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Increased runoff from Siberian rivers leads to Arctic wide freshening

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Abstract

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Key Points:

- Freshwater river input to the Arctic Ocean has increased with climate change, though this change is often not represented in ocean models
- Freshwater markers increased across the Arctic when comparing ocean model runs which realistically represent contemporary runoff increases
- The largest increases came from Siberian rivers, contributing to Eastern Arctic freshening and changes in export water properties

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Abstract
The effects of contemporary increases in riverine freshwater into the Arctic Ocean are estimated from ocean model simulations, using two runoff data sets. One runoff data set which is based on older climatological data, which has no inter-annual variability after 2007 and as such does not represent the observed increases in river runoff into the Arctic. The other data set comes from a hydrological model developed for the Arctic drainage basin, which includes contemporary changes in the climate. In the pan-Arctic this new data set represents an approximately 11% increase in runoff, compared with the older climatological data. Comparing two ocean model runs forced with the different runoff data sets, overall changes in different freshwater markers across the basin were found to be between 5-10%, depending on the area investigated. The strongest increases were seen from the Siberian rivers, which in turn caused the strongest freshening in the Eastern Arctic.

Plain Language Summary

With climate change, there is an increase in freshwater being added into the Arctic Ocean as the hydrological cycle intensifies. This study looks at understanding the impacts of this increased riverine water in the Arctic Ocean using a state of the art regional ocean model. Two runoff forcing data sets are used, one data set which only extends to 2007 and thus doesn't include recently observed runoff increases, and a newer data set which extends up to present day and represents contemporary increases in the river runoff into the Arctic. In comparative ocean model simulations forced with the two data sets, increasing the river runoff by approximately 11% over the time series corresponds to freshening in the Arctic ocean of 5-10%, depending on the metric used and area considered. Much of this increased freshwater found when comparison is driven by increased outflow from the major Siberian rivers. This in turn is seen to affect the Eastern Arctic primarily. This work shows that currently observed increased input of freshwater from rivers in the Arctic Ocean has likely already been influencing the surface properties of the Arctic, as well as affecting the properties of the water which is transported to lower latitudes.

1 Introduction

Freshwater plays a key role in the Arctic Ocean. In the Arctic Ocean, increased freshwater content, precipitation, river runoff, inflow at Bering Strait and sea ice melt has been observed and is predicted to continue, (Morison et al., 2012). 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 & Laiho, 2020).

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 (Stadnyk 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 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. 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).Stadnyk 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. This was expanded on in Lukovich et al. (2021), where they found climate change was the dominant signal impacting Hudson Bay dynamics, opposed to river regulation under CMIP5 future scenarios. In sensitivity experiments from Pemberton and Nilsson (2016), looking at the Arctic Ocean's 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. Brown et al. (2019) looked at the transient response of the Arctic Ocean to changes in river runoff and precipitation forcing. They used climatological river runoff forcing, where the forcing was increased by a linear amount to understand sensitivity. They found a fairly linear response in freshwater storage response to increases in river runoff forcing.

Coupled climate models may include a river runoff routing scheme, where precipitation and evaporation over land is routed to drain into the ocean basins (Delworth et al., 2002). There is significant uncertainty often in regional scale hydrological projections, with significant model variability in response to the same forcing set (Masson-Delmotte et al., 2021). Lehner et al. (2019) found that model's runoff sensitivity emerges as a property of the coupled system, as an individual model's internal climate impacts runoff estimates. In addition, coupled climate models often run at comparatively coarse resolutions compared to regional ocean model, giving a coarse spatial resolution, especially in coastal shelf regions (Masson-Delmotte et al., 2021).

Traditionally, ocean models have commonly relied on the Dai and Trenberth runoff dataset (Dai et al., 2009) for river runoff forcing (Griffies et al., 2016). Dai and Trenberth is a climatology based data set, from the largest ocean draining rivers globally, with data gaps filled with a land surface model. 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, as well as having significant data gaps and inconsistencies with the observed record. 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 (Gelfan et al., 2017). 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 is described. The results of an ocean model run from 2002 to 2019 with the different forcing products. Changes in freshwater content and export are considered. Pathways of river water, with particular focus to changes in the Eastern Arctic are also investigated.

2 Runoff Product Description

The older runoff data set being used in this study was produced by Dai et al. (2009). Dai and Trenberth provides a data set of global continental discharge from 1948-2007. 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

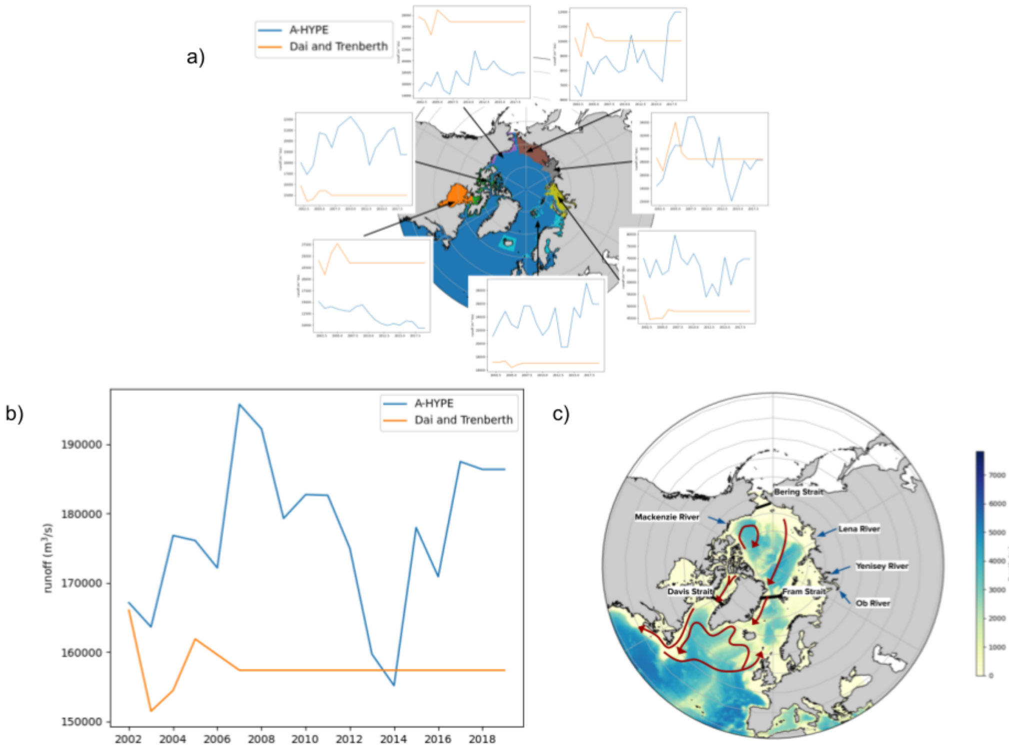

Figure 1. a) The annual average runoff, in m^3/s, for the two products, separated into regional contributions across the high Arctic and Hudson Bay. b) Annual average runoff in the Arctic region, excluding Hudson Bay, from 2002-2019 for A-HYPE and Dai and Trenberth, in m^3/s. The forcing used was supplied to the model in monthly values, but annual averages are shown here to understand the inter-annual variability seen in the products. c) Schematic of large scale Arctic Ocean circulation, with the four largest river discharge locations marked, and the major straits shown. The color bar indicates the depth of the bottom bathymetry, units in meters.

runoff field was used to estimate annual discharge in the region. Historically, to allow for common forcing in ocean modelling inter-comparison experiments (Biastoch et al., 2021), models were forced with the CORE dataset (Griffies et al., 2009). As part of the CORE protocol, river runoff was traditionally represented by climatological monthly fields, based on the major rivers and various infilling techniques (Dai et al., 2009). For this reason, after 2007 the final year of the Dai and Trenberth data set is repeated until the end of the model run. For forcing the ocean model, runoff estimates from Greenland from Bamber et al. (2012) were used with this data set.

A more recent Arctic runoff data set has been produced by the University of Calgary Hydrological Analysis Lab, based off of the Hydrological Predictions of the Environment (HYPE) model. HYPE is a semi-distributed catchment model, which simulates water flow and substance flux on their way from precipitation through different storage compartments and fluxes to the sea (Lindström et al., 2010). The Arctic-HYPE (A-HYPE) setup has been created specifically for the Arctic drainage basin (Gelfan et al., 2017). It includes representations of cryospheric processes, and includes a river regulation model, particularly in the Hudson Bay complex (Tefs et al., 2021), (Stadnyk et al., 2020). This data set extends up to present day, and includes many of the recent changes seen in Arctic runoff. A-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 et al. (2018).

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 with volume conserved. 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 and avoid associated numerical instability. This flooding of a coastal grid cell can happen in particular when there are shallow areas, or long fjords and estuaries where there is only weak exchange with the rest of the ocean. This redistribution is done through a system of manually edited polygons, which define the outflow areas of the river systems. As the A-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.

2.1 Runoff Product Comparison

Overall, the A-HYPE data set supplies more freshwater to the Arctic region, though this has significant regional variation. When just considering the high Arctic region, without Hudson Bay, on average the A-HYPE data set supplies $177,101 m^3/s$ of river runoff yearly, which the Dai and Trenberth data set supplies $158,487 m^3/s$. The difference represents an overall average increase of approximately 11 % over the Arctic region, for the entire time period of 2002-2019. See figure 1, which shows the regional annual average contributions in a), annual average runoff amounts for the entire Arctic region in b), and a schematic diagram of the study region bathymetry, major ocean circulation patterns and the four largest river locations in c).

There is considerable spatial variability to these increases. Regions where Dai and Trenberth provides larger runoff compared with HYPE include the Hudson Bay complex, the Mackenzie River region, and river input near Bering Strait on both the North American and Siberian side. For all other regions, the HYPE runoff exceeds the Dai and Trenberth amounts. Three of the largest four rivers discharge on the Eastern side of the Arctic, the Ob River, the Yenisei River and the Lena River. Overall, the Eastern half of the Arctic represents 71 % of the runoff discharge from the Dai and Trenberth data set, and 77 % with the A-HYPE data set. There is a significant discrepancy between the runoff contributions in the Hudson Bay region from Dai and Trenberth, compared with observations, which is likely due to the impacts of river regulation (Stadnyk et al., 2020).

There is also considerable inter-annual variability from the A-HYPE data set, while the Dai and Trenberth runoff is repeated after 2007, giving no variability throughout most of the study period. For the Arctic overall, the peak discharge is seen in 2008 from the A-HYPE data set. After this peak, there is a decrease in average discharge amounts, with the lowest discharge year is in 2014. There is then a recovery of the runoff amounts in the remainder of the time series. For detailed analysis of the trends and variability in the A-HYPE data set, see Stadnyk et al. (2021). After 2007, the annual average runoff from Dai and Trenebrth is $157,285m^3/s$, and from A-HYPE is $177,984m^3/s$. This is a slightly larger spread than when considering the entire time series, with the A-HYPE data set for being approximately 13 % greater than Dai and Trenberth.

3 Model and Methods

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 & Maqueda, 1997). The Arctic and Northern Hemisphere Atlantic (ANHA) configuration was used, with 1/4 degree resolution (Holdsworth & Myers, 2015), (Gillard et al., 2016), (Hu et al., 2018). This gives a resolution of between 8-18km for the Arctic Ocean. All model simulations were run from 2002 to 2019, with 2002-2005 considered the spin up period. For atmospheric forcing, the Canadian Meteorological Centre's global deterministic prediction system, CGRF, was used (Smith et al., 2014), as it has a high resolution with relatively small bias (Pennelly & Myers, 2021). The freshwater fluxes from Greenland are from Bamber et al. (2012) and Bamber et al. (2018). Further details on the model setup can be found in Hu et al. (2018).

Freshwater content and freshwater transports are calculated relative to 34.8 psu. While Schauer and Losch (2019) argues against the use of relative freshwater, it is a common metric particularly in the Arctic and allows for consistency with previous studies. Passive online tracers were also used in the model runs, to track the propagation of river runoff input into the model throughout the run. Tracers are inputted into the model at the boundary in the same grid cell and initial concentration as the river runoff input. The tracer concentrations measured the total amount of tracer integrated over the water column in meters. For a complete description of tracers in this model configuration see Hu et al. (2019) and Gillard et al. (2016).

4 Results

4.1 Increased Freshwater Content

Model simulations forced with the A-HYPE river runoff data set showed an overall freshening of the surface layer across most of the Arctic region by the end of the model integration. This can be seen from the spatial difference of the salinity of the top 50m, shown in figure 2 a) and b). In the early part of the model integration from 2005-2007, 2 a), changes in the surface salinity are generally constrained to the coastlines. The A-HYPE forced model run has fresher shelves in the Eastern Arctic, particularly around the major Siberian river discharge regions. The CAA in comparison shows a fresher surface in the Dai and Trenberth forced run, with the rest of the Arctic region showing little change in the beginning of the model run. The spatial pattern for the end of the model integration shows more significant differences, 2 b). The A-HYPE model run is fresher throughout most of the Arctic, with changes having migrated throughout the Central and Western Arctic. For example, the Kara Sea region receives large amounts of freshwater discharge, and over the entire model run has an average surface salinity of 29.3 in the A-HYPE forced run, compared to an average surface salinity of 30.6 in the Dai and Trenberth forced run. This is an approximately 4% freshening over the entire run period. The Canadian Arctic Archipelago (CAA) is overall slightly fresher in the Dai

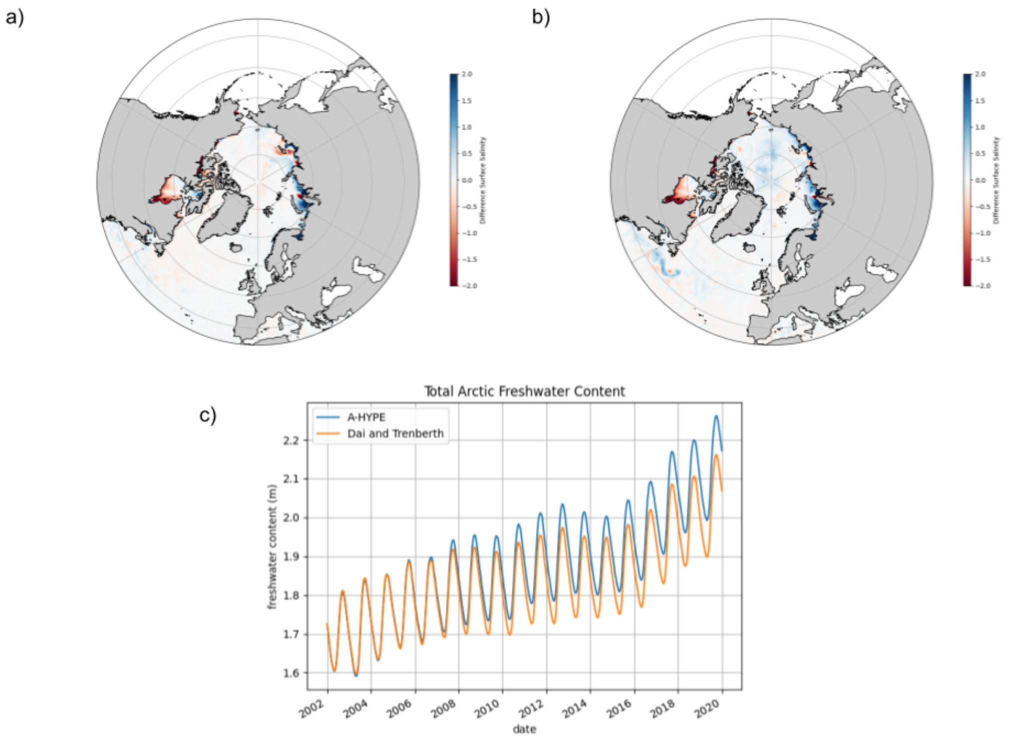

Figure 2. The average difference from 2005-2007, a), and 2017-2019, b), in the average salinity over the top 50m between the two model runs. A positive value indicates fresher surface in the A-HYPE forced, and a negative value indicates a fresher surface in the Dai and Trenberth forced run. c) Time series of freshwater content, in Sverdrups, for the two model runs over the whole Arctic domain. This is defined as the ocean above 60N, excluding Hudson Bay.

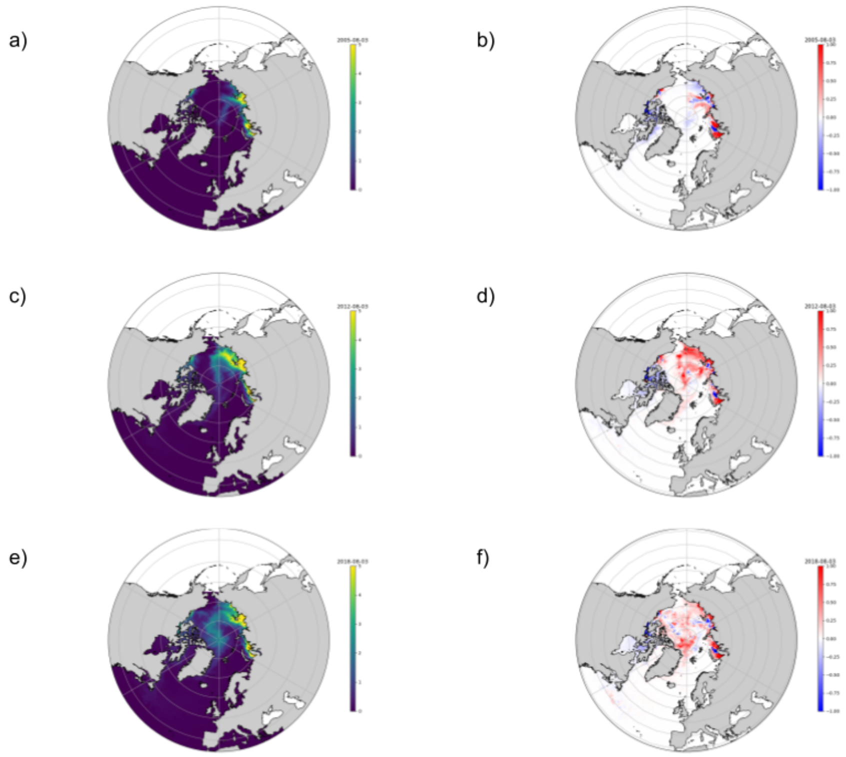

Figure 3. A-HYPE experiment River Tracer 2005-08-03, a), 2012-08-03, c) and 2018-08-03, e), as an example of the distribution of the river waters at the beginning of the time series. The colour bar shows the tracer concentration, measured as the total amount of tracer integrated over the water column in meters. Similarily, b), d) and f) show the difference in the river tracers values between the two runs for 2005-08-03, 2012-08-03 and 2018-08-03. The colour bar units are in meters, where positive values indicated higher river tracer values in A-HYPE forced run, and negative values are higher tracer values in the Dai and Trenberth forced run.

and Trenberth forced simulation. The average surface salinity in the A-HYPE forced run is 30.6, while in the Dai and Treneberh forced run is 30.4. Changes in the average surface salinity have also propagated down into the North Atlantic by the end of the model run.

The time series of freshwater content over the Arctic ocean is shown in figure 2 c), which is defined as the ocean region north of 60N, excluding Hudson Bay. For analysis of the impacts of river runoff forcing in Hudson Bay, see (Ridenour et al., 2019). In the time series, the A-HYPE forced model run shows a consistently higher freshwater content after 2008. Overall, the average freshwater content over the entire Arctic above the 34.8 isohaline is 1.91m in the A-HYPE forced run and 1.83m in the Dai and Trenberth forced run. This is an approximately 4 % increase in freshwater content on average over the whole Arctic in the A-HYPE forced model run. Much of this freshening is originally from Siberian river drainage, as seen in the spatial difference plots.

4.2 Links to Siberian Rivers

To understand where this increased freshening originates and how it propagates throughout the model domain, the model was run with passive tracers for river input.

Example snapshots of the river tracer propagation, and the difference between the river tracers in the pair of model runs can be seen in figure 3. The full time series of the river tracer shown in figure 3, a), c) and e) can be found at DOI: 10.7939/r3-4kj0-em27. The tracers start along the coasts, with the highest concentrations correlating with the discharge locations of the major river systems. The pathway of the tracers from the different regions can be seen to correlate with the freshening shown in figure 3, as would be expected as river runoff is known to be a large factor controlling surface water properties in the Arctic Ocean (Timmermans & Marshall, 2020). By the end of the time series, the tracers have propagated throughout the entire Arctic, as well as reaching into the North Atlantic.

The largest difference in the total volume of freshwater entering the Arctic between the two products comes from the the Siberian rivers, as shown in figure 1. This is also seen to be the largest difference in the river tracers as the model run progresses. There is a higher concentration of river tracers entering the Eurasian Basin in the A-HYPE forced model run. This water is then able to enter the transpolar drift, then propagating throughout the Arctic and eventually downstream out of Fram Strait. This behaviour of Siberian river water has been seen before, as the pathway of the Transpolar Drift is known to impact the propagation of Siberian waters from biological tracer studies (Paffrath et al., 2021), (Gamrani et al., 2023). The difference in the river tracers in figure 3 shows that the freshening seen in the Eastern half of the Arctic Ocean originated primarily from increased Siberian river outflow in the A-HYPE runoff data set.

The greatest difference in the river tracers can be seen in the 2012, which represents approximately the middle of the time series. During this period there is a large concentration of the tracers in the Arctic Ocean, leading to much higher concentrations in the A-HYPE forced run, especially along the Siberian Coast and Eurasian Basin. Later in the time series, this difference in the river tracers is lessened, as there has been more time for the river tracers to propagate downstream through the export gateways. By then end of the model run period, the weaker signal in the Dai forced run can be seen towards the Central Arctic and North of Greenland. There is consistently less river runoff entering the CAA in the A-HYPE model run, seen in both the difference in river water tracers, and the comparison of the regional runoff contributions, figure 1.

4.3 Propagation of Freshwater through Straits

The changed freshwater input into the Arctic Ocean has the potential to impact the export of freshwater through the major Arctic gateways. The two primary gateways between the Arctic and the North Atlantic are Davis Strait and Fram Strait. In order to consider if these runoff changes could influence downstream water properties, the volume and freshwater transports were calculated at these two major gateways for each model run.

As the focus of this analysis is on the export of freshwater from the Arctic, the southward flowing section of Fram Strait is primarily considered. This section is defined at 78.5N and between 1-6 W. There is an average volume transport of 5.55 Sv in the A-HYPE forced run, and 5.42 Sv in the Dai and Trenberth forced run. See figure 4, panels a) and b). We consider this difference primarily in terms of the freshwater transport, as seen in figure 4, panels c) and d). There is an average southward flow of $0.036Sv$ in the A-HYPE forced run and $0.034Sv$ from the Dai and Trenberth forced run. This compares well with (De Steur et al., 2018), which showed a 5 year average mean of the southward freshwater transport at Fram Strait 78.5 N of $0.040 \pm 0.015Sv$. Residence times of Siberian river water in other studies range from 3 years to 11 years (Alkire et al., 2017), (Jahn et al., 2010). For this reason, we consider the percentage change in the freshwater export from 2008 onward, which allows the changes from the river runoff to propagate to the strait. There is considerable variability throughout the time series. There is on average a 7.5 % increase in southward freshwater transport when using A-HYPE forcing, compared with Dai and Trenberth over the entire study period.

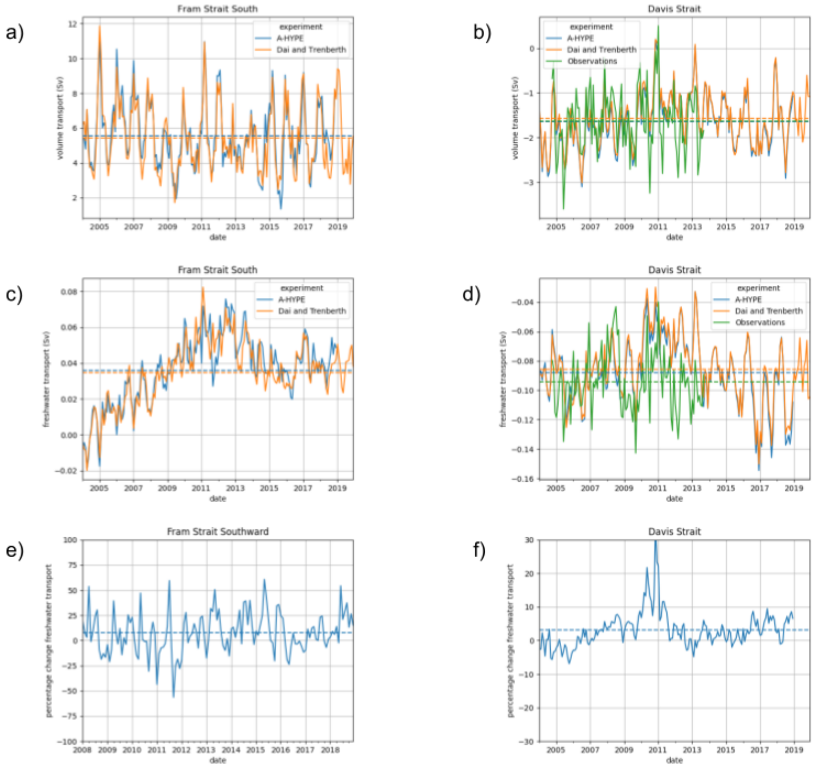

Figure 4. Time series of the southward volume transport, a), and freshwater transport, c), out of Fram Strait, in Sverdrups for both model runs. Similarily Davis Strait volume transport and freshwater transport are shown in b) and d), with observations from Curry et al. (2014). The percentage change in the freshwater transport for the two straits in the A-HYPE forced model run, compared to the Dai and Trenberth forced run are shown in e) and f) for southward Fram Strait and Davis Strait. A positive change indicates a increased freshwater transport from the A-HYPE forced run, and vice versa.

Davis Strait shows a similar behaviour. The Davis Strait section used is defined between 66.8 - 68.5 N and 52 to 63 W. There is an average volume transport at this section of -1.65 Sv in the A-HYPE forced run, and -1.57 Sv in the Dai and Trenberth forced run, where the negative denotes a southward total transport. The freshwater transport through this section was compared with available observations of transport across Davis Strait, from Curry et al. (2014). There in an average freshwater transport southward over the whole time series of $0.086 Sv$ with Dai and Trenberth forcing, $0.089 Sv$ with A-HYPE forcing and $0.094 Sv$ from the observations. In order to understand the impact of changing runoff forcing with A-HYPE, the percentage change can be considered. There is an average increase in freshwater transport out of Davis Strait of 3.1 % in the A-HYPE forced run over the entire study period. This is in spite of the decrease in runoff in the A-HYPE run in the CAA and Hudson Bay regions, which would affect the Davis Strait outflow (Ridenour et al., 2021), (Lu et al., 2014).

5 Conclusions

River runoff is an important source of freshwater into the Arctic Ocean, and can have a large impact on the stratification and circulation of the region. As the hydrological cycle intensifies with climate change, runoff is increasing into the Arctic Ocean, a trend which is expected to continue (Haine, 2020).

These two experiments in essence represent a realistic increase of river runoff since 2007, compared with a fixed static runoff since 2007. When comparing ocean model results using the two runoff products, A-HYPE produced an overall fresher ocean. This freshening came in particular from the Siberian rivers. This caused freshening first the Eastern basin, and Eastern Arctic. This anomaly can then be seen travelling through the transpolar drift. This eventually freshens the outflow through Fram Strait. This change was on the order of 5-10% depending on the area investigated, showing the strength of river runoff in controlling surface properties in the Arctic. This comes from an overall increase in runoff forcing of approximately 11%, though there is significant regional variability in the runoff amounts. This is consistent with Brown et al. (2019), where they found an approximately linear response in large scale freshwater to increases in river runoff forcing.

In line with previous studies, such as Alkire et al. (2017), Jahn et al. (2010), the transpolar drift played a major role in the distribution of river waters, affecting export timing through Fram Strait. In Wang et al. (2022), they showed that changes in the runoff pathways can affect whether a region is a carbon dioxide source or sink, highlighting the importance of accurately representing river runoff pathways. Other studies have shown there is a link between the atmospheric state, and the transport of river waters through either the transpolar drift or into the Canadian basin (Morison et al., 2012), (Alkire et al., 2015). This can affect whether riverine input is stored in the Beaufort Gyre in the Canadian Basin, or exported to lower latitudes (Proshutinsky et al., 2019), (Solomon et al., 2021). This study shows a likely link between volume and freshwater transport increases at the major straits and riverine freshwater increases. However the freshwater storage in the model simulations was not discussed, which can strongly impact the southward transport, and is potential future work.

There is also an increase in Davis Strait export seen with the A-HYPE forcing. This is with a decrease in runoff from the CAA and Hudson Bay regions in the A-HYPE data set. This shows the role of other sources in driving freshwater export from this gateway. During the export event in winter 2010, see also Myers et al. (2021), the differences between the two model runs is the strongest. This highlights the role atmospheric variability plays in the export of surface waters, and changing freshwater availability at the surface could likely impact the strength of such events in the future. As well, for both Davis Strait and Fram Strait, the A-HYPE forced model run shows closer agreement with observations, opposed to the Dai and Trenberth forced runs.

This work gives two main conclusions. First, that the Arctic Ocean surface properties are sensitive to river runoff changes, implying that recent observed increases in river runoff have likely had a wide scale impact on surface and near surface salinity. River runoff is able to explain a significant amount of the Arctic freshening observed over the past decade. Second, that Siberian Rivers play an important role in the surface waters throughout the Arctic. Changes then in Siberian outflow could affect surface circulation patterns and stratification throughout the Arctic. They are also shown here to impact the properties of Arctic waters exported into the North Atlantic. As the Arctic warms at an accelerated pace, changes in river runoff will drive large scale changes in the state of the Arctic Ocean.

6 Open Research

Model data can be requested at `https://canadian-nemo-ocean-modelling-forum-commuity-of-practice.readthedocs.io/en/latest/Institutions/UofA/index.html`. Runs used for this analysis are ANHA4-EPM015 and ANHA4-EPM151, which can be found on the website on the ANHA4 with tides simulation table. The source code and configuration information is available at `https://doi.org/10.5683/SP3/0AFNPL` and `https://doi.org/10.5683/SP3/DMGYXI`. Analysis scripts used for this work can be found at `https://github.com/t-gibbons/NEMO-Analysis.git`.

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Increased Runoff from Siberian Rivers leads to Arctic Wide Freshening

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Key Points:

- Freshwater river input to the Arctic Ocean has increased with climate change, though this change is often not represented in ocean models
- Freshwater markers increased across the Arctic when comparing ocean model runs which realistically represent contemporary runoff increases
- The largest increases came from Siberian rivers, contributing to Eastern Arctic freshening and changes in export water properties

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Abstract

The effects of contemporary increases in riverine freshwater into the Arctic Ocean are estimated from ocean model simulations, using two runoff data sets. One runoff data set which is based on older climatological data, which has no inter-annual variability after 2007 and as such does not represent the observed increases in river runoff into the Arctic. The other data set comes from a hydrological model developed for the Arctic drainage basin, which includes contemporary changes in the climate. In the pan-Arctic this new data set represents an approximately 11% increase in runoff, compared with the older climatological data. Comparing two ocean model runs forced with the different runoff data sets, overall changes in different freshwater markers across the basin were found to be between 5-10%, depending on the area investigated. The strongest increases were seen from the Siberian rivers, which in turn caused the strongest freshening in the Eastern Arctic.

Plain Language Summary

With climate change, there is an increase in freshwater being added into the Arctic Ocean as the hydrological cycle intensifies. This study looks at understanding the impacts of this increased riverine water in the Arctic Ocean using a state of the art regional ocean model. Two runoff forcing data sets are used, one data set which only extends to 2007 and thus doesn't include recently observed runoff increases, and a newer data set which extends up to present day and represents contemporary increases in the river runoff into the Arctic. In comparative ocean model simulations forced with the two data sets, increasing the river runoff by approximately 11% over the time series corresponds to freshening in the Arctic ocean of 5-10%, depending on the metric used and area considered. Much of this increased freshwater found when comparison is driven by increased outflow from the major Siberian rivers. This in turn is seen to affect the Eastern Arctic primarily. This work shows that currently observed increased input of freshwater from rivers in the Arctic Ocean has likely already been influencing the surface properties of the Arctic, as well as affecting the properties of the water which is transported to lower latitudes.

1 Introduction

Freshwater plays a key role in the Arctic Ocean. In the Arctic Ocean, increased freshwater content, precipitation, river runoff, inflow at Bering Strait and sea ice melt has been observed and is predicted to continue, (Morison et al., 2012). 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 & Laiho, 2020).

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 (Stadnyk 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 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. 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).Stadnyk 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. This was expanded on in Lukovich et al. (2021), where they found climate change was the dominant signal impacting Hudson Bay dynamics, opposed to river regulation under CMIP5 future scenarios. In sensitivity experiments from Pemberton and Nilsson (2016), looking at the Arctic Ocean's 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. Brown et al. (2019) looked at the transient response of the Arctic Ocean to changes in river runoff and precipitation forcing. They used climatological river runoff forcing, where the forcing was increased by a linear amount to understand sensitivity. They found a fairly linear response in freshwater storage response to increases in river runoff forcing.

Coupled climate models may include a river runoff routing scheme, where precipitation and evaporation over land is routed to drain into the ocean basins (Delworth et al., 2002). There is significant uncertainty often in regional scale hydrological projections, with significant model variability in response to the same forcing set (Masson-Delmotte et al., 2021). Lehner et al. (2019) found that model's runoff sensitivity emerges as a property of the coupled system, as an individual model's internal climate impacts runoff estimates. In addition, coupled climate models often run at comparatively coarse resolutions compared to regional ocean model, giving a coarse spatial resolution, especially in coastal shelf regions (Masson-Delmotte et al., 2021).

Traditionally, ocean models have commonly relied on the Dai and Trenberth runoff dataset (Dai et al., 2009) for river runoff forcing (Griffies et al., 2016). Dai and Trenberth is a climatology based data set, from the largest ocean draining rivers globally, with data gaps filled with a land surface model. 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, as well as having significant data gaps and inconsistencies with the observed record. 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 (Gelfan et al., 2017). 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 is described. The results of an ocean model run from 2002 to 2019 with the different forcing products. Changes in freshwater content and export are considered. Pathways of river water, with particular focus to changes in the Eastern Arctic are also investigated.

2 Runoff Product Description

The older runoff data set being used in this study was produced by Dai et al. (2009). Dai and Trenberth provides a data set of global continental discharge from 1948-2007. 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

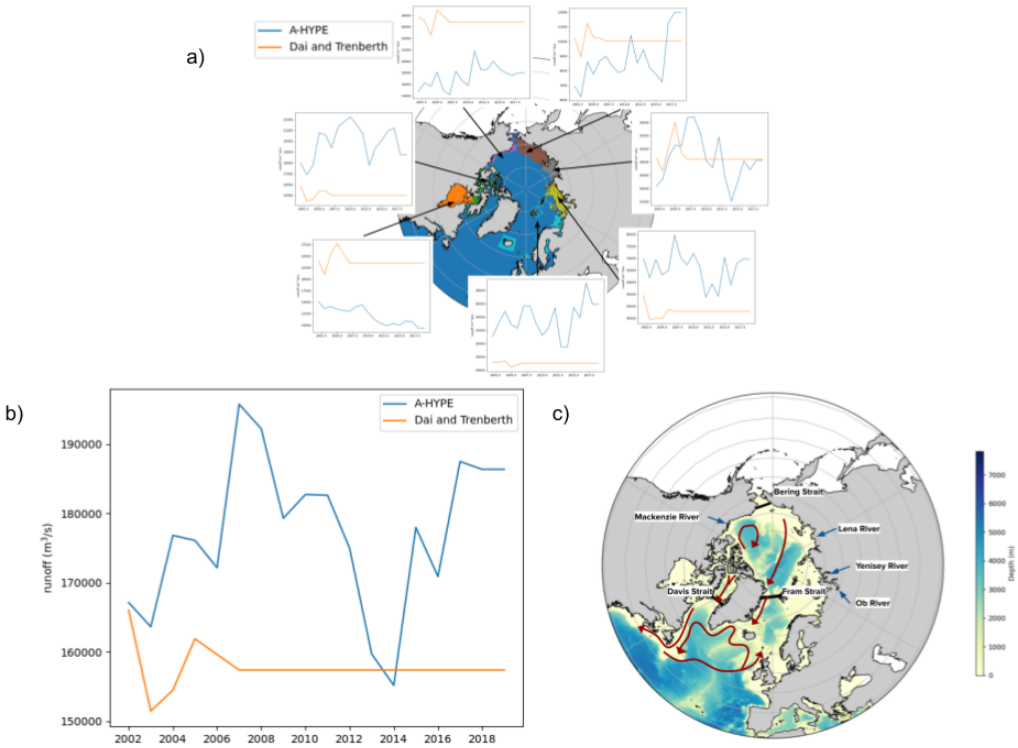

Figure 1. a) The annual average runoff, in m^3/s, for the two products, separated into regional contributions across the high Arctic and Hudson Bay. b) Annual average runoff in the Arctic region, excluding Hudson Bay, from 2002-2019 for A-HYPE and Dai and Trenberth, in m^3/s. The forcing used was supplied to the model in monthly values, but annual averages are shown here to understand the inter-annual variability seen in the products. c) Schematic of large scale Arctic Ocean circulation, with the four largest river discharge locations marked, and the major straits shown. The color bar indicates the depth of the bottom bathymetry, units in meters.

runoff field was used to estimate annual discharge in the region. Historically, to allow for common forcing in ocean modelling inter-comparison experiments (Biastoch et al., 2021), models were forced with the CORE dataset (Griffies et al., 2009). As part of the CORE protocol, river runoff was traditionally represented by climatological monthly fields, based on the major rivers and various infilling techniques (Dai et al., 2009). For this reason, after 2007 the final year of the Dai and Trenberth data set is repeated until the end of the model run. For forcing the ocean model, runoff estimates from Greenland from Bamber et al. (2012) were used with this data set.

A more recent Arctic runoff data set has been produced by the University of Calgary Hydrological Analysis Lab, based off of the Hydrological Predictions of the Environment (HYPE) model. HYPE is a semi-distributed catchment model, which simulates water flow and substance flux on their way from precipitation through different storage compartments and fluxes to the sea (Lindström et al., 2010). The Arctic-HYPE (A-HYPE) setup has been created specifically for the Arctic drainage basin (Gelfan et al., 2017). It includes representations of cryospheric processes, and includes a river regulation model, particularly in the Hudson Bay complex (Tefs et al., 2021), (Stadnyk et al., 2020). This data set extends up to present day, and includes many of the recent changes seen in Arctic runoff. A-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 et al. (2018).

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 with volume conserved. 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 and avoid associated numerical instability. This flooding of a coastal grid cell can happen in particular when there are shallow areas, or long fjords and estuaries where there is only weak exchange with the rest of the ocean. This redistribution is done through a system of manually edited polygons, which define the outflow areas of the river systems. As the A-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.

2.1 Runoff Product Comparison

Overall, the A-HYPE data set supplies more freshwater to the Arctic region, though this has significant regional variation. When just considering the high Arctic region, without Hudson Bay, on average the A-HYPE data set supplies $177,101m^3/s$ of river runoff yearly, which the Dai and Trenberth data set supplies $158,487m^3/s$. The difference represents an overall average increase of approximately 11 % over the Arctic region, for the entire time period of 2002-2019. See figure 1, which shows the regional annual average contributions in a), annual average runoff amounts for the entire Arctic region in b), and a schematic diagram of the study region bathymetry, major ocean circulation patterns and the four largest river locations in c).

There is considerable spatial variability to these increases. Regions where Dai and Trenberth provides larger runoff compared with HYPE include the Hudson Bay complex, the Mackenzie River region, and river input near Bering Strait on both the North American and Siberian side. For all other regions, the HYPE runoff exceeds the Dai and Trenberth amounts. Three of the largest four rivers discharge on the Eastern side of the Arctic, the Ob River, the Yenisei River and the Lena River. Overall, the Eastern half of the Arctic represents 71 % of the runoff discharge from the Dai and Trenberth data set, and 77 % with the A-HYPE data set. There is a significant discrepancy between the runoff contributions in the Hudson Bay region from Dai and Trenberth, compared with observations, which is likely due to the impacts of river regulation (Stadnyk et al., 2020).

There is also considerable inter-annual variability from the A-HYPE data set, while the Dai and Trenberth runoff is repeated after 2007, giving no variability throughout most of the study period. For the Arctic overall, the peak discharge is seen in 2008 from the A-HYPE data set. After this peak, there is a decrease in average discharge amounts, with the lowest discharge year is in 2014. There is then a recovery of the runoff amounts in the remainder of the time series. For detailed analysis of the trends and variability in the A-HYPE data set, see Stadnyk et al. (2021). After 2007, the annual average runoff from Dai and Trenebrth is $157,285m^3/s$, and from A-HYPE is $177,984m^3/s$. This is a slightly larger spread than when considering the entire time series, with the A-HYPE data set for being approximately 13 % greater than Dai and Trenberth.

3 Model and Methods

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 & Maqueda, 1997). The Arctic and Northern Hemisphere Atlantic (ANHA) configuration was used, with 1/4 degree resolution (Holdsworth & Myers, 2015), (Gillard et al., 2016), (Hu et al., 2018). This gives a resolution of between 8-18km for the Arctic Ocean. All model simulations were run from 2002 to 2019, with 2002-2005 considered the spin up period. For atmospheric forcing, the Canadian Meteorological Centre's global deterministic prediction system, CGRF, was used (Smith et al., 2014), as it has a high resolution with relatively small bias (Pennelly & Myers, 2021). The freshwater fluxes from Greenland are from Bamber et al. (2012) and Bamber et al. (2018). Further details on the model setup can be found in Hu et al. (2018).

Freshwater content and freshwater transports are calculated relative to 34.8 psu. While Schauer and Losch (2019) argues against the use of relative freshwater, it is a common metric particularly in the Arctic and allows for consistency with previous studies. Passive online tracers were also used in the model runs, to track the propagation of river runoff input into the model throughout the run. Tracers are inputted into the model at the boundary in the same grid cell and initial concentration as the river runoff input. The tracer concentrations measured the total amount of tracer integrated over the water column in meters. For a complete description of tracers in this model configuration see Hu et al. (2019) and Gillard et al. (2016).

4 Results

4.1 Increased Freshwater Content

Model simulations forced with the A-HYPE river runoff data set showed an overall freshening of the surface layer across most of the Arctic region by the end of the model integration. This can be seen from the spatial difference of the salinity of the top 50m, shown in figure 2 a) and b). In the early part of the model integration from 2005-2007, 2 a), changes in the surface salinity are generally constrained to the coastlines. The A-HYPE forced model run has fresher shelves in the Eastern Arctic, particularly around the major Siberian river discharge regions. The CAA in comparison shows a fresher surface in the Dai and Trenberth forced run, with the rest of the Arctic region showing little change in the beginning of the model run. The spatial pattern for the end of the model integration shows more significant differences, 2 b). The A-HYPE model run is fresher throughout most of the Arctic, with changes having migrated throughout the Central and Western Arctic. For example, the Kara Sea region receives large amounts of freshwater discharge, and over the entire model run has an average surface salinity of 29.3 in the A-HYPE forced run, compared to an average surface salinity of 30.6 in the Dai and Trenberth forced run. This is an approximately 4% freshening over the entire run period. The Canadian Arctic Archipelago (CAA) is overall slightly fresher in the Dai

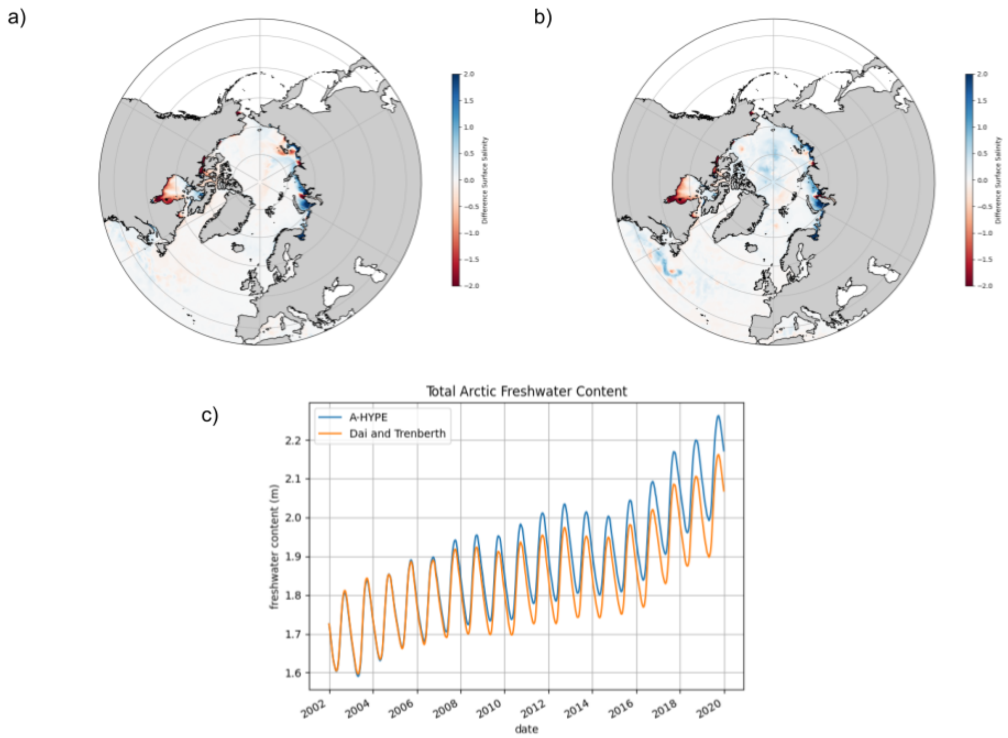

Figure 2. The average difference from 2005-2007, a), and 2017-2019, b), in the average salinity over the top 50m between the two model runs. A positive value indicates fresher surface in the A-HYPE forced, and a negative value indicates a fresher surface in the Dai and Trenberth forced run. c) Time series of freshwater content, in Sverdrups, for the two model runs over the whole Arctic domain. This is defined as the ocean above 60N, excluding Hudson Bay.

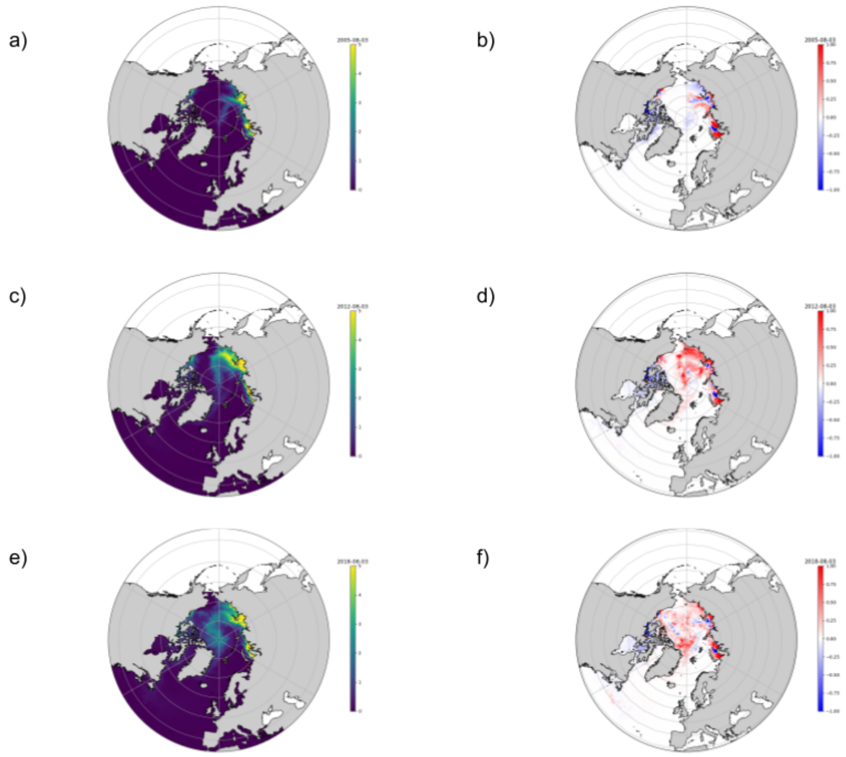

Figure 3. A-HYPE experiment River Tracer 2005-08-03, a), 2012-08-03, c) and 2018-08-03, e), as an example of the distribution of the river waters at the beginning of the time series. The colour bar shows the tracer concentration, measured as the total amount of tracer integrated over the water column in meters. Similarily, b), d) and f) show the difference in the river tracers values between the two runs for 2005-08-03, 2012-08-03 and 2018-08-03. The colour bar units are in meters, where positive values indicated higher river tracer values in A-HYPE forced run, and negative values are higher tracer values in the Dai and Trenberth forced run.

and Trenberth forced simulation. The average surface salinity in the A-HYPE forced run is 30.6, while in the Dai and Treneberh forced run is 30.4. Changes in the average surface salinity have also propagated down into the North Atlantic by the end of the model run.

The time series of freshwater content over the Arctic ocean is shown in figure 2 c), which is defined as the ocean region north of 60N, excluding Hudson Bay. For analysis of the impacts of river runoff forcing in Hudson Bay, see (Ridenour et al., 2019). In the time series, the A-HYPE forced model run shows a consistently higher freshwater content after 2008. Overall, the average freshwater content over the entire Arctic above the 34.8 isohaline is 1.91m in the A-HYPE forced run and 1.83m in the Dai and Trenberth forced run. This is an approximately 4 % increase in freshwater content on average over the whole Arctic in the A-HYPE forced model run. Much of this freshening is originally from Siberian river drainage, as seen in the spatial difference plots.

4.2 Links to Siberian Rivers

To understand where this increased freshening originates and how it propagates throughout the model domain, the model was run with passive tracers for river input.

Example snapshots of the river tracer propagation, and the difference between the river tracers in the pair of model runs can be seen in figure 3. The full time series of the river tracer shown in figure 3, a), c) and e) can be found at DOI: 10.7939/r3-4kj0-em27. The tracers start along the coasts, with the highest concentrations correlating with the discharge locations of the major river systems. The pathway of the tracers from the different regions can be seen to correlate with the freshening shown in figure 3, as would be expected as river runoff is known to be a large factor controlling surface water properties in the Arctic Ocean (Timmermans & Marshall, 2020). By the end of the time series, the tracers have propagated throughout the entire Arctic, as well as reaching into the North Atlantic.

The largest difference in the total volume of freshwater entering the Arctic between the two products comes from the the Siberian rivers, as shown in figure 1. This is also seen to be the largest difference in the river tracers as the model run progresses. There is a higher concentration of river tracers entering the Eurasian Basin in the A-HYPE forced model run. This water is then able to enter the transpolar drift, then propagating throughout the Arctic and eventually downstream out of Fram Strait. This behaviour of Siberian river water has been seen before, as the pathway of the Transpolar Drift is known to impact the propagation of Siberian waters from biological tracer studies (Paffrath et al., 2021), (Gamrani et al., 2023). The difference in the river tracers in figure 3 shows that the freshening seen in the Eastern half of the Arctic Ocean originated primarily from increased Siberian river outflow in the A-HYPE runoff data set.

The greatest difference in the river tracers can be seen in the 2012, which represents approximately the middle of the time series. During this period there is a large concentration of the tracers in the Arctic Ocean, leading to much higher concentrations in the A-HYPE forced run, especially along the Siberian Coast and Eurasian Basin. Later in the time series, this difference in the river tracers is lessened, as there has been more time for the river tracers to propagate downstream through the export gateways. By then end of the model run period, the weaker signal in the Dai forced run can be seen towards the Central Arctic and North of Greenland. There is consistently less river runoff entering the CAA in the A-HYPE model run, seen in both the difference in river water tracers, and the comparison of the regional runoff contributions, figure 1.

4.3 Propagation of Freshwater through Straits

The changed freshwater input into the Arctic Ocean has the potential to impact the export of freshwater through the major Arctic gateways. The two primary gateways between the Arctic and the North Atlantic are Davis Strait and Fram Strait. In order to consider if these runoff changes could influence downstream water properties, the volume and freshwater transports were calculated at these two major gateways for each model run.

As the focus of this analysis is on the export of freshwater from the Arctic, the southward flowing section of Fram Strait is primarily considered. This section is defined at 78.5N and between 1-6 W. There is an average volume transport of 5.55 Sv in the A-HYPE forced run, and 5.42 Sv in the Dai and Trenberth forced run. See figure 4, panels a) and b). We consider this difference primarily in terms of the freshwater transport, as seen in figure 4, panels c) and d). There is an average southward flow of $0.036Sv$ in the A-HYPE forced run and $0.034Sv$ from the Dai and Trenberth forced run. This compares well with (De Steur et al., 2018), which showed a 5 year average mean of the southward freshwater transport at Fram Strait 78.5 N of $0.040 \pm 0.015Sv$. Residence times of Siberian river water in other studies range from 3 years to 11 years (Alkire et al., 2017), (Jahn et al., 2010). For this reason, we consider the percentage change in the freshwater export from 2008 onward, which allows the changes from the river runoff to propagate to the strait. There is considerable variability throughout the time series. There is on average a 7.5 % increase in southward freshwater transport when using A-HYPE forcing, compared with Dai and Trenberth over the entire study period.

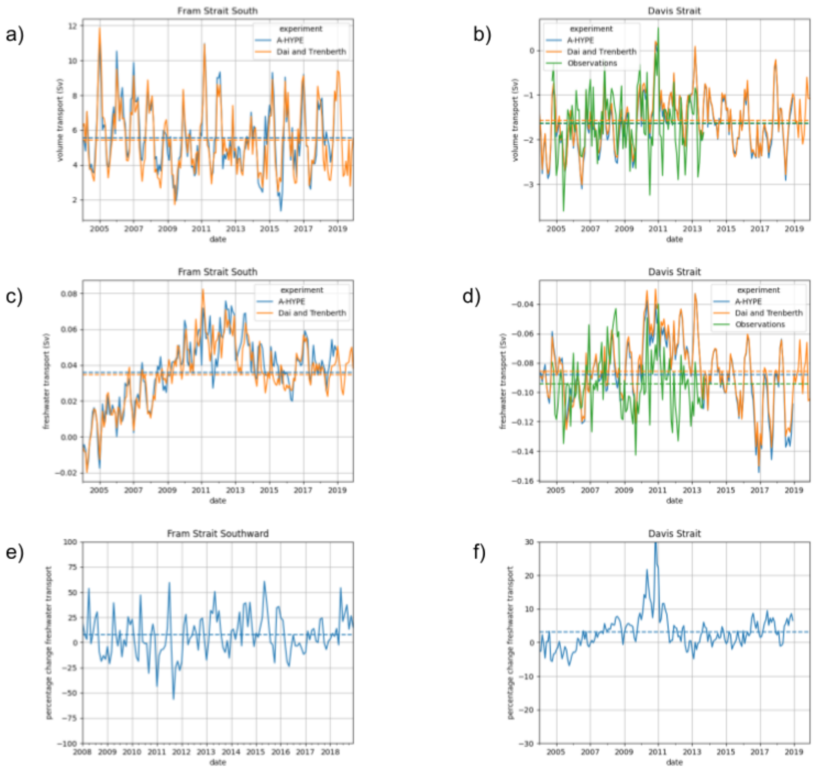

Figure 4. Time series of the southward volume transport, a), and freshwater transport, c), out of Fram Strait, in Sverdrups for both model runs. Similarily Davis Strait volume transport and freshwater transport are shown in b) and d), with observations from Curry et al. (2014). The percentage change in the freshwater transport for the two straits in the A-HYPE forced model run, compared to the Dai and Trenberth forced run are shown in e) and f) for southward Fram Strait and Davis Strait. A positive change indicates a increased freshwater transport from the A-HYPE forced run, and vice versa.

Davis Strait shows a similar behaviour. The Davis Strait section used is defined between 66.8 - 68.5 N and 52 to 63 W. There is an average volume transport at this section of -1.65 Sv in the A-HYPE forced run, and -1.57 Sv in the Dai and Trenberth forced run, where the negative denotes a southward total transport. The freshwater transport through this section was compared with available observations of transport across Davis Strait, from Curry et al. (2014). There in an average freshwater transport southward over the whole time series of $0.086Sv$ with Dai and Trenberth forcing, $0.089Sv$ with A-HYPE forcing and $0.094Sv$ from the observations. In order to understand the impact of changing runoff forcing with A-HYPE, the percentage change can be considered. There is an average increase in freshwater transport out of Davis Strait of 3.1 % in the A-HYPE forced run over the entire study period. This is in spite of the decrease in runoff in the A-HYPE run in the CAA and Hudson Bay regions, which would affect the Davis Strait outflow (Ridenour et al., 2021), (Lu et al., 2014).

5 Conclusions

River runoff is an important source of freshwater into the Arctic Ocean, and can have a large impact on the stratification and circulation of the region. As the hydrological cycle intensifies with climate change, runoff is increasing into the Arctic Ocean, a trend which is expected to continue (Haine, 2020).

These two experiments in essence represent a realistic increase of river runoff since 2007, compared with a fixed static runoff since 2007. When comparing ocean model results using the two runoff products, A-HYPE produced an overall fresher ocean. This freshening came in particular from the Siberian rivers. This caused freshening first the Eastern basin, and Eastern Arctic. This anomaly can then be seen travelling through the transpolar drift. This eventually freshens the outflow through Fram Strait. This change was on the order of 5-10% depending on the area investigated, showing the strength of river runoff in controlling surface properties in the Arctic. This comes from an overall increase in runoff forcing of approximately 11%, though there is significant regional variability in the runoff amounts. This is consistent with Brown et al. (2019), where they found an approximately linear response in large scale freshwater to increases in river runoff forcing.

In line with previous studies, such as Alkire et al. (2017), Jahn et al. (2010), the transpolar drift played a major role in the distribution of river waters, affecting export timing through Fram Strait. In Wang et al. (2022), they showed that changes in the runoff pathways can affect whether a region is a carbon dioxide source or sink, highlighting the importance of accurately representing river runoff pathways. Other studies have shown there is a link between the atmospheric state, and the transport of river waters through either the transpolar drift or into the Canadian basin (Morison et al., 2012), (Alkire et al., 2015). This can affect whether riverine input is stored in the Beaufort Gyre in the Canadian Basin, or exported to lower latitudes (Proshutinsky et al., 2019), (Solomon et al., 2021). This study shows a likely link between volume and freshwater transport increases at the major straits and riverine freshwater increases. However the freshwater storage in the model simulations was not discussed, which can strongly impact the southward transport, and is potential future work.

There is also an increase in Davis Strait export seen with the A-HYPE forcing. This is with a decrease in runoff from the CAA and Hudson Bay regions in the A-HYPE data set. This shows the role of other sources in driving freshwater export from this gateway. During the export event in winter 2010, see also Myers et al. (2021), the differences between the two model runs is the strongest. This highlights the role atmospheric variability plays in the export of surface waters, and changing freshwater availability at the surface could likely impact the strength of such events in the future. As well, for both Davis Strait and Fram Strait, the A-HYPE forced model run shows closer agreement with observations, opposed to the Dai and Trenberth forced runs.

This work gives two main conclusions. First, that the Arctic Ocean surface properties are sensitive to river runoff changes, implying that recent observed increases in river runoff have likely had a wide scale impact on surface and near surface salinity. River runoff is able to explain a significant amount of the Arctic freshening observed over the past decade. Second, that Siberian Rivers play an important role in the surface waters throughout the Arctic. Changes then in Siberian outflow could affect surface circulation patterns and stratification throughout the Arctic. They are also shown here to impact the properties of Arctic waters exported into the North Atlantic. As the Arctic warms at an accelerated pace, changes in river runoff will drive large scale changes in the state of the Arctic Ocean.

6 Open Research

Model data can be requested at `https://canadian-nemo-ocean-modelling-forum-commuity-of-practice.readthedocs.io/en/latest/Institutions/UofA/index.html`. Runs used for this analysis are ANHA4-EPM015 and ANHA4-EPM151, which can be found on the website on the ANHA4 with tides simulation table. The source code and configuration information is available at `https://doi.org/10.5683/SP3/0AFNPL` and `https://doi.org/10.5683/SP3/DMGYXI`. Analysis scripts used for this work can be found at `https://github.com/t-gibbons/NEMO-Analysis.git`.

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