On the generation of Maud Rise polynyas in the Weddell Sea

Birte Gülk

Doctoral thesis

UNIVERSITY OF GOTHENBURG

Department of Marine Sciences
University of Gothenburg
2024

UNIVERSITY OF GOTHENBURG

Dissertation for the Degree of Doctor of Philosophy, Ph.D.,
in Natural Sciences, specialising in Oceanography
University of Gothenburg, 2024

On the generation of Maud Rise polynyas in the Weddell Sea

ISBN 978-91-8069-723-1 (printed)
ISBN 978-91-8069-724-8 (pdf)
This book was typeset by the author using LaTeX.

SVANENMÄRKET
Trycksak
3041 0234

Front cover: © Martin Pfeifer

Back cover photo: The author. Photo credit: Estel Font

Printed by: Stema Specialtryck AB, Borås, 2024

Keywords: Maud Rise, Weddell Sea, open-ocean polynyas, Taylor Caps,
Ocean modeling

Contents

Abstract

The Weddell Sea is a region prone to the formation of open-ocean polynyas. Open-ocean polynyas are offshore openings of sea ice in the winter season, often accompanied by deep convection. Deep convection allows for the homogenization of the water column and the intense exchange of heat and gasses between the deep ocean and the atmosphere making them important for the formation of deep waters. In the 1970s, large polynyas were observed in the central Weddell Sea, called Weddell Sea polynyas. The Weddell Sea polynya has not reoccurred since, sparking questions about their frequency and climate relevance. Instead smaller and short-lived polynyas have irregularly occurred in the vicinity of Maud Rise, a seamount in the eastern Weddell Sea, most recently in 2016 and 2017. The interaction of Maud Rise with the large-scale ocean circulation in the Weddell Sea, the Weddell Gyre, forms two prominent hydrographic features: a warm-water Halo and a Taylor Cap. The Taylor Cap sits above Maud Rise and the warm-water Halo encircles it. Our knowledge of the processes and dynamics in the region of Maud Rise is based on a scarce number of observations. Various processes for the generation of the Maud Rise polynya have been proposed, and the adequate representation of Maud Rise polynyas in ocean models remains a challenge. This thesis proposes to investigate the mechanisms leading to the generation of the 2016 and 2017 polynyas, and provides a modeling approach for the adequate representation of these events in ocean models.

In this thesis, publicly available observations and newly gained SO-CHIC observations from 2022 are used, as well as two reanalyses and two new regional ocean model configurations. This thesis revealed large interannual variability of the Halo and Taylor Cap with a period of a near-vanishing Taylor Cap in the years preceding the polynya opening. The variability is largely controlled remotely through the advection of anomalous water masses from the Weddell Gyre. The flow-topography interaction of the Weddell Gyre and Maud Rise enhances the chances of polynya opening by generating anomalies in the stratification. These anomalies are found to be related to the Taylor Cap and depend on the strength of the impinging flow. Further, the role of thermobaric effects on ambient stratification is important in triggering the 2016 polynya. The numerical simulation highlighted that the 2016 polynya preconditioned the region for the 2017 polynya. The 2017 polynya was enabled by an Ekman transport of salinity from the Taylor Cap to the Halo destratifying the region immediately north of the rise. In summary, this thesis highlights the complexity of processes at play in the most recent polynya events at Maud Rise and emphasizes the role of the ocean. Moreover, it shows the importance of improving the available convection parameterizations to improve deep convection and polynyas in ocean models.

Sammanfattning

Öppningar i havsisen på öppet vatten, långt från land, under vinterhalvåret, så kallade polynyor i öppet hav, kan åtföljas av djupgående konvektion. Djup konvektion möjliggör homogenisering av vattenkolumnen och intensivt utbyte av värme och gaser mellan djuphavet och atmosfären. Weddellhavet är en region där polynyor kan uppstå ute på öppet hav. På 1970-talet observerades stora polynyor i de centrala delarna av Weddellhavet, så kallade Weddelhavspolynyor. Sedan dess har endast mindre och kortlivade polynyor uppstått på oregelbunden basis i närheten av Maud Rise, ett havsberg i östra delen av Weddellhavet, varav de senaste inträffade 2016 och 2017. Maud Rise är en dynamisk region med två framträdande hydrografiska egenskaper: en Taylorkolumn ovanpå Maud Rise och en omgivande varmvattenhalo. Dessa resulterar från interaktionen mellan cirkulationen i Weddell Gyre, d.v.s. den storskaliga medurs cirkulationsvirveln i området, och havsberget. Vår kunskap om processerna och dynamiken i området kring Maud Rise baseras på ett fåtal observationer. Olika processer som kan bidra till uppkomsten av polynyor vid Maud Rise har föreslagits och adekvat representation av Maud Rise polynyor i havsmodeller är fortfarande en utmaning. I denna avhandling används allmänt tillgängliga observationer och nyligen tillkomna observationer från 2022 ur projektet SO-CHIC, samt två reanalysprodukter och två regionala havsmodellkonfigurationer. Denna avhandling föreslår en kombination av mekanismer som leder till uppkomsten av polynyorna som observerades 2016 och 2017 och tillhandahåller en modelleringsmetod för adekvat representation av dessa polynyahändelser i havsmodeller.

Denna avhandling avslöjar stor mellanårlig variation hos såväl varmvattenhalon som Taylorkolumnen, med perioder av en nästan total avsaknad av Taylorkolumn under åren som föregår polynyans uppkomst. Variabiliteten styrs till stor del på distans genom advektion av anomala vattenmassor från cirkulationsvirveln Weddell Gyre. Interaktionen mellan flödet och havsbotten, när cirkulationen i Weddell Gyre möter berget Maud Rise, ökar möjligheterna för att en polynya ska uppstå genom att generera anomalier i skiktningen. Dessa anomalier visar sig vara relaterade till Taylorkolumnen och beror på styrkan hos det inkommande flödet. Vidare spelar termobariska effekter på den omgivande skiktningen en viktig roll för att föranleda polynyan under 2016. Dessutom påvisar den numeriska simuleringen att 2016 års polynya skapade förutsättningar för att en polynya skulle uppstå i området igen 2017. Den senare möjliggjordes genom transport av vatten med relativt sett förhöjd salthalt från Taylorkolumnen till halon. Sammanfattningsvis påvisar denna avhandling de mekanismer som spelar in i de senaste polynyahändelserna vid Maud Rise, samt demonstrerar vikten av att förbättra de hittills tillgängliga konvektionsparameteriseringarna i havsmodeller för att förbättra representationen av djupgående konvektion och polynyor.

Zusammenfasung

Das Weddellmeer ist eine Region, in der sich Polynyas häufiger formen. Polynyas sind küstenferne Öffnungen im Meereis, die häufig von Tiefenkonvektion begleitet werden. Diese Tiefenkonvektion ermöglicht die Homogenisierung der Wassersäule sowie den Austausch von Wärme und Gasen zwischen den Tiefen des Ozeans und der Atmosphäre. In den 1970er wurden im Weddellmeer große Polynyas entdeckt, sogenannte Weddellmeer Polynyas. Jedoch wurden diese seitdem nicht mehr beobachtet, was Fragen bezüglich ihrer Häufigkeit und Klimarelevanz aufwirft. Stattdessen sind kürzere und kleinere Polynyas in der Nähe von Maud Rise, einem Seeberg im östlichen Weddellmeer, beobachtet worden, zuletzt in 2016 und 2017. Maud Rise besitzt zwei hydrographische Merkmale, die durch die Ozeanströmung des Weddellwirbels ermöglicht werden: eine Warmwasserhalo und eine Taylor Cap. Die Warmwasserhalo umringt Maud Rise während die Taylor Cap auf dem Seeberg sitzt. Unser Wissen über die Prozesse und Dynamik in der Region von Maud Rise basiert jedoch auf nur wenigen Beobachtungen. Daher wurden viele verschiedene Prozesse für die Entstehung der Maud Rise Polynya vorgeschlagen, allerdings bleibt die Darstellung bis heute ein schwieriges Unterfangen für unsere Ozeanmodelle. Diese Arbeit plant die Mechanismen für die Entstehung der Polynya von 2016 und 2017 zu untersuchen und präsentiert einen Modellierungsansatz für eine realistische Darstellung dieser Ereignisse.

In dieser Dissertation werden öffentlich zugängliche Beobachtungen, neue Beobachtungen des SO-CHIC Projektes aus 2022, sowie zwei Reanalysen und zwei neue regionale Modell-Konfigurationen verwendet. Diese Thesis zeigt eine große Variabilität der Warmwasserhalo und Taylor Cap zwischen den Jahren, mit Zeiträumen, in welchen die Taylor Cap nahezu verschwindet. Dieses Ereignis trat besonders in den Jahren vor der Öffnung der Polynya auf und wird durch die Veränderung der Wassermassen im Weddellwirbel kontrolliert. Die Wechselwirkung zwischen Maud Rise und dem Weddellwirbel erhöht die Wahrscheinlichkeit, dass sich Polynyas öffnen, indem Anomalien in der Schichtung der Wassermassen erzeugt werden. Diese Anomalien sind an die Taylor Cap und die Stärke der auftreffenden Strömung gekoppelt. Außerdem spielen vertikale Instabilitäten in der Wassersäule eine wichtige Rolle für die Entstehung der Polynya in 2016. Darüber hinaus haben die numerischen Simulationen gezeigt, dass die Polynya von 2016 die Region für die Öffnung der Polynya in 2017 vorbereitet hat. Die Polynya von 2017 wurde dadurch ausgelöst, dass salzigeres in der oberen Wasserschicht von der Taylor Cap in die Warmwasserhalo transportiert wurde. Zusammenfassend liefert diese Thesis einen Überblick der komplexen Prozesse, die bei den jüngsten Polynya-Ereignissen am Maud Rise im Spiel waren und hebt die Rolle des Ozeans hervor. Weiter wird gezeigt, wie wichtig es ist, aktuelle numerische Darstellungen von Tiefenkonvektion zu verbessern, damit Tiefenkonvektion und Polynyas in Ozean Modellen besser dargestellt werden können.

Acknowledgements

Some say doing a PhD is a marathon. I personally would say it's an open-water swim. One starts at the known beach and starts swimming to another beach, where just the rough direction is known. On this swim, the weather conditions and currents are unknown. Some would say this is a crazy idea with poor preparation, but still, people undertake this adventure.

I am happy I took this adventure, but at the same time, I am thankful that I wasn't alone on the swim. Thank you, **Fabien**, for your guidance, for teaching me how to pass bad weather and strong currents, and for pushing my confidence. Also sometimes reminding me to focus on the wave ahead of me and not the one on the horizon.

Thank you, **Alberto** and **David**, for discussing my science and welcoming me to Southampton and Reading. These moments felt like swimming with the current.

Part of my open-water swim was accompanied by NEMO. Thank you, **Clément** and **Gurvan**, for giving advice and hints on how to handle NEMO and creating a running configuration. **Romain** and **Hervé** thanks for collaborating during parts of the thesis.

Thank you, **Hamish**, for helping me compile NEMO and MITgcm on the Swedish infrastructure. **Göran**, thank you for guiding me through the formalities of the PhD.

Such an open-water swim would not be the same without fellow swimmers. Thanks to the people at GU: **Adele, Alex, Doris, Estel (and Fuet), James, Johan, Johan, Linnea, Mauro, Milad, Nicolai, Rickard, Salar, Simon Solange, Stina, Theo, Tristan, Vincent, Yvonne** for having lunches, fikas, nights out, or even weekend trips. **Romain**, thank you for teaching me python, having dinners and board games at your place, or reading any first drafts. This community made stormy days calmer.

Being a PhD student in an European research project was an amazing experience. Thanks to everyone in **SO-CHIC** for creating a nice environment to learn and grow. Especially the ECR group with SO-CHIC: **Malin, Holly, Aditya, Margaret**. I learned a lot from you, and thanks for always having good words and making my visits to Kiel, Southampton, and Reading special. I am glad we had our small informal polynya group with **Martin** and **Lu**. These meetings brought up plenty of ideas regarding the polynya its aspects from all angles.

Thank you, **Göteborg Sim Masters**, for actually swimming with me either in pools around Göteborg (and beyond) or even any lake close by. Especially

Anaëlle, Emma and **Melanie** for the activities outside the pool, taking my mind from work. **Sani**, thank you for being such a nice flatmate and always offering hikes, meals, and coffee.
Thank you, **Andrea, Aditya, Kevin, Malin, Margaret, Romain** and **Stina**, for commenting, proofreading, or translating the abstract of this thesis. Helping me to swim through the last waves on the journey while the final beach of the PhD journey is in sight. **Martin** and **Laura**, you have done an amazing job on the cover design. I love it.

Thanks to my long-distance friends in Germany, **Merle, Doro**, and **Saskia**, your visits were a great opportunity to discover many new places while showing you around. Thanks to the friends from the previous swim in the university world, **my Uni Hamburg geeks**, for the online game nights and support along all our PhD journeys. **Patrick**, thanks for saving me every time my computer and me had a disagreement.
Arne, thanks for being the big brother and picking me up sometimes. A big whole-hearted thank you to **my parents**; you have always been there and cheering along this adventure and giving me confidence that I can do this. Your support in the years of this PhD and providing me motivation were invaluable.

Birte Gülk
Göteborg, April 2024

Funding Statement

This thesis was supported by the University of Gothenburg and SO-CHIC (European Union's Horizon 2020 research and innovation programme, grant No. 821001). Further, research visits, conferences and summer schools were supported by travel grants from Donation Board Scholarships and the Adlerbert scholarships at the University of Gothenburg.

Preface

This thesis is based on four scientific papers referred to in the text by their roman numerals, as listed below.

List of papers

This thesis is based on the following articles:

I Gülk, B., Roquet, F., Naveira Garabato, A. C., Narayanan, A., Rousset, C., & Madec, G. (2023). Variability and Remote Controls of the Warm-Water Halo and Taylor Cap at Maud Rise. *Journal of Geophysical Research: Oceans*, e2022JC019517

II Gülk, B., Roquet, F., Naveira Garabato, A. C., Bourdallé-Badie, R., Madec, G., & Giordani, H. (2024b). Impacts of Vertical Convective Mixing schemes and Freshwater Forcing on the 2016-2017 Maud Rise polynya openings in a regional ocean simulation. *Accepted for publication in Journal of Advances in Modeling Earth Systems (JAMES)*

III Narayanan, A., Roquet, F., Gille, S. T., Gülk, B., Mazloff, M. R., Silvano, A., & Naveira Garabato, A. C. (2024b). Ekman-Driven Salt Transport as a Key Mechanism for Open-Ocean Polynya Formation at Maud Rise. *Accepted for publication in Science Advances*

IV Gülk, B., Roquet, F., Ferreira, D., & Naveira Garabato, A. C. (2024a). On the role of barotropic and baroclinic flows in forming a Taylor Cap at Maud Rise, Weddell Sea. *In preparation for Journal of Physical Oceanography*

Birte Gülk's contribution

In *Paper I*, I set up the regional configuration with the help of Clément Rousset, Fabien Roquet, and Gurvan Madec. I ran the experiments, conducted the investigation, and wrote the manuscript. I performed the required revisions, with contributions from all co-authors.
In *Paper II*, I implemented the code modifications with the help of Fabien Roquet. I ran all simulations, conducted the analysis, wrote the manuscript, and made revisions as suggested by the co–authors and reviewers.

In *Paper III*, I helped analyze the data and contributed to the discussion of the results, as well as reviewing and editing the draft.
In *Paper IV*, I set up the idealized configuration with the help of David Ferreira. I ran the experiments, conducted the investigation, and wrote the draft.

Other publications not included in this thesis:

1. Sallée, JB and SO-CHIC consortium (including Gülk, B). (2023). Southern Ocean Carbon and Heat Impact on Climate. *Philosophical Transactions of the Royal Society A*. https://doi.org/10.1098/rsta.2022.0056

2. Zhou, L., Ayres, H., Gülk, B., Narayanan, A., de Lavergne, C., Ödalen, M., Silvano, A., Lindeman, M., & Wang, X. (2024). A review of Weddell Sea Polynya formation, cessation and climatic impacts. *In preparation for The Cryosphere*

3. Narayanan, A., Roquet, F., Dragomir, O., Gille, S. T., Gülk, B., Lindeman, M., Mazloff, M. R., Silvano, A., & Naveira Garabato, A. C. (2024a). Eastern Weddell Gyre Variability Impacts Maud Rise Stratification. *In preparation for Geophysical Research Letters*

1 | *Introduction*

In the austral winters of 1974 to 1976, large open water areas were observed in the sea-ice covered Weddell Sea in the Southern Ocean, the Weddell Sea polynya (WSP) (Figure 1.1 a-c; Zwally & Gloersen, 1977). Direct observations of the sea-ice cover had just become available with the advance of satellite telemetry. The event captured the imagination of climate scientists at the time, due to the potential for deep convection within a large polynya to contribute to the formation of bottom waters that circulate through the global oceans (Gordon, 1978). However, the processes driving the polynya's formation and its effects on the ocean and climate have remained a mystery as no similarly widespread WSP has been observed since then.

Instead, smaller and short-lived polynyas have occurred irregularly at Maud Rise, a small seamount in the eastern Weddell Sea. These polynyas are referred to as Maud Rise polynyas (MRPs) (Comiso & Gordon, 1987). A MRP can have a size of $\sim 50 \cdot 10^3\,\mathrm{km}^2$ (Cheon & Gordon, 2019), which is small compared to the WSP in the 1970's with $200 - 300 \cdot 10^3\,\mathrm{km}^2$ (Carsey, 1980), but they can grow into a WSP (Kurtakoti et al., 2018). The most recent MRPs were observed in 2016 and 2017 (Figure 1.1d and 1.3).

Even though MRPs are small and irregular, they are part of complex ocean circulation and have impact on atmospheric, biological and oceanic processes on a local and global scale. Yet, the formation mechanisms of the 2016 and 2017 MRPs events are not known with certainty; hypotheses are based on a scarce number of observations and models with unrealistic polynya properties. This thesis delves into the proposed mechanisms involved in forming and sustaining the most recent MRPs and challenges current model approaches to improve the representation of these polynyas and the related deep convection in ocean models.

1.1 Polynyas and deep water formation

Two types of polynyas can occur in ice-covered oceans: coastal and open-ocean polynyas. These types are differentiated by their location and formation process (Figure 1.2). Coastal polynyas appear close to the coast and are mechanically

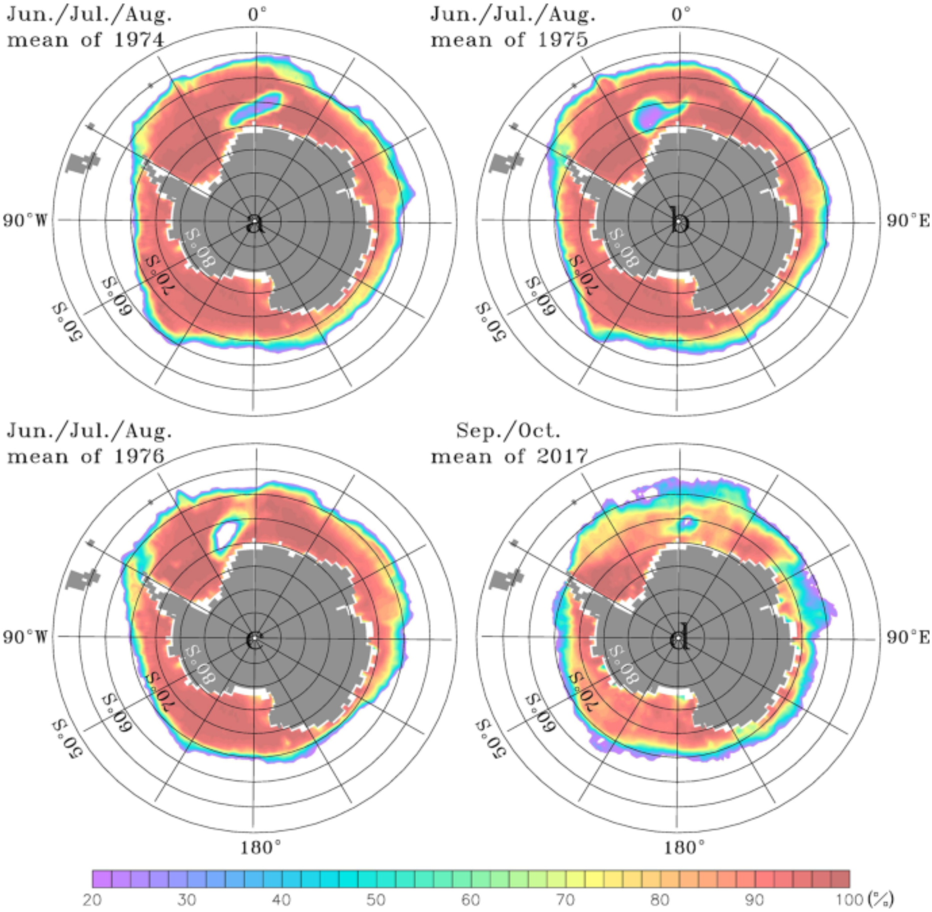

Figure 1.1: a-c) The sea-ice concentration showing the Weddell Sea polynya in 1974-1976 and d) during the 2017 Maud Rise polynya. Figure from Cheon and Gordon (2019).

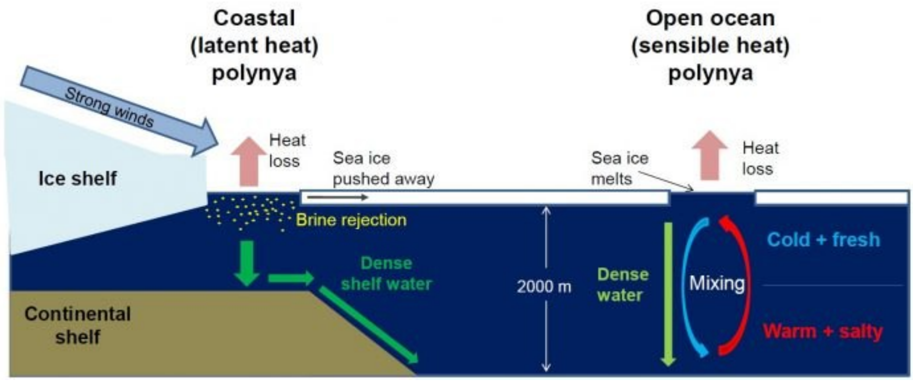

Figure 1.2: Schematic showing the different polynya types (Credit: Céline Heuzé)

forced by winds or oceanic currents (Morales Maqueda et al., 2004). They are known for high sea-ice production, as the freshly formed sea ice is exported by winds and the sea-ice cover is not able to close. During the freezing process of sea ice, the sea water rejects salinity to the upper ocean (brine rejection) and leads to a highly saline, dense water mass over the continental shelf, which can move down the continental slope and form deep waters.

Open-ocean polynyas occur offshore and are mainly thermodynamically forced by oceanic processes from below the sea ice (Morales Maqueda et al., 2004). First, warmer, saline subsurface waters must be brought to the surface, melting the sea ice. When the polynya is open, the upwelled ocean heat is released to the cold atmosphere, and the upper ocean gets cooler and denser. This leads to the formation of a heavy water mass, which sinks through the water column. This vertical motion is called deep convection.

In the Southern Ocean, many coastal polynyas open annually, and the deep water mass formed within them is Antarctic Bottom Water (AABW). AABW is the coldest, densest and most voluminous water mass in the global ocean and can be found at depth in all ocean basins, except the Arctic and North Atlantic Ocean (Johnson, 2008). Currently, the formation of deep waters in the Southern Ocean dampens climate change by taking up large amounts of anthropogenic carbon dioxide (CO_2) and excess heat (Sabine et al., 2004; Frölicher et al., 2015; Rintoul, 2018). Though open-ocean polynyas occur less frequently, the deep convection that can occur during these events can release sequestered heat and CO_2 to the atmosphere, and represents a potential alternative pathway for AABW formation. However, AABW formation through deep convection is expected to decline with future climate change (De Lavergne et al., 2014). Thus it is important to understand the dynamics that lead to open-ocean polynya formation in the Weddell Sea.

1.2 The Weddell Gyre, a key region for forming deep waters and polynyas at Maud Rise

The Weddell Sea is a region where coastal and open-ocean polynyas occur and the related deep waters are formed. The polynyas in the Weddell Sea form a portion of the total AABW formed in the Southern Ocean. The main source of the AABW is Circumpolar Deep Water (CDW), a warm and saline water mass. The CDW is provided by the Weddell Gyre, a wind-driven large-scale circulation within the Weddell Sea. The Weddell Gyre is bounded in the south and west by the Antarctic continent, while the northern and eastern boundaries are open (Figure 1.3; Schröder & Fahrbach, 1999; Reeve et al., 2019). At the open boundaries CDW enters the Weddell Gyre. The CDW originates from water mass exchange with the Antarctic Circumpolar Current (ACC) and is locally referred to as Warm Deep Water (WDW). Similar to the source water, WDW is a warm and saline water mass (Reeve et al., 2019; Ryan et al., 2016) with a high carbon concentration (Bernardello et al., 2014). While the WDW is conveyed through the Weddell Gyre, the southern limb splits into an inner limb and an outer limb. The outer limb flows along the ice shelves of the Weddell Sea and mixes with the highly saline and oxygen-rich shelf waters formed in coastal polynyas (Vernet et al., 2019). During this transformation process the dense AABW is formed (Jullion et al., 2014). The inner limb of the Weddell Gyre passes by a seamount called Maud Rise, this region is known for the occurrence of open-ocean polynyas and AABW formation (Gordon, 1982).

Maud Rise is located at 2.5° E and 65° S (Figure 1.3, yellow star) and rises from 5 000 m to 1 800 m. The local structure of stratification makes Maud Rise sensitive to polynyas. A Taylor Cap, an almost stagnant water cylinder, sits above Maud Rise. The Taylor Cap originates from the interaction of the Weddell Gyre flow with Maud Rise. When the Weddell Gyre impinges on Maud Rise, two jets are formed, one on the northern flank and one on the southern flank (Leach et al., 2011, Figure 1.4). The northern jet has a stronger transport (14 Sv, $1\,\mathrm{Sv} = 10^6\,\mathrm{m^3\,s^{-1}}$) than the southern one (4 Sv; Schröder & Fahrbach, 1999). The bifurcating flow pattern at Maud Rise leads to the formation of the Taylor Cap. Between the westward northern jet (Figure 1.4, violet arrow) and the Taylor Cap, an eastward return current (green arrow) is found (Cisewski et al., 2011). Hydrographic observations have proven the existence of a Taylor Cap at Maud Rise, with a mixed layer depth (MLD) $>$ 100 m and subsurface maximum temperatures of around 0.4 °C, while the northern jet has a MLD $<$ 100 m and a maximum subsurface temperature exceeding 1.0 °C (Gordon & Huber, 1990; Muench et al., 2001; De Steur et al., 2007). Further, it was observed that the Taylor Cap is more weakly stratified than in the surrounding regions (Shaw & Stanton, 2014). Commonly, the northern jet is referred to as the warm-water Halo. Between the Halo and the Taylor Cap, lateral and vertical mixing has been detected, affecting the density properties at depth (Mohrmann et al., 2022). The warm-water Halo leads to a reduction of sea-ice concentration (SIC) above Maud Rise due to its heat fluxes, but it

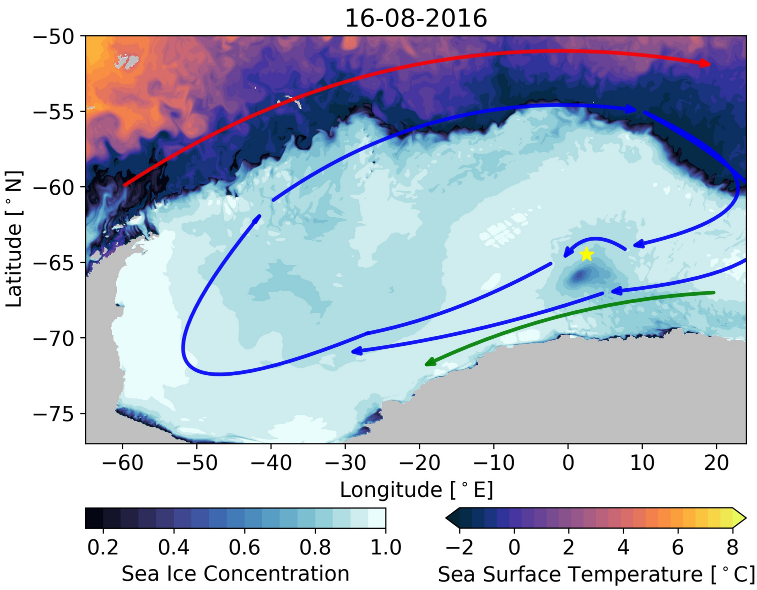

Figure 1.3: Sea-ice concentration and sea-surface temperature in the Weddell Sea on 16 August 2016 from GLORYS12 with the schematized flow in the region: the Weddell Gyre (blue), the Antarctic Circumpolar Current (red), and the Antarctic Slope Current (green). The star indicates Maud Rise.

does not open the polynya (Lindsay et al., 2008).

Observed polynyas at Maud Rise have an impact on a local scale and global scale. Locally, increased annual net productivity of phytoplankton (von Berg et al., 2020) and increased precipitation with the onset of the event (Weijer et al., 2017; Kurtakoti et al., 2018) was observed. On a global scale, the contribution to deep water formation can affect ocean circulation. The duration of the opening determines the depth and amount of water ventilated. The large WSPs in the 1970's led to vertical mixing in the upper 2 700 m (Gordon, 1982); the smaller MRPs homogenized the upper 500 to 800 m in 2016 (Campbell et al., 2019) and the upper 1 000 m in 2017 (Cheon & Gordon, 2019).

1.3 Potential Maud Rise polynya processes

The processes leading to the formation of open-ocean polynyas at Maud Rise are not fully understood yet. Limitations arise from the scarcity of ocean observations and models that are able to reproduce the polynya. Therefore, various theories entailing atmospheric, oceanic, and coupled processes have been put forward as triggering mechanisms. This section summarizes the previously proposed mechanisms.

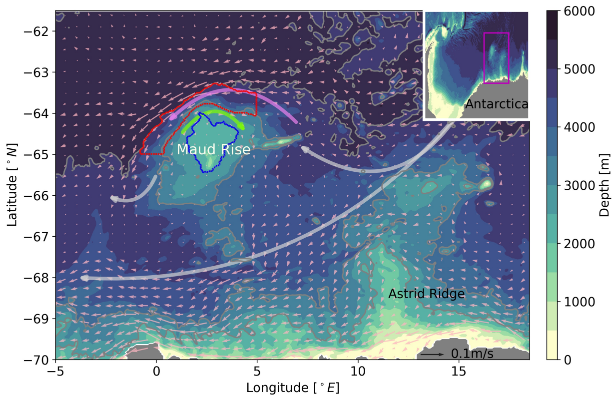

Figure 1.4: Topography of Maud Rise with schematized flow (gray and purple arrows) and depth-averaged mean flow from GLORYS12 for the period 2007-2017 (pink arrows). The inlay shows the Weddell Sea and the zoomed-in area (purple box). Red (blue) encircled areas indicate the locations of the warm-water Halo (Taylor Cap). Figure modified from Gülk et al. (2023).

Atmospheric processes that can play an important role in the formation of the MRP are atmospheric rivers (Francis et al., 2020) and polar cyclones (Francis et al., 2019). Atmospheric rivers are narrow corridors in the atmosphere that carry water vapor over long distances, e.g. from the tropics to Antarctica. They can lead to a melt of sea ice due to insulation by snow. Polar cyclones are low-pressure systems with a clockwise rotating wind (in the Southern Hemisphere) that work mechanically on the sea ice and cause sea-ice divergence.

Other studies have proposed coupled atmospheric-ocean processes, for example by Jena et al. (2019) and Campbell et al. (2019). Jena et al. (2019) identified an anomalous atmospheric warming combined with upward transport of warm water from depth to the surface due to a large oceanic eddy and a negative wind stress curl as possible mechanisms. Negative wind stress curl played a role in the formation hypothesis of Campbell et al. (2019) as well. They propose that the negative wind stress curl is associated with an increased length of winter storms and a concurrent increase in mixed layer salinity, triggering the polynya. To trigger a polynya, the water column needs to overturn and bring the subsurface heat reservoir to the surface, and melt the ice above. To overturn the water column, the density difference between the mixed layer and subsurface needs to be eroded. This density difference, expressed in terms of salinity, is referred to as the salt deficit (Martinson, 1990; Martinson & Iannuzzi, 1998; Wilson et al., 2019). The salt deficit can also be reduced by the advection of a surface salinity anomaly into the region of the polynya opening.

Kurtakoti et al. (2018) found such an anomaly originating from Astrid Ridge, to the southeast of Maud Rise (Figure 1.4), before a polynya opening. Water column stability can also be reduced by other processes, such as an intensified Weddell Gyre due to strengthened Southern Hemisphere westerlies, leading to stronger eddy activity at the southwestern flank of Maud Rise, enhancing the upwelling of WDW leading to a melting of the sea-ice cover (Cheon & Gordon, 2019). Eddies shed at the flank of Maud Rise are crucial in the theory of Holland (2001). Here, the eddies are shed on the northeastern flank, and they transmit divergent Ekman stresses to the sea ice. These Ekman stresses lead to an opening of the sea ice.

The structure of the water column at Maud Rise, with a cold and fresh surface layer and a warm and saline subsurface layer of WDW is susceptible to vertical mixing processes. One of those proposed vertical mixing processes is thermobaricity (Akitomo, 2006; McPhee, 2000). Thermobaricity arises from the fact that the compressibility of the water column is dependent on the temperature: e.g., if two parcels of the same density but different temperatures and salinities are brought to deeper depth, each parcel changes its density, and one can become lighter than the other. This could result in an unstable stratification where the lighter one lies below the heavier one. The water column aims for stable stratification and reorders these water parcels, which implies changes in density due to pressure changes again. This process continues until a stable stratification is reached. This process can propagate through the whole water column and trigger deep convection. Another vertical mixing process proposed to trigger deep convection and the opening of a polynya is thermobaric cabbeling (Harcourt, 2005). Thermobaric cabbeling combines thermobaricity and cabbeling. Cabbeling describes that if two water particles of the same density but different temperature and salinity properties are mixed, the new density is greater than the original density.

Another way to trigger deep convection is related to the Taylor Cap at Maud Rise. It was shown that if the Taylor Cap penetrates into the MLD, deep convection can occur (Alverson & Owens, 1996; Kurtakoti et al., 2018). Taylor Caps are based on the theory of Taylor Columns. Taylor Columns result from a barotropic (depth independent), frictionless, and steady flow that impinges on a topographic obstacle. The Taylor-Proudman theorem describes that a fluid in such a system has no vertical shear, and therefore fluid parcels cannot leave their horizontal plane. This implies that no flow occurs across the obstacle and the fluid parcels are forced to go around the obstacle due to squeezing (stretching) upstream (downstream) of the water column in the proximity of the topographic obstacle (Taylor, 1923; Proudman, 1916). As a result, a stagnant cylinder forms on top of the obstacle, the Taylor Column. In a stratified fluid, the topographic constraints of the obstacle are reduced with vertical distance to the obstacle; in this case, the phenomenon is referred to as Taylor Cap (Chapman & Haidvogel, 1992).

1.4 Representation of polynyas in ocean and climate models

Reproducing open-ocean polynyas in the Southern Ocean in models is limited by various factors and sensitive to choices in forcing and parameters. Mohrmann et al. (2021) analyzed the Earth System Models (ESMs) included in CMIP6 and showed that some models do not produce an open-ocean polynya at all, while others produce them too frequently. Further, the spatial extent can be overestimated. Some of the ESMs that produce a MRP/WSP have been used to study processes and provide hypotheses about the formation process (Kurtakoti et al., 2018; Rheinlænder et al., 2021). Another modeling approach is running an ocean general circulation model (OGCM) with a forced atmosphere. Sometimes these configurations are regionally confined and forced by oceanic data from global models, reanalysis products, or climatologies at the boundaries. Using this approach, a global OGCM by Cheon et al. (2015) replicated the WSP with similar spatial extent and location as the observed WSP in the 1970's, but models generating MRPs with reasonable size, location, and timing remain a challenge. So far, MRPs have been reproduced in OGCMs with data assimilation such as GLORYS12 (Lellouche et al., 2021) and Southern Ocean State Estimate (SOSE) (Mazloff et al., 2010).

Causes for the problematic reproduction of the polynya arise from the sensitivity of models to freshwater forcing and choices regarding vertical mixing. In the weakly stratified Southern Ocean, excessive freshwater in the upper layer can prohibit any vertical exchange with deeper layers, while insufficient freshwater amplifies deep convection, often producing unrealistically frequent polynyas (Stoessel et al., 2015; Kjellsson et al., 2015). Single vertical mixing parameter modifications, such as background vertical diffusivity or viscosity, can also affect the reproduction of polynyas and deep convection (Kjellsson et al., 2015; Heuzé et al., 2015). Further, the stratification in the Weddell Sea depends on the effect of restratification by transient eddies and the dense water overflow off the continental shelf (Dufour et al., 2017) and locally at Maud Rise on the model's ability to form the Taylor Cap. Therefore, a certain horizontal resolution is necessary to represent the steepness of the slopes at Maud Rise correctly and induce the formation of a Taylor Cap (Kurtakoti et al., 2018).

1.5 This thesis

We have seen that MRPs are important for preconditioning the water column for WSPs and ventilating the deeper ocean. Even though they are of global importance, the science community lacks continuous observations in the region of Maud Rise and models with good representation of those events. The Southern Ocean Carbon and Heat Impact on Climate (SO-CHIC) project aims to provide more observations and improved models of the Southern Ocean. This thesis is part of SO-CHIC and focuses on the dynamics and the polynya mechanisms at Maud Rise by addressing the following research questions:

- Which processes are important for the preconditioning and formation of the Maud Rise polynya in 2016 and 2017?

- What modifications can be made to ocean-sea ice models to improve the representation of Maud Rise polynyas?
- How does the Weddell Gyre shape the Maud Rise Taylor Cap properties?

In order to investigate these research questions, a combination of numerical simulations and observations are used, which are presented in Chapter 2. In Chapter 3, the papers answering the research aims of this thesis are summarized. Chapter 4 places the papers in perspective with each other and provides a discussion regarding the research questions. Further, Chapter 4 provides an outlook.

2 | *Data and Models*

2.1 Observations

Throughout the thesis and the papers, sea-ice and ocean observations are used. For sea-ice observations, satellite data from Advanced Microwave Scanning Radiometer for EOS (AMSR-E) and Advanced Microwave Scanning Radiometer 2 (AMSR2) with 6.25 km horizontal resolution (Spreen et al., 2008; Melsheimer & Spreen, 2019) is used.

For ocean observations, profiles compiled in the EN4.2.2 (Good et al., 2013) data base are combined with cruise data from the Maud Rise region. The EN4.2.2 profiles are regionally quality controlled and need to have a minimum depth exceeding 300 m, a minimum salinity $> 32\,\mathrm{g\,kg^{-1}}$ and a potential temperature $< 10^\circ$ C to be considered further; otherwise, the respective profile is excluded. The remaining profiles are vertically binned to 5 m intervals, and the MLD is defined by the density threshold $\Delta\sigma = 0.01\,\mathrm{kg\,m^{-3}}$ with respect to 10 m depth. This data set is complemented with measurements taken during the MaudNESS cruise (2005; De Steur et al., 2007) and the SO-CHIC cruise (2022; *Paper I* and Ward et al., 2022). The SO-CHIC cruise sampled the northern flank and a section connecting the eastern and western flank of Maud Rise extensively and provided 67 new CTD casts within two weeks in January 2022 (Ward et al., 2022). The ocean observations are used to provide a time specific state of the region (*Papers I* and *II*) as well as an estimation of the climatological state (*Paper II*).

2.2 GLORYS12

GLORYS12 is a global reanalysis provided by the Copernicus Marine Environment Monitoring Service (CMEMS) and is used in this thesis as boundary conditions for the regional configurations (Section 2.3) and in *Paper I* for comparing to the results of the configurations.

The ocean model employed in GLORYS12 is a global Nucleus for European Modelling of the Ocean (NEMO) configuration (Madec & NEMO System Team, 2019). GLORYS12 provides daily data from January 1st, 1993, onward on a 1/12° horizontal grid and 50 vertical levels. The time extent is updated yearly, and for this thesis, data from January 1st, 2007 until December 31st, 2019 is considered. The initial state for temperature and salinity is derived from the monthly gridded EN4.2.0 climatology (Good et al., 2013). The atmosphere is forced with state variables derived from ERA-Interim (Dee et al., 2011) until 2019 and ERA5 (Hersbach et al., 2023) afterwards. The model assimilates various observational sources, such as satellite and in situ observations. As satellite data along track altimeter data, satellite sea surface temperature (SST) and SIC and/or thickness are used. As in situ observations, the CORA database is integrated, which includes Argo floats, fixed moorings, gliders, drifters, Marine Mammals Exploring the Oceans Pole to Pole (MEOP) and ship-based observations (Szekely et al., 2019). More details on the assimilation can be found in Lellouche et al. (2021).

A validation on global scale has been conducted by Lellouche et al. (2021). Temperature, salinity, velocities, sea level anomaly, transports, and sea ice are compared to available observations, e.g., surface fields are compared to satellite data, temperature and salinity profiles against moorings, and to the World Ocean Atlas-13 (WOA13) (Boyer et al., 2013; Drévillon et al., 2021). In this validation, the major oceans are considered, but a comparison of regional seas has not been conducted. The Weddell Sea is considered within the Southern Ocean validation. But validation on a regional scale is necessary to help understand if ocean properties are represented correctly and to disentangle polynya-related and assimilated processes. Further, a regional validation is necessary for this thesis to asses the suitability of GLORYS12 as oceanic and ice boundary conditions for the regional NEMO configurations of Maud Rise (Section 2.3).

2.2.1 Validation

The validation of the Weddell Sea includes a comparison of vertical profiles of temperature and salinity, SIC and sea surface height (SSH). The temperature and salinity profiles provide information about the stratification of the water column, which is an important factor in polynya formation. The SIC provides information on the realism of the polynya. The SSH is expected to provide information about the quality of the dynamics in GLORYS12.

Temperature and Salinity

For temperature and salinity, EN4.2.2 profiles from Argo floats are chosen across the Weddell Sea (Figure 2.1, colored stars) and then compared to the closest data point from GLORYS12 (Figure 2.2). The locations are chosen across the Weddell Sea, either to focus on the region of Maud Rise (Figure 2.1, red/purple star) or to focus on the properties of the wider Weddell Gyre (Figure 2.1 orange/blue star).

The profiles in the Weddell Gyre (Figure 2.2 orange/blue lines) show a good agreement in temperature between GLORYS12 and EN4, while salinity devi-

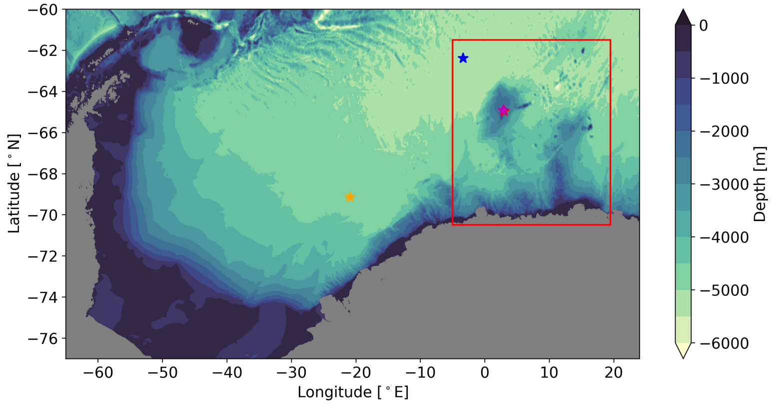

Figure 2.1: Bathymetry of the Weddell Sea, the grey area represents the Antarctic continent. The stars indicate the positions for the vertical profiles used in the temperature and salinity comparison. The red box indicates the horizontal boundaries of Maud12 and Maud36.

ates in the upper ocean. This deviation likely occurs from the profiling of the Argo and the ice cover during the sampling period (August and November 2016). For one, the location of the Argo float is interpolated between the last and first surfacings during ice cover. Further, Argo floats do not sample up to the surface when sea ice is present and remain below 100 m depth. The profiles above Maud Rise (Figure 2.2 red/magenta lines) were taken by the same float in consecutive dives in May 2016, where no sea ice was observed. While the temperature and salinity profiles for both times in general agree, GLORYS12 shows a nonphysical gradient around 250 m. The close similarity between EN4 and GLORYS12 is a result of the fact that GLORYS12 assimilates the EN4 data.

In the period of 2018, the EN4.2.2 data set shows data with higher salinities at 455 m depth than measured in years before and after (Figure 2.3a-c). The measurements originate from the same platforms as the tracks in Figure 2.3(a-c) indicate. Therefore, it likely stems from an offset or drift in the sensors. Due to the assimilation of EN4 in GLORYS12, a signature can be found in GLORYS12, leading to higher salinities in the region of Maud Rise in 2018 (Figure 2.3e). Therefore, the period from 2018 onward is excluded in this thesis.

Sea Ice Concentration

For the comparison of SIC, GLORYS12 is compared to the SIC from AMSR-E and AMSR2 with 6.25 km horizontal resolution (Spreen et al., 2008; Melsheimer & Spreen, 2019) in 2016 and 2017 (Figure 2.4). The opening of the polynya was observed by the satellites in early August 2016. At this time, GLORYS12 shows

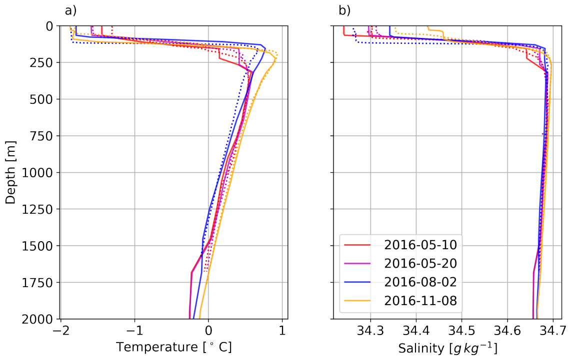

Figure 2.2: Vertical profiles of a) potential temperature and b) salinity at different locations and times from GLORYS12 (solid) and EN4.2.2 (dotted). The color of the profiles refers to the location in Figure 2.1.

only a reduction of SIC at the polynya location. The observed polynya has a lifetime of a couple of days; during this time, the reduced SIC in GLORYS12 evolves into a polynya (Figures 2.4 and 1.3). In 2017, the polynya signal in GLORYS12 was stronger and compared to the satellite observations. Both products show a polynya; GLORYS12 reproduces the location well and shows a small time delay for the initial opening in 2016. This indicates that the satellite data is well assimilated. However, the influence of the data assimilation versus model processes cannot be determined.

Sea Surface Height

For the comparison of SSH, GLORYS12 is compared to a merged satellite product using data from Envisat and Cryosat-2 with reference to the EGM2008 geoid (Dragomir, 2023). The satellite product provides monthly data from July 2002 to October 2018 on a 0.5° latitude x 1° longitude grid. The observational data is used to produce a climatology for the months February and September, which is then compared to the climatology of GLORYS12 (Figure 2.5).

The large-scale patterns of the climatologies represent the Weddell Gyre circulation, and they are mostly consistent; deviations appear close to the coastline. The satellite estimates show in particular a maximum SSH along the continental shelf between 10°W and 10°E which is not reproduced in the model. The origin of this feature remains unclear, as does the uncertainty associated with the satellite product in this near coastal region. Furthermore, the GLORYS12 data shows a hook-shaped feature around Maud Rise (Figure 2.5, solid contour), which cannot be resolved in the satellite data due to the coarser grid resolution.

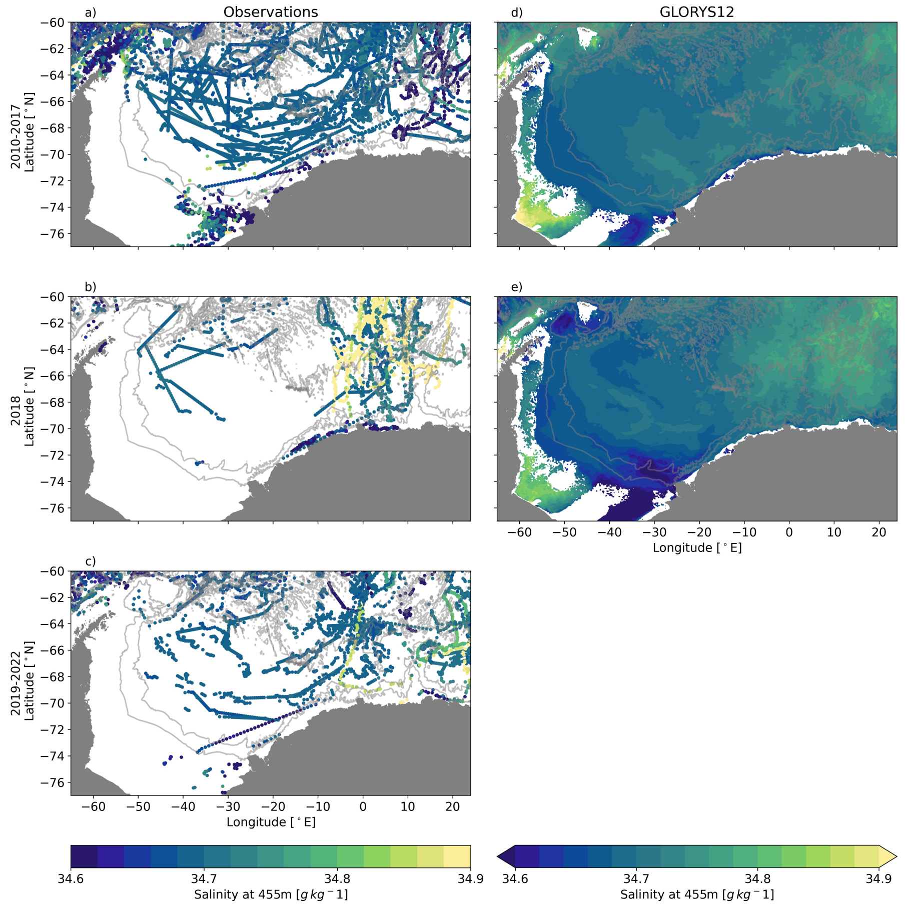

Figure 2.3: a-c) Salinity at 455 m depth of EN4.2.2 profiles for different years as indicated on the left. d-e) Maximum salinity at 454 m depth in GLORYS12. Grey lines indicate bathymetry levels of 2 500, 3 500, and 5 000 meters.

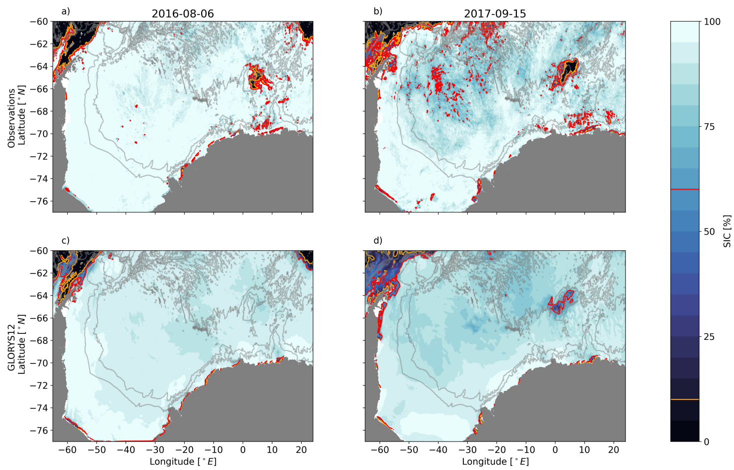

Figure 2.4: SIC in the Weddell Sea from satellite data (upper row) and GLORYS12 (lower row) for snapshots in August 2016 (left) and September 2017 (right). Grey lines indicate bathymetry levels of 2 500, 3 500, and 5 000 meters. The orange (red) lines indicate the 10% (60%) SIC contour.

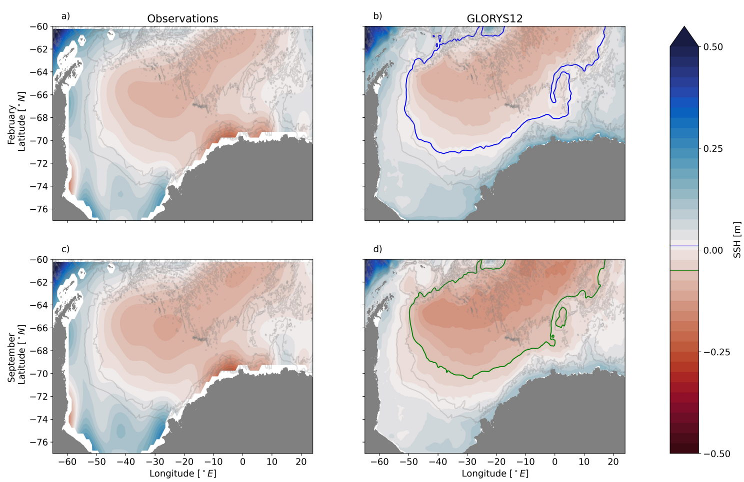

Figure 2.5: Climatology of SSH in the Weddell Sea for the satellite product (left) and GLORYS12 (right) in February (upper row) and September (lower row). Colored contour lines highlight the hook-shaped feature around Maud Rise. Grey lines indicate bathymetry levels of 2 500, 3 500, and 5 000 meters.

2.2.2 Summary

In the above-presented validation, a good agreement of in situ profiles, SIC and SSH between GLORYS12 and observations is found. GLORYS12 provides a good representation of the ocean and sea ice in high resolution. Limitations occur from 2018 onward due to the assimilation of too high salinities from different data sources, which pollutes the model output. Further, uncertainties occur regarding the polynya, e.g., how much of the signal is assimilated and how much is produced by the model itself. Besides these limitations, GLORYS12 agrees with the observations on various timescales, e.g., from daily to decadal temporal scales. An advantage of GLORYS12 is that it resolves the finer-scale features around Maud Rise, which are not present in products with a lower resolution, e.g., the used SSH product. Overall, GLORYS12 is a suitable data set for providing oceanic and ice boundary conditions for a regional configuration in the period before 2018.

2.3 Maud12 and Maud36

This section presents the regional NEMO configurations used in *Papers I* and *II*. The regional configurations are used to study polynya-related processes. Therefore, the domain of the configuration is limited to Maud Rise and covers the region from 5° W to 19.5° E and 61.5° S to 70.5° S (Figure 2.1, red box). The configuration uses the ocean and ice components of NEMO (Madec & NEMO System Team, 2019; NEMO Sea Ice Working Group, 2018) and has 50 vertical levels, with a finer vertical resolution in the upper ocean and a coarser one in the deep ocean. Further, two different horizontal resolutions are used. The low-resolution set-up uses 1/12°, Maud12, and the high-resolution set-up uses 1/36°, Maud36. This corresponds to a spatial resolution of 3.9 km and 1.3 km at 65° S, respectively. The boundary conditions for the topography are derived from GEBCO (GEBCO Compilation Group, 2022); for the atmosphere, they are derived from JRA55-do version 1.5 (Tsujino et al., 2018); and the lateral boundary forcing and initial state are taken from GLORYS12. The configurations provide daily output from January 1st, 2007 onward; results after 2017 are excluded, as GLORYS12 was found to be unreliable (Section 2.2).

2.4 SOSE

In *Paper III*, the results from SOSE iteration 135 (Mazloff et al., 2010) are analyzed. SOSE is a Southern Ocean Massachusetts Institute of Technology General Circulation Model (MITgcm) configuration for the region 30° S to 79° S with an adjoint method to assimilate observations. SOSE has a 1/6° horizontal resolution and uses 52 vertical levels. SOSE iteration 135 provides data for the period 2013-2019. The initial state is derived from CTD measurements of Argo floats, tagged seals, and ships. These data sets are also used during

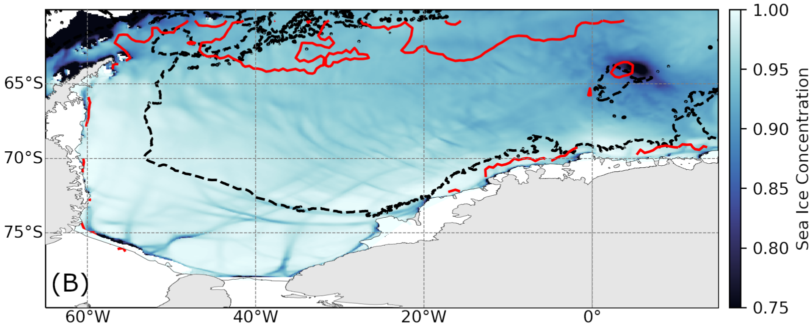

Figure 2.6: September mean SIC in SOSE in 2017. The red line is the September mean 75% SIC from satellite observations. The dashed black line indicates the 3 000 m isobath. Figure 1B from Narayanan et al. (2024b).

assimilation. Further, satellite data of sea level, SST, and sea surface salinity is assimilated. As atmospheric forcing, ERA5 is used. SOSE is known to conserve physical quantities and reproduce the polynya event in 2017 (Figure 2.6).

2.5 Idealized Taylor Cap configuration

In *Paper IV*, an idealized configuration with the MITgcm (Marshall et al., 1997) is set up to investigate the response of Taylor Caps to varied inflow conditions and stratification. The idealized configuration is set up on 60 x 40 x 100 grid points with a horizontal resolution of $\Delta x = \Delta y = 25\,\mathrm{km}$ and $\Delta z = 50\,\mathrm{m}$, leading to a domain size of 1 500 km x 1 000 km x 5 km. In the center of the domain, a Gaussian bump with slope and diameter resembling Maud Rise properties is placed (Figure 2.7). The maximum height of the bump is 2 000 m. The northern and southern boundaries are closed by a solid wall. At the eastern and western boundaries temperature and zonal velocities are prescribed.

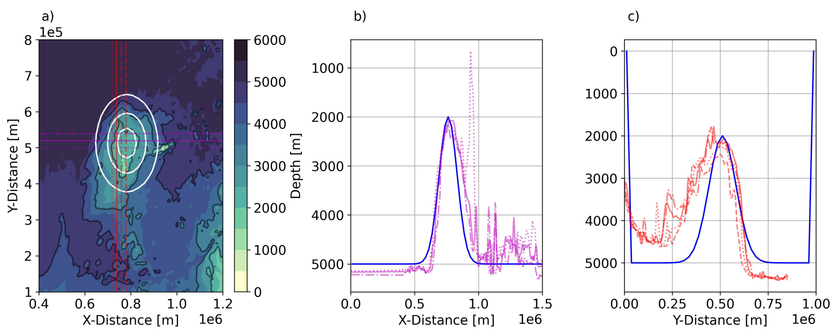

Figure 2.7: a) Comparison of Maud Rise bathymetry with 2 500, 3 500, and 4 500 m isobaths (grey lines) and the isobaths of the Gaussian bump (white circles). b,c) Cross section of the center of the Gaussian bump (blue) and of Maud Rise (magenta/ red) as indicated in a). Figure 1 from Gülk et al. (2024a).

3 | Summary of Papers

3.1 Paper I: Variability and Remote Controls of the Warm-Water Halo and Taylor Cap at Maud Rise

This study was published in *Journal of Geophysical Research: Oceans* in 2023 with coauthors Fabien Roquet, Alberto C. Naveira Garabato, Aditya Narayanan, Clément Rousset, and Gurvan Madec.

Motivation and aim

Several research cruises have proven the existence of a Taylor Cap and warm-water Halo around Maud Rise. These features were identified by the maximum temperature below the MLD and the MLD itself. The warm-water Halo has warmer maximum temperatures and shallower MLD along the northern and western flank of Maud Rise. Atop Maud Rise, colder temperatures and deeper MLD were found, the Taylor Cap (Gordon & Huber, 1990; Muench et al., 2001; De Steur et al., 2007). The subsurface water masses at Maud Rise provide the heat necessary to affect the sea-ice cover; in non-polynya years, a reduced SIC is found above Maud Rise (Lindsay et al., 2008). An enhanced upwelling of warm subsurface water can lead to the melting of the sea-ice cover (Cheon & Gordon, 2019). From the 1986, 1994, and 2005 cruise data, De Steur et al. (2007) estimated the variability on a decadal time scale. In this study, we investigated the interannual variability of the Halo and Taylor Cap by including more data sets. Further, we derived the remote controls of this variability. Understanding the variability on this time scale could indicate why the MRP occurs irregularly.

Methods

The study compiles EN4.2.2 profiles (Good et al., 2013) and the SO-CHIC cruise data encompassing the period January 2007-May 2022. We combine all available observations to determine the climatological state of the warm-water Halo and Taylor Cap by the maximum subsurface temperature (Figure 3.1). This climatological state is used to define the Taylor Cap and warm-water Halo by bathymetry. Using the geographic definitions, we estimate a time series of the maximum subsurface temperature for each of the regions from the observations and compare it to numerical data from GLORYS12 (Lellouche et al., 2021), Maud12, and Maud36 for the period January 2007-December 2017.

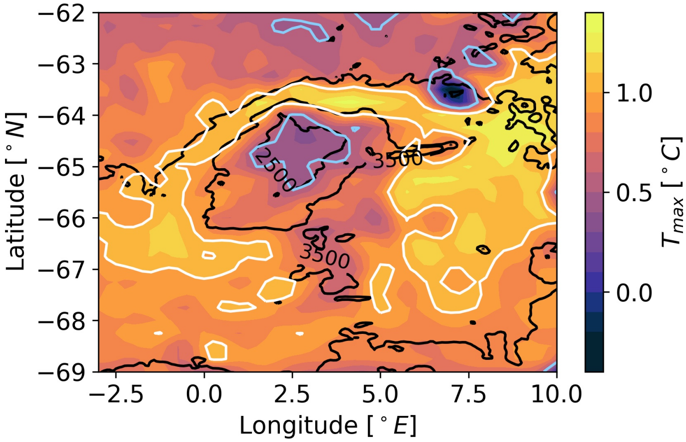

Figure 3.1: Interpolated subsurface temperature maximum of the observations acquired during the period 2007-2022 with the 2 500, 3 500, and 5 000 m isobaths (black lines) and 0.5° C (lightblue) and 1.0° C (white) isotherms. Figure 3 from Gülk et al. (2023).

Further, the controls of the variability are derived by calculating a heat budget for the Taylor Cap and tracking the subsurface density in the region. The heat budget is separated into lateral heat transport, vertical heat transport, and surface fluxes, as well as the eddy components of the lateral transport.

Summary of the results

The time series of the maximum subsurface temperature in the warm-water Halo showed that the numerical data sets are in the range of the observational data points (Figure 3.2). In the Taylor Cap, this agreement is found until 2016. Afterwards, the observations and GLORYS12 show a cooling, while the regional configurations, Maud12 and Maud36, remain warm. This deviation originates from the failure to reproduce the polynya in 2016 and 2017 in the regional configurations, which affects the subsurface temperatures. The time series further showed that the Taylor Cap has the tendency to warm within several years, and the highest subsurface temperatures were found in the years preceding the polynya opening in all models and observations. In 2014, the Taylor Cap was as warm as the Halo, leading to the vanishing of the temperature difference between the two regions. Further zonal sections from Maud36 showed flattened isopycnals and non-distinguishable temperature and salinity properties, indicating a near-vanishing of the Taylor Cap. The warming of the Taylor Cap was followed by an abrupt cooling during the opening of the polynya in 2016 and 2017. For the near-vanishing of the Taylor Cap to occur, two different processes played an important role, one acting on the Taylor Cap and the other acting on the Halo. The Taylor Cap was warming slowly and steadily, starting in 2011. The heat budget analysis showed that warmer waters were transported by eddies into the Taylor Cap. Further, the Halo ex-

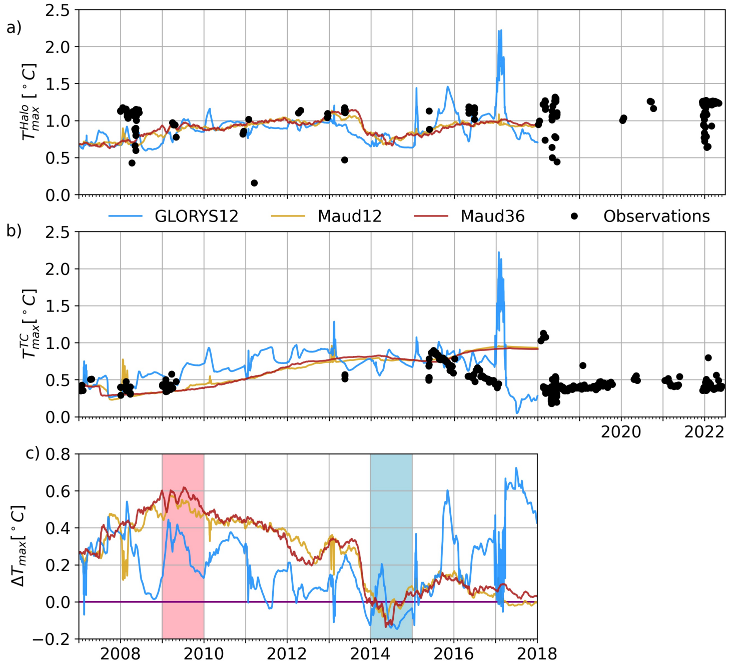

Figure 3.2: Maximum subsurface temperature for GLORYS12 (blue), Maud12 (yellow), Maud36 (red) and the observations (black dots) in (a) the Halo, and (b) the Taylor Cap. (c) Difference between the maximum subsurface temperature in the Halo and Taylor Cap in the models. The purple line is 0° *C. The year with the largest/smallest difference are shaded with red/blue. Figure 4 from Gülk et al. (2023).*

perienced the advection of anomalously cold and fresh deep waters originating from the Weddell Gyre, which was identified by the tracking of the subsurface density. Combining these processes leads to a warmer-than-usual Taylor Cap and a colder-than-usual warm-water Halo.

In conclusion, this study highlighted the variability of the Halo and Taylor Cap driven by the Weddell Gyre and local eddy transport and showed the warmest temperatures in the Taylor Cap before the polynya in 2016.

3.2 Paper II: Impacts of Vertical Convective Mixing schemes and Freshwater Forcing on the 2016-2017 Maud Rise polynya openings in a regional ocean simulation

This study is accepted for publication in *Journal of Advances in Modeling Earth Systems (JAMES)* with coauthors Fabien Roquet, Alberto C. Naveira Garabato, Romain Bourdallé-Badie, Gurvan Madec, and Hervé Giordani.

Motivation and aim

The representation of open-ocean polynyas is a challenge for OGCMs. Open-ocean polynyas have been produced by ESMs (Rheinlænder et al., 2021; Kurtakoti et al., 2018), but commonly these models either generate too frequent polynyas or none at all (Mohrmann et al., 2021). Further, the spatial and temporal scales are often overestimated. The larger WSP has been reproduced by Cheon et al. (2015) in an OGCM. The lack of realistic polynya representation in models arises from the problematic representation of deep convection. Reproducing deep convection in models is sensitive to freshwater forcing (Stoessel et al., 2015; Kjellsson et al., 2015) and choices regarding vertical mixing (Heuzé et al., 2015; Kjellsson et al., 2015). Besides technical choices, not all processes that could lead to a MRP are currently available in models, such as thermobaricity (Akitomo, 2006; McPhee, 2003). This study seeks to test the importance of freshwater forcing and vertical convective mixing schemes, including a scheme allowing for thermobaric effects, in the representation of the polynya openings in 2016 and 2017 and identify the processes triggering deep convection and the polynya.

Methods

In this study, we employ various simulations using Maud12. As part of the study, we test and modify different vertical convective mixing schemes: Enhanced Vertical Diffusion (EVD), Eddy-Diffusivity Mass-Flux (EDMF) (Giordani et al., 2020), and several modifications of EDMF. EVD represents vertical convective mixing if the water column is unstable by mixing of vertical neighboring grid cells. EDMF is a sub-grid scale parameterization presenting penetrative convective plumes through the water column. This approach combines local eddy turbulence and large-scale mass fluxes (Giordani et al., 2020). We modify EDMF to include thermobaric effects and a frictional term, representing lateral entrainment. The study consists of three sets of numerical experiments. In the first set, we test the different vertical convective mixing schemes during the period 2007-2017, identifying the scheme that represents the regional oceanic properties best. Using this vertical convective mixing scheme, we combine it with different surface freshwater forcings after 2011 to reproduce polynyas. From this set, the simulation reproducing the 2016 and 2017 polynya closest to observation is used to identify polynya-related processes by investigating salt advection, salt deficit, and convective resistance. In the last set, this freshwater forcing is combined with the different mixing schemes after 2011 to identify the impact of the modifications. As observational data sets, we use climatologies derived from EN4.2.2 and SIC from AMSR-E and AMSR2.

Summary of the results

From the first set of experiments, none of the runs produced a polynya, but they are used to identify why Maud12 does not produce a MRP. In all simulations, an excessive freshwater forcing mainly originating from ice accumulation within the domain was identified, pointing to a necessary reduction of the freshwater forcing. Further, in this set it was identified that employing the last modification of EDMF (including thermobaric effects and the frictional term) provided the best representation of salinity, temperature, and MLD properties throughout the simulation time. Using the last modification of EDMF, combining it with reduced precipitation showed that Maud12 reproduces polynyas at Maud Rise, and the freshwater forcing governed the length of the opening. The simulation with similarities to observations (Figure 3.3) was used to identify the processes triggering the polynya. This analysis showed that the stratification in 2016 was weakened and that deep convection and the related polynya were initiated by thermobaric instabilities at the interface of cold, fresh surface water and warm, salty subsurface waters. The polynya event in 2016 preconditioned the water column for the 2017 opening, which resulted from the advection of an anomalous salt anomaly in the upper 100 m. Lastly, in the third set of experiments, we investigated how the deep convection patterns are varying between the different vertical convective mixing schemes. This analysis has shown that any of the EDMF simulations showed highly localized deep MLD patterns, while EVD deepened the MLD in the whole domain.

This study highlighted the sensitivity of models in the region of Maud Rise to the choice of the convection scheme and freshwater forcing, and that employing a penetrative mixing scheme can lead to more localized deep convection. Sensitivity tests generated a MRP and highlighted the importance of vertical instabilities in forming the 2016 MRP and the preconditioning role of the 2016 MRP for the 2017 MRP.

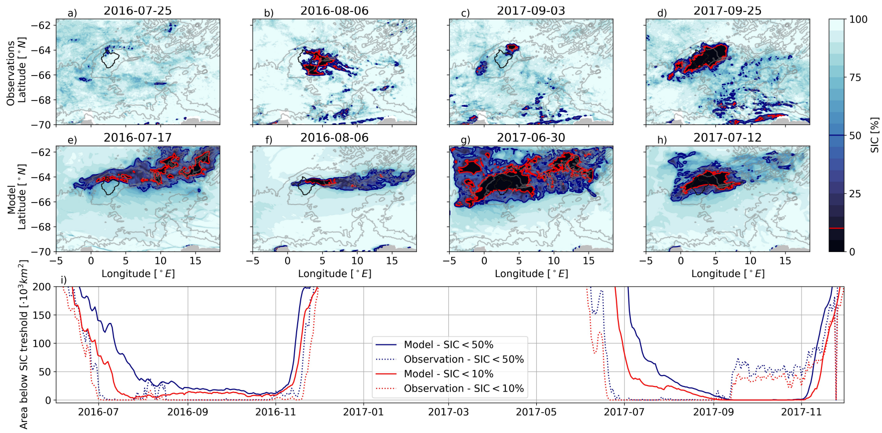

Figure 3.3: Snapshots of SIC from satellite observations (a-d) and the model run (e-h) in 2016 and 2017. The 50% (10%) SIC contour is indicated in blue (red). i) Area with SIC $< 50\%$ *(blue;* $< 10\%$*; red) in the region* $4°$ *W-*$10°$ *E and* $62°$ *S-*$67°$ *S from the model (solid) and the observations (dotted). Figure 4 from Gülk et al. (2024b).*

3.3 Paper III: Ekman-Driven Salt Transport as a Key Mechanism for Open-Ocean Polynya Formation at Maud Rise

This study is accepted for publication in *Science Advances* with lead-author Aditya Narayanan and coauthors Fabien Roquet, Sarah T. Gille, Birte Gülk, Matthew R. Mazloff, Alessandro Silvano, and Alberto C. Naveira Garabato.

Motivation and aim

In the Weddell Sea, stratification is set by salinity (Roquet et al., 2022). Therefore, a large difference in salinity between the upper and deeper oceans can prevent deep convection and, with it, an opening of the polynya. Observations in the region of Maud Rise have shown an increase in mixed-layer salinity preceding the polynya and highlighted that only small amounts of additional salt were necessary to trigger deep convection (Campbell et al., 2019). Numerical studies have found evidence of an upper-ocean salt anomaly eroding the stratification and preconditioning the polynya opening (*Paper II* and Kurtakoti et al., 2018). This study aims to highlight the importance of local-scale Ekman transports at the northern flank of Maud Rise in destabilizing the upper-ocean stratification and triggering the 2017 MRP.

Methods

This study uses the SOSE iteration 135 (Section 2.4), which has a polynya and shows an increase in upper-ocean salinity in 2015-2016 as observed by floats (Campbell et al., 2019). To analyze the possible different processes at play in the polynya, first an upper-ocean salinity budget and then an Ertel potential vorticity (PV) framework are employed. The upper-ocean salinity budget

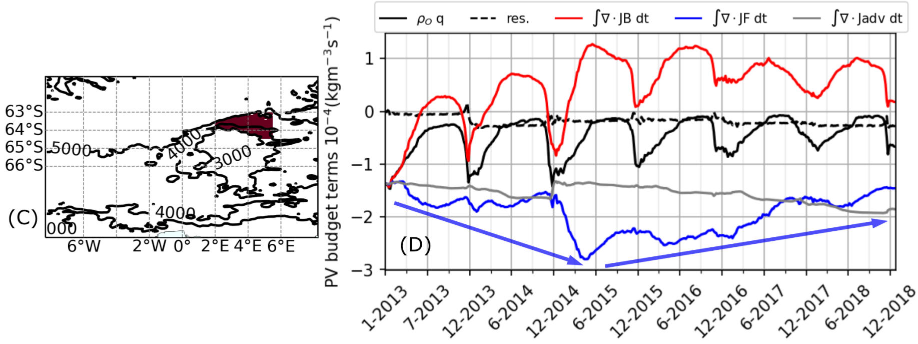

Figure 3.4: c) Selected area over the northern flank of Maud Rise over which PV budget terms are spatially averaged. d) Components of the PV budget: PV (black), buoyancy PV term (J^B,red), frictional PV term (J^F, blue), advection PV term (J^A, gray), and the PV budget residual (broken black). The blue arrows visually approximate the slope of the J^F curve, and indicate that this slope changes sign in mid-2015. Figure 5c,d from Narayanan et al. (2024b).

focuses on the uppermost 20 m and divides the changes in the budget into horizontal and vertical advection, horizontal and vertical diffusion, salt surface fluxes, and a correction term. This salt budget is complemented by the salinity Ekman transports within the Ekman layer. Further, the Ertel PV budget is applied to the upper 500 m to identify the processes affecting the stratification. The PV budget is maintained in buoyancy forcing, surface frictional forcing, and advection. Whereby the surface frictional forcing represents, to a large extent, the wind-driven lateral Ekman forces.

Summary of the results

First, this study investigated the increase in the upper-ocean salinity in the region of Maud Rise in 2015 and 2016 by the salt budget. This budget highlighted that the input from the surface is compensated by vertical mixing processes. The salt increase mainly originated from the Ekman transport of salinity, which was found to be strongest at the front between the warm-water Halo and Taylor Cap at Maud Rise's northern flank. This region is the region of interest in the PV budget, and here the (de-)stabilizing processes regarding the stratification in the upper 500 m are examined. The PV framework showed that the stratification weakened in 2015-2016 (Figure 3.4), aligning with the increase in upper-ocean salinity. This also leads to a reduction of the horizontal density gradient, which is one of two components setting the Ekman transport. The second component is the net ocean surface stress. From 2015 onward, the frictional component of the PV budget increased mainly due to increased surface stresses as the density gradient was weakened. The increased frictional component led to an Ekman transport of salt from the Taylor Cap into the northern flank across the front, destabilizing the water column enough to initiate the polynya opening.

3.4 Paper IV: On the role of barotropic and baroclinic flows in forming a Taylor Cap at Maud Rise, Weddell Sea

This study is in preparation for submission to *Journal of Physical Oceanography* with coauthors Fabien Roquet, David Ferreira, and Alberto C. Naveira Garabato.

Motivation and aim

Taylor Caps are important for polynya formation; when they interact with the surface mixed layer, they can trigger deep convection (Alverson & Owens, 1996). Such a Taylor Cap has been identified in various observations and models on top of Maud Rise. Model studies have shown substantial variability in the Taylor Cap properties and also a near-vanishing (*Paper I* and Kurtakoti et al., 2018). The behavior of Taylor Caps has been investigated in many idealized studies, where changes to the Caps' height and width were related to variations in inflow velocities or surface forcing. De Steur et al. (2007) showed that with an increased inflow velocity, the isopycnals are shoaled and the local subsurface temperature maximum is closer to the surface. Previous studies have a barotropic inflow, but the real ocean has a vertical shear. Therefore, this study aims to determine the role of barotropic and baroclinic inflow conditions on the generation of Taylor Caps in an idealized set-up with Maud Rise-like properties.

Methods

In this study, the idealized Taylor Cap configuration set up in MITgcm is used (Section 2.5). In this configuration, the stratification is controlled by temperature with a constant salinity. The study incorporates two sets of experiments.

The first set is a series of experiments with increased complexity (Figure 3.5), starting with a barotropic ocean and inflow (case A), then adding a temperature stratification, followed by vertical shear. From the barotropic ocean case, we modify the temperature structure by adding a vertical temperature gradient in the form of 20 equally thick temperature layers (case B). In the next step, a linear meridional gradient is added. The meridional gradient is applied, so that the meridional temperature average is the same as before. This stratification implies vertical shear, which is thermal wind-balanced. This stratification is once run with the baroclinic inflow only (case C1) and once combined with a barotropic inflow (case C2). In the last simulation of this series, an e-folding scale temperature profile was employed. This stratification is once run with the resulting thermal wind-balanced inflow (case D1) and once combined with a barotropic inflow (case D2). Throughout all simulations in this series, the barotropic component is $u_{bt} = -0.1\,\mathrm{m\,s^{-1}}$.

The second set of experiments investigates how the strength of the barotropic component u_{bt} influences the Taylor Cap properties. Therefore, case

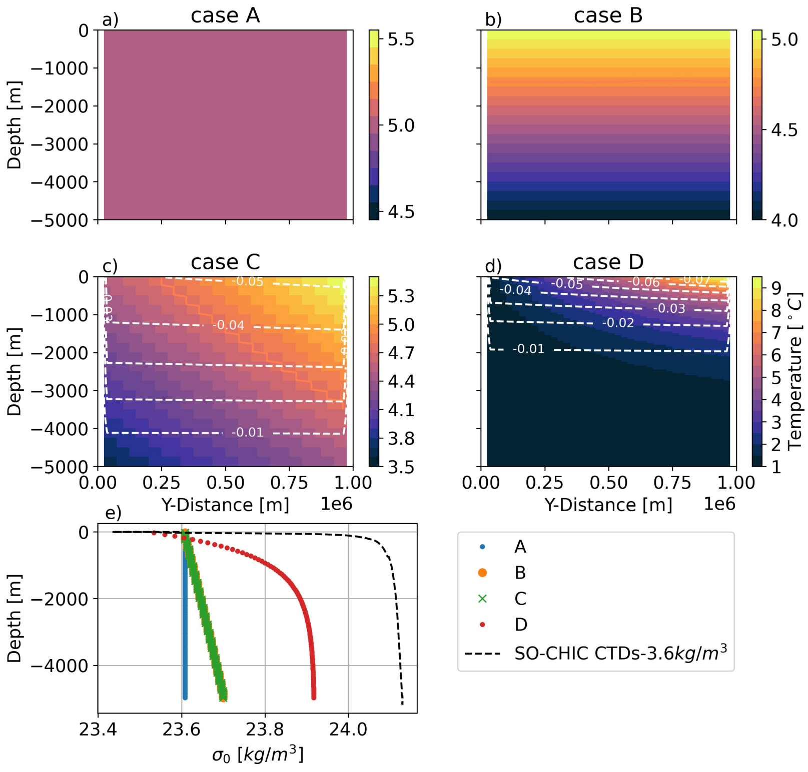

Figure 3.5: a-d) Meridional temperature sections representing the different temperature stratification. The white lines in c,d) indicate the baroclinic velocities derived from the temperature stratification. e) Horizontal mean density profile of the cases and mean σ_0 from the SO-CHIC cruise in 2022 (Gülk et al., 2023) (black dashed line). Cases C1 and C2 (D1 and D2) have the same stratification and are therefore only referenced as case C (D). Figure 2 from Gülk et al. (2024a).

C2 was rerun with different values for the barotropic component u_{bt} between $0\,\mathrm{m\,s^{-1}}$ and $-0.25\,\mathrm{m\,s^{-1}}$.

Summary of the results

The first set of simulations showed that a baroclinic flow can only generate a Taylor Cap if the flow impinging on the topographic obstacle is sufficiently fast. Case C1 generated a Taylor Cap only with the baroclinic component, while in case D1, the baroclinic component was too weak at the interface of bump and flow to generate a Taylor Cap (Figure 3.6). Here, a combination with a barotropic component (case D2) was necessary to generate a Taylor Cap. Having a baroclinic component in the inflow increased the doming of the isopycnals in all simulations where a Taylor Cap was generated. From this set of experiments, it can be summarized, that a Taylor Cap is generated by the

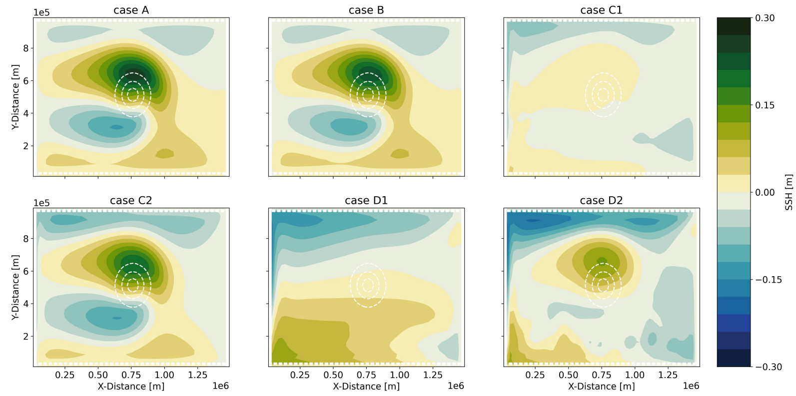

Figure 3.6: SSH of the last output of the different cases. Here, the meridional gradient is removed. The white circles indicate 2 500, 3 500, and 4 500 m isobaths. Figure 4 from Gülk et al. (2024a).

barotropic flow, while the baroclinic flow increases the doming of isopycnals in the water column.

In the second set of simulations, we showed that the upward displacement of isopycnals in the Taylor Cap region is related to the inflow velocity. With higher inflow velocities, the isopycnals were displaced more than in the lower velocity cases. Also, the peak of the isopycnals was displaced westward. Further, the higher inflow velocities lead to a reduction of the upper ocean density difference in the Taylor Cap when $u_{bt} \leq -0.1\,\mathrm{m\,s^{-1}}$.

Summarizing the study, a sufficiently fast impinging flow is needed to generate a Taylor Cap. In the region of Maud Rise, the stratification-induced baroclinic component is too weak to provide such a flow. Therefore, the Taylor Cap is generated by the barotropic flow of the Weddell Gyre. The baroclinic flow modifies the vertical structure of the water column and leads to a doming of the isopycnals.

4 | *Conclusion and Outlook*

In this Chapter, I am combining the results from the papers (Chapter 3) regarding the proposed research questions in Section 1.5: polynya-related processes in 2016 and 2017 (Section 4.1), modeling challenges regarding the representation of MRPs (Section 4.2), and the behavior of Taylor Caps with respect to the impinging flow (Section 4.3), and providing a discussion with other studies. These themes are chosen to provide a better understanding of the Maud Rise region and how models can be improved to generate open-ocean polynyas that are more realistic. Section 4.4 summarizes the limitations and perspectives encountered during the thesis. Lastly, the thesis is concluded by the final remarks in Section 4.5.

4.1 Maud Rise polynya preconditioning and formation

One aim of this thesis was to assess the preconditioning and formation processes of the MRP in 2016 and 2017. These processes were investigated in *Papers I, II* and *III*.

Synthesis of the work

Paper I identified that the local dynamical system at Maud Rise consisting of the Taylor Cap and Halo was highly variable. Especially the eastern limb of the Weddell Gyre led to a variability in the Halo, conveying subsurface water masses into the region of Maud Rise. In *Paper I*, we showed that in 2013 and 2014, a cold and fresh water mass was advected into the region. *Paper III* showed that this period was followed in 2015 and 2016 by an increase in the upper ocean salinity and therefore weakened stratification. During this time, the Taylor Cap atop Maud Rise accumulated heat and salt through increased eddy transport across the front (*Papers I* and *III*). *Paper II* highlighted that in 2016, a vertical instability at the interface of the cold, fresh surface waters and warm, saline subsurface waters acted on the weak stratification and triggered deep convection. This deep convection event preconditioned the water column for the stronger and longer polynya event in 2017. Here, the final process leading to deep convection was an anomalous surface salt advection. *Paper III* identified this anomalous surface salt advection as Ekman-driven salt transport across the front between the Taylor Cap and Halo.

Discussion

Combining *Papers I, II* and *III* highlights the complexity of processes at play to generate a polynya at Maud Rise. Further, they combine many published observational and model-based theories regarding the formation process and provide a road map for generating a MRP.

The Weddell Gyre sets the stratification of the region of Maud Rise (*Paper I*; Cheon & Gordon, 2019). If a weakly stratified water mass, e.g., one with an increased surface salinity, is advected within the Gyre to Maud Rise, the initiation of a polynya is more likely (*Paper III*; Campbell et al., 2019). On this weakened stratification, vertical instabilities at depth can trigger deep convection and lead to a brief opening of the polynya, as seen in 2016. The region prone to these instabilities is the flanks of Maud Rise between the Taylor Cap and Halo (*Paper II*; Akitomo, 2006; McPhee, 2000). This brief opening preconditions the water column for a stronger event in the following winter season (*Paper II*; Campbell et al., 2019). To initiate the deep convection, an additional trigger is necessary. Kurtakoti et al. (2018) and *Paper III* found that an additional input of salt can initiate it. Both studies identified different origins of this salt; while Kurtakoti et al. (2021) identified the Astrid Ridge to the east of Maud Rise as the origin, *Paper III* identified the Taylor Cap as the origin. Both processes are plausible mechanisms; the results may be model-dependent. An advantage of using SOSE is that the 2017 polynya properties are in agreement with observations, while the generated polynya in Kurtakoti et al. (2018) is extending closer to Astrid Ridge, therefore indicating an interaction with processes there. *Papers I* and *III* and Kurtakoti et al. (2018) showed that the subsurface heat and salt properties of the Taylor Cap are changing before the polynya opening.

4.2 Modeling suggestions

Besides the polynya-related processes, this thesis focused on the generation of open-ocean polynyas and deep convection events in OGCMs and why there has been a lack of simulations representing this in the past. This question was studied in *Papers I* and *II.*

Synthesis of the work

Paper I investigated the effect of higher horizontal resolution by using Maud12 and Maud36. Neither of the resolutions led to the formation of an open-ocean polynya, and similar ocean properties were found. Both simulations showed similar results regarding Taylor Cap subsurface maximum temperatures and behavior and reproduced the expected hydrographic features. *Paper II* showed that Maud12 was affected by excessive freshwater in the upper ocean due to the open-boundary conditions and uncertainties in atmospheric reanalysis products. Combining different vertical convective mixing schemes with perturbed freshwater forcing led to the generation of the 2016 and 2017 polynya events with reasonable properties. The generated polynyas were sensitive to the freshwater forcing, which affected the duration of the opening, while the choice of the convective mixing scheme affected the size of the polynya opening.

Discussion

In *Paper I*, we showed that increasing the horizontal resolution from 1/12° to 1/36° led to a better representation of eddies in the domain, but similar subsurface properties were found. Decreasing the resolution could affect the representation of the warm-water Halo and Taylor Cap; to represent the warm-water Halo, approximately 1/10° horizontal resolution would be necessary (Neme et al., 2021, their Figure 7). For representing the Taylor Cap, a realistic representation of the slopes of Maud Rise and its height are necessary (Kurtakoti et al., 2018). *Paper II* connects to work previously conducted by Kjellsson et al. (2015), Stoessel et al. (2015), Heuzé et al. (2015). Contrary to *Paper II*, these studies have focused on how to prevent excessive open-ocean polynyas and deep convection in relation to vertical mixing choices and freshwater input. All studies highlighted that there is a fine balance between too weak and too strong stratification impacted by freshwater and mixing choices. *Paper II* showed also, that employing thermobaricity in a model as well as having a penetrative convective mixing scheme can improve MLD and deep convection properties. Both, are commonly not integrated in ocean and climate models.

4.3 The dynamics shaping the Maud Rise Taylor Cap

The Taylor Cap can play an important role in triggering deep convection and the formation of an open-ocean polynya. Therefore, the behavior of the Taylor Cap at Maud Rise and its variability were studied in *Papers I* and *IV*.

Synthesis of the work

In *Papers I* and *III* the Taylor Cap properties changed before the opening of the polynya, an increase in salinity and heat was observed. In *Paper I*, it was highlighted that the Taylor Cap properties were nearly vanished and that eddies formed at the inner flank of the Halo played an important role in modifying the Taylor Cap properties. In *Paper IV*, the role of the large-scale circulation in shaping the Taylor Cap was investigated. This study showed that the barotropic inflow generates the Taylor Cap, while the doming of the isopycnals is a response to the baroclinic inflow. The barotropic flow at Maud Rise is set by the large-scale circulation of the Weddell Gyre, while the baroclinic flow is a response to local forcing, e.g., surface forcing.

Discussion

Alverson and Owens (1996) highlighted that deep convection can be triggered if the Taylor Cap penetrates the mixed layer. *Paper IV* showed that the height of the Taylor Cap is a response to the strength of the inflow, in agreement with other studies such as Chapman and Haidvogel (1992) and De Steur et al. (2007). This leads to a shallower depth of the warmer subsurface waters. Further, *Paper IV* showed that the upper ocean stratification can be reduced if the impinging flow is fast enough. In summary, a faster impinging flow leads to a higher Taylor Cap and reduced stratification, making the water column more susceptible to deep convection.

It remains open if the near-vanishing of the Taylor Cap observed in *Paper I* is only a result of the eddy transport or if the flow from the Weddell Gyre had a high variability. The near-vanishing occurred simultaneously with the inflow of a cold, fresh deep waters, which might have reduced the baroclinic component and therefore flattened the isopycnals in 2014. The hypothesis of *Paper IV* remains to be tested in the regional configuration used in *Paper I*.

4.4 Limitations and Perspective

Conducting research in the polar regions is a challenging work. There are several factors impacting and limiting it, originating from observations and models.

One challenge is the scarcity of observations. The region of Maud Rise has seen extensive cruise observations on average every decade, starting in 1986 (Gordon & Huber, 1990), with the last known one being the SO-CHIC cruise in 2022. This limits the possibility of understanding the Maud Rise region and why the polynya occurs irregularly. With the start of the Argo program and MEOP, more in situ measurements became available. During the period of sea-ice cover, in situ observations are still rare. Argo profiles are available during the ice cover, but the estimated locations are based on linear interpolation between the last surface before the ice cover and the first surface after. This may lead to suspicious tracks, which should be handled with care.

Besides uncertainties in ocean observation, atmospheric reanalysis products suffer from a lack of observations as well (Siems et al., 2022). Atmospheric reanalysis products are commonly used in OGCMs and impact their results. An over- or underestimation of, for example, precipitation can lead to a too stratified or too weakly stratified water column and hamper or amplify deep convection events.

The scarcity and uncertainties of ocean and atmospheric observations at Maud Rise led to many sensitivity runs of Maud12 to generate a MRP and find a balance between forcing and modeling. We showed that using a recently developed convective mixing scheme (Giordani et al., 2020) and modifications of it led to a reasonable generation of a MRP. I am excited to see, how this scheme is performing in larger regional simulations like the Weddell Sea or Southern Ocean or even on a global scale. Maybe it could resolve some of the deep convection issues we have seen in various model types in the past (Kjellsson et al., 2015; Heuzé et al., 2015; Stoessel et al., 2015) and provide a better prediction about the ocean uptake of heat and carbon. With this, we could make future predictions on the probability of the WSP emergence under climate change.

4.5 Closing remarks

MRPs are known to ventilate the waters up to 1 000 m depth and to precondition the water column for the occurrence of the larger WSP. These WSPs lead to bottom water formation and can lead to an uptake of CO_2 and heat. Yet, the generation of realistic MRPs and WSPs has been a challenge for models, due to insufficient representation of deep convection.

This thesis focused on the generation of the MRPs in 2016 and 2017 in the Weddell Sea using a modeling approach supported by available observations. First, the processes preceding the 2016 MRP were determined: a warming of the Taylor Cap (*Paper I*). Then the actual 2016 polynya event was triggered by a vertical instability leading to convection of the water column. This event preconditioned the water column for the 2017 MRP (*Paper II*). The 2017 MRP was enabled by cross-frontal Ekman transport of salinity from the Taylor Cap into the Halo (*Paper III*). This chain of processes combines many proposed theories from observational and modeling studies in generating the MRP. The processes of Maud Rise are largely affected by the properties of the Weddell Gyre and the water masses conveyed in it (*Papers I* and *IV*).

Further research is needed to fully understand the complex ocean processes and circulation in the Weddell Gyre and their interactions with large-scale climate variability. By providing a successful model approach to simulate realistic MRPs for the first time, this thesis contributes to our understanding of one key part of that intricate system, which will help to improve predictions on the occurrence and significance of open-ocean polynyas in future climate scenarios.

Bibliography

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).

Alverson, K., & Owens, W. B. (1996). Topographic preconditioning of open-ocean deep convection. *Journal of physical oceanography*, *26*(10), 2196–2213.

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.

Boyer, T. P., Antonov, J. I., Baranova, O. K., Garcia, H. E., Johnson, D. R., Mishonov, A. V., O'Brien, T. D., Seidov, D., Smolyar, I., Zweng, M. M., Et al. (2013). World ocean database 2013.

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.

Chapman, D. C., & Haidvogel, D. B. (1992). Formation of Taylor caps over a tall isolated seamount in a stratified ocean. *Geophysical & Astrophysical Fluid Dynamics*, *64*(1-4), 31–65. https://doi.org/10.1080/03091929208228084

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., Lee, S.-K., Gordon, A. L., Liu, Y., Cho, C.-B., & Park, J. J. (2015). Replicating the 1970s' Weddell polynya using a coupled ocean-sea ice model with reanalysis surface flux fields. *Geophysical Research Letters*, *42*(13), 5411–5418.

Cisewski, B., Strass, V. H., & Leach, H. (2011). Circulation and transport of water masses in the Lazarev Sea, Antarctica, during summer and winter 2006. *Deep Sea Research Part I: Oceanographic Research Papers*, *58*(2), 186–199.

Comiso, J., & Gordon, A. L. (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. G. (2007). The warm-water "Halo" around Maud Rise: Properties, dynamics and impact. *Deep Sea Research Part I: Oceanographic Research Papers*, *54*(6), 871–896.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M., Balsamo, G., Bauer, d. P., Et al. (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation

system. *Quarterly Journal of the royal meteorological society*, *137*(656), 553–597.
Dragomir, O. C. (2023). *Dynamics of the subpolar southern ocean response to climate change* (Doctoral dissertation). University of Southampton, School of Ocean and Earth Science.
Drévillon, M., Lellouche, J.-M., Régnier, C., Garric, G., Bricaud, C., Hernandez, O., & Bourdallé-Badie, R. (2021). *GLORYS12 Quality information document* (tech. rep.). Copernicus Marine Environment Monitoring Service (CMEMS).
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.
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.
Francis, D., Mattingly, K. S., Temimi, M., Massom, R., & Heil, P. (2020). On the crucial role of atmospheric rivers in the two major Weddell Polynya events in 1973 and 2017 in Antarctica. *Science advances*, *6*(46), eabc2695.
Frölicher, T. L., Sarmiento, J. L., Paynter, D. J., Dunne, J. P., Krasting, J. P., & Winton, M. (2015). Dominance of the Southern Ocean in anthropogenic carbon and heat uptake in CMIP5 models. *Journal of Climate*, *28*(2), 862–886.
GEBCO Compilation Group. (2022). GEBCO 2022 Grid. https://doi.org/10.5285/e0f0bb80-ab44-2739-e053-6c86abc0289c
Giordani, H., Bourdallé-Badie, R., & Madec, G. (2020). An Eddy-Diffusivity Mass-Flux Parameterization for Modeling Oceanic Convection. *Journal of Advances in Modeling Earth Systems*, *12*(9), e2020MS002078.
Good, S. A., Martin, M. J., & Rayner, N. A. (2013). EN4: Quality controlled ocean temperature and salinity profiles and monthly objective analyses with uncertainty estimates. *Journal of Geophysical Research: Oceans*, *118*(12), 6704–6716.
Gordon, A. L. (1978). Deep antarctic convection west of Maud Rise. *Journal of Physical Oceanography*, *8*(4), 600–612.
Gordon, A. L. (1982). Weddell deep water variability.
Gordon, A. L., & Huber, B. A. (1990). Southern Ocean winter mixed layer. *Journal of Geophysical Research: Oceans*, *95*(C7), 11655–11672.
Gülk, B., Roquet, F., Ferreira, D., & Naveira Garabato, A. C. (2024a). On the role of barotropic and baroclinic flows in forming a Taylor Cap at Maud Rise, Weddell Sea. *In preparation for Journal of Physical Oceanography.*
Gülk, B., Roquet, F., Naveira Garabato, A. C., Bourdallé-Badie, R., Madec, G., & Giordani, H. (2024b). Impacts of Vertical Convective Mixing schemes and Freshwater Forcing on the 2016-2017 Maud Rise polynya openings in a regional ocean simulation. *Accepted for publication in Journal of Advances in Modeling Earth Systems (JAMES).*
Gülk, B., Roquet, F., Naveira Garabato, A. C., Narayanan, A., Rousset, C., & Madec, G. (2023). Variability and Remote Controls of the Warm-Water Halo and Taylor Cap at Maud Rise. *Journal of Geophysical Research: Oceans*, e2022JC019517.
Harcourt, R. R. (2005). Thermobaric cabbeling over Maud Rise: Theory and large eddy simulation. *Progress in Oceanography*, *67*(1-2), 186–244.

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., & Thépaut, J.-N. (2023). ERA5 hourly data on single levels from 1940 to present. https://doi.org/10.24381/cds.adbb2d47

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.

Holland, D. (2001). Explaining the Weddell Polynya–a large ocean eddy shed at Maud Rise. *Science*, *292*(5522), 1697–1700.

Jena, B., Ravichandran, M., & Turner, J. (2019). Recent reoccurrence of large open-ocean polynya on the Maud Rise seamount. *Geophysical Research Letters*, *46*(8), 4320–4329.

Johnson, G. C. (2008). Quantifying Antarctic bottom water and North Atlantic deep water volumes. *Journal of Geophysical Research: Oceans*, *113*(C5).

Jullion, L., Garabato, A. C. N., Bacon, S., Meredith, M. P., Brown, P. J., Torres-Valdés, S., Speer, K. G., Holland, P. R., Dong, J., Bakker, D., Et al. (2014). The contribution of the Weddell Gyre to the lower limb of the Global Overturning Circulation. *Journal of Geophysical Research: Oceans*, *119*(6), 3357–3377.

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. (2018). Preconditioning and formation of Maud Rise polynyas in a high-resolution Earth system model. *Journal of Climate*, *31*(23), 9659–9678.

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*(7), 2491–2510.

Leach, H., Strass, V., & Cisewski, B. (2011). Modification by lateral mixing of the Warm Deep Water entering the Weddell Sea in the Maud Rise region. *Ocean Dynamics*, *61*(1), 51–68.

Lellouche, J.-M., Greiner, E., Bourdallé-Badie, R., Garric, G., Melet, A., Drévillon, M., Bricaud, C., Hamon, M., Le Galloudec, O., Regnier, C., Candela, T., Testut, C.-E., Gasparin, F., Ruggiero, G., Benkiran, M., Drillet, Y., & Le Traon, P.-Y. (2021). The Copernicus Global 1/12° Oceanic and Sea Ice GLORYS12 Reanalysis. *Frontiers in Earth Science*, *9*. https://doi.org/10.3389/feart.2021.698876

Lindsay, R., Kwok, R., De Steur, L., & Meier, W. (2008). Halo of ice deformation observed over the Maud Rise seamount. *Geophysical research letters*, *35*(15).

Madec, G., & NEMO System Team. (2019). *NEMO ocean engine*. Scientific Notes of Climate Modelling Center, Institut Pierre-Simon Laplace (IPSL). https://doi.org/10.5281/ZENODO.1464816

Marshall, J., Hill, C., Perelman, L., & Adcroft, A. (1997). Hydrostatic, quasi-hydrostatic, and nonhydrostatic ocean modeling. *Journal of Geophysical Research: Oceans*, *102*(C3), 5733–5752.

Martinson, D. G. (1990). Evolution of the Southern Ocean winter mixed layer and sea ice: Open ocean deepwater formation and ventilation. *Journal of Geophysical Research: Oceans*, *95*(C7), 11641–11654.

Martinson, D. G., & Iannuzzi, R. A. (1998). Antarctic ocean-ice interaction: Implications from ocean bulk property distributions in the Weddell Gyre. *Antarctic sea ice: physical processes, interactions and variability*, *74*, 243–271.

Mazloff, M. R., Heimbach, P., & Wunsch, C. (2010). An eddy-permitting Southern Ocean state estimate. *Journal of Physical Oceanography*, *40*(5), 880–899.

McPhee, M. G. (2000). Marginal thermobaric stability in the ice-covered upper ocean over Maud Rise. *Journal of Physical Oceanography*, *30*(11), 2710–2722.

McPhee, M. G. (2003). Is thermobaricity a major factor in Southern Ocean ventilation? *Antarctic Science*, *15*(1), 153–160.

Melsheimer, C., & Spreen, G. (2019). AMSR2 ASI sea ice concentration data, Antarctic, version 5.4 (NetCDF) (July 2012 - December 2019). PANGAEA. https://doi.org/10.1594/PANGAEA.898400

Mohrmann, M., Heuzé, C., & Swart, S. (2021). Southern Ocean polynyas in CMIP6 models. *The Cryosphere*, *15*(9), 4281–4313.

Mohrmann, M., Swart, S., & Heuzé, C. (2022). Observed mixing at the flanks of Maud Rise in the Weddell Sea. *Geophysical Research Letters*, *49*(8), e2022GL098036.

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

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

Narayanan, A., Roquet, F., Dragomir, O., Gille, S. T., Gülk, B., Lindeman, M., Mazloff, M. R., Silvano, A., & Naveira Garabato, A. C. (2024a). Eastern Weddell Gyre Variability Impacts Maud Rise Stratification. *In preparation for Geophysical Research Letters.*

Narayanan, A., Roquet, F., Gille, S. T., Gülk, B., Mazloff, M. R., Silvano, A., & Naveira Garabato, A. C. (2024b). Ekman-Driven Salt Transport as a Key Mechanism for Open-Ocean Polynya Formation at Maud Rise. *Accepted for publication in Science Advances.*

Neme, J., England, M. H., & Hogg, A. M. (2021). Seasonal and Interannual Variability of the Weddell Gyre from a High-Resolution Global Ocean-Sea Ice Simulation during 1958–2018. *Journal of Geophysical Research: Oceans*, *126*(11), e2021JC017662.

NEMO Sea Ice Working Group. (2018). *Sea Ice modelling Integrated Initiative (SI^3) – The NEMO sea ice engine*. Zenodo. https://doi.org/10.5281/zenodo.1471689

Proudman, J. (1916). On the motion of solids in a liquid possessing vorticity. *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character*, *92*(642), 408–424.

Reeve, K. A., Boebel, O., Strass, V., Kanzow, T., & Gerdes, R. (2019). Horizontal circulation and volume transports in the Weddell gyre derived from Argo float data. *Progress in Oceanography*, *175*, 263–283.

Rheinlænder, J. W., Smedsrud, L. H., & Nisancioglu, K. H. (2021). Internal Ocean Dynamics Control the Long-Term Evolution of Weddell Sea Polynya Activity. *Frontiers in Climate*, *3*, 718016.

Rintoul, S. R. (2018). The global influence of localized dynamics in the Southern Ocean. *Nature*, *558*(7709), 209–218.

Roquet, F., Ferreira, D., Caneill, R., Schlesinger, D., & Madec, G. (2022). Unique thermal expansion properties of water key to the formation of sea ice on Earth. *Science Advances*, *8*(46), eabq0793.

Ryan, S., Schröder, M., Huhn, O., & Timmermann, R. (2016). On the warm inflow at the eastern boundary of the Weddell gyre. *Deep Sea Research Part I: Oceanographic Research Papers*, *107*, 70–81.

Sabine, C. L., Feely, R. A., Gruber, N., Key, R. M., Lee, K., Bullister, J. L., Wanninkhof, R., Wong, C., Wallace, D. W., Tilbrook, B., Et al. (2004). The oceanic sink for anthropogenic CO2. *science*, *305*(5682), 367–371.

Sallée, JB and SO-CHIC consortium (including Gülk, B). (2023). Southern Ocean Carbon and Heat Impact on Climate. *Philosophical Transactions of the Royal Society A*. https://doi.org/10.1098/rsta.2022.0056

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*(1-2), 501–527.

Shaw, W. J., & Stanton, T. P. (2014). Dynamic and double-diffusive instabilities in a weak pycnocline. Part I: Observations of heat flux and diffusivity in the vicinity of Maud Rise, Weddell Sea. *Journal of physical oceanography*, *44*(8), 1973–1991.

Siems, S. T., Huang, Y., & Manton, M. J. (2022). Southern Ocean precipitation: Toward a process-level understanding. *Wiley Interdisciplinary Reviews: Climate Change*, *13*(6), e800.

Spreen, G., Kaleschke, L., & Heygster, G. (2008). Sea ice remote sensing using AMSR-E 89-GHz channels. *Journal of Geophysical Research: Oceans*, *113*(C2).

Stoessel, A., Notz, D., Haumann, F. A., Haak, H., Jungclaus, J., & Mikolajewicz, U. (2015). Controlling high-latitude Southern Ocean convection in climate models. *Ocean Modelling*, *86*, 58–75.

Szekely, T., Gourrion, J., Pouliquen, S., & Reverdin, G. (2019). The cora 5.2 dataset for global in situ temperature and salinity measurements: Data description and validation. *Ocean Science*, *15*(6), 1601–1614.

Taylor, G. I. (1923). Experiments on the motion of solid bodies in rotating fluids. *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character*, *104*(725), 213–218.

Tsujino, H., Urakawa, S., Nakano, H., Small, R. J., Kim, W. M., Yeager, S. G., Danabasoglu, G., Suzuki, T., Bamber, J. L., Bentsen, M., Et al. (2018). JRA-55 based surface dataset for driving ocean–sea-ice models (JRA55-do). *Ocean Modelling*, *130*, 79–139.

Vernet, M., Geibert, W., Hoppema, M., Brown, P. J., Haas, C., Hellmer, H., Jokat, W., Jullion, L., Mazloff, M., Bakker, D., Et al. (2019). The Weddell Gyre, Southern Ocean: Present knowledge and future challenges. *Reviews of Geophysics*, *57*(3), 623–708.

von Berg, L., Prend, C. J., Campbell, E. C., Mazloff, M. R., Talley, L. D., & Gille, S. T. (2020). Weddell Sea phytoplankton blooms modulated by sea ice variability and polynya formation. *Geophysical Research Letters*, *47*(11), e2020GL087954.

Ward, B., Azevedo, A., Binase, Z., ten Doeschate, A., Els, H., Hamnca, S., Jacobs, L., Katsoulis, M., Lavanchy, S., Lavis, C., Lourenco, A., du Plessis, M., Rosenthal, H., Sallee, J.-B., Soares, B., Spira, T., & Steiger, N. (2022). SOCHIC cruise report. Zenodo. https://doi.org/10.5281/zenodo.6948850

Weijer, W., Veneziani, M., Stössel, A., Hecht, M. W., Jeffery, N., Jonko, A., Hodos, T., & Wang, H. (2017). Local atmospheric response to an open-ocean polynya in a high-resolution climate model. *Journal of Climate*, *30*(5), 1629–1641.

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.

Zhou, L., Ayres, H., Gülk, B., Narayanan, A., de Lavergne, C., Ödalen, M., Silvano, A., Lindeman, M., & Wang, X. (2024). A review of Weddell Sea Polynya formation, cessation and climatic impacts. *In preparation for The Cryosphere*.

Zwally, H. J., & Gloersen, P. (1977). Passive microwave images of the polar regions and research applications. *Polar Record*, *18*(116), 431–450.