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 surface low-salinity layer of the Arctic Ocean, which lies above the halocline, and in 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. Much uncertainty surrounds this broad picture, especially from spatial and temporal variability which is poorly observed and has poorly known sources (Brown et al., 2020).

Nevertheless, 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).

Overlapping 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 freshening between 1992 and 2012 (McPhee et al., 2009; Rabe et al., 2011, 2014; Giles et al., 2012; Proshutinsky et al., 2019). 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 and at higher spatial resolution. 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.

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). Changes in the Beaufort High are believed to contribute to the observed Beaufort Gyre freshwater increase (Cornish et al., 2020). 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 delineate 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, and the records are longer. 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.

Anthropogenic change in the Arctic freshwater system also has broader impacts. For example, we know that Arctic freshwater affects ocean biogeochemistry, like phytoplankton community composition, primary production, and ocean acidification (Carmack et al., 2016; Brown et al., 2020). 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 tend to slow the AMOC, which is principally driven by temperature contrasts (the water sinks because it is cold; see Weijer et al. 2019 for a recent review). 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.

Acknowledgments

Alexandra Jahn provided the data and code to make Jahn & Laiho (2020) Fig. 2, which is used in Fig. 1 here. Gunnar Spreen, Rebecca Woodgate, and Laura de Steur provided the data to extend the Haine et al. (2015) observational time series in Fig. 1. The PIOMAS data are taken from: `psc.apl.uw.edu/research/projects/arctic-sea-ice-volume-anomaly`. The code and data to make Fig. 1 are at `github.com/hainegroup/Arctic-Ocean-Freshwater-Synthesis`. Support from NASA grant 80NSSC20K0823 and comments by Ali Siddiqui, Sam Cornish, and Bill Williams are appreciated. This article is dedicated to Bob Dickson (1941–2019). With his vision, authority, and determination Bob led the field to the discoveries recounted here, and with his humanity he built the field to make them.

References

Brown, K. A., Holding, J. M., & Carmack, E. C. (2020, August). Understanding regional and seasonal variability is key to gaining a pan-Arctic perspective on Arctic Ocean freshening. *Frontiers in Marine Science*, *7*. doi: 10.3389/fmars.2020.00606

Carmack, E., Yamamoto-Kawai, M., Haine, T., Bacon, S., Bluhm, B., Lique, C., ... Williams, W. (2016). Fresh water and its role in the Arctic Marine System: sources, disposition, storage, export, and physical and biogeochemical consequences in the Arctic and global oceans. *J. Geophys. Res.*, *121*, 675–717. doi: 10.1002/2015jg003140

Cavalieri, D. J., & Parkinson, C. L. (2012, August). Arctic sea ice variability and trends, 1979–2010. *The Cryosphere*, *6*(4), 881–889. doi: 10.5194/tc-6-881-2012

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., ... Wehner, M. (2013). Long-term climate change: Projections, commitments and irreversibility. In T. F. Stocker et al. (Eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Cornish, S. B., Kostov, Y., Johnson, H. L., & Lique, C. (2020, February). Response of Arctic freshwater to the Arctic Oscillation in coupled climate models. *J. Climate*, *33*(7), 2533–2555. doi: 10.1175/jcli-d-19-0685.1

de Steur, L., Peralta-Ferriz, C., & Pavlova, O. (2018, December). Freshwater export in the East Greenland Current Freshens the North Atlantic. *Geophys. Res. Lett.*, *45*(24). doi: 10.1029/2018gl080207

Giles, K. A., Laxon, S. W., Ridout, A. L., Wingham, D. J., & Bacon, S. (2012, January). Western Arctic Ocean freshwater storage increased by wind-driven spin-up of the Beaufort Gyre. *Nature Geoscience*, *5*(3), 194–197. doi: 10.1038/NGEO1379

Haine, T. W. N. (2016). Ocean science: Vagaries of Atlantic overturning. *Nature Geoscience*, *9*, 479–480. doi: 10.1038/ngeo2748

Haine, T. W. N., Curry, B., Gerdes, R., Hansen, E., Karcher, M., Lee, C., ... Woodgate, R. (2015, February). Arctic freshwater export: Status, mechanisms, and prospects. *Glob. Planet. Change*, *125*, 13–35. doi: 10.1016/j.gloplacha.2014.11.013

Jahn, A., & Laiho, R. (2020, August). Forced changes in the Arctic freshwater budget emerge in the early 21st century. *Geophys. Res. Lett.*, *47*(15). doi: 10.1029/2020gl088854

Kay, J. E., Deser, C., Phillips, A., Mai, A., Hannay, C., Strand, G., ... Vertenstein, M. (2015, August). The community earth system model (CESM) large ensemble project: A community resource for studying climate change in the presence of internal climate variability. *Bull. Amer. Meteor. Soc.*, *96*(8), 1333–1349. doi: 10.1175/bams-d-13-00255.1

Laxon, S. W., Giles, K. A., Ridout, A. L., Wingham, D. J., Willatt, R., Cullen, R., ... Davidson, M. (2013, February). Cryosat-2 estimates of Arctic sea ice thickness and volume. *Geophys. Res. Lett.*, *40*(4), 732–737. doi: 10.1002/grl.50193

Lindsay, R., & Schweiger, A. (2015, February). Arctic sea ice thickness loss determined using subsurface, aircraft, and satellite observations. *Cryosphere*, *9*(1), 269–283. doi: 10.5194/tc-9-269-2015

Manucharyan, G. E., Spall, M. A., & Thompson, A. F. (2016, January). A theory of the wind-driven Beaufort Gyre. *J. Phys. Oceanogr.*, *43*(1), 273–282. doi: 10.1002/2015gl065957

McPhee, M. G., Proshutinsky, A., Morison, J. H., Steele, M., & Alkire, M. B. (2009, May). Rapid change in freshwater content of the Arctic Ocean. *J. Geophys. Res.*, *36*(10). doi: 10.1029/2009GL037525

Melling, H. (2011). The best laid schemes: A Nares Strait adventure. *Oceanography*, *24(3)*, 124–125. doi: 10.5670/oceanog.2011.63

Melling, H., Agnew, T. A., Falkner, K. K., Greenberg, D. A., Lee, C. M., Münchow, A., ... Woodgate, R. A. (2008). Fresh-water fluxes via Pacific and Arctic outflows across the Canadian polar shelf. In R. R. Dickson, J. Meincke, & P. Rhines (Eds.), *Arctic-Subarctic Ocean Fluxes: Defining the role of the Northern Seas in Climate* (pp. 193–247). Springer-Verlag. doi: 10.1007/978-1-4020-6774-7_10

Notz, D., & Marotzke, J. (2012, April). Observations reveal external driver for Arctic sea-ice retreat. *Geophys. Res. Lett.*, *39*(8). doi: 10.1029/2012GL051094

Proshutinsky, A., Krishfield, R., Toole, J. M., Timmermans, M.-L., Williams, W., Zimmermann, S., ... Zhao, J. (2019, dec). Analysis of the beaufort gyre freshwater content in 2003–2018. *Journal of Geophysical Research: Oceans*, *124*(12), 9658–9689. doi: 10.1029/2019jc015281

Rabe, B., Karcher, M., Kauker, F., Schauer, U., Toole, J. M., Krishfield, R. A., ... Su, J. (2014, February). Arctic Ocean basin liquid freshwater storage trend 1992–2012. *Geophys. Res. Lett.*, *41*(3), 961–968. doi: 10.1002/2013gl058121

Rabe, B., Karcher, M., Schauer, U., Toole, J. M., Krishfield, R. A., Pisarev, S., ... Kikuchi, T. (2011, February). An assessment of Arctic Ocean freshwater content changes from the 1990s to the 2006–2008 period. *Deep Sea Res., Part I*, *58*(2), 173–185. doi: 10.1016/j.dsr.2010.12.002

Sanderson, B. M., Xu, Y., Tebaldi, C., Wehner, M., O'Neill, B., Jahn, A., ... Lamarque, J. F. (2017, September). Community climate simulations to assess avoided impacts in 1.5 and 2°C futures. *Earth System Dynamics*, *8*(3), 827–847. doi: 10.5194/esd-8-827-2017

Schweiger, A., Lindsay, R., Zhang, J., Steele, M., Stern, H., & Kwok, R. (2011, September). Uncertainty in modeled Arctic sea ice volume. *J. Geophys. Res.*, *116*. doi: 10.1029/2011jc007084

Spreen, G., de Steur, L., Divine, D., Gerland, S., Hansen, E., & Kwok, R. (2020, June). Arctic sea ice volume export through Fram Strait from 1992 to 2014. *J. Geophys. Res.*, *125*(6). doi: 10.1029/2019jc016039

Vaughan, D. G., Comiso, J. C., Allison, I., Carrasco, J., Kaser, G., Kwok, R., ... Zhang, T. (2013). Observations: Cryosphere. In T. F. Stocker et al. (Eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Weijer, W., Cheng, W., Drijfhout, S. S., Fedorov, A. V., Hu, A., Jackson, L. C., … Zhang, J. (2019, August). Stability of the Atlantic Meridional Overturning Circulation: A review and synthesis. *J. Geophys. Res.*, *124*(8), 5336–5375. doi: 10.1029/2019jc015083

Woodgate, R. A. (2018, January). Increases in the Pacific inflow to the Arctic from 1990 to 2015, and insights into seasonal trends and driving mechanisms from year-round Bering Strait mooring data. *Prog. Oceanogr.*, *160*, 124–154. doi: 10.1016/j.pocean.2017.12.007

Zhang, R., Sutton, R., Danabasoglu, G., Kwon, Y.-O., Marsh, R., Yeager, S. G., … Little, C. M. (2019, June). A review of the role of the Atlantic Meridional Overturning Circulation in Atlantic Multidecadal Variability and associated climate impacts. *Rev. Geophys.*, *57*(2), 316–375. doi: 10.1029/2019rg000644

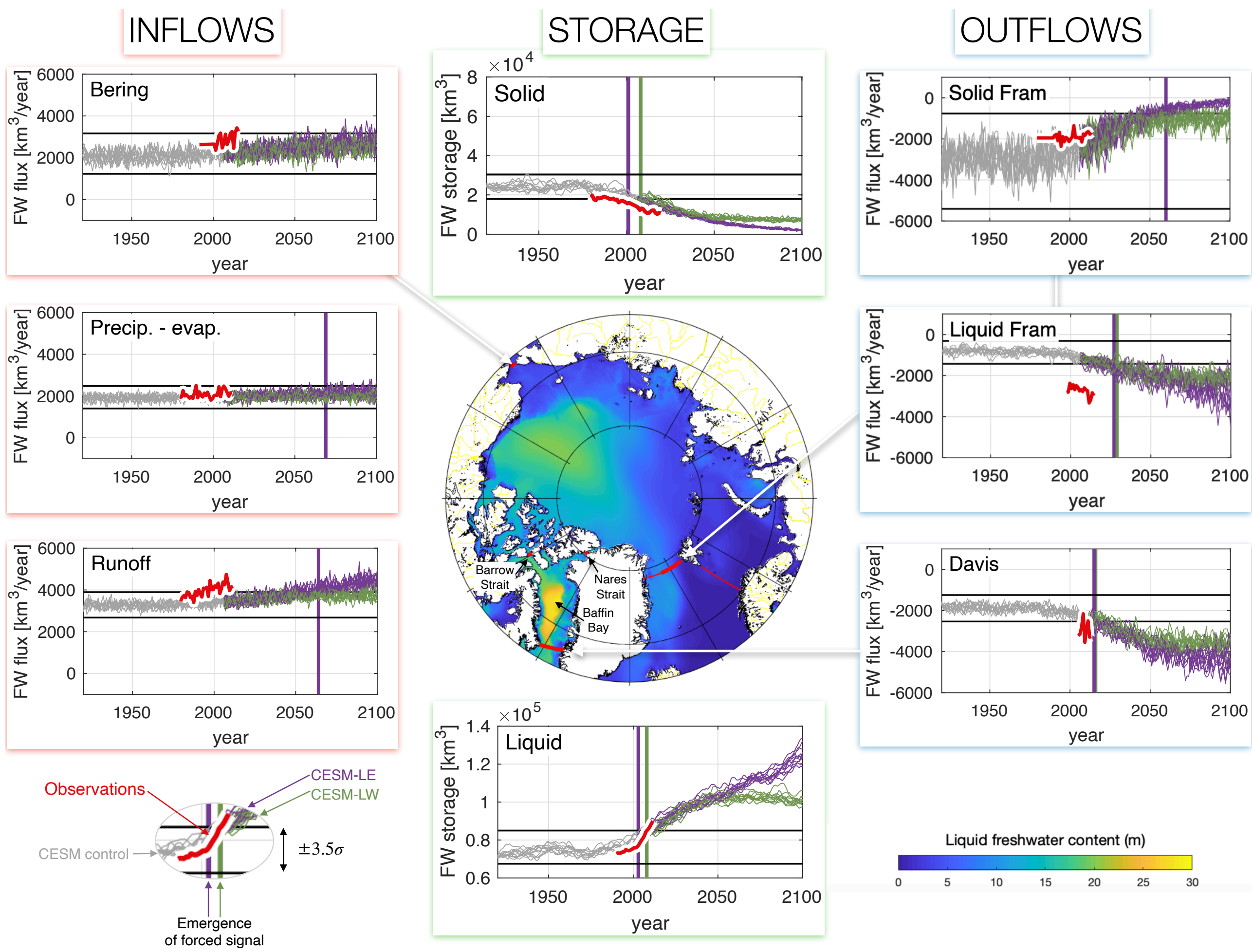

Figure 1. Climate model projections and observations of the Arctic Ocean freshwater cycle. The left and right subplots show the principal time series of freshwater (FW) inflows and outflows (km^{3}yr^{-1} relative to a salinity of 34.80; positive polewards). The middle subplots show the freshwater storage in the Arctic Ocean as sea ice (solid, top) and liquid (bottom) freshwater (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; the liquid storage data are adjusted to match the Jahn & Laiho 2020 Arctic Ocean control volume by excluding Baffin Bay). For estimates and discussion of the uncertainty in the observations, see Haine et al. (2015). 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.