

Increasing exchanges at Greenland-Scotland Ridge and their links with the North Atlantic Oscillation and Arctic Sea Ice

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[1] A global ice-ocean model shows increasing Atlantic water (AW) inflow at the Iceland-Scotland Ridge (ISR) during 1953–2002. As a result, the Greenland-Iceland-Norwegian (GIN) Sea is gaining more heat and salt from the North Atlantic Ocean, while the latter is being freshened mainly by exporting more salt to the GIN Sea. The exchanges of volume, heat, and freshwater at the Greenland-Scotland Ridge (GSR) are strongly correlated with the North Atlantic Oscillation (NAO) and their positive trend is closely linked to the NAO elevation in recent decades. The model confirms observations of decreasing dense water outflow at the Faroe-Scotland Passage since the 1950s. However, the simulated dense water outflow shows an increase at Denmark Strait, at the Iceland-Faroe Ridge, and at the GSR as a whole, owing to an increase in AW inflow that may cause an increase in AW recirculation and deep water production in the GIN Sea. The increase of the ISR heat inflow since 1965 contributes to continued thinning of the arctic sea ice since 1966. The influence of the heat inflow on arctic sea ice lags 2–3 years, which suppresses ice production even when the NAO temporarily shifts to a negative mode. Because of this delay, the decline of arctic sea ice is likely to continue if the inflow continues to increase and if the NAO does not shift to a sustained negative mode. **INDEX TERMS:** 4215 Oceanography: General: Climate and interannual variability (3309); 4207 Oceanography: General: Arctic and Antarctic oceanography; 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 4255 Oceanography: General: Numerical modeling; 4512 Oceanography: Physical: Currents. **Citation:** Zhang, J., M. Steele, D. A. Rothrock, and R. W. Lindsay (2004), Increasing exchanges at Greenland-Scotland Ridge and their links with the North Atlantic Oscillation and Arctic Sea Ice, *Geophys. Res. Lett.*, 31, L09307, doi:10.1029/2003GL019304.

1. Introduction

[2] Substantial changes in arctic climate have been detected in recent years. One of the changes is the decline of sea ice [Parkinson *et al.*, 1999; Rothrock *et al.*, 1999]. The decline is linked to changes in the atmospheric circulation characterized by the North Atlantic Oscillation (NAO), which has shifted to a generally strong positive phase in recent decades. In the Arctic, a positive NAO mode generally corresponds to a weakening of the Beaufort Sea high pressure cell and a

strengthening of the European subarctic low pressure cell [Walsh *et al.*, 1996]. Such a positive phase shift is correlated with an increase in surface air temperature [Rigor *et al.*, 2000], which contributes to the decline of arctic sea ice.

[3] The decline of arctic sea ice is also linked to changes in the oceanic circulation. Observations from recent scientific cruises have indicated an increased influence of warm, salty Atlantic water (AW) [Morison *et al.*, 1998], owing to a strengthened AW penetration into the Arctic Ocean at Fram Strait and through the Barents Sea in the 1990s in response to the positive NAO [e.g., Grotedefendt *et al.*, 1998; Zhang *et al.*, 1998]. The increased presence of AW and reduced halocline strength [Steele and Boyd, 1998] cause an increased upward ocean heat flux, suppressing ice growth and enhancing lateral melting [Zhang *et al.*, 2000].

[4] The AW finds its way to the Arctic by flowing northward across the Greenland-Scotland Ridge (GSR) and through the Greenland-Iceland-Norwegian (GIN) Sea. The GSR consists of Denmark Strait (DS) and the Iceland-Scotland Ridge (ISR), which is where major exchanges of volume, heat, and freshwater occur between the GIN Sea and the Atlantic Ocean. The GSR exchanges are closely related to AW penetration further into the Arctic at Fram Strait and through the Barents Sea [Karcher *et al.*, 2003], and therefore play a significant role in changes in arctic sea ice and climate. The present study examines the variability of these exchanges, particularly the AW and heat inflow (northward) at GSR and its link with the NAO and arctic sea ice 1953–2002. Special attention is paid to how these exchanges respond to the positive NAO phase shift. Our principal analysis tool is a global Parallel Ocean and sea Ice Model (POIM [Zhang and Rothrock, 2003]).

2. Model Description

[5] The POIM couples the Parallel Ocean Program developed at the Los Alamos National Laboratory and a multicategory thickness and enthalpy distribution sea-ice model [Zhang and Rothrock, 2003]. With its northern pole displaced to Greenland, the global POIM has an average resolution of about 35 km for the GIN Sea and North Atlantic Ocean. The model is driven by daily NCEP/NCAR reanalysis forcing and includes river runoff climatology for the Arctic. Model spin-up consists of an integration of 30 years using 1948 forcing repeatedly, which allows the model to reach an approximate steady state in volume exchanges at the GSR. After this spin-up, the model

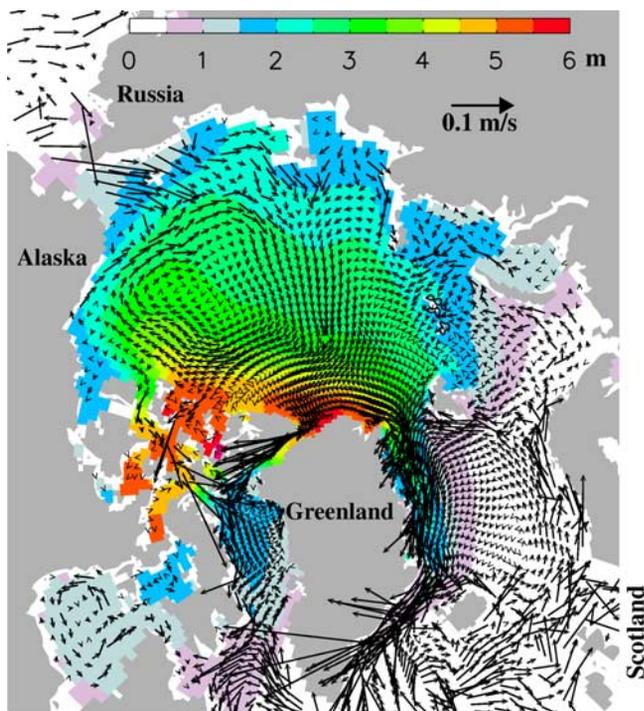


Figure 1. Simulated 1953–2002 mean ice thickness (m) superposed with 1953–2002 mean ocean velocity at 15-m depth. One vector is drawn for every four grid cells.

proceeds to simulate the period of 1948–2002. Results for 1953–2002 are presented here.

3. 1953–2002 Mean Ocean Circulation and Volume Transport

[6] The model simulates some of the major currents in the North Atlantic-GIN Sea region (Figure 1), such as the East Greenland Current (EGC), the Irminger Current (IC), and the Norwegian Atlantic Current (NAC). These currents are further illustrated by velocity transects at DS and the ISR, the latter consisting of the Iceland-Faroe Ridge (IFR) and Faroe-Scotland Passage (FSP) (Figure 2). During 1953–2002, the IC brings an average of 1.1 Sv (or $10^6 \text{ m}^3 \text{ s}^{-1}$) of AW into the GIN Sea at the eastern DS, while the NAC carries 7.3 Sv of AW northward at ISR (Table 1, Figure 2), agreeing rather well with the estimates of Hansen and Østerhus [2000]. The simulated EGC exits DS with an average of 5.8 Sv of cold Arctic water and recirculating AW. The volume outflow (southward) at the ISR occurs below the ocean surface layer and resembles overflow of dense water at depth (Figure 2). The mean ISR outflow is 2.7 Sv (Table 1), also in agreement with Hansen and Østerhus [2000]. The estimates of both the net inflow at the ISR and the net outflow at DS are somewhat larger than those made by Hunke *et al.* [2003] using an eddy-admitting global ice-ocean model.

4. Increasing Volume, Heat, and FW Exchanges at the GSR

[7] The simulated AW inflow at the ISR increases at a rate of 0.019 Sv yr^{-1} 1953–2002, as does the outflow at DS

at about the same rate (Figure 3a, Table 1). The increase is more pronounced since the 1960s. The interannual variability of both the ISR net inflow and the DS net outflow is significantly correlated with the NAO, while the positive trend appears to be closely linked to the NAO elevation over the past several decades. Note that the results are different from Nilsen *et al.*'s [2003] results that showed a reduction in the AW inflow without explicitly giving a correlation between the inflow and the NAO.

[8] The simulated DS branch of AW inflow is also increasing over the past decades and is correlated with the NAO, but with a weaker trend than the ISR inflow (Table 1). There is a weak positive trend in ISR outflow as well, but it is not significant at a 95% confidence level. The 1–5-year lagged correlations between the ISR outflow and NAO (the latter leads) are $-0.09, 0.38, 0.33, 0.38, 0.18$, respectively, and 1–5-year lagged correlations between the ISR outflow and inflow (the latter leads) are $0.18, 0.36, 0.49, 0.53, 0.38$, respectively. This suggests that the changes in AW inflow at ISR or the NAO have a certain influence on the ISR outflow 2–4 years later, owing perhaps to AW recirculation and deep water production in the GIN Sea.

[9] It is no surprise that an increased volume inflow of warm, salty AW at the ISR leads to an increased inflow of heat and salt (Figure 4). The simulated heat inflow at ISR increases at a rate of $0.84 \times 10^{12} \text{ W}$ per year 1953–2002, while the heat outflow at DS, much smaller in magnitude, increases to a lesser degree. These heat exchanges are significantly correlated with the NAO (Table 1). An increased inflow of salt at ISR, on the other hand, is equivalent to an increased outflow of liquid freshwater (FW) because AW salinity at ISR is generally greater than 34.8 psu, the reference salinity used to calculate FW (Figure 4b). The ISR outflow of liquid FW is also well correlated with the NAO (Table 1, Figure 4b). Given that the liquid FW outflow and ice outflow at DS (Table 1) do

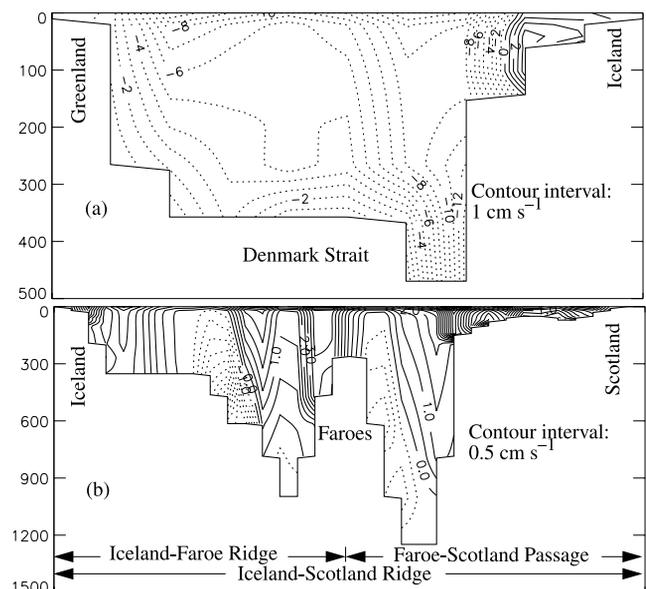


Figure 2. Vertical distributions of 1953–2002 mean ocean velocity (cm s^{-1}) across (a) Denmark Strait and (b) the Iceland-Scotland Ridge. Solid line: inflow (northward); dotted line: outflow (southward).

Table 1. Statistics of Annual Mean Exchanges of Volume (Sv), Heat (10^{12} W), Liquid Freshwater (10^4 $\text{m}^3 \text{s}^{-1}$), and Sea Ice (10^{12} $\text{m}^3 \text{yr}^{-1}$) Along the Greenland-Scotland Ridge (GSR) 1953–2002^a

	Mean 1953–2002	Trend, yr^{-1}	Correlation With NAO
Volume inflow at ISR	7.3 (7.0)	0.019	0.56
Volume outflow at ISR	2.7 (3.0)	0.003	–0.19
Net volume inflow at ISR	4.6 (4.0) [3.5]	0.016	0.66
Volume inflow at DS	1.1 (1.0)	0.005	0.47
Volume outflow at DS	5.8	0.022	0.65
Net volume outflow at DS	4.7 [3.8]	0.017	0.64
Dense water outflow (Sv)			
DS $\sigma_\theta > 27.80$	2.3 {2.7}	0.016	0.38
IFR $\sigma_\theta > 27.65$	0.8	0.008	–0.01
FSP $\sigma_\theta > 27.45$	0.9	–0.002	–0.23
Heat inflow at ISR	196	0.84	0.64
Heat outflow at DS	50	0.26	0.50
Net heat inflow at GSR	146	0.61	0.65
Liquid freshwater outflow			
ISR	7.3	0.042	0.54
DS	5.6	–0.002	0.28
GSR	12.9	0.061	0.62
Sea ice outflow at DS	1.1	0.001	0.33

^aVolume transport estimates in parentheses are from Hansen and Østerhus [2000], in square brackets from Hunke et al. [2003], and in curly brackets from Girton et al. [2001]. Bold numbers exceed the 95% confidence level. ISR: Iceland-Scotland Ridge; DS: Denmark Strait; IFR: Iceland-Faroe Ridge; FSP: Faroe-Scotland Passage.

not demonstrate statistically significant trends 1953–2002, the increase in liquid FW outflow at ISR alone is responsible for an overall increase in FW flux into the Atlantic Ocean from the Arctic. In other words, the Atlantic Ocean is gaining more FW mainly because it is exporting more salt at the ISR.

[10] What is the link between sea ice and the ISR heat transport? The simulated NH sea-ice thickness field (Figure 1) agrees with the observed thickness pattern [Bourke and McLaren, 1992]. The total NH ice volume (Figure 4a), which is closely correlated with the arctic sea-ice volume (not shown), decreases drastically after 1966, while the upward heat flux at the surface of the Arctic Ocean increases considerably (Figure 4c). With a lag of 2 or 3 years, the NH ice volume is closely correlated, negatively, with the ISR heat inflow (Figure 5). Similarly, with a lag of 1 or 2 years, an approximate time needed for upper-layer AW to travel from the ISR to the Arctic, the arctic upward oceanic heat flux is positively correlated with the ISR heat inflow. The arctic upward heat flux is in turn correlated with the NH ice volume, with 0- and 1-year lagged correlations of –0.53 and –0.35, respectively. This suggests that the changes in AW inflow and heat flux at the ISR are likely to affect arctic sea ice in the subsequent 2 to 3 years. In fact, the strong upswing of heat inflow at the ISR and upward oceanic heat flux since 1965 contributes to the steep decline of ice volume since 1966 (Figure 4).

5. Variability of Dense Water Outflow at GSR

[11] The model estimate of mean DS outflow of dense water is in close agreement with the observational estimate of Girton et al. [2001] (Table 1). Outflow of dense water with $\sigma_\theta > 27.80$ is often taken as overflow. The simulated DS overflow is somewhat correlated with the NAO. In contrast to the study of Girton et al. [2001], the simulated overflow has a positive trend of 0.016 Sv yr^{-1} (Figure 3c). The positive trend is certainly linked to the positive trend of AW inflow at the ISR.

[12] The model does not appear to adequately resolve the narrow overflow layer at either the IFR or the FSP. As a result, the simulated outflow of dense water with $\sigma_\theta > 27.80$ is zero at both locations. However, the variability of overflow at these locations can still be assessed by examining the outflow of dense water that falls somewhat short of the stringent criterion of $\sigma_\theta > 27.80$. The simulated IFR outflow of dense water with $\sigma_\theta > 27.65$ increases 1953–2002 (Table 1, Figure 3c). This suggests that an increase in

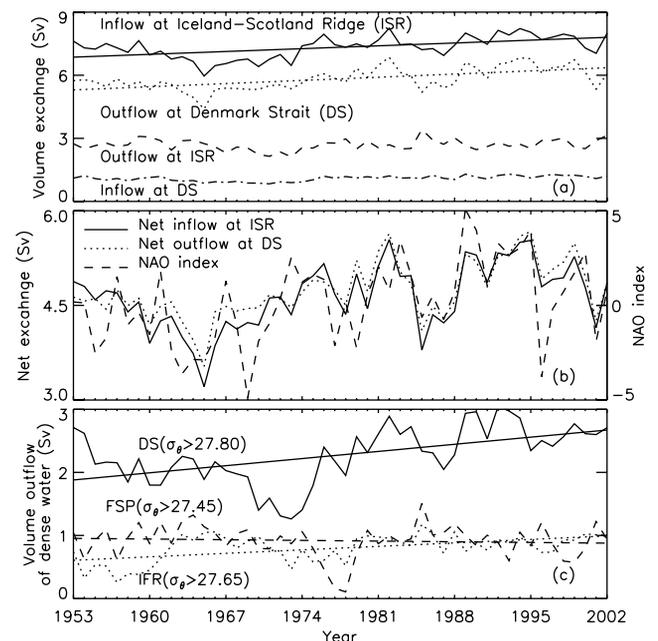


Figure 3. Simulated annual mean (a and b) volume exchanges and winter (December–March) North Atlantic Oscillation (NAO) index, and (c) volume outflow of dense water from Denmark Strait, Faroe-Scotland Passage (FSP), and Iceland-Faroe Ridge (IFR).

AW inflow at the ISR is likely to result in an increase in the IFR overflow.

[13] In contrast, the simulated FSP outflow of dense water with $\sigma_\theta > 27.45$ decreases 1953–2002, though not with statistical significance (Table 1, Figure 3c). However, it decreases markedly over 1996–2000. An increase in AW inflow at the ISR may have a tendency to reduce the FSP overflow. When AW inflow increases, the NAC may intensify and tend to oppose overflow at the FSP. Note, however, that the total dense water outflow at the ISR increases 1953–2002 because of the strong increase in the IFR outflow.

[14] The dense water outflow at either the IFR or the FSP is less responsive to the NAO than that at DS. This is because the ISR outflow is less responsive than the DS outflow to wind forcing [Bjastoch *et al.*, 2003]. Also, it takes 2–4 years for the NAO to somewhat affect the ISR outflow of all waters; it would take a longer time to affect ISR dense water outflow at depth. Time dissipates the effect of NAO.

6. Conclusions

[15] (1) *The exchanges of volume, heat, and FW at GSR are increasing.* The global POIM captures the basic features of ocean circulation and agrees with observations of some key ocean transports in the North Atlantic-GIN Sea region. The model shows an increasing AW inflow to the GIN Sea over the past half century, more pronounced since the 1960's. As a result, the GIN Sea is gaining more heat and salt from the North Atlantic Ocean, while the Atlantic Ocean is freshening by exporting more salty water to the GIN Sea at the ISR and importing more relatively fresh water at DS. The particularly strong increase in AW inflow since 1965 may partially contribute to the rapid freshening of the deep North Atlantic Ocean since the 1960s [Dickson *et al.*, 2002].

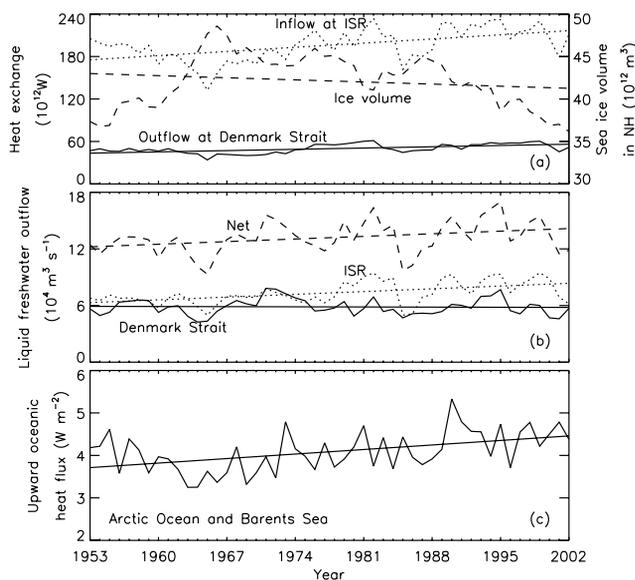


Figure 4. Simulated annual mean (a) heat exchanges at Denmark Strait and the Iceland-Scotland Ridge (ISR), and sea ice volume in the northern hemisphere (NH), (b) liquid freshwater exchanges, and (c) upward oceanic heat flux to ice in the Arctic Ocean and Barents Sea. Freshwater transport is calculated by $\iint [V(34.8 - S)/34.8] dA$, where S is salinity and V is the speed across a section of area A .

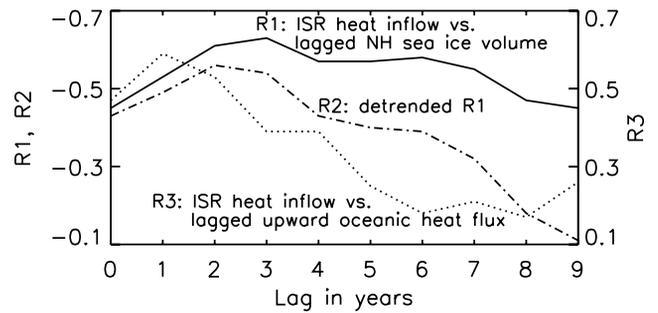


Figure 5. Lagged correlations between the heat inflow at the Iceland-Scotland Ridge (ISR) and the northern hemisphere (NH) sea ice volume, and between the heat inflow and the upward oceanic heat flux to ice in the Arctic Ocean and Barents Sea. The left axis scale is inverted.

[16] (2) *The exchanges of volume, heat, and FW at GSR are closely linked to the NAO.* The variability of key exchanges of volume, heat, and liquid FW at GSR is significantly correlated with the NAO. The positive trend of these exchanges is closely linked to the recent NAO elevation.

[17] (3) *Dense water outflow at GSR is increasing.* The simulated decrease of dense water outflow at FSP qualitatively agrees with the observations of a decreasing overflow there since 1950 [Hansen *et al.*, 2001]. Over the period 1996–2000, both model results and observations have downward trend. The simulated decrease in FSP dense water outflow is due to an increased AW inflow at the ISR associated with an intensified NAC. However, the total outflow of dense water at DS and the ISR increases 1953–2002, more strongly since late 1960s. This is because an increase in AW inflow at ISR is likely to cause an increase in AW recirculation and deep water production in the GIN Sea, which in turn leads to more outflow of dense water at DS and the IFR. While the ISR inflow is significantly correlated with the NAO and has a 2–4 year delayed effect on the total ISR outflow, the ISR outflow of dense water possesses no significant signature of the NAO. The increased dense water outflow at DS and the ISR tends to strengthen the global thermohaline circulation, although the freshening of the North Atlantic Ocean, via northward salty water transport at the ISR, tends to weaken it.

[18] (4) *Heat transport from the North Atlantic Ocean is melting arctic sea ice.* Changes in AW inflow and heat transport at the ISR have a significant impact on arctic sea ice 2–3 years later. The growing AW and heat inflow at ISR since 1965 may contribute to the steep decline of NH sea ice since 1966. In 1996 and 2001, the NAO indices turn significantly negative, but there is no significant increase in NH ice volume (Figures 3b and 4a). This may be attributed to the elevated heat transport at the ISR 2–3 years prior to either 1996 or 2001 (Figure 4a), which represents a delayed effect of NAO on sea ice given that the elevated heat transport is linked to a positive NAO. The lagged influence of the increased heat transport is likely playing a role in suppressing ice growth in the Arctic and adjacent seas and, therefore, holding ice volume in check when the NAO shifts temporarily to a negative mode, as in 1996 and 2001. In other words, if the AW and heat inflow at

ISR continue to increase as simulated by the model, and the NAO does not shift to an enduring negative mode, the decline of arctic sea ice is likely to continue.

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