Nansen Environmental and Remote Sensing Center

A non-profit environmental research center affiliated with the University of Bergen

Thormølensg. 47
N-5006 Bergen, Norway
Tel: +47 55 20 58 00
Fax: +47 55 20 58 01

Sensitivity of the Arctic and North Atlantic Oceans to the Bering Strait inflow: A modeling study

by

Ness Borghild, Counillon François, Dumont Dany

Mohn Sverdrup Center/Nansen Environmental and Remote Sensing Center

December 2010

Mohn Sverdrup Center/Nansen Environmental and Remote Sensing Center (NERSC)
Thormølensgate 47
N-5006 Bergen
Norway

phone +47 55205800
fax +47 55205801
email adm@nersc.no

TITLE	**REPORT IDENTIFICATION**
Sensitivity of the Arctic and North Atlantic Oceans to the Bering Strait inflow: A modeling study	NERSC Technical report no.317
CLIENT	**CONTRACT NO.**
EVITA	EVITA (535)
CLIENT REFERENCE	**AVAILABILITY**
	Public
INVESTIGATORS	**AUTHORIZATION**
Borghild Ness; Dr. François Counillon; Dr. Dany Dumont; Dr. Laurent Bertino	Bergen, December 17, 2010 Prof. Stein Sandven Director MSC/NERSC

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Abstract

Water from the Pacific Ocean flowing through the Bering Strait (BS) influences the circulation, heat and salt budget of the Arctic. With salinity between 31.4 and 32.9, it contributes a significantly amount to the Beaufort Gyre fresh water reservoir. The hydrography and volume transport of this inflow vary significantly over a seasonal cycle. *Woodgate et al.* (2010) suggested that warm water intrusions may act as a trigger for the onset of the seasonal melt of ice, as in the 2007 extreme event. In the current version of the TOPAZ system the BS inflow is simulated with a constant barotropic inflow and a mean seasonal hydrographic cycle. A modeling approach is adopted to understand the importance of the seasonal and inter-annual variability of the transport and the hydrography of the Bering Strait inflow for the Arctic and North Atlantic oceanic climate.

1 Introduction

The Arctic Ocean is, compared to many other oceans, relatively isolated. It is connected to the North Atlantic by a maze of islands in the Canadian Archipelago, and the Greenland and Barents Sea. The only other communication pathway goes through the Bering Strait (BS), connecting the Arctic with the Pacific Ocean. Located between Alaska and Siberia, this small channel, ~ 85 km wide and ~ 50 m deep, affects the Arctic Ocean.

Due to the mean sea level difference between the Pacific and Arctic Ocean the flow mainly goes northward, leading water the from the North Pacific through the Arctic and into the North Atlantic. While the dense water from the North Atlantic enters the Arctic basin close to the bottom, the freshwater from the Pacific is spilled higher in the Arctic water column. This may be compared to an estuarine circulation (*Carmack*, 2007), where freshwater from the Pacific, enters the Arctic, flows over the saltier water from the Atlantic and creates a freshwater front. Most of the water that flows through the Canadian Archipelago is, due to the location of the Pacific water in the Arctic water column and the relatively shallow channels, Pacific water. A change in the water properties, caused by the inflow, will therefore affect a larger region than the Arctic Ocean (e.g. see *Woodgate et al.*, 2005).

The circulation (*Proshutinsky and Johnson*, 2001) and the freshwater budget (*Cherniawsky et al.*, 2005; *Goosse et al.*, 1997) in the Arctic are affected by the Pacific waters that flow though the strait. Note that approximately 1/3 of the freshwater in the Arctic comes from the BS throughflow (*Woodgate et al.*, 2006). Due to its location in the top of water column, the BS inflow is also important for the Arctic sea-ice (*Woodgate et al.*, 2010).

The inflow has a strong seasonal and inter-annual variability in temperature, salinity and transport (*Woodgate et al.*, 2005; *Cherniawsky et al.*, 2005). The inflow will accordingly bring different amounts of water, with different properties, into the Arctic at different times of the year. Therefore we can expect the variability to be important for understanding the complex interplay between the circulation, ice cover and freshwater content in the Arctic.

Goosse et al. (1997) argue that the influence the strait has on a global ocean circulation model is small compared to the uncertainties of current ocean models. In this report we try to address the importance of the variability in the BS. This is motivated by determining the best strategy for a model that covers the Arctic and the North Atlantic, such as the TOPAZ system currently used, see Section 2. Since we are interested in the long term effects of the inflow, a coarse resolution version of TOPAZ is used to reduce the computational time. Hopefully, we may be able to assess the potential effect on the high resolution version of the TOPAZ system. Because of the close proximity to the BS, we have chosen to focus on the freshwater content in the Beaufort Gyre (BG), the distribution of salinity and sea ice in the Arctic Ocean and changes in the circulation. Further, we also include a discussion about the impact on the salinity and currents in the North Atlantic.

The outline of this report is as follows. Section 2 presents the model. Section 3 describes the four different methodologies tested for the BS inflow. Section 4 presents the results for the salinity budget (4.1), sea-ice (4.2) and circulation (4.3) in the Arctic Ocean. In Section 5, the impact on the North Atlantic Ocean is discussed. Subsection 5.1 and Subsection 5.2 present the results for the salinity and the currents, respectively. The conclusions are given in Section 6.

2 Model

The model uses version 2.2 of the HYbrid Coordinate Ocean Model (HYCOM). In HYCOM, the vertical coordinates are typically isopycnal in the open stratified ocean, with a transition towards z-coordinates in the mixed layer (e.g. *Bleck*, 2002; *Chassignet et al.*, 2006). This makes HYCOM a suitable model for an area that combines open stratified ocean, a wide shelf, and steep topography. The model is coupled to a one thickness category sea-ice model with elastic-viscous-plastic (EVP) rheology (*Hunke and Dukowicz*, 1997), and the thermodynamics is described in *Drange and Simonsen* (1996). The advection of concentration, ice thickness, snow and ice age are calculated using a 3^{rd} order weighted essentially non-oscillatory scheme (*Jiang and Shu*, 1996), with a 2^{nd} order Runge-Kutta time discretization. The TOPAZ system (*Bertino and Lisæter*, 2008) represents the Marine Core Service for the Arctic in MyOcean. It has a resolution varying from 12-16 km and assimilates available data with the Ensemble Kalman Filter (*Evensen*, 2003). In order to limit the computational cost required by our different experiments, a coarse resolution version of TOPAZ system is used. The resolution is approximately 55 km in the Arctic Basin increasing to $\sim$ 130 km at the southern border. Accordingly, the Canadian Archipelago consists of one main pathway connecting the Arctic to Baffin Bay. In addition, the model does not include data assimilation, as this could soften the sensitivity of our experiment.

The model covers the North Atlantic and the Arctic, as shown in Fig 1. The horizontal grid is created using a conformal mapping of the poles to new locations by the algorithm outlined in *Bentsen et al.* (1999). Vertically the model uses 28 hybrid layers, with minimum thickness of 3 m for the top layers. The model bathymetry is interpolated onto the model grid from the General Bathymetric Chart of the Oceans database (GEBCO) at 1-minute resolution, and the model is forced with 6-hourly forcing fields from the European Centre for Medium-Range Weather Forecasts (ECMWF) 40 year Reanalysis data (ERA40, *Uppala et al.*, 2005) and ERA interim (*Simmons et al.*, 2007).

The river discharge into the Arctic is poorly known. Therefore a monthly climatology is calculated over a period of 20 years by applying the ERA interim run-off data to the Total Runoff Integrating Pathways (TRIP, *Oki and Sud*, 1998) hydrological model. Rivers in HYCOM 2.2 are treated as a negative salinity flux with an additional mass exchange.

The model is initialized using temperature and salinity from a combination of the Polar science Hydrographic Center (PHC, *Steele et al.*, 2001) with the Levitus climatology (WOA05, *Locarnini et al.*, 2006) and spun-up from 1980 using atmospheric field from ECMWF. Lateral boundary conditions and sea surface salinity are relaxed towards the same climatology.

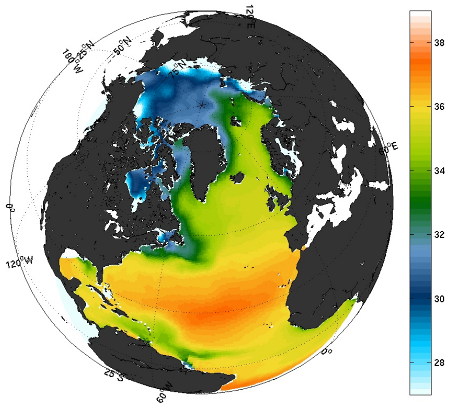


Figure 1: The salinity distribution in the model domain.

	Exp1	**Exp2**	**Exp3**	**Exp4**
Transport	Constant	Seasonal (c)	Inter-annual (d)	Inter-annual (d)
Hydrography	Seasonal (c)	Seasonal (c)	Seasonal (c)	Inter-annual (d)

Table 1: The conditions specified at the Bering Strait open boundary for the four experiments. (c): Climatological values; (d): Data; Seasonal transport values from *Woodgate et al.* (2005). Inter-annual data is provided by NCAR/EOL under sponsorship of the National Science Foundation (http://data.eol.ucar.edu/) and NODC.

The port in the BS is simulated with an additional inflow of water that is balanced with an outflow, of the same amount, at the southern boundary of the model. In the experiments conducted, the properties of the BS inflow and the data set used for the relaxation vary. The different parameterizations are discussed in the following section. Notice that with such coarse resolution, the BS only represent four grid cells.

3 Experiments

A sensitivity analysis is conducted, to better understand the impact of the Bering Strait inflow on the circulation, the salinity budget and sea-ice in the Arctic region. Four numerical experiments are carried out, see Table 1. The constant barotropic inflow in the control experiment (Exp1) is increased from 0.7 Sv (implemented in the current TOPAZ system) to 0.8 Sv, in accordance with the average volume transport found in *Woodgate et al.* (2005). In the second experiment (Exp2), the transport has a seasonal variation. Estimates made by *Woodgate et al.* (2005) are used for the seasonal values of the transport. The highest transport is found in June (1.3 Sv), the lowest in January (0.4 Sv) and the average is 0.8 Sv. Inter-annual transport is implemented in the third experiment (Exp3). The data come from moorings in the BS. It is provided by NCAR/EOL under sponsorship of the National Science Foundation (http://data.eol.ucar.edu/) and NODC. This data is used in *Woodgate et al.* (2005). In agreement with her work, only data from mooring site A3 were retained. Exp1, Exp2 and Exp3 relax toward PHC monthly climatology. In the last experiment, inter-annual hydrography and transport are used. Also here, the inter-annual data come from moorings in the BS (see description for Exp3 just above). Further, the water column properties were changed during summer (*Woodgate et al.*, 2005). Here, in the two top layers, the temperature and salinity were set to be 0.5 psu fresher and 1 °C warmer in May and October, and 1.0 psu fresher and 2 °C warmer from June to September. Notice, salinity values are from now on implicitly given in psu. If mooring data is not available, e.g. no measurements before 1990, climatological values from *Woodgate et al.* (2005) are used. Note, most of the mooring data, used to calculate the climatological values in *Woodgate et al.* (2005), are taken during an anti-cyclonic regime. We do not know how this affect the climatological transport and hydrography used to implement the BS inflow. The experiments have been run for 29 years (1 Jan 1980-31 Des 2008), where the first ten years are considered as spin-up.

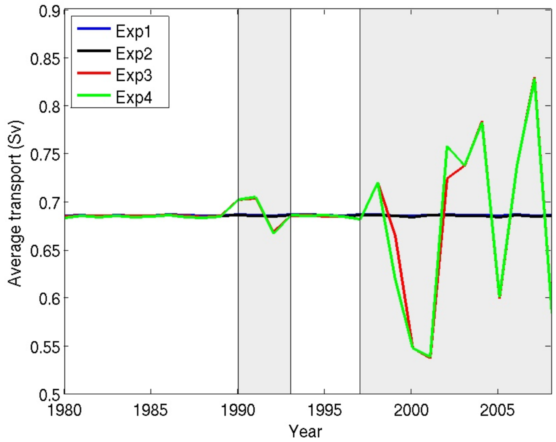


Figure 2: The time series of the average transport (Sv) observed in the Bering Strait from 1980 to 2008 for Exp1, Exp2, Exp3 and Exp4. Shaded areas are years where at least some mooring data is used.

	Exp1	**Exp2**	**Exp3**	**Exp4**
Transport (Sv)	0.686	0.685	0.682	0.682
Freshwater flux (mSv)	40.3	39.8	39.6	34.8
Heat flux (MW)	1.8	2.3	2.4	1.4

Table 2: The mean transport, freshwater and heat flux observed in the Bering Strait for the period 1990-2008. To stress the difference between the runs, the number of decimals included in the table are larger than the number of significant digits.

By calculating the average transport for each year, the significant inter-annual variation is clearly observed, see Fig 2. The minimum average transport is found in 2001 (~ 0.5 Sv) and the maximum in 2007 (~ 0.8 Sv). The difference makes a change of $\sim 40\%$ of the total averaged transport. For velocity and salinity the short timescale variability is larger than any inter-annual variability (*Woodgate et al.*, 2006).

To facilitate comparisons between experiments, the average transport, heat and freshwater flux in the BS are computed for the period 1990-2008. The mean transports only show a small change between the experiments, see Table 2. Accordingly, the amount of water brought through the BS and into the model domain is on average approximately the same. As shown in Fig 2, this does not mean that the same volume of water is brought into the Arctic every year. Note that the observed transports are smaller than the ones simulated, due to friction at the boundary. As a consequence of higher transport in months with low salinity, the control experiment (Exp1) overestimate the freshwater flux. The reduction of the freshwater flux is strongest for Exp4, because the mooring data is saltier than the climatological values. In average, the salinity is ~ 0.4 higher than the climatology for the period 1980-2008. A difference can also be observed for temperature, where the average drops by ~ 0.4°C when mooring data is used. This decrease can be explained by low summer temperatures in the measured data. Thus, the low heat flux in Exp4. The mean heat fluxes in Exp2 and Exp3 show that the variable transport brings more heat into the Arctic. In view of this table, one may expect more saline water and more ice in Exp4 and less ice in Exp2 and Exp3.

4 Results for the Arctic Ocean

For the TOPAZ system, the main area of interest is the Arctic region. Due to the fact that the BS inflow enters the Arctic Ocean, it is reasonable to believe that the largest changes will be observed there. We expect significant changes in the freshwater content in the BG (Section 4.1) and the sea-ice (Section 4.2). The assumptions are mainly based on the observed connections between the BS inflow and the freshwater content (e.g. *Proshutinsky et al.*, 2009), and the BS inflow and the sea-ice (e.g. *Woodgate et al.*, 2010). By including mooring data we hope to recreate the inter-annual variations in the Arctic, e.g. the ice anomaly in

2007. The downstream effect to the North Atlantic (e.g. *Goosse et al.*, 1997) is assumed to cause a smaller impact.

4.1 The Beaufort Gyre

The BG is the largest freshwater storage in the Arctic Ocean (*Proshutinsky et al.*, 2009). Located close to or in the Beaufort Sea, it is characterized by a salinity minimum at depths 5-400 m (*Proshutinsky et al.*, 2002). The extent of the gyre and the location of the core vary, mainly due to changes in the atmospheric circulation and the placement of the Arctic High center. In years with anti-cyclonic atmospheric circulation freshwater is accumulated due to deformation of the salinity field (downwelling due to Ekman pumping). From 1997-2007 this regime has dominated the Arctic circulation (*Proshutinsky et al.*, 2009). If a regime shift occur, from anti-cyclonic to cyclonic atmospheric circulation, the stored freshwater will be flushed through the Canadian Archipelago and the Fram Strait. After the spilling, the cyclonic regime will continue to deliver more freshwater than the anti-cyclonic, to the North Atlantic, since the cyclonic regime do not accumulate freshwater. The regime shift will also affect other factors e.g. the temperature and river runoff (*Proshutinsky and Johnson*, 2001).

Changing the properties of the BG will not only affect the freshwater budget and ice extent in the Arctic Ocean, but also the Atlantic overturning circulation. The circulation is influenced by differences in the freshwater flux from the Arctic (e.g. *Cherniawsky et al.*, 2005; *Goosse et al.*, 1997). Three mechanisms are mentioned in *Proshutinsky et al.* (2009) that may affect the water properties in the BG: the Arctic High center location, the wind curl strength and the characteristics of the surface layer water that feeds the gyre. Therefore, changing the BS inflow may affect the surface water feeding the BG and the water properties in the BG.

By computing the freshwater content, it is possible to get a picture of how much water has been accumulated above the 34.8 isoline. The liquid freshwater content (FWC) for the total water column is computed as follow:

$$FWC = \int_{z2}^{z1} \frac{[S_0 - S(z)]}{S_0}\,\mathrm{d}z, \tag{1}$$

where $z1 = 0$ and $z2$ is the depth where $S_0 = S(z)$. The reference salinity $S_0 = 34.8$ and the salinity at depth z is given by $S(z)$. Here the z-axis is defined as positive up with the surface at $z = 0$. The core of the gyre is defined to be bounded by 77 °N to 85 °N and 170 °E to 135 °W, the black box on Fig. 3. In the model the core is located too far northeast compared to observations, e.g. see *Proshutinsky et al.* (2009). FWC in the core region are calculated in grid cells where the bottom depth is greater than 300 m.

4.1.1 *Freshwater content*

There are almost no differences in the mean FWC of the core region, between the experiments, see Fig. 4. The steep increase from 1980 to 1983 may be an adjustment to the climatology. This increase contradicts the cyclonic regime dominating in the period 1980-1984. Observe the drop in FWC in the last two years of the period (1983-1984) and the increasing trend after 1984. The growth rates are largest in the anti-cyclonic regimes (1985-1988, 1997-2007). Further, the model captures the strong increase of FWC from 2003 to 2007. *Proshutinsky et al.* (2009) connects the growth to a trend in the wind stress curl. It is evident that the inter-annual variability is larger than the differences between the experiments.

It is clearly wrong that the FWC in the model is mainly increasing during the period of study. Due to the fact that the PHC measurements were mostly taken during an anti-cyclonic regime, the PHC is biased (*Proshutinsky et al.*, 2009). We could therefor expect an adjustment from the climatology to be necessary. Since the PHC has too much freshwater, it is surprising to see that the model restart suggest, a further increase of FWC during the spin-up.

Nevertheless, it should be noted that the FWC can be changed in two ways, either by increasing the depth

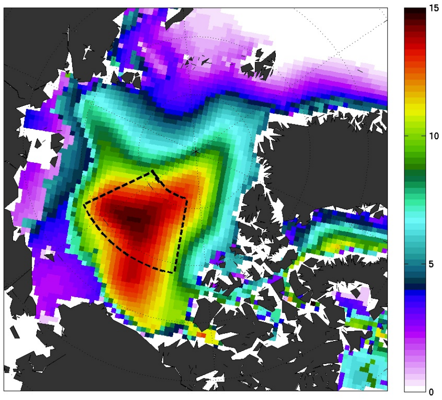


Figure 3: The mean freshwater content (m) calculated, relative to 34.8, for 2003 (Exp1). Dashed lines enclose the core of the Beaufort Gyre.

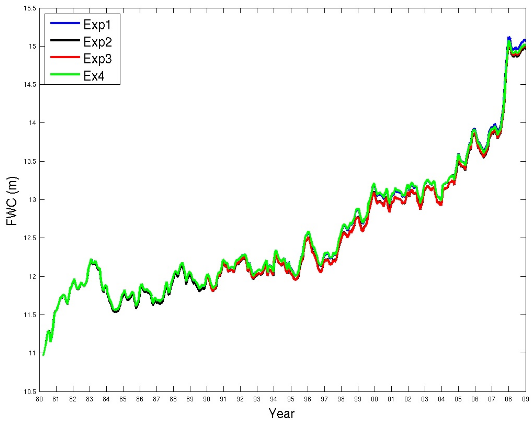


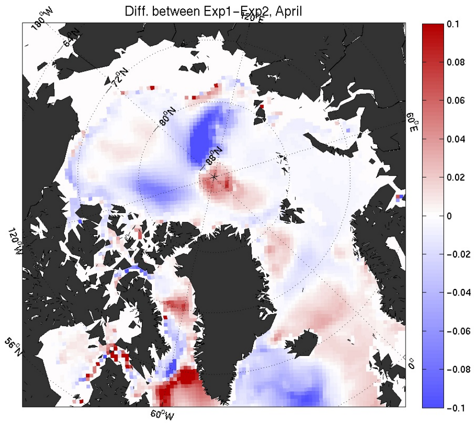
Figure 4: The time series of the mean freshwater content (m) in the region bounded by 77 °N to 85 °N and 170 °E to 135 °W from 1980 to 2008. Exp2 and Exp3 are the same until 1990, both are represented with the black line, since no mooring data exists.

of the 34.8 isoline or by reducing the salinity. By investigating the depth of the gyre (not shown), it is clear that the properties of the BG is the same in the four experiments. Summarizing the results leads to the assumption that the influence of the varying transport is minor, at least in the core of the BG, compared to other parameters.

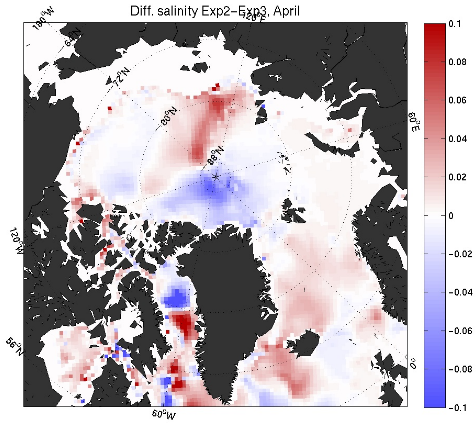
4.1.2 *Salinity at* 100 *m depth*

The difference in salinity distribution at 100 m depth is presented in Fig. 5. It shows that the BG is affected by the BS variability, but mainly on the outskirts of the BG, at the ∼ 6-7 m (cyan) contour of the freshwater content in Fig. 3. This mean that the salinity changes are largest outside the black box (Fig. 3) used for calculating the FWC. Accordingly, these results may explain why we have not observed any major changes in the FWC, see the previous section (Subsection 4.1.1).

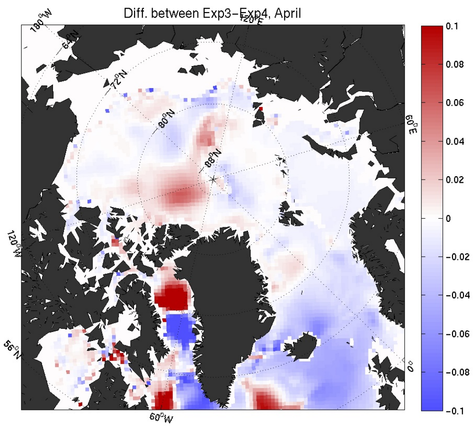
With a seasonal transport (Exp2) the FWC increase north of Greenland, but decreases along the Canadian coast and from the north pole to Siberia, see Fig. 5(a). Inter-annual transport (Exp3) leads to an increase of FWC southwards, from the North Pole to Siberia and a decrease north of Greenland, compared to Exp2, see Fig. 5(b). Note that this is the opposite effect than Exp2. Although the freshwater flux was significantly reduced in Exp4, see Table 2, the inter-annual hydrography only has a small impact on the



(a) Exp1-Exp2



(b) Exp2-Exp3



(c) Exp3-Exp4

Figure 5: Mean salinity anomaly for the month of April at 100 m depth for the period 2000-2008.

salinity distribution, see Fig. 5(c). The FWC has increased north of Greenland.

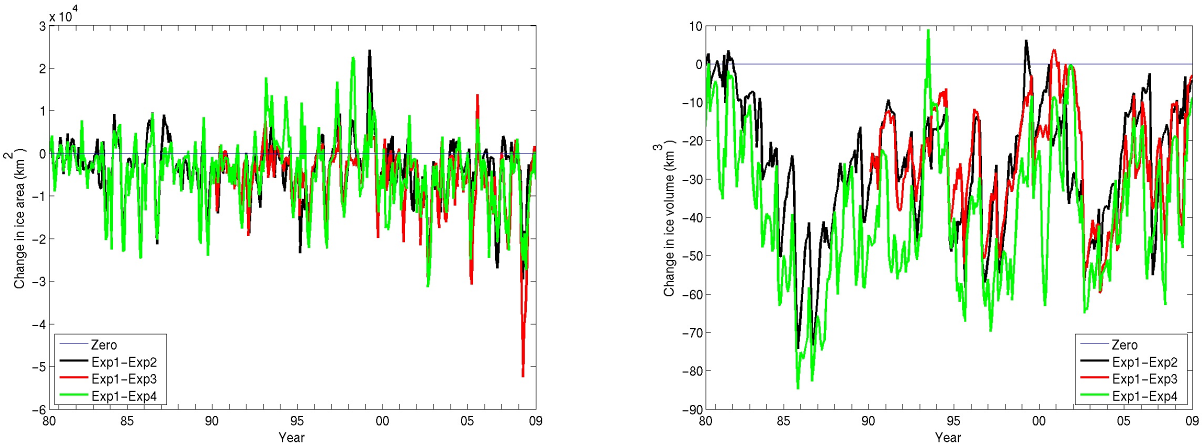
In this section the main focus is on the Arctic Ocean, but changes in the salinity distribution can also be observed in other parts of the model domain. This is shown in Subsection 5.1.

4.2 Sea-ice

The Atlantic water in the Arctic Ocean is denser, more saline and warmer than the water that originates from the Pacific. Due to the density difference, the water from the BS can be found high in the water column. One may therefore assume that the inflow have an impact on the sea-ice. Observations show that most of the ice-retreat happens in the region influenced by the BS inflow (*Woodgate et al.*, 2006).

4.2.1 *Evolution of ice*

Fig. 6 shows the evolution of change from the control experiment (Exp1) in total ice area and ice volume. The impact of the different approaches is small. Compared to the total ice area ($\sim 10^7\,\mathrm{km}^2$), the change in ice area is usually less than 3%. The same can be noted for the change in ice volume, where the difference is usually less than 7% of the total ($\sim 10^4\,\mathrm{km}^3$). Experiments with a varying transport have a larger ice area than the Exp1 (constant transport) after year 2000. Before that the change in ice area is approximately stable. The ice volume is larger in experiments with varying transport almost every year. There is a spin-up, then a stabilization around $\sim -30\,\mathrm{km}^3$, see Fig. 6(b). This result is not intuitive as the heat flux has



(a) Ice area (km^2)

(b) Ice volume (km^3)

Figure 6: Ice anomaly for the four experiments from 1980 to 2008. Exp2 and Exp3 are the same until 1990, both are represented with the black line, since no mooring data exists.

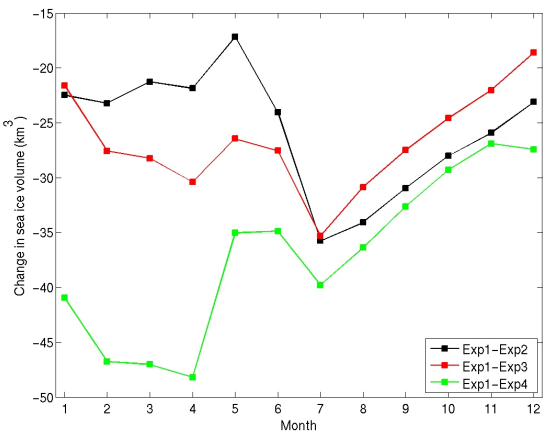
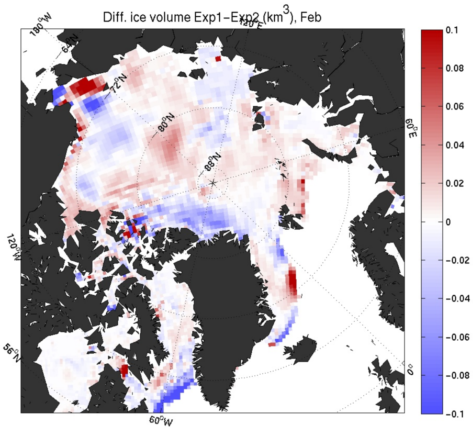


Figure 7: The change in mean seasonal ice volume (km^3) from Exp1 for the period 2000-2008

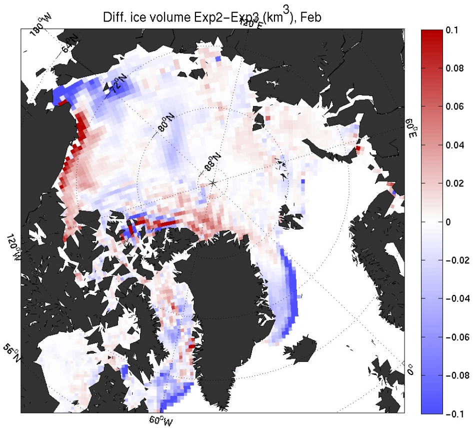
increased for Exp2 (seasonal transport) and Exp3 (inter-annual transport), see Table 2. No major change is observed for Exp4 either, where the heat flux (Table 2) was significantly reduced.

Woodgate et al. (2010) noted a correlation between years with high transport and anomalously warm inflow and years with considerable melt of ice in the Arctic. From Fig. 2 it can be observed an abnormally high transport in 2007 and abnormally low transport in 2000 and 2001. For the yearly mean inter-annual temperature, 2000 stands out as a minimum, while 2007 clearly is one of the warmer years (not shown). In 2007 there seems to be a small discrepancy in the ice area (Fig. 6(a)) for Exp3 (inter-annual transport) and Exp4 (inter-annual transport and hydrography). Unlike in *Woodgate et al.* (2010), the ice area has increased ($+\sim 2 \cdot 10^4\,km^2$). Note that the difference is not observed for the ice volume (Fig. 6(b)). No significant change is observed for the ice area in 2000, but the ice volume has increased for Exp4, showing the importance of the inter-annual hydrography in the BS. Other years that stand out for the ice area are 1994 (no inter-annual data this year, see Fig 2) and 1998. These observations have not been connected to any specific events.

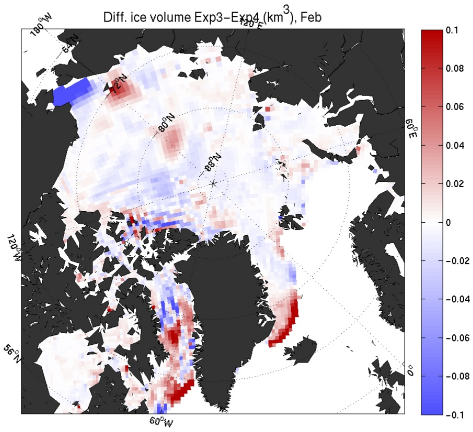
By studying the change in the mean seasonal ice volume from Exp1 for the period 2000-2008 (Fig. 7), it is clear that Exp4 have more ice than Exp1, Exp2 and Exp3. These discrepancies are largest in the first six months of the year. The ice increase may be a result of the inter-annual hydrography. These values are both more saline and colder than the climatology, as can be seen in Table 2. In the last six months the impact of the varying inflow is approximately the same.



(a) Exp1-Exp2



(b) Exp2-Exp3



(c) Exp3-Exp4

Figure 8: Mean ice volume anomaly for the month of February for the period 2000-2008.

4.2.2 *Change in ice distribution*

The change in ice distribution in February (Fig. 8) shows that seasonal transport (Exp2) changes the ice front, the ice volume north of Greenland and in the BS. The same can be noted for the inter-annual transport (Exp2), but here the differences are clearer along the Alaskan coast and in Baffin Bay. Inter-annual hydrography changes the ice front and the ice distribution in the BS and Baffin Bay. Note that the largest changes in the interior of the Arctic Ocean are observed with seasonal transport (change between Exp1 and Exp2).

When it arrives in the Arctic, the BS inflow enters the BG or follows the coasts on both sides. Leaving one branch flows trough the Canadian Archipelago to Baffin Bay, another through the Fram Strait. In the numerical model used, the main inflow from the Arctic to Baffin Bay goes through the McClure Strait. The minimum depth of the pathway is $\sim 80\,\mathrm{m}$. There is also a small shallow channel, leading surface water from the Arctic through the Queen Elizabeth Islands and meeting the main throughflow to Baffin Bay. Note that the depths of the channels do probably affect the properties of the water that enters the Baffin Bay region.

From the ice distribution it seems as the largest changes occur where the BS inflow enters or leaves the Arctic. The ice loss in Exp3 along the Alaskan coast may be a result of a property change in the coastal current, see Subsection 4.3.

4.3 Circulation

When entering the Arctic, the Pacific water divides into three currents. One follow the Alaskan coast, another the Siberian, while the third feeds into the BG. Atlantic water flows into the Arctic through the Fram Strait and the Barents Sea. This salty and warm water sinks, due to cooling, and travels cyclonically underneath the BG. Note that this is the opposite direction to the anti-cyclonic surface circulation, driven by the atmospheric wind. The Pacific water leaves the Arctic through the maze of Canadian islands or the Fram Strait. *Proshutinsky and Johnson* (2001) assumed that the troughflow from the BS to the Fram Strait is one of the factors that affect the general circulation in the Arctic.

As a response to the thermohaline flow, the inflow from rivers and the seasonal cycle of the BS inflow and the wind (*Proshutinsky and Johnson*, 2001), the mean circulation of the gyre also changes seasonally. The currents are strongest when the wind curl is at its maximum, in the winter, and decrease during summer. The main currents may be observed by defining the speed as

$$Spd = \sqrt{u^2 + v^2}, \tag{2}$$

where u and v are the velocities in the two horizontal directions.

4.3.1 *Currents*

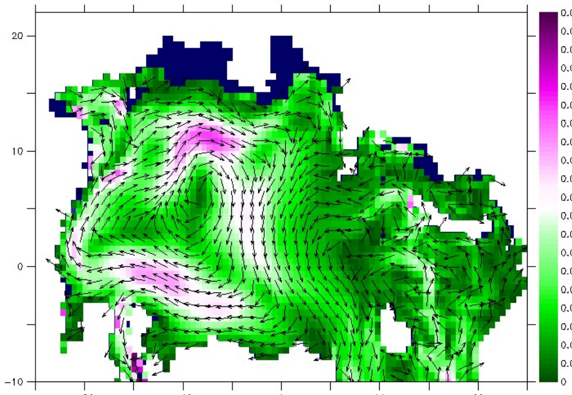
The anti-cyclonic current in the BG may be observed at 35 m depth in Fig. 9(a). In the model, water coming from the BS seems to feed directly into the BG. Probably due to the coarse resolution, the Alaskan Coastal Current is not observed. Since this current is not present, the inflow to Baffin Bay only comes from water in the BG. The communication with the North Atlantic can be observed as a outflow trough the Fram Strait and an inflow through the Barents Sea. Deeper down the circulation is cyclonic (not shown).

The seasonal variability of the circulation in Exp1 (constant transport) is small in the BG and the Chukchi Sea, see Fig. 9(a) and Fig. 9(c). Current changes are stronger in the Barents Sea. When studying experiments with varying transport, see Fig. 9(b) and Fig. 9(d), the seasonality of the gyre is clearer. Now it is evident that the currents in the Chukchi Sea are stronger and the current along the Alaskan coast is weaker in June. The seasonality noted in the Barents Sea, is similar to the changes observed in Exp1. Also, for all experiments the currents down through the Canadian Archipelago are stronger in December than in June.

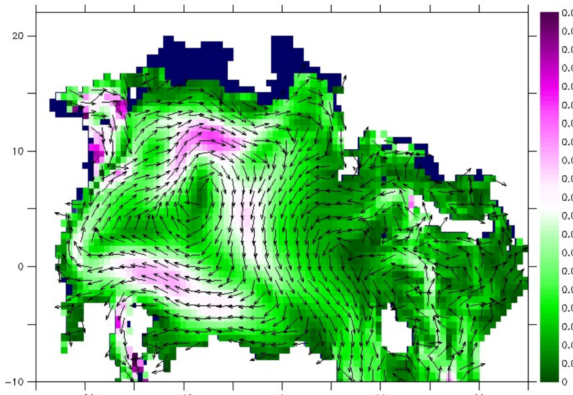
Compared to Exp1, experiments with varying transport have stronger currents in the Chukchi Sea and weaker currents along the Alaskan coast in June and the opposite in December. Also, the main current down to Baffin Bay is stronger in June and weaker in December (not shown).

From the observation above, it is reasonable to believe that the ice differences along the Alaskan coast are caused by the changes in the current. In other words, in our model the ice along the Alaskan coast is affected by the transport in the BS. Note that there is no ice anomaly between Exp3 (seasonal hydrography) and Exp4 (inter-annual hydrography) for this coastal section, see Fig. 8(c). The ice volume in the BS and in Baffin Bay may also be, at least partially, caused by changes in the circulation (not shown). Perturbations in the hydrography distribution are another contributing factor to ice changes in these areas. There are little or no current changes to explain the salinity changes in the Arctic (Fig. 5(a) and Fig. 5(b)) and the difference in ice volume along the eastern coast of Greenland (Fig. 8).

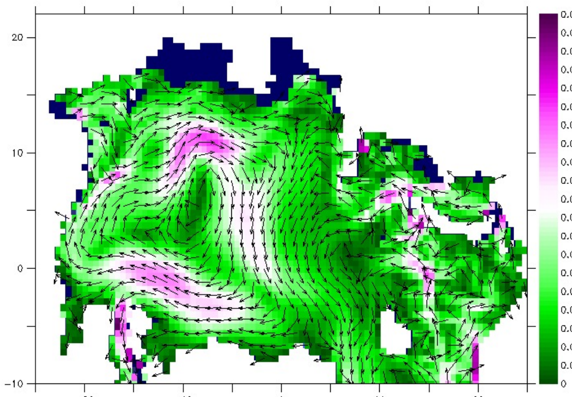
The monthly mean transport through the McClure Strait, for the period 2000-2008, show a small increase in transport from May to August for experiment with varying transport compared to Exp1. These months, are the months where the climatological transport (*Woodgate et al.*, 2005) in the BS is higher than the average transport. The maximum change between Exp2, Exp3 and Exp4 is about 3 % of the yearly average (1 Sv). This is also true for Exp1 (constant transport) from September to April, but in e.g. June the difference between Exp1 and the second lowest transport is $\sim$ 0.05 Sv. Note that *Melling et al.* (2008) estimated the transport in the Lancaster Sound to 0.7 Sv. Due to coarse resolution, the maze of islands in the Canadian Archipelago is replaced by one main channel, from the McClure Strait to the Lancaster Sound.



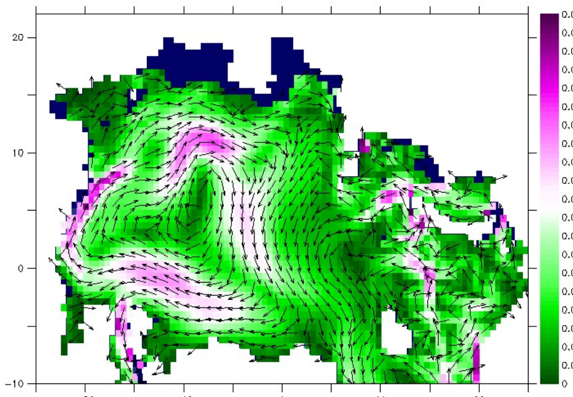
(a) Exp1 for the month of June



(b) Exp3 for the month of June



(c) Exp1 for the month of December



(d) Exp3 for the month of December

Figure 9: Mean speed (m/s) (colorbar) and the mean velocity direction (vectors) at 35 m depth for the period 2000-2008. Blue area is sea shallower than 35 m.

The flows through the Nares Strait (0.8 Sv), Hell Gate and Cardigan Strait (0.3 Sv) (*Melling et al.*, 2008) are accordingly not represented. One could therefore expect a larger volume transport in the Lancaster Sound and the Fram Strait. For that reason, the observed average of 1 Sv is reasonable representative.

The trend, mentioned above, may also be observed in Baffin Bay, but not in the Fram Strait, Iceland-Faroe Islands-Shetland-Scotland section and the section from Svalbard through Bear Island to Norway (not shown). This means that, in yearly mean, the variations in the BS do not affect significantly the amount of water being transported through the different straits. On the other hand, the differences in salinity and ice distribution have to be connected to changes in the currents, since the thermohaline circulation in itself, is too slow to account for the results.

However, it should be noted that the principal factor for the circulation in the Beaufort Gyre is the atmospheric wind, which explains why the impact from the BS is comparatively small. Further studies, with e.g. finer resolution model, would have a more realistic circulation and may enhance the sensitivity.

5 Results for the North Atlantic

Since the largest changes were not observed in the Arctic, but in other parts of the model domain, some new tests were considered (e.g. previously in our experiments it has clearly been noted salinity differences in Baffin Bay and close to Iceland (Fig. 5)). *Häkkinen and Proshutinsky* (2004) found that the largest freshwater anomalies in the Arctic Ocean are caused by the atmospheric wind, ice melt and growth and variability in the Atlantic inflow. The anomalies caused by the sea-ice in the BS region, traveled anti-cyclonically towards the Fram Strait. As they propagated, the anomalies would affect the convection and deep-water formation (*Wadley and Bigg*, 2002). Changes in the BS flux may therefore change the Atlantic overturning circulation (*Goosse et al.*, 1997). Further, the flux also influences the location of the Gulf Stream (*Woodgate et al.*, 2005).

5.1 Salinity

To highlight areas where changes are significant, we have divided the difference between the experiments with the square root of the variance of Exp1, see Fig. 10. Note that no change is observed in the Arctic. The BS inflow seems to influence the salinity in the Bay of Biscay, the sea south of Greenland and the coastal waters, close to separation point of the Gulf Stream, at the American coast. The two last regions are important for the location of the Gulf Stream. Even if the figures show the changes at 5m depth the same hot spots are found at least down to 100 m depth. At 1000 m depth the distribution has changed, see Fig. 11. Still the North Atlantic experiences changes, but here one also observe that the Arctic is affected. This imply that the BS inflow can have an impact on the water column as deep as 1000 m. The largest differences are found between constant (Exp1) and seasonal transport (Exp2).

5.2 Currents

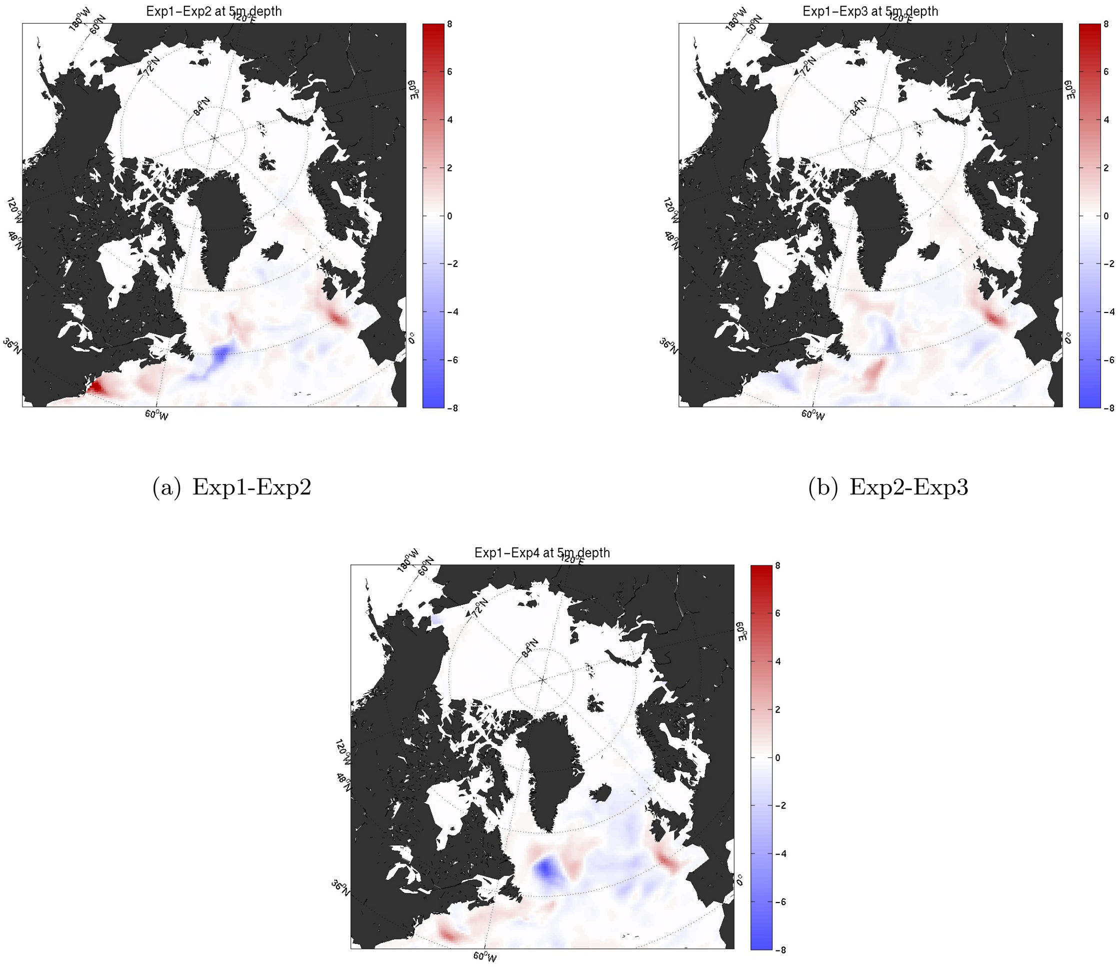
The speed at 5 m depth for Exp1 show the main currents in the region, see Fig. 12. Note that the location of the BG in the Arctic and the Gulf Stream are easily recognized. To distinguish the placement of the Gulf Stream in the different runs, the 35 salinity front is plotted, see Fig. 13. Notice how the salinity front follow the Gulf Stream observed in Fig. 12. In agreement with the result above, see Subsection 5.1, the significant changes are found where the Gulf Stream separates from the coast and in the sea south of Greenland. Note, Exp2 looks best at the detachment point at Cape Hatteras. Effects of inter-annual variation of the hydrography (Exp4) are here clearly apparent. This contradicts to the observations in the Arctic Ocean, where differences between Exp1-Exp2 and Exp2-Exp3 were more evident than between Exp3-Exp4. However the demarcation of the Gulf Stream does not seem realistic. The results therefore show that variations, both in hydrography and transport, in the BS inflow do have an impact on the location of the Gulf Stream in this model.

6 Conclusion

We have analyzed the sensitivity of the Arctic Ocean to the Bering Strait inflow for the period 1980-2008. The model HYCOM 2.2 used, is a coarse resolution version of the TOPAZ system covering the North Atlantic and the Arctic. The barotropic inflow in the Bering Strait is balanced with an outflow at the southern boundary.

Four different parameterizations of Bering Strait inflow were analyzed; constant transport and seasonal hydrography; seasonal transport and seasonal hydrography; inter-annual transport and seasonal hydrography; inter-annual transport and inter-annual hydrography. The main focus has been on changes in the salinity budget, the sea-ice and the circulation in the Arctic, but also the North Atlantic has been studied. The results for the Arctic show that:

- Changes in the inflow do not have a significant impact on the freshwater content at the core of the



(a) Exp1-Exp2

(b) Exp2-Exp3

(c) Exp3-Exp4

Figure 10: Mean salinity anomaly divided by the square root of the variance of Exp1 at 5 m depth for the period 2000-2008.

Beaufort Gyre. The outskirts of the gyre, do on the other hand, experience a change in the salinity distribution between the experiments.

- A varying transport has a larger impact on the salinity budget than an inter-annual hydrography.
- The overall impact on the ice cover is small. Compared to the control experiment (constant transport), it is observed an increase of ice volume for all three experiments. The ice area increases after year 2000.
- In contrast to *Woodgate et al.* (2010), it is not found a correlation between years with anomalously high transport and warm inflow and years with considerable ice melt in the Arctic.
- Varying transport causes a change in the circulation in the Arctic. The significant differences are found in the Chukchi Sea and along the Alaskan coast

Further, the results for the North Atlantic show that:

- The largest salinity changes occur along the path of the Gulf Stream, down to at least 100 m depth.

Differences in the circulation, ice and salinity distribution show that the Bering Strait inflow has a small impact on the Arctic Ocean. The changes in the North Atlantic are larger. Likely the differences result from changes in the circulation. An understanding of the impact from the Bering Strait is therefore important for modeling the exchange processes between the North Atlantic and the Arctic.

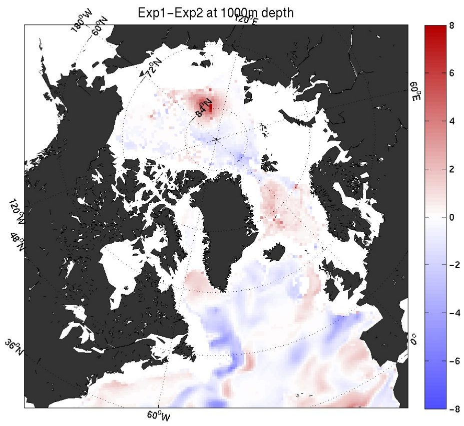


Figure 11: Mean salinity anomaly (Exp1-Exp2) divided by the square root of the variance of Exp1 at 1000 m depth for the period 2000-2008.

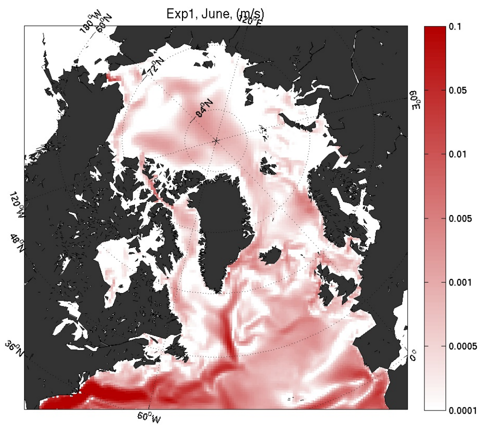


Figure 12: Mean speed (m/s) at 5 m depth for Exp1 for the month of June for the period 2000-2008.

References

Bentsen, M., G. Evensen, H. Drange, and A. Jenkins, Coordinate Transformation on a Sphere Using Conformal Mapping, *Monthly Weather Review*, *127*, 2733–2740, 1999.

Bertino, L., and K. Lisæter, The TOPAZ monitoring and prediction system for the Atlantic and Arctic Oceans, *Journal of Operational Oceanography*, *2008*, 15–18, 2008.

Bleck, R., An oceanic general circulation model framed in hybrid isopycnic-Cartesian coordinates, *Ocean Modelling*, *4*, 55–88, 2002.

Carmack, E., The alpha/beta ocean distinction: A perspective on freshwater fluxes, convection, nutrients and productivity in high-latitude seas, *Deep Sea Research Part II: Topical Studies in Oceanography*, *54*, 2578–2598, 2007.

Chassignet, E., H. Hurlburt, O. Smedstad, G. Halliwell, P. Hogan, A. Wallcraft, and R. Bleck, Ocean prediction with the hybrid coordinate ocean model (HYCOM), *Ocean Weather Forecasting*, pp. 413–426, 2006.

Cherniawsky, J., W. Crawford, O. Nikitin, and E. Carmack, Bering Strait transports from satellite altimetry, *Journal of Marine Research*, *63*, 887–900, 2005.

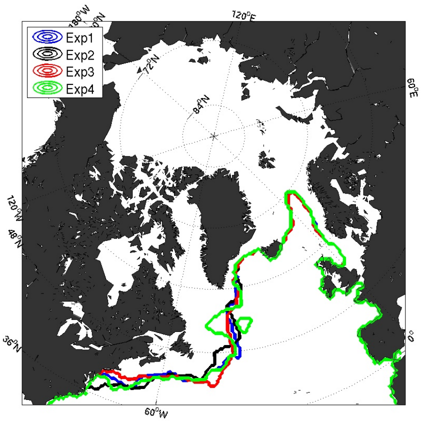


Figure 13: Mean 35 salinity front for the four experiments for the period 2000-2008.

Drange, H., and K. Simonsen, *Formulation of air-sea fluxes in the ESOP2 version of MICOM*, Nansen Environmental and Remote Sensing Center, 1996.

Evensen, G., The ensemble Kalman filter: Theoretical formulation and practical implementation, *Ocean dynamics*, *53*, 343–367, 2003.

Goosse, H., J. Campin, T. Fichefet, and E. Deleersnijder, Sensitivity of a global ice–ocean model to the Bering Strait throughflow, *Climate Dynamics*, *13*, 349–358, 1997.

Häkkinen, S., and A. Proshutinsky, Freshwater content variability in the Arctic Ocean, *Journal of Geophysical Research*, *109*, C03,051, 2004.

Hunke, E., and J. Dukowicz, An elastic-viscous-plastic model for sea ice dynamics, *Journal of Physical Oceanography*, *27*, 1849–1867, 1997.

Jiang, G., and C. Shu, Efficient implementation of weighted ENO schemes, *J. Comput. Phys*, *126*, 202–228, 1996.

Locarnini, R., J. Antonov, H. Garcia, and S. Levitus, *World ocean atlas 2005*, US Dept. of Commerce, National Oceanic and Atmospheric Administration, 2006.

Melling, H., T. Agnew, K. Kalkner, D. Greenberg, C. Lee, A. Muchow, B. Petrie, S. Prinsenberg, R. Samelson, and R. Woodgate, Fresh-water fluxes via Pacific and Arctic outflows across the Canadian polar shelf, *Arctic-Subarctic Ocean Fluxes: Defining the Role of the Northern Seas in Climate*, pp. 193–247, 2008.

Oki, T., and Y. Sud, Design of the global river channel network for Total Runoff Integrating Pathways (TRIP), *Earth Interactions*, *2*, 53, 1998.

Proshutinsky, A., and M. Johnson, Two regimes of the Arctic's circulation from ocean models with ice and contaminants, *Marine pollution bulletin*, *43*, 61–70, 2001.

Proshutinsky, A., R. Bourke, and F. McLaughlin, The role of the Beaufort Gyre in Arctic climate variability: Seasonal to decadal climate scales, *Geophysical Research Letters*, *29*, 2100, 2002.

Proshutinsky, A., R. Krishfield, M. Timmermans, J. Toole, E. Carmack, F. McLaughlin, W. Williams, S. Zimmermann, M. Itoh, and K. Shimada, Beaufort Gyre freshwater reservoir: State and variability from observations, *Journal of Geophysical Research*, *114*, 2009.

Simmons, A., S. Uppala, D. Dee, and S. Kobayashi, ERA-Interim: New ECMWF reanalysis products from 1989 onwards, *ECMWF Newsletter*, *110*, 25–35, 2007.

Steele, M., R. Morley, and W. Ermold, PHC: A global ocean hydrography with a high-quality Arctic Ocean, *Journal of Climate*, *14*, 2079–2087, 2001.

Uppala, S., P. Kållberg, A. Simmons, U. Andrae, V. Bechtold, M. Fiorino, J. Gibson, J. Haseler, A. Hernandez, G. Kelly, et al., The ERA-40 re-analysis, *Quarterly Journal of the Royal Meteorological Society*, *131*, 2961–3012, 2005.

Wadley, M., and G. Bigg, Impact of flow through the Canadian Archipelago and Bering Strait on the North Atlantic and Arctic circulation: An ocean modelling study, *Quarterly Journal of the Royal Meteorological Society*, *128*, 2187–2203, 2002.

Woodgate, R., K. Aagaard, and T. Weingartner, Monthly temperature, salinity, and transport variability of the Bering Strait through flow, *Geophysical Research Letters*, *32*, L04,601, 2005.

Woodgate, R., K. Aagaard, and T. Weingartner, Interannual changes in the Bering Strait fluxes of volume, heat and freshwater between 1991 and 2004, *Geophysical Research Letters*, *33*, L15,609, 2006.

Woodgate, R., T. Weingartner, and R. Lindsay, The 2007 Bering Strait oceanic heat flux and anomalous Arctic sea-ice retreat, *Geophysical Research Letters*, *37*, L01,602, 2010.