Arctic Ocean Freshening Linked to Anthropogenic Climate Change: All Hands on Deck

Thomas W. N. Haine[1]

[1]Earth & Planetary Sciences, Johns Hopkins University, Baltimore, MD United States

Key Points:

- A recent paper shows that observed increases in Arctic Ocean freshwater storage are anthropogenic.
- The paper anticipates future anthropogenic changes, which are testable predictions for observers.
- There are widespread impacts of anthropogenic freshwater change, both within the Arctic and the North Atlantic Oceans.

Corresponding author: Thomas W. N. Haine, `Thomas.Haine@jhu.edu`

Abstract

Arctic Ocean freshwater storage increased since the mid 1990s, but the cause was unknown. Now a recent paper in *Geophysical Research Letters* uses ensemble runs of a coupled climate model to suggest that the observed increase is anthropogenic. The paper quantifies when the anthropogenic signals should emerge from the noise of natural variability. This result contextualizes research on the Arctic Ocean freshwater system and sketches an unprecedented opportunity. Future work should elucidate mechanisms, seek to observe the anthropogenic freshwater changes, and investigate the impacts on biogeochemistry and the North Atlantic Ocean circulation.

Plain Language Summary

The Arctic is a region of clear man-made climate change. Changes in the Arctic Ocean salinity and currents have been seen, but the cause was unknown. A new paper shows that the changes are probably due to man-made climate change. The reason is they only occur in a climate model with man-made climate forcing. This is an important result because it helps scientists focus their research into how the changes work. It also points to a valuable opportunity to watch the Arctic Ocean respond to man-made climate change. There might be important future impacts on North Atlantic oceanography and North Atlantic climate that scientists can now look for.

Main Text

The cold poles are the condensers for Earth's freshwater cycle. Water evapourates from the warm tropical oceans and is then transported polewards by the atmosphere. At high latitudes the air cools and the water vapour it carries becomes saturated. Condensation occurs, and the resulting liquid water returns to Earth's surface as precipitation. This process freshens the polar oceans and salinifies the low-latitude oceans. Ocean currents flow equatorwards and return the freshwater as relatively low salinity seawater, thereby closing the freshwater cycle.

The strength of this cycle is virtually certain to increase in the 21st century due to anthropogenic climate change (Collins et al., 2013). Yet many questions remain about the timing and character of the increase across the globe. A new study in *Geophysical Research Letters* elucidates how this system is changing in the Arctic due to anthropogenic forcing (Jahn & Laiho, 2020). There are important implications for future Arctic change, future research on the mechanisms of change, and future observing priorities in the region.

The Arctic mediterranean consists of a polar ocean surrounded by land (Fig. 1), which means that the Arctic freshwater cycle is strong. The Arctic Ocean is freshened by net precipitation minus evapouration and by northward-flowing Eurasian and American runoff (collectively called the meteoric freshwater flux). The Arctic Ocean also receives relatively fresh inflow from the Pacific through Bering Strait. These sources of freshwater are stored in the low-salinity Arctic Ocean halocline and sea ice (solid freshwater). Ocean currents drain the anomalously fresh seawater west of Greenland through the Canadian Arctic Archipelago and into the North Atlantic Ocean via Davis Strait. Ocean currents also flow east of Greenland through Fram Strait into the Nordic Seas and on into the North Atlantic Ocean. An important stream of sea ice also drains the Arctic Ocean through Fram Strait.

Measurements of the Arctic Ocean freshwater cycle show conspicuous changes in the last few decades. Summer-time sea ice extent has decreased steadily since satellite observations began 40 years ago (Vaughan et al., 2013; Cavalieri & Parkinson, 2012). This development is shown by the red line in Fig. 1 (top middle subplot), which measures the volume of freshwater stored as sea ice in the Arctic (using the PIOMAS data product; Schweiger et al. 2011). The summer-time sea ice is also now thinner and younger (Laxon et al., 2013; Lindsay & Schweiger, 2015). These sea ice changes are attributed to anthropogenic effects because they only occur in coupled climate models perturbed by anthropogenic forcing (Notz & Marotzke, 2012).

Concurrent with this decline in sea ice is a conspicuous increase in liquid freshwater volume stored in the Arctic Ocean. Measurements of seawater salinity show a remarkable sustained freshening since the early 1990s (Proshutinsky et al., 2009; McPhee et al., 2009; Rabe et al., 2011, 2014; Giles et al., 2012). This development is also shown in Fig. 1 by the red line in the bottom middle subplot (taken from the synthesis of Haine et al. 2015). It measures the volume of freshwater that dilutes the upper Arctic Ocean to form the halocline (it is the volume-integrated salinity anomaly).

Independent measurements of the ocean freshwater fluxes into and out of the Arctic over the last twenty years corroborate this finding. In the presence of large variability and uncertainty, they show increasing freshwater inflow through Bering Strait and nearly unchanged outflows through Davis and Fram Straits (with some shifts between the individual flux terms; Haine et al. 2015). These data are shown by the red lines on the left and right subplots in Fig. 1. The meteoric freshwater flux to the Arctic Ocean is also likely increasing since the 1980s and 1990s. The integrated effect of the changes in these freshwater fluxes, plus the loss of freshwater stored in sea ice, plausibly matches the increase in liquid freshwater stored in the Arctic (Haine et al., 2015). The question is what causes these freshwater changes?

Now Alexandra Jahn and Rory Laiho of the University of Colorado at Boulder have provisionally answered this question (Jahn & Laiho, 2020). They show that the Arctic Ocean liquid freshwater storage increase is anthropogenic, like the sea ice decline. They examine the simulated Arctic Ocean freshwater cycle from 21st century projections of the Coupled Earth System Model (CESM), a climate model from the National Center for Atmospheric Research (thin coloured lines in Fig. 1). Jahn & Laiho (2020) use output from an ensemble of CESM runs, which is a set of many model projections that differ only in their natural, unforced climate variations. They consider two CESM ensemble experiments for the 21st century: the large ensemble (CESM-LE, Kay et al. 2015, purple lines) and the low warming ensemble (CESM-LW, Sanderson et al. 2017, green lines). The CESM-LE uses the IPCC RCP8.5 high-emission scenario and the CESM-LW uses a reduced emission scenario that stabilizes global warming at 2°C for several decades before 2100.

Jahn & Laiho (2020) define a metric to quantify the forced (anthropogenic) signal relative to background noise. They use the CESM pre-industrial control ensemble (gray lines) to characterize the natural variability in the Arctic freshwater system. Departures outside this variability envelope (horizontal lines) reveal the forced response. They define *emergence* as a permanent fluctuation away from the range of control variability, which is almost certainly anthropogenic (vertical purple and green lines). Applying this metric to the Arctic Ocean freshwater content, Jahn & Laiho (2020) find that all CESM ensemble runs show a permanent freshening (emergence of an anthropogenic signal) by the early 2020s. They conclude therefore that the observed increase in liquid freshwater storage in the real Arctic "is likely already driven by climate change."

These are state-of-the-science methods that exploit ensembles of control and projection climate model experiments. Still, the results are provisional. The detection of forced changes in the Arctic freshwater system need to be confirmed in other coupled climate models. The CESM freshwater fluxes are biased compared to the observations in Fig. 1, which affects the emergence metric in uncertain ways. For example, the model exports too much sea ice through Fram Strait and not enough liquid freshwater. Moreover, it is already known that the summer sea ice decline is anthropogenic (Notz & Marotzke, 2012). And Arctic-amplification of climate change is well known and well studied (Arctic amplification is the magnification of surface temperature increase by a factor of two to three times in the Arctic compared to the global average, Serreze & Barry 2011; Collins et al. 2013).

Despite these caveats the paper by Jahn & Laiho (2020) is an important advance. It clearly points to future research priorities because it frames the debate about the nature of the Arctic freshwater system. It contextualizes exploration of the processes at work, which are poorly-known. It projects how the system will change in the coming years and decades. And it provides a rationale to investigate downstream impacts on the North Atlantic Ocean. Most importantly, it revitalizes the arduous task of observing changes in the Arctic freshwater system.

The dynamics of the freshwater system emerge from the accumulation and interaction of many diverse mechanisms in the Arctic Ocean. Most of these mechanisms are poorly observed, poorly understood, and poorly modeled, for example by the CESM. Arctic liquid freshwater is stored predominantly in the Canadian Basin (Fig. 1 basemap), in particular in the Beaufort Gyre. The Beaufort Gyre is thought to be driven by a balance between the stress from anticyclonic winds encircling the Beaufort High in sea level pressure and ocean eddies (see for instance Manucharyan et al. 2016). But debates continue on the importance of sea ice, of ocean bathymetry, of the relationship to the Arctic Ocean general circulation, such as the Transpolar Drift, and of the transient dynamics of freshwater storage and release. Similar questions remain open about the mechanisms controlling other parts of the Arctic freshwater system.

The CESM experiments reported by Jahn & Laiho (2020) make clear projections about future change (Fig. 1). They quantify the sequence of emergence of forced signals and they characterize the variability of different elements of the freshwater system. Emergence of the forced CESM freshwater flux signal occurs first at Nares Strait in the Canadian Arctic Archipelago (in the 2000s), then at Davis Strait (in the 2010s), then at Fram Strait (first for liquid flux, circa 2030, then for solid flux, circa 2060; see Fig. 1 for locations). The forced signals at Bering and Barrow Straits do not occur before 2100 in the CESM experiments because of smaller signals relative to the natural variability.

Although the CESM forced signal is strong at Nares Strait, observing the freshwater flux there is logistically challenging (Melling, 2011) and the extant time series is short (Melling et al., 2008). At Davis Strait the CESM forced signal emergence is imminent, the logistics are easier, the records are longer, and the observing array has recently been re-funded after a hiatus (Craig Lee, personal communication). The CESM forced signal is weak at Bering Strait, but it is least challenging to observe because Bering Strait is narrow and shallow and the time series is relatively long and uninterrupted. In designing and interpreting data from a holistic Arctic freshwater measurement network, tradeoffs such as these must be carefully weighed. The Jahn & Laiho (2020) projections provide a rational basis to do so.

The impacts of anthropogenic change in the Arctic freshwater system are no less important. For example, we know that Arctic freshwater affects ocean biogeochemistry, like phytoplankton community composition, primary production, and ocean acidification (Carmack et al., 2016). It also lowers the density of downstream surface waters in the sub-Arctic deep water formation sites. The Arctic outflows freshen the Greenland, Iceland, Irminger, and Labrador Seas, which are the source regions for surface waters entering the deep limb of the Atlantic meridional overturning circulation (AMOC). The outflows thereby slow the AMOC, which is principally driven by temperature contrasts (the water sinks because it is cold). We know that the AMOC fluctuates naturally on timescales from days to centuries with widespread implications for climate variability (Zhang et al., 2019). To date, the observed AMOC variations appear to be natural and unforced (Haine, 2016). Nevertheless, we also know that the AMOC is very likely to weaken in the 21st century due to anthropogenic climate change (Collins et al., 2013). Jahn & Laiho (2020) illuminate the link between these ideas. They point to the prospect of observing and understanding changes in the Arctic freshwater system and its downstream effects. This chance to spectate on wholesale shifts in the climate system is an unprecedented scientific opportunity. It deserves an unprecedented scientific response.

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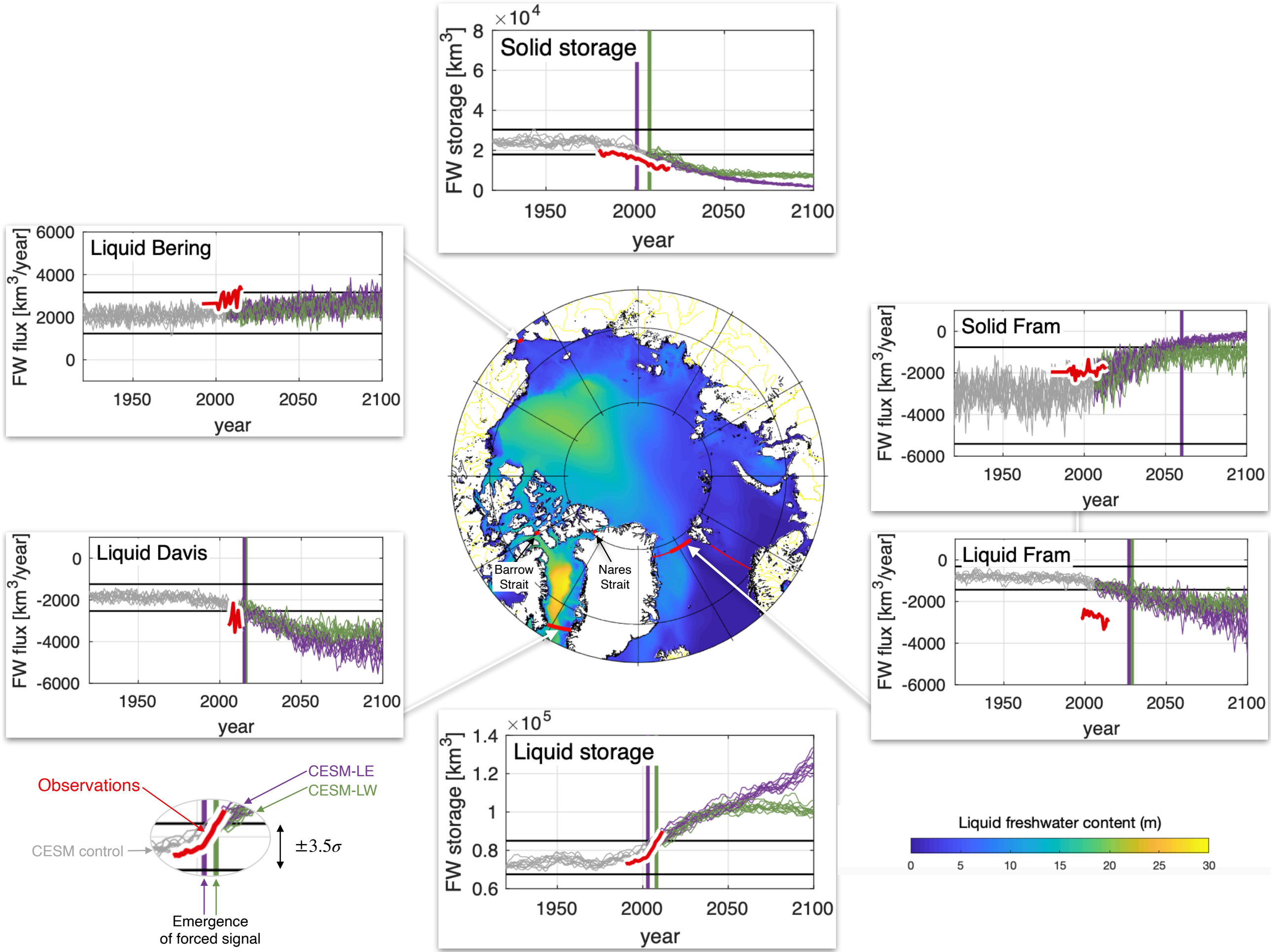

Figure 1. Climate model projections and observations of the Arctic Ocean freshwater cycle. The left and right subplots show the time series of freshwater (FW) flux across key gateway sections ($\mathrm{km^3 yr^{-1}}$ relative to a salinity of 34.80; positive polewards). The middle subplots show the freshwater volume stored in the Arctic Ocean as sea ice (solid, top) and liquid (bottom) freshwater ($\mathrm{km^3}$ relative to 34.80). Results from the Community Earth System Model (CESM) control (gray), large ensemble (LE, purple), and low warming (LW, green) experiments are shown in each case, adapted from Jahn & Laiho (2020) Fig. 2. The subplots show the times when the models show emergence of a forced, anthropogenic signal (meaning the time of first permanent departure from the $\pm 3.5\sigma$ envelope of control variability, where σ is the standard deviation; horizontal and vertical lines). The observations synthesized by Haine et al. (2015) are plotted in red (with updates from de Steur et al. 2018; Woodgate 2018, and Spreen et al. 2020). For estimates and discussion of the uncertainty in the observations, see Haine et al. (2015). The freshwater fluxes to the Arctic from the atmosphere (precipitation minus evapouration and runoff), and smaller fluxes, are omitted for clarity. The basemap shows the liquid freshwater content, which is the vertically-integrated salinity anomaly relative to 34.80, based on Haine et al. (2015) Fig. 6.