Impacts of River Runoff in the Arctic Ocean: Modelling Changes in Flow and Temperature

by

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Abstract

River runoff plays a very important role in the Arctic Ocean. The Arctic Ocean accounts for around 1% of the total world ocean volume, but receives around 11% of the worlds river runoff. In addition, the Arctic Ocean is a β ocean, where stratification is primarily determined by salinity as opposed to temperature as in most of the worlds oceans. This makes many processes in the Arctic Ocean sensitive to changes in river discharge. With climate change, inflow from rivers is expected to increase into the Arctic Ocean. River water temperatures are also rising, which will increase the heat flux from rivers into the Arctic Ocean. Ocean models can provide an important tool to understand the Arctic's response to these changes. This thesis will first introduce background information on Arctic Ocean processes, focusing on freshwater and river runoff. Ocean modelling basics will be reviewed, as well as specific information on the modelling configuration used in this work. The sensitivity of ocean model simulations to different river runoff forcing will be investigated. This will look at regional impacts particularly in the Canadian Arctic, and the propagation of runoff increases downstream into the North Atlantic. Riverine heat flux into the Arctic Ocean is also examined, by incorporating river water temperature information into ocean model simulations. Particular focus is given to the associated heat fluxes into the Arctic Ocean, as well as the impacts on sea ice.

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Chapter 1

Introduction

1.1 Arctic Ocean and Climate Change

The Arctic Ocean is the smallest of the world's five oceans, and has many unique properties. It is a shallow, highly stratified basin with water exchange with the Pacific and Atlantic Oceans. The Arctic Ocean is sometimes referred to as the Arctic Mediterranean, as it is a large deep basin of water, surrounded by land and smaller, shallow channels (Timmermans et al., 2020). See figure 1.1 for bathymetry of the Arctic Ocean and North Atlantic. Relatively warm and salty Atlantic water enters the Arctic Ocean through Fram Strait and the Barents Sea opening (Schauer et al., 2004). The only gateway between the Arctic and Pacific Ocean is through Bering Strait (Woodgate et al., 2012). Outflow from the Arctic Ocean to the North Atlantic goes through the Canadian Arctic Archipelago, and along the eastern side of Greenland through Fram Strait (Timmermans et al., 2020).

There are two main defining features of the surface level circulation in the Arctic Ocean, the Beaufort Gyre and the Transpolar Drift (Armitage et al., 2017). The Beaufort Gyre circulation is centered in the Canadian Basin, and is caused by the corresponding atmospheric circulation, the Beaufort high (Proshutinsky et al., 2019). The Transpolar Drift flows from the coast of Siberia, across the Arctic and into the North Atlantic down the east coast of Greenland (Timmermans et al., 2020). The strength and orientation of the Transpolar Drift is a consequence of the relative strengths of the atmospheric features, the Beaufort high and the Icelandic low (Timmermans et al., 2020). Over recent years, the Beaufort high and the Transpolar Drift have been seen to be strengthening, as a result of the current atmospheric patterns in the region (Kwok et al., 2013). The Beaufort Gyre can act as a reservoir for freshwater due to Ekman pumping. In the Northern hemisphere, a high pressure system in the atmosphere creates a corresponding anticyclonic circulation in the ocean, which then collects water from the surface in its Ekman layer. Since salinity dominates stratification in the Arctic Ocean, freshwater sits at the surface. This anticyclonic circulation then has a converging affect on freshwater, serving to thicken the freshwater layer at the surface of the Beaufort gyre. So strengthening of the Beaufort high can lead to increased freshwater storage in the Canadian basin, as the Beaufort gyre circulation strengthens, as well as a possible change in the pathways of freshwater from the changes in the Transpolar Drift.

Circulation in the North Atlantic is dominated by the sub-polar gyre. Wind driven Ekman transport creates a sea surface minimum in the center of the cyclonic gyre (Foukal et al., 2017). There is low stratification within the region, so topography can steer the currents even in the surface layers (Tréguier et al., 2005). Warm surface waters are brought northward from the mid latitudes in the North Atlantic Current, which originates near Grand Banks where the Gulf Stream branches. The central Labrador Sea is a key region for the Atlantic Meridional Overturning Circulation (AMOC), as it is one of the only sites for deep water formation. The interior of the Labrador Sea is weakly stratified, and in the winter there is a buoyancy loss from the ocean to the atmosphere, as the water is warmer than the surrounding air. This creates a saline, cold water mass which sinks deep in the water column. This deep convection creates Labrador Sea Water, a component of North Atlantic Deep Water, which is a key southward water mass in the AMOC.

As the global climate continues to change, from anthropogenic and natural processes, changes are expected in the Arctic Ocean. The Arctic overall is warming at double the global rate (*Canada's Changing Climate Report* 2019, Hanna et al., 2019). This phenomenon is termed Arctic Amplification, where 'trends and variability in surface air temperature tend to be larger in the Arctic region than for the Northern Hemisphere or globe as a whole' (Serreze et al., 2011). The IPCC report predicts that a 2° rise in global mean temperature by 2100 will translate to a 4° to 7° rise in Arctic temperatures (Aragón–Durand et al., 2018). As temperatures continue to increase in the Arctic, this can have large impacts on many processes in the Arctic Ocean. Summer sea ice extent has been steadily declining since satellite observations began over 40 years ago (Stocker, 2014), and sea ice is getting younger and thinner (Lindsay et al., 2015). A seasonally ice free Arctic is expected before mid-century based on current emission trends (Notz et al., 2018). Large changes have also been seen in freshwater sources and storage in the Arctic Ocean (Jahn et al., 2020).

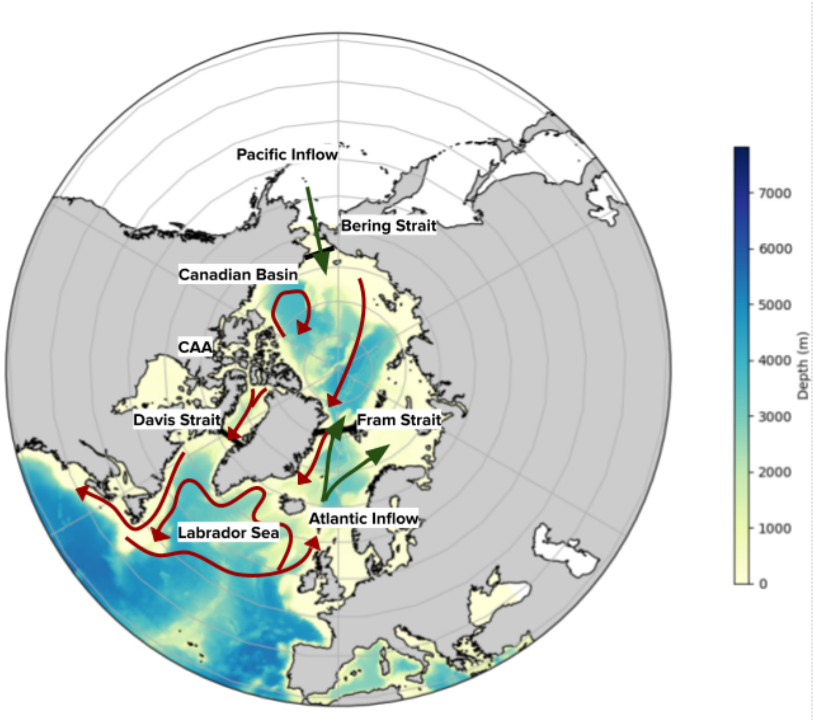


Figure 1.1: Map of the Arctic Ocean and North Atlantic, with the depth indicated by the colour scale, the generalized large scale circulation patterns indicated in red, primary inflows shown in green, and major gateways in black.

1.2 Freshwater in the Arctic Ocean

Freshwater plays a key role in the Arctic Ocean. Freshwater in this case is defined relative to a reference salinity, commonly the estimated mean salinity of the Arctic Ocean, from Aagaard et al. (1989). It is defined in this manner because in the Arctic Ocean, salinity is the main factor in determining the stratification of the water column. Water masses that are fresher than the mean salinity of the Arctic will be less dense, and will sit at the surface. This is in contrast with many other oceans, where temperature is the dominant factor in determining stratification (Timmermans et al., 2020). A consequence of salinity determining stratification is that it there can be then relatively warm, saltier water below fresher, colder water. This acts to stop mixing of the water column, and prevent heat convecting to the surface. Within the Greenland, Iceland and Norweigan seas, deep convection is mainly restricted to the cyclonic gyres. If the flux of fresh water into this region were to increase, this could cap these convective gyres, and weaken the overturning circulation and ocean ventilation which occurs there. The opposite effect, could lead to a “halocline catastrophe”, where the loss of the fresh water cap in much of the Arctic could allow deep water convection, and cause large vertical heat fluxes, an idea proposed by Aagaard et al. (1989).

There is a strong freshwater cycle in the Arctic Ocean, as it is an enclosed basin surrounded by land. As such, it receives large amounts of freshwater runoff from northward draining rivers from Eurasia and North America. It also receives freshwater from precipitation minus evaporation, and relatively fresh inflow from the Pacific through Bering Strait. Bering strait is a narrow strait, approximately 85km at its narrowest point, and is the only gateway between the Pacific and Arctic Oceans. It has a climatological flow estimate of approximately 0.8 Sv (Roach et al., 1995), and contributes around 1/3 of the freshwater entering the Arctic Ocean (Aagaard et al., 1989). The volume of Bering Strait inflow has almost doubled from observational data between 2001 to 2011 (Woodgate et al., 2012). The highest observed flow in the record was in 2014 of 1.2 Sv, which is over 60% higher than climatology (Woodgate, 2018). This change in volume transport impacts the freshwater and heat transport through the strait. Freshwater flux through the strait went from 2000-2500 km^3 in 2001 to 3000-3500 km^3 in 2011 (Woodgate et al., 2012). There is also large inter-annual variability in inflow amounts, with variation of approximately 1000 km^3 (Woodgate et al., 2012).

In recent years, there have been many changes seen in Arctic freshwater sources and pathways. These freshwater changes are likely linked to anthropogenic climate change (Haine, 2020). From climate model predictions of the 21st century, solid and liquid freshwater storage are the first observed impacts of climate change on the Arctic freshwater budgets, separable from natural variability (Jahn et al., 2020). Observed freshwater content changes have been dominated by strong increases in the Canadian basin, balanced by decreases in the Eurasian basin, from Morison et al. (2012). From Haine et al. (2015), more than half the freshwater storage in the Arctic is in the Canadian basin. Observations have shown a 40% increase in liquid freshwater content in the Beaufort Gyre, relative to climatology from the 1970s (Proshutinsky et al., 2019). In contrast, solid freshwater stored in sea ice has decreased. It has decreased by approximately 10 % for maximum sea ice coverage, and approximately 40 % for minimum sea ice coverage (Solomon et al., 2021).

1.3 Arctic River Runoff

River runoff is the largest source of freshwater discharge in the Arctic Ocean (Stadnyk, Broesky, et al., 2019). River discharge contributes around half of the freshwater discharge into the Arctic Ocean, and the Arctic Ocean receives approximately 11% of the worlds river discharge, while accounting for only 1% of the total ocean volume (Aagaard et al., 1989). The major rivers draining into the Arctic basin are shown in table 1.1. It is approximated that 40 million people could be impacted by changes in the Arctic river systems, particularly in Canada (Déry et al., 2011). Many studies agree that river runoff into the Arctic Ocean has been increasing in recent years (Arnell, 2005, Durocher et al., 2019 and Stadnyk, Broesky, et al., 2019). These increases are due to increased precipitation, permafrost melt, and human intervention affecting river flow (Stadnyk, Broesky, et al., 2019). In Durocher et al. (2019) they considered the stream flow records for rivers feeding into the Arctic Ocean, and they found an increase in river runoff from all sources considered, for the time period 1975-2015. Changes in discharge patterns of river runoff have also been observed. In coupled land-ocean-ice model simulations Park, Yoshikawa, et al. (2016) found 'regional trends toward later fall freezeup, earlier spring breakup, and consequently a longer annual ice-free period'. Increases in freshwater storage in the Beaufort Gyre has been linked to increasing river runoff (Proshutinsky et al., 2019). Proshutinsky et al. (2019) argues that the major source of river runoff is from the McKenzie river, while in contrast Morison et al. (2012) argues that the runoff from the Eurasian rivers being diverted into the Canadian basin is the major source. They agree though that river runoff is one of the major sources of the freshwater increase observed. From climate models, the pan-Arctic domain is expected to become wetter as the climate continues to warm (MacDonald et al., 2018). Arnell (2005) found that all the climate models used in their study saw an increase in precipitation, especially over the catchment region for river flow into the Arctic, under both the high and low emissions scenarios. Stadnyk, Broesky, et al. (2019) projected a 22% increase overall in river discharge into the Arctic by 2070.

River discharge can also be a source of heat for the Arctic Ocean. River discharge temperatures into the Arctic ocean can reach over 15 °(Lammers et al., 2007, Yang et al., 2021). The heat flux from the Mackenzie river alone has been observed at 9.5×10^{12} MJ (Yang et al., 2021). From high resolution climatological records, the estimated riverine heat flux is equivalent to 44% of the oceanic heat flux associated with Bering Strait (Whitefield et al., 2015). With increasing air temperatures in the Arctic, river water temperature is also expected to increase. Water temperatures have been shown to closely follow air temperature on a seasonal time scale (Sinokrot et al., 1993), and with increasing temperature more heat from river runoff is expected to Arctic Ocean (Yang et al., 2021). Increased river temperatures could potentially affect sea ice formation and melt, particularly in the Arctic shelf regions (Whitefield et al., 2015). In coupled model simulations Park, Watanabe, et al. (2020) showed that 'river heat contributed to up to 10% of the regional sea ice reduction in the Arctic shelf

Basin	Observed Mean Daily Discharge (m^3/s)	Continent
Yenisey	19,499	Eurasia
Lena	17,773	Eurasia
Ob	12,889	Eurasia
Mackenzie	9,211	N. America
Khatanga	6,757	Eurasia
Yukon	6,576	N. America
Pechora	4,823	Eurasia
Severnaya Dvina	3,416	Eurasia
Nelson	3,343	N. America
Kolyma	3,234	Eurasia
La Grande Riviere	3,039	N. America
Koksoak	1,458	N. America

Table 1.1: The observed discharge from the major rivers into the Arctic basin, from Stadnyk, Tefs, et al. (2021).

regions, from 1980-2015'.

1.4 Thesis Objectives

Compare ocean model simulations with two different runoff products, which vary regionally and temporally in amounts, to look at how increasing river runoff with climate change can affect the Pan-Arctic domain.

As river runoff continues to increase with climate change, understanding the expected affects in the Arctic Ocean and downstream to lower latitudes is important. Comparing ocean model simulations run with two different runoff forcing data sets which vary widely in regional and temporal amounts, can provide a test case for how runoff in these regions affects Arctic Ocean processes. This work also aims to look at the relative strengths and weaknesses of two different river runoff data sets available to ocean models. Since the Arctic Ocean is heavily influenced by freshwater river runoff, the choice of runoff data set can have a large impact on results in ocean model simulations. By comparing ocean model results run using different river runoff data sets, the sensitivity of the model to the changes can be examined and the accuracy of the model under different forcings can be assessed by comparing with available observations.

Look at the impact on ocean circulation and sea ice of including the water temperature information from river runoff in an ocean model simulation.

Rivers can be a significant seasonal source of heat into the Arctic Ocean. River water temperature can vary widely and seasonally, and can be quite different from the ambient surface water temperature in the Arctic Ocean. Ocean models generally do not represent this information, as river runoff input is assumed to be the same temperature as the surrounding ocean. Some runoff data sets though do include water temperature information, and ocean model simulations can be run which includes this information. These data sets can be used to assess riverine heat flux into the Arctic Ocean. Then including the water temperature information from river runoff in ocean model simulations can be used to look at the impacts within the Arctic Ocean, with specific focus given to the affects on sea ice.

Bibliography

Aagaard, Ko and Ee C Carmack (1989). "The role of sea ice and other fresh water in the Arctic circulation". In: *Journal of Geophysical Research: Oceans* 94.C10, pp. 14485–14498.

Aragón–Durand, Fernando et al. (2018). "Special Report on Global warming of 1.5° C (SR15)-Chapter 1: Framing and Context". In.

Armitage, Thomas WK et al. (2017). "Arctic Ocean surface geostrophic circulation 2003–2014". In: *The Cryosphere* 11.4, pp. 1767–1780.

Arnell, Nigel W (2005). "Implications of climate change for freshwater inflows to the Arctic Ocean". In: *Journal of Geophysical Research: Atmospheres* 110.D7.

Canada's Changing Climate Report (2019). Government of Canada.

Déry, Stephen J et al. (2011). "Interannual variability and interdecadal trends in Hudson Bay streamflow". In: *Journal of Marine Systems* 88.3, pp. 341–351.

Durocher, Martin et al. (2019). "Analysis of trends in annual streamflow to the Arctic Ocean". In: *Hydrological Processes* 33.7, pp. 1143–1151.

Foukal, Nicholas P and M Susan Lozier (2017). "Assessing variability in the size and strength of the N orth A tlantic subpolar gyre". In: *Journal of Geophysical Research: Oceans* 122.8, pp. 6295–6308.

Haine, Thomas WN (2020). "Arctic Ocean Freshening Linked to Anthropogenic Climate Change: All Hands on Deck". In: *Geophysical Research Letters* 47.22, e2020GL090678.

Haine, Thomas WN et al. (2015). "Arctic freshwater export: Status, mechanisms, and prospects". In: *Global and Planetary Change* 125, pp. 13–35.

Hanna, E et al. (2019). "Surface air temperature [in "State of the Climate in 2018"]". In: *Bull. Amer. Meteor. Soc* 100.9, S142–S143.

Jahn, Alexandra and Rory Laiho (2020). "Forced changes in the Arctic freshwater budget emerge in the early 21st century". In: *Geophysical Research Letters* 47.15, e2020GL088854.

Kwok, Ron, G Spreen, and S Pang (2013). "Arctic sea ice circulation and drift speed: Decadal trends and ocean currents". In: *Journal of Geophysical Research: Oceans* 118.5, pp. 2408–2425.

Lammers, Richard B, Jonathan W Pundsack, and Alexander I Shiklomanov (2007). "Variability in river temperature, discharge, and energy flux from the Russian pan-Arctic landmass". In: *Journal of Geophysical Research: Biogeosciences* 112.G4.

Lindsay, R and A Schweiger (2015). "Arctic sea ice thickness loss determined using subsurface, aircraft, and satellite observations". In: *The Cryosphere* 9.1, pp. 269–283.

MacDonald, Matthew K et al. (2018). "Impacts of 1.5 and 2.0° C Warming on Pan-Arctic River Discharge Into the Hudson Bay Complex Through 2070". In: *Geophysical Research Letters* 45.15, pp. 7561–7570.

Morison, James et al. (2012). "Changing arctic ocean freshwater pathways". In: *Nature* 481.7379, pp. 66–70.

Notz, Dirk and Julienne Stroeve (2018). "The trajectory towards a seasonally ice-free Arctic Ocean". In: *Current Climate Change Reports* 4.4, pp. 407–416.

Park, Hotaek, Eiji Watanabe, et al. (2020). "Increasing riverine heat influx triggers Arctic sea ice decline and oceanic and atmospheric warming". In: *Science advances* 6.45, eabc4699.

Park, Hotaek, Yasuhiro Yoshikawa, et al. (2016). "Quantification of warming climate-induced changes in terrestrial Arctic river ice thickness and phenology". In: *Journal of Climate* 29.5, pp. 1733–1754.

Proshutinsky, A et al. (2019). "Analysis of the Beaufort Gyre freshwater content in 2003–2018". In: *Journal of Geophysical Research: Oceans* 124.12, pp. 9658–9689.

Roach, AT et al. (1995). "Direct measurements of transport and water properties through the Bering Strait". In: *Journal of Geophysical Research: Oceans* 100.C9, pp. 18443–18457.

Schauer, Ursula et al. (2004). "Arctic warming through the Fram Strait: Oceanic heat transport from 3 years of measurements". In: *Journal of Geophysical Research: Oceans* 109.C6.

Serreze, Mark C and Roger G Barry (2011). "Processes and impacts of Arctic amplification: A research synthesis". In: *Global and planetary change* 77.1-2, pp. 85–96.

Sinokrot, Bashar A and Heinz G Stefan (1993). "Stream temperature dynamics: measurements and modeling". In: *Water resources research* 29.7, pp. 2299–2312.

Solomon, Amy et al. (2021). "Freshwater in the arctic ocean 2010–2019". In: *Ocean Science* 17.4, pp. 1081–1102.

Stadnyk, Tricia A, A Tefs, et al. (2021). "Changing freshwater contributions to the Arctic: A 90-year trend analysis (1981–2070)". In: *Elem Sci Anth* 9.1, p. 00098.

Stadnyk, Tricia Anne, Marie Broesky, et al. (2019). "Changing freshwater contributions to the Arctic: a 90-year trend analysis". In: *AGU Fall Meeting Abstracts*. Vol. 2019, GC51J–1088.

Stocker, Thomas (2014). *Climate change 2013: the physical science basis: Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge university press.

Timmermans, Mary-Louise and John Marshall (2020). "Understanding Arctic Ocean Circulation: A Review of Ocean Dynamics in a Changing Climate". In: *Journal of Geophysical Research: Oceans* 125.4.

Tréguier, Anne-Marie et al. (2005). "The North Atlantic subpolar gyre in four high-resolution models". In: *Journal of Physical Oceanography* 35.5, pp. 757–774.

Whitefield, Jonathan et al. (2015). "A new river discharge and river temperature climatology data set for the pan-Arctic region". In: *Ocean Modelling* 88, pp. 1–15.

Woodgate, Rebecca A (2018). "Increases in the Pacific inflow to the Arctic from 1990 to 2015, and insights into seasonal trends and driving mechanisms from year-round Bering Strait mooring data". In: *Progress in Oceanography* 160, pp. 124–154.

Woodgate, Rebecca A, Thomas J Weingartner, and Ron Lindsay (2012). "Observed increases in Bering Strait oceanic fluxes from the Pacific to the Arctic from 2001 to 2011 and their impacts on the Arctic Ocean water column". In: *Geophysical Research Letters* 39.24.

Yang, Daqing et al. (2021). "Heat flux, water temperature and discharge from 15 northern Canadian rivers draining to Arctic Ocean and Hudson Bay". In: *Global and Planetary Change* 204, p. 103577.

Chapter 2

Ocean Modelling

Ocean models are numerical representations of physical processes. They are useful in many different scenarios, they can allow for hypothesis testing, making future predictions and looking at properties or processes which are difficult to measure in real-world situations. The more complex an ocean model, the higher the computational cost to run. As such, all ocean models are a trade off of complexity, temporal and spatial domain, and computational costs, depending on the questions which are being investigated. This chapter will first cover the model basics, including primitive equations, model coordinates, time domain, boundary conditions, resolution and parametrizations. Then it will cover more details of the specific model setup used in this thesis, including technical specifications, model resolution and domain.

2.1 Ocean Model Basics

The main components of any model are its governing equations, initial conditions and boundary conditions. The Navier-Stokes equations, which described the flow of an incompressible fluid and the non-linear equation of state for seawater are the central equations of an ocean model. This gives the following six basic equations which make up the ocean model (Madec, 2016). These are momentum balance (2.1), hydrostatic equilibrium (2.2), incompressibility (2.3), heat and salt conservation equations (2.4), (2.5) and the equation of state (2.6). An orthogonal set of unit vectors is used, where $\mathbf{k}$ is the local vertical vector, and ($\mathbf{i}$,$\mathbf{j}$) are orthogonal to $\mathbf{k}$. U is the unit vector for velocity, with U_h denoting the horizontal components of velocity. T represents the potential temperature, S the salinity, and ρ the density. D^* are parametrizations of small scale physics, and F^* are surface forcing terms. The coriolis acceleration is f, g is the gravitional acceleration and ρ_0 is the reference density.

$$\frac{\partial U_h}{\partial t} = -[(\Delta \times U) \times U + \frac{1}{2}\Delta(U^2)]_h - f\mathbf{k} \times U_h - \frac{1}{\rho_0}\Delta_h p + D^U + F^U \tag{2.1}$$

$$\frac{\partial p}{\partial z} = -\rho g \tag{2.2}$$

$$\Delta \cdot U = 0 \tag{2.3}$$

$$\frac{\partial T}{\partial t} = -\Delta \cdot (TU) + D^T + F^T \tag{2.4}$$

$$\frac{\partial S}{\partial t} = -\Delta \cdot (SU) + D^S + F^S \tag{2.5}$$

$$\rho = \rho(T, S, p) \tag{2.6}$$

These equations are obtained through some simplifying assumptions made from scale considerations.

Spherical Earth Approximation: While the Earth is reality is a geoid, with gravity varying slightly after different points as a result, for simplification, the Earth is assumed to be a sphere. This allows gravity to be parallel to Earths' radius.
Thin Shell Approximation: The ocean's depth is much smaller than the radius of the Earth, with the maximum ocean depth of ∼10km compared to the radius of ∼6500km. The oceans depth can then be considered negligible in comparison, which allows for the assumption that the distance from the center of the Earth to any model grid point is constant, giving a constant gravity estimation.
Turbulent Closure Hypothesis: Small scale turbulent fluxes are expressed in terms of large scale features. This is because to there are more unknowns than equations for solving for turbulence, meaning it is not a closed system. There are different schemes which can be adopted for turbulence.
Boussinesq Approximation: Variations in fluid properties are ignored other than density. Density variations in a fluid are also ignored except when being multiplied by the gravitational constant. This can be used because the density of the open ocean in reality only varies a few percent from the surface to depth.

Hydrostatic Equilibrium: The vertical movement is a controlled by the vertical pressure gradient and the buoyancy force. This is true particularly when vertical accelerations are small compared with gravitational acceleration. While a majority of ocean models use this assumption, some research has been done on non-hydrostatic models.
Incompressibility: Water is assumed to be an incompressible fluid, so it has a constant volume during motion. This gives equation 2.3, that the divergence of the velocity vector is zero.

2.1.1 Discretization

An ocean model is a discretized representation of a domain, with the variables being calculated at the grid points. The variable setup on the grid is an important choice in discretizing equations. A common setup is the 'C-grid' (Mesinger et al., 1976). In this configuration, the scalar variables, such as temperature, salinity, pressure and density, are centered on the grid cells, with the vector points defined on the face of each cell. See figure 2.1. Relative to (i,j,k), variables are defined at some integer or integer and a half value on the grid.

When considering a gridded Earth, there exists at the poles a singularity. This is where the latitude and longitude lines converge to zero. This presents a problem for ocean modelling, particularly in the Arctic Ocean where this singularity is in the ocean. The southern pole is over land, and therefore does not present this issue in Antarctica. In order to deal with this, a tri-polar grid is generally adopted. Generally based on the method presented from Madec and Imbard (1996), a curvilinear mesh is constructed which places the singularity points over land, instead of in the ocean.

For the vertical coordinate, there are three traditional approaches which are generally applied. These are z-coordinate models, terrain following models and isopycnal layer models (Griffies et al., 2009). Z-coordinate models have a number of levels set by the depth, generally with thinner layers at the surface. Terrain following models have a number of levels based on the fraction of ocean depth, generally scaled between 0 and 1. Isopycnal models have a vertical discretization based on the density levels, which takes advantage of the fact that below the surface most flow is along isopycnals. All of these different methods have advantages and disadvantages, depending on the application. Z-coordinate models are the most common, with 22 of the 25 climate models which participated in the IPCC AR4 simulations using a z-coordinate system (Meehl et al., 2007).

The discretization in the time domain, or the time step has to also be defined. For the

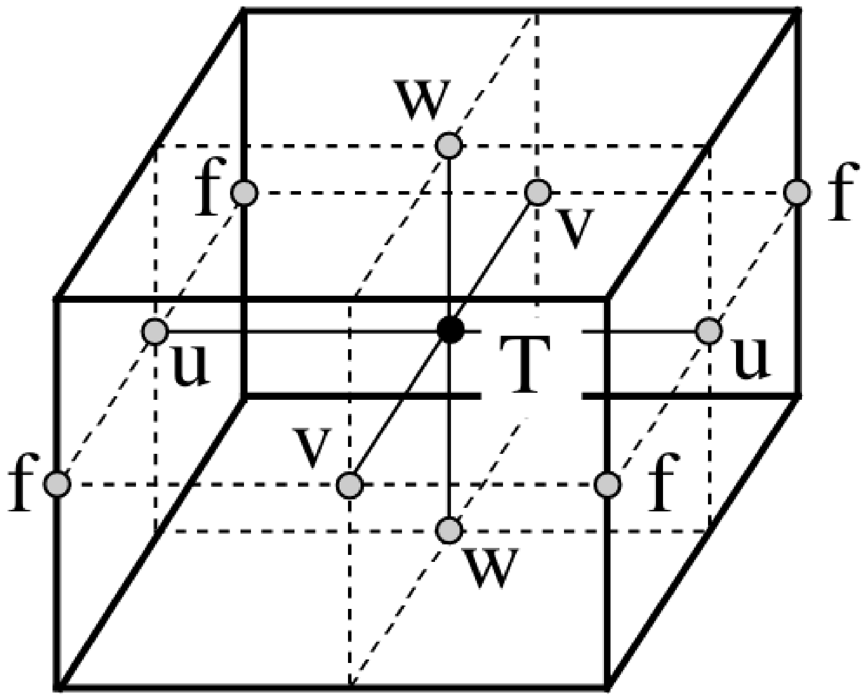


Figure 2.1: Arrangement of variables on the grid, where scalar variables, in this example T temperature, are at the center of the grid boxes, while the vector points (u,v,w) are defined at the center of the faces. Relative and planetary vorticity are defined at the f points. From Madec (2016).

NEMO ocean model, which is a commonly used ocean model which will be used for our model simulations the time step is defined in equation 2.7. In this case, x is the variable being solved for, RHS is the right hand side of the corresponding time evolving equation and Δt is the time step.

$$x^{t+\Delta t} = x^{t-\Delta t} + 2\Delta t RHS_x^{t-\Delta t, t+\Delta t} \tag{2.7}$$

This is called the leap-frogging method of time stepping, and it is widely used for advection processes in low-viscosity fluids (Madec, 2016). There can be a large phase-speed error associated with the leap frogging scheme when solving the wave equation. To prevent this, this method is often used with the Robert-Asselin time filter (Robert, 1966, Asselin, 1972). This is a quasi second order accurate scheme, and is generally the preferred scheme in ocean modelling for non-diffusive processes. For diffusive and damping processes, the leap frog method is not stable, so other time stepping schemes have to be employed. In this case, either a forward time differencing scheme with a time splitting technique can be used, or backward time differencing scheme.

2.1.2 Boundary Conditions

One challenge of modelling the ocean is the complex boundary conditions, from coastlines and bottom topography, as well as the interface between the atmosphere and the ocean, and sea ice and the ocean. The ocean floor boundary is defined as $z = -H(i,j)$, and the ocean surface is defined as $z = \eta(i,j,k,t)$, where η is the sea surface height. Flow along the bottom and coastal boundaries is bounded as there is no flow across solid boundaries. This causes turbulent fluxes from friction along the boundaries, which are parameterized as D^U. There are different fluxes between the different boundaries which need to be represented. The most significant flux between the land and the ocean is mass exchange from freshwater runoff. This is generally specified at the boundary near river mouths from some externally supplied runoff forcing data set. There is also flux between the atmosphere and ocean, of freshwater in the form of precipitation minus evaporation, horizontal momentum flux from wind stress and heat flux. These are similarly prescribed values. There is in reality some salt and heat flux from the ocean floor, but it is generally in small amounts, except in very specific areas where the effects are generally localized. This is generally neglected in models, as the fluxes are considered negligible.

2.2 Model Resolution

Resolution is an important question to consider in ocean models. A higher resolution can allow for a better representation of small scale features, but can also become prohibitively computationally expensive. A model's representation of mesoscale eddies is often used to talk about it's resolution. Mesoscale eddies are important processes in ocean models, they can act as key transporters of heat, salt and other biogeochemical variables (Dong et al., 2014). Their spatial scales vary dramatically, they can range from a few meters across, to hundreds of kilometers. The Rossby radius of deformation L_D, seen in equation 2.8, is a useful categorization of mesoscale eddy size at different latitudes (Gill et al., 1982).

$$L_D = \frac{(gD)^{\frac{1}{2}}}{f} \tag{2.8}$$

It depends on D, the depth and f, the Coriolis parameter which is dependant on latitude. As such, near the equator, eddies are much larger than at higher latitudes. There are different methods to dealing with eddies, depending on the application of the model, the length of integration, and the computational resources. Models with 1°resolution or coarser will generally only resolve eddies at lower latitudes, and will otherwise parameterize the effects of eddies. Higher resolution ocean models can become eddy-permitting (like Maltrud et al. (2005)) where some eddies are fully represented, or eddy-resolving (such as Pennelly et al. (2020)), where eddies are generated at a more realistic strength and rate.

2.3 Parameterizations

The primitive equations described above give a model which can represent a fluid on Earth, with a scale of a few meters in the vertical and a few kilometers in the horizontal. From Kolmogorov (1941) however, the smallest scales which are theorized to affect motion are approximately 0.5cm for length and 10 seconds in time. These smaller processes then are described in the above equations above as the D^* terms, which are important to the model but have to represented in terms of larger scale processes in order to solve the primitive equations. These are generally called the sub-grid scale physics, and these processes need to be parameterized in order to be represented in the model. In order to fully resolve all these processes, computers with 10 billion times faster speed and larger storage capacity would be needed compared with current capabilities (Fox-Kemper, 2018). Sub-grid scale physics can be very important, especially for long simulations where small scale processes actually balance the surface input of kinetic energy and heat.

One of the most common parameterizations, particularly for coarser resolution models, is the parameterization of the effects of mesoscale eddies. In this case, lateral turbulent fluxes are assumed to be linearly dependant on the lateral gradients of large scale features (Madec, 2016). It is well known that lateral mixing caused by mesoscale eddies is generally along isopycnal surfaces (McDougall, 1987). Using this, it can be assumed that the eddy-induced turbulent flux is is linearly dependant on large scale quantities computed along these surfaces. This is generally done using variations of the neutral diffusion scheme, as first proposed by Solomon (1971) and Redi (1982). This is combined with eddy-addvective diffusion from Gent et al. (1995).

Even at eddy-permitting and resolving resolutions, other sub-mesoscale mixing effects have to be parameterized. Theses are generally turbulent processes which cannot be represented through increasing resolution, as they are not represented by the primary equations. Internal wave mixing, where mixing occurs across isopycnal surfaces in the interior of the ocean is an important process. Internal wave breaking is responsible for much of the diapycnal mixing away from the ocean boundary (MacKinnon et al., 2017). Some early models would represent diapycnal mixing as a constant function, such as in Bryan et al. (1979). A more common method of representing mixing is with vertical Fickian diffusion, as shown below, where Ψ is the tracer concentration, z is the geopotential vertical coordinate, and κ is the constant for diapycnal diffusivity.

$$\frac{\partial}{\partial z}(\kappa\frac{\partial\Psi}{\partial z}) \tag{2.9}$$

Some challenges with more accurate parameterizations come from the way model points are often not along isopycnals, which can result in spurious numerical mixing from truncation errors (Ilıcak et al., 2012). There is also a sparsity of direct measurements of ocean mixing, which can be difficult to obtain without specialized ship based instrumentation. Modern ocean models will generally separate the parameterization of surface layer mixing, internal wave mixing and mixing near the boundary layer (MacKinnon et al., 2017).

2.4 NEMO Ocean Model Engine

All model simulations used throughout this work use the Nucleus for European Modelling of the Ocean (NEMO) ocean model engine (Rousset et al., 2015, Vancoppenolle et al., 2009) version 3.6. The ocean component of NEMO uses Océan PArallélisé (OPA) for ocean dynamics and thermodynamics (Madec, Delecluse, et al., 1997). It uses a sea ice module, Louvain-la-neauve Ice Model version 2 (LIM2) (Fichefet et al., 1997), which includes both dynamic and thermodynamic processes (Fichefet et al., 1997). A marine biogeochemical model was coupled to the physical model, Biogeochemistry with Light Iron and Nutrient limitations (BLING) (Galbraith et al., 2010). As previously discussed, model resolution is an important factor to consider in modelling. In a balance of reasonable computation time, an eddy-permitting resolution, and resolving of the major straits in the Canadian Arctic Archipelago, a $\frac{1}{4}^{\circ}$ resolution configuration was used throughout. The model domain covered the Arctic and Northern Hemisphere Atlantic (ANHA4) (Holdsworth et al., 2015, Gillard et al., 2016, Hu et al., 2018). The model domain and horizontal resolution is shown in figure 2.2. The domain has open boundaries at 20°south and Bering Strait. It is a z-coordinate

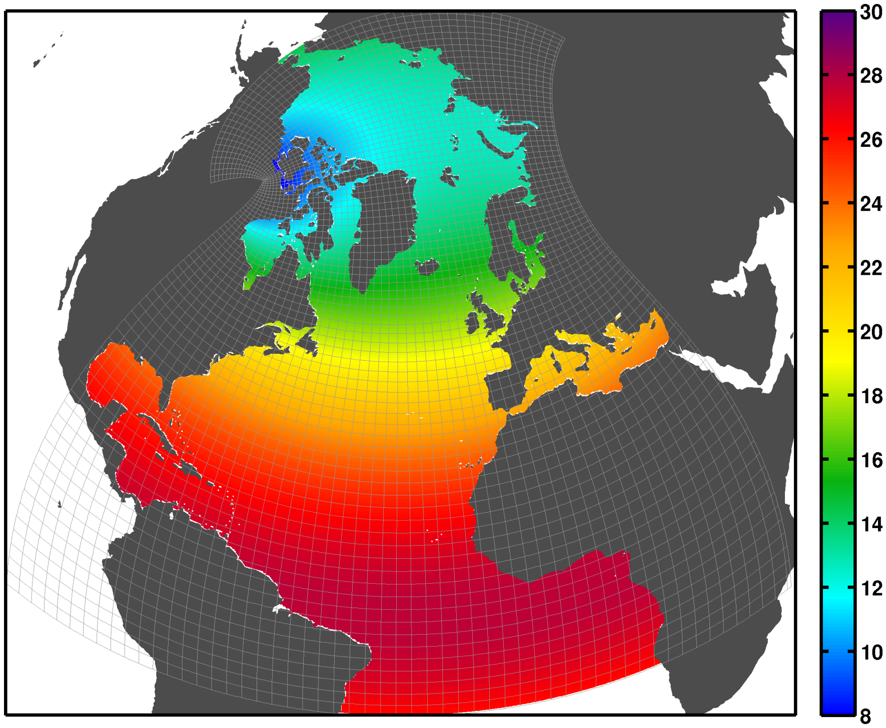


Figure 2.2: The ANHA4 model domain and resolution. In the Arctic Ocean, the horizontal resolution ranges from ∼18-8km.

model, with 50 vertical layers, where the thinnest layers, so the highest resolution, are at the surface, with the layers increasing in thickness with depth. This allows for better resolution of surface water processes, while saving computational costs for bottom waters which will not be in equilibrium in any case because of the short time period of integration. Turbulent kinetic energy (TKE) closure scheme is used for the vertical mixing scheme (Madec, Delecluse, et al., 1997). No temperature or salinity restoring to observations is used, as it can dampen runoff signals and hide model processes. 5 day averages of model output is used, though the model runs with a time step of 1080 seconds.

Bibliography

Asselin, Richard (1972). “Frequency filter for time integrations”. In: *Monthly Weather Review* 100.6, pp. 487–490.

Bryan, Kirk and LJ Lewis (1979). “A water mass model of the world ocean”. In: *Journal of Geophysical Research: Oceans* 84.C5, pp. 2503–2517.

Dong, Changming et al. (2014). “Global heat and salt transports by eddy movement”. In: *Nature communications* 5.1, pp. 1–6.

Fichefet, Thierry and MA Morales Maqueda (1997). “Sensitivity of a global sea ice model to the treatment of ice thermodynamics and dynamics”. In: *Journal of Geophysical Research: Oceans* 102.C6, pp. 12609–12646.

Fox-Kemper, Baylor (2018). “Notions for the motions of the oceans”. In: *New Frontiers in Operational Oceanography*, pp. 27–74.

Galbraith, Eric D et al. (2010). “Regional impacts of iron-light colimitation in a global biogeochemical model”. In: *Biogeosciences* 7.3, pp. 1043–1064.

Gent, Peter R et al. (1995). “Parameterizing eddy-induced tracer transports in ocean circulation models”. In: *Journal of Physical Oceanography* 25.4, pp. 463–474.

Gill, Adrian E and E Adrian (1982). *Atmosphere-ocean dynamics*. Vol. 30. Academic press.

Gillard, Laura C et al. (2016). “Meltwater pathways from marine terminating glaciers of the Greenland ice sheet”. In: *Geophysical Research Letters* 43.20, pp. 10–873.

Griffies, SM et al. (2009). “Problems and prospects in large-scale ocean circulation models”. In: *Proceedings of OceanObs* 9, pp. 410–431.

Holdsworth, Amber M and Paul G Myers (2015). “The influence of high-frequency atmospheric forcing on the circulation and deep convection of the Labrador Sea”. In: *Journal of Climate* 28.12, pp. 4980–4996.

Hu, Xianmin et al. (2018). “Thermodynamic and dynamic ice thickness contributions in the Canadian Arctic Archipelago in NEMO-LIM2 numerical simulations”. In: *The Cryosphere* 12.4, pp. 1233–1247.

Ilıcak, Mehmet et al. (2012). “Spurious dianeutral mixing and the role of momentum closure”. In: *Ocean Modelling* 45, pp. 37–58.

Kolmogorov, Andrey Nikolaevich (1941). "The local structure of turbulence in incompressible viscous fluid for very large Reynolds numbers". In: *Cr Acad. Sci. URSS* 30, pp. 301–305.

MacKinnon, Jennifer A et al. (2017). "Climate process team on internal wave–driven ocean mixing". In: *Bulletin of the American Meteorological Society* 98.11, pp. 2429–2454.

Madec, G (2016). "NEMO ocean engine, version 3.6 stable". In: *Note du Pole de modelisation de l'Institut Pierre-Simon Laplace* 27.

Madec, Gurvan, Pascale Delecluse, et al. (1997). "Ocean general circulation model reference manual". In: *Note du Pôle de modélisation*.

Madec, Gurvan and Maurice Imbard (1996). "A global ocean mesh to overcome the North Pole singularity". In: *Climate Dynamics* 12.6, pp. 381–388.

Maltrud, Mathew E and Julie L McClean (2005). "An eddy resolving global 1/10 ocean simulation". In: *Ocean Modelling* 8.1-2, pp. 31–54.

McDougall, Trevor J (1987). "Neutral surfaces". In: *Journal of Physical Oceanography* 17.11, pp. 1950–1964.

Meehl, Gerald A et al. (2007). "The WCRP CMIP3 multimodel dataset: A new era in climate change research". In: *Bulletin of the American meteorological society* 88.9, pp. 1383–1394.

Mesinger, Fedor and Akio Arakawa (1976). "Numerical methods used in atmospheric models". In.

Pennelly, Clark and Paul G Myers (2020). "Introducing LAB60: A 1/ 60° NEMO 3.6 numerical simulation of the Labrador Sea". In: *Geoscientific Model Development* 13.10, pp. 4959–4975.

Redi, Martha H (1982). "Oceanic isopycnal mixing by coordinate rotation". In: *Journal of Physical Oceanography* 12.10, pp. 1154–1158.

Robert, Andre J (1966). "The integration of a low order spectral form of the primitive meteorological equations". In: *Journal of the Meteorological Society of Japan. Ser. II* 44.5, pp. 237–245.

Rousset, C. et al. (2015). "The Louvain-La-Neuve sea ice model LIM3.6: global and regional capabilities". In: *Geoscientific Model Development* 8.10, pp. 2991–3005. DOI: `10.5194/gmd-8-2991-2015`. URL: `http://www.geosci-model-dev.net/8/2991/2015/`.

Solomon, Harold (1971). "On the representation of isentropic mixing in ocean circulation models". In: *Journal of Physical Oceanography* 1.3, pp. 233–234.

Vancoppenolle, Martin et al. (2009). "Simulating the mass balance and salinity of Arctic and Antarctic sea ice. 1. Model description and validation". In: *Ocean Modelling* 27.1–2, pp. 33–53. ISSN: 1463-5003. DOI: `10.1016/j.ocemod.2008.10.005`. URL: `http://www.sciencedirect.com/science/article/pii/S1463500308001613`.

Chapter 3

Impact of River Runoff in Ocean Model Simulations

3.1 Introduction

The Arctic Ocean is the smallest of the world's five oceans, and has many unique properties. As the global climate continues to change, from anthropogenic and natural processes, changes are expected in the Arctic Ocean. The Arctic overall is warming faster than the global average rate (*Canada's Changing Climate Report* 2019, Hanna et al., 2019), and many changes have been seen, and are predicted to continue. Impacts of Arctic amplification of global temperature rise on the Arctic Ocean, include loss of multi-year sea ice (Lindsay et al., 2015), rapid decrease in summer sea ice extent (Cavalieri et al., 2012) and changes in freshwater sources and storage (Haine, 2020). The IPCC report predicts that a 2° rise in global mean temperature by 2100 will translate to a 4° to 7° rise in Arctic temperatures (Aragón–Durand et al., 2018).

Freshwater plays a key role in the Arctic Ocean. In order to understand the role of this pure freshwater after it enters the marine environment, we use a definition of freshwater relative to a reference salinity, commonly the estimated mean salinity of the Arctic Ocean, from Aagaard et al. (1989). While Schauer et al. (2019) argues against the use of relative freshwater, as it is relative to the reference salinity chosen, it is a common metric particularly in the Arctic. In the Arctic Ocean, increased freshwater content, from increased precipitation, river runoff, inflow at Bering Strait and sea ice melt has been observed and is predicted to continue, (Morison et al., 2012 and others). These freshwater changes are likely linked to anthropogenic climate change (Haine, 2020). From climate model predictions of the 21st century, solid and liquid freshwater storage are the first observed impacts of climate change

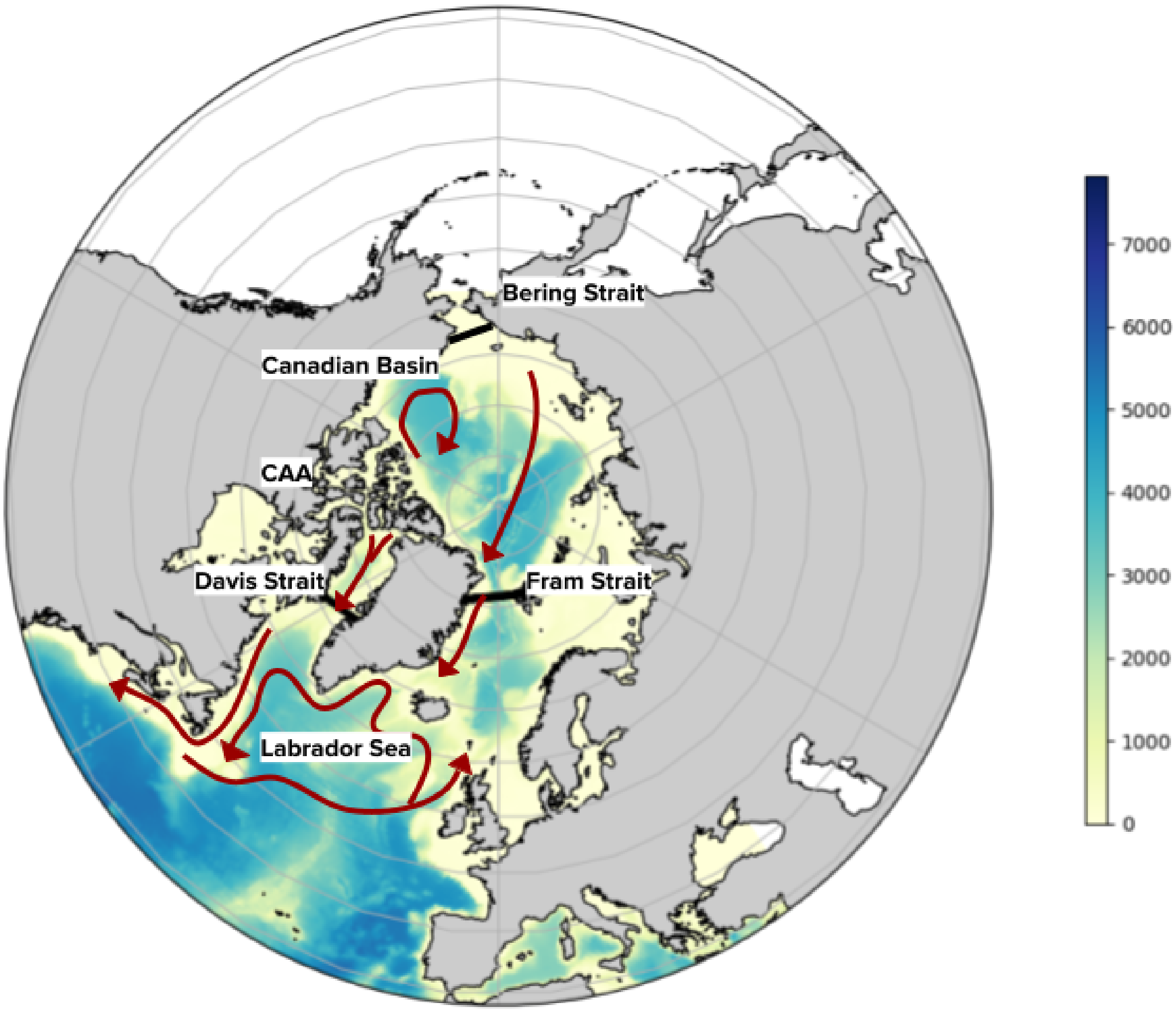


Figure 3.1: Map of the Arctic Ocean and North Atlantic, with the model bathymetry indicated by the colour scale. The major gateways are indicated in black, and the idealized basic circulation structure is shown in red.

on the Arctic freshwater budgets, separable from natural variability (Jahn et al., 2020). This freshwater can have a variety of impacts, in the Arctic Ocean and downstream.

River runoff is the largest source of freshwater discharge in the Arctic Ocean (Haine et al., 2015) and increasing river runoff into the Arctic basin is a major source of the freshwater increases observed (Stadnyk, Tefs, et al., 2021). It is approximated that 40 million people could be impacted by changes in the Arctic rivers, particularly in Canada (Déry et al., 2011). Many studies agree that river runoff into the Arctic Ocean has been increasing in recent years (Arnell, 2005, Durocher et al., 2019 and Stadnyk, Tefs, et al., 2021). River runoff into the Arctic ocean has increased in the 2000's compared to the 1980-2000 period by approximately 10% (Haine et al., 2015). In Durocher et al. (2019) they considered the stream flow records for rivers feeding into the Arctic Ocean, and they found an increase in river runoff from all sources considered, for the time period 1975-2015. These increases are due to increased precipitation, permafrost melt, forest fires and human intervention affecting river flow (Stadnyk, Tefs, et al., 2021). From climate models, the pan-Arctic domain is expected to become wetter as the climate continues to warm (MacDonald et al., 2018). River runoff is also expected to continue increasing in coming years with climate change (Arnell, 2005). Arnell (2005) found that all the climate models used in their study saw an increase in precipitation, especially over the catchment region for river flow into the Arctic, under both the high and low emissions scenarios. Stadnyk, Tefs, et al. (2021) projected a 22% increase overall in river discharge into the Arctic by 2070.

A few other modelling studies have looked at the impact of increasing river runoff on the Arctic Ocean, largely using simplified runoff fields. Nummelin et al. (2016) found that increasing river runoff perturbations linearly from 10% to 150% in a coupled ocean-sea ice model lead to increased stratification, and a warmer halocline and Atlantic water layer in the Arctic Ocean. Ridenour et al. (2019) used a series of Nucleus for European Modelling of the Ocean (NEMO) modelling experiments to examine the sensitivity of the Hudson Bay Complex to river discharge scenarios, focusing on the impact of river regulation. In sensitivity experiments from Pemberton et al. (2016), looking at the Arctic Oceans response to freshwater input changes, they also found that the Atlantic water layer warms, weakening of the Beaufort Gyre circulation and increasing freshwater export from Fram Strait, with a corresponding decrease in export through the Canadian Arctic Archipelago. Hosing experiments in the sub-polar North Atlantic, where large amounts of freshwater are released from 50-70 °N have shown a large amounts of freshwater can impact the convective overturning in the North Atlantic (Manabe et al., 1995, Mignot et al., 2007). In more recent modelling studies, where excess freshwater is released closer to the coast, there is a smaller impact on convection, as most of the freshwater remains in the coastal boundary currents and does not propagate into the interior (Dukhovskoy et al., 2019).

Traditionally, ocean models have commonly relied on the Dai and Trenberth runoff dataset (Dai et al., 2009) for river runoff forcing. Dai and Trenberth is a climatology based data set, from the largest ocean draining rivers globally. There are limitations with this data set, especially in the Arctic Ocean, as it does not include many of the recent changes that have been observed in the Arctic. This study aims to compare ocean model results using Dai and Trenberth, with a newer runoff data set created using the Hydrological Predictions of the Environment (HYPE) model (Lindström et al., 2010). The Arctic HYPE runoff data set described in Stadnyk, Tefs, et al. (2021) and Stadnyk, MacDonald, et al. (2020) includes recent changes observed in the Arctic, and has up to date runoff scenarios which extend into current years. By forcing an ocean model simulation with the two different runoff products and comparing the results, this study aims to look at the high latitude oceans response to river runoff, consider areas where ocean models may be misrepresenting the affects of freshwater inputs and understand the model sensitivity to runoff fields. Comparing the impacts of these runoff products gives a more realistic view of changing runoff forcing, as it does not rely on a uniform linear increase of runoff input, but rather a more regional view of how runoff could increase and potential impacts of these changes. First this paper compares the two runoff data sets, on both spatial and temporal scales, and then the ocean model used is described. The model runs completed with the different forcing products are then compared, focusing on freshwater and circulation changes. Particular focus is given to the changes in the Canadian Arctic Archipelago, the Sub-polar North Atlantic, and the Canadian Basin.

3.2 Runoff Data Sets

3.2.1 Description

The older runoff data set being used in this study was produced by Dai et al. (2009) with runoff estimates from Greenland from Bamber, Van Den Broeke, et al. (2012). Dai and Trenberth provides a data set of global continental discharge from 1948-2007. They included data from the 925 largest ocean draining rivers globally, which accounts for approximately 73% of global total runoff. The average length of stream flow records for the top 10 highest flow rivers is 79.9 years, for the top 50 rivers it is 54.2 years and 50 years for the top 200 rivers. Temporal gaps in gauge records for rivers are filled using linear regression using stream flow simulated by a land surface model, Community Land Model Version 3 (CLM3) (Oleson et al., 2010). For areas where there are no river monitoring available, the simulated CLM3 runoff field was used to estimate annual discharge in the region.

A more recent Arctic runoff data set has been produced by the Hydrological Modelling Lab at the University of Calgary, based off of the Hydrological Predictions of the Environment (HYPE) model. HYPE is a semi-distributed catchment model, which simulates water flow and substances on their way from precipitation through different storage compartments and fluxes to the sea (Lindström et al., 2010). The Arctic-HYPE setup has been created specifically for the Arctic drainage basin. It includes representations of cryospheric processes, and includes a river regulation model, particularly in the Hudson Bay complex (Stadnyk, MacDonald, et al., 2020). This data set extends up to present day, and includes many of the recent changes seen in Arctic runoff. HYPE is forced using the HydroGFDv2 atmospheric reanalysis product (Berg et al., 2018). This runoff data set is combined with an updated estimate of the Greenland freshwater fluxes, from Bamber, Tedstone, et al. (2018).

The freshwater fluxes from Greenland are from Bamber, Van Den Broeke, et al. (2012) and Bamber, Tedstone, et al. (2018). Bamber, Van Den Broeke, et al. (2012) covers the years 1958-2010, where runoff was derived from a reconstruction of the surface mass balance of the Greenland Ice Sheet and surrounding, non-glaciated tundra, using a high-resolution regional climate model. Bamber, Tedstone, et al. (2018) uses a combination of satellite observations of glacier flow speed and regional climate modeling to reconstruct the land ice freshwater flux from the Greenland ice sheet and Arctic glaciers and ice caps for the period 1958–2016.

For both runoff data sets, the runoff forcing files for the model are produced in a similar manner. Runoff values from the data sets were combined with runoff values from the Greenland ice sheet. These values are then translated onto the model grid. Based off of the runoff value in a grid cell, the runoff would be distributed over nearby grid cells, in order to not over flood a grid cell with large amounts of freshwater at the surface layer. This is done through a system of polygons, which simulate the outflow areas of the river systems. As the HYPE data set was only produced for the Arctic region, for runoff in the lower latitudes of the domain it was combined with the Dai and Trenberth runoff. This constrains the changes in the data sets for the model to the terrestrial Arctic and the Greenland ice sheet.

3.2.2 Comparison

Overall, HYPE and Dai and Trenberth have a similar annual average over the entire model domain, with $730000 m^3/s$ with HYPE and $720000 m^3/s$ from Dai and Trenberth. The difference between the two runoff products varies regionally however, as is shown in figure 3.2. Higher runoff values in HYPE are seen on the Western side of the Arctic, particularly in the Canadian Arctic Archipelago region, where HYPE has almost 4 times more annual average runoff. This is likely due to the resolution of the Dai and Trenberth data set, which only has a horizontal resolution of 1°. Since the CAA primarily consists of smaller rivers, these are not represented in Dai and Trenberth, giving much lower runoff values from the region. CLM3 used in the Dai and Trenberth data set also likely under estimates precipitation amounts in the this region, contributing to the difference in estimates between the runoff products. The

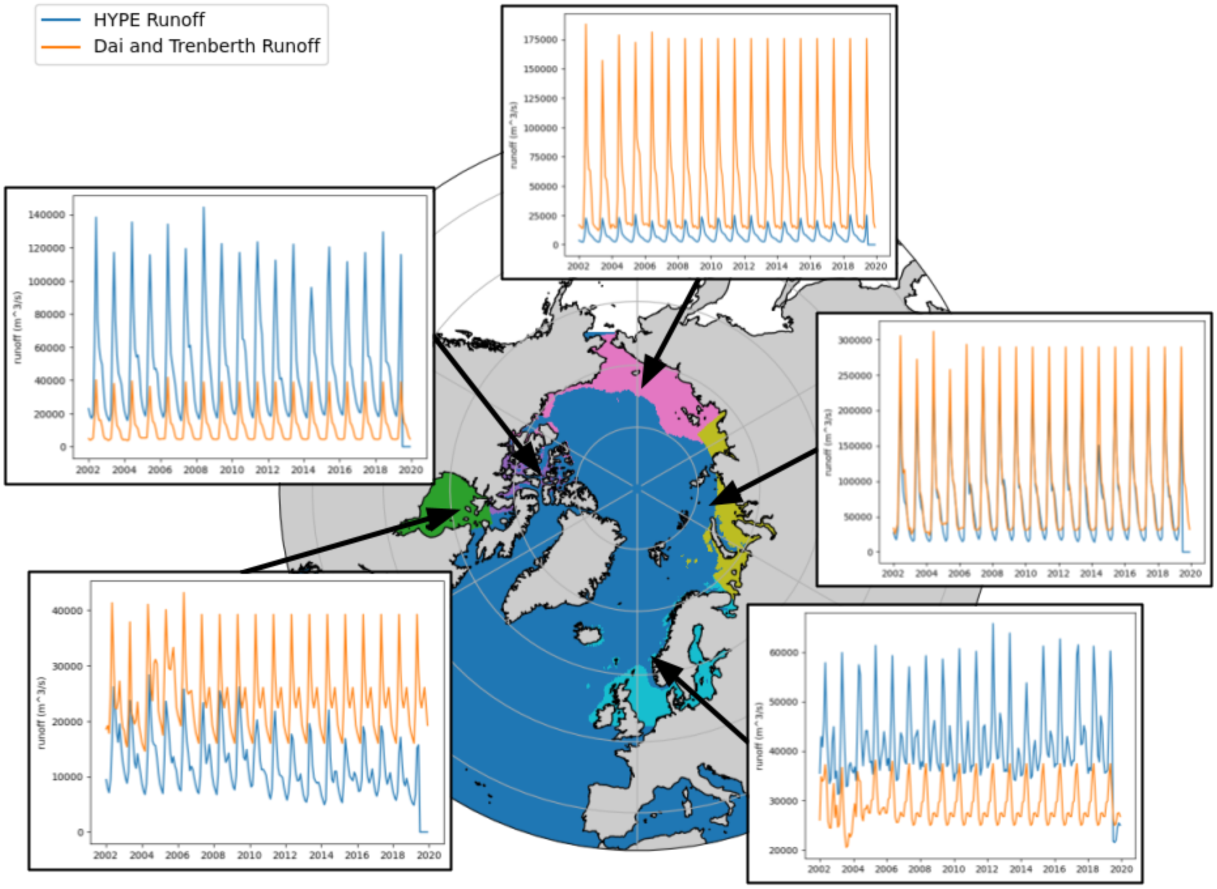


Figure 3.2: Comparison of runoff amounts for different regions around the Arctic Ocean.

Hudson Bay complex also see's higher runoff from the HYPE data set. In contrast, there is higher runoff values on the Eastern side of the Arctic, off the Russian coast in Dai and Trenberth with an annual average of $87000m^3/s$, compared with $75000m^3/s$ from HYPE. This is partially due to data availability in this region for HYPE, as much more up to date information is known about human impacts and activities on the Canadian Arctic, allowing for a more accurate representation of the Canadian coast. The focus of Dai and Trenberth on major rivers also is less of a limitation on this coast, as the majority of the runoff from the Russian coast comes from major rivers. The runoff inputs along the Beaufort and Chucki Seas, which includes the McKenzie river output, is larger from Dai and Trenberth data set compared with the HYPE data set, with $14000m^3/s$ from Dai and Trenberth compared with $1000m^3/s$ from HYPE.

In some regions, differences in the seasonal cycle of runoff exist. For the Eastern Arctic, the seasonal cycle is very similar between the runoff products, despite large magnitude dif-

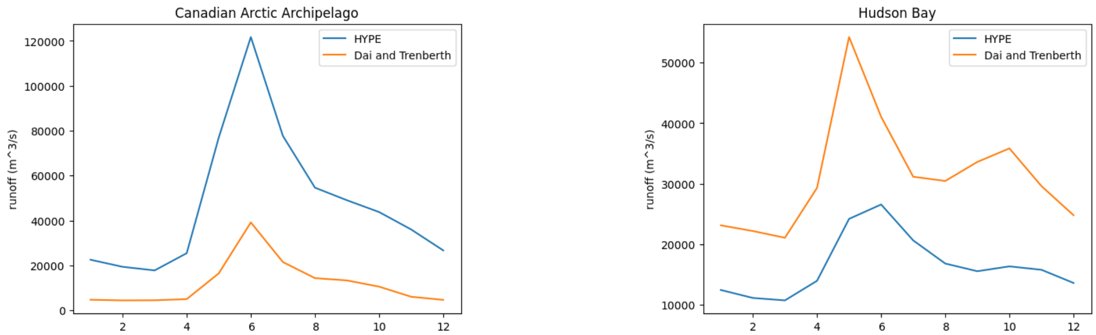


Figure 3.3: The monthly average runoff amounts for the Canadian Arctic Archipelago, and the Hudson Bay Complex, for both runoff data sets.

ferences. In the Canadian Arctic Archipelago (CAA) and the Hudson Bay region, changes in the peak and timing of runoff are also present, see figure 3.3. In the CAA, spring runoff begins sooner, there is a sharper peak of runoff in the summer months, with a more gradual tapering of runoff in the fall in the HYPE data set, compared with Dai and Trenberth. This is likely related as well to the coarse resolution of the Dai and Trenberth data set, as it does not accurately represent the smaller rivers in the region. This can affect timing and seasonal patterns, as they will melt quicker in the spring. HYPE's extension into more recent years could also play a role in this, as it could be some evidence of a climate signal in the seasonal pattern. As the Arctic has been warming with climate change, an earlier spring freshet is expected. Differences in the seasonal cycle can also be seen in the Hudson Bay region. The Dai and Trenberth dataset shows a sharper spring peak, as well as a sharper fall peak. This is likely related to the lack of regulation affects included in the Dai and Trenberth dataset. The Hudson Bay region has extensive hydroelectric projects in its catchement region, which can affect flow timing and seasonality. For a more in depth discussion of the affect of regulation on runoff in the Hudson Bay region, see Ridenour et al. (2019).

3.3 Model Description

All model simulations compared used the Nucleus for European Modelling of the Ocean (NEMO) ocean model engine (Rousset et al., 2015, Vancoppenolle et al., 2009) version 3.6. It uses a sea ice module, Louvain-la-neauve Ice Model version 2 (LIM2) (Fichefet et al., 1997), which includes both dynamic and thermodynamic processes (Fichefet et al., 1997). A marine biogeochemical model coupled to the physical model, Biogeochemistry with Light Iron and Nutrient Limitations (BLING) (Galbraith et al., 2010). A more complete description of BLING can be found in Castro de la Guardia et al. (2019). The domain of interest is the pan-Arctic, so the Arctic and Northern Hemisphere Atlantic (ANHA) configuration was used. This configuration uses a tripolar grid, to prevent a singularity at the poles, and instead shifts the meeting points of grid lines over land, where they do not affect the region of study. It has open boundaries at the Bering strait, and the 20°south (Myers, Buchart, et al., 2021). Initial and open boundary conditions were obtained from the global 1/4°GLORYS2v3 simulation (Ferry et al., 2010). The model uses z-coordinates, with 50 vertical levels. Higher resolutions can give more accurate results, especially of smaller scale processes, but have a much higher computational cost. There is a balance between having a high enough resolution to accurately represent the processes of interest, while keeping computational cost reasonable. In this case, a 1/4 degree resolution was used, which allows for proper representation of boundary currents and other mesoscale processes, and allows for a longer time integration. This is referred to as the ANHA4 configuration, for the 1/4 degree resolution (Holdsworth et al., 2015, Gillard et al., 2016, Hu et al., 2018). This gives a resolution of between 8-18km for the Arctic Ocean. The placement of the tripolar grid also serves to increase the resolution in the CAA, giving a high enough resolution in the area to resolve the major straits and exchanges.

Model simulations were completed with two different atmospheric forcing products, in order to separate out the response of ocean to the atmosphere versus the runoff forcing. A relatively high resolution forcing data set for ice–ocean models derived from the Canadian Meteorological Centre's global deterministic prediction system, CGRF (Smith et al., 2014), and the ERA-Interim atmospheric forcing set, a reanalysis product produced by the European Centre for Medium-Range Weather Forecasts (Uppala et al., 2005, Dee et al., 2011). CGRF is a re-forecast product which combines daily forecasts to produce the final product. CGRF is not a reanalysis product, so is not as well constrained to available observations, but has a high resolution with relatively small bias. All model simulations were run from 2002 to 2019, with 2002-2005 considered the spin up period. ERA-Interim has a temporal resolution of every 3 hours for wind and temperature, and every 24 hours for precipitation and radiation. In comparison, CGRF has a temporal resolution of 1 hour for wind, temperature, precipitation and radiation. ERA-Interim has a spatial resolution of 1°, and CGRF a spatial resolution of 0.45° longitude and 0.3° latitude.

3.4 Methods

The freshwater content was calculated for the four different model runs, integrated both to the depth of 200m and to the 34.8 isohaline as below.

$$FWC = \int_{z}^{0} [S_{ref} - S]/S_{ref} dz \tag{3.1}$$

A reference salinity, S_{ref}, of 34.8 psu is used throughout from Aagaard et al. (1989) and S is the salinity. In order to look at the temporal variability of the freshwater content in different regions, time series of the freshwater content over different regions was also calculated. Volume and freshwater transports were calculated for the main Arctic gateways and exchanges as follows.

$$Volume\, Transport = \int V \Delta [x\, or\, y] \Delta z\, dz \tag{3.2}$$

Where V is the u or v velocity component, multiplied by the width of the grid cell face along that axis and z is the thickness of the cell, integrated over the full depth. The freshwater transport was calculated in a similar manner.

$$Freshwater\, Transport = \int V\, FWC\, \Delta [x\, or\, y] \Delta z\, dz \tag{3.3}$$

The Montgomery stream function was calculated, based on Aksenov et al. (2011). The stream function in this case integrated over the top 200m, to be comparable with the freshwater content calculated. Salinity anomalies in the sub-polar North Atlantic were calculated, based on Holliday et al. (2020). The salinity anomaly was taken as the difference from the average salinity over a certain time period at each grid point. The average salinity was calculated as the average of all model runs, over the full model time series, excluding the spin-up period.

3.5 Differences in Ocean Model Runs

The freshwater content varies widely between the model runs using the HYPE forcing versus Dai and Trenberth, as can be seen in figure 3.4. This figure shows the total difference for the average over the partial time series, for the top 200m, under both atmospheric forcing data sets used. Red indicates higher freshwater content in model runs with Dai and Trenberth, while blue indicates higher freshwater content in model runs with HYPE. There is a higher freshwater content in the Dai and Trenberth model runs consistently seen along the Siberian Shelf and Eastern Coast of the Arctic Ocean. This can be seen starting from the initial time

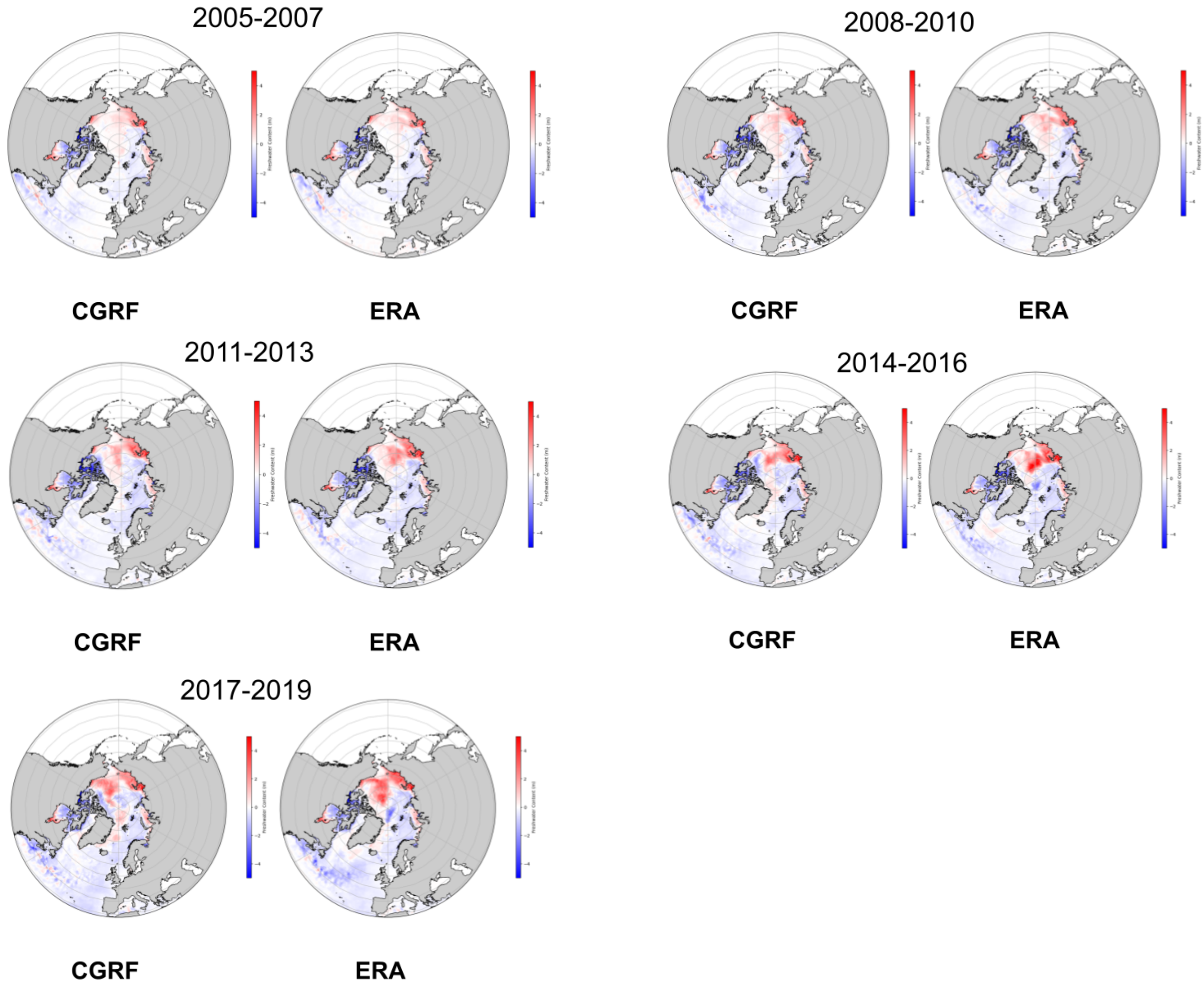


Figure 3.4: Difference in the freshwater content integrated over the top 200m, using a reference salinity of 34.8, between the model runs using Dai and Trenberth versus HYPE, for the two different atmospheric products used.

period, but the magnitude of the difference increases in the 2014-2016 period and 2017-2019 period, where Dai and Trenberth model runs have between 3-5m more freshwater in this region. The interior of the Canadian Basin also sees higher freshwater content in the Dai and Trenberth model runs. This difference can be seen to grow in the later time periods, with a 2014-2016 and 2017-2019 in particular showing a much higher freshwater content in Dai and Trenberth runs. The 2017-2019 period shows ∼3m more freshwater content in the Canadian Basin in model runs with Dai and Trenberth. The CAA shows a consistent higher freshwater content in the HYPE model runs, with freshwater content differences reaching over 5m for all time periods. There is higher freshwater content in the North Atlantic in the HYPE model runs, especially from 2011 onward. Freshwater content differences in these regions range from 0.5m to 2.5m in the later time periods. Impacts of these runoff differences in the CAA, the Labrador Sea and sub-polar North Atlantic, and the Canadian Basin regions will be examined more fully, to look at these differences seen from the freshwater content.

3.5.1 Canadian Arctic Archipelago

The CAA is a shallow shelf area, composed of 36,000 islands, and is a major gateway for circulation out of the Arctic. The terrestrial watershed of the CAA itself is comparable in size to the largest North American watershed regions (Holmes et al., 2012). Continental shelf regions are also important to the global carbon cycle, as carbon transport and sequestration is generally intensified in the these regions through the continental shelf pump (Thomas et al., 2004). The CAA represents approximately 20% of the Arctic continental shelf region (Carmack, Barber, et al., 2006), however in the CAA there is considerable uncertainty around it's role as a CO2 source or sink. It has been shown to have a very high temporal and spatial variability in the air-sea CO2 flux (Else et al., 2012, Geilfus et al., 2018). It is an area where there are large difference in runoff amounts between the two products, as shown in figure 3.2. In line with these differences, the modelled freshwater content in the CAA is much higher in model runs with HYPE, as shown in figure 3.5. This difference in the freshwater content begins to become particularly pronounced after 2009, and is clear irregardless of the atmospheric forcing product used. There is also an increase in freshwater content for all model runs over the time period, though this trend is larger in the HYPE forced model runs. The HYPE forced model runs have a higher freshwater content than the Dai and Trenberth forced model runs of between 1-4m after 2009. This difference decreases slightly towards the end of the time series, with the freshwater content in the CAA plateauing for all model runs after 2016. The freshwater content in the HYPE model runs after this point is between 0.5m to 2m higher than the Dai and Trenberth forced runs.

One impact of increased freshwater input into the CAA can be seen when looking at the mixed layer depth. The mixed layer depth can an indicator of biological productivity. A shallower mixed layer means less available nutrients, and leads to less primary productivity (Carmack, Yamamoto-Kawai, et al., 2016), which can have impacts on the entire biological food chain. When there is more freshwater added into a region, it can further stratify the water column, and serve to reduce the mixed layer depth. As shown in figure 3.5, there is a shallower mixed layer in model runs with HYPE, particularly after 2010. This is inline with the increase in freshwater content in the region in the HYPE model runs from 2009-2010.

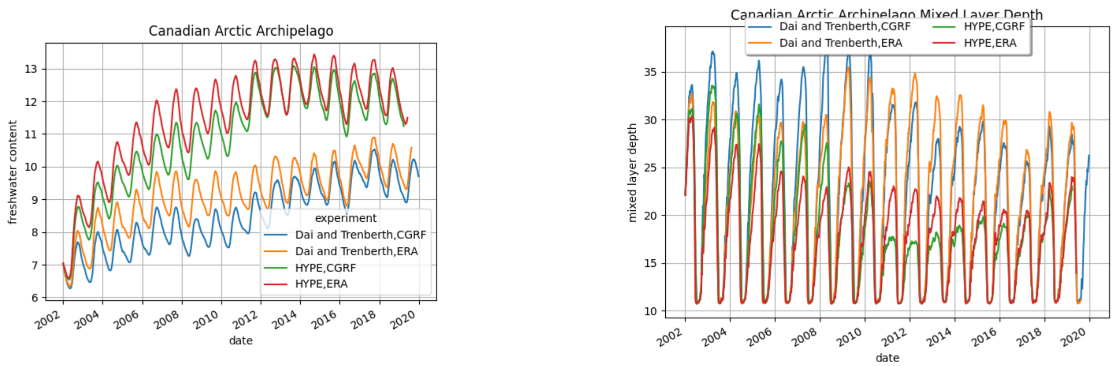


Figure 3.5: The time series of the freshwater content over the top 200m and the mixed layer depth in the CAA.

The mixed layer depth decreases in all model runs starting in 2012, though the decreases are larger in HYPE forced simulations. This implies that biological processes in this region may be overestimated in ocean models using the Dai and Trenberth runoff data set.

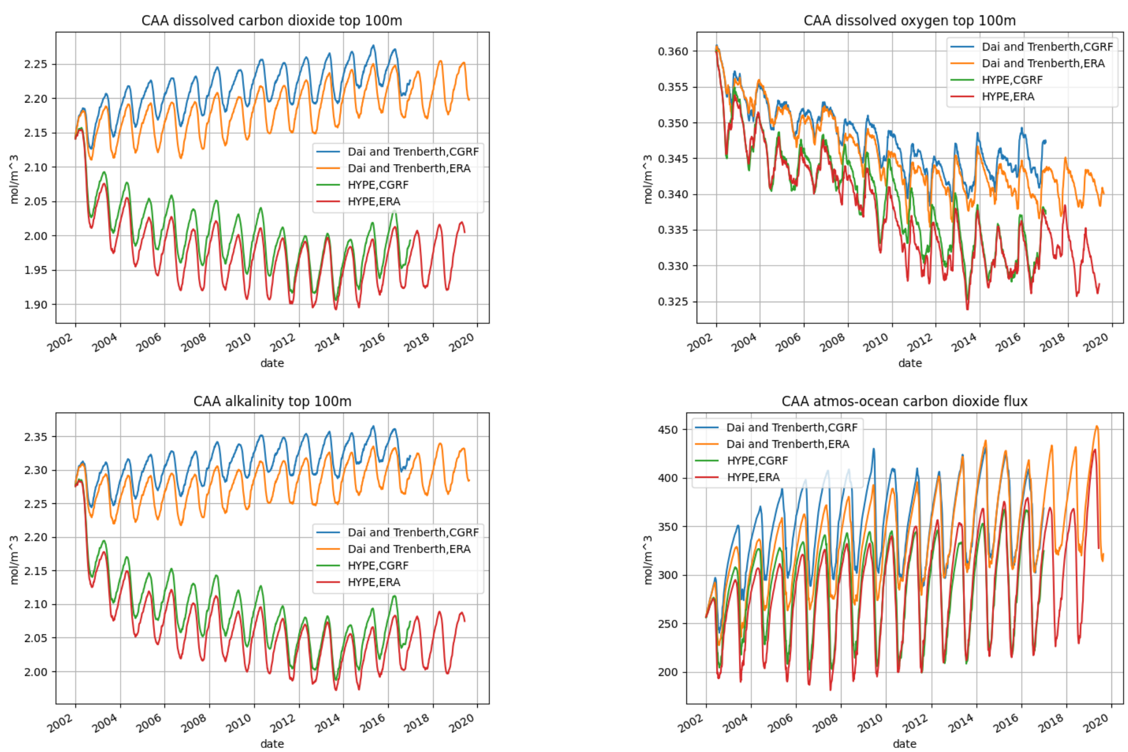


Figure 3.6: Time series of the average dissolved carbon dioxide, oxygen and alkalinity in the CAA for the different model runs.

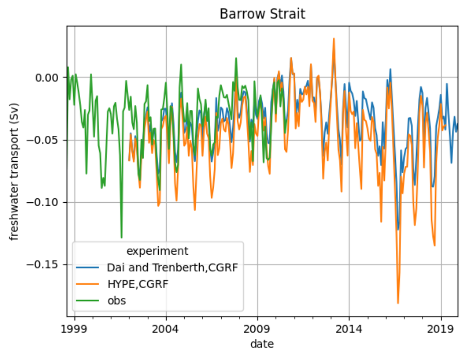
Riverine input of freshwater is also in itself an important source of nutrients to the Arctic Ocean, delivering riverine carbon and other nutrients which can increase primary production

(Letscher et al., 2013). To further investigate this, the dissolved carbon dioxide, oxygen and alkalinity were considered in the region as well, see figure 3.6. There is a much higher dissolved carbon concentrations in the model runs using Dai and Trenberth, higher alkalinity and slightly higher dissolved oxygen. There is also a slightly higher atmospheric-ocean carbon dioxide flux in Dai and Trenberth model runs. A decrease in CO2 uptake when there are large increases in dissolved organic carbon (DOC) river delivery has been shown in the Siberian shelf region before (Anderson et al., 2009, Manizza et al., 2011). This is in line with the increase in runoff shown in the CAA with HYPE, increasing riverine DOC, which then in turn causes a decrease in dissolved carbon dioxide.

3.5.2 Sub-Polar North Atlantic

With an increase in freshwater being added into the Arctic, especially into the CAA, there is a corresponding increase seen in freshwater transport seen out of the region. Barrow Strait is a small channel close to the interface between the CAA and Baffin Bay. Looking at the freshwater transport through Barrow Strait can help understand where the excess freshwater in the CAA with HYPE forced model runs is going. Through Barrow Strait, there is increased eastward freshwater transport in model runs driven by HYPE, under both sets of atmospheric forcing conditions, compared with observations, see figure 3.7. Observations of freshwater transport shown are from Peterson et al. (2012). The mean freshwater transport through Barrow Strait in the HYPE model runs is -48.6 mSv with CGRF forcing and -61.6 mSv with ERA forcing, compared with -35.2 mSv and -49.5 mSv respectively with Dai and Trenberth forcing. This is in comparison with a mean transport of -32.8 mSv from observations. It is of note though that the observations only cover up to 2010, and some of the large transport years in the model are seen after this. In years with higher transport towards the end of the time series, the HYPE model runs consistently have increased freshwater transport compared to Dai and Trenberth, under both atmospheric forcing products. For example, 2016 shows a particularly high transport year, which is in line with strong southward freshwater transport out of Baffin Bay in 2016 (Rysgaard et al., 2020). The HYPE forced runs show an average freshwater transport in 2016 of -75.7 mSv with CGRF forcing and -88.2 mSv with ERA forcing. In comparison, the Dai and Treneberth runs for 2016 have an average freshwater transport of -52.1 mSv with CGRF and -70.4 mSv with ERA.

Davis Strait is the main Arctic gateway on the western side of Greenland, and serves as an important connection between the Arctic Ocean and the Labrador Sea. This same pattern persists of higher freshwater transport in the HYPE forced runs through Davis Strait. The net freshwater transport for the pairs of model runs can be seen in figure 3.8. The freshwater



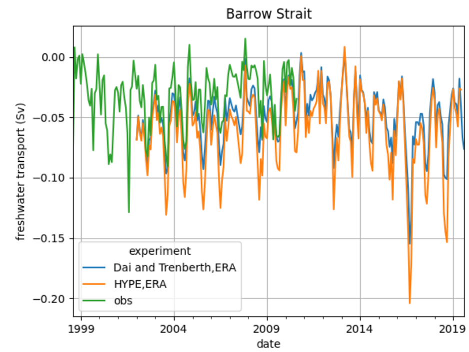
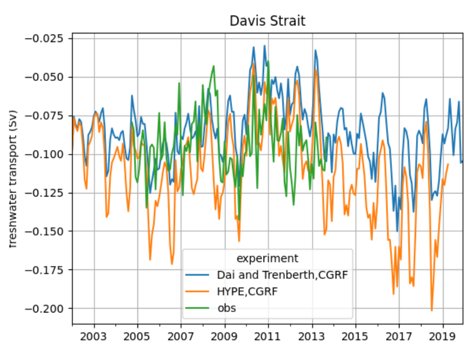


Figure 3.7: Net freshwater transport through Barrow Strait, where positive is westward transport and negative is eastward transport. Transport is shown for the pairs of model runs, with the data from the observational moorings from Peterson et al. (2012).

transport through this section was compared with available observations of transport across Davis Strait, from Curry et al. (2014), extended to 2014 by Myers, Castro de la Guardia, et al. (2021). Not only is there overall higher freshwater transport through the strait, there are also large freshwater transport events which seem to be enhanced in model runs using HYPE forcing. This becomes particularly evident towards the end of the time series, where the differences between the runoff forcing products becomes even more pronounced. For example in 2016, there is an increase in southward freshwater transport in all model runs, but the HYPE model runs show the largest freshwater transport under both atmospheric forcing sets. This is also true in large southward transport seen in 2007, 2010, 2013, 2018 and 2019. The annual average freshwater transport from each model run, compared to observations can be seen in table 3.1. While the observational data only covers a portion of the model time period, comparing the mean freshwater transport gives an idea of accuracy of the results from the different simulations. For all years, comparing between model runs with the same atmospheric forcing, the HYPE forced run always has a higher annual average freshwater transport than the Dai and Trenberth. When comparing the pairs of model runs with the two runoff forcing data sets, runs using ERA atmospheric forcing in general show higher annual average freshwater transport. This shows that both the atmospheric forcing as well as the runoff inputs make a difference in the freshwater export through Davis Strait. The runoff forcing product in this case though is a more significant factor than the atmospheric forcing. For the overlapping time period, there is reasonably good agreement between the model simulations and observed freshwater transport. The model run using Dai and Trenberth runoff forcing, and CGRF atmospheric forcing consistently underestimates the observed values. The run using HYPE and ERA forcing consistently overestimates the observed values, though shows a better performance towards the end of the time period.

Year	Dai and Trenberth, CGRF	Dai and Trenberth, ERA	HYPE, CGRF	HYPE, ERA	Observations
2002	-87.5 mSv	-90.6 mSv	-93.1 mSv	-96.8 mSv	None
2003	-85.1 mSv	-93.1 mSv	-98.7 mSv	-109 mSv	None
2004	-87.7 mSv	-95.2 mSv	-105 mSv	-114 mSv	-93.1 mSv
2005	-98.9 mSv	-110 mSv	-123 mSv	-134 mSv	-105 mSv
2006	-101 mSv	-131 mSv	-129 mSv	-160 mSv	-91.5 mSv
2007	-85.0 mSv	-115 mSv	-107 mSv	-139 mSv	-92.2 mSv
2008	-84.1 mSv	-119 mSv	-109 mSv	-142 mSv	-73.1 mSv
2009	-85.2 mSv	-130 mSv	-109 mSv	-152 mSv	-110 mSv
2010	-51.6 mSv	-101 mSv	-73.8 mSv	-122 mSv	-85.3 mSv
2011	-59.9 mSv	-87.1 mSv	-81.8 mSv	-109 mSv	-87.5 mSv
2012	-67.5 mSv	-94.3 mSv	-88.4 mSv	-115 mSv	-103 mSv
2013	-77.5 mSv	-104 mSv	-105 mSv	-124 mSv	-102 mSv
2014	-84.5 mSv	-113 mSv	-116 mSv	-129 mSv	None
2015	-95.8 mSv	-128 mSv	-126 mSv	-142 mSv	None
2016	-97.1 mSv	-141 mSv	-139 mSv	-166 mSv	None
2017	-108 mSv	-139 mSv	-144 mSv	-169 mSv	None
2018	-102 mSv	-116 mSv	-135 mSv	-151 mSv	None
2019	-86.5 mSv	-98.5 mSv	-116 mSv	-112 mSv	None

Table 3.1: Net annual average freshwater transport through Davis Strait, for each of the model simulations and the observations for available years. A negative value indicates a net southward transport.



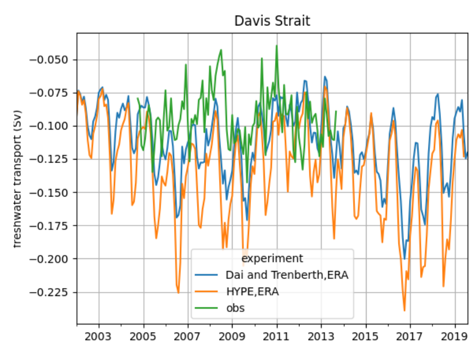


Figure 3.8: Net freshwater transport through Davis Strait, where positive is Northward transport and negative is Southward

The net average volume transport for Barrow and Davis Strait over the full time series was also calculated, as shown in 3.2. In Davis Strait, the impacts of the atmospheric forcing on total transport can be seen more clearly. With the model runs using CGRF forcing, the

Strait	Dai and Trenberth, CGRF	Dai and Trenberth, ERA	HYPE, CGRF	HYPE, ERA
Davis	-1.65 Sv	-2.01 Sv	-1.76 Sv	-2.00 Sv
Barrow	-0.5Sv	-0.66Sv	-0.51Sv	-0.62Sv

Table 3.2: Net average volume transport through Davis and Barrow Strait over the full time period.

HYPE forced model run shows a higher total southward volume transport. However, with the ERA atmospheric forcing, the volume transport is essentially equivalent, irregardless of the runoff forcing data set used. In Barrow Strait, the total volume transport between the pairs of model runs with the same atmospheric forcing is comparable.

Freshwater increases in the Labrador Sea have been traced back through the CAA previously. McGeehan et al. (2012) showed the importance of an accurate representation of the CAA in ocean models to be able to replicate the freshwater transports observed out of the Arctic into the Labrador Sea. Zhang et al. (2021) showed that tracers representing freshwater from the Beaufort Gyre move primarily through Davis Strait instead of through Fram Strait, freshening the Western shelves of the Labrador Sea. We also see an increase in freshwater content on the western shelves in the HYPE model runs, as shown in figure 3.9. In the HYPE model runs, there is consistently higher freshwater content on the Labrador shelves, compared with the Dai and Trenberth model runs. The seasonal pattern of freshwater content on the shelves is very similar between the pairs of model runs, and all model runs show an increase in the freshwater content on the shelves beginning in around 2017. This event is enhanced with the HYPE forced model runs. Freshening of the Western Labrador shelves from water released through the CAA is in line with previous modelling studies, which have shown how Greenland melt water can propagate into the interior of the Labrador Sea (Myers, 2005, Myers, Donnelly, et al., 2009, McGeehan et al., 2012). This freshening of the HYPE model runs can be seen in particular towards the end of the time series, after the large freshwater pulses through Davis strait in the HYPE model runs starting in 2016, see figure 3.8.

The freshwater content in the Labrador Sea and the sub-polar North Atlantic is also enhanced in the HYPE model simulations, starting towards the end of 2013 in the time series, see figure 3.9. There is freshening observed in all model runs over the Labrador Sea region, beginning in 2012. The HYPE model runs however see an even larger freshwater content increase, starting from approximately 2013, using both atmospheric forcing data sets. This overall freshening event shown in the model is in line with an observed freshening of the area. In observations, the sub-polar North Atlantic saw a large scale freshening event from

2012-2016, which was due mainly to offshore wind transport (Holliday et al., 2020). This time period and domain align with the freshening observed in the model results. The salinity anomaly in the sub-polar North Atlantic region shows a similar pattern to Holliday et al. (2020), where they showed unusual wind patterns causing changes in ocean circulation. The salinity anomaly for each model run, compared against the mean over the total time period, excluding the spin up, for all model runs, was calculated and compared with the observational data in figure 3.10 for 2016. Overall, all model runs were able to replicate the basic pattern of the observed freshening event. The HYPE model runs show enhanced freshening, compared to the Dai and Trenberth runs. The observational data from EN4 (Good et al., 2013) was updated from Holliday et al. (2020), with version EN.4.2.2, with the g10 bias corrections. This signal of freshening in the region is evident in the model under both atmospheric forcing conditions and both runoff forcing products used. The magnitude of the event however is enhanced in model runs using HYPE. This is likely because of greater freshwater transport out of the CAA and already enhanced freshwater on the Labrador shelves under HYPE scenarios, which allows a larger offshore transport into the sub-polar North Atlantic under the right conditions.

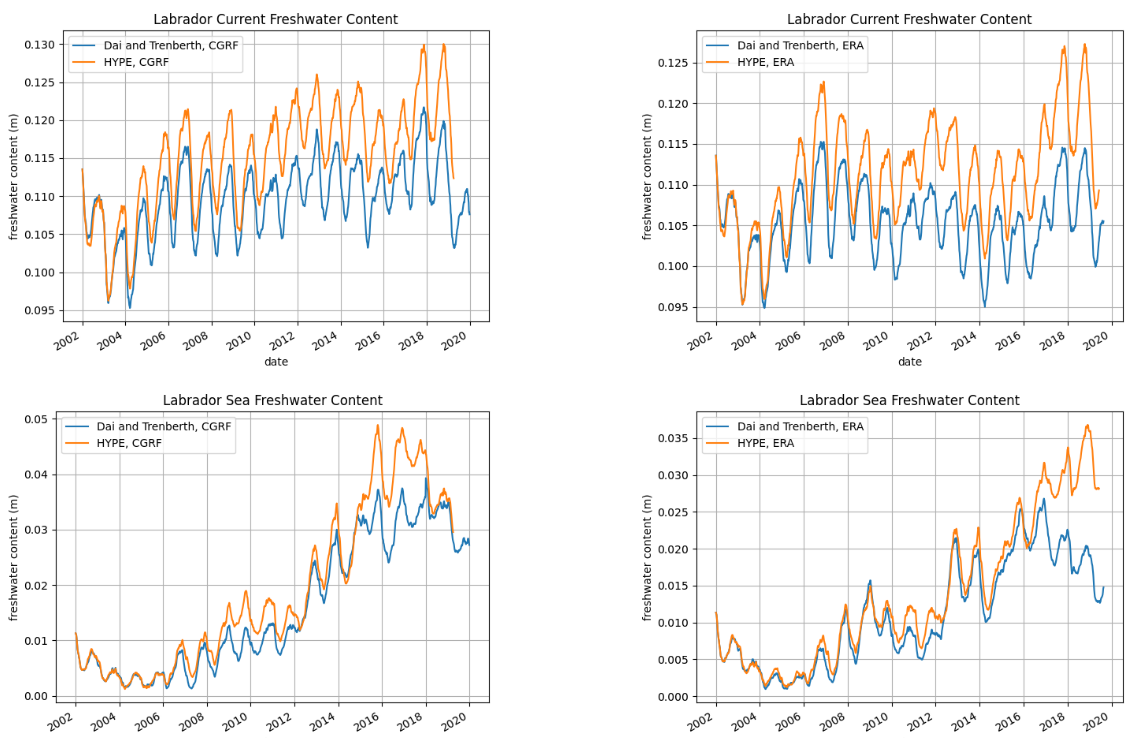
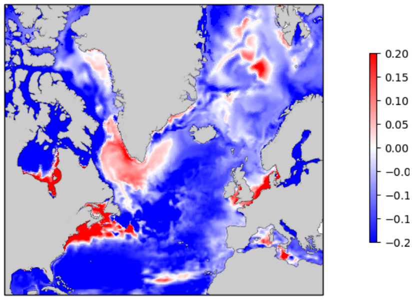
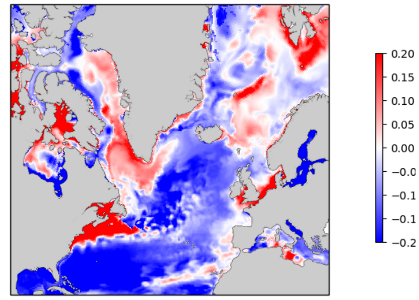


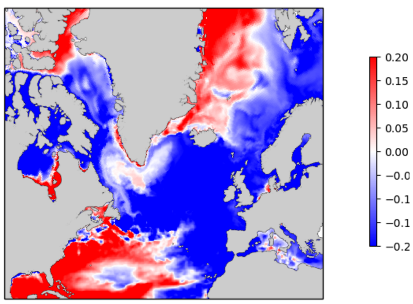
Figure 3.9: The freshwater content, calculated relative to the 34.8 isohaline, in the western Labrador Shelves and the Labrador Sea.



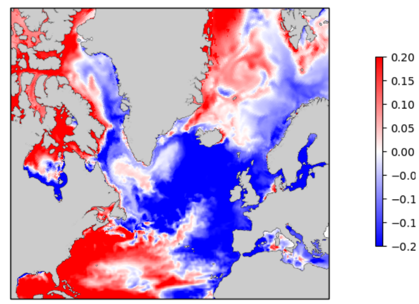
(a) HYPE, ERA



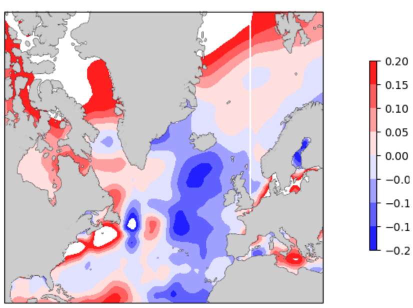
(b) Dai and Trenberth, ERA



(c) HYPE, CGRF



(d) Dai and Trenberth, CGRF



(e) Observed salinity anomaly

Figure 3.10: The salinity anomaly for 2016, calculated for the four different model runs from the mean salinity from 2006-2019 of all runs, and for the observations from the mean over the same time period.

3.5.3 Canadian Basin

The Canadian Basin is a deep oceanic basin in the Arctic Ocean, which is primarily dominated by the Beaufort Gyre. The Beaufort Gyre is caused by the corresponding atmospheric circulation the Beaufort High, and can act as a large freshwater reservoir. This is due to the anti-cyclonic motion of the Beaufort Gyre, which can converge surface waters in the center of the gyre with Ekman pumping. As seen in figure 3.4, the freshwater content in the Canadian Basin is higher in model runs using Dai and Trenberth, compared with HYPE for all time periods. When considering the time series of the freshwater content in the Canadian Basin seen in figure 3.5, it can be seen that the Dai and Trenberth model runs have a slightly higher freshwater content in the region throughout the time period, after the spin up period. The area used for calculating the time series of the freshwater content is following the definition of the Beaufort Gyre from Proshutinsky, Krishfield, Timmermans, et al. (2009) of the region as the area with ocean depths greater than 300 m within 70.5 to 80.5 °N and 130 to 170 °W. For most of the time series, the freshwater content patterns seem to follow the atmospheric forcing closely, with runs forced with ERA with consistently higher freshwater content than runs forced with CGRF. Within the pairs of model runs using the same atmospheric forcing products the model runs using Dai and Trenberth are consistently higher than HYPE. Overall however, all model runs underestimate the amount of freshwater in the region when compared to observations.

Previous studies have debated the amount of freshwater contributions to the Beaufort Gyre from the McKenzie river versus Siberian rivers. Morison et al. (2012) linked freshwater content changes in the Canadian Basin to diverted Eurasian river runoff during low periods of the Arctic Oscillation index. In model experiments, Proshutinsky, Krishfield, Toole, et al. (2019) showed the McKenzie river as a dominant source of the freshwater accumulation seen in the Beaufort Gyre. In this study, these regions which have been identified previously as being large sources of freshwater to the Beaufort Gyre are higher in the Dai and Trenberth runoff data set, compared with HYPE. This can be seen in figure 3.2. This can help explain why there is a consistently higher freshwater content in the Canadian Basin in runs using Dai et al. (2009) between the atmospheric forcing products. The atmospheric forcing data set used also plays a strong role in the freshwater content in the Beaufort gyre. This is inline with the Beaufort gyre being a wind driven circulation pattern (Timmermans et al., 2020). Overall though, all model runs have lower freshwater content in the Beaufort gyre than is found in observations from Proshutinsky, Krishfield, Toole, et al. (2019). This could be from a number of factors, as underestimation of stratification and sea ice concentration, which are linked to freshwater content in ocean models is common (Wang et al., 2016). As resolution can be linked to these source of error for freshwater collection in the Beaufort Gyre, a higher resolution version of the same model and configuration was also compared. This simulation is 1/12 °resolution ,with CGRF atmospheric forcing and Dai and Trenberth runoff forcing. As can be seen in figure 3.11, it does show a higher freshwater content than the 1/4 °resolution

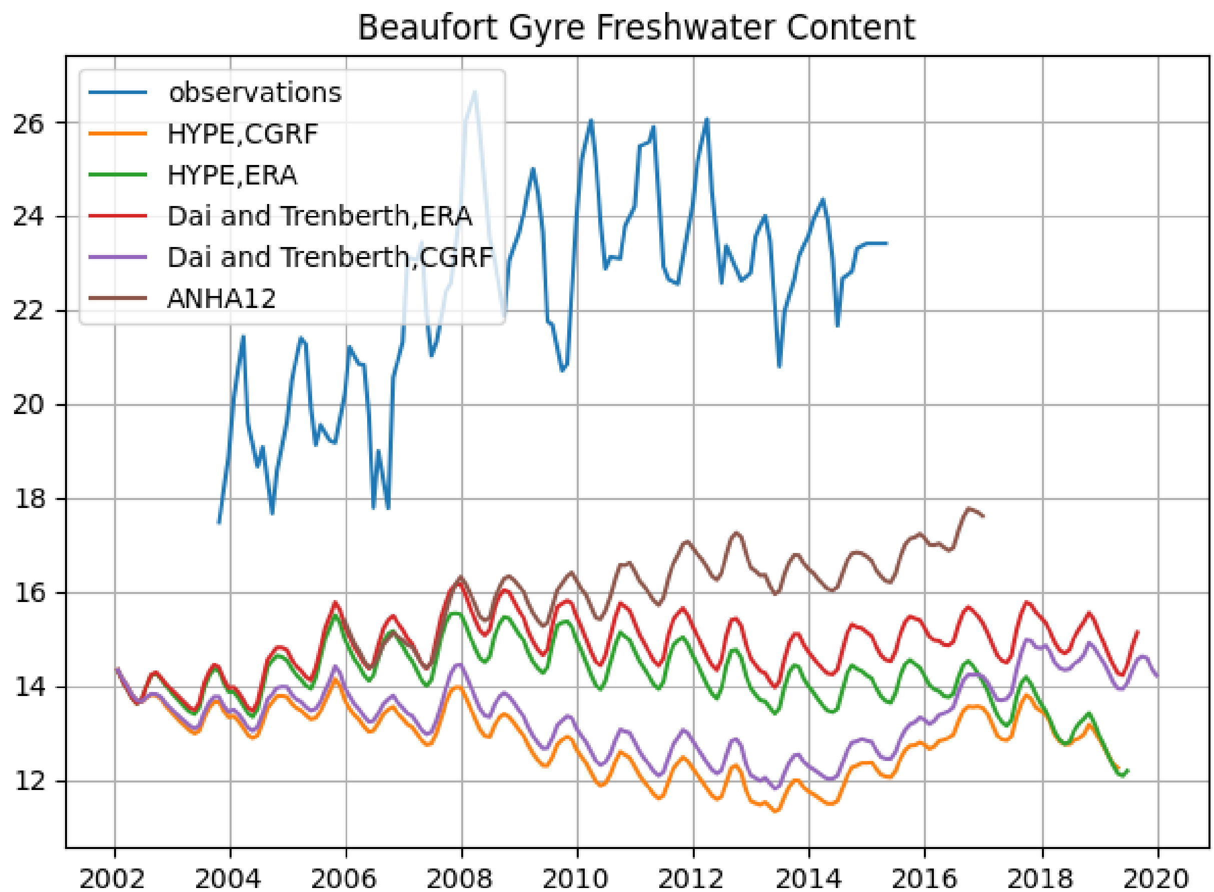


Figure 3.11: Freshwater content in the Beaufort Gyre for the four model runs, as well as a higher resolution model for comparison, with observations from Proshutinsky, Krishfield, Toole, et al. (2019). The freshwater content is calculated from the surface to the 34.8 isohaline.

model runs, but still underestimates observations. This indicates that while model resolution does likely play some role in freshwater storage in the Beaufort Gyre, only increasing model resolution or representation of river runoff cannot fully represent observations.

3.6 Conclusions

We compared model runs forced with two different runoff products, and two different atmospheric forcing products. Overall the model runs completed with HYPE saw a higher average freshwater content, with corresponding changes in transports and circulation. However the affects varied regionally, with the Canadian Arctic Archipelago being one region in particular which saw a large increase in runoff corresponding to a large increase in freshwater content in the region. These effects propagated, with increased freshwater transport out of Davis Strait, a freshening of the western Labrador shelves and eventually the interior of the subpolar North Atlantic. This pattern seen in the HYPE model simulations occurred without a corresponding increase in the freshwater content in the Beaufort Gyre, where other studies have linked freshwater pulses from the Beaufort Gyre through similar pathways before. The lower freshwater content in the Beaufort Gyre is likely linked to decreased runoff in the HYPE data set from the two main sources of freshwater for the region, notably the McKenzie river and the Siberian Shelf region. In the Dai and Trenberth data set, both of these sources have a higher freshwater output, and in response the freshwater content in the Beaufort Gyre in the Dai and Trenberth model runs is increased, across both atmospheric forcing data sets used. There is also a very strong response of the Beaufort Gyre to the atmospheric forcing. The wind patterns are shown to be a predominant factor in the variability of the Beaufort Gyre freshwater content. Overall though, the freshwater content in the Beaufort Gyre in all model runs is significantly underestimated compared to observed freshwater content. This indicates to a model failing of accurately representing the freshwater storage in the Canadian Basin. This could be due to model resolution, underestimation of sea ice melt and stratification, which are all important factors in freshwater storage in the Beaufort Gyre.

The increase in freshwater input into the Canadian Arctic Archipelago region gives a strong example of the potential impacts with climate change, as freshwater output from rivers into the Arctic Ocean is expected to continue increasing dramatically. As the freshwater content in the CAA increases, we expect to see impacts within the region on biological productivity, as the water column becomes more stratified, more riverine nutrients are delivered to the area, which can have impacts as well on the carbon dioxide uptake of the region. We also see the potential for large freshwater pulses to the lower latitudes, which have previously been traced to the larger freshwater storage basins in the Arctic ocean. These results show the importance of the CAA on freshening events which occur in the shelf and in the interior of the Labrador sea. One of the most recent large scale freshening events which has been observed in the sub-polar North Atlantic, which is well replicated in the model results, transported freshwater collected off the Labrador shelf offshore from anomalous wind patterns Holliday et al., 2020. Model results show that freshening effects of these wind patterns in enhanced in the model runs which have larger freshwater collection on the shelves. With increased riverine freshwater input expected with climate change, this gives an expected pathway for this freshwater collection at lower latitudes and shows a mechanism by which freshwater can be transported into the sub-polar North Atlantic. This in turn could have a potential impact on the strength of the Atlantic Meridional Overturing Circulation, given that it is one of the main sites of deep water formation in the North Atlantic (Lique et al., 2018).

3.7 Acknowledgements

EN.4.2.2 data were obtained from https://www.metoffice.gov.uk/hadobs/en4/ and are © British Crown Copyright, Met Office, [year of first publication], provided under a Non-Commercial Government Licence http://www.nationalarchives.gov.uk/doc/non-commercial-government-licence/version/2/

Bibliography

Aagaard, Ko and Ee C Carmack (1989). “The role of sea ice and other fresh water in the Arctic circulation”. In: *Journal of Geophysical Research: Oceans* 94.C10, pp. 14485–14498.

Aksenov, Yevgeny et al. (2011). “The Arctic circumpolar boundary current”. In: *Journal of Geophysical Research: Oceans* 116.C9.

Anderson, Leif G et al. (2009). “Out-gassing of CO2 from Siberian Shelf seas by terrestrial organic matter decomposition”. In: *Geophysical Research Letters* 36.20.

Aragón–Durand, Fernando et al. (2018). “Special Report on Global warming of 1.5° C (SR15)-Chapter 1: Framing and Context”. In.

Arnell, Nigel W (2005). “Implications of climate change for freshwater inflows to the Arctic Ocean”. In: *Journal of Geophysical Research: Atmospheres* 110.D7.

Bamber, JL, AJ Tedstone, et al. (2018). “Land ice freshwater budget of the Arctic and North Atlantic Oceans: 1. Data, methods, and results”. In: *Journal of Geophysical Research: Oceans* 123.3, pp. 1827–1837.

Bamber, Jonathan, Michiel Van Den Broeke, et al. (2012). “Recent large increases in freshwater fluxes from Greenland into the North Atlantic”. In: *Geophysical Research Letters* 39.19.

Berg, Peter, Chantal Donnelly, and David Gustafsson (2018). “Near-real-time adjusted reanalysis forcing data for hydrology”. In: *Hydrology and Earth System Sciences* 22.2, pp. 989–1000.

Canada’s Changing Climate Report (2019). Government of Canada.

Carmack, Eddy, David Barber, et al. (2006). “Climate variability and physical forcing of the food webs and the carbon budget on panarctic shelves”. In: *Progress in Oceanography* 71.2-4, pp. 145–181.

Carmack, Edward C, Michiyo Yamamoto-Kawai, et al. (2016). “Freshwater and its role in the Arctic Marine System: Sources, disposition, storage, export, and physical and biogeochemical consequences in the Arctic and global oceans”. In: *Journal of Geophysical Research: Biogeosciences* 121.3, pp. 675–717.

Castro de la Guardia, Laura et al. (2019). “Assessing the role of high-frequency winds and sea ice loss on Arctic phytoplankton blooms in an ice-ocean-biogeochemical model”. In: *Journal of Geophysical Research: Biogeosciences* 124.9, pp. 2728–2750.

Cavalieri, Donald J and Claire L Parkinson (2012). “Arctic sea ice variability and trends, 1979–2010”. In: *The Cryosphere* 6.4, pp. 881–889.

Curry, B et al. (2014). “Multiyear volume, liquid freshwater, and sea ice transports through Davis Strait, 2004–10”. In: *Journal of Physical Oceanography* 44.4, pp. 1244–1266.

Dai, Aiguo et al. (2009). “Changes in continental freshwater discharge from 1948 to 2004”. In: *Journal of climate* 22.10, pp. 2773–2792.

Dee, Dick P et al. (2011). “The ERA-Interim reanalysis: Configuration and performance of the data assimilation system”. In: *Quarterly Journal of the royal meteorological society* 137.656, pp. 553–597.

Déry, Stephen J et al. (2011). “Interannual variability and interdecadal trends in Hudson Bay streamflow”. In: *Journal of Marine Systems* 88.3, pp. 341–351.

Dukhovskoy, DS et al. (2019). “Role of Greenland freshwater anomaly in the recent freshening of the subpolar North Atlantic”. In: *Journal of Geophysical Research: Oceans* 124.5, pp. 3333–3360.

Durocher, Martin et al. (2019). “Analysis of trends in annual streamflow to the Arctic Ocean”. In: *Hydrological Processes* 33.7, pp. 1143–1151.

Else, BGT et al. (2012). “Sea surface pCO2 cycles and CO2 fluxes at landfast sea ice edges in Amundsen Gulf, Canada”. In: *Journal of Geophysical Research: Oceans* 117.C9.

Ferry, Nicolas et al. (2010). “Mercator global Eddy permitting ocean reanalysis GLORYS1V1: Description and results”. In: *Mercator-Ocean Quarterly Newsletter* 36, pp. 15–27.

Fichefet, Thierry and MA Morales Maqueda (1997). “Sensitivity of a global sea ice model to the treatment of ice thermodynamics and dynamics”. In: *Journal of Geophysical Research: Oceans* 102.C6, pp. 12609–12646.

Galbraith, Eric D et al. (2010). “Regional impacts of iron-light colimitation in a global biogeochemical model”. In: *Biogeosciences* 7.3, pp. 1043–1064.

Geilfus, N-X et al. (2018). “Spatial and temporal variability of seawater pCO2 within the Canadian Arctic Archipelago and Baffin Bay during the summer and autumn 2011”. In: *Continental Shelf Research* 156, pp. 1–10.

Gillard, Laura C et al. (2016). “Meltwater pathways from marine terminating glaciers of the Greenland ice sheet”. In: *Geophysical Research Letters* 43.20, pp. 10–873.

Good, Simon A, Matthew J Martin, and Nick A Rayner (2013). “EN4: Quality controlled ocean temperature and salinity profiles and monthly objective analyses with uncertainty estimates”. In: *Journal of Geophysical Research: Oceans* 118.12, pp. 6704–6716.

Haine, Thomas WN (2020). "Arctic Ocean Freshening Linked to Anthropogenic Climate Change: All Hands on Deck". In: *Geophysical Research Letters* 47.22, e2020GL090678.

Haine, Thomas WN et al. (2015). "Arctic freshwater export: Status, mechanisms, and prospects". In: *Global and Planetary Change* 125, pp. 13–35.

Hanna, E et al. (2019). "Surface air temperature [in "State of the Climate in 2018"]". In: *Bull. Amer. Meteor. Soc* 100.9, S142–S143.

Holdsworth, Amber M and Paul G Myers (2015). "The influence of high-frequency atmospheric forcing on the circulation and deep convection of the Labrador Sea". In: *Journal of Climate* 28.12, pp. 4980–4996.

Holliday, N Penny et al. (2020). "Ocean circulation causes the largest freshening event for 120 years in eastern subpolar North Atlantic". In: *Nature Communications* 11.1, pp. 1–15.

Holmes, Robert Max et al. (2012). "Seasonal and annual fluxes of nutrients and organic matter from large rivers to the Arctic Ocean and surrounding seas". In: *Estuaries and Coasts* 35.2, pp. 369–382.

Hu, Xianmin et al. (2018). "Thermodynamic and dynamic ice thickness contributions in the Canadian Arctic Archipelago in NEMO-LIM2 numerical simulations". In: *The Cryosphere* 12.4, pp. 1233–1247.

Jahn, Alexandra and Rory Laiho (2020). "Forced changes in the Arctic freshwater budget emerge in the early 21st century". In: *Geophysical Research Letters* 47.15, e2020GL088854.

Letscher, Robert T et al. (2013). "Dissolved organic nitrogen dynamics in the Arctic Ocean". In: *Marine Chemistry* 148, pp. 1–9.

Lindsay, R and A Schweiger (2015). "Arctic sea ice thickness loss determined using subsurface, aircraft, and satellite observations". In: *The Cryosphere* 9.1, pp. 269–283.

Lindström, Göran et al. (2010). "Development and testing of the HYPE (Hydrological Predictions for the Environment) water quality model for different spatial scales". In: *Hydrology research* 41.3-4, pp. 295–319.

Lique, C and MD Thomas (2018). *Latitudinal shift of the Atlantic Meridional Overturning Circulation source regions under a warming climate. Nat. Climate Change, 8, 1013–1020.*

MacDonald, Matthew K et al. (2018). "Impacts of 1.5 and 2.0° C Warming on Pan-Arctic River Discharge Into the Hudson Bay Complex Through 2070". In: *Geophysical Research Letters* 45.15, pp. 7561–7570.

Manabe, Syukuro and Ronald J Stouffer (1995). "Simulation of abrupt climate change induced by freshwater input to the North Atlantic Ocean". In: *Nature* 378.6553, pp. 165–167.

Manizza, Manfredi et al. (2011). "A model of the Arctic Ocean carbon cycle". In: *Journal of Geophysical Research: Oceans* 116.C12.

McGeehan, Timothy and Wieslaw Maslowski (2012). "Evaluation and control mechanisms of volume and freshwater export through the Canadian Arctic Archipelago in a high-resolution pan-Arctic ice-ocean model". In: *Journal of Geophysical Research: Oceans* 117.C8.

Mignot, Juliette, Andrey Ganopolski, and Anders Levermann (2007). "Atlantic subsurface temperatures: Response to a shutdown of the overturning circulation and consequences for its recovery". In: *Journal of Climate* 20.19, pp. 4884–4898.

Morison, James et al. (2012). "Changing arctic ocean freshwater pathways". In: *Nature* 481.7379, pp. 66–70.

Myers, Paul, Liam Buchart, et al. (2021). "An Overview of NEMO Modelling for the BaySys Project". In.

Myers, Paul G (2005). "Impact of freshwater from the Canadian Arctic Archipelago on Labrador Sea water formation". In: *Geophysical Research Letters* 32.6.

Myers, Paul G, Laura Castro de la Guardia, et al. (2021). "Extreme High Greenland Blocking Index Leads to the Reversal of Davis and Nares Strait Net Transport Toward the Arctic Ocean". In: *Geophysical Research Letters* 48.17, e2021GL094178.

Myers, Paul G, Chris Donnelly, and Mads H Ribergaard (2009). "Structure and variability of the West Greenland Current in summer derived from 6 repeat standard sections". In: *Progress in Oceanography* 80.1-2, pp. 93–112.

Nummelin, Aleksi et al. (2016). "Consequences of future increased Arctic runoff on Arctic Ocean stratification, circulation, and sea ice cover". In: *Journal of Geophysical Research: Oceans* 121.1, pp. 617–637.

Oleson, Keith W et al. (2010). "Technical description of version 4.0 of the Community Land Model (CLM)". In.

Pemberton, Per and Johan Nilsson (2016). "The response of the central Arctic Ocean stratification to freshwater perturbations". In: *Journal of Geophysical Research: Oceans* 121.1, pp. 792–817.

Peterson, Ingrid et al. (2012). "Wind-forcing of volume transport through Lancaster Sound". In: *Journal of Geophysical Research: Oceans* 117.C11.

Proshutinsky, A, R Krishfield, JM Toole, et al. (2019). "Analysis of the Beaufort Gyre freshwater content in 2003–2018". In: *Journal of Geophysical Research: Oceans* 124.12, pp. 9658–9689.

Proshutinsky, Andrey, Richard Krishfield, Mary-Louise Timmermans, et al. (2009). "Beaufort Gyre freshwater reservoir: State and variability from observations". In: *Journal of Geophysical Research: Oceans* 114.C1.

Ridenour, Natasha A et al. (2019). "Sensitivity of freshwater dynamics to ocean model resolution and river discharge forcing in the Hudson Bay Complex". In: *Journal of Marine Systems* 196, pp. 48–64.

Rousset, C. et al. (2015). "The Louvain-La-Neuve sea ice model LIM3.6: global and regional capabilities". In: *Geoscientific Model Development* 8.10, pp. 2991–3005. DOI: `10.5194/gmd-8-2991-2015`. URL: `http://www.geosci-model-dev.net/8/2991/2015/`.

Rysgaard, S et al. (2020). "An updated view on water masses on the pan-west Greenland continental shelf and their link to proglacial fjords". In: *Journal of Geophysical Research: Oceans* 125.2, e2019JC015564.

Schauer, Ursula and Martin Losch (2019). ""Freshwater" in the ocean is not a useful parameter in climate research". In: *Journal of Physical Oceanography* 49.9, pp. 2309–2321.

Smith, Gregory C et al. (2014). "A new atmospheric dataset for forcing ice–ocean models: Evaluation of reforecasts using the Canadian global deterministic prediction system". In: *Quarterly Journal of the Royal Meteorological Society* 140.680, pp. 881–894.

Stadnyk, Tricia A, Matthew K MacDonald, et al. (2020). "Hydrological modeling of freshwater discharge into Hudson Bay using HYPE". In: *Elementa: Science of the Anthropocene* 8.

Stadnyk, Tricia A, A Tefs, et al. (2021). "Changing freshwater contributions to the Arctic: A 90-year trend analysis (1981–2070)". In: *Elem Sci Anth* 9.1, p. 00098.

Thomas, Helmuth et al. (2004). "Enhanced open ocean storage of CO2 from shelf sea pumping". In: *Science* 304.5673, pp. 1005–1008.

Timmermans, Mary-Louise and John Marshall (2020). "Understanding Arctic Ocean Circulation: A Review of Ocean Dynamics in a Changing Climate". In: *Journal of Geophysical Research: Oceans* 125.4.

Uppala, Sakari M et al. (2005). "The ERA-40 re-analysis". In: *Quarterly Journal of the Royal Meteorological Society: A journal of the atmospheric sciences, applied meteorology and physical oceanography* 131.612, pp. 2961–3012.

Vancoppenolle, Martin et al. (2009). "Simulating the mass balance and salinity of Arctic and Antarctic sea ice. 1. Model description and validation". In: *Ocean Modelling* 27.1–2, pp. 33–53. ISSN: 1463-5003. DOI: `10.1016/j.ocemod.2008.10.005`. URL: `http://www.sciencedirect.com/science/article/pii/S1463500308001613`.

Wang, Qiang et al. (2016). "An assessment of the Arctic Ocean in a suite of interannual CORE-II simulations. Part II: Liquid freshwater". In: *Ocean Modelling* 99, pp. 86–109.

Zhang, Jiaxu et al. (2021). "Labrador Sea freshening linked to Beaufort Gyre freshwater release". In: *Nature communications* 12.1, pp. 1–8.

Chapter 4

Addition of Temperature for Incoming River Runoff

4.1 Introduction

With global warming, the Arctic is rapidly warming (*Canada's Changing Climate Report* 2019). Overall, the Arctic is warming at around double the global average rate, and surface temperatures every year from 2014-2019 exceeded all previous records in the Arctic (Hanna et al., 2019). This trend of increased warming is expected to continue into the future with climate change. The IPCC report predicts that a 2° rise in global mean temperature by 2100 will translate to a 4° to 7° rise in Arctic temperatures (Aragón–Durand et al., 2018). There has been observed a corresponding increase in river runoff in recent years (Shiklomanov et al., 2021), associated with increased air temperatures and rapidly melting sea ice. This trend is expected to continue into the future, with a 22% increase in river discharge into the Arctic Ocean expected by 2070 (Stadnyk, Tefs, et al., 2021). Water temperatures usually follow air temperatures (Sinokrot et al., 1993), and have also increased with climate change. Park, Yoshikawa, et al. (2017) found a warming trend of 0.16 °C per decade from 1979-2013 and Van Vliet et al. (2011) predicts increase in river temperatures between 1.3 °C to 3.8 °C in the future with climate change. This increase in river water temperatures has been shown to impact marine environments, from fish health (Kyle et al., 2001, Islam et al., 2019), nutrient transport (McClelland et al., 2012) and sea ice (Whitefield et al., 2015, Park, Watanabe, et al., 2020).

Some observational data exists on the water temperature of major rivers draining into the Arctic Ocean, largely on a sub-basin scale. Observational work on the Lena River has looked at the changing thermal conditions from human impacts and climate change (Liu et al., 2005, Yang, Liu, et al., 2005). Lammers et al. (2007) presented an observational river temperature data set for 20 majors rivers along the Russian coast. Yang, Shrestha, et al. (2021) examined the heat flux data from 15 Northern Canadian rivers, which drain into the Arctic Ocean and Hudson Bay. In order to look at the impacts of this heat flux however, ocean models need to be employed. While ocean models will generally account for the freshwater flux from rivers, the heat flux information is generally ignored. Whitefield et al. (2015) presented a high resolution river discharge and water temperature data set, which was applied to a regional ocean-ice model and found and 8TW increase in summer heat flux and reduction a 10 % reduction in September sea ice extent. Park, Watanabe, et al. (2020) used a coupled land-ocean-sea ice model simulations to look at the impact of riverine heat on Arctic sea ice and the ocean heat budget, where they find it contributed to up to 10% of of the regional sea ice reduction along the Arctic shelves. This study aims to expand upon this previous work, using an alternative river temperature source to look at the sensitivity of ocean model simulations and results to riverine heat flux information. Ocean model simulations were run for the Arctic Ocean, accounting for the water temperature of incoming river runoff. This chapter will first discuss the runoff data set used, then the ocean model used. The ocean model results will be compared with a twin model experiment which does not include the runoff temperature information, focusing on impacts on Arctic sea ice.

4.2 Runoff Dataset

An Arctic runoff data set has been produced by the Hydrological Modelling Lab at the University of Calgary, based off of the Hydrological Predictions of the Environment (HYPE) model. HYPE is a semi-distributed catchment model, which simulates water flow and substances on their way from precipitation through different storage compartments and fluxes to the sea (Lindström et al., 2010). The Arctic-HYPE setup has been created specifically for the Arctic drainage basin. It includes representations of cryospheric processes, and includes a river regulation model, particularly in the Hudson Bay complex (Stadnyk, MacDonald, et al., 2020). This data set extends up to present day, and includes many of the recent changes seen in Arctic runoff. HYPE is forced using the HydroGFDv2 atmospheric reanalysis product (Berg et al., 2018). This runoff data set was combined with an updated estimate of the Greenland freshwater fluxes, from Bamber et al. (2018). They used a combination of satellite observations of glacier flow speed and regional climate modeling to reconstruct the land ice freshwater flux from the Greenland ice sheet for the period 1958–2016 (Bamber et al., 2018). This provides both runoff amounts and water temperature, for the entire Arctic terrestrial domain.

4.2.1 Temperature and Heat Flux Analysis

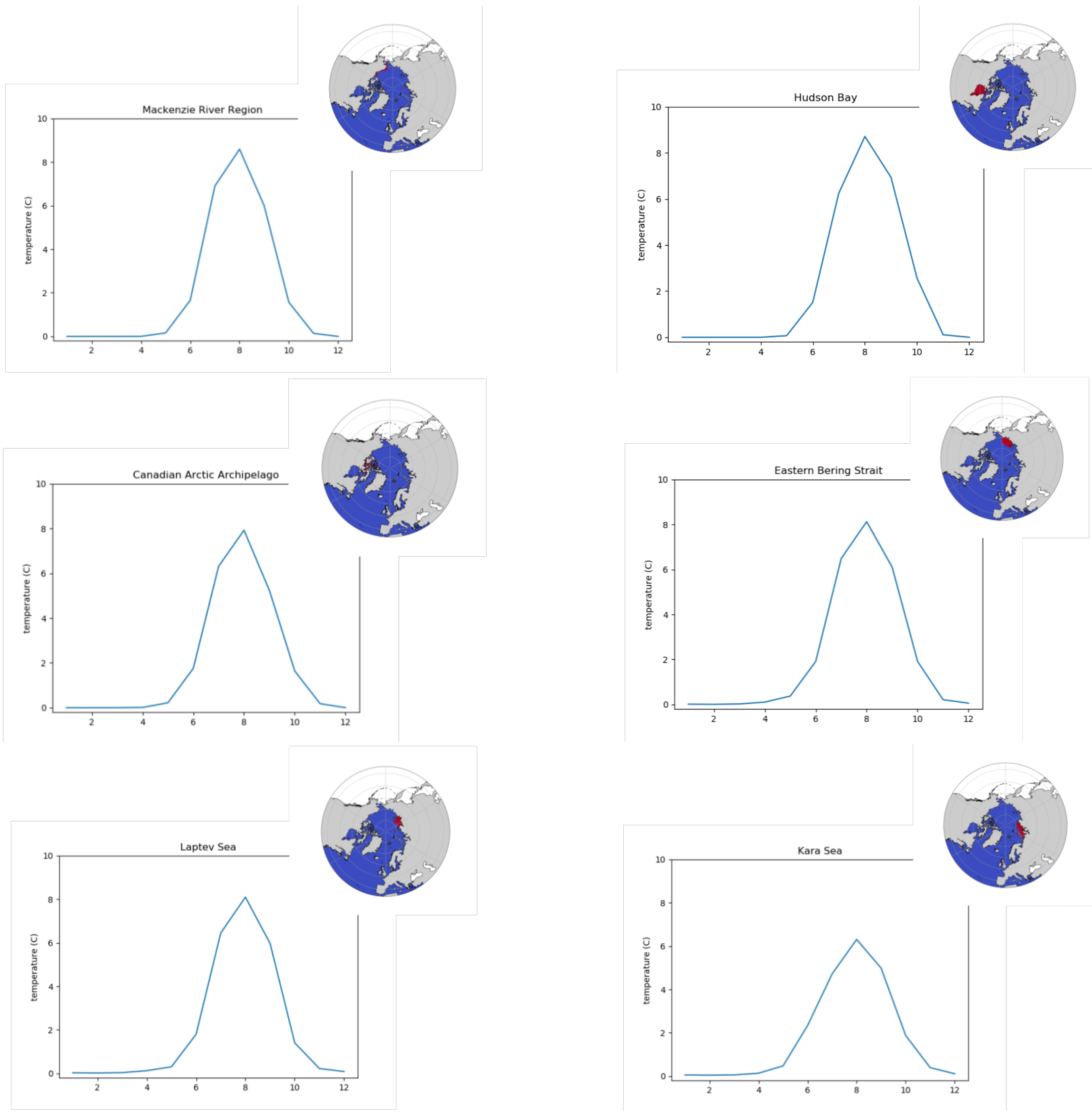


Figure 4.1: The average seasonal cycle of river temperature over the indicated regions. All regions have a seasonal temperature peak in the summer, with winter flow temperatures of 0 °.

Six regions were defined, in order to quantify the water temperature and heat flux. The regions are shown in figure 4.1, and cover Hudson Bay, the Canadian Arctic Archipelago (CAA), the Mackenzie River region, Eastern Bering Strait, the Laptev Sea and the Kara Sea. The monthly average water temperature, averaged over the different regions in the Arctic is shown in figure 4.1. Water temperatures generally peak in August to September, with average water temperatures in August reaching between 8-10 °C. The Kara Sea region has the coolest summer water temperatures, with the average peak reaching only ∼6 °C. Water temperatures in all regions begin to increase from 0 °C in winter in April to May, which aligns with the spring freshet where river ice begins to break up and total flow increases. Water temperatures begin tapering off to zero in October to November. Higher fall temperatures are seen in the Hudson Bay and Eastern Bering Strait regions, where October water temperatures average over 2°C. This pattern of river temperatures aligns with observed patterns from Yang, Shrestha, et al. (2021), with the maximum water temperatures in July-August.

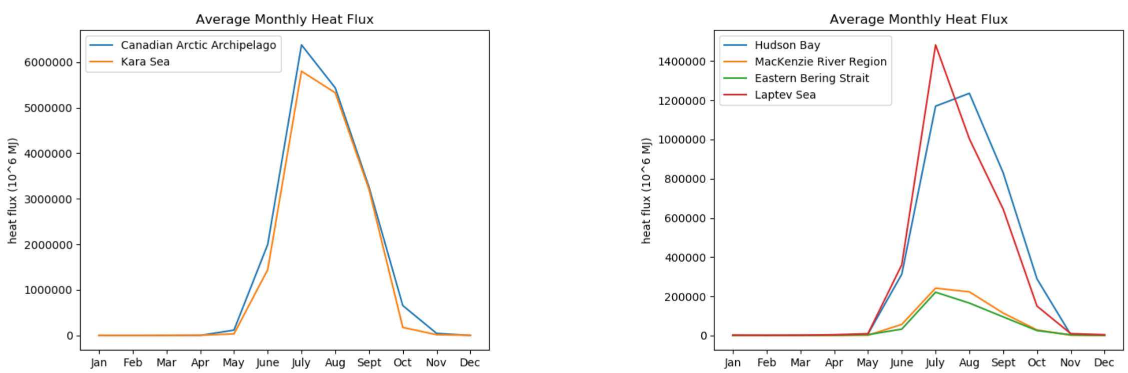


Figure 4.2: The average monthly heat flux over the six regions. Heat fluxes peak in the summer months, with the highest heat fluxes from the Kara Seas and CAA regions shown on the left and the four other regions shown on the right.

The heat flux from the different regions was also calculated, as shown in figure 4.2. This was calculated using equation 4.1, from Yang, Shrestha, et al. (2021).

$$HF = 86400 \cdot C_p \cdot \rho \cdot Q \cdot WT \cdot (N/10^{12}) \tag{4.1}$$

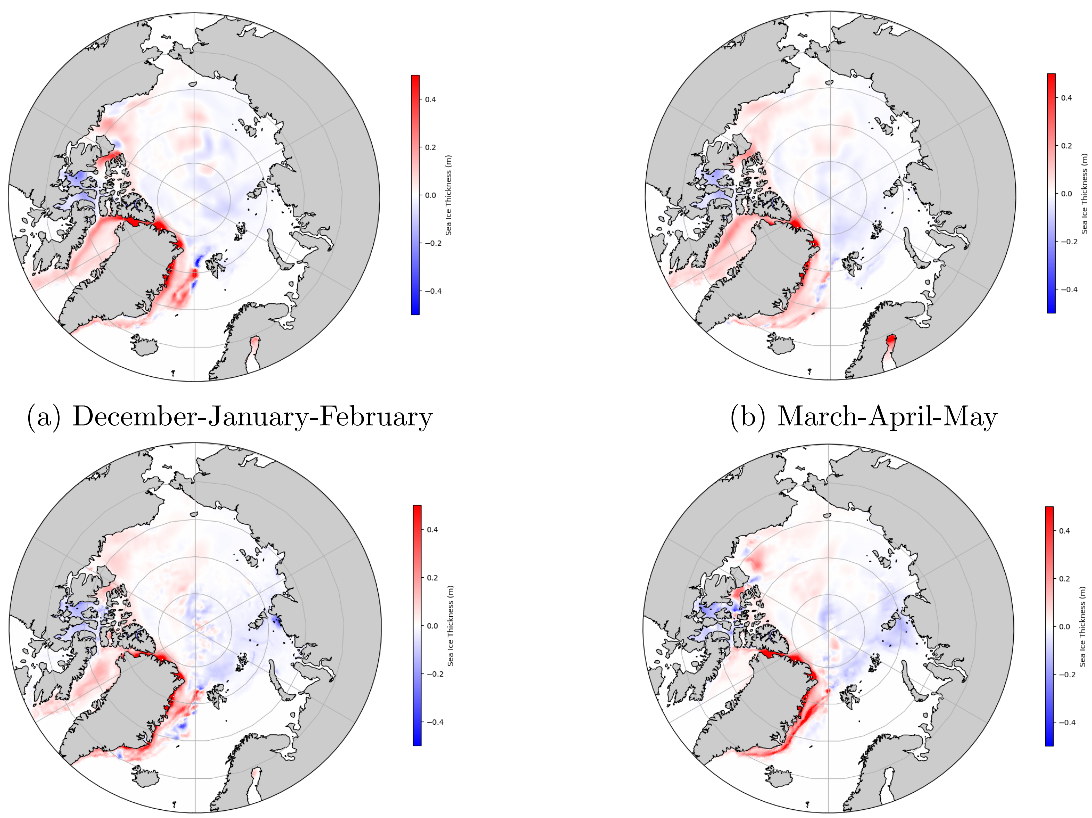
Where HF is the total heat flux per month (10^6 MJ) relative to 0 °C, WT is the monthly mean water temperature (°C), N is the number of days in a given month, C_p is the specific heat capacity for river water (4.184 J/(°Cg)), ρ is the density of water ($10^6 g/m^3$) and 86400 is the constant for converting from seconds to days. The average sum of the heat flux for each month over the regions was calculated. The CAA and Kara Sea regions exhibited the largest summer heat flux by far, with a peak of $6,000,000 \times 10^6 MJ$ in July. The Kara Sea region shows higher heat flux throughout all of the summer months, with a more rapid increase during the spring freshet in April to May, and higher fall heat flux in October and November. This high heat flux compared with the relatively cool peak summer water temperatures in the Kara Seas is likely related to high flow volumes from this region. Hudson Bay also has a large heat flux of just over $1,200,000 \times 10^6 MJ$, with the peak heat flux shifted more the August. The lowest heat flux comes from the Mackenzie River region, with a July peak in heat flux of only $200,00 \times 10^6 MJ$. This low heat flux is likely related to the low flow volumes from the Mackenzie river region in the HYPE data set. Yang, Shrestha, et al. (2021) gives an June flow volume from the Mackenzie of $20,000 m^3/s$ for example, while over the whole Mackenzie river region in the HYPE data set the average June flow volume is $7,570 m^3/s$. This is a large limitation of the heat flux inputs into the model, as the Mackenzie river from observations is a large source of heat into the Arctic Ocean.

4.3 Model Description

Model simulations were run with the state of the art ocean model, Nucleus for European Modelling of the Ocean (NEMO) ocean model engine (Rousset et al., 2015, Vancoppenolle et al., 2009) version 3.6. It uses a sea ice module, Louvain-la-neauve Ice Model version 2 (LIM2) (Fichefet et al., 1997), which includes both dynamic and thermodynamic processes. A marine biogeochemical model coupled to the physical model, Biogeochemistry with Light Iron and Nutrient Limitations (BLING) (Galbraith et al., 2010). A more complete description of BLING can be found in Castro de la Guardia et al. (2019). The configuration use covered the Arctic and Northern Hemisphere Atlantic (ANHA). It has open boundaries at the Bering strait, and 20°south (Myers et al., 2021). Initial and open boundary conditions were obtained from the global 1/4°GLORYS2v3 simulation (Ferry et al., 2010). The model uses z-coordinates, with 50 vertical levels. A 1/4 degree horizontal resolution was used, which allows for better representation of boundary currents and other mesoscale processes, and allows for a longer time integration. This is referred to as the ANHA4 configuration, for the 1/4 degree resolution (Holdsworth et al., 2015, Gillard et al., 2016, Hu et al., 2018). This gives a horizontal resolution of between 8-18km for the Arctic Ocean. It uses a tri-polar grid, to prevent a singularity at the poles in the ocean. The placement of the tri-polar grid also serves to increase the resolution in the Canadian Arctic Archipelago, giving a high enough resolution in the area to resolve the major straits and exchanges. The Canadian Meteorological Centre's global deterministic prediction system (CGRF) was used for atmospheric forcing. CGRF is a higher resolution re-forecast product, which combines daily forecasts into a final product (Smith et al., 2014). As such, it is not as well constrained to observations as a reanalysis product, but has a high resolution with a relatively small bias.

Two twin model runs were completed, where one run included the water temperature information from the HYPE data set. Otherwise the runs were identical, using the same configuration, atmospheric forcing and runoff flow. This water temperature information was only available for the Arctic domain, including the Hudson Bay region. Outside of this area, the model domain did not include any water temperature information. Both setups were run from 2002 to 2017, with 5 day average output. By comparing results from the two model runs, we can look at the Arctic Oceans sensitivity to riverine heat flux.

4.4 Results and Discussion



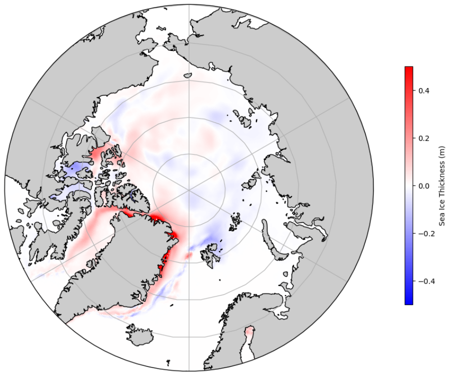
(a) December-January-February

(b) March-April-May

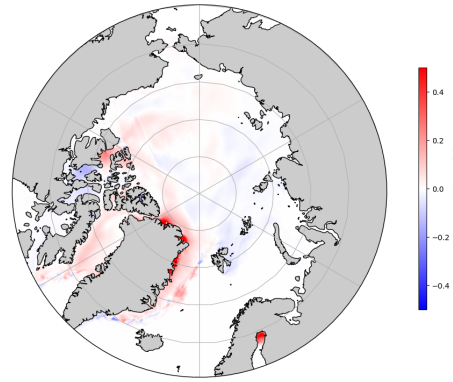
(c) June-July-August

(d) September-October-November

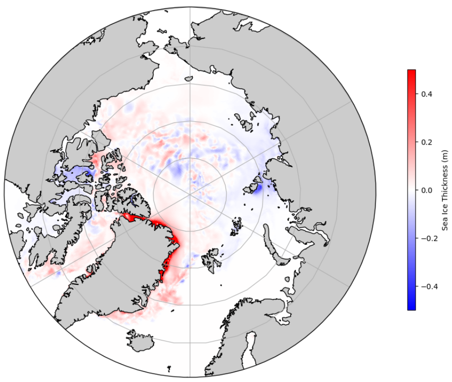
Figure 4.3: Difference in average sea ice thickness in 2013 between the model runs for the different seasons. Red indicates thicker sea ice in the model run with riverine heat flux, and blue indicates thicker sea ice in the model run without.



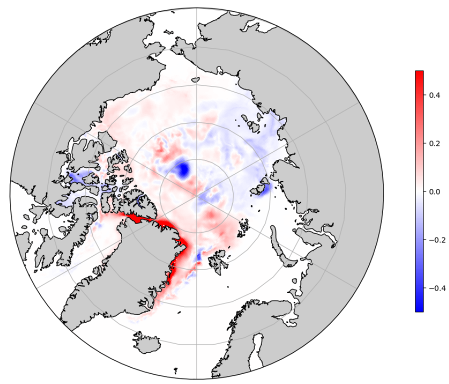
(a) December-January-February



(b) March-April-May



(c) June-July-August



(d) September-October-November

Figure 4.4: Difference in average sea ice thickness in 2016 between the model runs for the different seasons.

The difference in the seasonal sea ice thickness between the model runs can be seen in figures 4.3 and 4.4. This shows the results for 2016 and 2013 as examples of the seasonal pattern seen. A negative thickness difference indicates the model run with river water temperature has a lower sea ice thickness, compared with the model run without river water temperatures. The largest differences are seen in the fall (September-October-November), particularly in 2016. Differences can be seen in particular in the CAA and Laptev Sea regions in 2016. There is between 0.2m to 0.3m thinner sea ice in these regions in the fall. In the central Arctic, there is up to 0.5m thinner sea ice in the fall. The smallest difference in sea ice is seen in the spring (March-April-May). The same pattern though of slightly thinner sea ice in the CAA and Laptev Sea still persists however. In 2013, the differences in sea ice thickness are more consistent throughout the seasons. Slightly thicker sea ice is seen in the model run with river water temperature information around the Mackenzie River region throughout all seasons. Thinner sea ice is seen in the CAA, between 0.1m-0.3m thinner. Thinner sea ice is also in contrast seen in the Kara Sea region, as opposed to the Laptev Sea region in 2016.

Thicker sea ice in the model run with river water temperature is seen consistently around the northern coast of Greenland, extending down through the boundary currents along eastern Greenland and Baffin Bay. Water temperature information was not included for runoff from Greenland, as these runoff flow estimates were from Bamber et al. (2018). This thicker sea ice however aligns with Fram and Nares Straits, which are major straits for southward flow out of the Arctic. As more heat flux is added into the model simulation through river water temperature, this could lead to a more mobile sea ice pack. A more mobile pack will allow for greater export of the thick ice north of Greenland and CAA out through Nares and Fram Strait, thus allowing the southward flowing boundary currents to carry thicker ice until that excess ice is melted by warmer waters further south. Sea ice ridging can also occur through the straits, particularly at Nares Strait, which could cause thicker sea ice from a more mobile sea ice pack.

Comparing the sea ice thickness results with the heat flux shown in figure 4.2, some similarities and differences can be seen. High heat flux can be seen into the CAA, which aligns with a consistently lower sea ice thickness seen in the model run. The Kara Sea also shows a high heat flux, but this does not translate to thinner sea ice in the model run for all years. While 2013 showed thinner sea ice in both the CAA and Kara Sea region, in 2016 the sea ice thickness was comparable between the model runs in this region. The distribution of this heat flux is likely a factor in the model results. As the CAA is a shallow, shelf region, changes in heat flux are likely to contribute significantly to the sea ice production. The Kara and Laptev Sea regions however drain into the Eurasian Basin, which is heavily influenced by the path and strength of the Transpolar Drift. This likely allows the heat flux to dissipate and travel to other regions in the Arctic Ocean, under certain atmospheric and circulation conditions.

4.5 Conclusion

River runoff can be an important source of not only freshwater, but also heat into the Arctic Ocean (Whitefield et al., 2015). With climate change, warming is expected to affect Arctic river stream flow temperatures. This can have downstream consequences on the Arctic Ocean, where it can affect marine ecosystems, stratification and Arctic sea ice. We integrated available river water temperature information produced by the HYPE hydrological model into a ocean-ice model to test the models sensitivity to this parameter. In most ocean models, river water temperature is not included, so understanding where and how this information affects ocean model results is an important question for model development. First the seasonal water temperature cycles, and the associated heat flux were analyzed. The CAA and Kara Sea regions were found to be significant sources of heat into the Arctic Ocean in the HYPE data set. This was compared with the sea ice thickness from the model results. This extra heat flux can be seen to have a strong influence on the CAA, with consistently thinner sea ice seen in model simulations that included the river water temperature information. This pattern of increased heat flux leading to reduced sea ice is less clear in the Kara Sea region, with some years showing thinner sea ice, and others showing little change between a model simulation without river water temperature information. This could be due the stronger surface circulation in this region, which could allow for the redistribution and dissipation of this heat flux in this area. Thicker sea ice through Fram and Nares Strait, and downstream along the coastal boundary currents was also consistently found in the model run with river water temperature included. This is likely due to the heat influx creating a more mobile sea ice pack, increasing ice transport down to lower latitudes through these gateways.

For the completed model runs, LIM2 was used a sea-ice component. Major limitations are known for LIM2, such as the inability to simulate ice arches, commonly found through Nares Strait, overestimation of ice thickness, and the lack of land fast ice (Buchart, 2021). This could play a role in the sea ice thickness found through Fram and Nares Strait, and downstream along boundary currents. The lack of land fast ice could also change the response of the ocean model to the increased riverine heat flux in the central Arctic. Using a different sea-ice module could significantly change the results found in this chapter. An updated version of the LIM module, LIM3 could be employed to improve the accuracy of these results.

Bibliography

Aragón–Durand, Fernando et al. (2018). "Special Report on Global warming of 1.5° C (SR15)-Chapter 1: Framing and Context". In.

Bamber, JL et al. (2018). "Land ice freshwater budget of the Arctic and North Atlantic Oceans: 1. Data, methods, and results". In: *Journal of Geophysical Research: Oceans* 123.3, pp. 1827–1837.

Berg, Peter, Chantal Donnelly, and David Gustafsson (2018). "Near-real-time adjusted reanalysis forcing data for hydrology". In: *Hydrology and Earth System Sciences* 22.2, pp. 989–1000.

Buchart, Liam (2021). "Sea Ice Modelling in the Pikialasorsuaq: Parameters Sensitivities and Future Prospects". In.

Canada's Changing Climate Report (2019). Government of Canada.

Castro de la Guardia, Laura et al. (2019). "Assessing the role of high-frequency winds and sea ice loss on Arctic phytoplankton blooms in an ice-ocean-biogeochemical model". In: *Journal of Geophysical Research: Biogeosciences* 124.9, pp. 2728–2750.

Ferry, Nicolas et al. (2010). "Mercator global Eddy permitting ocean reanalysis GLORYS1V1: Description and results". In: *Mercator-Ocean Quarterly Newsletter* 36, pp. 15–27.

Fichefet, Thierry and MA Morales Maqueda (1997). "Sensitivity of a global sea ice model to the treatment of ice thermodynamics and dynamics". In: *Journal of Geophysical Research: Oceans* 102.C6, pp. 12609–12646.

Galbraith, Eric D et al. (2010). "Regional impacts of iron-light colimitation in a global biogeochemical model". In: *Biogeosciences* 7.3, pp. 1043–1064.

Gillard, Laura C et al. (2016). "Meltwater pathways from marine terminating glaciers of the Greenland ice sheet". In: *Geophysical Research Letters* 43.20, pp. 10–873.

Hanna, E et al. (2019). "Surface air temperature [in "State of the Climate in 2018"]". In: *Bull. Amer. Meteor. Soc* 100.9, S142–S143.

Holdsworth, Amber M and Paul G Myers (2015). "The influence of high-frequency atmospheric forcing on the circulation and deep convection of the Labrador Sea". In: *Journal of Climate* 28.12, pp. 4980–4996.

Hu, Xianmin et al. (2018). “Thermodynamic and dynamic ice thickness contributions in the Canadian Arctic Archipelago in NEMO-LIM2 numerical simulations”. In: *The Cryosphere* 12.4, pp. 1233–1247.

Islam, Siraj Ul et al. (2019). “Modelling the impacts of climate change on riverine thermal regimes in western Canada’s largest Pacific watershed”. In: *Scientific reports* 9.1, pp. 1–14.

Kyle, Rebecca E and Timothy P Brabets (2001). *Water temperature of streams in the Cook Inlet basin, Alaska, and implications of climate change.* Vol. 1. 4109. US Department of the Interior, US Geological Survey.

Lammers, Richard B, Jonathan W Pundsack, and Alexander I Shiklomanov (2007). “Variability in river temperature, discharge, and energy flux from the Russian pan-Arctic landmass”. In: *Journal of Geophysical Research: Biogeosciences* 112.G4.

Lindström, Göran et al. (2010). “Development and testing of the HYPE (Hydrological Predictions for the Environment) water quality model for different spatial scales”. In: *Hydrology research* 41.3-4, pp. 295–319.

Liu, Baozhong et al. (2005). “Long-term open-water season stream temperature variations and changes over Lena River Basin in Siberia”. In: *Global and Planetary Change* 48.1-3, pp. 96–111.

McClelland, James W et al. (2012). “The Arctic ocean estuary”. In: *Estuaries and Coasts* 35.2, pp. 353–368.

Myers, Paul et al. (2021). “An Overview of NEMO Modelling for the BaySys Project”. In.

Park, Hotaek, Eiji Watanabe, et al. (2020). “Increasing riverine heat influx triggers Arctic sea ice decline and oceanic and atmospheric warming”. In: *Science advances* 6.45, eabc4699.

Park, Hotaek, Yasuhiro Yoshikawa, et al. (2017). “Warming water in Arctic terrestrial rivers under climate change”. In: *Journal of Hydrometeorology* 18.7, pp. 1983–1995.

Rousset, C. et al. (2015). “The Louvain-La-Neuve sea ice model LIM3.6: global and regional capabilities”. In: *Geoscientific Model Development* 8.10, pp. 2991–3005. DOI: 10.5194/gmd-8-2991-2015. URL: http://www.geosci-model-dev.net/8/2991/2015/.

Shiklomanov, Alexander et al. (2021). “River freshwater flux to the Arctic Ocean”. In: *Arctic hydrology, permafrost and ecosystems*. Springer, pp. 703–738.

Sinokrot, Bashar A and Heinz G Stefan (1993). “Stream temperature dynamics: measurements and modeling”. In: *Water resources research* 29.7, pp. 2299–2312.

Smith, Gregory C et al. (2014). “A new atmospheric dataset for forcing ice–ocean models: Evaluation of reforecasts using the Canadian global deterministic prediction system”. In: *Quarterly Journal of the Royal Meteorological Society* 140.680, pp. 881–894.

Stadnyk, Tricia A, Matthew K MacDonald, et al. (2020). "Hydrological modeling of freshwater discharge into Hudson Bay using HYPE". In: *Elementa: Science of the Anthropocene* 8.

Stadnyk, Tricia A, A Tefs, et al. (2021). "Changing freshwater contributions to the Arctic: A 90-year trend analysis (1981–2070)". In: *Elem Sci Anth* 9.1, p. 00098.

Van Vliet, MTH et al. (2011). "Global river temperatures and sensitivity to atmospheric warming and changes in river flow". In: *Water Resources Research* 47.2.

Vancoppenolle, Martin et al. (2009). "Simulating the mass balance and salinity of Arctic and Antarctic sea ice. 1. Model description and validation". In: *Ocean Modelling* 27.1–2, pp. 33–53. ISSN: 1463-5003. DOI: `10.1016/j.ocemod.2008.10.005`. URL: `http://www.sciencedirect.com/science/article/pii/S1463500308001613`.

Whitefield, Jonathan et al. (2015). "A new river discharge and river temperature climatology data set for the pan-Arctic region". In: *Ocean Modelling* 88, pp. 1–15.

Yang, Daqing, Baozhong Liu, and Baisheng Ye (2005). "Stream temperature changes over Lena River basin in Siberia". In: *Geophysical Research Letters* 32.5.

Yang, Daqing, Rajesh R Shrestha, et al. (2021). "Heat flux, water temperature and discharge from 15 northern Canadian rivers draining to Arctic Ocean and Hudson Bay". In: *Global and Planetary Change* 204, p. 103577.

Chapter 5

Conclusion

River runoff is an important source of freshwater and heat into the Arctic Ocean. With climate change, changes in the amounts and patterns of both flow and temperature have already begun and are expected to continue into the future (Durocher et al., 2019, Yang et al., 2021 and others). Current projections expect 22% increases in river discharge by 2070 (Stadnyk et al., 2019), with increases in average water temperature also expected. As such, it is important to understand impacts of this river runoff on the Arctic Ocean currently, and how that is likely to change in the future. Ocean models are useful tools for looking at these changes, as they can simulate key parameters over comprehensive spatial and temporal scales. Understanding the sensitivities of models to runoff forcing and limitations of current approaches can help with predicting future impacts of these changes.

5.1 Key Findings

5.1.1 Importance of the CAA as a Source of River Runoff

While previous modelling studies have looked at the importance of the CAA as an export gateway for freshwater out of the Arctic Ocean into lower latitudes, little importance has been given to the region as a source of freshwater input. When comparing the HYPE and Dai and Trenberth runoff data sets, some of the largest differences in magnitude of river runoff were shown in this region, with HYPE having ∼3 times more runoff. This change affected not only biogeochemical markers in the region, representing productivity, air-sea carbon fluxes and stratification, but also affected freshwater transport to lower latitudes. Increase in freshwater transport was seen then through Davis Strait and increased freshwater content in the Labrador Current. Under the appropriate atmospheric conditions, as seen in 2012-2016, there can be significant offshore transport into the sub-polar gyre region. With the HYPE model runs, the salinity anomaly in the sub-polar North Atlantic was enhanced due to the extra freshwater input from the CAA. This points to the importance of the CAA as not only a pathway for Arctic freshwater to lower latitudes, but also as a source of freshwater from riverine input.

5.1.2 Underestimation of Freshwater Content in the Beaufort Gyre

The Beaufort Gyre is one of the main sites of freshwater storage in the Arctic Ocean (Proshutinsky, Krishfield, Timmermans, et al., 2009). The freshwater layer in the Beaufort Gyre has been observed to be thickening in recent years (Proshutinsky, Krishfield, Toole, et al., 2019), and release of this freshwater could have many downstream impacts. In this analysis, the observed freshwater content was compared with the modelled freshwater content in the Beaufort Gyre. All model runs, irregardless of runoff and atmospheric forcing, were found to significantly underestimate the freshwater storage in the Beaufort Gyre. A 1/12°resolution model run was also compared, to understand the significance of resolution in this finding. While the higher resolution model run did perform better compared to observations than the lower resolution counterparts, it still underestimated the freshwater content in the region. This shows that not just a better representation of river runoff, or improvement in model horizontal resolution are needed to fix modelling of the Beaufort Gyre. An underestimation of stratification and sea ice concentration, which are linked to freshwater content, in ocean models is common and could play a role in this result.

5.1.3 Large Heat Fluxes Missing in Ocean Model Simulations

Riverine heat is known to be a significant source of heat flux into the Arctic Ocean. River water temperatures are also known to be increasing with climate change, as water temperatures follow increases in air temperatures. It is also a parameter commonly excluded from ocean model simulations, where only the freshwater flux from rivers is accounted for. Using water temperature information from the HYPE, analysis on the heat flux into the Arctic Ocean was completed and the ocean model was adapted to include this information. The heat flux from the CAA and Kara Seas in particular was significant, and the impact could be seen in the sea ice thickness. The signal of this was very clear in the CAA, however in the Kara Sea region it differed between different years. This could be due to the differences in surface circulation between theses regions. This could lead to more heat flux being redistributed or dissipated in the Kara Sea, compared to the CAA. Affects were generally seasonal, with the largest differences seen in the fall.

5.2 Limitations and Future Work

Major limitations in this work stem from the short time period of integration. As model results only cover a ∼15 year time period, long term trends in runoff and their affects on the ocean were difficult to quantify. Extension of the time series before 2000 would allow for capturing of more recent changes. In addition, future simulations would allow for considering questions of longer term freshwater storage, propagation of runoff increases and surface circulation changes.

Some limitations of the HYPE data set have been identified, particularly low flow amounts from some of the major Arctic rivers. This could likely have has an impact on freshwater storage and heat content results for the Canadian Basin and central Arctic. A few other river runoff data sets exist which include water temperature information for forcing ocean models. Comparing ocean model results using another runoff data set including water temperature information could provide insight into how heat flux from these large rivers impacts high Arctic sea ice processes. Without including water temperature information, more accurate runoff representation could likely be achieved through combining the Dai and Trenberth data set for the major Arctic rivers, as those results are better correlated to observations, with the HYPE data set for the rest of the Arctic domain, as it has a better spatial resolution for smaller Arctic rivers. While this would not resolve the lack of climate signal seen in the Dai and Trenberth rivers, as river information only extends to 2007 in that data set, but it could improve the low flow volumes found for some of the major Arctic rivers in HYPE.

Future work considering the trends in river runoff in a coupled land-ocean-sea ice model could reduce biases from the interface, and allow for a more complete picture of these changes. The different runoff data sets were developed very differently, not only from each other but also from the ocean model used. Fully incorporating the hydrological model with the ocean model could help identify the biases associated with this interface and have a consistent response to the atmospheric forcing across the models.

Bibliography

Durocher, Martin et al. (2019). “Analysis of trends in annual streamflow to the Arctic Ocean”. In: *Hydrological Processes* 33.7, pp. 1143–1151.

Proshutinsky, A, R Krishfield, JM Toole, et al. (2019). “Analysis of the Beaufort Gyre freshwater content in 2003–2018”. In: *Journal of Geophysical Research: Oceans* 124.12, pp. 9658–9689.

Proshutinsky, Andrey, Richard Krishfield, Mary-Louise Timmermans, et al. (2009). “Beaufort Gyre freshwater reservoir: State and variability from observations”. In: *Journal of Geophysical Research: Oceans* 114.C1.

Stadnyk, Tricia Anne et al. (2019). “Changing freshwater contributions to the Arctic: a 90-year trend analysis”. In: *AGU Fall Meeting Abstracts*. Vol. 2019, GC51J–1088.

Yang, Daqing et al. (2021). “Heat flux, water temperature and discharge from 15 northern Canadian rivers draining to Arctic Ocean and Hudson Bay”. In: *Global and Planetary Change* 204, p. 103577.

Comprehensive Bibliography

Aagaard, Ko and Ee C Carmack (1989). "The role of sea ice and other fresh water in the Arctic circulation". In: *Journal of Geophysical Research: Oceans* 94.C10, pp. 14485–14498.

Aksenov, Yevgeny et al. (2011). "The Arctic circumpolar boundary current". In: *Journal of Geophysical Research: Oceans* 116.C9.

Anderson, Leif G et al. (2009). "Out-gassing of CO2 from Siberian Shelf seas by terrestrial organic matter decomposition". In: *Geophysical Research Letters* 36.20.

Aragón–Durand, Fernando et al. (2018). "Special Report on Global warming of 1.5° C (SR15)-Chapter 1: Framing and Context". In.

Armitage, Thomas WK et al. (2017). "Arctic Ocean surface geostrophic circulation 2003–2014". In: *The Cryosphere* 11.4, pp. 1767–1780.

Arnell, Nigel W (2005). "Implications of climate change for freshwater inflows to the Arctic Ocean". In: *Journal of Geophysical Research: Atmospheres* 110.D7.

Asselin, Richard (1972). "Frequency filter for time integrations". In: *Monthly Weather Review* 100.6, pp. 487–490.

Bamber, JL, AJ Tedstone, et al. (2018). "Land ice freshwater budget of the Arctic and North Atlantic Oceans: 1. Data, methods, and results". In: *Journal of Geophysical Research: Oceans* 123.3, pp. 1827–1837.

Bamber, Jonathan, Michiel Van Den Broeke, et al. (2012). "Recent large increases in freshwater fluxes from Greenland into the North Atlantic". In: *Geophysical Research Letters* 39.19.

Berg, Peter, Chantal Donnelly, and David Gustafsson (2018). "Near-real-time adjusted reanalysis forcing data for hydrology". In: *Hydrology and Earth System Sciences* 22.2, pp. 989–1000.

Bryan, Kirk and LJ Lewis (1979). "A water mass model of the world ocean". In: *Journal of Geophysical Research: Oceans* 84.C5, pp. 2503–2517.

Buchart, Liam (2021). "Sea Ice Modelling in the Pikialasorsuaq: Parameters Sensitivities and Future Prospects". In.

Canada's Changing Climate Report (2019). Government of Canada.

Carmack, Eddy, David Barber, et al. (2006). "Climate variability and physical forcing of the food webs and the carbon budget on panarctic shelves". In: *Progress in Oceanography* 71.2-4, pp. 145–181.

Carmack, Edward C, Michiyo Yamamoto-Kawai, et al. (2016). "Freshwater and its role in the Arctic Marine System: Sources, disposition, storage, export, and physical and biogeochemical consequences in the Arctic and global oceans". In: *Journal of Geophysical Research: Biogeosciences* 121.3, pp. 675–717.

Castro de la Guardia, Laura et al. (2019). "Assessing the role of high-frequency winds and sea ice loss on Arctic phytoplankton blooms in an ice-ocean-biogeochemical model". In: *Journal of Geophysical Research: Biogeosciences* 124.9, pp. 2728–2750.

Cavalieri, Donald J and Claire L Parkinson (2012). "Arctic sea ice variability and trends, 1979–2010". In: *The Cryosphere* 6.4, pp. 881–889.

Curry, B et al. (2014). "Multiyear volume, liquid freshwater, and sea ice transports through Davis Strait, 2004–10". In: *Journal of Physical Oceanography* 44.4, pp. 1244–1266.

Dai, Aiguo et al. (2009). "Changes in continental freshwater discharge from 1948 to 2004". In: *Journal of climate* 22.10, pp. 2773–2792.

Dee, Dick P et al. (2011). "The ERA-Interim reanalysis: Configuration and performance of the data assimilation system". In: *Quarterly Journal of the royal meteorological society* 137.656, pp. 553–597.

Déry, Stephen J et al. (2011). "Interannual variability and interdecadal trends in Hudson Bay streamflow". In: *Journal of Marine Systems* 88.3, pp. 341–351.

Dong, Changming et al. (2014). "Global heat and salt transports by eddy movement". In: *Nature communications* 5.1, pp. 1–6.

Dukhovskoy, DS et al. (2019). "Role of Greenland freshwater anomaly in the recent freshening of the subpolar North Atlantic". In: *Journal of Geophysical Research: Oceans* 124.5, pp. 3333–3360.

Durocher, Martin et al. (2019). "Analysis of trends in annual streamflow to the Arctic Ocean". In: *Hydrological Processes* 33.7, pp. 1143–1151.

Else, BGT et al. (2012). "Sea surface pCO2 cycles and CO2 fluxes at landfast sea ice edges in Amundsen Gulf, Canada". In: *Journal of Geophysical Research: Oceans* 117.C9.

Ferry, Nicolas et al. (2010). "Mercator global Eddy permitting ocean reanalysis GLORYS1V1: Description and results". In: *Mercator-Ocean Quarterly Newsletter* 36, pp. 15–27.

Fichefet, Thierry and MA Morales Maqueda (1997). "Sensitivity of a global sea ice model to the treatment of ice thermodynamics and dynamics". In: *Journal of Geophysical Research: Oceans* 102.C6, pp. 12609–12646.

Foukal, Nicholas P and M Susan Lozier (2017). “Assessing variability in the size and strength of the N orth A tlantic subpolar gyre”. In: *Journal of Geophysical Research: Oceans* 122.8, pp. 6295–6308.

Fox-Kemper, Baylor (2018). “Notions for the motions of the oceans”. In: *New Frontiers in Operational Oceanography*, pp. 27–74.

Galbraith, Eric D et al. (2010). “Regional impacts of iron-light colimitation in a global biogeochemical model”. In: *Biogeosciences* 7.3, pp. 1043–1064.

Geilfus, N-X et al. (2018). “Spatial and temporal variability of seawater pCO2 within the Canadian Arctic Archipelago and Baffin Bay during the summer and autumn 2011”. In: *Continental Shelf Research* 156, pp. 1–10.

Gent, Peter R et al. (1995). “Parameterizing eddy-induced tracer transports in ocean circulation models”. In: *Journal of Physical Oceanography* 25.4, pp. 463–474.

Gill, Adrian E and E Adrian (1982). *Atmosphere-ocean dynamics*. Vol. 30. Academic press.

Gillard, Laura C et al. (2016). “Meltwater pathways from marine terminating glaciers of the Greenland ice sheet”. In: *Geophysical Research Letters* 43.20, pp. 10–873.

Good, Simon A, Matthew J Martin, and Nick A Rayner (2013). “EN4: Quality controlled ocean temperature and salinity profiles and monthly objective analyses with uncertainty estimates”. In: *Journal of Geophysical Research: Oceans* 118.12, pp. 6704–6716.

Griffies, SM et al. (2009). “Problems and prospects in large-scale ocean circulation models”. In: *Proceedings of OceanObs* 9, pp. 410–431.

Haine, Thomas WN (2020). “Arctic Ocean Freshening Linked to Anthropogenic Climate Change: All Hands on Deck”. In: *Geophysical Research Letters* 47.22, e2020GL090678.

Haine, Thomas WN et al. (2015). “Arctic freshwater export: Status, mechanisms, and prospects”. In: *Global and Planetary Change* 125, pp. 13–35.

Hanna, E et al. (2019). “Surface air temperature [in “State of the Climate in 2018”]”. In: *Bull. Amer. Meteor. Soc* 100.9, S142–S143.

Holdsworth, Amber M and Paul G Myers (2015). “The influence of high-frequency atmospheric forcing on the circulation and deep convection of the Labrador Sea”. In: *Journal of Climate* 28.12, pp. 4980–4996.

Holliday, N Penny et al. (2020). “Ocean circulation causes the largest freshening event for 120 years in eastern subpolar North Atlantic”. In: *Nature Communications* 11.1, pp. 1–15.

Holmes, Robert Max et al. (2012). “Seasonal and annual fluxes of nutrients and organic matter from large rivers to the Arctic Ocean and surrounding seas”. In: *Estuaries and Coasts* 35.2, pp. 369–382.

Hu, Xianmin et al. (2018). “Thermodynamic and dynamic ice thickness contributions in the Canadian Arctic Archipelago in NEMO-LIM2 numerical simulations”. In: *The Cryosphere* 12.4, pp. 1233–1247.

Ilıcak, Mehmet et al. (2012). “Spurious dianeutral mixing and the role of momentum closure”. In: *Ocean Modelling* 45, pp. 37–58.

Islam, Siraj Ul et al. (2019). “Modelling the impacts of climate change on riverine thermal regimes in western Canada’s largest Pacific watershed”. In: *Scientific reports* 9.1, pp. 1–14.

Jahn, Alexandra and Rory Laiho (2020). “Forced changes in the Arctic freshwater budget emerge in the early 21st century”. In: *Geophysical Research Letters* 47.15, e2020GL088854.

Kolmogorov, Andrey Nikolaevich (1941). “The local structure of turbulence in incompressible viscous fluid for very large Reynolds numbers”. In: *Cr Acad. Sci. URSS* 30, pp. 301–305.

Kwok, Ron, G Spreen, and S Pang (2013). “Arctic sea ice circulation and drift speed: Decadal trends and ocean currents”. In: *Journal of Geophysical Research: Oceans* 118.5, pp. 2408–2425.

Kyle, Rebecca E and Timothy P Brabets (2001). *Water temperature of streams in the Cook Inlet basin, Alaska, and implications of climate change*. Vol. 1. 4109. US Department of the Interior, US Geological Survey.

Lammers, Richard B, Jonathan W Pundsack, and Alexander I Shiklomanov (2007). “Variability in river temperature, discharge, and energy flux from the Russian pan-Arctic landmass”. In: *Journal of Geophysical Research: Biogeosciences* 112.G4.

Letscher, Robert T et al. (2013). “Dissolved organic nitrogen dynamics in the Arctic Ocean”. In: *Marine Chemistry* 148, pp. 1–9.

Lindsay, R and A Schweiger (2015). “Arctic sea ice thickness loss determined using subsurface, aircraft, and satellite observations”. In: *The Cryosphere* 9.1, pp. 269–283.

Lindström, Göran et al. (2010). “Development and testing of the HYPE (Hydrological Predictions for the Environment) water quality model for different spatial scales”. In: *Hydrology research* 41.3-4, pp. 295–319.

Lique, C and MD Thomas (2018). *Latitudinal shift of the Atlantic Meridional Overturning Circulation source regions under a warming climate. Nat. Climate Change, 8, 1013–1020.*

Liu, Baozhong et al. (2005). “Long-term open-water season stream temperature variations and changes over Lena River Basin in Siberia”. In: *Global and Planetary Change* 48.1-3, pp. 96–111.

MacDonald, Matthew K et al. (2018). “Impacts of 1.5 and 2.0° C Warming on Pan-Arctic River Discharge Into the Hudson Bay Complex Through 2070”. In: *Geophysical Research Letters* 45.15, pp. 7561–7570.

MacKinnon, Jennifer A et al. (2017). “Climate process team on internal wave–driven ocean mixing”. In: *Bulletin of the American Meteorological Society* 98.11, pp. 2429–2454.

Madec, G (2016). “NEMO ocean engine, version 3.6 stable”. In: *Note du Pole de modelisation de l’Institut Pierre-Simon Laplace* 27.

Madec, Gurvan, Pascale Delecluse, et al. (1997). “Ocean general circulation model reference manual”. In: *Note du Pôle de modélisation*.

Madec, Gurvan and Maurice Imbard (1996). “A global ocean mesh to overcome the North Pole singularity”. In: *Climate Dynamics* 12.6, pp. 381–388.

Maltrud, Mathew E and Julie L McClean (2005). “An eddy resolving global 1/10 ocean simulation”. In: *Ocean Modelling* 8.1-2, pp. 31–54.

Manabe, Syukuro and Ronald J Stouffer (1995). “Simulation of abrupt climate change induced by freshwater input to the North Atlantic Ocean”. In: *Nature* 378.6553, pp. 165–167.

Manizza, Manfredi et al. (2011). “A model of the Arctic Ocean carbon cycle”. In: *Journal of Geophysical Research: Oceans* 116.C12.

McClelland, James W et al. (2012). “The Arctic ocean estuary”. In: *Estuaries and Coasts* 35.2, pp. 353–368.

McDougall, Trevor J (1987). “Neutral surfaces”. In: *Journal of Physical Oceanography* 17.11, pp. 1950–1964.

McGeehan, Timothy and Wieslaw Maslowski (2012). “Evaluation and control mechanisms of volume and freshwater export through the Canadian Arctic Archipelago in a high-resolution pan-Arctic ice-ocean model”. In: *Journal of Geophysical Research: Oceans* 117.C8.

Meehl, Gerald A et al. (2007). “The WCRP CMIP3 multimodel dataset: A new era in climate change research”. In: *Bulletin of the American meteorological society* 88.9, pp. 1383–1394.

Mesinger, Fedor and Akio Arakawa (1976). “Numerical methods used in atmospheric models”. In.

Mignot, Juliette, Andrey Ganopolski, and Anders Levermann (2007). “Atlantic subsurface temperatures: Response to a shutdown of the overturning circulation and consequences for its recovery”. In: *Journal of Climate* 20.19, pp. 4884–4898.

Morison, James et al. (2012). “Changing arctic ocean freshwater pathways”. In: *Nature* 481.7379, pp. 66–70.

Myers, Paul, Liam Buchart, et al. (2021). “An Overview of NEMO Modelling for the BaySys Project”. In.

Myers, Paul G (2005). “Impact of freshwater from the Canadian Arctic Archipelago on Labrador Sea water formation”. In: *Geophysical Research Letters* 32.6.

Myers, Paul G, Laura Castro de la Guardia, et al. (2021). "Extreme High Greenland Blocking Index Leads to the Reversal of Davis and Nares Strait Net Transport Toward the Arctic Ocean". In: *Geophysical Research Letters* 48.17, e2021GL094178.

Myers, Paul G, Chris Donnelly, and Mads H Ribergaard (2009). "Structure and variability of the West Greenland Current in summer derived from 6 repeat standard sections". In: *Progress in Oceanography* 80.1-2, pp. 93–112.

Notz, Dirk and Julienne Stroeve (2018). "The trajectory towards a seasonally ice-free Arctic Ocean". In: *Current Climate Change Reports* 4.4, pp. 407–416.

Nummelin, Aleksi et al. (2016). "Consequences of future increased Arctic runoff on Arctic Ocean stratification, circulation, and sea ice cover". In: *Journal of Geophysical Research: Oceans* 121.1, pp. 617–637.

Oleson, Keith W et al. (2010). "Technical description of version 4.0 of the Community Land Model (CLM)". In.

Park, Hotaek, Eiji Watanabe, et al. (2020). "Increasing riverine heat influx triggers Arctic sea ice decline and oceanic and atmospheric warming". In: *Science advances* 6.45, eabc4699.

Park, Hotaek, Yasuhiro Yoshikawa, Kazuhiro Oshima, et al. (2016). "Quantification of warming climate-induced changes in terrestrial Arctic river ice thickness and phenology". In: *Journal of Climate* 29.5, pp. 1733–1754.

Park, Hotaek, Yasuhiro Yoshikawa, Daqing Yang, et al. (2017). "Warming water in Arctic terrestrial rivers under climate change". In: *Journal of Hydrometeorology* 18.7, pp. 1983–1995.

Pemberton, Per and Johan Nilsson (2016). "The response of the central Arctic Ocean stratification to freshwater perturbations". In: *Journal of Geophysical Research: Oceans* 121.1, pp. 792–817.

Pennelly, Clark and Paul G Myers (2020). "Introducing LAB60: A 1/ 60° NEMO 3.6 numerical simulation of the Labrador Sea". In: *Geoscientific Model Development* 13.10, pp. 4959–4975.

Peterson, Ingrid et al. (2012). "Wind-forcing of volume transport through Lancaster Sound". In: *Journal of Geophysical Research: Oceans* 117.C11.

Proshutinsky, A, R Krishfield, JM Toole, et al. (2019). "Analysis of the Beaufort Gyre freshwater content in 2003–2018". In: *Journal of Geophysical Research: Oceans* 124.12, pp. 9658–9689.

Proshutinsky, Andrey, Richard Krishfield, Mary-Louise Timmermans, et al. (2009). "Beaufort Gyre freshwater reservoir: State and variability from observations". In: *Journal of Geophysical Research: Oceans* 114.C1.

Redi, Martha H (1982). "Oceanic isopycnal mixing by coordinate rotation". In: *Journal of Physical Oceanography* 12.10, pp. 1154–1158.

Ridenour, Natasha A et al. (2019). "Sensitivity of freshwater dynamics to ocean model resolution and river discharge forcing in the Hudson Bay Complex". In: *Journal of Marine Systems* 196, pp. 48–64.

Roach, AT et al. (1995). "Direct measurements of transport and water properties through the Bering Strait". In: *Journal of Geophysical Research: Oceans* 100.C9, pp. 18443–18457.

Robert, Andre J (1966). "The integration of a low order spectral form of the primitive meteorological equations". In: *Journal of the Meteorological Society of Japan. Ser. II* 44.5, pp. 237–245.

Rousset, C. et al. (2015). "The Louvain-La-Neuve sea ice model LIM3.6: global and regional capabilities". In: *Geoscientific Model Development* 8.10, pp. 2991–3005. DOI: 10.5194/gmd-8-2991-2015. URL: http://www.geosci-model-dev.net/8/2991/2015/.

Rysgaard, S et al. (2020). "An updated view on water masses on the pan-west Greenland continental shelf and their link to proglacial fjords". In: *Journal of Geophysical Research: Oceans* 125.2, e2019JC015564.

Schauer, Ursula, Eberhard Fahrbach, et al. (2004). "Arctic warming through the Fram Strait: Oceanic heat transport from 3 years of measurements". In: *Journal of Geophysical Research: Oceans* 109.C6.

Schauer, Ursula and Martin Losch (2019). "“Freshwater” in the ocean is not a useful parameter in climate research". In: *Journal of Physical Oceanography* 49.9, pp. 2309–2321.

Serreze, Mark C and Roger G Barry (2011). "Processes and impacts of Arctic amplification: A research synthesis". In: *Global and planetary change* 77.1-2, pp. 85–96.

Shiklomanov, Alexander et al. (2021). "River freshwater flux to the Arctic Ocean". In: *Arctic hydrology, permafrost and ecosystems*. Springer, pp. 703–738.

Sinokrot, Bashar A and Heinz G Stefan (1993). "Stream temperature dynamics: measurements and modeling". In: *Water resources research* 29.7, pp. 2299–2312.

Smith, Gregory C et al. (2014). "A new atmospheric dataset for forcing ice–ocean models: Evaluation of reforecasts using the Canadian global deterministic prediction system". In: *Quarterly Journal of the Royal Meteorological Society* 140.680, pp. 881–894.

Solomon, Amy et al. (2021). "Freshwater in the arctic ocean 2010–2019". In: *Ocean Science* 17.4, pp. 1081–1102.

Solomon, Harold (1971). "On the representation of isentropic mixing in ocean circulation models". In: *Journal of Physical Oceanography* 1.3, pp. 233–234.

Stadnyk, Tricia A, Matthew K MacDonald, et al. (2020). "Hydrological modeling of freshwater discharge into Hudson Bay using HYPE". In: *Elementa: Science of the Anthropocene* 8.

Stadnyk, Tricia A, A Tefs, et al. (2021). "Changing freshwater contributions to the Arctic: A 90-year trend analysis (1981–2070)". In: *Elem Sci Anth* 9.1, p. 00098.

Stadnyk, Tricia Anne, Marie Broesky, et al. (2019). "Changing freshwater contributions to the Arctic: a 90-year trend analysis". In: *AGU Fall Meeting Abstracts*. Vol. 2019, GC51J–1088.

Stocker, Thomas (2014). *Climate change 2013: the physical science basis: Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge university press.

Thomas, Helmuth et al. (2004). "Enhanced open ocean storage of CO2 from shelf sea pumping". In: *Science* 304.5673, pp. 1005–1008.

Timmermans, Mary-Louise and John Marshall (2020). "Understanding Arctic Ocean Circulation: A Review of Ocean Dynamics in a Changing Climate". In: *Journal of Geophysical Research: Oceans* 125.4.

Tréguier, Anne-Marie et al. (2005). "The North Atlantic subpolar gyre in four high-resolution models". In: *Journal of Physical Oceanography* 35.5, pp. 757–774.

Uppala, Sakari M et al. (2005). "The ERA-40 re-analysis". In: *Quarterly Journal of the Royal Meteorological Society: A journal of the atmospheric sciences, applied meteorology and physical oceanography* 131.612, pp. 2961–3012.

Van Vliet, MTH et al. (2011). "Global river temperatures and sensitivity to atmospheric warming and changes in river flow". In: *Water Resources Research* 47.2.

Vancoppenolle, Martin et al. (2009). "Simulating the mass balance and salinity of Arctic and Antarctic sea ice. 1. Model description and validation". In: *Ocean Modelling* 27.1–2, pp. 33–53. ISSN: 1463-5003. DOI: 10.1016/j.ocemod.2008.10.005. URL: http://www.sciencedirect.com/science/article/pii/S1463500308001613.

Wang, Qiang et al. (2016). "An assessment of the Arctic Ocean in a suite of interannual CORE-II simulations. Part II: Liquid freshwater". In: *Ocean Modelling* 99, pp. 86–109.

Whitefield, Jonathan et al. (2015). "A new river discharge and river temperature climatology data set for the pan-Arctic region". In: *Ocean Modelling* 88, pp. 1–15.

Woodgate, Rebecca A (2018). "Increases in the Pacific inflow to the Arctic from 1990 to 2015, and insights into seasonal trends and driving mechanisms from year-round Bering Strait mooring data". In: *Progress in Oceanography* 160, pp. 124–154.

Woodgate, Rebecca A, Thomas J Weingartner, and Ron Lindsay (2012). "Observed increases in Bering Strait oceanic fluxes from the Pacific to the Arctic from 2001 to 2011 and their impacts on the Arctic Ocean water column". In: *Geophysical Research Letters* 39.24.

Yang, Daqing, Baozhong Liu, and Baisheng Ye (2005). "Stream temperature changes over Lena River basin in Siberia". In: *Geophysical Research Letters* 32.5.

Yang, Daqing, Rajesh R Shrestha, et al. (2021). "Heat flux, water temperature and discharge from 15 northern Canadian rivers draining to Arctic Ocean and Hudson Bay". In: *Global and Planetary Change* 204, p. 103577.

Zhang, Jiaxu et al. (2021). "Labrador Sea freshening linked to Beaufort Gyre freshwater release". In: *Nature communications* 12.1, pp. 1–8.