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Key Points:

- Upper Arctic Ocean liquid freshwater trend 1992–2012: 600±300 km^3/yr
- Two thirds of the trend was due to changes in salinity, one third due to layer thickness
- Covariability of liquid freshwater content and Arctic Ocean Oscillation

Supporting Information:

- Readme
- Text S1

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Arctic Ocean basin liquid freshwater storage trend 1992–2012

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Abstract Freshwater in the Arctic Ocean plays an important role in the regional ocean circulation, sea ice, and global climate. From salinity observed by a variety of platforms, we are able, for the first time, to estimate a statistically reliable liquid freshwater trend from monthly gridded fields over all upper Arctic Ocean basins. From 1992 to 2012 this trend was 600 ± 300 km^3 yr^{-1}. A numerical model agrees very well with the observed freshwater changes. A decrease in salinity made up about two thirds of the freshwater trend and a thickening of the upper layer up to one third. The Arctic Ocean Oscillation index, a measure for the regional wind stress curl, correlated well with our freshwater time series. No clear relation to Arctic Oscillation or Arctic Dipole indices could be found. Following other observational studies, an increased Bering Strait freshwater import to the Arctic Ocean, a decreased Davis Strait export, and enhanced net sea ice melt could have played an important role in the freshwater trend we observed.

1. Introduction

The Arctic Ocean is an important source and pathway for freshwater: 11% of the global continental runoff flows directly into the Arctic Ocean [*Fichot et al.*, 2013]. Freshwater is added and removed by melting and forming sea ice, respectively. Additional freshwater enters the Arctic Ocean from the Pacific through the Bering Strait [*Woodgate et al.*, 2006, 2012]. This water affects the stratification [*Korhonen et al.*, 2012; *Rudels et al.*, 2004], sea ice [*MacDonald*, 2000], and the regional circulation [*McPhee et al.*, 2009; *Giles et al.*, 2012; *Morison et al.*, 2012] in the Arctic Ocean. Freshwater is also exported from the Arctic to the North Atlantic and the Nordic Seas, where it has the potential to affect deep convection [*Koenigk et al.*, 2007; *Rennermalm et al.*, 2007] and the horizontal gyre circulation [*Brauch and Gerdes*, 2005].

Liquid freshwater from the Arctic Ocean is important for the global thermohaline circulation and climate [e.g., *Häkkinen*, 1999; *Manabe and Stouffer*, 1999a, 1999b; *Haak et al.*, 2003]. However, many processes underlying the dynamics of freshwater variability are not fully understood. Even hindcasts from atmospherically forced state-of-the-art coupled general circulation models of the Arctic sea ice and ocean leave several open questions as to the pathways of liquid freshwater in the Arctic Ocean and the variability of the exports on either side of Greenland [*Jahn et al.*, 2012]. A comprehensive intercomparison analysis of models resolving eddies and the complicated topography of the passages west of Greenland is still outstanding. Therefore, it is difficult to predict the redistribution of Arctic freshwater through the 21st century using state-of-the-art climate models [*Holland et al.*, 2007].

Existing observational studies on liquid freshwater content changes in the Arctic Ocean cover either only part of the Arctic basins [*Proshutinsky et al.*, 2009; *Giles et al.*, 2012], only periods of a few years or specific seasons [*Rabe et al.*, 2011; *Morison et al.*, 2012], or they analyzed variability over a century using very sparse data [*Polyakov et al.*, 2008, 2013]. Here we present, for the first time, a time series of liquid freshwater content in the entire upper Arctic Ocean basin and a statistically reliable trend estimate for the recent two decades. In our analysis of salinity profiles during 1992–2012 we compare our observational results to output from a sea ice ocean general circulation model and to several atmospheric indices. We further identify the likely contributions to the changes in liquid freshwater by comparing to other observational analyses.

2. Methods

We analyzed salinity profiles from conductivity-temperature-depth devices on various platforms, including observations from ships and from autonomous drifting buoys. We chose profiles from all seasons during the

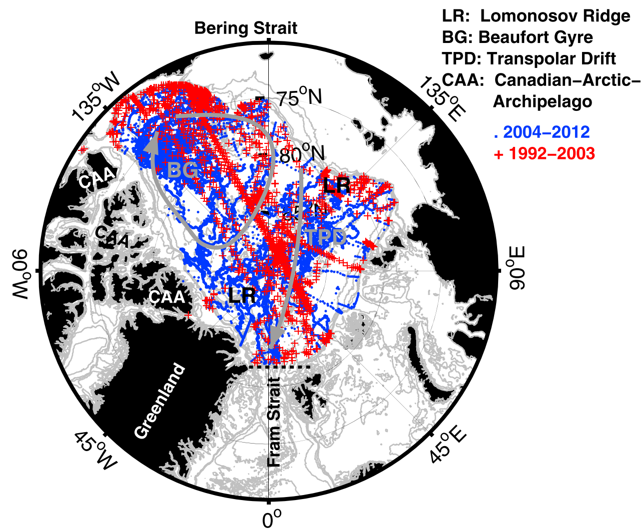

Figure 1. Map of the Arctic Ocean with names of geographic locations and ocean circulation features referred to in the text. The bathymetry is based on the International Bathymetric Chart of the Arctic Ocean [*Jakobsson et al.*, 2008] database. The region under investigation is enclosed by the thick black line, representing the 500 m isobath and a cutoff at 82°N north of the Fram Strait (dashed line). The "Eurasian Basin" is located on the European side of the Lomonosov Ridge, whereas the "Amerasian Basin" is located on the North American side. The Beaufort Gyre and the Transpolar Drift (thick, gray lines) are permanent features of the upper Arctic Ocean circulation but vary in time with respect to extent and pathway. The salinity profile locations are shown before the beginning of 2004 (red crosses) and after (blue dots).

years 1992–2012 and limited our domain to that part of the Arctic Ocean basins with a water depth greater than 500 m (Figure 1). This excludes the Arctic shelf areas, although there are indications from observations [*Polyakov et al.*, 2008] and the North Atlantic-Arctic Ocean Sea Ice Model (NAOSIM) simulation [e.g., *Karcher et al.*, 2005] that they contribute little to the multiyear variability of the total Arctic Ocean liquid freshwater content. Following *Rudels et al.* [1996] and *Rabe et al.* [2011], we calculated the liquid freshwater inventories from our observations, relative to a salinity of 35, from the surface to the 34 isohaline. These inventories were then objectively mapped in space and time using methods similar to *Böhme et al.* [2008, and references therein]. This resulted in maps of inventories on a regular horizontal grid for each month. We used the area integral of these maps (liquid freshwater content) to analyze time variability. The same processing procedure was used to map the depth of the 34 isohaline. From both quantities, we derived the depth-averaged salinity in the layer between the surface and this isohaline.

The uncertainty in the liquid freshwater content trend was calculated from a probability analysis, including the statistical error estimate of each monthly field of freshwater inventories.

Further details of the observational data sources, data processing, and uncertainty estimates are given in the supporting information. A description of the version of the NAOSIM model we use is given in *Karcher et al.* [2012].

3. Liquid Freshwater Storage Trend, Composition, and Atmospheric Forcing

Our observations show that the liquid freshwater content of the upper Arctic Ocean basins increased from the mid-1990s throughout the following decade (Figure 2a). For the 21 years of data since 1992 we derived a liquid freshwater content trend for the upper Arctic Ocean basins of about 600 $\pm$ 300 km^3 yr^{-1}, relative to a salinity of 35 (see supporting information for details of the uncertainty estimates). This equates to an increase of about 12000 km^3 from 1992 to 2012, equivalent to a 3 m layer of freshwater or a 30% increase in storage. The increase is more than the mean total annual freshwater export (liquid and solid) out of the Arctic Ocean [*Dickson et al.*, 2007]. In the following, we will look at large-scale changes reported from observations to identify possible reasons for the liquid freshwater storage increase.

The liquid freshwater changes are, in part, composed of a trend in the thickness of the layer between the surface and the 34 isohaline (Figure 2b). On average over the whole domain, this layer became about 15 m thicker in the 21 years, contributing 30% to the liquid freshwater content trend (see equation (7) in the sup-

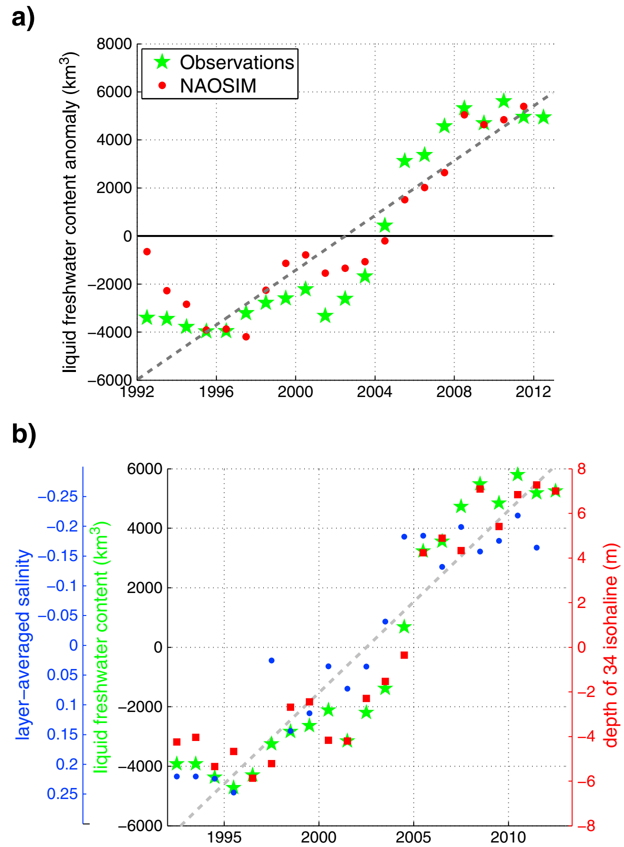

Figure 2. Time series of annual means for 1992–2012. (a) Liquid freshwater content anomalies from the time mean for the upper Arctic Ocean from observations (green pentagons) and the NAOSIM model (red dots). (b) liquid freshwater inventory from the surface to the depth of the 34 isohaline (green pentagons), depth of the 34 isohaline (red squares), and depth-averaged salinity between this isohaline and the surface (blue dots). The observation-based liquid freshwater trend over the 21 years (grey dashed line in Figures 2a and 2b) is estimated at 600 ± 300 km^3 yr^{-1}.

porting information). Much of the increase in liquid freshwater, however, consisted of a freshening of this layer throughout most of the Arctic Ocean: most regions showed a negative trend in the depth-averaged salinity in this layer, a decrease of 0.6 on average over the whole domain for the 21 years. This makes up 65% of the liquid freshwater content trend. The remaining 5% were due to a nonlinear combination of the above two contributors.

Our results suggest that changes in the thickness of the layer above the 34 isohaline had less effect on the local liquid freshwater storage trend than the freshening. Changes in Ekman pumping, driven by the surface wind stress curl, have been associated with changes in the thickness of this layer [*Proshutinsky et al.*, 2009; *Rabe et al.*, 2011]. At the same time, there would have to be horizontal Ekman transport leading to an enhanced net import of fresher waters from the Arctic rim into the basins. This, in turn, could have changed the depth-averaged salinity above the 34 isohaline. A link of the changes in both components of the freshwater inventory trends, such as a common driver, is suggested by the similarity of the time series in Figure 2b. The strength of the Arctic sea level pressure high would influence the cyclonicity and, hence, Ekman pumping and convergence in the Arctic Ocean. The time integral of the joint Ekman effects would then contribute to a change in liquid freshwater storage. Negative values of the Arctic Oscillation (AO) (see *Thompson and Wallace* [1998], for a definition) represent a strengthening of the Arctic sea level pressure high. Hence, we have compared the cumulative sum of the AO since 1992 to our liquid freshwater content time series (Figure 3; all time series are detrended and demeaned). However, there is no obvious covariability of both time series, and there is only barely significant correlation with the negative AO lagging 6 years behind the liquid freshwater content. In recent years, a dipole pattern (AD) in sea level pressure between the western and eastern Arctic has been particularly strong [e.g., *Overland and Wang*, 2010; *Overland et al.*, 2012, for 2007–2012]. This pattern would likely freshen the Transpolar Drift and lead

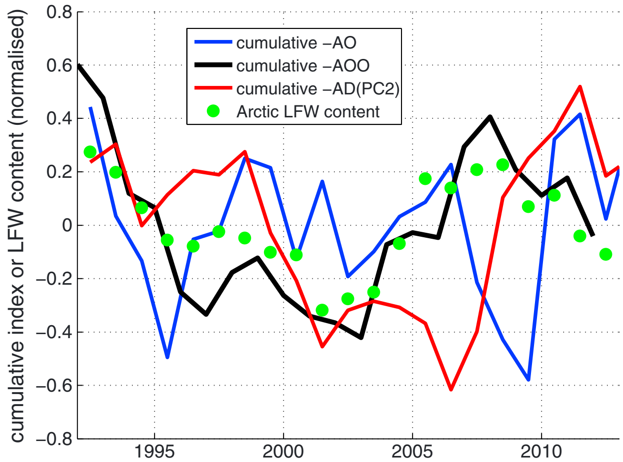

Figure 3. Cumulative sum of different atmospheric indices since 1992: Arctic Oscillation (AO; blue, solid), Arctic Ocean Oscillation (AOO; black, solid), and Arctic Dipole (AD; red, solid). The AD index was calculated as the "PC2" in *Overland and Wang* [2010] and was extended to the end of 2012 by J. Overland and M. Wang (personal communication, 2013) . The AO index was downloaded from http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml (last accessed in May 2013) and is described in *Thompson and Wallace* [1998]. The AOO index is defined in *Proshutinksy and Johnson* [1997] and was updated in *Proshutinsky et al.* [2013]. All indices were multiplied by −1. For comparison, the liquid freshwater (LFW) content anomalies from the time mean (as in Figure 1a) are shown as green dots. All time series were normalized by twice the corresponding standard deviation, detrended, and demeaned.

to enhanced freshwater exports through the Fram Strait. A comparison of the cumulative AD and our liquid freshwater time series (Figure 3) shows only barely significant correlation. However, any of these correlations near the level of significance would only explain about 20% of the variability of the liquid freshwater time series.

Proshutinksy and Johnson [1997] simulated the barotropic response of the Arctic Ocean to changes in sea level pressure patterns in the Arctic. They derived the Arctic Ocean Oscillation (AOO) [*Proshutinsky et al.*, 1999] as an index describing the cyclonicity of the Arctic Ocean circulation driven by pressure differences between the maximum or minimum in the Canada Basin and the Central Arctic. This index is primarily a measure of the strength of the Beaufort Gyre and does not necessarily describe the extent of the gyre. Nevertheless, during the time period under study, the negative cumulative AOO compares very well with changes in liquid freshwater content (Figure 3), with significant correlation at zero lag, explaining about 70% of the variability. This indicates that the liquid freshwater content changes have a stronger connection to regional (e.g., Amerasian Basin) changes in the sea level pressure fields than the larger-scale changes described by the indices for the AD and the AO, at least within the 21 years under investigation. We suggest that the response of the ocean circulation to atmospheric forcing is primarily through the AOO mode of circulation.

4. Discussion of Potential Sources

We can attempt to identify likely contributors to the liquid freshwater trend during 1992–2012 from other observational studies, although a comprehensive budget over this time period is not possible with the available observations. So far, a quasi-synoptic budget has only been calculated for a 32 days period during summer 2005 [*Tsubouchi et al.*, 2012].

The liquid freshwater storage trend we observed was concurrent with an observed decline in sea ice and enhanced net sea ice melt: there was an increase in sea ice melt in parts of the Arctic Ocean, evidenced by hydrographic [*Korhonen et al.*, 2012] and localized tracer [*Yamamoto-Kawai et al.*, 2009] observations.

The modal ice thickness in the Transpolar Drift in 2007 was observed to be only 50% of the thickness in 2001 [*Rabenstein et al.*, 2010]. *Kwok et al.* [2009] derived a 862 $km^3\ yr^{-1}$ loss of sea ice volume in autumn during 2003–2007. At the same time, there was a reduction in Fram Strait sea ice area export [*Kwok et al.*, 2009] and thickness [*Hansen et al.*, 2013]. Although we do not know the ice volume export from the Arctic during the time period under investigation, the observations of ice volume and thickness as well as the temporally and spatially limited hydrographic observations hint at a significant contribution of net ice melt to the liquid freshwater content trend we observed. The freshwater inflow from the Pacific through the Bering Strait (relative to a salinity of 34.8) was observed to have increased by about 500 to 1000 km^3/yr between the late 1990s and 2011 [*Woodgate et al.*, 2012, 2006]. This was largely due to an increase in volume transport that was mainly driven by an increase in the pressure head between the Pacific and Arctic oceans [see also *Woodgate and Aagaard*, 2005]. The freshwater content on part of the Eurasian shelves has been estimated to vary by up to 600 km^3 on time scales of 10–15 years during 1970–1995 [*Dmitrenko et al.*, 2008]. These changes would affect the input of freshwater to the Arctic Ocean accordingly, but they were an order of magnitude smaller than the trend we observed.

A significantly positive trend and interannual variability in river water input to the Arctic Ocean have been observed since the 1970s [*Overeem and Syvitski*, 2010]. However, these were an order of magnitude smaller than the changes in freshwater content we observed. Time mean net precipitation over the Arctic Ocean has been estimated at about 2000 km^3/yr^{-1} but errors are as high as 20% [*Serreze et al.*, 2006]. Observational trend estimates over the past two decades are not available.

In addition to changes in freshwater inputs, the increase in liquid freshwater storage may be associated with a decrease in exports. However, year-round observations of southward liquid freshwater transports in the Fram Strait showed no noticeable trend between 1998 and 2008 [*de Steur et al.*, 2009], neither did summer observations until 2011 [*Rabe et al.*, 2013a]. Note that the accuracy of the observed exports is of similar order as the annual changes in storage we observed. Existing analyses of a few years of data on the western side of Greenland show no trend in the liquid freshwater transports through the Nares Strait [*Rabe et al.*, 2013b].

A new analysis of the Davis Strait data from the late 1980s shows a significant reduction in southward liquid freshwater transports by about 1200 km^3yr^{-1} between 1987–1990 and 2004–2010 [*Curry et al.*, 2014]. This change was composed of both an increased freshwater outflow and a more saline Atlantic Water inflow into the Baffin Bay through Davis Strait. Taking into account the uncertainty estimates and known freshwater inputs into the bay, this change is of similar order as the liquid freshwater trend we observed.

As there is excellent agreement between the liquid freshwater storage in NAOSIM and our observations (Figure 2a), we look for possible freshwater changes prior to our observational analysis in the simulation. The model suggests a high liquid freshwater export rate through the Fram Strait until the mid-1990s and a shift to low export with no trend after 1997 [*Jahn et al.*, 2012, Figures 4a and 4b]. However, the pathways of liquid freshwater exports varied between models in the intercomparison by *Jahn et al.* [2012].

5. Long-Term Context

Our results show a clear relationship between the AOO and variability in the liquid freshwater content for 1992–2012. On the other hand, our results do not confirm the AO or the AD as drivers of this variability. However, there may be a relation of the AO or AD to liquid freshwater content on longer time scales, as suggested for the AO by *Polyakov et al.* [2008] and *Häkkinen and Proshutinsky* [2004]. From 1989 to 1996 the AOO index was negative (cyclonic) [*Proshutinsky et al.*, 2013], due to anomalously cyclonic wind stresses. At the same time, the AO and AD were in a strongly positive phase. Both the state of the AOO and AO would favor a spin-down of the Beaufort Gyre, an eastward deviation of the freshwater on the Eurasian shelves toward the Makarov and Canada basins [*Steele and Boyd*, 1998] and a shift of the Transpolar Drift pathways [e.g., *McLaughlin et al.*, 1996; *Morison et al.*, 1998]. NAOSIM supports the role of both drivers in the strong freshwater decrease in the upper Arctic Ocean until the late 1990s [*Karcher et al.*, 2005].

Subsequent to the strongly positive phase around 1990, the AO and AD indices attained a less positive state, and the AOO became dominantly anticyclonic. This was associated with an overall spin-up of the Beaufort Gyre [*Proshutinsky et al.*, 2013] that is further supported by the observed and simulated (NAOSIM) iodine-129 distribution, a tracer for Atlantic-derived water in the Arctic [*Karcher et al.*, 2012]. Those results indicate that the regional ocean surface stress curl due to wind and ice motion in the Amerasian Basin forced the Beaufort Gyre intensity via Ekman pumping. At the same time, there was a shift of both the Transpolar Drift pathways and return of the front between waters with and without Pacific Water [e.g., *Steele et al.*, 2004; *Morison et al.*, 2006]. This is supported by tracer observations between the end of the 1990s and 2005 in the Transpolar Drift [e.g., *Alkire et al.*, 2007; *Morison et al.*, 1998] and the Fram Strait [*Falck et al.*, 2005; *Dodd et al.*, 2012]. The changes in the upper Arctic ocean since the late 1990s lead to an accumulation of freshwater in the

Transpolar Drift [*Steele et al.*, 2004] and in the Canada Basin [see *Proshutinsky et al.* [2009], for 2003–2007]. Much of this freshwater is likely to have consisted of river water from the Siberian shelves, as model simulations [*Karcher et al.*, 2006] and observations [*Abrahamsen et al.*, 2009] suggest. This could have been partly driven by cyclonic motion near the Siberian shelves, as observed by *Morison et al.* [2012].

6. Concluding Remarks

There are implications of the freshwater content changes for the Arctic region: evidence of the effects of enhanced stratification due to fresher surface waters in the Canada Basin (western Arctic) have been identified in the occurrence of two subsurface temperature maxima [*Jackson et al.*, 2010]. These were either much less pronounced or not present in historical data from the 1970s [*Toole et al.*, 2010]. The regional effect of the freshening in the Eurasian Basin, with the shallowest halocline in the Arctic Ocean basins, remains to be investigated.

From a theoretical perspective, any change in liquid freshwater input to the Arctic Ocean would result in an adjustment of the fresh upper ocean layer, which, in turn, would influence the baroclinic component of the exports on either side of Greenland [*Rudels*, 2010]. Hence, if liquid freshwater input increased in the long term, the export would adjust accordingly. However, this does not consider the effects of the wind-driven circulation nor any feedback between the ocean and the atmosphere. According to NAOSIM, the liquid freshwater content is currently at a similar levels as existed in the beginning of the 1980s [*Jahn et al.*, 2012, Figures 8a and 8b]. It remains to be seen if the freshwater content of the Arctic Ocean will continue to increase in the future, and when and at which rate the fairly constant levels since 2008 will be followed by a decrease.

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References

Abrahamsen, E. P., M. P. Meredith, K. K. Falkner, S. Torres-Valdes, M. J. Leng, M. B. Alkire, S. Bacon, S. W. Laxon, I. Polyakov, and V. Ivanov (2009), Tracer-derived freshwater composition of the Siberian continental shelf and slope following the extreme Arctic summer of 2007, *Geophys. Res. Lett.*, *36*, L07602, doi:10.1029/2009GL037341.

Alkire, M. B., K. K. Falkner, I. Rigor, M. Steele, and J. Morison (2007), The return of Pacific waters to the upper layers of the central Arctic Ocean, *Deep-Sea Res. I*, *54*, 1509–1529.

Böhme, L., M. P. Meredith, S. E. Thorpe, M. Biuw, and M. Fedak (2008), The ACC frontal system in the South Atlantic: Monitoring using merged Argo and animal-borne sensor data, *J. Geophys. Res.*, *113*, C09012, doi:10.1029/2007JC004647.

Brauch, J. P., and R. Gerdes (2005), Reaction of the northern North Atlantic and Arctic oceans to a sudden change of the NAO, *J. Geophys. Res.*, *110*, C11018, doi:10.1029/2004JC002436.

Curry, B., C. M. Lee, B. Petrie, R. E. Moritz, and R. Kwok (2014), Multi-year volume, liquid freshwater, and sea ice transports through Davis Strait, 2004–2010, *J. Phys. Oceanogr.*, doi:10.1175/JPO-D-13-0177.1, in press.

de Steur, L., E. Hansen, R. Gerdes, M. Karcher, E. Fahrbach, and J. Holfort (2009), Freshwater fluxes in the East Greenland Current: A decade of observations, *Geophys. Res. Lett.*, *36*, L23611, doi:10.1029/2009GL041278.

Dickson, R., B. Rudels, S. Dye, M. Karcher, J. Meincke, and I. Yashayaev (2007), Current estimates of freshwater flux through Arctic and subarctic seas, *Prog. Oceanogr.*, *73*, 210–230, doi:10.1016/j.pocean.2006.12.003.

Dmitrenko, I. A., S. A. Kirillov, and L. B. Tremblay (2008), The long-term and interannual variability of summer fresh water storage over the eastern Siberian shelf: Implication for climatic change, *J. Geophys. Res.*, *113*, C03007, doi:10.1029/2007JC004304.

Dodd, P. A., B. Rabe, E. Hansen, E. Falck, A. Mackensen, E. Rohling, C. Stedmon, and S. Kristiansen (2012), The freshwater composition of the Fram Strait outflow derived from a decade of tracer measurements, *J. Geophys. Res.*, *117*, C11005, doi:10.1029/2012JC008011.

Falck, E., G. Kattner, and G. Budeus (2005), Disappearance of Pacific Water in the northwestern Fram Strait, *Geophys. Res. Lett.*, *32*, L14619, doi:10.1029/2005GL023400.

Fichot, C. G., K. Kaiser, S. B. Hooker, R. M. W. Amon, M. Babin, S. Belanger, S. A. Walker, and R. Benner (2013), Pan-Arctic distributions of continental runoff in the Arctic Ocean, *Scient. Rep.*, *3*, 1053, doi:10.1038/srep01053.

Giles, K. A., S. W. Laxon, A. L. Ridout, D. J. Wingham, and S. Bacon (2012), Western Arctic Ocean freshwater storage increased by wind-driven spin-up of the Beaufort Gyre, *Nat. Geosci.*, *5*, 194–197, doi:10.1038/ngeo1379.

Haak, H., U. Jungclaus, U. Mikolajewicz, and M. Latif (2003), Formation and propagation of great salinity anomalies, *Geophys. Res. Lett.*, *30*, 1473, doi:10.1029/2003GL01765.

Häkkinen, S. (1999), A simulation of the thermohaline effects of a great salinity anomaly, *J. Climate*, *12*, 1781–1795.

Häkkinen, S., and A. Proshutinsky (2004), Freshwater content variability in the Arctic Ocean, *J. Geophys. Res.*, *109*, C03051, doi:10.1029/2003JC001940.

Hansen, E., S. Gerland, M. A. Granskog, O. Pavlova, A. H. H. Renner, J. Haapala, T. B. Lyning, and M. Tschudi (2013), Thinning of arctic sea ice observed in Fram Strait: 1990–2011, *J. Geophys. Res. Oceans*, *118*, 5202–5221, doi:10.1002/jgrc.20393.

Holland, M. M., J. Finnis, A. P. Barrett, and M. C. Serreze (2007), Projected changes in Arctic Ocean freshwater budgets, *J. Geophys. Res.*, *112*, G04S55, doi:10.1029/2006JG000354.

Jackson, J. M., E. C. Carmack, F. A. McLaughlin, S. E. Allen, and R. G. Ingram (2010), Identification, characterization, and change of the near-surface temperature maximum in the Canada Basin, 1993–2008, *J. Geophys. Res.*, *115*, C05021, doi:10.1029/2009JC005265.

Jahn, A., et al. (2012), Arctic Ocean freshwater—How robust are model simulations?, *J. Geophys. Res.*, *117*, C00D16, doi:10.1029/2012JC007907.

Jakobsson, M., R. Macnab, L. Mayer, R. Anderson, M. Edwards, J. Hatzky, H. W. Schenke, and P. Johnson (2008), An improved bathymetric portrayal of the Arctic Ocean: Implications for ocean modeling and geological, geophysical and oceanographic analyses, *Geophys. Res. Lett.*, *35*, L07602, doi:10.1029/2008GL033520.

Karcher, M., R. Gerdes, F. Kauker, C. Köberle, and I. Yashayaev (2005), Arctic Ocean change heralds North Atlantic freshening, *Geophys. Res. Lett.*, *32*, L21606, doi:10.1029/2005GL023861.

Karcher, M., R. Gerdes, and F. Kauker (2006), Modeling of δ^{18}O and ^{99}Tc dispersion in Arctic and subarctic seas, *ASOF Newsletter*, Issue No 5. Available from: http://asof.npolar.no (last accessed: 8th January, 2014).

Karcher, M., J. N. Smith, F. Kauker, R. Gerdes, and W. M. Smethie Jr. (2012), Recent changes in Arctic Ocean circulation revealed by iodine-129 observations and modeling, *J. Geophys. Res.*, *117*, C08007, doi:10.1029/2011JC007513.

Koenigk, T., U. Mikolajewicz, H. Haak, and J. Jungclaus (2007), Arctic freshwater export in the 20th and 21st centuries, *J. Geophys. Res.*, *112*, G04S41, doi:10.1029/2006JG000274.

Korhonen, M., B. Rudels, M. Marnela, A. Wisotzki, and J. P. Zhao (2012), Time and space variability of freshwater content, heat content and seasonal ice melt in the Arctic Ocean from 1991 to 2011, *Ocean Sci. Discuss.*, *9*, 2621–2677, doi:10.5194/osd-9-2621-2012.

Kwok, R., G. F. Cunningham, M. Wensnahan, I. Rigor, H. J. Zwally, and D. Yi (2009), Thinning and volume loss of the Arctic Ocean sea ice cover: 2003–2008, *J. Geophys. Res.*, *114*, C07005, doi:10.1029/2009JC005312.

MacDonald, R. W. (2000), Arctic estuaries and ice: A positive-negative estuarine couple, in *The Freshwater Budget of the Arctic Ocean, NATO Science Partnership Sub-Series: 2*, vol. 70, edited by E. L. Lewis et al., pp. 383–407, Kluwer Academic, Netherlands.

Manabe, S., and R. J. Stouffer (1999a), The role of thermohaline circulation in climate, *Tellus A*, *51*, 91–109.

Manabe, S., and R. J. Stouffer (1999b), Are two modes of thermohaline circulation stable?, *Tellus A*, *51*, 400–411.

McLaughlin, F. A., E. C. Carmack, R. W. Macdonald, and J. K. B. Bishop (1996), Physical and geochemical properties across the Atlantic/Pacific water mass front in the southern Canadian Basin, *J. Geophys. Res.*, *101*, 1183–1197, doi:10.1029/95JC02634.

McPhee, M. G., A. Proshutinsky, J. H. Morison, M. Steele, and M. B. Alkire (2009), Rapid change in freshwater content of the Arctic Ocean, *Geophys. Res. Lett.*, *36*, L10602, doi:10.1029/2009GL37252.

Morison, J., M. Steele, T. Kikuchi, K. Falkner, and W. Smethie (2006), Relaxation of central Arctic Ocean hydrography to pre-1990s climatology, *Geophys. Res. Lett.*, *33*, L17604, doi:10.1029/2006GL026826.

Morison, J., R. Kwok, C. Peralta-Ferriz, M. Alkire, I. Rigor, R. Andersen, and M. Steele (2012), Changing Arctic Ocean freshwater pathways, *Nature*, *481*, 66–70, doi:10.1038/nature10705.

Morison, J. H., M. Steele, and R. Andersen (1998), Hydrography of the upper Arctic Ocean measured from the nuclear submarine USS Pargo, *Deep-Sea Res. I*, *45*, 15–38.

Overeem, I., and J. P. M. Syvitski (2010), Shifting discharge peaks in Arctic rivers, 1977–2007, *Geogr. Ann.*, *92A*(2), 285–296.

Overland, J. E., and M. Wang (2010), Large-scale atmospheric circulation changes are associated with the recent loss of Arctic sea ice, *Tellus A*, *62*, 1–9, doi:10.1111/j.1600-0870.2009.00421.x.

Overland, J. E., J. A. Francis, E. Hanna, and M. Wang (2012), The recent shift in early summer Arctic atmospheric circulation, *Geophys. Res. Lett.*, *39*, L19804, doi:10.1029/2012GL053268.

Polyakov, I., U. S. Bhatt, J. E. Walsh, E. P. Abrahamsen, A. V. Pnyushkov, and P. F. Wassmann (2013), Recent oceanic changes in the Arctic in the context of long-term observations, *Ecol. Appl.*, *23*, 1745–1764, doi:10.1890/11-0902.1.

Polyakov, I. V., V. Alexeev, F. I. Belchansky, I. A. Dmitrenko, V. Ivanov, S. Kirillov, A. Korablev, M. Steele, L. A. Timokhov, and I. Yashayaev (2008), Arctic Ocean freshwater changes over the past 100 year and their causes, *J. Climate*, *21*, 364–384, doi:10.1175/2007JCLI1748.1.

Proshutinksy, A. Y., and M. A. Johnson (1997), Two circulation regimes of the wind-driven Arctic Ocean, *J. Geophys. Res.*, *102*, 12,493–12,514.

Proshutinsky, A., I. Polyakov, and M. Johnson (1999), Climate states and variability of Arctic ice and water dynamics during 1946–1997, *Pol. Res*, *18*(2), 135–142, doi:10.1111/j.1751-8369.1999.tb00285.x.

Proshutinsky, A., R. Krishfield, M.-L. Timmermans, J. Toole, E. Carmack, F. McLaughlin, W. J. Williams, S. Zimmermann, M. Itoh, and K. Shimada (2009), Beaufort Gyre freshwater reservoir: State and variability from observations, *J. Geophys. Res.*, *114*, C00A10, doi:10.1029/2008JC005104.

Proshutinsky, A., D. Dukhovskoy, M.-L. Timmermans, and J. Bamber (2013), Arctic circulation regimes and their transformations under the influence of climate change, *Geophys. Res. Abstr.*, *15*, EGU General Assembly, Abstract EGU2013-1581.

Rabe, B., M. Karcher, U. Schauer, J. Toole, R. Krishfield, S. Pisarev, F. Kauker, R. Gerdes, and T. Kikuchi (2011), An assessment of Arctic Ocean freshwater content changes from the 1990s to 2006–2008, *Deep-Sea Res. I*, *58*, 173–185, doi:10.1016/j.dsr.2010.12.002.

Rabe, B., P. A. Dodd, E. Hansen, E. Falck, U. Schauer, A. Mackensen, A. Beszczynska-Möller, G. Kattner, E. J. Rohling, and K. Cox (2013a), Export of Arctic freshwater components through the Fram Strait 1998–2011, *Ocean Sci.*, *9*, 91–109, doi:10.5194/os-9-91-2013.

Rabe, B., H. L. Johnson, A. Mnchow, and H. Melling (2013b), Geostrophic ocean currents and freshwater fluxes across the Canadian polar shelf via Nares Strait, *J. Mar. Res.*, *70*, 603–640, doi:10.1357/002224012805262725.

Rabenstein, L., S. Hendricks, T. Martin, A. Pfaffhuber, and C. Haas (2010), Thickness and surface-properties of different sea-ice regimes within the Arctic Trans Polar Drift: Data from summers 2001, 2004 and 2007, *J. Geophys. Res.*, *115*, C12059, doi:10.1029/2009JC005846.

Rennermalm, A. K., E. F. Wood, A. J. Weaver, M. Eby, and S. J. Derý (2007), Relative sensitivity of the Atlantic meridional overturning circulation to river discharge into Hudson Bay and the Arctic Ocean, *J. Geophys. Res.*, *112*, G04S45, doi:10.1029/2006JG000330.

Rudels, B. (2010), Constraints on exchanges in the Arctic Mediterranean—Do they exist and can they be of use?, *Tellus A*, *62*, 109–122, doi:10.1111/j.1600-0870.2009.00425.x.

Rudels, B., L. G. Anderson, and E. P. Jones (1996), Formation and evolution of the surface mixed layer and halocline of the Arctic Ocean, *J. Geophys. Res.*, *101*(C4), 8807–8821.

Rudels, R., E. P. Jones, U. Schauer, and P. Ericksson (2004), Atlantic sources of the Arctic Ocean surface and halocline waters, *Polar Res.*, *23*, 181–208.

Serreze, M. C., A. P. Barrett, A. G. Slater, R. A. Woodgate, K. Aagaard, R. B. Lammers, M. Steele, R. Moritz, M. Meredith, and C. M. Lee (2006), The large-scale freshwater cycle of the Arctic, *J. Geophys. Res.*, *111*, C11010, doi:10.1029/2005JC003424.

Steele, M., and T. Boyd (1998), Retreat of the cold halocline layer in the Arctic Ocean, *J. Geophys. Res.*, *103*(C5), 10,419–10,439.

Steele, M., J. Morison, W. Ermold, I. Rigor, M. Ortmeyer, and K. Shimada (2004), Circulation of summer Pacific halocline water in the Arctic Ocean, *J. Geophys. Res.*, *109*, C02027, doi:10.1029/2003JC002009.

Thompson, D. W. J., and J. M. Wallace (1998), The Arctic Oscillation signature in the wintertime geopotential height and temperature fields, *Geophys. Res. Lett.*, *25*, 1297–1300.

Toole, J. M., M. L. Timmermans, D. K. Perovich, R. A. Krishfield, A. Proshutinsky, and J. A. Richter-Menge (2010), Influences of the ocean surface mixed layer and thermohaline stratification on Arctic Sea ice in the central Canada Basin, *J. Geophys. Res.*, *115*, C10018, doi:10.1029/2009JC005660.

Tsubouchi, T., S. Bacon, A. C. N. Garabato, Y. Aksenov, S. W. Laxon, E. Fahrbach, A. Beszczynska-Moeller, E. Hansen, C. M. Lee, and R. B. Ingvaldsen (2012), The Arctic Ocean in summer: A quasi-synoptic inverse estimate of boundary fluxes and water mass transformation, *J. Geophys. Res.*, *117*, C01024, doi:10.1029/2011JC007174.

Woodgate, R., and K. Aagaard (2005), Revising the Bering Strait freshwater flux into the Arctic Ocean, *Geophys. Res. Lett.*, *32*, L02602, doi:10.1029/2004GL021747.

Woodgate, R. A., K. Aagaard, and T. J. Weingartner (2006), Interannual changes in the Bering Strait fluxes of volume, heat and freshwater between 1991 and 2004, *Geophys. Res. Lett.*, *33*, L15609, doi:10.1029/2006GL026931.

Woodgate, R. A., T. J. Weingartner, and R. Lindsay (2012), Observed increases in Bering Strait oceanic fluxes from the Pacific to the Arctic from 2001 to 2011 and their impacts on the Arctic Ocean water column, *Geophys. Res. Lett.*, *39*, L24603, doi:10.1029/2012GL054092.

Yamamoto-Kawai, M., F. A. McLaughlin, E. C. Carmack, S. Nishino, K. Shimada, and N. Kurita (2009), Surface freshening of the Canada Basin, 2003–2007: River runoff versus sea ice meltwater, *J. Geophys. Res.*, *114*, C00A05, doi:10.1029/2008JC005000.