Chapter 17
Simulating the Long-Term Variability of Liquid Freshwater Export from the Arctic Ocean

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17.1 Introduction

The fresh water export from the Arctic has not been measured yet. The major problem lies in the transport over the shallow East Greenland shelf that is not easily accessible for oceanographic vessels and so far has been off-limits for moored instrumentation. Even if we would be able to start measurements now, we would have no statistics to evaluate trends and natural variability of the transport. For long time series and for predictions of future changes, there is no other means than numerical models of the oceanic circulation and the water mass distribution. For past times, models can perhaps be combined with observations of different variables to yield better reconstructions of long-term variability in fresh water fluxes between the Arctic and the sub-polar North Atlantic.

The liquid fresh water export from the Arctic Ocean through the passages of the Canadian Archipelago, Fram Strait and the Barents Sea is constrained by the fresh water fluxes entering the Arctic Ocean and by changes in the fresh water contents in the Arctic halocline. If one knew the fluxes entering the Arctic Ocean and the changes in the salinity very precisely, the export rates could be determined as a residual. (We use this technique to derive export rates in a coupled climate model in Section 17.5.) Different components of the Arctic Ocean fresh water balance exhibit very different long-term variability. Serreze et al. (2006) provide a recent compilation of estimates of the interannual variability of river discharge, net precipitation, Bering Strait inflow, and Fram Strait ice flux. Fram Strait ice transport shows by far the largest standard deviation of these fresh water fluxes. River run-off into the Arctic Ocean has increased over the last 50 years by approximately 5% (Peterson et al. 2002). Interannual variability as shown by Peterson et al. is of similar or smaller magnitude. Compared to fluctuations in other components of the fresh water balance, this is a small variability. The variability in river discharge is also indicative of the variability of the total atmospheric moisture convergence at

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high northern latitudes and thus the net precipitation over the Arctic Ocean. The fresh water flux from the Pacific into the Arctic Ocean fluctuates seasonally, but interannually fluctuations are small around a mean of 2,500 ± 300 km^3/year[1] (relative to a reference salinity of 34.8; Woodgate et al. 2005). This means that over recent decades, the fresh water balance of the Arctic was determined by lateral exchanges with lower latitudes, temporal changes in the fresh water content, and rather constant sources of fresh water.

The size of the Arctic Ocean liquid fresh water reservoir of 74,000 km^3 (Serreze et al. 2006, using a reference salinity of 34.8) and an average export rate of 3,000–6,000 km^3/year gives an average renewal time for the reservoir of 10–20 years. This implies that the Arctic Ocean system is capable of sustaining substantial anomalies in the fresh water export rate over decades (e.g. Proshutinsky et al. 2002). In model simulations, occasional high liquid fresh water export events exceed the long-term mean by at least 1,000 km^3/year (Karcher et al. 2005) and last for several years. Köberle and Gerdes (2007) found that the simulated liquid fresh water export from the Arctic between 1970 and 1995 was 500 km^3/year larger than on average over the second half of the 20th century. This long-term enhanced export rate corresponds to a decline of the Arctic liquid fresh water reservoir by 12,500 km^3 between 1970 and 1995.

This review will commence with an assessment of the uncertainties and their causes in current ocean–sea ice models for the Arctic Ocean. It is important to be aware of the consequences of uncertainties in the forcing fields (like precipitation and run-off), their implementation in different models, and their impact on the simulation of liquid fresh water export rates from the Arctic. The specific effects associated with numerical resolution in the Arctic Ocean and the passages connecting it with the global ocean will be discussed. The following section describes the variability in liquid fresh water export over the last five to six decades as it is simulated in models of the NAOSIM (North Atlantic/Arctic Ocean Sea Ice Models) hierarchy. This includes two outstanding events that are responsible for much of the long-term changes in the Arctic Ocean liquid fresh water reservoir. Possible downstream effects of such fresh water export events and the possible development of liquid fresh water export from the Arctic Ocean during the 21st century are the topics of Sections 17.4 and 17.5, respectively. In the last section, we summarize the current state of the art and try to identify the most important problems affecting the modeling of fresh water exports from the Arctic Ocean.

17.2 Uncertainties in Model Estimates of Arctic Liquid Fresh Water Export

Although numerical models are our primary if not only means to assess the long-term variability in the liquid fresh water export from the Arctic, there are relatively few model results documented in the literature. The reasons for this shortage are

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[1] Fresh water fluxes are given in km^3 $year^{-1}$ or Sv with 1 Sv = 10^6 m^3 s^{-1} = 31,536 km^3 $year^{-1}$.

fourfold. There is a lack of data to validate this aspect of the models, thus a natural way to communicate model results is blocked. Secondly, one of the major pathways for fresh water from the Arctic to lower latitudes, the Canadian Archipelago, needs extremely high horizontal and vertical resolution to be properly represented. Thirdly, ocean–sea ice as a climate sub-system must be provided with proper boundary conditions. This is a general problem that affects all ocean–sea ice simulations and which can have severe consequences for the stability of the large-scale oceanic circulation in a model. Finally, surface fresh water fluxes and their variability over decades are poorly known over the Arctic.

In the following, we shall briefly address these four items that remain an obstacle for model based statements about Arctic fresh water export rates. Figure 17.1 compares observational and model based fresh water transports in the East Greenland Current at Fram Strait. Hansen et al. (2006) analysed data from the moorings F11–F14 which are located in the core of the EGC over and east of the shelf break at 79° N. Their calculated average fresh water transport from July 1997 to July 2005 is southward with around 1,000 km^3/year. NAOSIM (North Atlantic/Arctic Ocean–Sea Ice Models) freshwater transport results (Karcher et al. 2003, 2005) for the same period and sub-sampled for the area that is covered by the moorings are very similar except that the model does not capture all the high frequency variability that is in the observed data. However, the total southward fresh water transport in the model is almost twice as high as the observational estimate. The model transport is enhanced by contributions from outside the area covered by the mooring array, namely from southward flow of very fresh water over the shallow East Greenland shelf and still relatively fresh water east of the core of the EGC. Hydrographic sections and geostrophic calculations indicate that the fresh water transports east of the 0° E should be very small and that the model overestimates the fresh water transport there. However, there are no observations over the East Greenland shelf to validate the model. Transports over the shallow shelf can be substantial according to the model. This notion is reinforced by hydrographic and $\delta^{18}O$ measurements by Meredith et al. (2001) who found a large volume of meteoric water on the East Greenland shelf.

Holfort and Meincke (2005) report continuous measurements of salinity and velocity at 74° N on the East Greenland shelf. They describe the uncertainties involved in estimating fresh water transports from these measurements. Among other factors, uncertainties are due to the incomplete coverage of the shelf (the two moorings are just 8 km apart with a bottom mounted ADCP between them) and the extrapolation of the measured salinity profile to the surface. For the Arctic Ocean liquid fresh water balance a further uncertainty lies in the unknown amount of sea ice that melted between Fram Strait and 74° N. A strong seasonal cycle in the salinity time series from the uppermost instrument (at 20 m depth) indicates a strong influence of sea ice melt at and upstream of the mooring site. Overall, we have to state that observationally based estimates of liquid fresh water transport in the EGC are not suited to validate model results at present.

Simulated liquid fresh water transports through the second large export pathway, the Canadian Archipelago, differ substantially from model to model (Dickson et al.

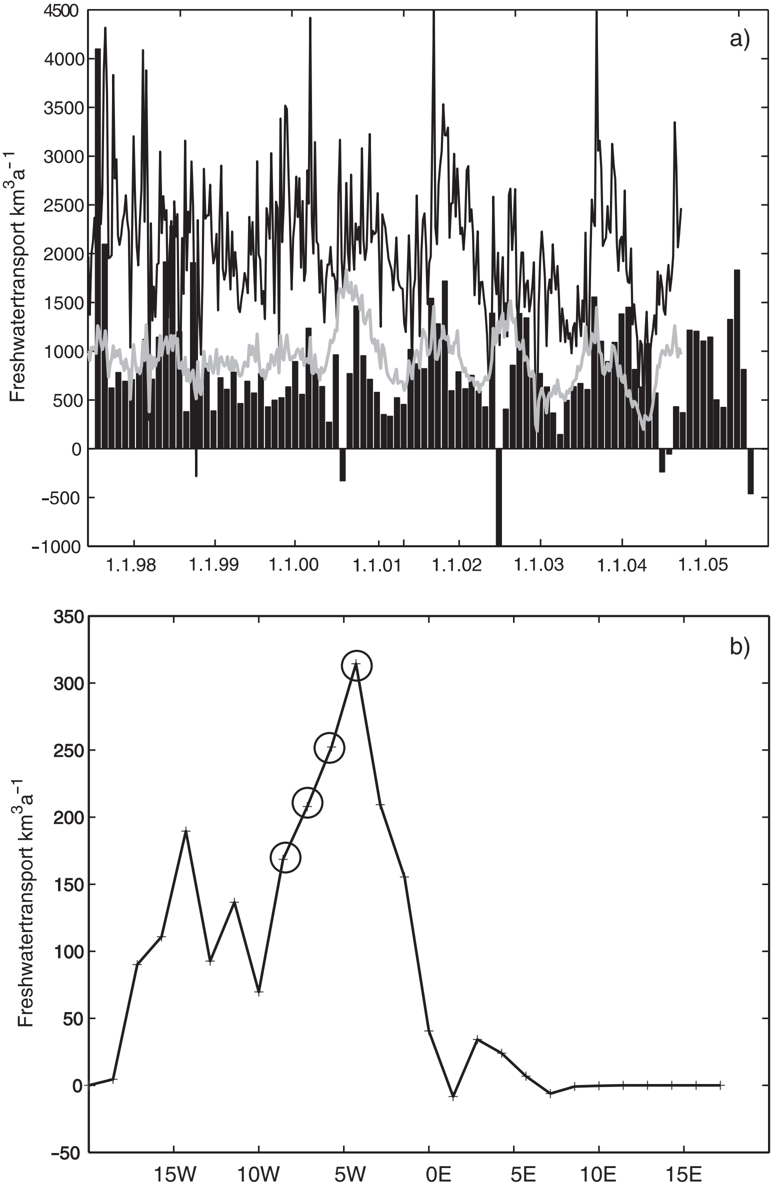

Fig. 17.1 (top) Comparison of observed and modeled (NAOSIM) freshwater fluxes through Fram Strait. Black bars: Monthly average of the observed fresh water flux in the EGC at 79° N. Thick gray line: Modelled fresh water flux for the same section as covered by the moorings. Thin black line: Modelled total fresh water flux, including the Greenland shelf region. (bottom) Average (1997–2005) modelled freshwater flux across Fram Strait in km^3 a^{-1} per grid box. The circles indicate the position of moorings F11–F14 across the East Greenland Current. All fluxes are calculated using a reference salinity of 35.0. (Observed data courtesy of E. Hansen and J. Holfort, personal communication, 2007)

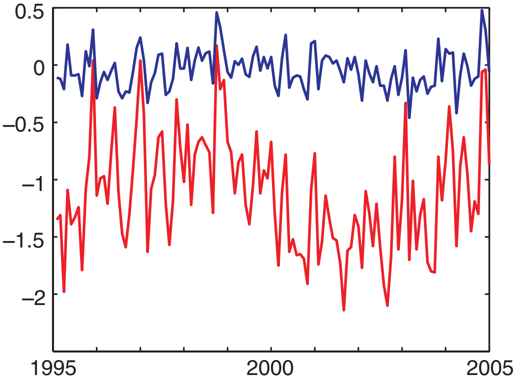

Fig. 17.2 Time series of net volume transport through Davis Strait in the 1/4° resolution version (blue) and in the 1/12° resolution version of NAOSIM (Fieg et al., manuscript in preparation). Northward transports are positive; axis labels are in Sv

2007). Considering the narrow channels that connect the Arctic Ocean with Baffin Bay, model resolution is an obvious candidate for the differences. Figure 17.2 shows volume transport time series of net volume transport through Davis Strait (which is identical to that through the Canadian Archipelago) in two versions of NAOSIM. In the lower resolution version (1/4° resolution in a rotated spherical grid) the volume transport almost vanishes whereas the higher resolution version (1/12°) has a more realistic southward transport of around 1 Sv. Results from the even lower resolution version of NAOSIM with 1° resolution suggest, however, that an exaggerated Channel width may at least help in getting a realistic net outflow of water though the Archipelago (Köberle and Gerdes 2007).

The resolution dependent representation of the Canadian Archipelago topography is a critical issue in modelling the Arctic freshwater balance. This is aggravated by the possible resolution dependence of the fresh water export distribution between the Archipelago and Fram Strait.

The magnitude of the liquid fresh water flux through the Canadian Archipelago is around 0.1 Sv or approximately 3,000 km^3/year in the high-resolution NAOSIM version. This is of the same order of magnitude as the liquid Fram Strait export and about twice as large as the estimate of Aagard and Carmack (1989). Newer observational estimates put the total liquid fresh water transport through the Canadian Archipelago at around 3,000 km^3/year (Prinsenberg and Hamilton 2004, 2005). These estimates rely on 3 years of mooring data in Lancaster Sound and assumptions about the additional flow through other channels, especially Nares Strait. The transport through the Canadian Archipelago is not solely determined by resolution. The passages in the model have to be well resolved. This might be achieved in coarse resolution models by overly wide channels through the Canadian Arctic. In a 1°-resolution model, Prange and Gerdes (2006) find an average southward fresh water transport of almost 1,400 km^3/year while Köberle and Gerdes (2007) simulate a transport of more than 2,200 km^3/year with different surface forcing and a somewhat different land–sea configuration. Another important factor is the representation of flow through Bering Strait. In a simple two-dimensional model, Proshutinsky et al. (2007) show that inflow through Bering Strait sets up a surface elevation pattern with highest amplitudes along the North American coast and indicating strong flows through the Canadian Archipelago and Fram Strait. Simulations with a comprehensive model (Karcher and Oberhuber 2002) that includes an artificial tracer for Pacific Water confirm this direct path from Bering Strait to the Canadian Archipelago. All these relatively coarse resolution models have a prescribed volume influx at Bering Strait while the higher resolution NAOSIM models have a closed boundary where only hydrographic properties are imposed.

Many Arctic Ocean models employ ‘virtual salt fluxes’ instead of fresh water fluxes to represent precipitation, melt water, and continental run-off. This is imposed by a rigid-lid condition that leads to volume conservation and cannot accommodate volume fluxes across the surface. In this case, a choice of reference salinity is necessary to convert fresh water fluxes into salt fluxes. Usually, a constant value or the local surface salinity is used. A constant value S_{ref} with which the surface fresh water flux becomes $F^S = (-P + E - R)S_{ref}$, allows tracer conservation when the total surface fresh water fluxes (including evaporation) sum up to zero over the model surface. However, locally very large errors are possible. This includes the possible occurrence of negative salinities near strong fresh water sources like the Siberian river mouths during summer. Local surface salinity SSS, $F^S = (-P + E - R)SSS$, avoids these errors but involves a spatially variable weighting of the fresh water fluxes which implies a deviation from the originally specified surface fresh water fluxes. Prange and Gerdes (2006) discuss these choices and their consequences for the Arctic Ocean fresh water balance. Depending on the chosen surface boundary condition, Fram Strait liquid fresh water transports differ by up to 1,000 km^3/year. In the case of prescribed volume fluxes through the surface, the Arctic Ocean is becoming saltier while in case of ‘virtual salt fluxes’ with the local SSS for conversion from fresh water fluxes, the Arctic Ocean is getting fresher in Prange and Gerdes’ calculation.

In equilibrium, the exchanges of volume and salt between the subpolar North Atlantic and the Arctic Ocean are strongly constrained by the mass and salt balances of the Arctic Ocean. On short time scales, inflow and outflow salinities do not change substantially and an increase in the run-off, precipitation minus evaporation, or Bering Strait inflow will result in increasing transports of both the Atlantic inflow and the outflow of Polar Water. Besides other processes, this exchange will eventually lead to a new equilibrium. Important questions are how long the adjustment processes will last (determined by the size of the involved fresh water reservoirs and the magnitude of the flux anomaly) and what changes in fresh water content in the Arctic Ocean will develop during the transition phase. Over decadal or longer time scales, the outflow with the EGC can be described by a simple formula derived from a 1.5-layer model of the Polar Water flow (Köberle and Gerdes 2007). The volume transport is proportional to the square of the upstream thickness of the Polar Water layer. An adjustment of the lateral fluxes thus likely involves changes in the thickness of the

Arctic halocline. In a model with prescribed fresh water input through precipitation, run-off and Bering Strait inflow (usually with prescribed salinity), the lateral fluxes will adjust accordingly to reach equilibrium. A bias in the prescribed fluxes will result in a bias in the lateral fluxes as well as in the Arctic hydrography. Even in a perfect model, the biases in fresh water fluxes prescribed as forcing will introduce biases in the distribution of salinity and the lateral fluxes in a model. The equilibrium response in the volume transports of in- and outflows to a change in run-off and precipitation is amplified by a factor $S_{ref}/\Delta S$ where S_{ref} is the salinity of the inflow or the outflow and ΔS is the salinity difference between inflow and outflow. Because of the large salinity contrast between inflow and outflow in the case of the Arctic, this factor is only O(10) for current conditions. However, the uncertainty in precipitation over the Arctic Ocean as expressed in the different integral numbers of fresh water flux from different data sets is almost 0.1 Sv. For the ocean area north of 65° N with the exception of the Nordic Seas and the Barents Sea south of 79° N and east of 50° E we calculate 5,600 km^3/year in the Large and Yeager (2004) dataset, 2,900 km^3/year in the ERA40 reanalysis data based Röske (2006) atlas, and 5,000 km^3/year in the satellite-based NASA GPCP V1DD data set. An ocean model confronted with a precipitation data set that is perhaps 0.1 Sv off will react either with a bias in the exchanges between the Arctic and adjacent seas of around 1 Sv or a corresponding change in the outflow salinities, i.e. a massive bias in the Arctic Ocean hydrography.

Because of the above difficulties to satisfactorily combine prescribed fresh water fluxes, lateral exchange rates, and hydrograhy in the interior Arctic, many modellers have relied on additional artificial fresh water sources. Perhaps the most frequently used device is the restoring of modelled surface salinity to climatological values. Steele et al. (2001) discuss the effect of surface salinity restoring in different Arctic Ocean models. Köberle and Gerdes (2007) discuss the spatial and temporal distribution of the restoring flux in their model under NCAR/NCEP reanalysis forcing. Biases in the model that were compensated for include a lack of fresh water originating at the Siberian rivers and following the transpolar drift into the interior Arctic Ocean. Run-off in their model is around 1,000–2,000 km^3/year less than more recent estimates (Shiklomanov et al. 2000). More important, however, was the failure of the model to disperse the fresh water away from the coasts. The insufficient communication between shallow shelf seas and the deep interior is a common problem in this class of ocean models. River water is accumulating near the river mouths, leading to unrealistically low salinities. This diminishes the efficiency of the fresh water flux that is transformed into a salt flux by multiplying with the local surface salinity. In other areas of the Arctic, the flux adjustment is typically less than 0.5 m/year in each direction. These values still are comparable to the annual mean precipitation in this area.

The flux adjustment partly compensates for a mismatch between the climatological surface salinities, based on observations mainly between 1950 and 1990, and the forcing period that extends to 2001. For instance, north of the strong fresh water input through the flux adjustment Köberle and Gerdes (2007) find an area where fresh water is extracted. This can be ascribed to the changed pathways of river water in times of the strongly positive North Atlantic Oscillation (NAO) towards the end of the 20th century (Steele and Boyd 1998) that is not well represented in the climatological surface salinities. Similarly, the climatology might not reflect completely the supposed high ice export rates from the Arctic during positive NAO phases, thus featuring relatively low surface salinities in the sea ice formation regions and relatively high salinities in the melting regions of the EGC.

Restoring introduces a negative feedback that acts against surface salinity anomalies. With time-varying atmospheric forcing the restoring term represents a strongly varying component in the Arctic Ocean fresh water balance. To avoid the feedback that damps variability, surface fresh water fluxes are prescribed. A naïve application of fresh water fluxes will lead to large biases in simulated hydrography and lateral exchanges as explained above. A flux-compensation can be introduced as described for instance in Köberle and Gerdes (2007). Basically, the restoring term is evaluated for an experiment run and averaged over a certain period. In a repetition of the run with otherwise identical forcing, this climatology of the restoring term is applied as a fixed salt flux to the surface box of the ocean model. This is an artificial fresh water flux that, however, compensates for biases in the forcing fields and deficiencies of the model. Since the flux is constant in time and there is no connection with the surface salinity, the former feedback is no longer present. This allows much larger variability in all components of the fresh water balance. As an example we show in Fig. 17.3 time series for Arctic fresh water content in a model run with restoring and a model run with flux adjustment.

While this procedure seems a feasible solution to the problem, potentially it has a grave drawback. Prescribing surface temperature through bulk formulae that tie the SST to fixed atmospheric temperatures and surface fresh water fluxes (mixed boundary conditions) is known to cause too high sensitivity in large-scale models of the oceanic circulation (Zhang et al. 1993; Rahmstorf and Willebrand 1995; Lohmann et al. 1996). Regional models are more constrained by lateral boundary conditions where large-scale transports are prescribed. In the example of Fig. 17.3, we see that the fresh water content is systematically higher in the flux-adjusted case but the value at the end of the integration is close to that of the restored case again. This indicates that no substantial shift in the circulation regime has occurred due to the change in the surface boundary conditions. We conclude that this model

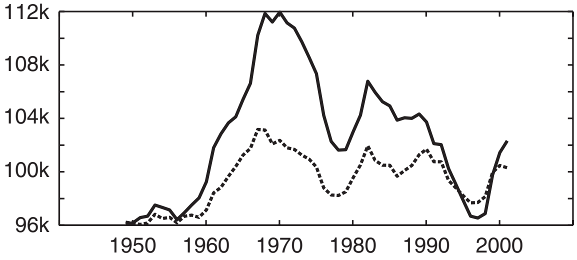

Fig. 17.3 Arctic Ocean liquid fresh water content from the NAOSIM hindcast simulation of Köberle and Gerdes (2007). The solid line shows the result with surface fresh water flux adjustment while the dashed line shows the results under restoring of surface salinity

apparently does not suffer from the tendency to unrealistically high sensitivity of the large-scale oceanic circulation under mixed boundary conditions.

17.3 Variability of Liquid Fresh Water Export Since 1950

As an example of the variability in ocean–sea ice models that are forced with realistic atmospheric forcing for the last decades we show in Fig. 17.4, the lateral fresh water fluxes from the flux-adjusted simulation of Köberle and Gerdes (2007).

Fram Strait export dominates the variability of lateral transports of liquid fresh water. The Fram Strait fresh water export in turn is determined by the fresh southward component because the northward volume transport of Atlantic water is less than one third of the East Greenland Current and the salinities of the inflow are much closer to the reference value than those of the outflow in the EGC. Fram Strait export is responsible for the extremely low total export rates in the mid-1960s and for the large export of the mid-1970s.

In this model result, the export through the Canadian Archipelago is somewhat smaller than Fram Strait export and shows less variability. However, between the mid-1980s and the mid-1990s, this component contributes significantly to the large fresh water exports during that period (Belkin et al. 1998). It is also largely responsible for overall decreasing exports after 1995. Because of the limited resolution of the model, the representation of the passage through the Canadian Archipelago is

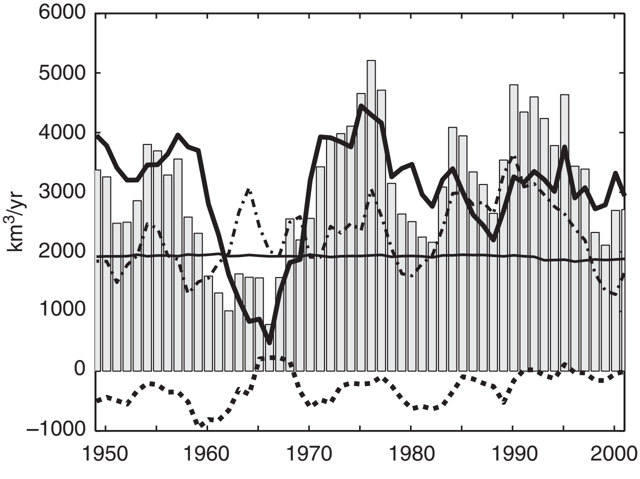

Fig. 17.4 Time series of the lateral liquid fresh water fluxes out of the Arctic Ocean. All fluxes are given in km^3/year. Bars represents the total fresh water export, the solid line is the transport through Fram Strait, the dash-dotted line is the transport through the Canadian Archipelago, the dashed line is the transport through the Barents Sea, and the thin solid line is the transport through the Bering Strait. Transports are calculated using a reference salinity of 35

rather crude. However, as noted above, the simulated mean fresh water transport through the Canadian Archipelago is within the range of recent observational estimates. Surface fluxes exhibit large interannual variability while the export rate is rather smoothly varying with a quasi-decadal time scale. On decadal to multidecadal time scales, the Arctic liquid fresh water reservoir responds mainly to changes in the export rate. The liquid fresh water export rate from the Arctic Ocean was extremely low in the 1960s and showed two periods of high values afterward. Especially the late 1970s and early 1980s were characterized by large export rates.

Häkkinen and Proshutinsky (2004) have analyzed similar hind cast simulations with the Goddard Space Flight Center (GSFC) model. There is no restoring or flux adjustment in this model. They do not show fresh water transport rates but show that liquid fresh water content changes in the Arctic Ocean can largely be explained by the oceanic exchanges with lower latitudes. As in Köberle and Gerdes (2007), their model result features accumulation of liquid fresh water in the Arctic Ocean in the early 1960s, in the early and late 1980s, and a strong decline afterwards. Both papers identify the export through Fram Strait as the most important component of the Arctic fresh water balance responsible for these fluctuations although Köberle and Gerdes point at reduced sea ice formation in the late 1960s and the early 1980s contributing to the increase in fresh water content during those periods. Relatively little ice formation in the late 1990s also contributed to the increase in fresh water content at the end of the integration period.

In both simulations, variability of Bering Strait inflow, continental run-off and precipitation are neglected. Häkkinen and Proshutinsky (2004) give a detailed justification of these omissions. The known anomalies in these forcing functions are clearly much smaller than those resulting in the model for lateral fresh water fluxes and for surface fluxes associated with fluctuations in sea ice formation.

The robust results in these and other simulations with different versions of the NAOSIM system are the increase in Arctic Ocean fresh water content during the first half of the 1960s, a dramatic reduction in fresh water content in the mid-1990s, and an overall downward trend from maximum fresh water content in the mid-1960s to a minimum in the mid-1990s. All these changes seem to be associated mostly with changes in Fram Strait liquid fresh water export.

The reduced fresh water export during the early 1960s allowed the Arctic liquid fresh water reservoir to increase, a prerequisite for the following fresh water export events and the long period of enhanced export rates to the subpolar North Atlantic. According to Köberle and Gerdes (2007), this important event was caused by low volume transports in the EGC. Averaged from mid-1963 to mid-1969 the mean southward volume transport in the EGC was only 2.4 Sv while it increased to 4 Sv for the period mid-1975 to mid-1980. The initial trigger of this volume transport anomaly in the 1960s was an anomalous sea ice export from the Barents Sea into the northward flowing Atlantic waters that determine the salinity of the West Spitzbergen Current (WSC). The fresh Polar Water in the west and the deep reaching saline Atlantic Water in the east characterizes salinity in Fram Strait at a time of normal fresh water export. In the early 1960s, on the other hand, there is little zonal salinity contrast in the upper 200 m (Fig. 17.5). Unfortunately, these salinity anomalies cannot be verified with historical hydrographic data. The published salinity time series from the Sørkapp section across the WSC near the southern tip of Svalbard begin in 1965 (Dickson et al. 1988) and thus would just have missed the event.

A strong reduction in the zonal density gradient in Fram Strait resulted in a strong reduction in the sea surface height difference between Greenland and Svalbard and a corresponding drop in the barotropic transport through the strait. The overall atmospheric situation during the minimum export event is characterized by an anomalous high SLP over most of the Arctic Ocean and the Nordic Seas. The anomalous atmospheric circulation favoured ice transport from the interior Arctic Ocean through the Barents Sea to the Norwegian Sea. Stratification in the Barents Sea was enhanced, heat losses over the Barents Sea reduced. The transport of Atlantic water into the Arctic Ocean through both pathways, Fram Strait and Barents Sea, was reduced.

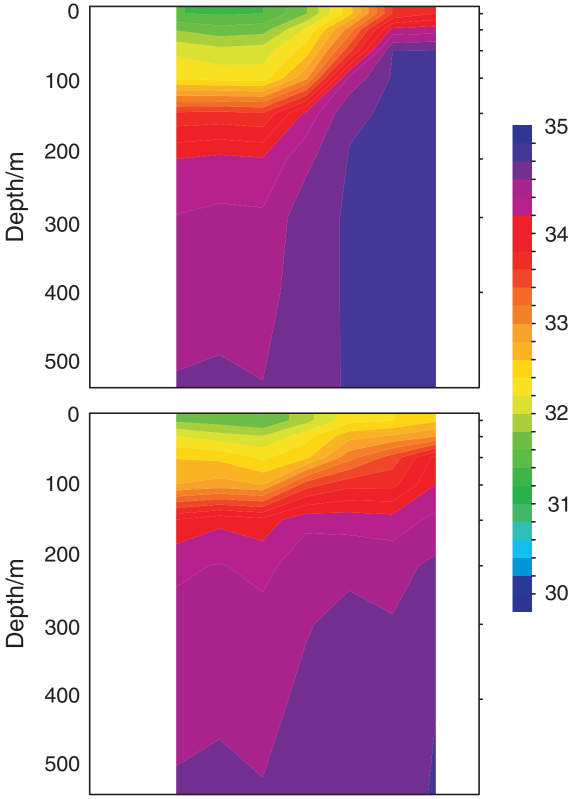

Fig. 17.5 Salinity section through Fram Strait in the NAOSIM version of Köberle and Gerdes (2007). The lower panel shows the reduced upper ocean salinity gradient between Greenland and Svalbard during the low export event of the early 1960s. The upper panel shows the more normal salinity distribution in the 1970s with a pronounced salinity contrast between Atlantic and Polar waters

Analyzing Atlantic layer warming events, Gerdes et al. (2003) had identified an inflow of sea ice into the Barents Sea from the interior Arctic Ocean during the early 1960s (Fig. 17.6). This inflow resulted in a very stable stratification and reduced heat loss from the ocean to the atmosphere. The time series of ice transport through a section from Svalbard to the northern tip of Novaja Semlja shows southwestward ice transport in excess of 1,000 km^3/year for several years in the early 1960s.

A second outstanding liquid fresh water export event happened during the mid-1990s. Karcher et al. (2005) have diagnosed this event in a NCAR/NCEP driven simulation with the 1/4° resolution NAOSIM version. This model was run with restoring of surface salinity (180 days relaxation time) towards climatology. Thus, it likely underestimates the variability of components of the Arctic Ocean fresh water balance. A long-term increasing trend in Fram Strait liquid fresh water transport culminates in an event in the mid-1990s where the transports in several years exceeded the background value by 500–1,000 km^3/year (Fig. 17.7). Most of the freshwater exported during this event continued with the East Greenland Current (EGC) to Denmark Strait.

The liquid export maximum followed a large-scale change of the hydrographic structure in the Arctic as illustrated in the sequence of vertically integrated freshwater content maps in Fig. 17.8. In the beginning of the 1990s, a large freshwater deficit relative to the 1980s extends from the eastern Eurasian Basin to the Mendeleev Ridge. This is consistent with the 'retreat of the cold halocline' (Steele and Boyd 1998), a widespread salinification of the eastern Eurasian Basin observed in the first half of the 1990s. It was attributed to a diversion of Laptev Sea-origin river water eastward along the Siberian shelf sea instead of into the interior of the Arctic Ocean. The changed river water pathway as well as increasing inflow of

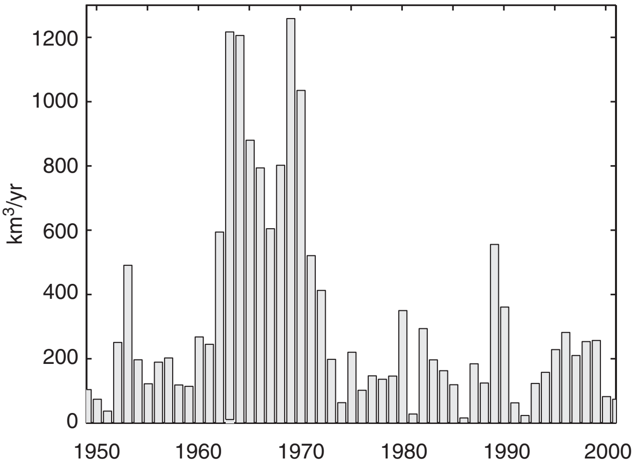

Fig. 17.6 Time series of net sea ice transport through a section between Svalbard and Novaja Semlja. Positive values indicate south-westward transport. The mean transport over the duration of the simulation is 314 km^3/year

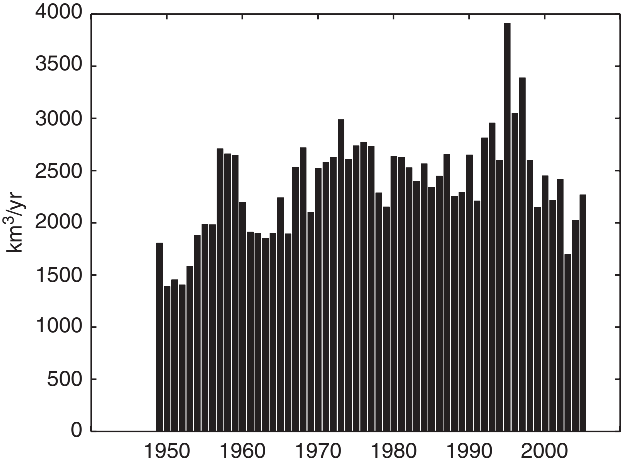

Fig. 17.7 Time series of annual mean liquid fresh water transport through Fram Strait after Karcher et al. (2005). Transports are given in km³/year. Positive values indicate southward transport anomalies

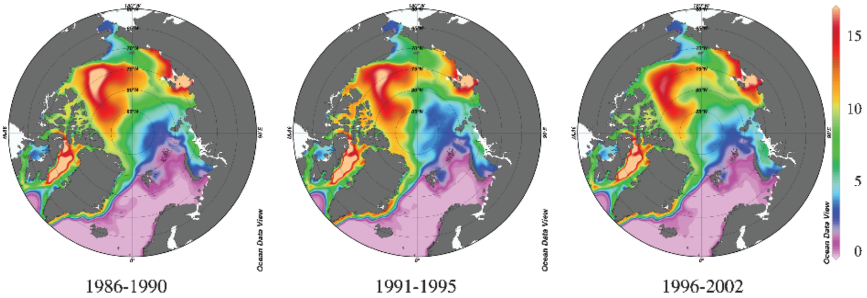

Fig. 17.8 Pentadal averages of simulated (Karcher et al. 2005) liquid fresh content during the second half of the 1980s (left), the first (middle) and the second half (right) of the 1990s. The scale is in meters of pure fresh water that is must be added to a water column of salinity 34.8 to arrive at the actual salinity

Atlantic Water into the Arctic (Karcher et al. 2003) was due to exceptionally large positive index state of the North Atlantic Oscillation until the mid-1990s. In conjunction with the more cyclonic wind stress, this led to an eastward shift of the Atlantic Water boundary in the lower halocline beyond the Lomonosov Ridge towards the Canadian Basin (McLaughlin et al. 2002). The fresh water previously residing in the central Canada Basin and the Beaufort Sea was pushed towards Fram Strait. The thicker layer of Polar Water in Fram Strait geostrophically forced a larger outflow of fresh water into the EGC.

After the export event, the fresh water distribution in the Arctic returned to its more normal state (Fig. 17.8). Downstream, the freshwater export event of the mid-1990s was characterized by a freshening that occurred over a larger depth interval than the GSA signal that was more confined to shallower levels. The signature that has been verified by measured salinity time series in Denmark Strait and is thought to relate to the origin of the low salinity in the liquid fresh water export from the Arctic rather than the export of ice and subsequent melt (Karcher et al. 2005).

To help evaluate model results, it is instructive to compare the liquid fresh water export time series through Fram Strait in the low resolution (Fig. 17.4) and medium resolution (Fig. 17.7) versions of NAOSIM. First inspection reveals that the reduced export of the early 1960s is much less pronounced in the medium resolution model. On the other hand, that model produces a far larger Fram Strait export around 1995 than the low resolution model. Do these differences imply that the model results are arbitrary and that model specifics have a larger influence on the outcome than the atmospheric forcing? Largest differences are due to the negative feedback for salinity anomalies affected by the surface restoring term. Another source of differences are different spin-up histories that produce different initial conditions and that are felt for 10–20 years, corresponding to the renewal time of the Arctic liquid fresh water reservoir.

When we compare results with surface salinity restoring in both model versions and similar spin-up procedures (Fig. 17.9), we find high export rates in the 1970s and in the mid-1990s in both cases. The minimum export in the early 1960s is now somewhat hidden in an adjustment period from very low exports at the end of the spin-up to the higher exports in the 1970s. Overall, the results are quite similar considering the different resolutions. Differences between the models in the relative magnitude of the export in the 1970s and 1990s are partly due to the trend in the fresh water transport through the Canadian Archipelago in the low-resolution version. Here, the flow through the Canadian Archipelago carries an increasing amount of the total

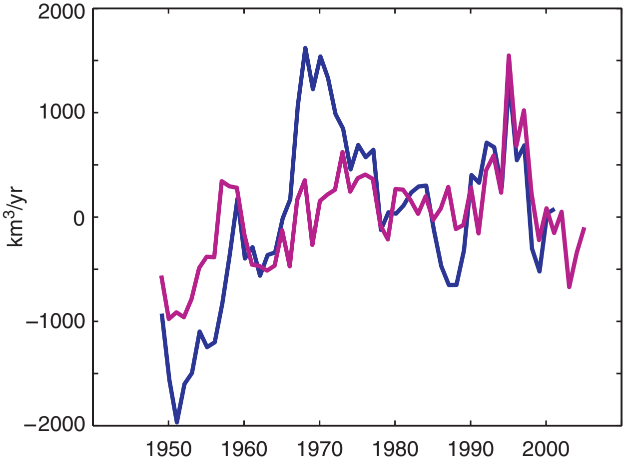

Fig. 17.9 Net liquid fresh water transport anomalies in Fram Strait for the low-resolution version (blue) and the medium-resolution (magenta) version of NAOSIM. Both models use restoring to climatological surface salinities (in contrast to the low-resolution results shown earlier) and are initialised with climatological hydrography

fresh water export from the Arctic Ocean while the medium resolution version has an unrealistically small transport. The export through Fram Strait is thus higher in the low-resolution version during the 1970s but lower during the 1990s.

This comparison again highlights some of the difficulties that still exist in hindcast simulations of the Arctic Ocean: Spin-up, resolution, and treatment of surface fresh water fluxes and run-off. We believe that a flux adjustment as in Köberle and Gerdes (2007) is a viable way to perform hindcasts in regional models. It is obvious that the flux adjustment is something to be documented and interpreted. The possible nonlinear instability of this kind of boundary condition has to be checked. Resolution to resolve the transports through the Canadian Archipelago is achievable now or in the near future. Eddy resolving resolution is certainly in reach for regional models of the Arctic and the sub-polar North Atlantic. Ideally, a model spin-up would be carried out using atmospheric forcing for a long time before the period of interest begins. Given the strong multi-decadal variability, the period of interest is usually as long as consistent and area-wide forcing data, namely the reanalysis data, exist. Kauker et al. (2007) have constructed atmospheric forcing data for the whole 20th century that could be used to spin-up models that are used to investigate the last decades of the century.

17.4 Downstream Effects of Fresh Water Export Events

Increasing fresh water export and large export events from the Arctic Ocean to the subpolar seas are potentially important processes for the deep water formation in the northern North Atlantic. Both major pathways, Fram Strait and the Canadian Archipelago, have been identified as sources for observed large-scale freshenings in the Nordic Seas and the subpolar North Atlantic (Belkin et al. 1998).

There is wide agreement that the GSA of the 1970s was triggered by release of large amounts of sea ice from the Arctic through Fram Strait and to some degree from the Barents Sea. Numerical simulations confirm this picture (Häkkinen 1993; Haak et al. 2003; Köberle and Gerdes 2003). For liquid fresh water export events, the relationship with deep water formation is less clear. Gerdes et al. (2005) show that the deep convection in the Labrador Sea occurred during phases of strongly positive NAO. The only exception in their 50 years hindcast was in the early 1980s when a delay of convection compared to the NAO index (their Fig. 2) was caused by relatively fresh water reaching the convection site of the interior Labrador Sea from the boundary. Gerdes et al. also show (their Fig. 7) salinity variability in the East and West Greenland Currents compared with the interior of the Labrador Sea. The time series of the EGC and WGC are well correlated, indicating propagation of salinity anomalies around the southern tip of Greenland. However, the boundary current time series are uncorrelated with the signals in the interior Labrador Sea. It appears that only certain freshening events in the boundary currents are filtered out and reach the interior Labrador Sea. A similar diagnostic is shown in Fig. 17.10 for the higher resolution version of the NAOSIM model (Fieg et al. manuscript in preparation).

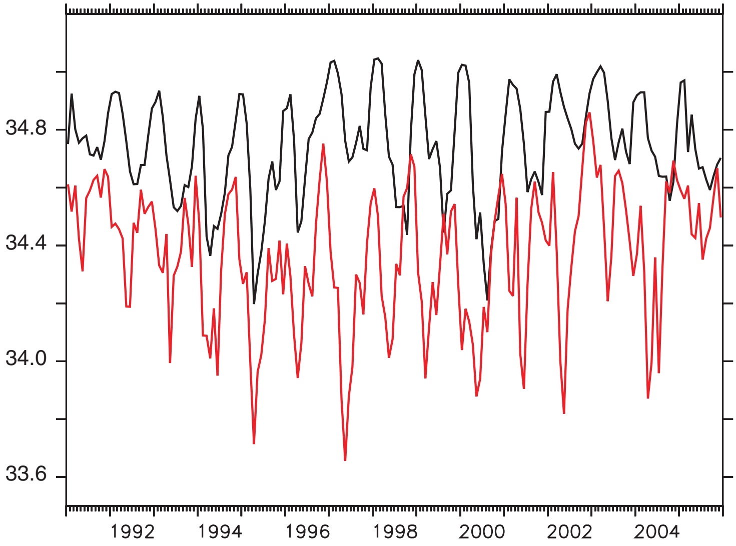

Fig. 17.10 Salinity time series from the 1⁄12° resolution NAOSIM model (red: West Greenland Current; black: interior Labrador Sea). Note that the model was initialised in 1990 from results of an integration with the corresponding ¼° model

The interannual variability in the interior of the Labrador Sea is much reduced compared to the variability in the boundary current. Thus, we see the decoupling of the interior Labrador Sea from the WGC even in a model that resolves local eddies very well.

Apparently, not every fresh water export event will affect convection and deep water production in the Labrador Sea. In model results, the same is true for the Greenland Sea. The circumstances under which a freshening in the EGC or WGC will affect the adjacent deep basins are not well understood. Sensitivity experiments with a regional eddy-permitting model indicate that fresh water exports that propagate through Davis Strait are not likely to impact Labrador Sea convection directly. Myers (2005) found that enhancing the freshwater export through Davis Strait had little effect on the fresh water content of the Labrador Sea interior and on Labrador Sea Water formation. Similar conclusions were drawn by Komuro and Hasumi (2005) who compare model simulations with and without an open passage connecting the Arctic Ocean and Baffin Bay. Only salinity anomalies moving through Fram Strait directly affect deep water formation while anomalies through the Canadian Archipelago are carried with the rather tight and topographically constrained Labrador Current along the periphery of the Labrador Sea.

17.5 Possible Future Developments

As the hydrologic cycle increases because of global warming, we expect the Arctic fresh water balance and especially the fluxes to lower latitudes to change. Scenario calculations for the development during the 21st century are our best estimate how these changes will evolve – despite all inadequacies still present in these calculations. Results submitted for the fourth assessment report of the IPCC are available from a number of climate research centers. Here, we cannot produce a comprehensive analysis of all these results and must confine ourselves to examine just one example. Figure 17.11 shows results from the A1B scenario calculation with the UK Met Office model HadCM3. The total surface fluxes (including run-off and exchanges with sea ice) and monthly salinity fields are publicly available on the PCMDI (Program for Climate Model Diagnosis and Intercomparison) server (http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php). From this information, we calculated the temporal change of fresh water content in the Arctic and the lateral transports across the boundaries of the Arctic Ocean.

The surface fluxes increase by around 30% over the 21st century. Partly, this is due to sea ice effects. The ice volume is decreasing, as is the difference in ice volume between winter and the preceding summer. This indicates that formation and export of sea ice decrease over the 21st century, which implies that sea ice contributes a positive trend on the surface fresh water fluxes. From the information available to us, we are not able to further distinguish between sea ice exchanges and meteoric fresh water. Precipitation over the Arctic Ocean increases from around 5,500 km^3/year to around 7,500 km^3/year in this scenario calculation.

The lateral exchanges shown in Fig. 17.11 are very variable and determine the higher frequency variability in liquid Arctic Ocean fresh water content. There are a few episodes of very low export rates, comparable to the early 1960s event in the Köberle and Gerdes (2007) hindcast for the second half of the 20th century. These episodes are associated with pronounced increases in Arctic Ocean fresh water

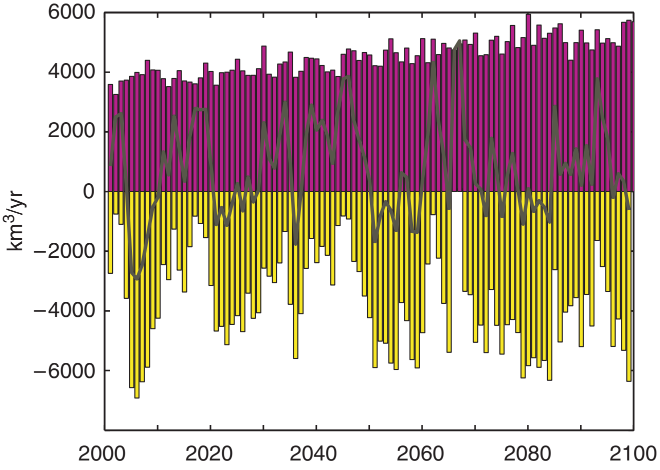

Fig. 17.11 Components of the Arctic Ocean fresh water balance in the A1B scenario calculation for the 21st century with the UK Met Office model HadCM3. Red bars indicate annual surface fresh water fluxes including continental run-off and exchanges with the sea ice. Yellow bars represent the sum of all lateral net liquid fresh water transports to lower latitudes. The solid black line is the rate of change of the Arctic Ocean liquid fresh water content (calculated with a reference salinity of 34.8)

content. Overall, however, we see little change in the liquid fresh water export rate from the Arctic Ocean in the first half of the 21st century. The fresh water content increases over this period. Only in the last decades of the 21st century do the exports gain in strength and counterbalance the increase in surface fluxes. The fresh water balance has gained a new equilibrium with larger fluxes of liquid fresh water through the Arctic Ocean and a thicker Arctic halocline.

For an early detection of global change effects in the northern high latitude seas, sea ice, surface fluxes, and salinity distribution are more suitable than lateral fresh water fluxes because the latter reacts slowest.

17.6 Discussion and Conclusion

Numerical models have been increasingly used with the aim to reconstruct the state of the Arctic ocean–sea ice system and its variability over recent decades. With prescribed atmospheric forcing as well as continental run-off so-called hindcast simulations have been performed. A good overview of many recent simulations can be found in a special issue of the *Journal of Geophysical Research* dedicate to the Arctic Ocean Model Intercomparison Project (AOMIP; Holloway et al. 2007). Results from these calculations can be directly compared with many observational data and estimates. The analysis and the validation of these simulations are still ongoing. Despite its undisputed importance for the high-latitude Atlantic and the large-scale oceanic circulation, the liquid fresh water transport from the Arctic Ocean is not the focus of any detailed study done in the AOMIP framework yet. This is due to problems many ocean–sea ice models have with representing the fresh water balance of the Arctic Ocean and the lack of validation data.

Here, we have presented mostly results from the NAOSIM simulations that, however, are representative for the class of models that are involved in AOMIP. The family of models provides the opportunity to investigate the influence of different model choices, especially of the horizontal and vertical resolution. Salient results of these simulations are the multidecadal variability of the fresh water export and the decreasing trend in the Arctic liquid fresh water from the mid-1960s to the mid-1990s that paralleled the decreasing ice volume (Köberle and Gerdes 2003, 2007).

The time series of fresh water transport through Fram Strait is punctuated by events that potentially have a large downstream impact. A better understanding of the triggers of these events, the frequency of the events and how these conditions will change in the future is necessary. Model simulations indicate that fresh water export events are preceded by redistribution of salt in the Arctic Ocean (Karcher et al. 2005). Should this relationship be confirmed to be robust, it would provide the opportunity to estimate Arctic liquid fresh water export events from interior Arctic hydrographic conditions. This implies predictive potential of conditions in the Arctic for the downstream basins. The temporal variability in the division of fresh water export between the Canadian Archipelago and Fram Strait is an essential process in this respect. Unfortunately, here is great uncertainty in model results and little guidance from observations.

Coupled climate models, for example the Hadley Center model HadCM3, show similar behaviour for the 21st century. We took a cursory look at the A1B scenario run where atmospheric CO_2 concentrations increase by 1% annually until doubling from pre-industrial values. For the first half of the 21st century the export rate of liquid fresh water from the Arctic remains rather constant although the fresh water content increases due to increasing precipitation and run-off. Only in the last decades of the 21st century do the exports gain in strength and counterbalance the increase in surface fluxes. The fresh water balance reaches a new equilibrium with larger fluxes of liquid fresh water through the Arctic Ocean and a thicker Arctic halocline.

Based on model results, long-term variability of liquid fresh water and sea ice export from the Arctic to the subpolar Atlantic are among the key variables for the large-scale ocean circulation. For a quantitative assessment, there are still many uncertainties. Some of the uncertainties have their origin in the numerical models, especially the treatment of surface boundary conditions and the quality of fresh water source data. This problem currently limits our ability to determine the strength of the feedbacks between the fresh water content in the interior Arctic (strongly related to its surface elevation) and the Fram Strait export or the Bering Strait inflow. How strongly will increasing future fresh water content lead to a decrease in Bering Strait inflow and an increase in fresh water export to the Atlantic?

The communication between the fresh boundary currents and the centers of deep water formation governs the large-scale impact of fresh water exported from the Arctic. What constrains these exchanges and what do we need to change in models to improve their representation? What are the most relevant processes for incorporating the fresh water into deep and intermediate water masses? What are the thresholds beyond which the downward transport of fresh water ceases?

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