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Key Points:

- Overturning in the Subpolar North Atlantic Program moorings reveal a rapid communication between the largest upper-ocean freshening event and the Iceland Scotland Overflow Waters
- Salinity variations of the Nordic Seas bottom waters reveal no connection to this recent deep ocean freshening in the Iceland Basin
- The extreme rate of freshening has provided us with a natural tracer that is helping us identify and understand key Atlantic Meridional Overturning Circulation processes

Correspondence to:

L. Chafik,
leon.chafik@noc.ac.uk

Rapid Communication of Upper-Ocean Salinity Anomaly to Deep Waters of the Iceland Basin Indicates an AMOC Short-Cut

Léon Chafik[1] ⓘ and **N. Penny Holliday[1]** ⓘ

[1]National Oceanography Centre, Southampton, UK

Abstract The mooring observations of the Overturning in the Subpolar North Atlantic Program reveal a significant freshening of the Iceland Scotland overflow waters that did not involve the Nordic Seas, the source of the dense Deep North Atlantic Water (Devana et al., 2021, https://doi.org/10.1029/2021GL094396). Their study suggests that this freshening at depth in the Iceland Basin stems from the largest upper-ocean freshening event in 120 years that rapidly communicated through entrainment with the Iceland Scotland Overflow Waters. This communication, which is very likely driven by strong wintertime heat losses, strongly adds to our thinking that the progression of this extreme freshening event is providing us with a natural tracer that is helping to identify and understand key processes that determine the strength and variability of the overturning circulation and its sensitivity to ongoing climate change. Continued monitoring of the overturning in the North Atlantic is therefore necessary.

Plain Language Summary The largest surface freshening event in 120 years observed in 2016 in the eastern Subpolar North Atlantic is now found to have rapidly communicated with the deep waters that sustain the Atlantic overturning circulation, a rich system of ocean currents that is key to the European and global climate.

1. Introduction

Low-salinity waters reaching the subpolar North Atlantic (SPNA) from higher latitudes have important climate ramifications (Dickson et al., 1988; Holliday et al., 2020). Not only are these freshwater pulses able to influence mid-latitude weather systems (Oltmanns et al., 2020), but they have long been thought to have a large impact on the state of the Atlantic Meridional Overturning Circulation (AMOC) – the current system moving warm surface waters northward and cold deep waters in the opposite direction – and hence on our climate (e.g., Jackson et al. (2015)). However, since direct measurements of the AMOC in the SPNA only commenced in 2014 (Lozier et al., 2017), the relationship between freshwater pulses on multiple time scales and AMOC strength is yet far from understood, although there is a consensus that large freshening events, such as the great salinity anomalies (Dickson et al., 1988), play a critical role in causing basin-scale ocean circulation changes (e.g., Zhang and Vallis (2006)).

Devana et al. (2021) reports that the Iceland Scotland Overflow Waters (ISOW), a main component of the AMOC lower limb in the Subpolar North Atlantic (Johns et al., 2021; Zou et al., 2017), and which is formed in the first place in the Nordic Seas through various processes (Greenland Sea deep convection, densification on the Arctic shelves, and transformation of Atlantic-origin waters; e.g., Eldevik et al., 2009), has experienced a significant freshening in the Iceland Basin (IB) since 2017 (Figure 1). This was just after the largest upper-ocean freshening event was observed in 2016 in the upper 1000m (Figure 2a) of the eastern SPNA (Holliday et al., 2020), caused by diversion of Arctic-origin freshwater from the Labrador Current into the interior basin as a result of a reorganization of the wind-stress curl (Holliday et al., 2020; their Figure 10). Using the Overturning in the Subpolar North Atlantic Program (OSNAP) mooring array in the IB, Devana et al. (2021) provide evidence of an apparent link between the surface and the deep layers. They show that the freshening reported by Holliday et al. (2020) communicated rapidly with the deep waters through entrainment (see schematics in Figure 1a), and had a magnitude (−0.01 psu in 1 year) greater than the decade-long 1990s freshening reported by (Dickson et al., 2002; −0.01 psu in 10 years).
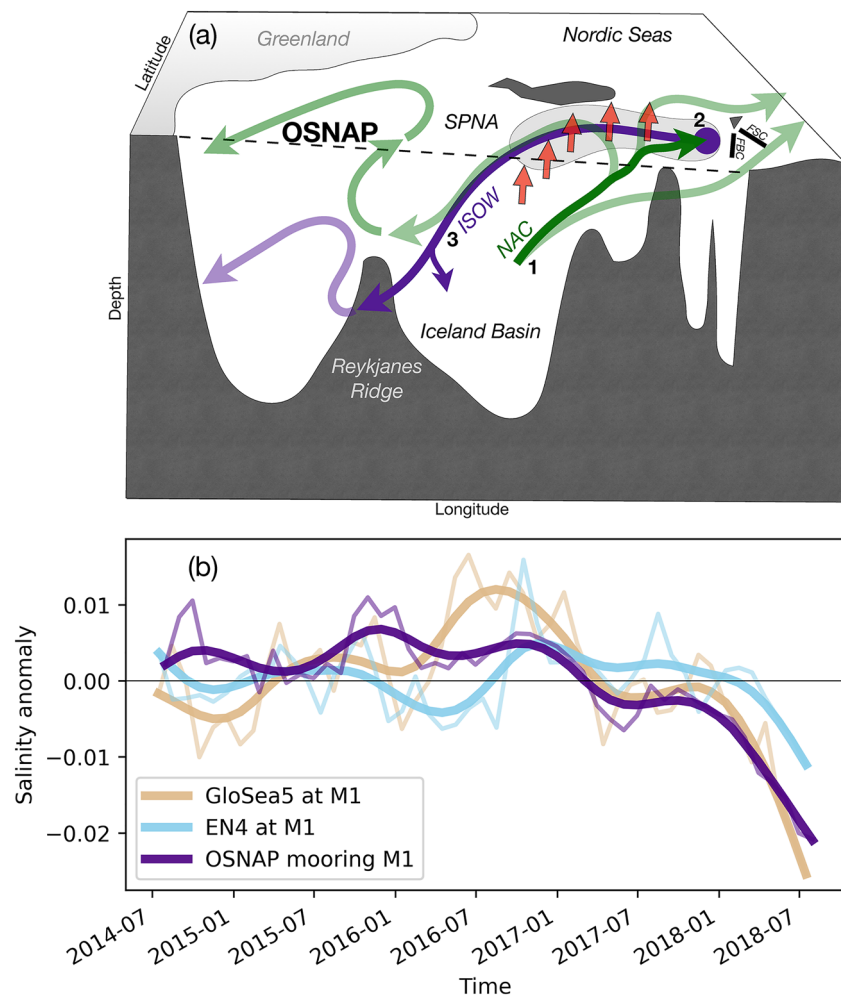
Figure 1. The conveyor belt of the subpolar North Atlantic (SPNA) and the recent deep ocean freshening. (a) A schematic of the overturning in the SPNA. The North Atlantic Current (NAC) pathways are shown in green. The deep-ocean flow of the Iceland Scotland Overflow Water are shown in purple. The gray region denotes the entrainment zone in the Iceland Basin. The red arrows indicate heat loss to the atmosphere that is necessary for the freshening signal to reach the depths of the Faroe Bank Channel (FBC) sill. The filled circle (purple) is the entrainment zone just downstream of the FBC and the bold arrows and numbers indicate the three stages of the entrainment pathway described in Devana et al. (2021): (a) northward advection of the freshening signal to the entrainment zone (2–8 months; dark green NAC path), (b) entrainment into the overflow layer (6–12 months), and (c) southward advection of the signal within ISOW to the Overturning in the Subpolar North Atlantic Program (OSNAP) line (6–15 months). (b) Monthly time series of salinity anomaly (time-mean subtracted) at the OSNAP mooring M1 (purple lines) located along the eastern slope of the Reykjanes Ridge, from the gridded hydrographic database EN4 (blue lines), and from the GloSea5 ocean reanalysis (beige lines). The overlaid smoothed time series (thick lines) are constructed using a 12-month running mean. The salinity time series from EN4 and ocean reanalysis have been produced by linearly interpolating to the location of the M1 mooring (see Devana et al., 2021, their Figure 1).

There are several key aspects to the work by Devana et al. (2021) that are worthy of discussion. First of all, this work shows that without deep temperature and salinity recorders in place, the transfer of this freshening signal from the upper-ocean to the ISOW layer and the effect of entrainment would not have been identified at this early stage. This ISOW freshening signal is surprisingly well captured when using the GloSea5 ocean reanalysis (Blockley et al., 2014) at the OSNAP mooring M1, which is located just east of the Reykjanes Ridge crest along the western boundary current, while the timing and the magnitude of the freshening signal is misrepresented and underestimated, respectively, in the EN4 hydrographic database (Good et al., 2013). However, it appears that there is a large salinity distinction at depth in the interior IB between the OSNAP moorings and GloSea5 or EN4 (not shown). Second, this significant freshening suggests that surface salinity anomalies can rapidly become entrained into deep layers with a total propagation time of about 1.5–2.5 years to reach the OSNAP line (see the
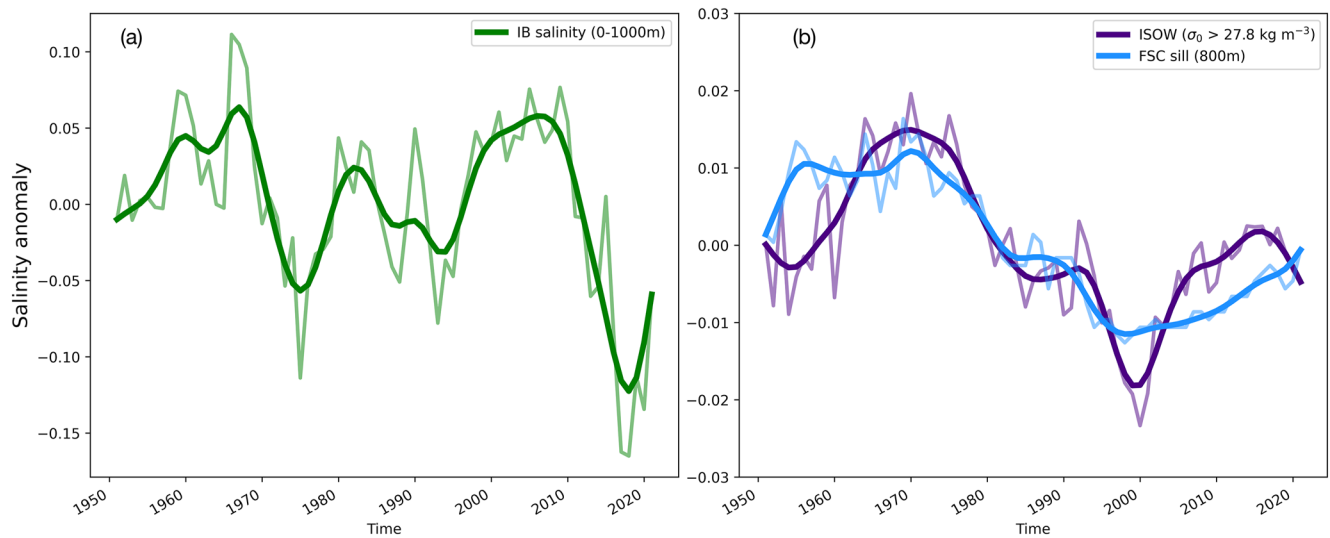
Figure 2. A long-term perspective on salinity in the Iceland Basin (IB) and Nordic Seas. (a) Annual-mean upper-ocean (0–1000m) salinity anomaly (time-mean subtracted) as averaged in the IB near the Overturning in the Subpolar North Atlantic Program line (21–31°W, 57–59°N). (b) Annual-mean salinity anomaly (time-mean subtracted) for the Iceland Scotland Overflow (ISOW) layer ($\sigma_0 > 27.8$ kg m^3; purple lines) near the deep western boundary current along the eastern flank of the Reykjanes Ridge (27–31°W, 58–60°N). The 27.8 isopycnal is allowed to vary with time during the calculations. Annual-mean deep salinity (800m) in the Faroe-Shetland Channel (FSC; blue lines) calculated from all stations along two standard hydrographic sections in the channel (see approximate location in Figure 1a). *Note.* That the FSC sill time series represents properties of water at the level of the deep sill, that is, the level at which water can pass unrestricted into the North Atlantic from the Nordic Seas. The FSC time series highlights that this rapid freshening signal of ISOW is not observed in the Nordic Seas. The monthly EN4 hydrographic data is used to construct the annual-mean IB and ISOW salinity variations. The data in the FSC can be obtained from the ICES Report on Ocean Climate. The thick lines represent the low-frequency (10-year smoothing is applied) variability of the three time series in both panels.

three stages in Figure 1a). The third important point is that this observed signal did not originate from the Nordic Seas, in contrast to the multidecadal freshening event reported by Dickson et al. (2002) (Figure 2b). Salinity variations of the Nordic Seas overflow waters in the Faroe-Shetland Channel (FSC) where they enter the North Atlantic (Hansen & Østerhus, 2007; Hansen et al., 2018; Turrell et al., 1999) reveal no sign of this recent freshening signal seen in the IB at the OSNAP array. This is in contrast to longer time scales and prior to this recent anomaly when variations of the ISOW and FSC salinities are seen to co-vary (Figure 2b). This point is of great importance as it tells us that anomalous ISOW salinity signals do not always have to originate from the Nordic Seas, at least not during this exceptionally large upper-ocean freshening event. This linkage raises the question of how increased Arctic freshwater changes in the future may influence the long-term properties of the North Atlantic Deep Water via entrainment in the IB, and hence the state of the overturning circulation.

The upper-ocean waters of the North Atlantic Current (NAC) are gradually transformed into the denser North Atlantic Deep Water along its path (Chafik & Rossby, 2019). The transformation within the NAC is typically to "intermediate" water types with a depth range of about 800–1500m, but these new results suggest that the entrainment zone just downstream of the Faroe Bank Channel (cf. Figure 1) can act as a shortcut for property anomalies to reach the deepest waters of the IB. Although not examined by Devana et al. (2021), the key mechanism or shortcut by which this takes place must be wintertime convection driven by strong heat loss, as discussed in Petit et al. (2020), that can mix the low-salinity waters to the depths of the FBC sill where it can be entrained and advected to greater depths along the ISOW path. Backtracking this ISOW freshening signal to its upper-ocean source was, however, not possible to achieve in the high-resolution model FLAME used by Devana et al. (2021). This is not a surprise since overflow processes in z-coordinate models are poorly represented when compared to isopycnal coordinate models (e.g., Wang et al., 2015), and entrainment in overflows continue to be an issue in climate models and more sophisticated advection and physically based stratified shear mixing schemes are prerequisites to better represent this mixing process (S. Legg, personal communication). The FLAME model was, instead, used to explain and piece together the observed total advection time scale of the salinity signal from the entrainment zone to the OSNAP array (Figure 1). The model demonstrated that the advection of this deep signal traced the two main ISOW pathways: a fast pathway along the Reykjanes Ridge (6–8 months) and a slow interior pathway (12–15 months). The time scales suggested by the model indeed confirms that this ISOW salinity signal

during the OSNAP period was confined to the IB (see the three stages in Figure 1a) and disconnected from the Nordic Seas.

It is, however, still too early whether this event will only be recorded as a pulse in the time series or will be influenced by the development of a forthcoming decadal-scale freshening of the overflows in the Nordic Seas. There is evidence that this surface freshening has already impacted the eastern Nordic Seas along the NAC pathway (Holliday et al. (2020); their Figure 8), and so we might expect a subsequent freshening of the Iceland Scotland overflow waters in the FSC (following Eldevik et al., 2009), but this remains to be seen. And since this signal is expected to follow the path of the deep western boundary current and could result in density anomalies in the AMOC lower limb, it has the potential to have an influence on the downstream AMOC variability. However, in the context of past historical changes in temperature and salinity, the changes described here are unusual in that the salinity reduced significantly while temperature did not. We will need longer observational records in order to observe whether density compensation will mean the AMOC is unaffected, or whether the reduced density of the deepest waters has a dynamic effect on the large-scale circulation.

It is indeed serendipity that OSNAP was in the water during this large upper-ocean freshening event and that the moorings recorded the progression of this rapid freshening event of the ISOW layer in the IB. Entrainment is of course going on all the time and nothing out of the ordinary (Prater & Rossby, 2005) but the neat finding here is to identify the progression of this anomalous event. The extreme rate of this freshening has thus provided us with a natural tracer that is helping us pinpoint and understand key processes that determine the strength and variability of the AMOC. Continued monitoring of the overturning in the North Atlantic is therefore necessary to our understanding of how sensitive this vital ocean current system is to ongoing global climate change.

Data Availability Statement

The Overturning in the Subpolar North Atlantic Program M1 mooring time series can be accessed through this link: https://doi.org/10.35090/9k7z-8a91. The metoffice EN4 hydrographic data can be accessed through this link: https://www.metoffice.gov.uk/hadobs/en4/download-en4-2-2.html. The GloSea5 ocean reanalysis is from the Copernicus Marine Environment Monitoring Service (CMEMS) and can be accessed through this link: https://resources.marine.copernicus.eu/product-detail/GLOBAL_REANALYSIS_PHY_001_031/INFORMA-TION. The FSC sill salinity time series can be accessed here: (https://ocean.ices.dk/core/iroc).

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