

RESEARCH LETTER

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Key Points:

- Upper Arctic Ocean liquid freshwater trend 1992–2012: $600 \pm 300 \text{ km}^3/\text{yr}$
- 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 $600 \pm 300 \text{ km}^3 \text{ yr}^{-1}$. 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., Hinkinen, 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

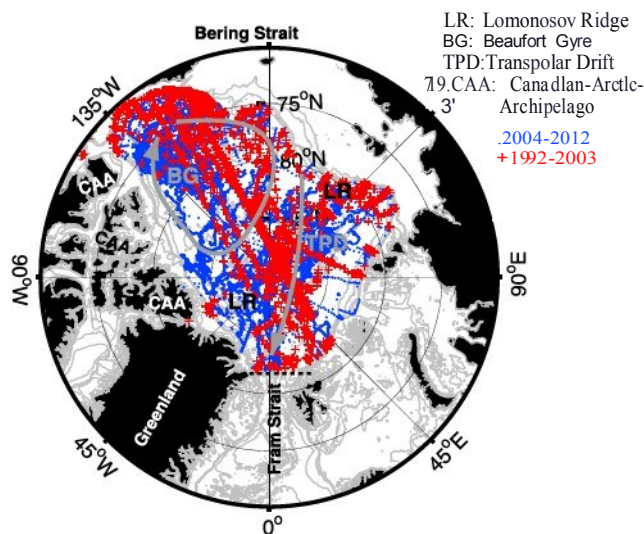


Figure 1. Map of the Arctic Ocean with names of geographic locations and ocean circulation features referred to in the text. The bathymetry is based on the International Bathymetric Chart of the Arctic Ocean [Jakobsson *et al.*, 2008] database. The region under investigation is enclosed by the thick 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 Bohme *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 $600 \pm 300 \text{ km}^3 \text{ yr}^{-1}$ 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-

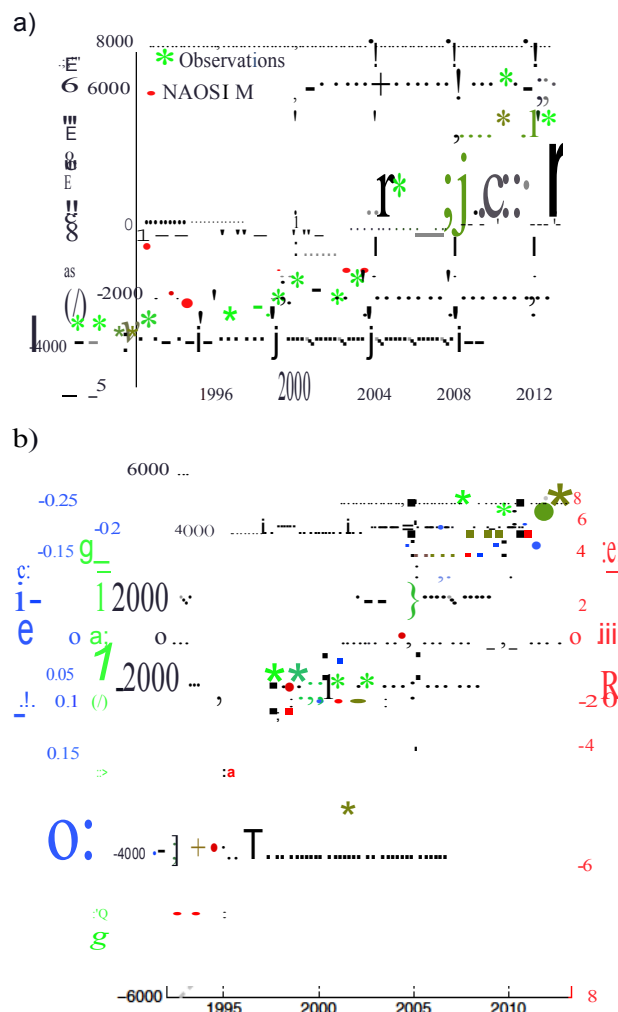


Figure 2. Time series of annual means for 1992–2012. (a) Liquid freshwater content anomalies from the time mean for the upper Arctic Ocean from observations (green pentagons) and the NAOSIM model (red dots). (b) liquid freshwater inventory from the surface to the depth of the 34 isohaline (green pentagons), 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 $600 \pm 300 \text{ km}^3 \text{ yr}^{-1}$.

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 physical variability 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

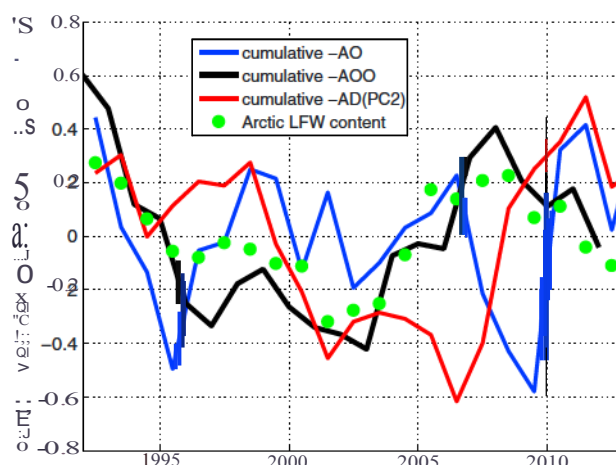


Figure 3. Cumulative sum of different atmospheric indices since 1992: Arctic Oscillation (AO; blue, solid), Arctic Ocean Oscillation (AOO; black, solid), and Arctic Dipole (AD; red, solid). The AD index was calculated as the "PC2" in *Overland and Wang* [2010] and was extended to the end of 2012 by J. 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 *Proshutinsky 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.

Proshutinsky 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 $862 \text{ km}^3 \text{ yr}^{-1}$ 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 km³/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 km³ 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 km³/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 km³/yr⁻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 Hiikkinen 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 level as existed in the beginning of the 1950s [Jahn *et al.*, 2012, Figures Sa and Sb]. 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 2005 will be followed by a decrease.

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