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MSc in Climate Change

ROTATIONAL STASIS

An exploratory study of how the Coriolis force affects the AMOC using the VEROS Model

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Abstract

In the backdrop of the worldwide climate challenge, this study investigates the influence of the Coriolis force on the Atlantic Meridional Overturning Circulation (AMOC) by comparing theoretical predictions and computational simulations with and without this rotational force using the VEROS model. Our results demonstrate that the absence of the Coriolis force leads to a shallower but stronger AMOC, highlighting the fundamental role of Earth's rotation in modulating the vertical and horizontal structure of ocean currents. These findings not only emphasize the importance of the Coriolis force in oceanic thermohaline circulation but also have significant implications for understanding future changes in global climate dynamics as influenced by alterations in Earth's rotational behaviors. This research contributes to our understanding of the physical mechanisms driving large-scale ocean circulation and its representation in climate models.

Contents

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Rationale

The dynamics of the ocean are central to our understanding of the global climate system, yet the specific mechanisms that govern these processes are still largely unknown in climate science. This thesis focuses on the Atlantic Meridional Overturning Circulation (AMOC), a vital element of the Earth's climate system, to examine its interaction with the Coriolis force. The AMOC is instrumental in distributing heat worldwide, impacting weather patterns, sea level fluctuations, and the carbon cycle (McCarthy *et al.*, 2017). However, the fundamental forces driving the AMOC are not fully understood, with only a few prevailing theories currently suggested.

This research operates under the assertion that in-depth knowledge of the AMOC and the forces that influence it is essential for precise climate modeling and forecasting. The Coriolis force, a consequence of the Earth's rotation, is recognized for its effect on oceanic and atmospheric currents. Nonetheless, its specific influence on the structure and operation of the AMOC is still to be thoroughly investigated. Through this study, the intention is to elucidate the intricate patterns of ocean circulation and their effects on global climate variability.

The theory and results section of this report has been written with accessibility in mind, catering to a non-scientific audience. The section is structured to guide readers through the entire concept, providing the same clarity I needed to understand the problem in hand. I hope it does the same for them.

The Perspective section was written to have a look at the bigger picture and offers a broader outlook on the research conducted, providing an opportunity to reflect on the implications of the findings, potential applications, and future directions beyond the immediate scope of the study.

Addressing this gap, the thesis will critically evaluate existing hypotheses and introduce novel insights into the AMOC's behavior. Through a combination of observational data analysis, numerical simulations, and theoretical modeling, this work seeks to advance our understanding of the AMOC's dynamics. The findings of this research are expected to contribute significantly to the broader field of climate science, offering new perspectives on the physical mechanisms driving the AMOC and enhancing the predictive capabilities of climate models. In doing so, this study underscores the importance of unraveling the complex interplay between the ocean, ice, and atmosphere to comprehend their collective impact on Earth's climate system.

Introduction

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The current state of Earth's climate presents a grim outlook, marked by a perceptible and alarming decline. Observations across the planet consistently report increases in atmospheric temperatures, shifts in weather patterns, and more frequent and severe extreme weather events, all consequences of anthropogenic climate change (IPCC, 2021). Confronted with increasingly frequent extreme weather events and shifting climatic patterns, it becomes evident that our planet's climate system is a complex and dynamic entity. This intricate system, governed by a multitude of physical processes, remains incompletely understood, more so in the domain of oceanography. The oceans, which cover more than 70% of the Earth's surface, play a pivotal role in climate regulation, absorbing and redistributing heat, carbon, and moisture. Among the ocean's various circulatory systems, the Atlantic Meridional Overturning Circulation (AMOC) stands out due to its significant impact on global climates. However, the precise mechanisms by which the AMOC influences and responds to changing climatic conditions, and how factors such as the Coriolis force modulate its behaviour, are not fully deciphered. As the world grapples with the ramifications of a changing climate, the urgency to unravel these oceanic mysteries intensifies, with the aim to enhance predictive models and inform mitigation strategies.

The Coriolis force is indeed a crucial factor in the functioning of the AMOC, which plays a significant role in climate regulation by transporting heat meridionally across the Atlantic. The importance of the AMOC and the influences acting upon it, including the Coriolis effect, have been documented and explored in various studies.

The AMOC is a critical component of the Earth's climate system, influencing regional and global climate patterns through its extensive heat and freshwater transports. The mechanics of the AMOC are complex, with the Coriolis force playing a pivotal role in structuring and maintaining its movement across the Atlantic Ocean. According to (Gregory and Tailleux, 2011), the interplay between kinetic energy, geostrophic balances, and pressure gradients, all modulated by the Coriolis effect, is essential for understanding the AMOC's behavior under climate change scenarios. Furthermore, (Buckley and Marshall, 2015) highlight the critical role of the Coriolis forces in shaping the mean structure and variability of the AMOC, emphasizing its influence across different temporal scales. Additionally, (Kuhlbrodt *et al.*, 2007) review the driving processes of the AMOC, discussing how the Coriolis-induced wind-driven upwelling and vertical mixing contribute to the circulation's dynamics, thereby affecting its overall stability and intensity. These interactions underscore the importance of understanding the fundamental forces at play within the AMOC, particularly the Coriolis effect, to better predict its future responses to changing climatic conditions. On top of that, literature on the North Atlantic circulation emphasizes the impacts of a weakening AMOC on global climate and highlights past abrupt changes in the AMOC's strength, which are related to changes in temperature and salinity patterns — again, factors intertwined with the Coriolis effect's influence on ocean currents (Thornalley *et al.*, 2018). The Coriolis force, in combination with other elements also affects the mean current profile in a wind-driven mixed layer, influencing the dynamics of ocean currents within the AMOC system (Polton *et al.*, 2005).

One study discusses the stability of the AMOC and indicates that there are feedback mechanisms, such as salt advection feedback, which are influenced by the Coriolis force, affecting the AMOC's strength and stability. This study underscores the complexity of the AMOC and how various feedbacks can lead to different responses to changes in external forcings, like freshwater input, which can be influenced by the Coriolis effect due to its impact on current patterns (Jackson *et al.*, 2022). The coriolis force also modulates the path of the Gulf stream and the formation of deep water in the North Atlantic, integral processes for the continuation of the AMOC (Johns *et al.*, 2011).

As the climate continues to warm, the importance of studying these interactions becomes increasingly crucial. This thesis aims to explore how the Coriolis force influences the AMOC, potentially affecting its strength and stability. By deepening our understanding of these interactions, we can better predict future changes in the AMOC and prepare for their broader climatic impacts.

Foundation

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3.1 Background

Before diving into the how the ocean has been represented digitally to perform experiments on, this section aims to provide the readers with what the AMOC is and the geographical extent it covers and other practicalities associated with it.

At an elementary comprehension level, the AMOC can be thought of as a system of ocean currents that spans much of the North and South Atlantic Ocean. The term "current" describes the motion in the ocean that is mainly driven by wind, water density differences, and tides (National Oceanic and Atmospheric Administration, 2023). The AMOC is actually part of a larger conveyor belt which circulates throughout the entirety of the oceans, often referred to as the 'Thermohaline Circulation' (THC). This system plays a vital role in regulating climate by distributing heat and nutrients around the planet.

Figure 3.1 represents the basic outline of the THC along with other details that influence its dynamics. Our focus now shifts towards the Atlantic Ocean basin wherein lies the AMOC.

Figure 3.2 shows a schematic diagram of the AMOC highlighting various components of this ocean current's system north of 26°. Red colours indicate warm, shallow currents and blue colours indicate cold, deep return flow.

The AMOC is driven by differential solar heating, with the equator receiving more solar energy than the poles. This, combined with the Coriolis effect due to Earth's rotation, influences wind patterns like trade winds and westerlies, shaping global ocean currents. (Stull, 2017)(National Oceanic and Atmospheric Administration, 2023). The AMOC's northward movement is

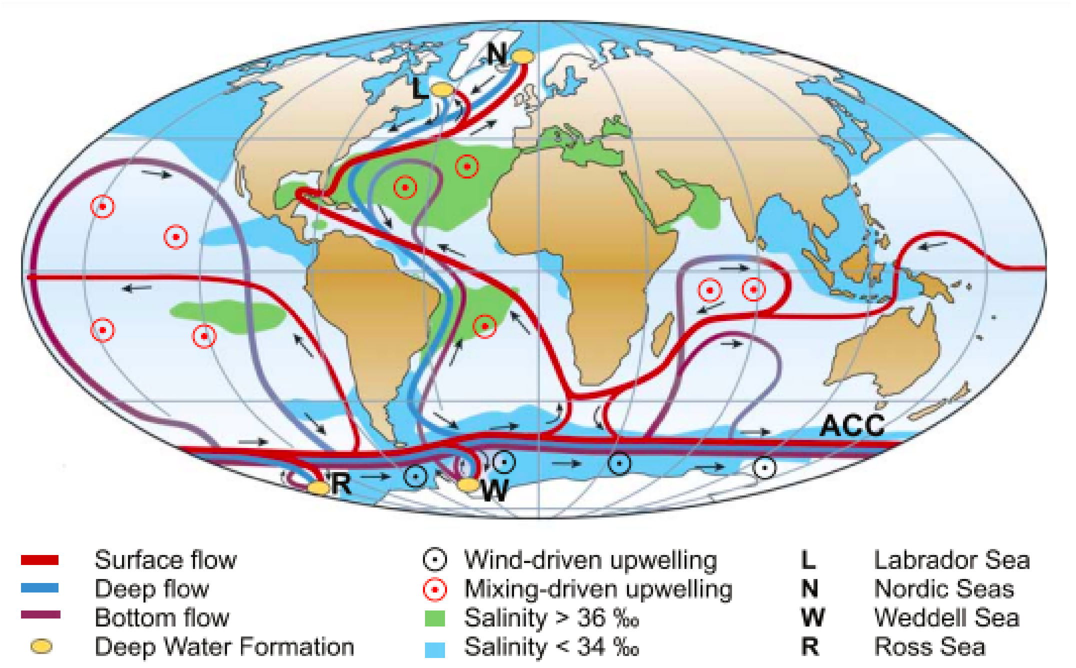

Figure 3.1: Global Overturning Circulation System from (Kuhlbrodt *et al.*, 2007)

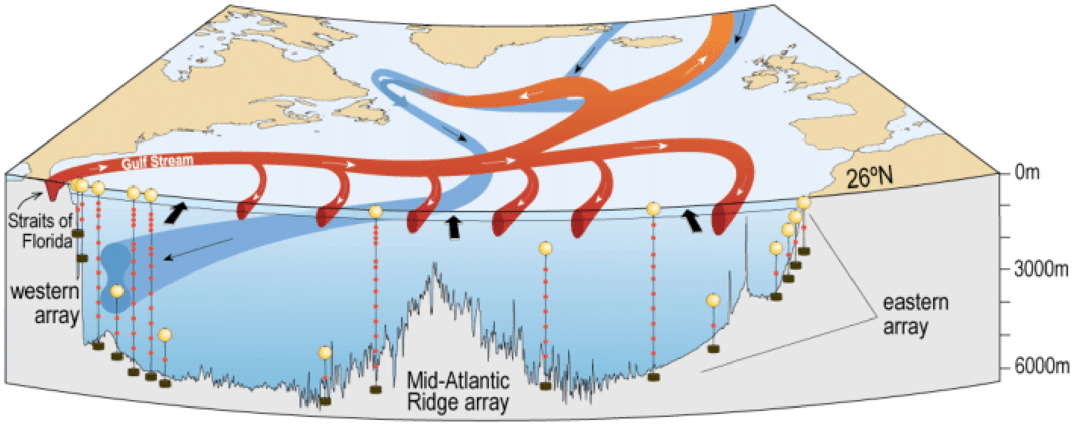

Figure 3.2: Cross section of the AMOC North of 26°N from (McCarthy *et al.*, 2017)

affected by the Coriolis effect, which causes water to veer right in the Northern Hemisphere. This leads to western boundary intensification, where currents accelerate and narrow at ocean basins' western edges, as explained by (Stommel, 1948) discussing Coriolis force variation with latitude. As the AMOC waters cool in the Labrador and Nordic Seas, they undergo brine rejection during ice formation, increasing water salinity and density. This dense water sinks, forming North Atlantic Deep Water (NADW), as documented by (Aagaard and Carmack, 1989) in their study of these thermohaline processes.The NADW formed in the high latitude North Atlantic sinks and flows southwards along the ocean basin, forming a critical component of the AMOC. This deep limb of the AMOC is essential for the return flow of water back to the equator, completing the global conveyor belt of ocean circulation. The AMOC plays a crucial role in regulating climate by distributing heat and influencing weather patterns across the globe.

3.2 Model Setup

To answer the burning questions outlined by this report, we are employing the VEROS model (Häfner *et al.*, 2018). VEROS, the versatile ocean simulator is adapted from the FORTRAN based model pyOM2. The model also incorporates the turbulent kinetic energy module for vertical mixing, following the framework established by (Gaspar *et al.*, 1990). This approach enhances the simulation of energy dissipation and mixing processes in the marine environment.

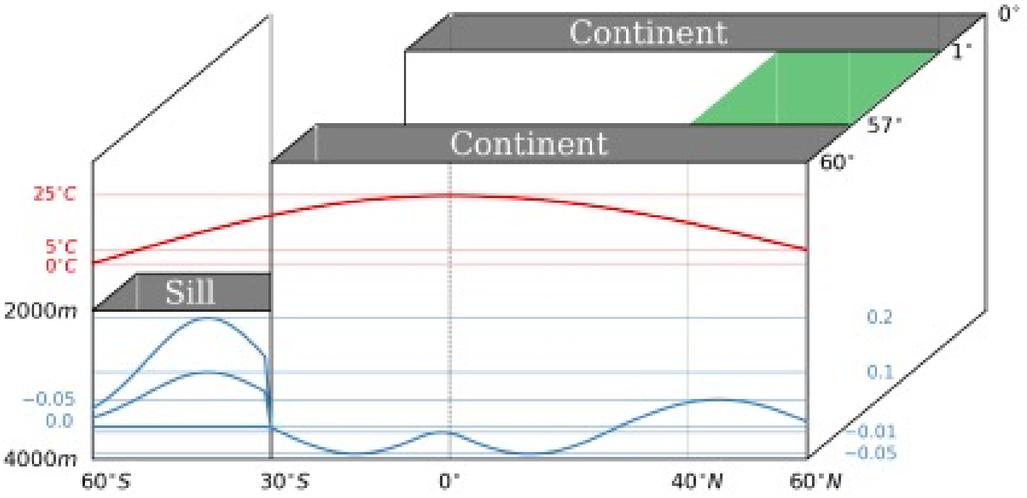

Figure 3.3: Simplistic representation of the VEROS Box Model

Figure 3.3 is a simplistic depiction of the scaled down Box VEROS model derived from (Hansen, 2023). The main point of departure from the (Hansen, 2023) model is that the wind forcing has been turned off for the experiments in this report for the sake of focusing more on the thermohaline driven flow. The modeling domain extends latitudinally from 60°S to 60°N and longitudinally over 60° in the east-west direction. It features a maximum depth of 4000 meters, incorporating a sill at a depth of 2000 meters positioned south of 40°S.

This configuration establishes periodic boundary conditions in the upper half of the domain's southern region, effectively simulating a combination of a basin and a channel. This setup is designed to replicate the dynamics of the Atlantic basin, including Drake Passage and the Southern Ocean. The model employs a Turbulent Kinetic Energy (TKE) model, as outlined in (Gaspar *et al.*, 1990), to accurately simulate vertical mixing processes within this geophysical framework.

To ensure the model attains a steady state, it will be operated at coarse resolution for a duration of 200 years. This extended run period is designed to allow for complete spin-up, ensuring that the resulting data reflects conditions in a dynamically stable ocean environment. Most of the experiments done on the spin up version are run for another 200 years. The wind forcing has been turned off in this model acquired from (Hansen, 2023) so as to focus the effects of the coriolis on the thermohaline driven circulation. As a measure to combat the noise and general imbalance caused by the absence of the coriolis force, horizontal friction was increased hundredfold and the diffusivity parameters were increased tenfold. Another change introduced was the raising of the temperature in the Southern boundary to be 5° more than the Northern boundary. Various model runs have also been performed with this same setup but with different coriolis force values to assess it's impact on the AMOC.

The model constitutes of 60 longitudinal, 124 latitudinal and 40 depth grid points which makes it have a course resolution of 1 degrees. Of the 40 layers in depth, a Vinkour grid is refined towards the surface with initial intervals of 10 meters. This resolution specifies how finely the model grid divides the ocean in each dimension. A higher number of grid points means a finer resolution, capturing more detail but requiring more computational power. The main outputs obtained from the model are the 'averages' and 'overturning' datasets. The 'averages' diagnostic outputs time-averaged values of specified variables. This is useful for understanding the general state of the ocean over a period rather than instantaneous values, which can be noisy or highly variable. The model outputs the averaged values once every year and the model samples the variables every 10 hours to compute the averages. The 'overturning' diagnostic specifically focuses on the meridional overturning streamfunction, highlighting large-scale vertical and meridional water movements in the ocean. The overturning streamfunction is output approximately every 7.6 days, with data also sampled every 10 hours.

The VEROS model was run on a cluster of the Danish Center for Climate Computing. The Danish Center for Climate Computing provides a rich set of High Perofrmance Computing (HPC) utilities, applications, compilers and programming libraries.

Theory

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The following section was written with the aim of educating its readers to delve into the relevant physical concepts that underpin the experiments that were done and to set a boundary to the scope of the research.

4.1 Coriolis Force

The Coriolis force which can be thought of as an artifact of Earth's rotation is an apparent or fictitious force because it is observable from a rotating frame of reference. This deflects the direction of the wind to the right in the northern hemisphere and to the left in the southern hemisphere. This is why the windflow around low and high-pressure systems circulates in opposing directions in each hemisphere (Met Office, 2024).

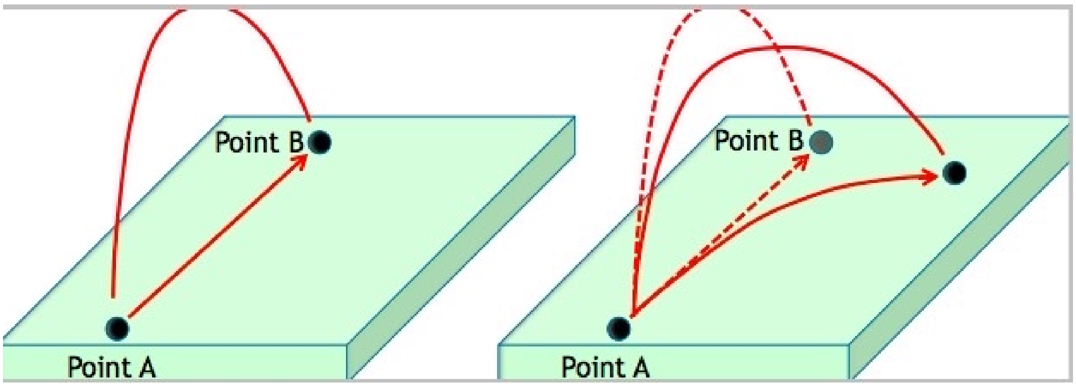

Figure 4.1: Coriolis Force Depiction from (Battistel, 2012).

Figure 4.1 is a simple depiction of the Coriolis Force in the Northern Hemisphere where fluids and objects are deflected towards the right under the rotation of the earth.

The Coriolis Force is governed by the physical equation which is given as

$$-\vec{f} \times \vec{v}$$

Given the vector $\vec{f}$ as

$$\vec{f} = (0, 0, 2\Omega \sin\theta)$$

where $\Omega = 7.292 \times 10^{-5}$ radians per second is the rate of rotation of the earth and θ is the latitude, which ranges from -90° (south pole) to 0° (equator) to 90° (north pole). Meanwhile, v is the parcel's velocity (its relative velocity, to be exact), and the x refers to a cross product.

The critical role of the Coriolis force as an essential driver of the Atlantic Meridional Overturning Circulation (AMOC) cannot be understated. The Coriolis force is important for striking up the geostrophic balance with the pressure gradient force. The Coriolis force influences the balance between the pressure gradient force and the horizontal flow, which in turn affects the strength of the AMOC. The AMOC exerts a strong control on the stratification and distribution of water masses, and the amount of heat transported by the ocean, with the Coriolis force playing a crucial role in this circulation system (Kuhlbrodt et al., 2007).

4.2 Equations of Motion

To describe the equations of motion relevant to this experiment we are starting off from Newton's second law of motion which reads as

$$\vec{F} = m\vec{a} \tag{4.1}$$

Now, a water particle with mass 'm' will be accelerated in the fluid with the relation

$$\vec{a} = \frac{1}{m}\vec{F}_{\text{net}} \tag{4.2}$$

where $\vec{F}_{\text{net}}$ represents the sum of the forces acting on the particle which will be delved into in this very same section.

Since we are dealing with the vast ocean, it makes more sense to consider per unit volume calculations of the particles as it will make it easier for the derivations moving forward. So equation 4.2 morphs into

$$\vec{a} = \frac{1}{\rho V}\vec{F}_{\text{net}} \tag{4.3}$$

And thus the density term enters into the fray. The $\vec{F}_{\text{net}}$ term can be described as the sum of gravity, pressure gradient, coriolis and friction per unit volume.

Acceleration can also be defined as the rate of change of velocity and this is how it is often described as in the equations of motions for the ocean.

For more clarity the velocity vector of the ocean is divided into 3 dimensions as seen in Figure 4.2

Where the x-axis is referred to as the 'zonal' direction, the y-axis as the 'meridonial' direction and the z-axis as the 'vertical' direction.

The concepts discussed so far together with some astute assumptions like Newtonian fluids, Incompressibility and Isothermality lay the foundation for the most widely accepted equations of motion governing large scale circulation in the ocean. It is also referred to as the Navier-Stokes equation and is given by

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} + 2\mathbf{\Omega} \times \mathbf{u} = -\frac{1}{\rho}\nabla p + \mu\nabla^2\mathbf{u} + \rho g\hat{z} \tag{4.4}$$

Where the terms are acceleration, advection, Coriolis force, pressure gradient, diffusion and gravity respectively. For large-scale ocean dynamics, the full

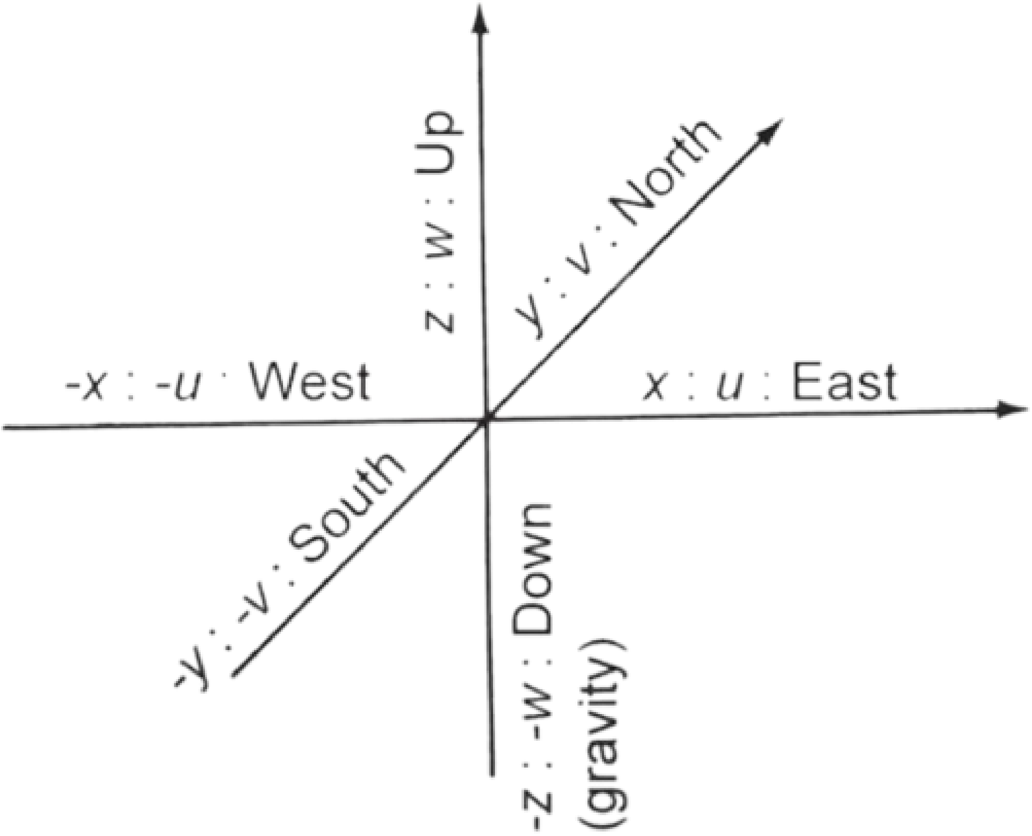

Figure 4.2: Velocity Vector of the ocean

Navier-Stokes equations are often too complex to solve directly because they include all scales of motion. Through a process known as scaling, specific terms of the equations that are less significant at large scales can be approximated or neglected, leading to simplified models that still capture the essential dynamics of large-scale motions. This simplification is particularly important for understanding and predicting the behavior of the AMOC.

Another important concept to keep in mind is the idea of continuity in the ocean. It can be thought of as the ocean having 'no holes' inside it, meaning there is conservation of mass and volume. Physically, it can written as

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{4.5}$$

In the case of large-scale circulations, the Rossby number - which is the ratio of the accelration and transport term to the Coriolis force - is usually less than 1, indicating that through the process of scaling, certain terms of the Navier-Stokes equations are ignored and equation 4.4 reduces to

$$2\mathbf{\Omega} \times \mathbf{u} = -\frac{1}{\rho}\nabla p + \mu\nabla^2\mathbf{u} + \rho g\hat{z} \tag{4.6}$$

Further assuming the system to be in steady state and the fluid being inviscid, hydrostatic and adiabatic leads us to some important physical oceanography relations

1) Geostrophic balance

$$-f \cdot \mathbf{v} = -\frac{1}{\rho}\frac{\partial p}{\partial x} \tag{4.7}$$

$$f \cdot \mathbf{u} = -\frac{1}{\rho}\frac{\partial p}{\partial y} \tag{4.8}$$

The equations refer to a state of equilibrium where the coriolis force balances out the pressure gradient force.

2) Hydrostatic balance

$$0 = -\frac{\partial p}{\partial z} + \rho g \tag{4.9}$$

Hydrostatic balance in the ocean refers to a state where the upward force due to pressure (the pressure gradient force) is balanced by the downward force of gravity. This balance is foundational in understanding the structure and behavior of the ocean's water column and has implications for large-scale oceanographic phenomena.

4.2.1 Abyssal Layer Depth

This subsection is dedicated to deriving the equation that determines the Abyssal layer depth, which will facilitate a comparative analysis of the Atlantic Meridional Overturning Circulation (AMOC) characteristics across two distinct experimental setups.

Noting that ρ and f are independent from z and that g does not vary with x or y. When we differentiate the geostrophic balance equations with respect to z and apply the hydrostatic pressure assumption, we get a part of the thermal wind relation given as:

$$\frac{g}{\rho_0}\frac{\partial \rho}{\partial x} = f\frac{\partial u}{\partial z} \tag{4.10}$$

The thermal wind equation relates the vertical shear of ocean currents to horizontal density gradients (inferred from temperature and salinity differences). This equation illustrates that in regions with density gradients, ocean currents will change with depth due to the balance between Coriolis forces and horizontal pressure gradients.

In the absence of Coriolis force, Equation 4.10 becomes:

$$\frac{P_y}{\rho_0} = K_h u_{zz} \tag{4.11}$$

and then taking its vertical derivative, we get:

$$\frac{P_{yz}}{\rho_0} = K_h u_{zzz} \tag{4.12}$$

but we know the hydrostatic equilibrium as

$$P_y = \rho g \tag{4.13}$$

So substituting Eq. 4,13 into 4,12 we get:

$$\frac{g}{\rho_0}\frac{\partial \rho}{\partial x} \approx K_h \frac{\partial^3 u}{\partial z^3} \tag{4.14}$$

where K_h is the horizontal diffusion coefficient and u_{zzz} is the third partial derivative of the horizontal velocity. With the absence of the coriolis force, the vertical shear of the ocean currents to the horizontal density gradients is balanced by the diffusivity and depth integrated transport.

Another important relation to be kept in mind is from the (Munk, 1966) paper which relates the interplay between vertical advection and diffusion of density, essential in understanding stratification, mixing and maintaining thermocline structure given by:

$$w\frac{\partial \rho}{\partial z} = \frac{\partial}{\partial z}\left(K_z \frac{\partial \rho}{\partial z}\right) \tag{4.15}$$

where K_z is the vertical diffusion coefficient.

Another key assumption that is considered is the interchangeability between the zonal and meridonial derivative as portrayed in (Bryan, 1987) which is also a huge source of uncertainty as later discussed.

To find out an equation for the depth of the Abyssal layer, we start off by using the Continuity equation (Eq. 4,5):

$$\frac{u}{L} = \frac{w}{D} \tag{4.16}$$

where ’D’ is the abyssal layer depth and ’L’ is the meridonial length scale.

Using this relation to isolate vertical velocity w and plugging this relation into Munk’s density equation for advection - diffusion (Eq. 4,15), we get a an equation for zonal velocity given as:

$$\frac{u \cdot D}{L} = \frac{K_z}{D} \tag{4.17}$$

$$u = \frac{K_z \cdot L}{D^2} \tag{4.18}$$

Now, substituting Eq. 4,18 in the thermal wind relation (first for the case with coriolis force) we get:

$$\frac{fK_zL}{D^3} = g\frac{\rho}{\rho_0 L} \tag{4.19}$$

Rearranging the terms, we get an equation for the depth of the Abyssal layer with the presence of coriolis force as:

$$D_c^3 = \frac{fK_zL^2\rho_0}{g\rho} \tag{4.20}$$

where D_c represents the depth of the Abyssal layer depth with the coriolis force.

Now for the case of no coriolis force, we use Eq. 4,14 which reads as:

$$\frac{\rho g}{\rho_0 L} = K_h \frac{u}{D^3} \tag{4.21}$$

The Prandlt number (Pr) was used on to bridge the gap between the terms K_z and K_h and the relation is given as:

$$K_h \approx 10K_z \tag{4.22}$$

Substituting Eq. 4,22 and Eq. 4,18 into Eq. 4,21 we get:

$$\frac{\rho g}{\rho_0 L} = \frac{10K_z^2L^2}{D^5} \tag{4.23}$$

From this, we get the depth of the Abyssal layer depth for the case of no coriolis force as:

$$D_{wc}^5 = \frac{10K_z^2 L^2 \rho_0}{\rho g} \tag{4.24}$$

where D_{wc} represents the depth of the Abyssal layer with no coriolis force.

Now that the unknown terms have been avoided, a comparison between the two Abyssal layer depths are done to understand the quantifiable theoretical difference between the two experiments :

$$\frac{D_c}{D_{wc}} = \frac{\left(\frac{fK_z L^2 \rho_0}{g\rho}\right)^{\frac{1}{3}}}{\left(\frac{10K_z^2 L^2 \rho_0}{g\rho}\right)^{\frac{1}{5}}} \tag{4.25}$$

the right hand side upon further simplification first reads as:

$$1.58 \times K_z^{-\frac{1}{15}} \times L^{\frac{4}{15}} \times f^{\frac{1}{3}} \times g^{-\frac{2}{15}} \tag{4.26}$$

and then as:

$$1.58 \times f^{\frac{1}{3}} \times \left(\frac{L^4}{K_z g^2}\right)^{\frac{1}{15}} \tag{4.27}$$

substituting widely accepted values of these variables:

- Gravitational acceleration, g: $g = 10\,\mathrm{m/s^2}$
- Coriolis parameter, f: $f = 10^{-4}\,\mathrm{rad/s}$
- Meridonial length scale, L: $L = 1000\,\mathrm{km}$
- Diffusivity, K_z: $K_z = 10^{-4}\,\mathrm{m^2/s}$

The comparative analysis of Abyssal layer depths between scenarios with and without the Coriolis effect, as outlined in Equation 4.25, indicates a ratio of approximately 4. This finding theoretically supports the hypothesis that in the absence of the Coriolis force, a scenario with significant overturning circulation would result in a shallower Abyssal layer.

4.2.2 Strength of Overturning

The strength of the overturning is obtained by integrating the meridional transport across the Atlantic basin (zonally) and then doing a cumulative integral in depth. It can physically be represented as:

$$\Phi = U \cdot D \tag{4.28}$$

where U is the horizontal velocity component and D is the depth of the Abyssal layer.

Doing a compartive analysis for the cases of without coriolis force and with coriolis force, we get:

$$\frac{\phi_{wc}}{\phi_c} = \frac{U \cdot D_{wc}}{U \cdot D_c} \tag{4.29}$$

Substituting Eq. 4,18 in 4,29 we get the ratio to be almost 4 again as it boils down to the ratios of the depth of the Abyssal layers. Theoretical evidence indicates that in the absence of the Coriolis force, the overturning circulation could be up to four times stronger and concurrently shallower by a factor of four.

4.2.3 Steam function

Streamfunctions (ψ) are a powerful mathematical tool used in physical oceanography to analyze two-dimensional, incompressible, inviscid flows. They offer a concise and elegant way to represent the flow field and simplify calculations related to ocean circulation.

Mathematically, a streamfunction is defined in terms of the velocity components (u, v) as:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{4.30}$$

This equation represents the continuity equation, which ensures conservation of mass in the flow. By introducing the streamfunction, we can express the horizontal velocities in terms of ψ:

$$u = -\frac{\partial \Psi}{\partial y} \tag{4.31}$$

$$v = \frac{\partial \Psi}{\partial x} \tag{4.32}$$

By analyzing the contours of the streamfunction, we can visualize the pathways and intensity of major ocean currents. The mass transport across a specific section can be determined by calculating the integral of the normal velocity component across the section, which can be expressed in terms of the streamfunction. Streamfunctions also form the basis for numerical ocean models. By solving the governing equations for the streamfunction, along with other relevant equations (e.g., momentum equations), ocean models can simulate and predict ocean circulation patterns (Kundu, 1990) (Gill, 1982).

Results

5

In this section, we present the findings from our ocean model simulations. We start by describing the plots used to visualize the data and explain their significance. The initial focus is on the spin-up phase, establishing a baseline for the model's performance under normal conditions. To compare the model outputs we mainly focus on the data variables 'vsf_depth' from the overturning dataset which is essentially the vertical streamfunction and 'psi' from the averages dataset which is the horizontal streamfunction which gives us a comprehensive overview of the meridional overturning circulation.

5.1 Spin Up

We start by examining the Streamfunction lines of the thermohaline-driven circulation from the spin-up run, where the Coriolis force is active and wind forcing has been turned off. The Streamfunction represents the vertically integrated horizontal flow of water, providing a comprehensive view of the large-scale circulation patterns. This visualization helps us understand how the ocean circulation is influenced primarily by thermohaline processes, which are driven by temperature and salinity differences.

Figure 5.1 depicts the Zonal Streamfunction at the final time step (around 200 years) of the spin-up. The x-axis represents the zonal coordinates ranging from 0 degrees to 60 degrees while the y-axis represents the meridonial coordinates from -60 S to 60 N. Significant concentration of positive streamfunction values is observed near -60 degrees latitude, indicating a strong northward flow, likely associated with the Antarctic Circumpolar Current (ACC) or deep-water masses moving northward. In the upper layers and northern latitudes, the streamfunction values are relatively low, suggesting weaker surface currents. The circulation patterns appear relatively uniform in the zonal direction, indicating consistent flow across different longitudes within the model's domain.

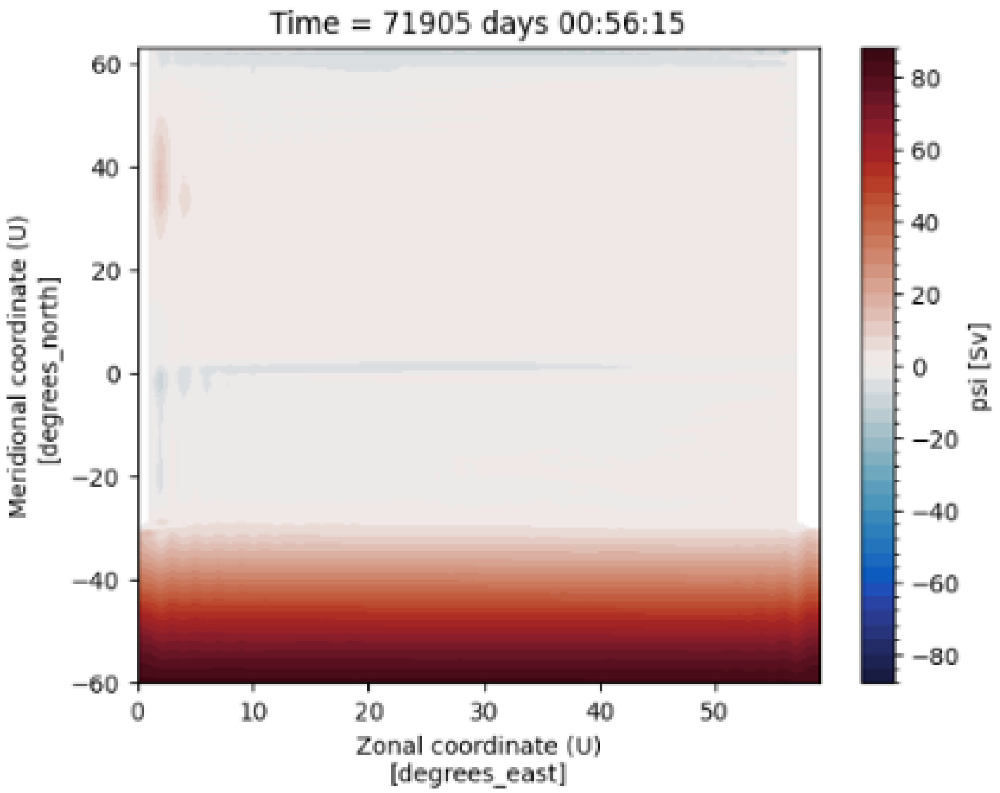

Figure 5.1: Zonal Streamfunction of Thermohaline-Driven Circulation After Spin-Up

Notably, the absence of subtropical gyres in the plot can be attributed to the lack of wind stress in the model.

Figure 5.2 shows the streamfunction contour plot of the meridional overturning circulation as a function of latitude on the x-axis and depth on the y-axis. The figure is a snapshot from the last time-step again at 200 years when the system has reached equilibrium. Around 0° latitude and between 3000 to 3500 meters depth, indicating significant upwelling and northward transport of deep water. Near 60°N latitude and at shallower depths, showing significant downwelling and southward transport in the upper layers of the ocean. This is consistent with the return flow of deep water masses to the surface. This visualization helps to understand the equilibrium state of the modeled ocean circulation under the influence of thermohaline forcing and the Coriolis effect, emphasizing the importance of density-driven processes in shaping the MOC without the influence of wind stress.

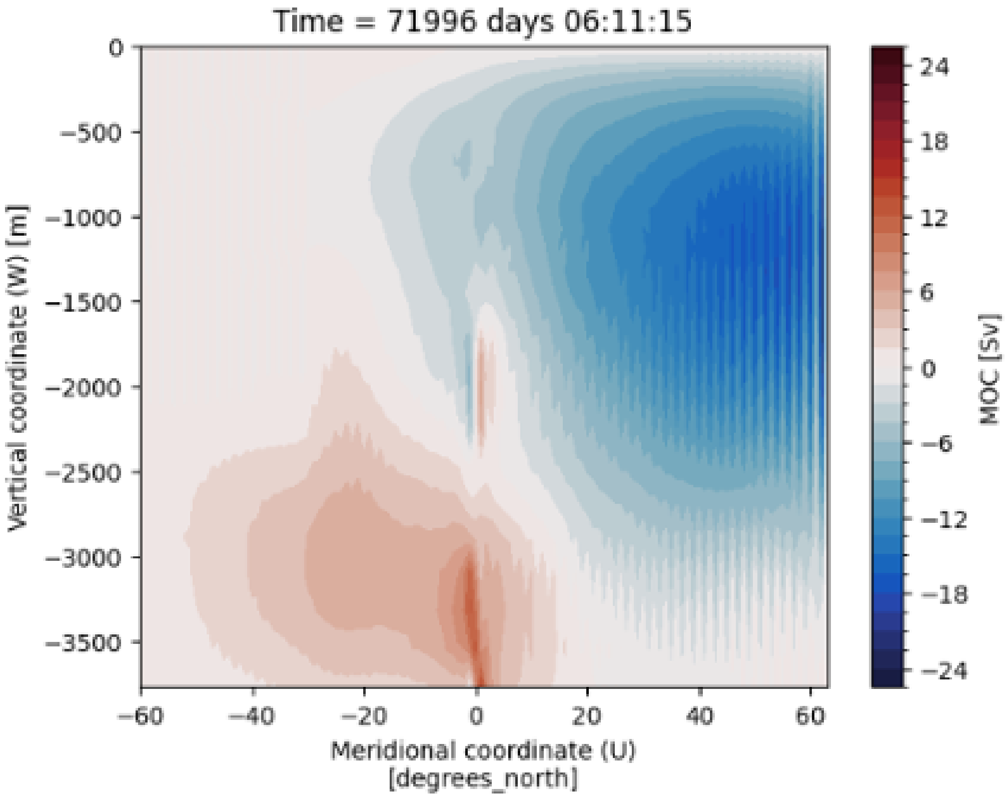

Figure 5.2: Meridional Overturning Circulation (MOC) Streamfunction After Spin-Up

5.2 A System in Chaos

This section presents the results obtained from simulations where the Coriolis force has been disabled. The figures illustrate the 'psi' and 'vsf_depth' parameters at the conclusion of a 400-year simulation period, following the deactivation of the Coriolis force after the initial spin-up phase.

Figure 5.3 refers to a highly disorganized and chaotic structure of the MOC streamfunction, with irregular and fragmented areas of positive and negative values throughout the depth and latitude range. Many regions with localised extremes are observed and a general lack of structured circulation can be inferred. Due to the absence of the coriolis parameter, there is a loss of geostrophic balance and a dominance of thermohaline forcing driving the movement of water leading to chaotic and unpredictable flow patterns. Another thing to note is the higher strength of the MOC flow at 80 Sv compared to 24 Sv in the spin up phase at the same cross sectional points. This could be

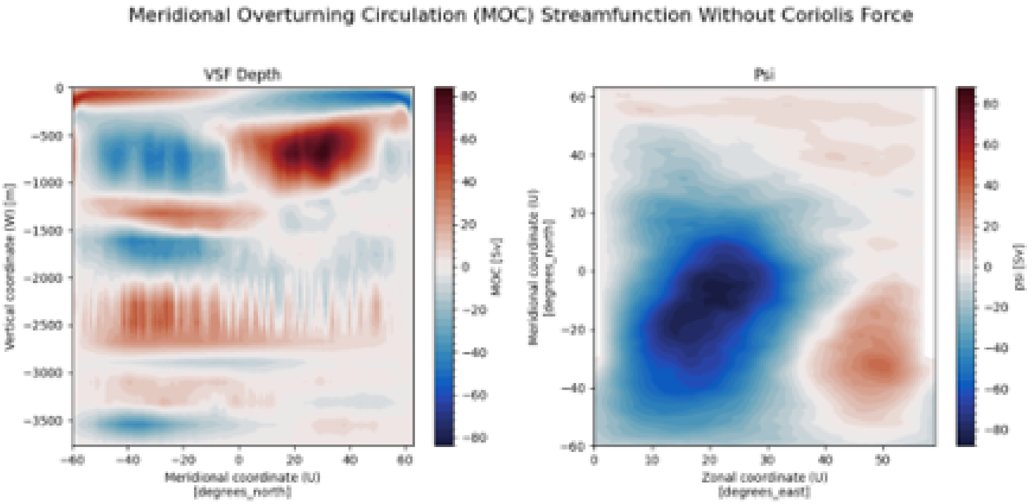

Figure 5.3: Meridional and Zonal Overturning Circulation Streamfunction Without Coriolis Force

thought of as due to increased vertical exchange of water masses and reduced lateral shear between the layers.

The results obtained above are drastically different from the control run of the spin-up phase where no parameters were altered. Figure 5.4 illustrates a predictable MOC pattern and strength, consistent with expected outcomes where things are in order.

5.3 Perturbation I

This section deals with the initial steps to reduce the noise obtained from turning off the coriolis parameter. As a first measure, two of the vertical parameters 'kappaM_min' - the vertical viscosity and 'kappaH_min' - the vertical diffusivity parameter were increased by tenfold in order to compensate for the lack of coriolis force and hopefully to get a distinct meridonial overturning circulation pattern. Figure 5.5 shows the results that were obtained.

From figure 5.5 it is clear that a lot of the noise from turning off the coriolis force has been reduced and the overturning circulation is taking shape although it has not been fully defined at this stage. But the strength of the circulation is still higher than the norm and it appears to be contained in the upper layers of the ocean. Looking at the 'Psi' plot on the right it is clear that the system is

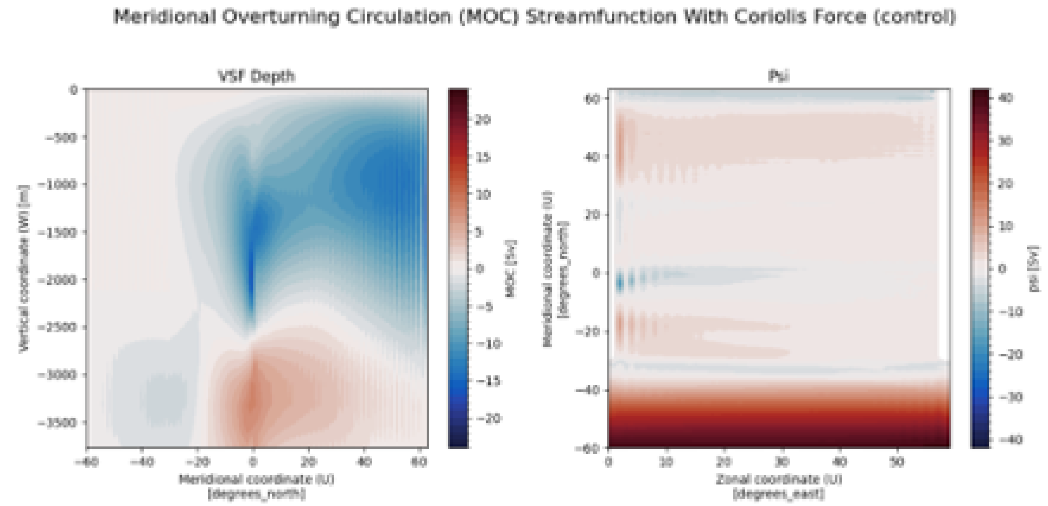

Figure 5.4: Meridional and Zonal Overturning Circulation Streamfunction With Coriolis Force (control run)

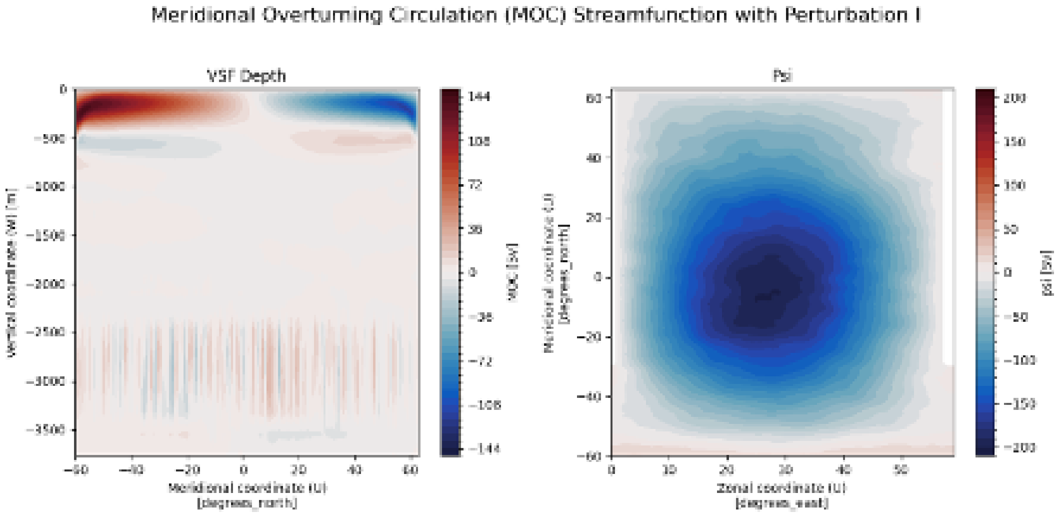

Figure 5.5: Meridional and Zonal Overturning Circulation Streamfunction With Perturbation I

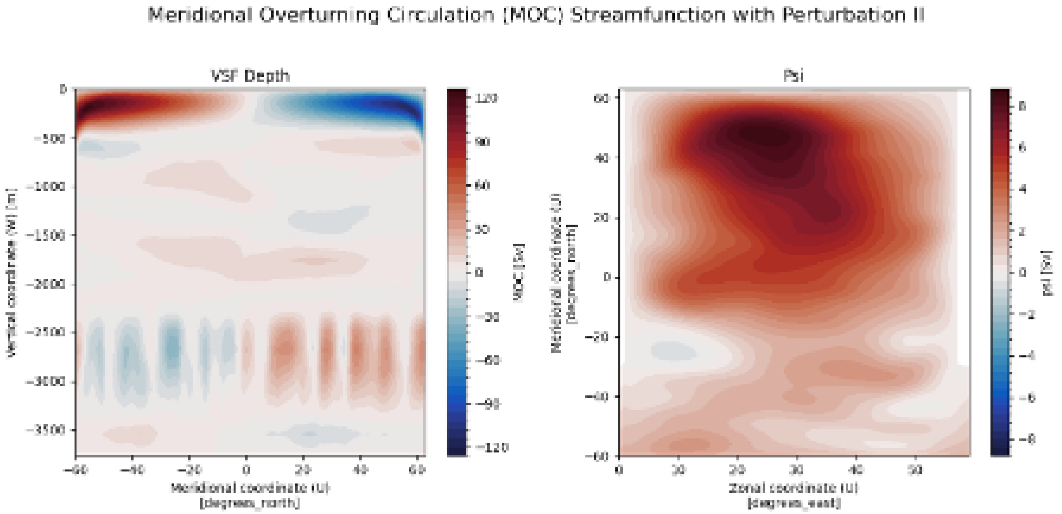

Figure 5.6: Meridional and Zonal Overturning Circulation Streamfunction With Perturbation II

not in equilibrium with a unusually high uni-directional gyre in the subtropics. The result of this perturbation can be inferred as promising and heading in the right direction for a world with a complete overturning circulation in the absence of coriolis force.

5.4 Perturbation II

As means to improve upon the previous iteration, the changes that was made for this run was: increasing the horizontal friction by a factor of 100 hoping this would compensate for the lack of geostrophic balance. This approach helps create a new temperature-driven flow pattern that could help stabilize the system when the Coriolis force is turned off. Figure 5.6 represents the results that were obtained

It is observed that a further comprehensive overturning circulation has been established with further noise reduction achieved in the deeper layers of the ocean. While the horizontal stream function plot still appears to be rather unpredictable. From the vertical stream function plot it can be deduced that there are two overturning cells and therefore, this perturbation step is taken as a stepping stone to obtain a more comprehensive and singular overturning circulation cell.

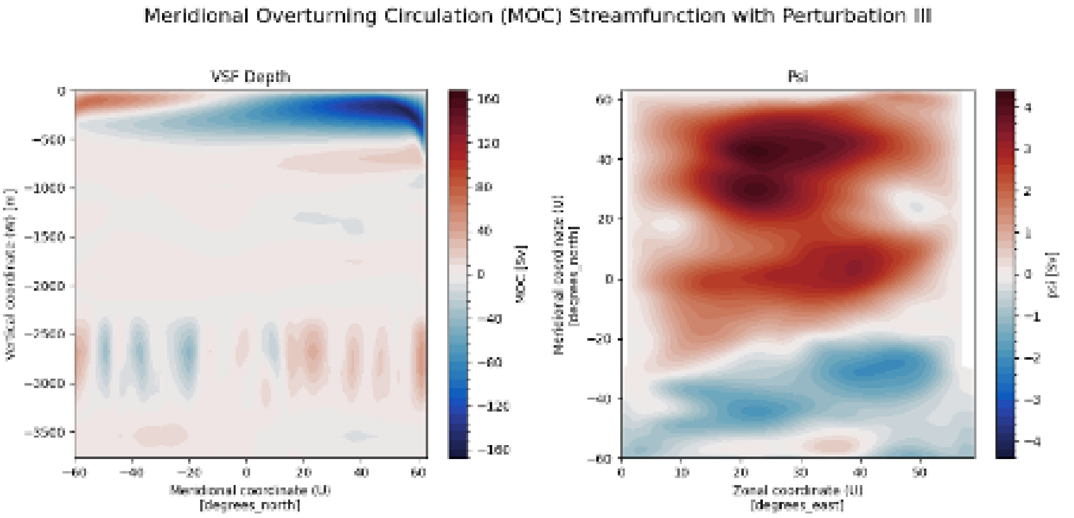

Figure 5.7: Meridional and Zonal Overturning Circulation Streamfunction With Perturbation III

5.5 Perturbation III

Further improving upon the previous iteration, the change that was made for this run was: making the temperature at the southern boundary 5° C higher than the northern boundary with the intention of getting only one overturning cell and suppressing the southern cell at the same time making analysis easier. This approach helps create a new temperature-driven flow pattern that could help stabilize the system when the Coriolis force is turned off. Figure 5.7 represents the results that were obtained

It is observed that a development of one complete overturning cell has been achieved and this is where we stop with our changes we make to the oceanic model even though the horizontal stream function is still in tatters and unpredictable due to the lack of wind stress. It is observed that the generated vertical stream function is at a magnitude of almost 4-5 times in strength when compared to the case where there is coriolis force and shallower by the same amount.

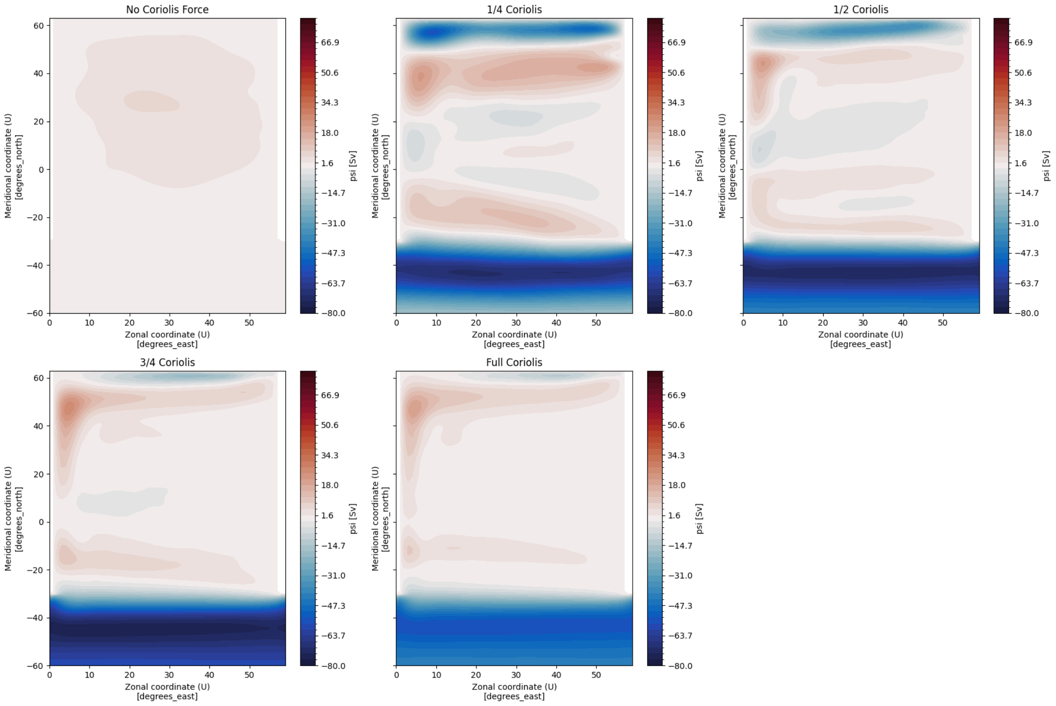

Figure 5.8: Impact of Varying Coriolis Forces on the Horizontal Stream Function

5.6 Turbulant Evolution

This section sheds light on how the variation in the magnitude of the coriolis force has an affect on the shape and strength of the overturning circulation with the same specifications retained as from the previous run. Figure 5.8 and 5.9 shows the results from several runs where the coriolis force has been increased in increments of 0.25.

Figure 5.8 is the depiction of the evolution of the horizontal stream function or the 'Psi' parameter from the averages dataset. The trend goes from weak and disorganized in the first subplot where there is no coriolis force to the gyres taking shape upon injection of the coriolis force and it's stabilised form in the last subplot where there is full coriolis force. The higher value of the 'Psi' values can be attributed to the enhanced model parameters. The introduction of the Coriolis force stabilizes the horizontal stream function, reducing chaotic flows. Enhanced diffusivity and friction dampen smaller eddies, while the absence of wind stress minimizes surface currents. This results in a more organized, stable overturning circulation with diminishing regions of upwelling, indicated by the reduction of upward vertical flow near the top.

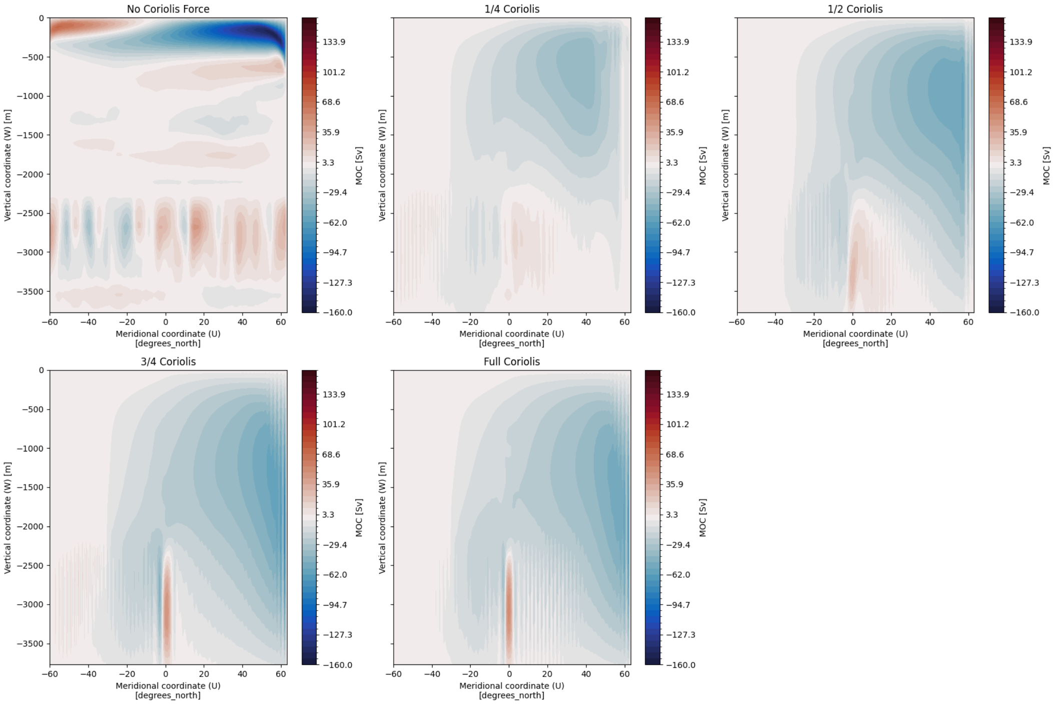

Figure 5.9: Impact of Varying Coriolis Forces on the Vertical Stream Function

Figure 5.9 illustrates the evolution of the vertical stream function, represented by the 'vsf_depth' parameter from the overturning dataset. Initially, with no Coriolis force, the vertical stream function is highly chaotic and disorganized. As the Coriolis force is gradually introduced, from 1/4 to full strength, the vertical stream function becomes increasingly structured and stable.

The presence of the Coriolis force significantly influences the vertical circulation, organizing the water movement into coherent patterns. Enhanced diffusivity and friction within the model help to dampen smaller eddies and irregularities, while the absence of wind stress limits surface disruptions. Consequently, the vertical overturning circulation shows reduced regions of vertical movement, particularly upwelling and downwelling, leading to a more stable and organized pattern. The highest values of the 'vsf_depth' parameter can be attributed to the enhanced model parameters, reflecting a more robust and stabilized circulation system.

In the vertical stream function plots, a significant overturning strength of 160 Sv is observed without the Coriolis force, primarily concentrated in the top 500-700 meters of the ocean. When the Coriolis force is introduced, the maximum overturning strength reduces to 53 Sv, indicating upwelling, and is distributed more variably throughout the ocean layers. Additionally, a minimum value of -81 Sv, indicating downwelling, is concentrated in the deeper layers of the ocean model between 2500-3500 meters. This demonstrates how the presence of the Coriolis force significantly alters the magnitude and distribution of the overturning circulation in the ocean

Discussion

6

6.1 Uncertainties

While no ocean model can perfectly replicate the complexity of the real world, certain uncertainties are inherent in the VEROS model and its outputs. These uncertainties stem from the simplifications, parameterizations, and assumptions necessary for model implementation. Consequently, the results produced by the VEROS model should be interpreted with an understanding of these limitations and potential sources of error.

While the simplified box version of the VEROS model provides valuable insights into ocean circulation processes, it also introduces several uncertainties due to its idealized nature and the exclusion of critical forcing mechanisms. The lack of real world continental barriers is a huge source of uncertainty as they play a crucial role in shaping ocean currents, gyre formations, deep water circulation, and upwelling/downwelling zones. The VEROS model is also devoid of a bottom topography and this could lead to deep water currents dispersing more broadly and losing intensity, impacting the global thermohaline circulation. This would reduce the efficiency of deep water mass formation and transport, affecting the global distribution of nutrients and heat (Todd *et al.*, 2019). There is currently no ice sheet model in VEROS. Some realistic setups employ a simple ice mask that cut off atmospheric forcing for water that gets too cold instead (The VEROS Development Team, 2023). This of course has a direct impact on the North Atlantic Deep Water (NADW) formation (Muschitiello *et al.*, 2019).

Solving continuous numerical equations also introduces noise in a few ways and no ocean model is completely free of this. The process of discretization which is converting these continuous governing equations into discrete algebric equations involves approximating integrals and derivatives using finite numerical schemes. These schemes can't perfectly capture the continuous behavior, leading to errors (Roy, 2012). These errors can manifest as noise in the model solutions particularly at high frequencies waves or near sharp gradients. Some numerical schemes approximate derivatives in the governing equations by neglecting higher-order terms. This simplification, called truncation, can lead to errors in the model solutions. These errors can sometimes appear as noise, particularly at high frequencies or in complex flows. Moreover, models of coarse resolution may not resolve the sub-grid processes which causes "sub-grid process discrepancy" (Sun *et al.*, 2021).

6.2 Simulated Futures

Both the VEROS model output and the theoretical predictions indicate that the meridional overturning circulation (MOC) would be stronger and confined to the upper echelons of the ocean in the absence of the Coriolis force. Although they follow a similar trend, there is a slight difference in their magnitudes.

	Strength of Circulation	**Abyssal Layer Depth**
With Coriolis	$\approx$ 53 Sv	$\approx$ 1700m
Without Coriolis	160 Sv	500m

Table 6.1: Comparison of Absolute Max Circulation Strength and Abyssal Layer Depth With and Without Coriolis Force

Table 6.1 summarizes the results obtained from the model runs following the final perturbation, demonstrating a strong alignment with theoretical predictions. The maximum circulation strength in downwelling regions is just over three times higher without the Coriolis force. The abyssal layer depth with the Coriolis force is similarly just over three times deeper. Comparative analysis using Equation 4.25 indicates that, under normal conditions, the abyssal layer depth is predicted to be four times deeper and the strength of circulation to be approximately one-fourth as strong compared to the case with no Coriolis force.

The model's underestimation of the theoretical predictions provides another avenue for discussion. It could be due to a lack of parametrization of some real world factors or numerical approximations done in the model and this is point of departure where the study should be further studied into. What this means is that the coriolis force is responsible for a deeper and a balanced overturning circulation with better energy dissipation. This observation can be attributed to the fundamental dynamics governing ocean circulation and the specific alterations in diffusivity, viscosity, and friction. The simultaneous increase in vertical diffusivity and viscosity may seem counter-intuitive, as they typically have opposing effects on vertical motion. However, their combined impact can be understood through the specific dynamics of ocean circulation. Increased vertical diffusivity enhances the mixing of water masses, leading to a more uniform distribution of temperature and salinity. This less stratified ocean supports stronger vertical motions, contributing to a shallower yet more robust overturning circulation. Enhanced vertical mixing facilitates the upward and downward movement of water. Higher vertical viscosity does not directly increase vertical mixing; rather, it acts to stabilize the flow by damping turbulence and reducing small-scale instabilities. This stabilization ensures that vertical motions driven by diffusivity and density gradients remain coherent and less chaotic. Thus, while vertical viscosity itself does not enhance vertical mixing, it plays a role in maintaining a stable environment where the effects of increased vertical diffusivity can be more effective and thus it leads to a shallower and stronger overturning circulation at the end of "Perturbation I" (Section 5,3). Increased horizontal friction dampens horizontal velocity gradients, leading to a more uniform horizontal flow. This frictional damping reduces the lateral spreading of water masses, confining the circulation to a shallower depth. The combination of enhanced mixing and reduced lateral spreading results in a more concentrated and vigorous overturning cell as observed at the end of "Perturbation II" (Section 5,4). Horizontal friction contributes to the dissipation of kinetic energy in the ocean. By reducing horizontal shear, the energy associated with small-scale motions and turbulence is dissipated more effectively, promoting a stable and robust Thermohaline Circulation. Thermohaline forcing still remains the largest contributor the movement of water even in the world without a coriolis force, but the interplay with other physical parameters as discussed has lead to a reshaping of the overturning circulation.

Another theoretical deduction about the strength of the circulation given by:

$$\Phi = U \cdot D \tag{6.1}$$

To bring in the coriolis term into this equation we are replacing the horizontal velocity component from the thermal wind relation and it takes the form:

$$U = \frac{gD}{Lf\rho_0} \tag{6.2}$$

and the abyssal layer depth takes the form of Equation 4,20:

$$D_c = (\frac{fK_z L^2 \rho_0}{g\rho})^{1/3} \tag{6.3}$$

Substituting Equation 6,2 and 6,3 into 6,1 it is clear that the strength of the overturning is proportional to the coriolis with the relation:

$$\Phi \propto f^{-\frac{2}{3}} \tag{6.4}$$

Model run outputs for the absolute maximum 'vsf_depth' values at 30 N for various levels of coriolis force is depicted in Figure 6,1

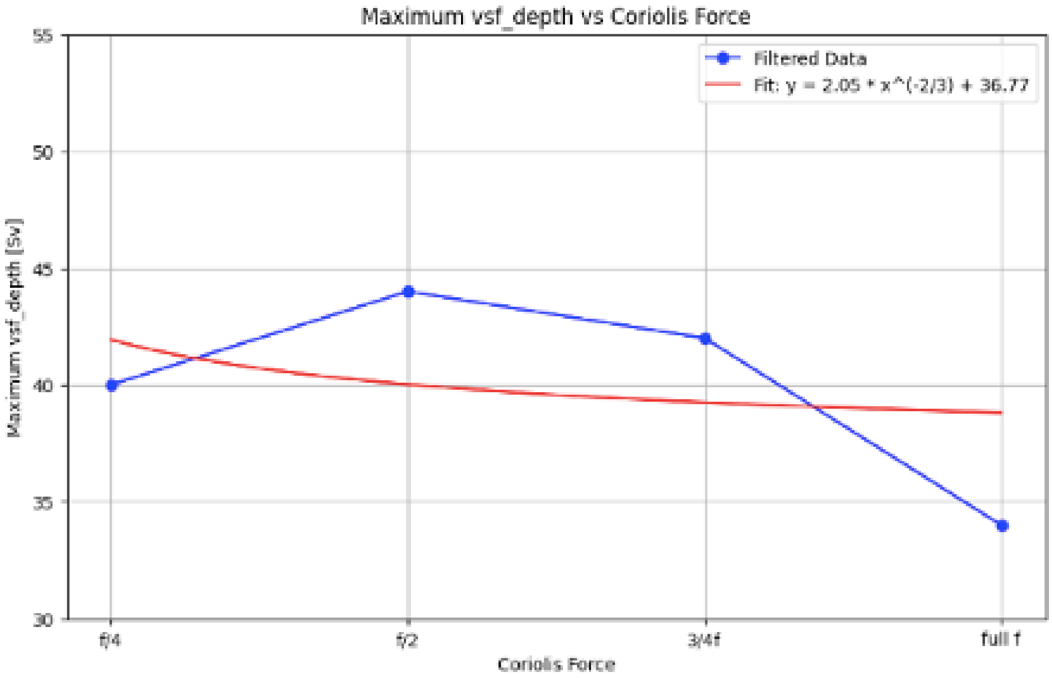

Figure 6.1: Overturning Strength for different orders of coriolis force fitted to $f^{-\frac{2}{3}}$

From Figure 6,1 it is evident that except for the point at ’f/4’ the others points seem to follow the trend backed by theory. This is of course a small sample size and further studies can look into the anomaly in the case of ’f/4’.

6.3 AMOC and Climate Change

The role of the AMOC cannot be understated in the Earth’s climate system by regulating global temperatures and maintaining the Thermohaline circulation (Rahmstorf, 2002). One of the key functions of the AMOC is its role in regulating the temperature of the North Atlantic through the Gulf Stream. The Gulf Stream, a powerful ocean current originating in the Gulf of Mexico, transports warm tropical waters northward along the eastern coast of the United States and across the Atlantic Ocean to Western Europe. This warm water transport significantly influences the climate of the North Atlantic region, contributing to milder winters and more temperate conditions in Western Europe compared to other regions at similar latitudes (Bryden *et al.*, 2005) (Zhang, 2008).

Climate change poses significant risks to the stability and strength of the AMOC. Increased greenhouse gas emissions lead to global warming, which in turn affects the density gradients that drive the AMOC. Melting polar ice and increased precipitation dilute seawater, reducing its salinity and density, which can weaken the deep-water formation in the North Atlantic. A weakened AMOC could result in drastic climate changes, including cooling of the North Atlantic, disruption of weather patterns, and impacts on marine ecosystems (Caesar *et al.*, 2018). The general consensus seems to be of a slow down of the AMOC with the backdrop of increasing anthropogenic emissions with some studies speculating the collapse as early as 2050 (Peter Ditlevsen, 2023).

Simulations from the CMPI6 ensemble as seen in Figure 6,1 also seem to point a slow down and eventual "tipping" of the AMOC leading to catastrophic chain of events. Given the uncertainties surrounding future Representative Concentration Pathways (RCPs) and the inherent model uncertainties, it is increasingly critical to understand the physical mechanisms driving the Atlantic Meridional Overturning Circulation (AMOC). This paper aims to elucidate

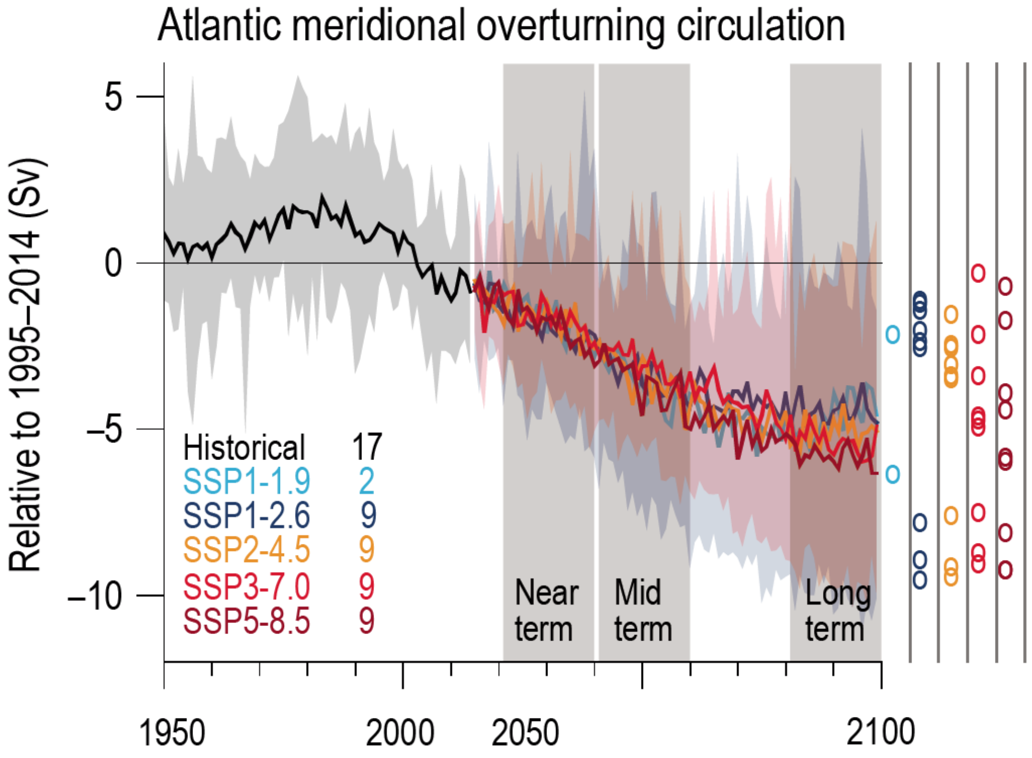

Figure 6.2: CMIP6 annual mean Atlantic Meridional Overturning Circulation (AMOC) strength change in historical and scenario simulations from (Lee *et al.*, 2021).

these mechanisms. Some of the leading hypotheses that are used to explained the driving mechanism is:

- The AMOC is controlled by the meridional density difference (Stommel, 1961) (Boer *et al.*, 2010).
- The AMOC is controlled by the Southern Ocean winds (Toggweiler and Samuels, 1995).
- The AMOC is controlled by the strength of the deep water formation in the North Atlantic (Rhein *et al.*, 2011) (Delworth and Zeng, 2016).
- The AMOC is controlled by the strength of the subpolar gyre (Böning *et al.*, 1996).

While (Kuhlbrodt *et al.*, 2007), seems to suggest that it could be a combination of two or more of the above stated hypotheses, there is a need of the hour to completely nail down the complete physical mechanisms governing the AMOC.

6.4 Further Studies

In this section, we will explore potential avenues for future research on the physical mechanisms driving the AMOC based on the findings and limitations of the current study. Future research should extend to examining how wind-driven circulation responds to variations in the Coriolis force. Wind-driven circulation, influenced by surface wind stress, plays a crucial role in shaping oceanic currents and their interaction with thermohaline processes. By analyzing the impact of the Coriolis force on wind-driven components, such as the Ekman transport and gyre circulations, we can better understand the holistic behavior of ocean currents under different rotational scenarios. There is also room for the manipulation of other model parameters which can help us understand the full physical mechanism driving the AMOC.

More laboratory studies should also be conducted in the style of (Whitehead *et al.*, 2003), where the lack of coriolis force can be realistically mimicked in an experimental setup.

Conclusion

7

This study aimed to investigate the effect of the Coriolis force on the Atlantic Meridional Overturning Circulation (AMOC). The research involved theoretical scaling analysis and computer simulations using the ocean model VEROS. Through theoretical analysis, we derived equations for the abyssal layer depth with and without the influence of the Coriolis force and calculated the strength of the overturning circulation. The simulations corroborated these theoretical findings, demonstrating that the overturning circulation is both shallower and stronger by a magnitude of almost 3-4 times in the absence of the Coriolis force. The strength of the overturning is poised to change with the Coriolis force as:

$$\Phi \propto f^{-\frac{2}{3}} \tag{7.1}$$

The primary reason for this significant change is the loss of geostrophic balance, replaced by increased vertical diffusivity, viscosity, and lateral friction. These factors drive the overturning circulation into the upper echelons and with even higher energy. The results of this study are significant as they enhance our understanding of the mechanisms behind the AMOC, an area not yet fully established in oceanographic research.

The research questions posed at the beginning of this thesis have been addressed through both theoretical and computational methods. Specifically, we demonstrated that the absence of the Coriolis force results in a more vigorous and shallower overturning circulation, highlighting the critical role of geostrophic balance in modulating the AMOC.

Despite the valuable insights gained, this study has some limitations. The experimental setup did not include the effects of wind stress, focusing solely on the thermohaline circulation. This limitation may affect the applicability of the results under more realistic oceanic conditions where wind stress plays a significant role.

Future research should explore the inclusion of wind stress in ocean models to provide a more comprehensive understanding of the AMOC. Investigating this aspect could offer deeper insights into the interplay between different forces driving the overturning circulation and help overcome the limitations identified in this study.

In conclusion, this research provides important contributions to our understanding of the AMOC by elucidating the impact of the Coriolis force. It is hoped that these findings will pave the way for further research and practical applications in oceanography, shedding light on the complex dynamics of the AMOC and setting in motion other relevant studies that can achieve a more comprehensive understanding of this critical oceanic process.

8

Perspectives

The findings of this study on the effect of the Coriolis force on the Atlantic Meridional Overturning Circulation (AMOC) have several broader implications. Understanding the mechanisms that drive the AMOC is crucial for predicting future climate changes, as the AMOC plays a key role in regulating global climate patterns. This research contributes to our broader understanding of ocean dynamics and their impact on climate systems.

From a practical perspective, the insights gained from this study can inform climate models and improve their accuracy in predicting future climate scenarios. Policymakers and climate scientists can use these findings to develop more effective strategies for mitigating the impacts of climate change. The increased understanding of the AMOC's behavior without the Coriolis force can also aid in the design of better oceanographic experiments and observational programs.

Looking into the factors that will affect the rotation of the earth, tidal friction - the gravitational interaction between the Earth and the Moon, is one of the main factors slowing down the Earth's rotation. The friction occurs due to the deformation of the Earth and ocean tides as the Earth rotates. Over geological timescales, this results in the gradual lengthening of the day. Tidal friction causes the Earth's rotation to slow down by approximately 1.7 milliseconds per century (Dickman, 1993) (Tides and the Earth's Rotation, 2024). Interactions between the Earth's core and mantle also affect the rotation rate. Variations in the flow of the liquid outer core can change the distribution of mass within the Earth, affecting its rotational dynamics. These interactions can lead to changes in the Earth's rotation rate over decades to centuries (Tides and the Earth's Rotation, 2024). Post-glacial rebound, the process of the Earth's crust rising after being depressed by the weight of ice sheets, redistributes the Earth's mass and can affect its rotation. This process occurs over thousands of years as the crust slowly returns to its original shape after the melting of large ice sheets (Dickman, 1993). Although the the change in earth's rotation is in large timescales, it is important to have a perspective on this as part of this study.

In the long term, this research envisions a future where the mechanisms behind the AMOC are fully understood, allowing for more accurate climate predictions and better-informed climate policies. Continued exploration of the factors influencing ocean circulation will be essential in achieving this goal, paving the way for a deeper comprehension of our planet's climate system and its future trajectory.

9

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