarctica was supported by the STINT-NRF Mobility Grant of S. Swart.

Göteborg, March 27, 2022

Martin Mohrmann

Preface

This thesis consists of a synthesis and four publications/manuscripts. An agreement between the University of Gothenburg and the respective Journals allows us to reprint the respective papers in the printed version of this thesis.

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

B) **Mohrmann M.**, Swart S. and Heuzé C. (2022) **Observed mixing at the flanks of Maud Rise in the Weddell Sea**. Accepted for publication in Geophysical Research Letters. doi: 10.1029/2022GL098036

C) Zhou L., Heuzé C., **Mohrmann M.** (2022) **Early Winter Triggering of the Maud Rise Polynya**. Geophysical Research Letters. doi: 10.1029/2021GL096246

D) **Mohrmann M.**, Swart S. and Heuzé C. (2022) **Autumn mixed layer processes can trigger Maud Rise Polynya formation**. In preparation for submission to Journal of Climate.

Publications not included in this thesis:

1. Swart S., du Plessis M., Thompson A. F., Biddle L. C., Giddy I., Linders T., **Mohrmann M.** and Nicholson, S. A. (2020) **Submesoscale Fronts in the Antarctic Marginal Ice Zone and Their Response to Wind Forcing**. Geophysical Research Letters. doi: 10.1029/2019GL086649

2. Heuzé C., Zhou L., **Mohrmann M.** and Lemos A. (2021) **Spaceborne infrared imagery for early detection of Weddell Polynya opening**. The Cryosphere. doi: 10.5194/tc-15-3401-2021

3. **Mohrmann M.**, Swart S. and Heuzé C. (2021) **Vertical profiles of salinity, temperature and pressure measured by the vertical profiling floats in the eastern Weddell Sea around Maud Rise in 2018-2021** [Data publication]. Pangaea. doi: 10.1594/PANGAEA.938743

Contents

Abstract

The Weddell Sea Polynya is an intermittent, ice free area in the marginal ice zone with an extent of up to 350 000 km². It was first observed by satellites in the winter seasons of 1974-1976. In 2016 and 2017, an open-ocean polynya opened over the Maud Rise oceanic plateau in the eastern Weddell Sea, which was the largest since the 70's. Polynyas have an important role in ocean-atmosphere heat exchange, deep water and sea-ice formation. A deep layer of relatively warm Circumpolar Deep Water below the mixed layer provides the potential heat source to keep the polynya open during winter, but it is not yet fully understood how this heat is transported towards the surface. Due to its rare occurrence, most of what we know about the Weddell and Maud Rise Polynyas is based on modelling studies.

This thesis is delineated into two main themes related to the Maud Rise Polynya. Firstly, this work assesses the presence and magnitude of Southern Ocean polynyas in global climate models. For this purpose, a novel algorithm to detect polynyas in satellite observational products and climate model output is applied to sea-ice concentration and thickness data. We find that both coastal and open-ocean polynyas are not well represented in climate models in terms of extent or frequency. This part discusses methods to improve the models towards a more realistic representation of polynyas.

The second theme of the thesis uses new hydrographic observations at Maud Rise and the regional vicinity from autonomous profiling floats programmed to profile at high-frequency (1-3 days), that I deployed and managed. These unique observations are used in two subsequent studies. In the first, salinity and temperature profiles collected over several annual cycles indicate strong spatial gradients between relatively cold and fresh water over Maud Rise and warmer, saltier water surrounding it (Maud Rise Halo). These spatial patterns are tightly correlated with the Maud Rise bathymetry. At the transition between those two water masses at the flank of Maud Rise, interleaving is shown to occur, which causes double diffusive and thermobaric mixing to depths of 800 m. The second study focuses on the upper ocean mixed layer dynamics. The deepest wintertime mixed layers occurred over Maud Rise, but polynyas usually form over the Maud Rise Halo - a region of warm water flow surrounding the plateau region. We find that the winter water over Maud Rise is substantially thicker, and that entrainment of this winter water in autumn makes the mixed layer comparatively cold and fresh compared to the halo region. In this study a comparison with earlier profiling float observations during the 2016 and 2017 polynyas reveals that the mixed layer is significantly saltier in the autumn season. This allows for the mixed

layer to deepen more rapidly and by doing so entrain warmer water from below into the mixed layer. This results in a delayed onset of sea-ice formation. In conclusion, this thesis contributes to an improved understanding of the Maud Rise oceanography and related drivers of polynya formation, by focusing on (1) large-scale forcing seen in climate models, (2) intermediate depth water mass interleaving and mixing processes and (3) mixed layer processes as a regulator to polynya occurrence.

Sammanfattning

Åren 2016/2017 bildades en stor polynia på det öppna havet över undervattenshöjden Maud Rise i östra Weddellhavet. Det är den största sedan Weddellpolynian under 70-talet. Weddellpolynian var en öppen vattenyta i centrala Weddellhavet med en utsträkning på up till 350 000 km². Första observationen skedde via satellit i vintrarna 1974-1976 och polynian har inte dykt upp sedan dess. Polynior har en viktig roll i värmeutbytet mellan hav och atmosfär, djupvatten- och havsisbildning. Ett djupt skikt av relativt varmt, circumpolar djupvatten under blandskiktet bidrar till värmen som behövs för att hålla polynian öppen under vintern. Det är dock fortfarande något oklart hur värmen därifrån transporteras till havsytan där den smälter isen. Eftersom Weddell- och Maud Rise Polynior dyker upp så sällan är de flesta kunskaper vi har baserade på numeriska modellstudier.

Det här arbetet består av två större delar i sammanhang med Maud Rise Polynian. Först utvärderas uppträdande och storlek av polynior i Södra Havet i globala klimatmodeller. En ny algoritm används för att hitta polynior i satellitobservationsbaserade havsisprodukter och klimatmodelldata för isens koncentration och tjocklek. Vi konstaterar att polynior inte är särskilt realistiska i modellerna än så länge och vi diskuterar olika metoder för att förbättra modellerna så att de blir mer realistiska i framtiden.

I andra delen av projektet används in situ observationer i närheten av Maud Rise, de samlades in med hjälp av robotsonder. Salinitets- och temperaturprofilerna som samlades in under flera år visade starka gradienter mellan relativt kallt och sött vatten över Maud Rise och varmare, saltare vatten runt omkring. Fördelningen är direkt korrelerat till Maud Rises batymetri. Vid övergången mellan vattenmassorna vid Maud Rises flank blandar sig vattenmassorna och orsakar dubbel diffusiva och termobariska instabiliteter till ett djup av ungefär 800 m. Efter beskrivningen av blandningen vid fronten läggs fokus mer på ytan, på blandskiktets dynamik. Havet över Maud Rise har ett tjockt blandskikt under vintern men polynior uppstår vanligtvis precis bredvid Maud Rise i den så kallade Maud Rise Halo. Det konstaterades att vintervattnet över Maud Rise är mycket tjockare jämfört med Haloregionen omkring. Observationerna jämfördes med tidigare observationer under 2016/2017 polynian och det konstaterades att blandskiktet var saltare och blev djupare mycket snabbare under hösten då en polynia uppstod. Havsisbildning fördröjs av den processen. Sammanfattat bidrar våra resultat till en förbättrad förståelse av (1) de storskaliga drivkrafterna, (2) blandning av vattenmassorna i djupet och (3) processerna i blandskiktet som kan leda till polyniabildning.

1 Introduction

1.1. Background

Polynyas are areas of open water within the winter sea-ice cover. Even though the area of polynyas is small compared to the area of the sea-ice cover in the Southern Ocean, polynyas account for about 10% of sea-ice formation and are the largest contributors to Antarctic Bottom Water (AABW) formation (Nakata et al., 2015; Ohshima et al., 2016). AABW is the deepest and most volumetric layer of the major oceans, thus polynyas also play an important role in the oxygenation of the deep ocean and for the global oceanic circulation. Polynyas characteristically lead to a heat loss of several hundred W m^{-2} to the atmosphere during the winter months (Willmott et al., 2007), making them some of the most active regions of the global ocean for air-sea temperature and gas exchange (Miller & DiTullio, 2007).

Polynyas are commonly classified into either coastal polynyas or open-ocean polynyas. Coastal polynyas are latent heat polynyas: they are mechanically forced by winds driving the sea-ice apart or away from a geographical feature (Morales Maqueda et al., 2004). The heat loss of the upper ocean to the atmosphere is compensated by constant sea-ice formation and advection. This is why coastal polynyas are referred to as the 'sea-ice factories' of the Southern Ocean (Ohshima et al., 2016). Coastal polynyas occur in all the major seas of the Southern Ocean; Arrigo and Van Dijken (2003) mention at least 37 reoccurring polynyas around the Antarctic continent. Coastal polynyas can be observed every winter, albeit with large variation in extent and position. In contrast, large open-ocean polynyas have only been observed in the Weddell and the Cosmonaut Sea (Barber & Massom, 2007) and are also referred to as sensible heat polynyas (Williams et al., 2007). Their heat loss is believed to be compensated by a reservoir of Circumpolar Deep Water

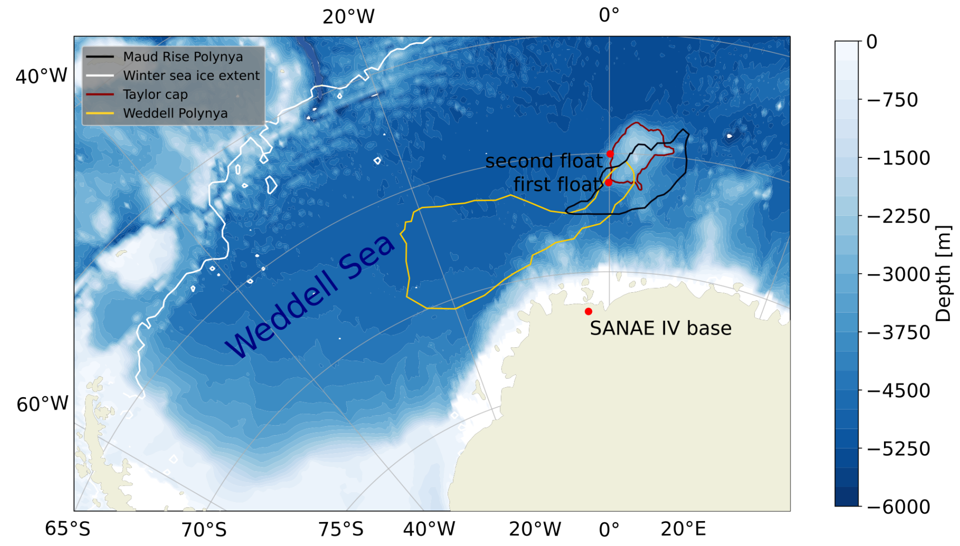

Figure 1.1. Map of the Weddell Sea. Maud Rise is visible by its shallower bathymetry (GEBCO Bathymetric Compilation Group, 2021) at about 3°E. Contour lines show the September sea-ice extent (white line), the outline of the Maud Rise Polynya as observed at the 15 November 2017 (black line), the outline of the Weddell Sea Polynya as observed in October 1975 (yellow line), and the 3500 m isobath as an indicator for the extent of the Taylor Column (red line). The deployment positions of our two profiling floats at the western flank of Maud Rise and the position of the SANAE IV base are marked in red.

(Schröder & Fahrbach, 1999), with a neutral density range from 27.5 to 28.2 kgm^{-3} (Tamsitt et al., 2018), that is transported to the surface by deep convection (Martinson et al., 1981).

The Weddell Sea and Maud Rise Polynyas are the main focus for this Ph.D. thesis. With an average spatial extent about 200 000 km^2 (Carsey, 1980), a Weddell Sea Polynya persisted in the three consecutive years of 1974-1976 (Figure 1.1). It had only been observed by microwave satellite imagery during its active years, but in situ observations of cold fresh chimneys a year afterwards indicated deep convective mixing (Gordon, 1978)- a theory supported by numerical simulations (e.g. Hirabara et al., 2012). The presence of the Weddell Sea Polynya is attributed to either heat buildup in the deep water, brine rejection, deep convection, divergent, rotational winds, increased

SAM index, atmospheric rivers or a combination of all these factors (e.g. Cheon & Gordon, 2019; Comiso & Gordon, 1987; Francis et al., 2019; Yukimoto et al., 2019). Many studies are based on satellite observations of the sea-ice cover (Arbetter et al., 2004; Carsey, 1980) and numerical modelling (Cheon et al., 2014; Dufour et al., 2017; Heuzé et al., 2015; Hirabara et al., 2012; Kjellsson et al., 2015; Lockwood et al., 2021; Martin et al., 2013; Martinson et al., 1981; Zanowski et al., 2015), but there are few in situ measurement from within open-ocean polynyas (Campbell et al., 2019).

The flanks of Maud Rise are the origin of most open-ocean polynyas in the Weddell Sea (Heuzé et al., 2021). Over the top of Maud Rise sits a cold and relatively fresh water mass, held in place due to the conservation of vorticity. This is called a Taylor cap and currents, even in shallow depths, are diverted around it (Beckmann et al., 2001; Taylor, 1917). Surrounding the Taylor Column (Figure 1.1), currents transport the relatively warm Weddell Deep Water westwards. Caused by the instabilities at the interface between this current and the waters over the Maud Rise, cyclonic eddies form and contribute to a shoaling of the mixed layer at the flanks of Maud Rise (Holland, 2001), with warm underlying Weddell Deep Water below the mixed layer. This 'ring' like region of shallow mixed layer depths and warm currents is called the Maud Rise Halo (de Steur et al., 2007).

Following the 1976 Weddell Sea Polynya event, polynya presence was not detected in the region for several decades, leading to debates as to whether global warming changed the conditions for its formation (De Lavergne et al., 2014) or whether polynyas were part of a low frequency variability in the Southern Ocean (Broecker et al., 1999). However, in late 2016 a polynya emerged close to Maud Rise, followed by an even larger one the following winter in 2017 (Figure 1.1). These polynya events did not persist throughout the winter-spring sea-ice season and were significantly smaller in extent (80 000 km^2). These most recent polynya events of 2016-2017 fuelled significant scientific interest in order to understand their characteristics, cause and effect on the local ocean and climate environment (e.g. Campbell et al., 2019; Cheon & Gordon, 2019; Francis et al., 2019; Heuzé et al., 2019; Swart et al., 2018). Many of these studies were supplemented by the advanced methods of scientific observations and modelling compared with the 1970's (Section 2.2, 3.1, 3.3). The spatial and temporal resolution of both measurements and numerical models is progressing fast, allowing scientists to focus on processes that occur within the time scales of a day and spatial scales of few kilometers (e.g. Swart et al., 2020, and Section 2.2). Related to this, the research approach and main questions have also adjusted over the decades. During the

1970's, climate research and the knowledge about global warming were in its infancy (Hünemörder, 2004), but have received central importance beyond the academic interest since then. Modern climate models predict a winter sea-ice decrease towards the end of the this century of 15-50 % on average (Roach et al., 2020), depending on the "Shared Socioeconomic Pathways" as possible development paths of society in the near future. The drastic changes in sea-ice extent will obviously affect the occurrence of polynyas. The polynyas in turn also affect the climate through significant air-sea exchanges of CO_2 and heat Bernardello et al. (2014) by solubility or/and biological pumps, deep water formation (Ohshima et al., 2016) and change of the sea surface Albedo factor.

1.2. Aims and research questions

The aim of this study is to contribute to a better understanding and description of the processes related to open-ocean polynyas, with a focus on the Weddell Sea. To do this, four main aims of the PhD are presented.

1. Assess the current state of polynya representation in climate models and compare to satellite observations.

Much of the current knowledge of processes inside open-ocean polynyas is derived from numerical modeling (see Section 1.1). Considering the impact of polynyas on sea-ice formation, heat/gas exchange and deep water production, their realistic representation in climate models is essential. We determined how realistic Climate and Earth System models that participated in the latest Climate Model Intercomparison Project phase 6 (CMIP6, (Eyring et al., 2016)) represent both coastal and open-ocean Southern Ocean polynyas, and how misrepresentations might impact the ocean-climate system and processes within the climate models. This is undertaken using large datasets from 27 CMIP6 models together with satellite sea-ice observations that provide the 'realistic' comparison. The study looks to address questions such as, how much do the climate models deviate from observations of polynya events, and what are the main drivers for these comparative differences?

2. Observe and understand frontal mixing along the northern flank of Maud Rise and its impact on polynya formation

The properties of the relatively cold and fresh Taylor cap in contrast to the relatively warm Maud Rise Halo (de Steur et al., 2007), and their influence on stability of the water column (Akitomo, 2006; Wilson et al., 2019), have been described previously. To date however, the Maud Rise region has lacked a more detailed observational description of the frontal structure, and associated dynamical processes related to mixing. We aim to determine why the flanks of Maud Rise are more prone to the onset of deep convection compared to adjacent regions. In our unique datasets from high-frequency profiling floats we discovered that the water column at the flanks of Maud Rise had many intrusions of water masses (Warm Deep Water in Maud Rise Deep Water and the other way around) between 200-1000 m depth. Characterizing these intrusions and their impact on horizontal and vertical mixing became a major focus in Paper B.

3. Predict and understand the preconditioning of the Maud Rise Polynya

The occurrence of the Maud Rise Polynya in 2016 and 2017 came as a suprise in the scientific community, and thus it was only sampled sparsely by two profiling floats that were over Maud Rise at the same time coincidentally. However, the formation of Maud Rise Polynyas is preceded by many month of atmospheric and oceanographic preconditioning (Campbell et al., 2019; Cheon & Gordon, 2019; Kurtakoti et al., 2018) and should therefore be predictable. The preconditioning of polynyas is investigated with two complementary methods. First, we investigate wether (and if so, how long in advance) polynyas can be predicted (Paper C) using only remote sensing observations of the sea ice, ocean surface and air-sea fluxes. Second, we investigate how spatial differences in the depth of the mixed layer and annual differences in the salinity of the mixed layer can contribute to a preconditioning of the Maud Rise Polynya (Paper D). With significant fortune, we discovered that one of our high-frequency profiling floats closely followed the trajectory of a SOCCOM profiling float deployed 4 years earlier (Johnson et al., 2021) and which sampled during the polynya event of 2017. This provided us with unique opportunity to compare the properties and dynamics of the mixed layer during and after polynya events so as to assess if the conditions of the mixed layer play a major role in polynya formation or not.

2 Field work and instruments

2.1. Expedition to the Southern Ocean and Antarctica

In late 2018, I had the chance to join a research expedition to Antarctica onboard the South African research icebreaker vessel SA Agulhas II. The transect southwestwards from Cape Town and then along the Greenwich Meridian into the Weddell Sea provided a great opportunity to deploy autonomous ocean platforms in the Antarctic marginal ice zone. My purpose during the cruise was to deploy the first high-frequency profiling float (which we introduce in detail in Section 2.2) upon crossing of the Maud Rise. In addition, I assisted in the deployments of other oceanographic instruments, in particular ocean gliders, Wave Gliders, a Sailbuoy and other standard Argo profiling floats at other sites along the way. Several of these instruments were key deployments for the ROAM-MIZ (Robotic Observations And Modelling of the MIZ) project at GU. Furthermore, I completed daily shifts to sample seawater every six hours for phytoplankton concentration. Biological samples were stored for later analysis, which was conducted by other working groups at GU and the University of Cape Town.

The field trip featured an unexpected two month stay at South African National Antarctic Expedition field station IV (SANAE IV), including common station tasks, such as producing water via snow melt, kitchen duties (Figure 2.1), digging cable trenches in the snow to the new RADAR stations and lots of other related snow shovelling. While I remained at the SANAE IV base, the SA Agulhas II continued on with another scientific team on board to search for Shackelton's sunken ship, the Endurance, which was only found three years later. In late February 2019, it was time for me to leave Antarctica

Figure 2.1. Left side: Image taken from the highest platform of the SA Agulhas II, the "crows nest". The front of the ship is visible to the left, the right side is the Antarctic ice shelf, which is several times higher than the ship. The bay was filled with a thin layer of pancake/grease ice, while there was thicker sea-ice further from the shelf. This is a classic example for a coastal summer polynya. Right side: Life at the South African Antarctic station SANAE IV. I baked 200 kanelbullar (cinnamon buns) for the whole station, which disappeared within minutes.

on the return leg to Cape Town. Again, I assisted with the recovery of several autonomous instruments on the homeward-bound leg. My profiling float, the "star" of this thesis, remained deployed and sent data from Maud Rise for an additional two years following this voyage.

For our research group and the ROAM-MIZ project, the trip was a big success given the successful deployments of autonomous platforms, which collected lots of exciting data that soon contributed to several publications (du Plessis et al., 2022; Giddy et al., 2021; Mohrmann, Heuzé, et al., 2021; Mohrmann et al., 2022; Swart et al., 2020). The time in the field was a great way to meet other researchers and to get a realistic impression of the conditions in the Weddell Sea. I was developing the idea to model the currents under the influence of sea-ice with different aerodynamic roughness (Section 4.5) on the cruise, because the incredibly smooth ocean surface in the presence of thin ice (e.g. Figure 2.1) was impressive to me. It convinced me that this should also influence the wind driven currents.

2.2. Profiling floats

The global programme of Argo floats, autonomously profiling the ocean from the surface to 2000 m every 10 days, features very few instruments in the Weddell Sea. This is probably due to the relative novelty of floats with under sea-ice capability, the high probability of instrument loss, and infrequent research cruises for deployments. To address this poor data coverage, we deployed two profiling floats in 2018 and 2020.

I recommended to use profiling floats with under ice functionality from the French manufacturer NKE Instrumentation. The floats were delivered to Cape Town, South Africa prior to the SANAE station supply voyages of the South African icebreaker SA Agulhas in 2018/2019 and 2019/2020. I deployed the first float on the way to the South African Antarctic research station on the 16th of December 2018 at 66.2°S, 0.0°E. I chose the deployment location after Campbell et al. (2019), who worked with floats deployed at the same spot in the same season but four years prior, which, they posture, eventually got trapped in the Taylor Cap above Maud Rise and remained there for several years. We hoped for the same outcome for our float, but aimed for a higher temporal sampling resolution. It was with great pleasure to see our float taking on an extremely similar Lagrangian path towards Maud Rise. Three years later in autumn 2021, the float was still above Maud Rise and had crossed a front at the southern flank of Maud Rise on two occassions (Figure 4.3).

I had initially planned the deployment of the second profiling float at the same location as the first, but due to a change in course of the research vessel, the float was deployed at 65°S, 0.0°E. This second float did not drift towards Maud Rise, but went southwestward instead (Fig. 2.2). Both floats captured more than one complete seasonal cycle in their respective regions. The two floats allowed us to compare and discover significant differences in the water stratification over Maud Rise compared to the south-western region in proximity to Maud Rise.

We used IRIDIUM satellite communication to receive the near real-time measurement data from the floats and to adapt the sampling scheme and frequency of the floats several times during their mission to either save battery or increase the sampling frequency. We focused on the sea-ice formation seasons, which we captured at a daily resolution by both floats. The change of upper ocean properties due to deep water entrainment and brine rejection are of special interest because they provide the kinetic energy to vertically

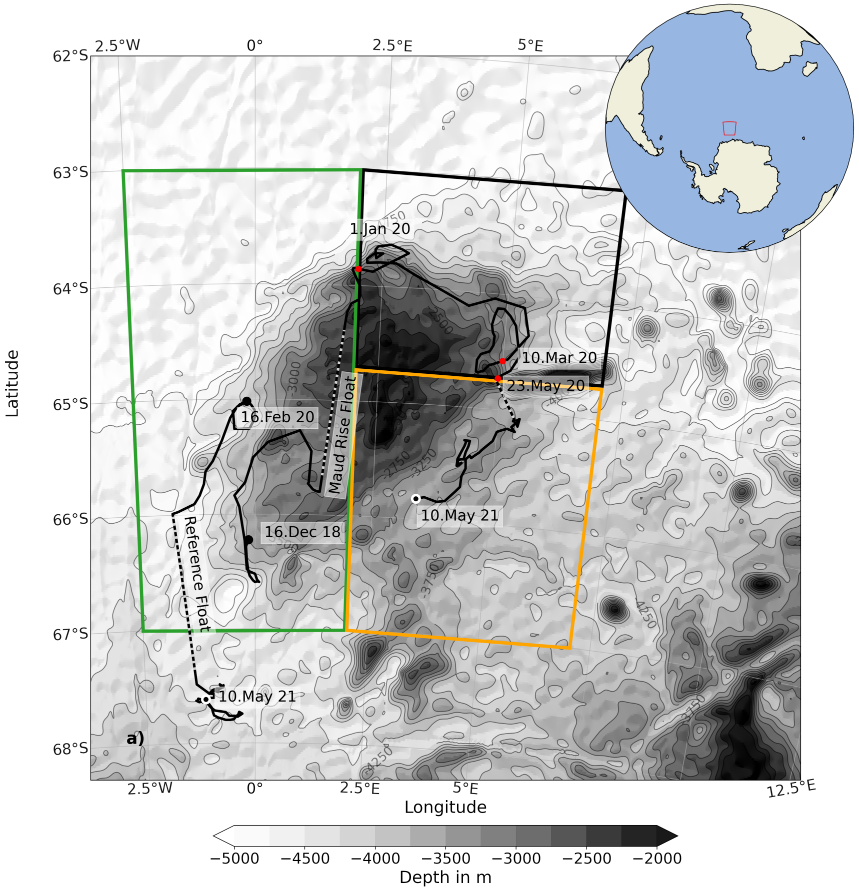

Figure 2.2. Trajectory of profiling floats over Maud Rise. Deployment locations of the profiling floats deployed by us are marked with black dots and the last known position as of May 2021 is marked with a black dot with white outline. Interpolated positions during sampling under the sea-ice are dashed. Red dots mark points of interest that are referenced in the text. Shading indicates the bathymetry, with contours every 250 m. (Figure 1 from Mohrmann et al., 2022)

mix the weakly stratified ocean. During December and May 2018/2019, I programmed the floats to profile daily down to 500 m depth. Every 3 days the floats would undertake one deep dive (2000 m). Conductivity, temperature and pressure were sampled every 10 seconds during ascent of the profiling floats, and the values are binned into 1 m intervals from the surface to 25 m depth, 10 m intervals from 25-200 m depth and 25 m from 200 m - 2000 m (maximum) depth. For the first float that was deployed, we had to use a reduced 3 daily sampling rate under the sea-ice, which was mainly motivated by a technical restriction of limited internal memory by which to store the dive data while drifting under sea-ice. The second float came with an improved memory capacity and was programmed to sample daily, with the trade off that it was sampling for just one and a half year before it (presumably) ran out of battery under the sea-ice during the austral winter of 2021.

Our measurement strategy provided us with a unique dataset from under sea-ice around Maud Rise, which gave insights to processes occurring faster than the 10 daily sampling rate of traditional floats participating in the ARGO- and SOCCOM-float programs and also at enhanced spatial resolution. The trajectory of the floats is shown in Figure 2.2. The floats are the first official Swedish contribution to the Argo float program, and the data has now been shared with the scientific community via the global data assimilation centers (see e.g. www.argo.net and Mohrmann, Swart, et al. (2021)).

Figure 2.3. Impressions from the field work in the Weddell Sea and Antarctica. (a) Antarctic ice shelf in the Weddell Sea sector, (b) our first NKE profiling float, (c) Southern Thule Island, (d) the research vessel SA Agulhas II, (e) preparation of Seagliders before deployment (with the PhD candidate for scale), (f,g) snow mobile excursion at SANAE IV base in Antarctica.

2.3. Self-constructed CTD

In 2018, I started to construct a CTD from relatively cheap, widely available parts. My aims were to learn more about electronics in the process and to be able to do my own CTD measurements easily. The commonly used name of the instrument, CTD, describes the main sensors of the instrument, for Conductivity (which converts to salinity), Temperature and Depth (derived from pressure). My build was inspired by an American project called "oceanography for everyone", which is a custom built CTD that is light and sturdy enough to be carried in any regular backpack and can be deployed using nothing more than just a rope and a kayak. However, I became increasingly frustrated by the accessibility of certain parts, such as 3D printed plastic casing parts and hard-to-find Arduino accessories.

Instead, I constructed a modular metal case from HVAC parts, allowing safe deployment to a depth of 150 m, limited by (1) the pressure rating of the casing, (2) the pressure sensitivity of affordable pressure and salinity sensors, and (3) the amount of rope that can be reasonably handled by hand. The depth rating is more than enough for the Swedish coast with its islands and fjords and the Baltic Sea except for some of the deepest basins in the Baltic Sea or the Norwegian Trench in the Kattegat, so it is an acceptable limitation. I added Wireless and Bluetooth connectivity, so that the case does not have to be opened for data downloads or control commands. A live view mode is available, so that the status of the CTD and the ongoing measurements can be displayed in real time on any smartphone. However, the live view is only updated if the CTD is close to the surface, since the CTD is not wired and cannot transmit from greater depths. The data at depth is instead buffered to a SD card and transmitted when the connection becomes available again. The CTD is fully functional and has been deployed several times to a depth of up to 120 m (Figure 2.4). It demonstrated a reasonable precision in measurement values and shows that such self-constructed CTD could be a useful replacement of commercial CTDs when money, boat time or weight are limited. The flexibility and simplicity of the concept and the open programming environment make the CTD easy to tinker with. With a total cost of less than 500€ it is also significantly cheaper than commercial CTDs. Replacement of the standard USB-power bank and data download can easily be done in 2 minutes. The CTD has a battery run-time of 8 hours for a measurements frequency of $1s^{-1}$. Notable disadvantages to many commercial systems is the absence of an active pump which leads to increased temporal lag in temperature and salinity measurements. This can be compensated by a slow descent velocity (about 10cm s^{-1}, i.e. not free falling) of the CTD, to give the sensors more time to adjust.

In summary, I learned a great deal about electronics during the process and it led to interesting discussions with colleagues from within the department and involvement in external projects (SCOOT, Vinnova marina drönare). Of course, a first successful design is also an inspiration for further possibilities and improvements. It would be a great tool for outreach and teaching due to its simplicity. Moreover, it would be fun to include additional sensors.

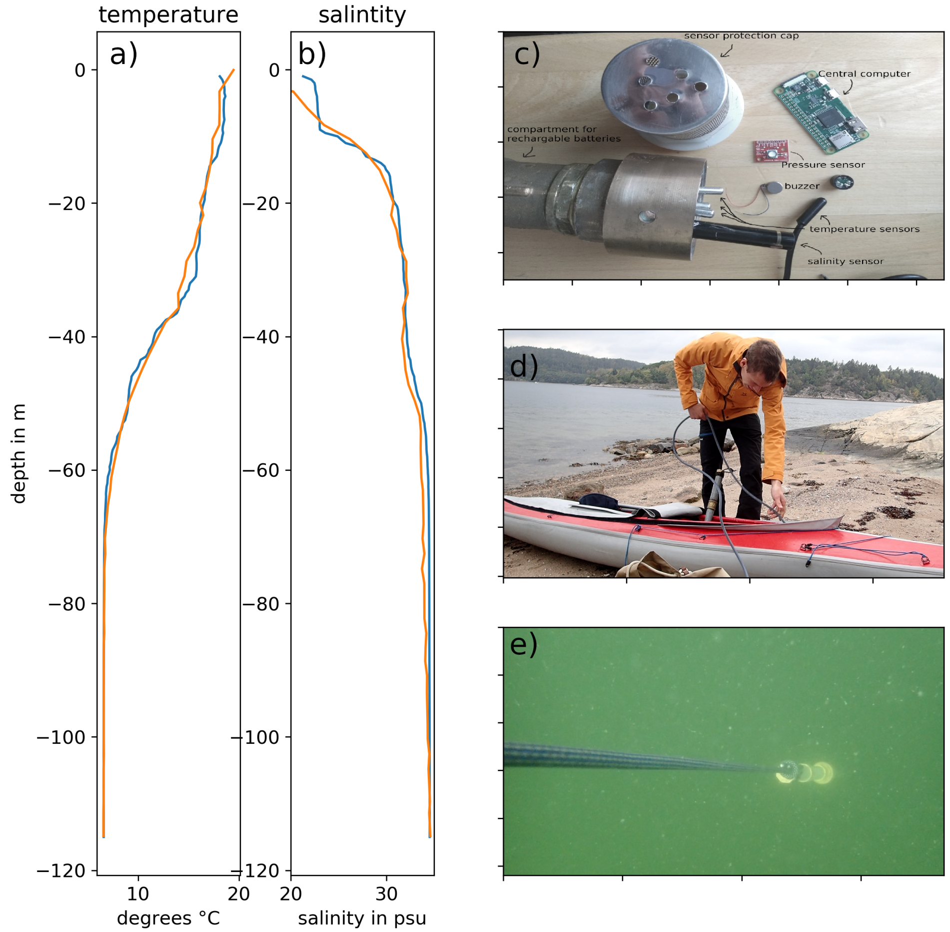

Figure 2.4. **(a)** Temperature and **(b)** salinity profiles recorded at Alsbäckdjupet in Gullmarsfjord, Sweden from my self-built CTD (orange line) and the scientific -grade Seabird CTD on board of the RV Skagerak (blue line). **(c)** Head of the self-built CTD with spare electronic components, as included in the assembled CTD. **(d)** Preparing for deployment at Stora Börnö in Gullmarsfjorden. **(e)** Underwater image of the CTD.

3 Data and Methods

The Weddell Sea is a remote place with infrequent research cruises covering this geographical area. The seasonal ice coverage complicates the collection of measurements by autonomous platforms since most field observational platforms require frequent satellite communication, which is not possible from under the sea-ice. Measurement equipment with under sea-ice capabilities are often custom made and the manufactures ask for a high surcharge. For this reason, we combine many different data sources in our study to complement our understanding of the Weddell Sea polynya beyond our own in situ observations.

Open-ocean polynyas in the Weddell Sea are characterized by an interaction between the ocean, sea-ice, and atmosphere. The deployed profiling floats capture the ocean's salinity and temperature and even allow for broad-scale estimates (without the ability to directly measure fine-scale turbulent mixing) of mixing and currents (Paper B). Sea-ice state is observed by satellites (Section 3.1). Finally, we rely on reanalysis data from ECMWF-ERA5 for atmospheric parameters such as winds and precipitation (Section 3.2). We use the ECMWF-ERA5 (Hersbach et al., 2020) reanalysis because it has repeatedly demonstrated to reproduce the surface fields of parameters ranging from wind speed (Schmidt et al., 2017) to air-sea heat fluxes (Yu et al., 2019) accurately with in situ observations, compared with other reanalysis products in both the global and Southern Ocean.

3.1. Satellite Measurements

The only method to obtain observational year round sea-ice concentration for the entire Southern Ocean is through satellite observations. Our primary region of interest, the Weddell Sea around Maud Rise, is obstructed by clouds most of the time, which makes observations in the visual wavelengths impossible on a regular basis and seriously hampers the retrievability in the thermal infrared (discussed in detail in Heuzé et al. 2021, in which I am co-author). Observations in the microwave spectrum are somewhat insensitive to atmospheric moisture and are routinely used to provide images of sea-ice cover (as in Zhou et al., 2022, in which I am co-author). Satellites either use (passive) natural occurring microwave radiation or active radar, most commonly Synthetic Aperture Radar (SAR). The latter provides observations at higher spatial resolution but over a smaller footprint and, over polar regions, only approximately every 5 days. The satellite data are commonly available as already processed daily sea-ice products. The one we use in paper A is the OSI-450 Global sea-ice concentration climate data record (Lavergne et al., 2019), which compiles data from several different satellites and reanalysis models from 1979 to near real-time into one consistent sea-ice concentration product with a spatial resolution of 12.5x12.5 km, which is about four times higher than the resolution of global CMIP6 models. More detailed but difficult to process SAR images are available for example from the Sentinel-1 mission. These images can be downloaded from the websites of the European Organisation for the Exploitation of Meteorological Satellites (eumetsat.int) or from the Copernicus Open Access Hub (scihub.copernicus.eu). We did not use SAR images in this thesis, but they were used by members of the team e.g. to plan float deployment.

For the heat budget of the mixed layer and the polynya formation in particular, knowledge about the sea-ice thickness is essential. Unfortunately, this information is not easily available using satellites, and the available products do not extend very far into the past (2002) compared with sea-ice concentration observations (1970s). The sea-ice thickness can be derived using freeboard measurements. Radar satellite altimetry is one method, but it records only a one-dimensional track of sea-ice thickness and requires much interpolating in space and time to estimate the sea-ice thickness. We opted for the SMOS sea-ice thickness (Huntemann et al., 2014) instead. The SMOS thin-ice thickness product is from a Microwave Imaging Radiometer using Aperture Synthesis, so it is a passive instrument that is picking up faint microwave emissions from the surface of the earth. The product includes sea-ice thickness in daily resolution for the whole Southern Ocean, but has an uncertainty of about 30% of the absolute value, works poorly during melting conditions and in low sea-ice concentrations and provides satisfactory results up to 0.5 m sea-ice thickness only (Huntemann et al., 2014). This product was ideal for comparison to the CMIP6 models, as we only needed information in winter, in the days where sea ice was thinner than 10 cm.

3.2. Reanalysis Data

Reanalysis models incorporate many different datasets to create one coherent, long-term dataset of past weather and ocean state. Datasets from global data assembly centers (e.g. our float data) are regularly gridded in space and time, using averaging and interpolation techniques. This provides datasets without spatial or temporal gaps and makes it easier to analyze certain events or to create timelines, consisting of many different observations that would have to be combined and interpolated manually otherwise.

In the Southern Ocean, vertical mixing is closely linked to atmospheric parameters, such as wind, heat fluxes, and precipitation. These parameters can be extracted from atmospheric reanalysis models. Some reanalysis models of the atmosphere (e.g. ERA-5, NCEP–DOE) have a relatively good performance in the representation of winds or near-surface temperatures in the Southern Ocean and on the ice shelves (Schmidt et al., 2017; Zhu et al., 2021). From the ocean however, few observations are available, and a large part of the data is actually produced by an integrated numerical forecast model. Heuzé et al. (2019) found that the ensemble mean global reanalysis product GREP provided a relatively realistic representation of the mixed layer depth during the 2017 polynya. Reanalyses do not necessarily have accurate dynamics though, as they "only" react to the ingested sea ice. Therefore, we kept our usage of ocean reanalysis products in this thesis to a minimum, and instead relied primarily on in-situ observations.

3.3. CMIP6 Model Output

Global climate models have the advantage that the data from remote locations is conveniently available, not only for the past, but often also for future projections and parameter sensitivity experiments. The Climate Model Intercomparison Project (CMIP, Eyring et al., 2016) is a collaborative network started in 1995 to foster climate model improvements and facilitate research about climate change. Within CMIP, variable names, definitions of derived variables, and output formats are unified, and experiments or scenarios that are simulated are standardized. This allows for a relatively easy comparison of the many climate models that participate.

The sixth edition (CMIP6) climate models have high relevance in the scientific community (e.g. featured in IPCC reports, Pörtner et al., n.d.), and many international climate and Earth System models are participating (Eyring et al., 2016). The CMIP6 experiment and participation guidelines were finalised in 2018, and by the time of completion of this thesis, more than 30 modelling groups have contributed to the 'historical' experiment - the scenario based as much as possible on observations of the Earth between 1850 and 2015 (Eyring et al., 2016). CMIP6 includes data from modelling groups all over the world and features models with varying complexity, resolution and scope. These models were developed to give a global perspective of the Earth's climate, and are thus not usually optimized to represent Southern Ocean processes particularly well. However, since these models are often used for future climate predictions, it is useful to analyse them for their performance, for example in polynya representation.

Despite the unification of boundary conditions, Beadling et al. (2020) and Roach et al. (2020) found large multi-model spreads in sea-ice extent and the representation of the Antarctic Circumpolar Current (ACC). The sea-ice extent of most models is outside the 2σ standard deviation environment derived from the observations (Beadling et al., 2020). What was missing was an assessment of how realistic the representation of polynyas in the Weddell Sea is for the CMIP6 models. This knowledge could help to chose the most realistic models for polynya related studies, and to potentially improve models with a bad representation.

In Paper A, we assess the polynya activity in terms of the area, position and frequency of polynya occurrences. We use the sea-ice concentration and thickness output of 27 CMIP6 models (Section 3.3) to evaluate how well polynyas are represented (in comparison to satellite observations). The models' seasonal polynya area and likelihood are collected statistically and causes and effects of deviations from observation data are discussed, based on the model components and properties, such as atmospheric forcing (Section 3.3).

4 Summary of Contributions

4.1. Paper A: Southern Ocean polynyas in CMIP6 models

Peer-reviewed publication by Martin Mohrmann, Céline Heuzé, and Sebastiaan Swart in 'The Cryosphere'

For this study I developed a method to track the area and spatial distribution of polynyas from sea-ice concentration and thickness in the Southern Ocean. We analysed 27 models participating with a "historical scenario" in the Climate Model Intercomparison Project phase 6 (CMIP6) and

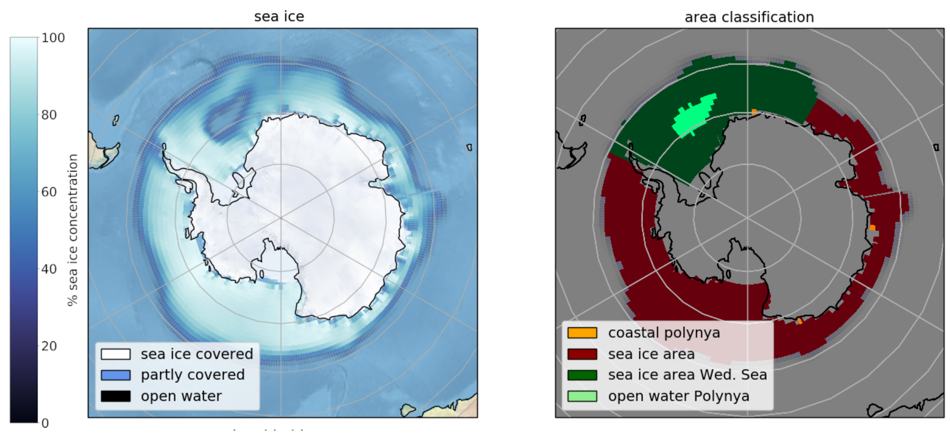

Figure 4.1. Visualization of the result of the polynya tracking algorithm. Left is the monthly sea-ice concentration per grid cell output as produced by the CAMS-CSM1-0 model (September 1976); right is the outcome of our area classifications as per the next figure (Figure 3 from Mohrmann et al., 2021).

two satellite based sea-ice products (introduced in Section 3.1). Each model run consists of 165 years of the historical scenario and is a model reproduction of the Earth's climate between 1850 and 2015. For comparison, we have 37 years of observational sea-ice concentration and 10 years of observational sea-ice thickness available (introduced in Section 3.1). As part of the method, I developed an algorithm to detect both coastal and open ocean polynyas in the sea-ice observations and the CMIP6 model output. As a first step, a flood fill algorithm detects connected sea-ice areas and areas of open water within the marginal ice zone. The areas of open water are automatically classified as coastal polynyas if adjacent to the Antarctic continent or as open-ocean polynyas if surrounded by sea-ice. A threshold value is used to distinguish open water from ice covered areas at 30% sea-ice coverage or alternatively at a sea-ice thickness of 12 cm, based on values used in prior studies (Kern et al., 2007; Nakata et al., 2015) and my own sensitivity tests. The algorithm is applied to the daily and monthly sea-ice concentration/thickness of all 27 models, totalling more than 300 000 time steps for all the models and observations, and the results are summarized/aggregated by their maximum yearly polynya area. A visualization of the result of this algorithm is shown for one model and one time step in Figure 4.1.

We found that all global climate models form coastal polynyas, but only half produce open-ocean polynyas such as the Weddell Sea polynya. In four of the models there is a significant overestimation of open-ocean polynyas (by more than five times) compared to the observations. The cause (and consequence) of this overestimation leads to unrealistically strong deep ocean convection in the Southern Ocean, especially in the Weddell Sea. At the same time, these same models reproduce the most realistic values of ACC strength and wind stress curl around the Weddell Sea.

We conclude that global climate models still struggle to realistically represent polynya activity. One cause is that most models cannot resolve (and instead permit or parameterize) small scale ocean processes, such as frontal mixing, bathymetric interactions, and vertical instabilities. These processes can better be explored using in situ observations from profiling floats, which is the focus of Paper B.

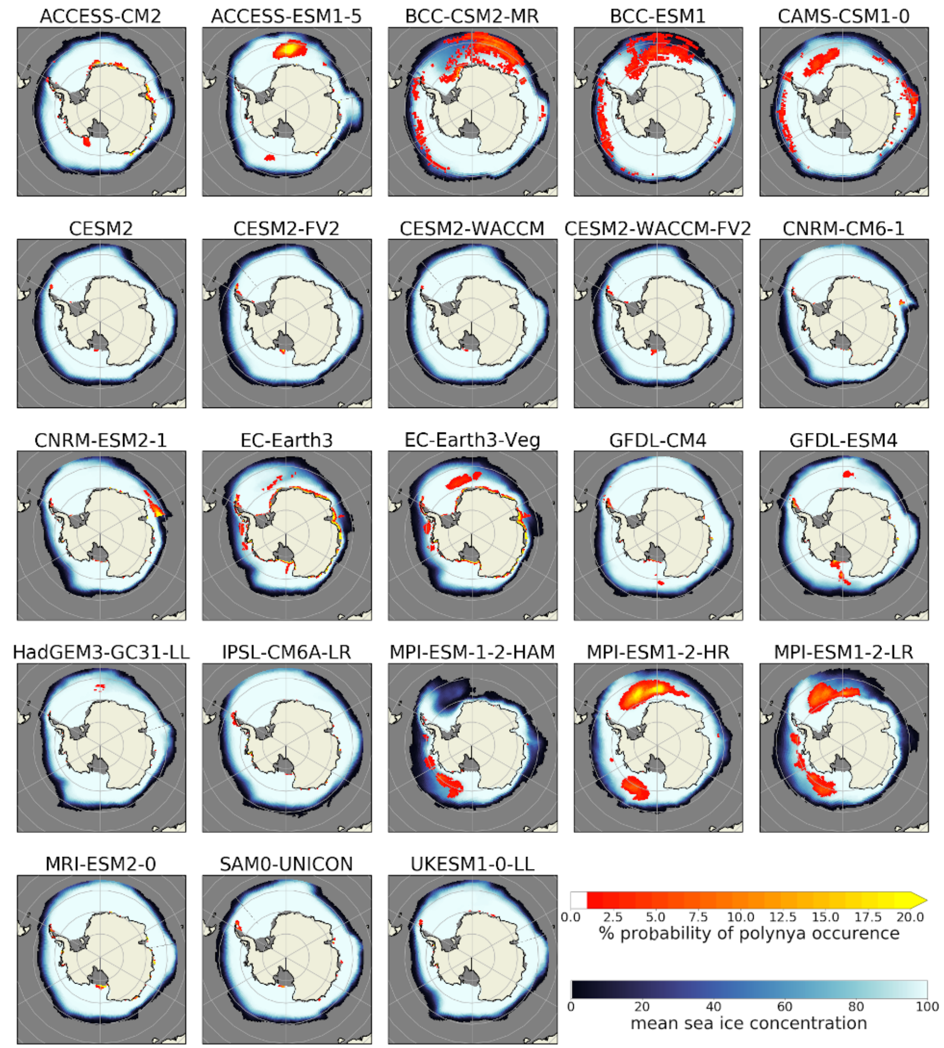

Figure 4.2. Spatial distribution of polynyas in CMIP6 models, computed from the monthly sea-ice thickness output for September. The red-to-yellow colours indicate the number of years where polynyas occurred within the 165 years of the historical model run for each grid cell. The blue colors show the average sea-ice concentration in %. (Figure 3 from Mohrmann et al., 2021)

4.2. Paper B: Observed mixing at the flanks of Maud Rise in the Weddell Sea

Manuscript by Martin Mohrmann, Sebastiaan Swart, and Céline Heuzé, accepted for publication in 'Geophysical Research Letters'

In this paper we use the data collected by our two profiling floats, supplemented by historical SOCCOM float data, to describe the connection between the local bathymetry of Maud Rise and the intermediate water mass properties (below the mixed layer). The presence of a cold and fresh Taylor Column had been observed earlier (Alverson & Owens, 1996). With the help of these multiple float datasets, we characterize and map the Taylor Column in more detail. We also find a sharp front between the cold and fresh Maud Rise Deep Water of the Taylor Column and the warmer and saltier (and lighter) Warm Deep Water of the Maud Rise Halo. The front is approximately associated with the position of the 3500 m isobath and is especially pronounced (sharp) at the northern flank of Maud Rise, where the bathymetric slopes are steepest. The float data reveals vertical profiles with multiple inversions in the temperature and salinity at the front, which we interpret as frontal water mass interleaving. I decided to adapt a method that evaluates the root mean square of the vertical spiciness curvature (Shcherbina et al., 2009) to quantify in which regions the interleaving is especially intense, and thus causes water mass exchange between the Taylor Column and the surrounding waters. The observed intrusions fulfill conditions favourable for double-diffusive and thermobaric mixing, opening a pathway of heat from the intermediate depths to the surface mixed layer, which has implications for the vertical distribution of heat and salt and thus likely contributes to the formation of polynyas.

In Paper B, our investigation of the regional distribution of water masses and their interleaving was restricted to intermediate depth (200 m - 800 m), below the mixed layer. We did not observe any interleaving in the mixed layer, presumably due to a higher amount of background mixing. Moreover, the mixed layer gradients of the mixed layer are weaker then the gradients at depth; the mixed layer is more exposed to seasonal changes. Thus, a remaining question is the role of the mixed layer dynamics on the polynya formation, that we investigate in Paper D. But first, we investigate the role of the intermediate depths further in paper C, this time focussing on the preconditioning of the polynya.

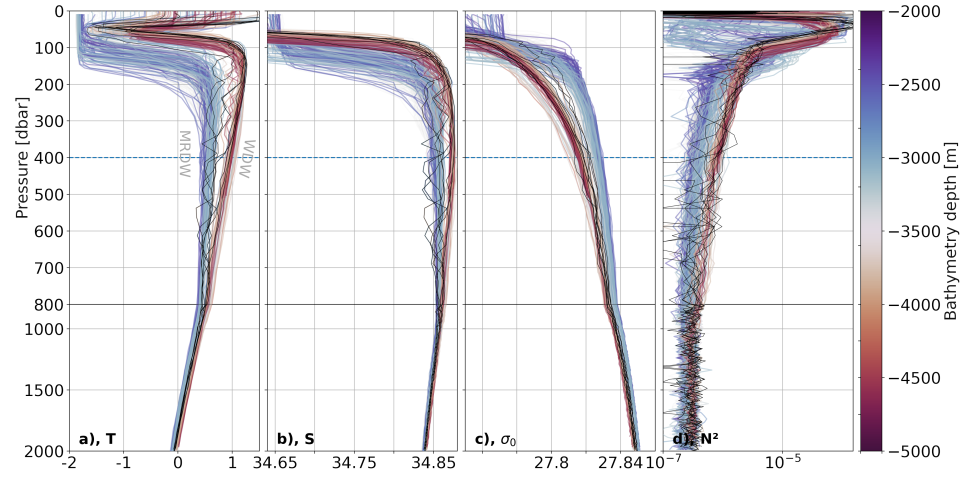

Figure 4.3. Vertical profiles of a) conservative temperature, b) absolute salinity, c) potential density, and d) squared Brunt-Väisälä frequency (N^2) as observed by the Maud Rise Float. All profiles are colored according to the bathymetric depth. Blue indicates profiles where the bathymetry is <3500 m; red indicates bathymetry >3500 m. Profiles shown are limited to those from the western (green) or northeastern (black) sectors depicted in Figure 2.2. Profiles with evidence of water mass intrusions (by visual inspection) are shown in black. (Figure 3 from Paper B)

4.3. Paper C: Early Winter Triggering of the Maud Rise Polynya

Peer-reviewed and published publication by Lu Zhou, Céline Heuzé, and Martin Mohrmann in 'Geophysical Research Letters'

Remote sensing observations (SMOS and radar altimetry) show that the sea-ice is anomalously thin 2-4 months before the sea-ice opens and forms a polynya. Such predictions with a time scale of multiple months could potentially be used in the future to obtain better in situ measurements from polynyas, which are needed to quantify the influence of the ocean for polynya formation and maintenance. To better comprehend the cause of the early sea-ice thinning, a mixed layer heat budget was computed based on the measurements of profiling floats, data from the atmospheric and oceanic reanalysis models ERA5 (Hersbach et al., 2020), ORAS5, SMOS sea-ice thickness (Huntemann et al., 2014) and geostrophic velocity products (AVISO altimetry, DUACS; Armitage et al., 2018; Pujol et al., 2016). We found that sea-ice thinning is forced both by the oceanic and atmospheric circulations, both dynamically and thermodynamically. That is, the sea ice is stressed by anomalous Weddell Gyre and cyclonic wind. These circulation anomalies also lead to advection of warm water into the region and, most importantly, enhance entrainment of warm water, melting the sea ice from below. I was the one to suggest and perform the mixed layer heat budget using the float data. I also contributed to the writing and created figures for this paper. I was inspired to extend this analysis further into the mixed layer salinity and buoyancy budgets for paper D, which were subsequently removed but helped me see the clear role of salinity in polynya preconditioning.

4.4. Paper D: Autumn mixed layer processes can trigger Maud Rise Polynya formation

Manuscript by Martin Mohrmann, Sebastiaan Swart, and Céline Heuzé, currently in preparation for submission to Journal of Climate

Our first float, which I deployed in 2018 while on an expedition to Antarctica, and one of the SOCCOM floats active during the 2016/2017 polynya both drifted along a spatial trajectory around the edge of Maud Rise that is remarkably similar. For a significant period of time (see Figure 1 in manuscript D) there were only 50 km separating their respective trajectories. We speculated that the Maud Rise dynamics would transport our float into the Taylor Column as we had seen previously for the SOCCOM float (Campbell et al., 2019), but we did not expect the trajectories to be in such close proximity to each other. The similarity of the trajectories suggests a long term, clockwise circulation around Maud Rise as is being confirmed by new high-resolution model simulations (Birte Gülk, personal communication).

During the analysis of Paper B, I had noticed that over Maud Rise the vertical extent of the mixed layer is substantially deeper during winter and a thick layer of winter water remains at depths of 50-150 m over the summer season. In contrast, in the Maud Rise Halo, the mixed layer remains relatively shallow during winter (de Steur et al., 2007), and the thin layer of winter water that remains in autumn is quickly eroded, presumably by advection (Muench et al., 2001) and upwelling (Campbell et al., 2019).

The spatial proximity of the two floats provide us with the opportunity to compare the mixed layer characteristics, extend and stratification between polynya-occuring years (SOCCOM float dataset in 2016/2017) and polynya-free years (our more recent float data). For the polynya years, we find an increased mixed layer salinity already in February, many months before sea-ice and polynyas form, suggesting the important role of early oceanographic preconditioning. Moreover, in the months leading to Maud Rise Polynyas, the mixed layer deepening rate is twice as high as in other years, which in turn contributes to an earlier increase of the mixed layer salinity.

We find that the autumn deepening of the mixed layer has different effects on the heat budget over Maud Rise compared to the Maud Rise Halo. Over Maud Rise, the mixed layer deepening into a thick layer of winter water cools the autumn mixed layer, while in the Maud Rise Halo the deepening into the Warm Deep Water instead warms the autumn mixed layer.

In autumn, cooling and brine rejection reduce the density of the mixed layer and weaken the pycnocline. The water column, stabilized only by the salinity difference at the bottom of the mixed layer, requires little energy to mix. The pycnocline erodes over time in winter; entrainment makes the upper layer saltier and the water below fresher. The weakening or even elimination of the pycnocline is documented in Wilson et al. (2019), however deep convection events have hardly been observed under the sea-ice, even though they are believed to be a crucial factor in the formation of polynyas (Cheon et al., 2014). Initially, I had hoped to close this observational gap with our (up to) daily sampling rate of the floats, but a negative feedback effect of heat entrainment leading to ice melt and restabilization of the mixed layer makes the water column surprisingly resistant to sub-mixed layer convection. Because we do not directly observe deep convection, we focused instead on describing the negative feedback loop that apparently prevents deep convection from happening. In fact, due to the high sampling frequency of the floats, we observe melting events occuring in winter under the sea-ice. These are characterized by (1) a subtle warming of the mixed layer, (2) a sudden fresh layer that is decoupled from the former mixed layer by a new halocline, and finally (3) a somewhat fresher mixed layer after the fresh anomaly is mixed into the former deeper mixed layer again.

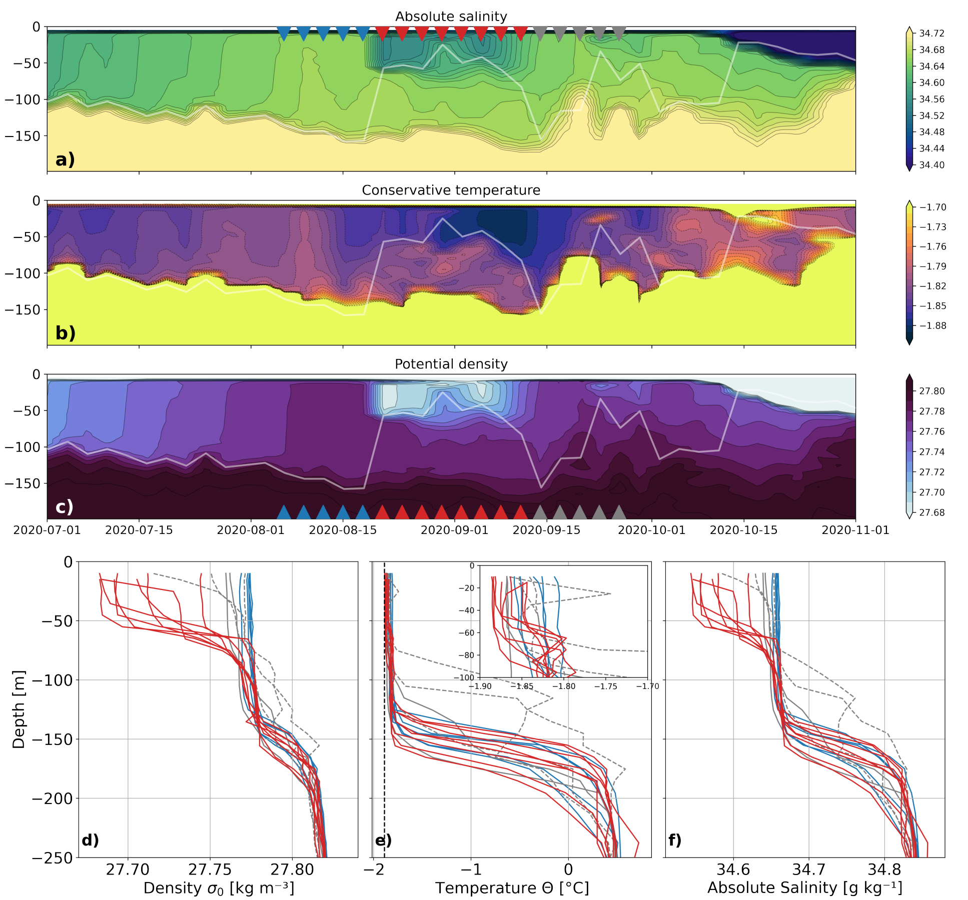

Figure 4.4. Winter melting event under the sea-ice. Contour plots of absolute salinity (a), conservative temperature (b) and potential density (c). The times of vertical profiling are indicated with coloured triangles, to differentiate the profiles in (d,e,f) prior (blue), during (red) and after (grey) the melting event. (Figure 6 from Paper D)

4.5. Shelved project: Responses of Open-Ocean Polynyas to Wind Forcing

The response of the ocean below an open-ocean polynya, around which the wind forcing is modulated by sea-ice, is modeled analytically. I modeled the air-sea momentum transfer implicitly by taking into account the aerodynamic roughness of different types of sea-ice (Guest & Davidson, 1991), which communicates the wind stress to the water. The ice surrounding the polynya causes variations of the effective drag coefficient. The shape of an open-ocean polynya is approximated by a circular ice-free area. The model is advanced by taking into account areas of grease ice or frazil ice around the edge of the polynya, that have a different drag coefficient than the water or solid ice. I applied the method of the Green's function to express a generalized analytical solution of such a system dependent on the wind forcing that is acting on the surface.

For a direction independent homogeneous wind field acting on a round open-ocean polynya, upwelling starts on the right and downwelling on the left side (looking downwind) of the polynya. This instantaneous result resembles the result one can derive using the equation for Ekman pumping. However, after some days the vertical water displacement creates a pressure perturbation (in the shape of Bessel Functions) with a typical scale of the Rossby Radius around the ice edges. The growing pressure perturbations caused by advective upwelling (downwelling) of denser deep water (lighter mixed layer water) turn the current inside the open-ocean polynya slowly against the wind direction. The addition of zones of grease or frazil ice at the outer rim of the polynya can shift these currents further towards the center of the open-ocean polynya and spread out the up- and downwelling zones as well as the boundary jet currents along the ice edges. Due to the smooth structure forming at the surface, grease and frazil ice are highly effective modulators of the wind forcing and lead to equally strong upwelling and ice edge jets as a thicker sea-ice cover in our model.

We also apply a symmetrical cyclonic wind forcing, which is centered in the middle of the polynya. This kind of wind forcing leads to an upwelling effect distributed over the whole area (again similar to Ekman upwelling), but is sharply limited by strong downwelling at the outer edges where the wind is modulated by the sea-ice cover. The upwelled water is transported radially outwards in the mixed layer and, depending on the structure and mobility of the surrounding sea-ice, a large part is downwelled at the outer edges. This

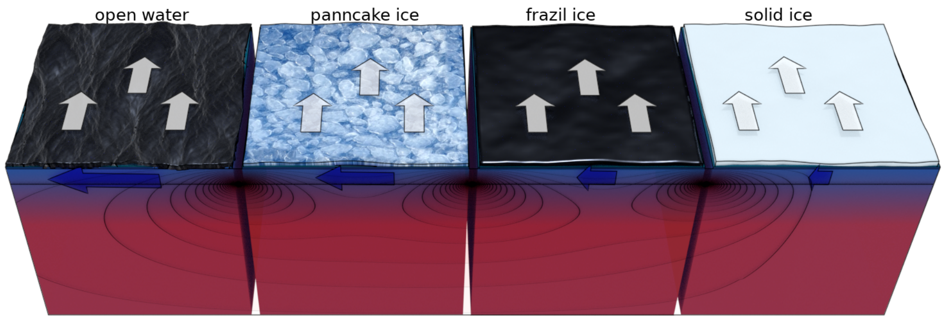

Figure 4.5. Open water and three sea-ice types are shown in this schematic image. In the Weddell Sea, the deeper layer of CDW is warmer than the surface water (red-blue gradient). The wind forcing (white arrows) is transporting momentum into the ocean, modulated by the aerodynamic roughness of different sea-ice types (indicated by upper texture of the cubes). The wind drag causes Ekman transport of water in the mixed layer (blue arrows). The difference in effective wind drag between open water areas and different sea-ice types causes upwelling around the ice edges. The contour plots shown on the front side of the cubes are derived using the model. We also find along-front jets building up, caused by the pressure perturbations of the upwelling (not shown here).

structure could be part of the upwards heat flux from the depths, that helps maintain the polynya. Over time, the water in the mixed layer is accelerated in a circular motion, driven by the cyclonic winds.

This project is shelved for now due to the following reasons: The analytical solution of the 3-dimensional Boussinesq equations was possible, but the resulting equations are very long, ugly and hard to interpret. The simplification of the upwelling as a slowly building pressure perturbation that I chose has been criticized and is questionable for responses on long time scales (longer than a few days). Moreover, the preliminary results show that the system of advective wind-driven currents contributes only to a small part to the maintenance of open-ocean polynyas on the the scale of the Weddell Sea Polynya, and could effectively only maintain a small polynya up to a diameter of 20 km. Therefore, I decided to focus on processes that contribute more to the formation of open-ocean polynyas instead. However, this was an informative exercise that led me to better understand to which extend sea ice

with varying sea surface roughness modulates upwelling along ice edges.

4.6. Placing the thesis parts into perspective

Polynyas in climate projection:

The first aim of this thesis was to assess polynya representation in the current generation of climate models. In Paper A, we found that only half of the 27 models form open-ocean polynyas, but also a few models show them almost every year due to unrealistically strong deep convection in the Weddell Sea. Because polynyas are mainly maintained by heat supply from Circumpolar Deep Water/Warm Deep Water (Dufour et al., 2017; Martin et al., 2013; Martinson et al., 1981; Reintges et al., 2017), the significant model biases suggest difficulties in modelling the stability of the water column - a point which is also discussed in Heuzé (2020). It is no surprise that the largest biases appear in the Weddell Sea, because the Weddell Sea and especially the Maud Rise region have an exceptionally low vertical density stratification (Wilson et al., 2019). We found correlations between the strength of the Southern Hemisphere Westerlies, the ACC and the polynya activity in agreement with Cheon et al. (2014) and Hirabara et al. (2012). We also found that it is not only physical parameters that affect the polynya activity in the models, but also technical properties such as the horizontal model resolution, the choice of vertical grids, and their mixing schemes. Related important biases of CMIP6 (and other) models have been reported for the bottom density (Heuzé, 2020), sea-ice extent and ACC transport (Beadling et al., 2020; Roach et al., 2020), and heat content of the intermediate ocean (Dufour et al., 2017).

Models can only be as good as the observations used to tune them, which is why the second aim of this thesis was to obtain new hydrographic observations at Maud Rise and the regional vicinity. The two profiling floats deployed for this thesis enabled us to observe day-to-day changes in the vertical water stratification for a period of 3 years in total. In contrast to earlier float campaigns (e.g. K & S, 2018), a direct observation of the response to short-term storm or melting events was possible due to our daily sampling resolution. The Lagrangian trajectory that our first float took was a success and advantage for us, since the Maud Rise flank is where the onset of the polynya is observed most often.

In Paper B, we analysed the effects of frontal mixing along the flanks of Maud Rise and found that thermobaric effects and double diffusive mixing of the observed intrusions could lead to a vertical displacement of several hundred metres due to the low background stratification. The observed front is sharp and distinct, but horizontal mixing occurs in the form of intrusions. These processes happen on scales of O(1 km), and so cannot be represented in CMIP6 models directly. The high profiling frequency of our floats enabled us to describe the front and its across front mixing with finer spatial and temporal resolution than previous measurements, e.g. CTD-casts (Bersch et al., 1992; Leach et al., 2010; Muench et al., 2001) or floats with standard 10-day sampling rates (Campbell et al., 2019). Using more than 1 000 vertical profiles that were sampled during the last 10 years by profiling floats in the region, we confirmed the presence and spatial extent of the Taylor cap and the surrounding Warm Deep Water earlier described by (e.g. Akitomo, 2006; Alverson & Owens, 1996; Beckmann et al., 2001; Bersch et al., 1992; de Steur et al., 2007; Muench et al., 2001), and we further specified the bathymetric depth of the transition between Maud Rise Deep Water and Warm Deep Water occuring at approximately 3500 m. Furthermore, we found that the intermediate water properties underlay only very weak seasonal changes and were mostly governed by the bathymetry. The Maud Rise frontal mixing along the northern flank of Maud Rise was observed in autumn, and is coincidentally the time when our float reached and crossed the front. However, the position and water properties of the cold Taylor cap and the warmer halo do not seem to change much over time (compare e.g. Bersch et al. (1992), de Steur et al. (2007) and the profiles from our Paper B). It is likely that the observed frontal mixing also happens in winter time under the sea-ice and its vertical mixing could be the initial cause of the Maud Rise Polynyas.

Oceanic preconditioning and prediction of polynyas:

Aside from the initial opening of the polynyas in close proximity to the flanks of Maud Rise (Heuzé et al., 2021), Maud Rise Polynyas widen (or even grow into Weddell Sea polynyas) only after extended times of preconditioning. The preconditioning process consists of a subsurface advection of heat and salt anomalies (van Westen & Dijkstra, 2020), the buildup of a heat reservoir at depth (Dufour et al., 2017; Kurtakoti et al., 2021) or mixed layer salt anomalies (Campbell et al., 2019).

The long preconditioning period of the polynya suggests that a signature of an upcoming polynya may, perhaps, be detectable well before (many months) the polynya actually opens. In fact, we show that all polynya events

can be predicted two weeks prior to their opening by satellite infrared imagery (Heuzé et al., 2021), and as early as four months ahead by the SMOS ice thickness and radar altimetry (Zhou et al., 2022). The polynya events are preceded by sea-ice thinning and cyclonic wind anomalies that start already in early winter. Using a mixed layer heat budget equation, we found that the primary process to keep the polynya open is the entrainment of heat from depth, and this process is significantly enhanced during years of polynya formation (Zhou et al., 2022).

The mixed layer properties may play a substantial role in the preconditioning of the Maud Rise Polynya. Campbell et al. (2019) observed increased summer/autumn mixed layer salinity leading up to polynya formation (see their Figure 2). Kurtakoti et al. (2018) found in a modelling study that already in May before polynya formation, the upper 100 m is saltier and the subsurface fresher. In summary, several months before polynya formation the sea surface salinity increases, which might be due to increased entrainment of saltier waters. In our fourth study (Paper D, manuscript draft), the float observations from 2016/2017 during and before the polynya are compared with our float observations from 2020/2021 when there was no polynya present.

We characterize the mixed layer salinity anomalies many months prior to polynya formation and their relation to mixed layer deepening. We found that, in comparison to our reference years, the mixed layer had increased its salinity already at the start of February, in agreement with (Campbell et al., 2019), but the mixed layer depth was not significantly deeper. Thus, the summer mixed layer salinity anomaly may be driven by a process other than entrainment, such as advection. However, the mixed layer deepening from February to the end of May was twice as high during polynya years producing a positive upper ocean salinity anomaly later in the year (May in Paper D) and linked primarily to entrainment from below the mixed layer.

The effect of the autumn mixed layer deepening on entrainment of heat into the mixed layer can differ depending on the properties of the underlying water masses. In the presence of a thick layer of cold winter water, as found over Maud Rise, the mixed layer deepening cools the mixed layer and sea-ice formation sets in relatively early (i.e. middle to end of May). For a thin, eroded layer of winter water as observed in the vicinity of the Maud Rise Halo, entrainment of the underlying Warm Deep Water warms the mixed layer and leads to reduced sea-ice formation, which often can be observed throughout winter as a low sea-ice concentration halo (Lindsay et al., 2004). Based on our observations of increased summer mixed layer salinity several months before polynya formation, we believe that these salinity anomalies act as an early preconditioning and predictor of the polynya.

5 Reflection and Future Perspectives

If I were to do this PhD again from the start, I would not change the general course of the projects we focused on. However, in hindsight I would have saved a significant amount of time if the collected float data were submitted to one of the global data assimilation centres from the start, instead of completing this only recently. The processing of the float data required many thousands lines of code, and I likely reproduced many steps that would automatically be undertaken by the Global Data Assimilation System's float data processing pipeline. Additionally, it would have been favorable if the deployment position of our second profiling float on the SA Agulhas II voyage was located further south, e.g. at around 66.2°S, 0°E, as planned originally. Due to conditions beyond our control the ship had to deviate from its planned route. Perhaps future float deployments at our planned deployment location will reveal the forms of observations we would have collected if the field work had gone according to plan. Of course, with the skill set and knowledge I have built over the past four and a half years, I expect I could reproduce most of my work within a year, but this is the nature of education and rather a reason to feel thankful instead of ruing over lost time.

The presented work by (Mohrmann, Heuzé, et al., 2021) provides robust statistical knowledge about the polynya activity in CMIP6 models with comparison to observations. In this work, we had limited scope to discuss physical forcings and processes and their effects on Southern Ocean polynyas. I believe that additional studies, that discuss the atmospheric and oceanic preconditioning of polynyas across all CMIP6 models are required. These should then be complemented with model-specific studies, either to determine the causes for biases or for deeper investigations of processes driving polynya formation (or lack thereof) in such models.

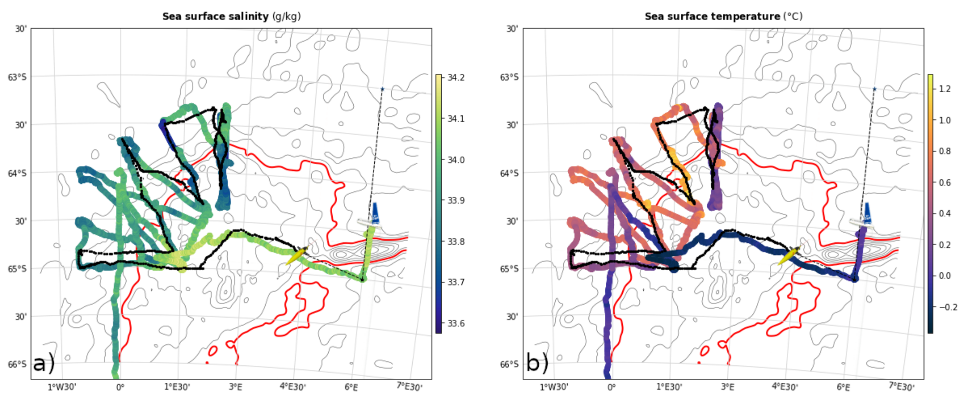

Figure 5.1. First look at the ongoing data collection by a glider and Sailbouy within the ROAM-MIZ & SO-CHIC project (www.roammiz.com). Seaglider trajectory (black line) and Sailbouy trajectory indicating surface values of (a) salinity and (b) temperature over the Maud Rise bathymetry (black contours). The 3500 m isobath as indicator for the Taylor Cap region is marked with a red contour.

Paper B (Mohrmann et al., 2022) about the frontal mixing processes provides the first observational characterization of the warm-water front located around the Taylor Column of Maud Rise. Our findings suggest that the front has significant potential to cause horizontal and vertical mixing and therefore the vertical and lateral exchange of properties, such as heat. However, due to the Lagrangian nature of the profiling floats, a quantification of the scales of horizontal interleaving and water mass exchange as well as a temporal/spatial mapping of the front and its variability were not entirely possible. However, the paper contributed to the planning of a new field campaign (SO-CHIC), in which multiple observational platforms, namely profiling floats, a Sailbuoy, profiling glider and UpTempO buoys are currently collecting high-resolution observations over Maud Rise and its flanks, covering finer temporal and spatial scales over a wider geographic region. In addition, Deep Argo profiling floats will be able to observe the front all the way to the sea floor. We believe that the collected data will provide a greatly improved characterization of the front and the general oceanographic and biogeochemical processes occurring at this unique part of the global ocean.

If I were to work on this topic for an additional two or more years, I would extend my CMIP6 polynya analysis to include additional scenarios.

Our analysis of the 'historical' scenario is an evaluation of the current state of polynya representation in CMIP models. Alternative choices could be the Shared Socioeconomic Pathways (SSPs) that could allow a prediction of polynya activity under future climatic conditions. However, with recent biases we found in the representation of polynyas in most models (in comparison to observations), such a study might benefit from selecting the models with the most realistic outcome in the Mohrmann, Heuzé, et al. (2021) study. From the observations, the sharp gradients at the northern flank of Maud Rise were the biggest surprise. Ongoing or future planned observations are likely to provide more insight about the observed potential instabilities that contribute to vertical mixing, and thus influence the formation of the Maud Rise Polynya. The floats used in this study sampled with a vertical resolution of only 25 m below 200 m water depth. In hindsight, the discovery of the frontal interleaving between 200 - 800 m depth makes it desirable to have higher vertical resolution at depth. Even microstructure measurements could be great to quantify the mixing rates between Warm Deep Water and Maud Rise Deep Water in this dynamically active region.

I am excited that further research of the Maud Rise region and its polynyas at the University of Gothenburg and other institutions around the globe continues actively. High-resolution models combined, for example, with the latest high-resolution SO-CHIC-based observational campaigns (Figure 5.1) hope to bring more clarity about the key processes, such as mixed layer shoaling in the Maud Rise Halo or mapping the distribution of water mass heterogeneity and mixing around Maud Rise, that ultimately determine the presence of this fascinating natural phenomenon, known as the Maud Rise Polynya.

6 References

Akitomo, K. (2006). Thermobaric deep convection, baroclinic instability, and their roles in vertical heat transport around Maud Rise in the Weddell Sea. *Journal of Geophysical Research: Oceans*, *111*(C9). https://doi.org/https://doi.org/10.1029/2005JC003284

Alverson, K., & Owens, W. B. (1996). Topographic Preconditioning of Open-Ocean Deep Convection. *Journal of Physical Oceanography*, *26*(10), 2196–2213. https://doi.org/10.1175/1520-0485(1996)026<2196:TPOOOD>2.0.CO;2

Arbetter, T. E., Lynch, A. H., & Bailey, D. A. (2004). Relationship between synoptic forcing and polynya formation in the Cosmonaut Sea: 1. Polynya climatology. *Journal of Geophysical Research: Oceans*, *109*(C4).

Armitage, T. W. K., Kwok, R., Thompson, A. F., & Cunningham, G. (2018). Dynamic Topography and Sea Level Anomalies of the Southern Ocean: Variability and Teleconnections. *Journal of Geophysical Research: Oceans*, *123*(1), 613–630. https://doi.org/https://doi.org/10.1002/2017JC013534

Arrigo, K. R., & Van Dijken, G. L. (2003). Phytoplankton dynamics within 37 Antarctic coastal polynya systems. *Journal of Geophysical Research: Oceans*, *108*(C8).

Barber, D. G., & Massom, R. A. (2007). The role of sea ice in Arctic and Antarctic polynyas. *Elsevier oceanography series*, *74*, 1–54.

Beadling, R., Russell, J., Stouffer, R., Mazloff, M., Talley, L., Goodman, P., Sallée, J., Hewitt, H., Hyder, P., & Pandde, A. (2020). Representation of Southern Ocean Properties across Coupled Model Intercomparison

Project Generations: CMIP3 to CMIP6. *Journal of Climate*, *33*(15), 6555–6581.

Beckmann, A., Timmermann, R., Pereira, A. F., & Mohn, C. (2001). The effect of flow at Maud Rise on the sea-ice cover–numerical experiments. *Ocean Dynamics*, *52*(1), 11–25.

Bernardello, R., Marinov, I., Palter, J. B., Galbraith, E. D., & Sarmiento, J. L. (2014). Impact of Weddell Sea deep convection on natural and anthropogenic carbon in a climate model. *Geophysical Research Letters*, *41*(20), 7262–7269. https://doi.org/https://doi.org/10.1002/2014GL061313

Bersch, M., Becker, G., Frey, H., & Koltermann, K. (1992). Topographic effects of the Maud Rise on the stratification and the circulation of the Weddell Gyre. *Deep-Sea Research*, *39*, 303–331. https://doi.org/https://doi.org/10.1016/0198-0149(92)90111-6

Broecker, W. S., Sutherland, S., & Peng, T.-H. (1999). A Possible 20th-Century Slowdown of Southern Ocean Deep Water Formation. *Science*, *286*(5442), 1132–1135. https://doi.org/10.1126/science.286.5442.1132

Campbell, E. C., Wilson, E. A., Moore, G. K., Riser, S. C., Brayton, C. E., Mazloff, M. R., & Talley, L. D. (2019). Antarctic offshore polynyas linked to Southern Hemisphere climate anomalies. *Nature*, *570*(7761), 319–325.

Carsey, F. (1980). Microwave observation of the Weddell Polynya. *Monthly Weather Review*, *108*(12), 2032–2044.

Cheon, W. G., & Gordon, A. L. (2019). Open-ocean polynyas and deep convection in the Southern Ocean. *Scientific reports*, *9*(1), 1–9.

Cheon, W. G., Park, Y.-G., Toggweiler, J., & Lee, S.-K. (2014). The relationship of Weddell Polynya and open-ocean deep convection to the Southern Hemisphere westerlies. *Journal of physical oceanography*, *44*(2), 694–713.

Comiso, J., & Gordon, A. (1987). Recurring polynyas over the Cosmonaut Sea and the Maud Rise. *Journal of Geophysical Research: Oceans*, *92*(C3), 2819–2833.

De Lavergne, C., Palter, J. B., Galbraith, E. D., Bernardello, R., & Marinov, I. (2014). Cessation of deep convection in the open Southern Ocean under anthropogenic climate change. *Nature Climate Change*, *4*(4), 278–282.

de Steur, L., Holland, D., Muench, R., & McPhee, M. (2007). The warm-water "Halo" around Maud Rise: Properties, dynamics and Impact. *Deep Sea Research Part I: Oceanographic Research Papers*, *54*(6), 871–896. https://doi.org/https://doi.org/10.1016/j.dsr.2007.03.009

Dufour, C. O., Morrison, A. K., Griffies, S. M., Frenger, I., Zanowski, H., & Winton, M. (2017). Preconditioning of the Weddell Sea polynya by the ocean mesoscale and dense water overflows. *Journal of Climate*, *30*(19), 7719–7737.

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 [e2021JC017760 2021JC017760]. *Journal of Geophysical Research: Oceans*, *127*(4), e2021JC017760. https://doi.org/https://doi.org/10.1029/2021JC017760

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.

Francis, D., Eayrs, C., Cuesta, J., & Holland, D. (2019). Polar cyclones at the origin of the reoccurrence of the Maud Rise Polynya in austral winter 2017. *Journal of Geophysical Research: Atmospheres*, *124*(10), 5251–5267.

GEBCO Bathymetric Compilation Group. (2021). The GEBCO 2021 Grid - a continuous terrain model of the global oceans and land. https://doi.org/10.5285/c6612cbe-50b3-0cff-e053-6c86abc09f8f

Giddy, I., Swart, S., du Plessis, M., Thompson, A. F., & Nicholson, S.-A. (2021). Stirring of Sea-Ice Meltwater Enhances Submesoscale Fronts in the Southern Ocean [e2020JC016814 2020JC016814]. *Journal of Geophysical Research: Oceans*, *126*(4), e2020JC016814. https://doi.org/https://doi.org/10.1029/2020JC016814

Gordon, A. L. (1978). Deep antarctic convection west of Maud Rise. *Journal of Physical Oceanography*, *8*(4), 600–612.

Guest, P. S., & Davidson, K. L. (1991). The aerodynamic roughness of different types of sea ice. *Journal of Geophysical Research: Oceans*, *96*(C3), 4709–4721.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., ... Thépaut, J.-N. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049. https://doi.org/https://doi.org/10.1002/qj.3803

Heuzé, C., Ridley, J., Calvert, D., Stevens, D., & Heywood, K. (2015). Increasing vertical mixing to reduce Southern Ocean deep convection in NEMO3. 4. *Geoscientific Model Development*, *8*(10), 3119–3130.

Heuzé, C. (2020). Antarctic Bottom Water and North Atlantic Deep Water in CMIP6 models. *Ocean Science Discussions*, 1–38.

Heuzé, C., Garric, G., Lavergne, T., Gourrion, J., Deshayes, J., Juza, M., Szekely, T., Aguiar, E., Mourre, B., Pascual, A., et al. (2019). The Weddell Sea Polynya. *Journal of Operational Oceanography*, *12*, S91–S123.

Heuzé, C., Zhou, L., Mohrmann, M., & Lemos, A. (2021). Spaceborne infrared imagery for early detection of Weddell Polynya opening. *The Cryosphere*, *15*(7), 3401–3421. https://doi.org/10.5194/tc-15-3401-2021

Hirabara, M., Tsujino, H., Nakano, H., & Yamanaka, G. (2012). Formation mechanism of the Weddell Sea Polynya and the impact on the global abyssal ocean. *Journal of oceanography*, *68*(5), 771–796.

Holland, D. M. (2001). Explaining the Weddell Polynya–a Large Ocean Eddy Shed at Maud Rise. *Science*, *292*(5522), 1697–1700. https://doi.org/10.1126/science.1059322

Hünemörder, K. F. (2004). *Die Frühgeschichte der globalen Umweltkrise und die Formierung der deutschen Umweltpolitik (1950-1973)* (Vol. 53). Franz Steiner Verlag.

Huntemann, M., Heygster, G., Kaleschke, L., Krumpen, T., Mäkynen, M., & Drusch, M. (2014). Empirical sea ice thickness retrieval during the freeze up period from SMOS high incident angle observations. *The Cryosphere*, *8*(2), 439–451.

Johnson, K. S., Riser, S. C., Boss, E. S., Talley, L. D., Sarmiento, J. L., Swift, D. D., Plant, J. N., Maurer, T. L., Key, R. M., Williams, N. L., Wanninkhof, R. H., Dickson, A. G., Feely, R. A., & Russell, J. L. (2021). SOCCOM float data - Snapshot 2021-05-05. https://doi.org/https://doi.org/10.6075/J0T43SZG

K, J., & S, R. (2018). Soccom float data—snapshot 2018-12-31. *Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) Float Data Archive*.

Kern, S., Spreen, G., Kaleschke, L., De La Rosa, S., & Heygster, G. (2007). Polynya Signature Simulation Method polynya area in comparison to AMSR-E 89GHz sea-ice concentrations in the Ross Sea and off the Adélie Coast, Antarctica, for 2002–05: first results. *Annals of Glaciology*, *46*, 409–418.

Kjellsson, J., Holland, P. R., Marshall, G. J., Mathiot, P., Aksenov, Y., Coward, A. C., Bacon, S., Megann, A. P., & Ridley, J. (2015). Model sensitivity of the Weddell and Ross seas, Antarctica, to vertical mixing and freshwater forcing. *Ocean Modelling*, *94*, 141–152.

Kurtakoti, P., Veneziani, M., Stössel, A., Weijer, W., & Maltrud, M. (2021). On the Generation of Weddell Sea Polynyas in a High-Resolution Earth System Model. *Journal of Climate*, *34*, 2491–2510. https://doi.org/10.1175/JCLI-D-20-0229.1

Kurtakoti, P., Veniziani, M., Stössel, A., & Weijer, W. (2018). Preconditioning and Formation of Maud Rise Polynyas in a High-Resolution Eart System Model. *Journal of Climate*, *31*(23), 9659–9678. https://doi.org/https://doi.org/10.1175/JCLI-D-18-0392.1

Lavergne, T., Sørensen, A. M., Kern, S., Tonboe, R., Notz, D., Aaboe, S., Bell, L., Dybkjær, G., Eastwood, S., Gabarro, C., et al. (2019). Version 2 of the EUMETSAT OSI SAF and ESA CCI sea-ice concentration climate data records. *The Cryosphere*, *13*(1), 49–78.

Leach, H., Strass, V., & Cisewski, B. (2010). Modification by lateral mixing of the Warm Deep Water entering the Weddell Sea in the Maud Rise region. *Ocean Dynamics*. https://doi.org/10.1007/s10236-010-0342-y

Lindsay, R. W., Holland, D. M., & Woodgate, R. A. (2004). Halo of low ice concentration observed over the Maud Rise seamount. *Geophysical Research Letters*, *31*(13). https://doi.org/https://doi.org/10.1029/2004GL019831

Lockwood, J. W., Dufour, C. O., Griffies, S. M., & Winton, M. (2021). On the role of the antarctic slope front on the occurrence of the weddell sea polynya under climate change. *Journal of Climate*, *34*(7), 2529–2548. https://doi.org/10.1175/JCLI-D-20-0069.1

Martin, T., Park, W., & Latif, M. (2013). Multi-centennial variability controlled by Southern Ocean convection in the Kiel Climate Model. *Cimate Dynamics*, *40*, 2005–2022. https://doi.org/https://doi.org/10.1007/s00382-012-1586-7

Martinson, D. G., Killworth, P. D., & Gordon, A. L. (1981). A convective model for the Weddell Polynya. *Journal of Physical Oceanography*, *11*(4), 466–488.

Miller, L., & DiTullio, G. (2007). Gas fluxes and dynamics in polynyas. *Elsevier Oceanography Series*, *74*, 163–191.

MODIS Characterization Support Team. (2017). MODIS 500m Calbrated Radiance Product. https://doi.org/http://dx.doi.org/10.5067/MODIS/MYD0HKM.061

Mohrmann, M., Heuzé, C., & Swart, S. (2021). Southern Ocean polynyas in CMIP6 models. *The Cryosphere*, *15*(9), 4281–4313. https://doi.org/0.5194/tc-15-4281-2021

Mohrmann, M., Swart, S., & Heuzé, C. (2021). Vertical profiles of salinity, temperature and pressure measured by vertical profiling floats in the eastern Weddell Sea around Maud Rise in 2018 - 2021. https://doi.org/https://doi.org/10.1594/PANGAEA.938743

Mohrmann, M., Swart, S., & Heuzé, C. (2022). Observed mixing at the flanks of Maud Rise in the Weddell Sea. *Geophysical Research Letters*. https://doi.org/10.1029/2022GL098036

Morales Maqueda, M., Willmott, A., & Biggs, N. (2004). Polynya dynamics: A review of observations and modeling. *Reviews of Geophysics*, *42*(1).

Muench, R. D., Morison, J. H., Padman, L., Martinson, D., Schlosser, P., Huber, B., & Hohmann, R. (2001). Maud Rise revisited. *Journal of Geophysical Research: Oceans*, *106*(C2), 2423–2440. https://doi.org/https://doi.org/10.1029/2000JC000531

Nakata, K., Ohshima, K. I., Nihashi, S., Kimura, N., & Tamura, T. (2015). Variability and ice production budget in the Ross Ice Shelf Polynya based on a simplified polynya model and satellite observations. *Journal of Geophysical Research: Oceans*, *120*(9), 6234–6252.

Ohshima, K. I., Nihashi, S., & Iwamoto, K. (2016). Global view of sea-ice production in polynyas and its linkage to dense/bottom water formation. *Geoscience Letters*, *3*(1), 13.

Pörtner, H.-O., Roberts, D., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., V., M., Okem, A., & Rama, B. (n.d.). Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. *IPCC, 2022*.

Pujol, M.-I., Faugère, Y., Taburet, G., Dupuy, S., Pelloquin, C., Ablain, M., & Picot, N. (2016). DUACS DT2014: the new multi-mission altimeter data set reprocessed over 20 years. *Ocean Science*, *12*(5), 1067–1090. https://doi.org/10.5194/os-12-1067-2016

Reintges, A., Martin, T., Latif, M., & Park, W. (2017). Physical controls of Southern Ocean deep-convection variability in CMIP5 models and the Kiel Climate Model. *Geophysical Research Letters*, *44*(13), 6951–6958.

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., et al. (2020). Antarctic sea ice area in CMIP6. *Geophysical Research Letters*, *47*(9), e2019GL086729.

Schmidt, K. M., Swart, S., Reason, C., & Nicholson, S.-A. (2017). Evaluation of Satellite and Reanalysis Wind Products with In Situ Wave Glider Wind Observations in the Southern Ocean. *Journal of Atmospheric and Oceanic Technology*, *34*(12), 2551–2568. https://doi.org/10.1175/JTECH-D-17-0079.1

Schröder, M., & Fahrbach, E. (1999). On the structure and the transport of the eastern Weddell Gyre. *Deep Sea Research Part II: Topical Studies in Oceanography*, *46*(1), 501–527. https://doi.org/https://doi.org/10.1016/S0967-0645(98)00112-X

Shcherbina, A. Y., Gregg, M. C., Alford, M. H., & Harcourt, R. R. (2009). Characterizing Thermohaline Intrusions in the North Pacific Subtropical Frontal Zone. *Journal of Physical Oceanography*, *39*(11), 2735–2756. https://doi.org/10.1175/2009JPO4190.1

Swart, S., Campbell, E., Heuzé, C., Johnson, K., Lieser, J., Massom, R., Mazloff, M., Meredith, M., Reid, P., Sallee, J.-B., et al. (2018). Return of the Maud Rise polynya: Climate litmus or sea ice anomaly?[in "State of the Climate in 2017"]. *Bulletin of the American Meteorological Society*, *99*(8), S188–S189.

Swart, S., du Plessis, M. D., Thompson, A. F., Biddle, L. C., Giddy, I., Linders, T., Mohrmann, M., & Nicholson, S.-A. (2020). Submesoscale fronts in the Antarctic marginal ice zone and their response to wind forcing. *Geophysical Research Letters*, *47*(6), e2019GL086649.

Tamsitt, V., Abernathey, R. P., Mazloff, M. R., Wang, J., & Talley, L. D. (2018). Transformation of Deep Water Masses Along Lagrangian Upwelling Pathways in the Southern Ocean. *Journal of Geophysical Research: Oceans*, *123*(3), 1994–2017. https://doi.org/https://doi.org/10.1002/2017JC013409

Taylor, G. I. (1917). Motion of solids in fluids when the flow is not irrotational. *Proceedings of the Royal Society A, mathematical, physical and engineering sciences*, *93*. https://doi.org/https://doi.org/10.1098/rspa.1917.0007

van Westen, R. M., & Dijkstra, H. A. (2020). Multidecadal preconditioning of the Maud Rise polynya region. *Ocean Science*, *16*(6), 1443–1457. https://doi.org/10.5194/os-16-1443-2020

Williams, W., Carmack, E., & Ingram, R. (2007). Physical oceanography of polynyas. *Elsevier Oceanography Series*, *74*, 55–85.

Willmott, A., Holland, D., & Maqueda, M. M. (2007). Polynya modelling. *Elsevier Oceanography Series*, *74*, 87–125.

Wilson, E. A., Riser, S. C., Campbell, E. C., & Wong, A. P. (2019). Winter upper-ocean stability and ice–ocean feedbacks in the sea ice–covered Southern Ocean. *Journal of Physical Oceanography*, *49*(4), 1099–1117.

Yu, L., Jin, X., & W., S. (2019). Surface heat budget in the Southern Ocean from 42°S to the Antarctic marginal ice zone: four atmospheric reanalyses versus icebreaker Aurora Australis measurements. *Polar Research*, *38*. https://doi.org/10.33265/polar.v38.3349

Yukimoto, S., Kawai, H., Koshiro, T., Oshima, N., Yoshida, K., Urakawa, S., Tsujino, H., Deushi, M., Tanaka, T., Hosaka, M., et al. (2019). The Meteorological Research Institute Earth System Model version 2.0, MRI-ESM2. 0: Description and basic evaluation of the physical component. *Journal of the Meteorological Society of Japan. Ser. II.*

Zanowski, H., Hallberg, R., & Sarmiento, J. L. (2015). Abyssal ocean warming and salinification after Weddell polynyas in the GFDL CM2G coupled climate model. *Journal of Physical Oceanography*, *45*(11), 2755–2772.

Zhou, L., Heuzé, C., & Mohrmann, M. (2022). Early Winter Triggering of the Maud Rise Polynya [e2021GL096246 2021GL096246]. *Geophysical Research Letters*, *49*(2), e2021GL096246. https://doi.org/https://doi.org/10.1029/2021GL096246

Zhu, J., Xie, A., Qin, X., Wang, Y., Xu, B., & Wang, Y. (2021). An Assessment of ERA5 Reanalysis for Antarctic Near-Surface Air Temperature. *Atmosphere*, *12*(2). https://doi.org/10.3390/atmos12020217