Causes of Decadal Changes of the Freshwater Content in the Arctic Ocean

ARMIN KÖHL AND NUNO SERRA
Institut für Meereskunde, Universität Hamburg, Hamburg, Germany

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ABSTRACT

Decadal changes of the liquid freshwater content in the Arctic Ocean are studied with a suite of forward and adjoint model simulations. Adjoint sensitivities show that freshwater volume changes in the Norwegian Atlantic Current north of the Lofoten basin and a salinity maximum in the Fram Strait and in the Canadian Archipelago lead to an enhanced northward transport of freshwater. The dynamical sensitivities indicate that stronger freshwater export from the Arctic is related to an enhanced cyclonic circulation around Greenland, with an enhanced export through the Canadian Archipelago and a stronger circulation within the Fram Strait. Associated with this circulation around Greenland is a large-scale cyclonic circulation in the Arctic. Cyclonic wind stress anomalies in the Arctic Ocean as well as over the Nordic seas and parts of the subpolar Atlantic are optimal to force the freshwater transport changes.

Results from a simulation over the period 1948–2010 corroborate the result that Arctic freshwater content changes are mainly related to the strength of the circulation around Greenland. Volume transport changes are more important than salinity changes. Freshwater content changes can be explained by wind stress–driven transport variability, with larger export for cyclonic atmospheric forcing. By redistributing freshwater within the Arctic, cyclonic wind stress leads to high sea level in the periphery of the Arctic, and the stronger gradient from the Arctic to the North Atlantic enhances the export through the passages. A second mechanism is the wind-driven Sverdrup circulation, which can be described by Godfrey’s (1989) “island rule” including friction. For this, wind stress in the Arctic is not important.

1. Introduction

Decadal changes of the freshwater content in the Arctic Ocean are of importance because the freshwater is exported via the Fram Strait and the passages of the Canadian Arctic Archipelago (CAA) into regions of deep water formation in the Nordic seas and the North Atlantic (Karcher et al. 2005; Gerdes et al. 2008). This export has an impact on the deep water formation and on the global thermohaline circulation (Häkkinen and Proshutinsky 2004; Jungclaus et al. 2005). The Arctic Ocean is a net source of freshwater for the Atlantic and is gaining freshwater through inputs from Eurasian and North American river runoff, precipitation, and the inflow from the Pacific through the Bering Strait (Carmack 2000; Serreze et al. 2006; Dickson et al. 2007).

The variability of the freshwater storage in the Arctic and of its export into the Atlantic and the Nordic seas has been the subject of many studies. Arctic Ocean model simulations have suggested that the decadal variability of the Arctic Oscillation (AO) induces an Arctic basinwide oscillation with cyclonic and anticyclonic circulation anomalies (Proshutinsky and Johnson 1997; Maslowski et al. 2000). The Beaufort Gyre is shown to accumulate freshwater under anticyclonic wind forcing due to Ekman pumping and to release it when the wind is weaker or cyclonic (Proshutinsky et al. 2002). Analyzing the switch from a high North Atlantic Oscillation (NAO) state to low NAO, Brauch and Gerdes (2005) found that the subpolar cyclonic circulation becomes weaker with a reduced Atlantic Water inflow into the Arctic via the Barents Sea. On the other hand, during the cyclonic circulation regime, precipitation increases over the ocean and wind divergence leads to ice melt and accumulation of freshwater in the upper ocean (Polyakov et al. 1999).

Proshutinsky et al. (2002) argues that the accumulated freshwater leads to a difference in dynamic height between the Beaufort Gyre (higher) and the North Atlantic, which induces an increased freshwater export. On the other hand, as the Atlantic water inflow into the Arctic is described as a wind-driven barotropic response to the
AO, the simulated Arctic liquid freshwater content (FWC) anomalies were also explained by changes in the Atlantic water inflow (Häkkinen and Proshutinsky 2004). Along this line, Polyakov et al. (1999) suggested, by analyzing seasonal variations, that cyclonic regimes cause excess ice export and freshwater export through Fram Strait into the Greenland Sea and increased inflow of the Atlantic water over the Barents Sea Opening (BSO). Based on similar arguments, Dukhovskoy et al. (2004) provide a mechanism for an auto-oscillatory system that involves accumulated freshwater in the Beaufort Gyre and heat and freshwater exchange between the Arctic Ocean and the Nordic seas. From analyzing model results, Lique et al. (2009) find that the Arctic FWC changes relate to sea ice and liquid freshwater export through the passages.

Proshutinsky et al. (2009), Rabe et al. (2011), and Giles et al. (2012) analyze observations and find strong positive trends in the Beaufort Gyre. The latter two works estimate an increase in FWC in the Arctic Ocean of about 8400 and 8000 km³, respectively, for the periods between 1992–99 and 2006–08 and between 1995 and 2010. Causes of these recent changes can be as manifold as the sources of freshwater in the Arctic are.

Using a system of adjoint and forward simulations with models using various resolutions we revisit here the mechanisms contributing to the changes of the freshwater content in the Arctic Ocean and test their robustness. We restrict our focus to the liquid freshwater content (called freshwater content or FWC in the following) and the associated transports. Changes in sea ice, although integrated in the model dynamics, are not part of our analysis and are treated as a given input. The paper includes the model description in section 2, the conclusions from the analysis of the adjoint sensitivity (section 3), and a brief validation description in section 2, the conclusions from the analysis of the adjoint model. Because of the instability of tangent linear models related to chaotic dynamics of eddying models (Köhl and Willebrand 2002), the adjoint sensitivity studies are based on the 32-km resolution version. As in Hoteit et al. (2005), we still had to use larger viscosities in the adjoint model to prevent it from developing unstable modes. To this end, an additional harmonic viscosity of $10^2$ m² s⁻¹ was employed in the adjoint model. Additionally, the modules for the mixed layer parameterization and the sea ice model were excluded from the adjoint model. Liu et al. (2012) demonstrated that excluding mixing parameterization from the adjoint has a minor impact, mainly on size of the regional signal. The exclusion of the sea ice model means that the adjoint essentially describes sensitivities of a model without sea ice, which will lead to larger sensitivities to wind than for a model with sea ice.

3. Sensitivities of the freshwater export from the Arctic

As an introduction to the analysis of the liquid freshwater content and the freshwater transport variability, and in order to reveal the related key regions, we present adjoint sensitivities of the liquid freshwater export from the Arctic into the North Atlantic. For a given scalar target quantity (in this case the freshwater transport across a specific section), adjoint sensitivities represent the first-order derivative of that quantity with respect to model parameters. Within this linear framework, parameters can be determined (e.g., regions of forcing perturbations) that most efficiently change the target quantity. In a first ocean application, Marotzke et al. (1999) determined regions that influence the meridional heat transport in the North Atlantic. The advantage over
classical sensitivity studies is that with one adjoint sensitivity experiment all sensitivities can be calculated at once and no a priori hypotheses has to be formulated. Thereby, mechanisms can be identified according to the regions of occurrence of large sensitivities and to their evolution (e.g., Köhl 2005; Kauker et al. 2009; Heimbach et al. 2010; Koldunov et al. 2013).

The freshwater transport $F = f [\rho(T, S), S]$ between North Atlantic and Arctic across a certain section and averaged over a certain time depends on the strength of the volume transport and on the freshwater content of the transported water. Here, $\rho$ is the potential density, $T$ is the potential temperature, and $S$ is the salinity. Given that the transport, except for the near-surface region, can be described mainly by the thermal wind relation, these two aspects can be described by decomposing the sensitivity to salinity into its dynamic and kinematic contributions (Marotzke et al. 1999). The kinematic sensitivity is given by

$$\left( \frac{\partial F}{\partial S} \right)_{\rho} = \left( \frac{\partial F}{\partial S} \right)_{T} + \frac{\beta}{\alpha} \left( \frac{\partial F}{\partial T} \right)_{S}$$  \hspace{1cm} (1)$$

and the dynamic part is the last term on the right-hand side; here $\alpha$ and $\beta$ are the thermal and haline expansion coefficients, respectively. Since dynamic sensitivities essentially describe the effect of density anomalies on $F$, the associated patterns correspond to optimal density perturbations for changing $F$. Via the thermal wind relation, an optimal circulation can be constructed from these patterns. Kinematic sensitivities describe the effect of the part of salinity anomalies that is density compensated and has therefore no effect on the circulation but is just advected with the mean circulation. Patterns correspond to regions of water masses that are transported across the section, during the period of time in regard and where anomalies in freshwater content would have an effect on $F$.

The sensitivities of the 2005 average freshwater transport between the Arctic and the Atlantic (positive northward) with respect to model parameters over the period 2002–05 were computed. Adjoint sensitivities are often only weakly dependent on the background state, therefore choosing the mean freshwater transport from another year would lead to similar results. The transport was calculated across a model grid line covering the CAA, the Fram Strait, and the BSO (a section termed CAFSBO hereinafter) as indicated in Fig. 1a. Kinematic sensitivities are shown as a mean for the target year 2005 at 150-m depth in Fig. 1b. In the Fram Strait, positive sensitivities indicate that high salinity values north and northwest of the section enhance the poleward freshwater transport, since saltier water gets exported into the Nordic seas. On the other hand, low salinities just south of BSO and Spitsbergen enhance the freshwater content of water imported into the Arctic. Likewise, positive sensitivities are also visible in the CAA, through which water is exported into the Labrador Sea.

Over the course of the preceding 3 years (Fig. 1a), kinematic sensitivities are advected in the adjoint integration similar to passive tracers but backward in time (i.e., advected upstream against the mean flow). The negative sensitivities carried by the Norwegian Atlantic and Irminger Current are seen in the figure to reach the Greenland–Iceland–Scotland Ridge. A contribution from the Baltic Sea, advected via the Norwegian Coastal Current, is also visible. The sensitivities positive maximum moves to the north of Greenland and to the region over the North Pole. The small positive signals in the East Greenland Current and north of Scandinavia emerge in the adjoint model from downstream of the Denmark Strait and from the north Barents Sea, respectively. The latter are the places where optimal anomalies will be found just at the beginning of the target year. Since they will not be able to cross the CAFSBO section from there in the target year, there seems to be no obvious reason why these could affect the freshwater transport.

The dynamic sensitivities shown in Fig. 1c reveal the major geostrophic pathways relevant for the freshwater exchange between the Arctic and the Atlantic. Two routes become evident after investigating the spatial gradients of the sensitivities and consequently, the anomalies in geostrophic transport they imply. East of Greenland, a weakening of the Norwegian North Atlantic Current and an enhancement of the East Greenland Current lead to a net southward volume flux. West of Greenland, mainly the northward West Greenland Current is enhanced while a weakening of the southward Baffin Current seems to be less evident. Together they are leading to a net northward flux through the Davis Strait. Both contributions, east and west of Greenland, enhance anomalies of northward freshwater transport. In the Arctic, a large-scale cyclonic circulation anomaly (anomalies along the Arctic slopes in Fig. 1c) is associated with conditions favorable to export freshwater into the North Atlantic. This can be understood via the description presented by Proshutinsky and Johnson (1997): because of a high correlation between the atmospheric and oceanic circulations and the water mass structure (with cold, low-salinity surface waters and relatively warm, high-salinity deep waters) during the cyclonic atmospheric circulation, the freshwater moves toward the center of the Arctic from the shelf regions. Consequently, the export of freshwater is enhanced.

An additional pathway of export of freshwater is indicated by the strong gradient in the center of the Arctic
nearly along the line 180° and 0°W. This pathway closely fits the path of the Transpolar Drift during positive phases of the vorticity index (Mysak 2001), which closely follows the Arctic Oscillation. Although this pathway is consistent with a positive AO in 2002, for the rest of the period, the AO is close to neutral. The importance of the Transpolar Drift for the export of Arctic sea ice was recently discussed [e.g., Nghiem et al. (2007), who describe the current as a pathway for exporting ice through the Fram Strait as well as toward Baffin Bay]. These two pathways are consistent with the two paths north of Greenland deduced from Fig. 1c, which extend from the location of Transpolar Drift toward the south.

The sensitivities of the freshwater transport across the CAFSBO section to meridional and zonal wind stress shown in Fig. 2 reveal essentially the same optimal conditions for strong northward transport of freshwater: an anticyclonic wind in the Arctic, as well as around Greenland and within the Fram Strait. This is in agreement with reduced water flow toward the Fram Strait (Proshutinsky and Johnson 1997). The sensitivities in the Fram Strait have values of 100 mSv (N m⁻²) larger
than anywhere else (1 Sv = 10^6 m^3 s^-1). In the Arctic, the locations of the largest sensitivities are along the Eurasian shelf area and, with opposite sign, in the area just north of Greenland and the CAA. The sensitivities separately calculated for the freshwater transport east and west of Greenland (not shown) reveal that the signal in the Arctic relates to the transport through the CAA, while the wind stress in the Fram Strait is optimal for modifying the flux east of Greenland. The patterns are dominated by the sensitivities in the target year 2005 and sensitivities of the preceding years are much smaller.

4. Simulated salinity anomalies and freshwater content changes

Long-term time series of freshwater content changes in the Arctic are rare. However, the three great salinity anomalies in the 1970s, 1980s, and 1990s (Dickson et al. 1988; Belkin et al. 1998) were previously linked to either freshwater or sea ice pulses from the Arctic via the Fram Strait, local forcing, and outflow via the CAA, respectively (Belkin et al. 1998; Belkin 2004). In this respect, decadal changes of upper ocean salinity within the subpolar Atlantic have been studied from station data at Fylla Bank (64°N, 54°W) by several authors (e.g., Reverdin et al. 1997). We present here an updated version of the salinity time series until 2009 based on the quality-controlled and bias-corrected EN3 v2a dataset (Ingleby and Huddleston 2007) compared to salinities from the model (Fig. 3). A value of 0.5 was added to the observational data for comparison purposes. To reduce the influence from the seasonal cycle, the data were averaged as in Deser et al. (2002) over the months April–July, since data are not sufficiently available during other months.

The model matches the observations well for the salinity anomalies in the 1970s and 1980s, whereas the 1990s anomaly remains almost invisible. The overall agreement breaks down after 2003, after which the observed salinity continues to be high while the model declines. The increase in salinity after the mid-1990s coincides with the change of observations from bottle data to CTDs but may also be related to the increase of freshwater content in the Arctic Ocean, which happened over the same period.

An anomalous accumulation of freshwater in the Arctic Ocean was recently reported by Rabe et al. (2011), who describe the change in inventory from the period 1992–99 to the period of high-density data sampling during 2006–08. They found an increase of 8400 km^3 of freshwater leading regionally to changes ranging from 1 to 8 m. To show the realism of our model, we show in Fig. 4 the simulated distribution of freshwater content change for the depth above the 34 isohaline. The definition of the freshwater content is, as in Rabe et al. (2011), relative to the reference salinity S_0 = 35:

\[
FWC = \int_H^0 f_w \, dz = \int_H^0 \frac{S - S_0}{S_0} \, dz, \tag{2}
\]

with H being the depth of the 34 isohaline for the case of Fig. 4 and the bottom for all figures to follow.
The magnitude and regional distribution of the FWC anomaly match the observations fairly well, with maximum values offshore of the East Siberian Sea and a secondary smaller maximum in the Eurasian Basin. Giles et al. (2012) suggest that the trend in wind field curl drives freshwater accumulation via convergence while Kwok and Cunningham (2010) connect the 6300 km$^3$ of loss of multiyear sea ice with the local freshening of the Beaufort Gyre. However, during the transition of the AO to a positive phase, the model of Zhang et al. (2003) shows a reduction of Arctic sea ice but a decrease in freshwater storage while the sea ice and freshwater exports via a Fram Strait increase. Rabe et al. (2011) identified several reasons for the recent change. Changes in the depth of the lower halocline, forced by Ekman pumping, explain less than a quarter of the main contribution, which is the salinity contribution due to freshening of the water column caused by increased sea ice melt and by advection of increased amounts of river water. Morison et al. (2012) attributed the changes to a cyclonic shift in the ocean pathway of Eurasian runoff forced by a positive AO state. Since our simulation is forced with climatological runoff, increased fluxes from the rivers are unimportant for our simulated FWC anomalies.

5. Decadal changes of Arctic freshwater export

In the following, we want to address the main mechanisms leading to interdecadal changes of freshwater content in the Arctic over the last 50 years. The present analysis focuses on liquid freshwater only. Changes in the sea ice are represented as part of the surface flux.

Figure 5 shows the total (top to bottom) balance of the FWC in the Arctic, which is defined as the region between Bering Strait and the CAFSBO section (green line in Fig. 1a). In agreement with Polyakov et al. (2008), the FWC (not shown) was declining between 1970 and 1995 whereas since 1995 an increase is noticeable. Most
prominent are two events around 1980 and 1999 (and a smaller event centered on 1987) during which the Arctic gained freshwater (black curve). From the mid-1990s onward, the content change remains positive with values around 0.03 Sv, leading to an overall increase between the time periods 1992–99 and 2006–08 of 9360 km$^3$, consistent with the recent estimate of 8400 km$^3$ by Rabe et al. (2011). On average, the surface input of slightly more than 0.2 Sv (dark blue curve), to which about 0.07 Sv of inflow from the Pacific through Bering Strait (red curve) is added, is balanced by an equivalent of 0.27 Sv export into the North Atlantic (green curve), close to the observational estimates between 0.27 and 0.3 Sv (Serreze et al. 2006; Dickson et al. 2007). The contribution from Bering Strait is nearly constant in time.

Interannual-to-decadal FWC changes in the Arctic can, to a large extent, be represented by the variability of the exchange with the Atlantic ($r = 0.91$), while surface fluxes act against and play a role mainly on shorter and interdecadal time scales ($r = 0.29$; note the different sign of the surface flux). The total variability of the export is identical to that of the FWC and about twice the variability of the surface fluxes. In particular, the above described events of freshwater increase are well represented in the exchange with the Atlantic but hardly visible in the fluxes. It also becomes clear that the increase in FWC is mainly related to the former while the latter actually reduces the increase. We note also that the contribution from the relaxation (not shown), which necessarily leads to a damping, has nearly no variability.

From analyzing observational data for the period of freshwater loss between 1970 and 1995, Polyakov et al. (2008) also found that FWC anomalies generated from river discharge or precipitation were too small to trigger long-term FWC variations, while they suggested that freshwater export in response to winds is the key contributor and that the meteoric input acts to moderate the FWC changes. Recently, Rabe et al. (2013) demonstrated that observed freshwater transport changes are much larger than known trends in the Arctic freshwater inflow from rivers and from the Pacific.

To present the robustness of the results across different model resolutions, Fig. 6 shows the FWC change anomalies together with the exchange with the Atlantic from the 8-km (as in Fig. 5), 16-km, and 32-km resolution versions of the model (the latter corresponds to the resolution of the adjoint model). The dependency on the resolution is minor and shows up only as difference in higher-frequency variability.
6. Processes and mechanisms

a. Decomposing the freshwater transport

Since we showed that the exchange with the Atlantic is the most relevant factor for determining the FWC in the Arctic, we will in the following focus on 1) the relevance of different pathways through which water is exchanged and 2) the importance of transport changes in relation with changes in water mass properties. To this end, the freshwater transport is decomposed into the contributions from the time-mean velocity $\bar{v}$ and freshwater $f_w$ and from their deviations $v'$ and $f'_w$:

$$F = \int \int f_w v \, dz \, dx$$
$$= \int \int (f_w v' + f'_w v + f'_w v') \, dz \, dx. \quad (3)$$

Besides the constant from the product of the two mean values, the product of the two anomalies explains very little variability. Therefore in Fig. 7a only the changes due to variability in either volume transport (red curve) or freshwater (i.e., salinity; green curve) are shown together with the total (black curve). The increased Arctic export until about 1990 and the three anomalous reductions in export are related to changes in volume transport, whereas changes in salinity tend to increasingly reduce the export until about the mid-1990s, after which no further reduction is visible. The reduction can be understood as a response to the increased freshwater export and consequently reduced FWC (Fig. 5) in the Arctic.

To investigate whether the response of the salinity change (green curve in Fig. 7a) is a local feature, that contribution to the freshwater export is further decomposed into contributions from different passages. Three passages are considered: the CAA west of Greenland, the Fram Strait, and the BSO. Figure 7b shows the total export variability from changing salinity (green curve) together with the two components from the export through the Fram Strait (red and black). The results from the other passages are not shown, because there the contribution from changing salinity is small. The overall trend and much of the interannual variability of the three curves match, indicating that the majority of the transport changes related to salinity modifications take place in the Fram Strait and/or regions directly affected by the transport through the Fram Strait. Salinity changes far downstream from the Fram Strait that result from a number of different processes are of secondary relevance. A simple interpretation would be that the increase in northward volume transport within the Fram Strait causes a salinity anomaly (saltier north/fresher south of the strait) that remains rather local and affects the salinity-related transport anomalies in such a way that it near perfectly compensates for the volume-related transport anomalies. The existence of such a shortcut loop is indicated by the large negative sensitivities north of the Fram Strait in Fig. 1c. However, there is a large peak in freshwater export due to reduced salinity after about 2005. During this period the velocity-related transport anomaly is much smaller.

Since the freshwater transport is mainly governed by the volume transport, a simple idea of how the changing transports affect the freshwater export would be a changing inflow of saline Atlantic water and compensating outflow of fresh Arctic water, as suggested by Häkkinen and Proshutinsky (2004). However, the compensation
in the Fram Strait already suggested that this view is too simple. Consequently, the volume transport time series of the Atlantic inflow presented in Fig. 8 (blue curve) shows only moderate correlation ($r = 0.54$) with the freshwater export (magenta curve).

To investigate further the modes of variability and the causes of the volume transport changes, the volume transport through the CAFSBO section is calculated separately for the openings east and west of Greenland (Fig. 8). West of Greenland the passages are further split into the Nares Strait (red curve) and all other smaller passages (black curve). East of Greenland the passages are the Fram Strait (green curve) and the BSO (cyan curve). The time-mean transports from the model for the period 1990–2005 compare well with the estimates summarized by Beszczynska-Möller et al. (2011) (in Sv; second value from the model): BSO: 2.0, 2.8; Fram Strait: 1.7–2.0, 1.6; Nares Strait: 0.7–0.8, 1.35; Davis Strait: 2.3–2.6, 2.2. The western passages show nearly the same variability with high correlation to the freshwater transport ($r = 0.93$). Because the total transport across all passages is close to the Bering Strait transport, and therefore almost constant, the variability of total transport east of Greenland is just opposite to that of the western passages. The correlation between the freshwater transport and the Fram Strait transport is $r = -0.82$, whereas it is reduced and even nonexistent for the BSO ($r = 0.05$). The freshwater transport is thus governed by the strength of the circulation around Greenland.

b. Godfrey’s island rule

Joyce and Proshutinsky (2007) have successfully applied Godfrey’s (1989) “island rule” to explain the southward transport through Davis Strait and an overall cyclonic flow around Greenland, which we see here as the main driver of the variability of the Arctic FWC. Their study also implied an increased transport during positive AO. The difficulty of applying the island rule to the circulation around Greenland is dealing with the narrow passages, which require the inclusion of a frictional term. We therefore adopt here their implementation of the island rule, including a fitting parameter $RL/W$ that accounts for the friction inside the CAA channels. Here $R$ is the friction parameter, $L$ the length of the frictional path, and $W$ the channel width:

$$
(f_1 - f_2 + RL/W)\Psi_g = (f_1 - f_3 + RL/W)\Psi_b - \int_P \tau \, dl. \quad (4)
$$

The variables $\Psi_g$ and $\Psi_b$ are the transports through the passages west of Greenland and through the Bering Strait, respectively. The vector $\tau$ represents the wind stress and $f_1$, $f_2$, and $f_3$ are the latitudes of the northernmost and southernmost point of Greenland and of the Bering Strait, respectively. Joyce and Proshutinsky (2007) selected a path $P$ that circumvents the Arctic along the shelf (as indicated in Fig. 10a). However, the equation also holds for a simpler path (shown in Fig. 10b) that avoids much of the shelf area in the Arctic. As expected, the results based on both paths are nearly identical and we show only the result from the simpler path in Fig. 9. The resulting time series (black curve) shows a high correlation with the export west of Greenland ($r = 0.78$, red curve) and, using the friction term $RL/W$ as a tuning parameter, approximately the same amplitude. However, for this friction parameter, the mean value is about 1 Sv lower than the actual transport in the model. As expected from the result of Joyce and Proshutinsky (2007), the AO index shows a high correlation to the island rule estimate ($r = 0.80$) and to the freshwater transport ($r = 0.73$), confirming the close relation between the state of the atmospheric circulation and the change of the FWC, as suggested by Proshutinsky and Johnson (1997).
Although the island rule result clearly suggests that the wind stress is the main driver of the variability of the freshwater content, the result is still somewhat unexpected since the alternative path demonstrates that the wind stress in the Arctic seems to be rather unimportant, in contrast to what is suggested by the sensitivities shown in Fig. 2. The sensitivities point only to possible causes and, without a matching variability in the

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**Fig. 8.** Volume transports (positive northward) through various passages connecting the Arctic and the North Atlantic together with the total freshwater flux ($\times 10$; magenta). Spitsbergen is the transport of North Atlantic water defined as water with temperatures greater than $3^\circ$C.

**Fig. 9.** Volume transports (positive northward) through the passages west of Greenland together with the total freshwater flux ($\times 10$) and the estimate from using Godfrey’s island rule with the friction parameter $RL/W = 5 \times 10^{-3}$ s$^{-1}$ (see text). The AO index was retrieved from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center.
forcing, highly sensitive regions may remain unimportant. Moreover, we have to recall that the exclusion of the sea ice model from the adjoint renders the sensitivities to wind stress too large. Because of the sea ice cover in the Arctic, the wind stress variability is about a factor 2–3 smaller there than in the Nordic seas or the Fram Strait.

c. Role of the sea level in the Arctic

Correlations to forcing fields are often used to identify regions important for driving variability. The correlations between the freshwater transport and the zonal and meridional wind stress shown in Fig. 10 (note that southward transport is defined negative, so a larger export implies larger FWC in areas with negative correlation) reveal high correlation in the Arctic as well as in the subpolar North Atlantic, suggesting the importance of Arctic wind stress for the exchange of freshwater. However, as the pattern is almost identical to the loading pattern of the AO index, it is unclear 1) via what mechanism Arctic wind stress affects the transports or 2) if the result is just a consequence of the large-scale atmospheric mode of variability.

Although the results from the island rule suggest little relevance of the Arctic wind stress, other mechanisms, such as those proposed by Proshutinsky et al. (2002), may, because of the large scale of the wind patterns, conjointly drive export variability. Proshutinsky et al. (2002) proposed that the accumulation of freshwater leads (with some time lag) to an increase in the gradient of dynamic height between the Beaufort Gyre and the Atlantic enhancing the outflow of freshwater and ice from the Arctic. This mechanism is supported by Jahn et al. (2010a), who showed a 1-yr and 6-yr lag between freshwater export and the atmospheric circulation, attributing the transport changes to sea level changes upstream of the CAA and Fram Strait.

To test whether this mechanism plays a role in our simulations, we calculate the correlation of the freshwater transport to sea level (Fig. 11a). Consistent with Proshutinsky et al. (2002), the FWC shows very high correlation to sea level (r > 0.8; not shown) in most of the Arctic except in the central Arctic near the Lomonosov Ridge, where temperature variations may become more important (Dmitrenko et al. 2008). Since freshwater transport is positive northward, large export is associated with low sea level (and low FWC) in most of the central Arctic including the Beaufort Gyre. On the other hand, high sea level along the periphery is seen (Fig. 11a). This distribution is consistent with the scheme of Proshutinsky and Johnson (1997, their Fig. 3), in which during cyclonic conditions the sea level is high in the periphery and low in the center. This increases the sea level difference across the passages from the Arctic to the North Atlantic and provides a mechanism for enhancing the transport. A relation to the sea level gradient has also been demonstrated from observations (Peterson et al. 2012). This mechanism is not covered by the island rule but visible in the sensitivities to wind stress (Fig. 2). On the other hand,
the positive correlation in the center of the Arctic does not support the hypothesis that the accumulation of freshwater has some role in driving the exchange; at least, it is completely masked by the pattern of the wind-driven freshwater redistribution.

The correlation in the Arctic is only part of the story, since even higher correlation exists in the Davis Strait (the east–west gradient may be just an expression of the enhanced transport) and the subpolar North Atlantic. These regions are covered by the island rule and the correlation there can be understood from the response of the circulation to the wind stress forcing. Both correlations explain also why accumulation cannot be of relevance in our simulation. If the sea level rise, through increased FWC, was the main driver of freshwater transport, then the transport and FWC should be in phase. In our simulation, however, freshwater transport and the FWC change (which for sinusoidal oscillation would be 90° out of phase with FWC) are in phase. Thus, if the freshwater transport curve matches those of the FWC changes, FWC cannot be the driver of freshwater transport. A lag cannot account for this, because a 270° phase shift is required, which does not agree with the irregular oscillations.

In our simulations, the only consequence of accumulated freshwater in the Arctic is the above suggested compensating part of the export: the freshwater transport due to salinity variations through Fram Strait. We further investigated the regions where the FWC may influence the transport variability due to salinity changes by correlating the corresponding transport time series with the FWC fields (Fig. 11b). The result can be compared with the kinematic sensitivities shown in Fig. 1b (note the different sign since sensitivities are with respect to salinity instead of freshwater perturbations). There is a relatively good agreement near Fram Strait and the BSO; these places show also the highest correlations. Further locations with smaller correlation exist in the center of the Arctic supporting the idea that accumulated freshwater enhances this part of the exchange.

7. Conclusions

Our model simulations are shown to capture well the large great salinity anomalies in the 1970s and 1980s and also reproduce the recently observed accumulation of freshwater in the Arctic during the period 1992–99 to 2006–08 (Rabe et al. 2011) in size and regional pattern.

In agreement with Proshutinsky et al. (2002), we find that the Arctic Ocean is accumulating freshwater during anticyclonic atmospheric circulation and releasing freshwater to the North Atlantic during cyclonic conditions. Compared to Rabe et al. (2011), our simulation reveals that their recently observed accumulation of freshwater cannot be attributed to changes within the Arctic. By contrast, in our model, changes of the Arctic surface fluxes (including the changes in sea ice) work against the accumulation. In agreement with Köberle and Gerdes (2007), changes in FWC are mainly
explained by changes in lateral exchanges through the passages linking the Arctic and the North Atlantic. This implies that a loss of freshwater in the Arctic should be associated with an equivalent gain in the North Atlantic. Changes in volume transport were found to be most relevant. However, at Fram Strait and consistent with Lique et al. (2009) and Jahn et al. (2010b), both changes in the velocity and in the FWC play a role. There, we find that transport changes related to FWC anomalies work against the part related to velocity changes.

Two mechanisms related to the wind stress forcing could be identified. In the Arctic, cyclonic wind stress redistributes freshwater from the center to the periphery. The associated sea level response leads to a pressure difference to the North Atlantic that drives stronger transports through the CAA. Although the pressure difference has been demonstrated as a mechanism before, we see no relation to the hypothesized accumulation of freshwater. This was also noted by Houssais and Herbaut (2011), who found little statistical connection between the SSH variability in the Beaufort Gyre and the transport through a channel in the CAA, which is controlled by the upstream SSH gradient. The Beaufort Gyre mainly plays a passive role in accumulating the freshwater rather than causing transport anomalies through an increased pressure gradient. However, indications exist that through modification of the freshwater content of the transported water, accumulation provides a negative yet small feedback.

The second mechanism is the wind-driven Sverdrup circulation, which in agreement with Joyce and Proshutinsky (2007) can be described by the island rule including friction. Modifications of the path of integration demonstrate that wind stress in the Arctic is not important for this mechanism and that the sensitivity of freshwater transport to the wind stress in the Arctic is owing to the first mechanism. The second mechanism is similar to the wind-driven modulation of the Atlantic inflow suggested by Häkkinen and Proshutinsky (2004). However, our simulation suggests that changes of wind stress forcing primarily modulate the circulation around Greenland and not around Spitsbergen as suggested by Polyakov et al. (1999), Häkkinen and Proshutinsky (2004), and Köberle and Gerdes (2007) and that a modulated inflow of Atlantic water and the export through the Fram Strait is therefore much less relevant.

In this context, the relevance of the circulation around Spitsbergen for the modulation of the freshwater content stands in contradiction to the observation-based estimates by de Steur et al. (2009) and Rabe et al. (2009). They find a constant freshwater export between 1998 and 2008 from the Arctic Ocean through the Fram Strait despite the increase in Arctic FWC. The increase in Arctic FWC is, however, consistent with the role of the circulation around Greenland for the freshwater balance, which suggests that the role of the Fram Strait for the freshwater export variability might be over rated. However, it might be a feature of our model only, since Jahn et al. (2012) found from comparing 10 different ocean–sea ice models that the contribution of the Fram strait transports to the freshwater balance is the most inconsistent contribution among the models.

Curry et al. (2011) recently estimated that freshwater fluxes through the Davis Strait nearly equal those from the Fram Strait and we see from our model results that the associated variability is the key for understanding the freshwater balance in the Arctic. Monitoring freshwater transports through the CAA is therefore a necessary component for monitoring and predicting changes of the Arctic FWC.

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REFERENCES


