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Rapid Cooling and Increased Storminess Triggered by Freshwater in the North Atlantic

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Key Points:
- Large freshwater events result in distinct cold anomalies with sharp temperature gradients in the subpolar North Atlantic in winter
- A strong, freshwater-induced cold anomaly promotes an enhanced storminess, which reinforces the anomaly by modulating the surface flow
- Consistent with this mechanism, large freshwater events in the past have preceded positive North Atlantic Oscillation periods in winter

Supporting Information:
- Supporting Information S1

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Abstract Recent winters have been unique due to the rapid and extreme cooling of the subpolar North Atlantic. Here, we present a novel view on its causes and consequences. Combining in-situ observations with remote sensing and atmospheric reanalysis data, we show that increased freshening of the subpolar region gives rise to a faster surface cooling in fall and winter. Large freshwater events, in particular, result in pronounced cold anomalies with sharp temperature gradients that promote an enhanced storminess. The storms reinforce the cooling by driving stronger heat losses and modulating the surface flow. Consistent with this mechanism, past freshwater events have been followed by cold anomalies in winter of approximately −2°C and increases in the North Atlantic Oscillation index of up to ~0.6 within 3 years. We expect that future freshwater discharges into the North Atlantic will amplify the cold anomaly and trigger an enhanced wintertime storminess with far-reaching climatic implications.

Plain Language Summary Recent winters have been unique due to a rapid and extreme cooling of the subpolar North Atlantic. Combining ocean and atmospheric data, we show that increased freshwater in this region leads to shallower surface layers that adjust faster to the lower air temperature in fall and winter. The faster surface cooling increases the south-north temperature gradient, which promotes the development of storms. The storms, in turn, reinforce the cooling by modulating the surface flow. Accordingly, past freshwater events have been followed by an extremely cold ocean surface in the subpolar North Atlantic in winter and major changes in large-scale weather patterns. We expect that future freshwater discharges from Greenland and the Arctic will amplify the cooling and trigger an enhanced wintertime storminess with far-reaching implications for the climate.

1. Introduction

Recent winters have been characterized by a rapid and extreme cooling of the subpolar North Atlantic, which has been unprecedented in over 30 years and stands in marked contrast to the warming observed over most of the Earth's surface (Josey et al., 2018). Given the importance of the North Atlantic sea surface temperature (SST) for the large-scale weather and climate (Czaja & Frankignoul, 2002; Sutton & Dong, 2012), it is critical to understand the causes and effects of this anomaly.

Previous studies have attributed the cooling to a slowdown of the Atlantic overturning circulation due to increased freshwater fluxes from Greenland (Caesar et al., 2018; Rahmstorf et al., 2015). This idea is motivated by paleoclimate records, suggesting that past cooling events were caused by a freshwater-forced shutdown of deep ocean convection in the subpolar North Atlantic and a subsequent collapse of the overturning (Barber et al., 1999; Clark et al., 2001, 2002). However, observations show that this buoyancy-driven mechanism cannot easily explain the recent heat transport into the subpolar region (Lozier et al., 2019).

The influences of the cold anomaly on the climate are likewise uncertain. Yet, earlier studies have found that *increased* SSTs in the subpolar region initially trigger a transient baroclinic response in the atmosphere, forcing enhanced ocean heat losses (Deser et al., 2007; Kushnir et al., 2002). After a few weeks, a barotropic equilibrium response emerges that is associated with reduced ocean heat losses and thus represents a positive feedback to the SST anomaly (Deser et al., 2007; Kushnir et al., 2002).

However, we hypothesize that freshwater modulates this atmospheric response by strengthening the stratification, allowing for a faster adjustment of the surface to the lower air temperatures in fall and winter. By eroding the SST anomaly during the transient response, the faster surface cooling interferes with the setup of

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Table 1
Main Data Products and Indices Involved in this Study

Data/index	Period
Hydrographic observations from Argo floats	2002–2018
Remote sensing-based SST data	1982–2018
Absolute dynamic topography from altimetry	1993–2018
Atmospheric data from the reanalysis ERA-Interim	1979–2018
Freshwater index (F_{NA})[a]	1979–2018
Cold anomaly index (CAI)[b]	1982–2019

[a]F_{NA}: Mean NAO in July and August, multiplied by −1. [b]CAI: Mean SST in the cold anomaly region, multiplied by −1.

the equilibrium response and instead increases the meridional SST gradient, key source of baroclinic instability (Hoskins et al., 1985). To test this hypothesis, we investigate the chain of mechanisms initiated by freshwater. The main data products involved in this study are listed in Table 1, while a detailed data description is provided in the supporting information.

2. Results

2.1. Detection of Surface Freshwater

Motivated by earlier studies that discovered a significant anticorrelation of the North Atlantic Oscillation (NAO) in summer with the melting over Greenland (Hanna et al., 2013) and the Arctic sea ice export (Haine et al., 2015), both potential sources of freshwater, we use the mean NAO in July and August, multiplied by −1, as an index ("F_{NA}") to describe the freshwater variability in the subpolar North Atlantic (Figure 1a).

Based on a scaling analysis of the surface mass balance, we find that the surface freshening associated with F_{NA} can be estimated from

$$\beta \, \Delta \, SSS \approx \alpha \, \Delta \, SST, \tag{1}$$

where both sides have been regressed on F_{NA}, α and β are the thermal and haline expansion coefficients, *SSS* is the surface salinity, and Δ refers to the change from summer to winter (see supporting information for details).

The inferred surface freshening is most pronounced in the western subpolar region, off the coast of Newfoundland, from where it expands eastward into the central gyre, following the mean geostrophic flow (Figure 1b). Both F_{NA} and the inferred freshening are characterized by a significantly positive trend over the investigated period and their correlation is largest on time scales above 5 years (Figure 1c). Thus, F_{NA} identifies periods of increased freshwater rather than individual years.

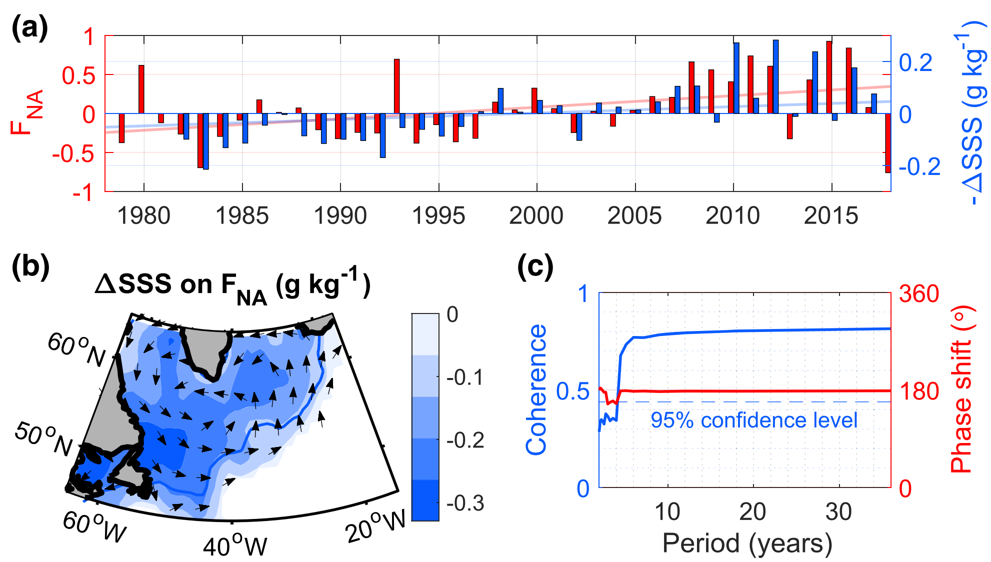

Figure 1. (a) Variability of F_{NA}, which is the mean NAO index in July and August, multiplied by −1, and the inferred surface freshening ($-\Delta SSS$) from summer (August) to winter (January through March) in the region enclosed by the blue 95% confidence line in panel (b). Also shown are the trends. (b) Regression of the inferred SSS change on F_{NA} in the region where an anomalous surface cooling is observed. Thick contours mark the 95% confidence level, and arrows indicate the direction of the mean geostrophic flow. (c) Multitapered coherence and phase shift between F_{NA} and the seasonal SSS change in the region enclosed by the blue 95% confidence line in panel (b), computed using eight tapers. Significance analyses are provided in the supporting information.

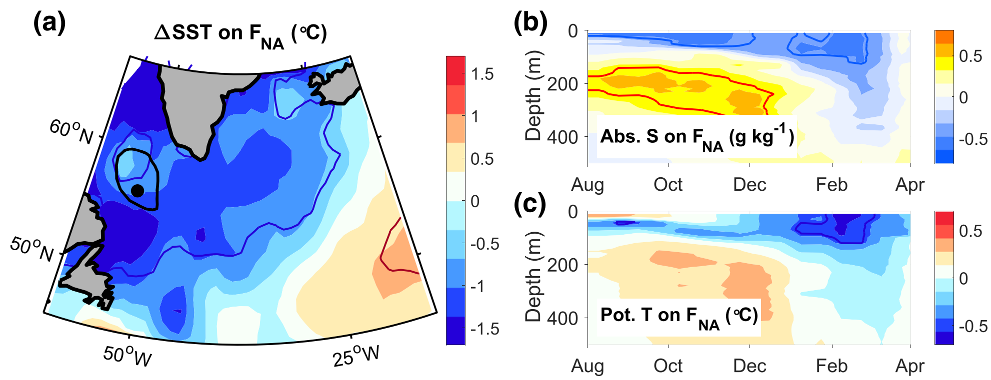

Figure 2. Regressions of (a) the SST change from summer (August) to winter (January through March) and (b, c) the absolute salinity and potential temperature in the Labrador Sea on F_{NA}, based on 17-year long mooring and Argo float observations. The black contour in panel (a) delineates the Argo float sampling region, and the circle marks the mooring location. Colored contours indicate the 95% confidence levels.

2.2. Influence of Surface Freshwater on the SST

The surface mass balance states that an enhanced surface freshening strengthens the stratification, which allows for an increased surface cooling in fall and winter before the freshwater is mixed down. This freshwater-induced surface cooling is one order of magnitude larger than the cooling resulting from the anomalous surface heat flux associated with F_{NA}.

Hydrographic observations from the Labrador Sea over the period 2002–2018 show that an increased surface freshening leads not only to an anomalous cooling relative to the summer (Figure 2a) but also to a cold surface anomaly relative to the climatological mean (Figures 2b and 2c). While the positive subsurface temperature and salinity anomalies are expected from the increased advection of heat and salt in negative NAO periods (Reverdin, 2010; Sarafanov, 2009), the cold surface anomaly can only be explained by the freshwater-induced surface cooling.

However, the hydrographic observations were acquired over a time with an overall elevated freshening (Figure 1a). When considering the full period of satellite observations, the anticorrelation between the freshening in summer and the SST in the subsequent winter only holds for positive freshwater anomalies (Figures 3a–3c), reflecting the transition from the regime where the surface heat fluxes control the SST anomaly to the regime where the freshwater dominates.

The freshwater-induced cold anomaly is most pronounced in the eastern subpolar region (Figures 3a and 3b), where the correlation of the SST, multiplied by −1 (the cold anomaly index "CAI"), with the positive F_{NA} values amounts to ~0.57, which increases for higher values of F_{NA} (Figure 3c). The associated heat flux anomaly is directed upwards and thus cannot account for the cold anomaly. On the contrary, the cold anomaly weakens the heat loss to the atmosphere by reducing the air-sea temperature contrast (Figure 3d).

Southeast of the cold anomaly over the Gulf Stream, the SST is increased (Figure 3a), giving rise to a sharper meriodonal SST gradient, key source of baroclinic instability in the atmosphere (Hoskins et al., 1985). Thus, we next investigate the interaction of the cold anomaly with the atmosphere.

2.3. Atmospheric Feedbacks

Regressing the sea level pressure (SLP) onto the cold anomaly, we find that the cold anomaly is accompanied by an anomalous low over and southeast of Greenland (Figure 4a), representative of a positive NAO. In addition, the standard deviation of the 2- to 6-day band-pass-filtered SLP is increased (Figure 4b), implying an enhanced storminess (Blackmon, 1976; Blackmon et al., 1977; Ulbrich et al., 2008). Consistent with the increased cyclonic activity, the heat loss over the Labrador Sea, south of the sea ice edge, is amplified (Figure 4c), and the wind stress curl under the low is higher (Figure 4d).

A high wind stress curl has been identified as an important driver of the subpolar gyre circulation, which retains cold, fresh polar water in the interior gyre (Chafik et al., 2019; Häkkinen et al., 2011). Altimetry

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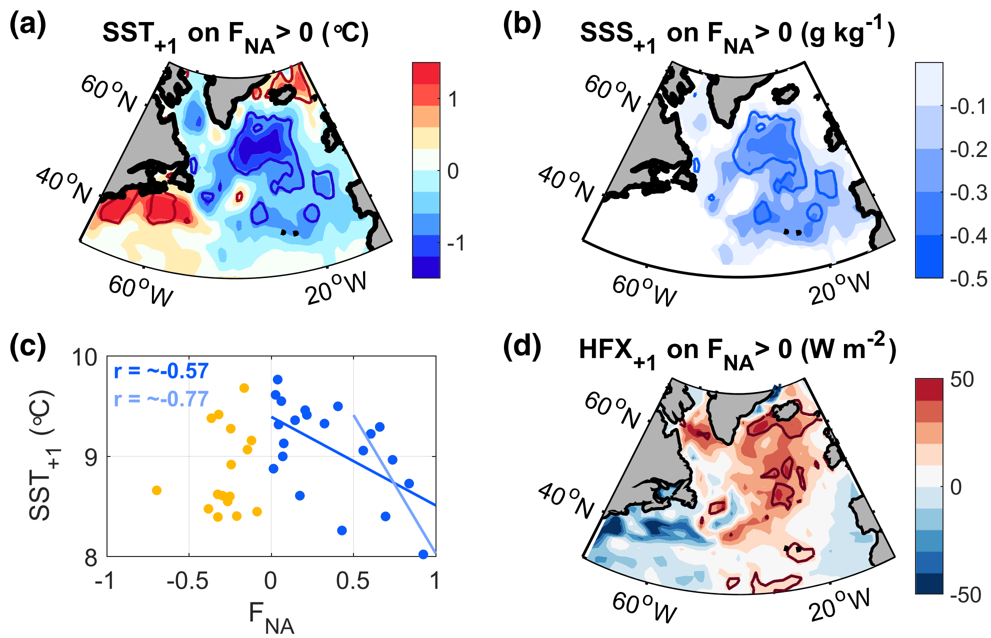

Figure 3. (a, b, d) Regression of the SST, the inferred SSS in the cold anomaly region, and the surface heat fluxes in winter (January through March) on F_{NA} from the preceding summer, with only positive F_{NA} included. A positive heat flux anomaly means that the ocean loses less heat. Thick contours indicate the 95% confidence levels. (c) Relationship between F_{NA} and the SST in the region delineated by the thick blue contour in panel (a). When multiplied by −1, this SST anomaly corresponds to the cold anomaly index (CAI). Also shown are the correlation coefficients and regression lines for $F_{NA}>0$ and $F_{NA}>0.5$.

data confirm that the obtained wind stress curl is associated with a stronger cyclonic circulation, implying an increased advection of polar water off the coast of Newfoundland toward the anomaly, hence reinforcing it (Figure 4e). The correlation between the surface flow pattern and the cold anomaly is ~0.80.

2.4. Summary of the Feedback Mechanism

Closer inspection of the timing of the correlations reveals that the cold anomaly emerges in the winter immediately *following* a high F_{NA} summer and occurs in *the same* winter with the enhanced wind stress curl (Figure 4f). It then continues to intensify and peaks 1 year *after* the wind stress curl reaches its maximum (Figure 4f), as expected from the subpolar gyre response (Lohmann et al., 2009). We sum up:

1. Increased freshening of the subpolar region gives rise to a faster surface cooling.
2. After large freshwater anomalies, a distinct cold anomaly appears.
3. The cold anomaly promotes an enhanced storminess.
4. The resulting higher wind stress curl strengthens the subpolar gyre circulation.
5. The stronger subpolar gyre circulation reinforces the cold anomaly.

This chain of events is supported by the change in the sign of the heat flux anomaly, which is initially downward due to the reduced air-sea contrast (Figure 3d) and then upward and driven by the atmospheric forcing (Figure 4c). However, the discrepancy between the two heat flux anomalies also reveals a nonlinearity in the direct relation between freshwater and the atmosphere: There exists a threshold for the freshwater, after which the sign of the heat flux anomaly reverses, reflecting the transition from the ocean-driven to the atmospherically driven heat flux anomaly.

A composite of the largest freshwater events over the investigated period, included in the supporting information, shows the transition of the heat flux anomaly from being positive in January and February to negative in March. It shows that the most *negative* NAO summers were followed by a *positive* NAO in winter. A regression on these large freshwater events reveals, in addition, a high sensitivity of the atmospheric response to small variations in the freshwater when the freshwater concentration is already high, consistent with the nonlinear relation between F_{NA} and the SST (Figures 3c and S7–S10).

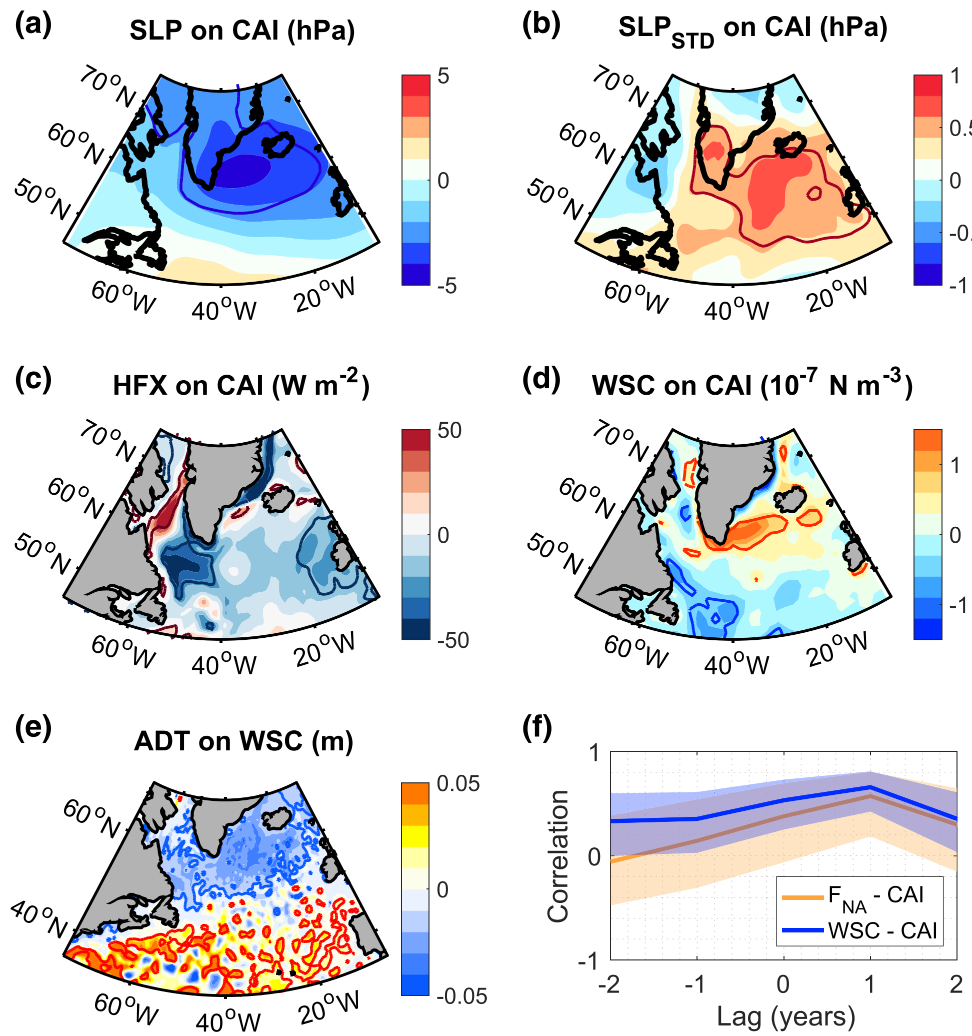

Figure 4. (a–d) Regressions of (a) the SLP, (b) the 2- to 6-day band-pass-filtered standard deviation of the SLP, (c) the surface heat flux (positive downward), and (d) the wind stress curl on CAI, multiplied by the regression of CAI on positive F_{NA}. (e) Regressions of the absolute dynamic topography on the wind stress curl within the red contour in panel (d) ('WSC'), multiplied by the regressions of WSC on CAI and CAI on positive F_{NA}. (f) Correlations of CAI with F_{NA} and the WSC, with the envelopes indicating the 95% confidence levels. A positive lag implies that the cold anomaly lags F_{NA} and the WSC. All variables are in winter (January through March).

2.5. Implications of Freshwater Events for the North Atlantic Climate

Considering that the observational record is still short with regard to the occurrence of large freshwater events, we inspect the evolution of these events individually. Two large freshwater events are the Great Salinity Anomaly in 1969–1972 (Lazier, 1980) and the recent freshening (Holliday et al., 2020) peaking in 2008–2012 and 2015/2016 (supporting information). The Great Salinity Anomaly preceded a cold anomaly of approximately −1.5°C, while the recent freshening culminated in an anomalous approximately −2°C (supporting information). Both events were followed by an enhanced storminess, reflected in increases of the winter NAO of ~0.61 after 1970 and ~0.72 after 2010 (Figure 5a).

Additional salinity anomalies have been reported for the 1980s and 1990s (Belkin et al., 1998). Although the sparse sampling prevents the determination of the exact starting dates, compilations of historical salinity data suggest that they appeared in the Labrador Sea in 1980 (Reverdin et al., 1997; Yashayaev & Loder, 2016) and 1993 (Yashayaev & Clarke, 2006; Yashayaev & Loder, 2016), consistent with increased values of F_{NA} (Figure 1a). Both events were followed by a reduced SLP and a negative SST anomaly in the subpolar region within 3 years (Figure 5).

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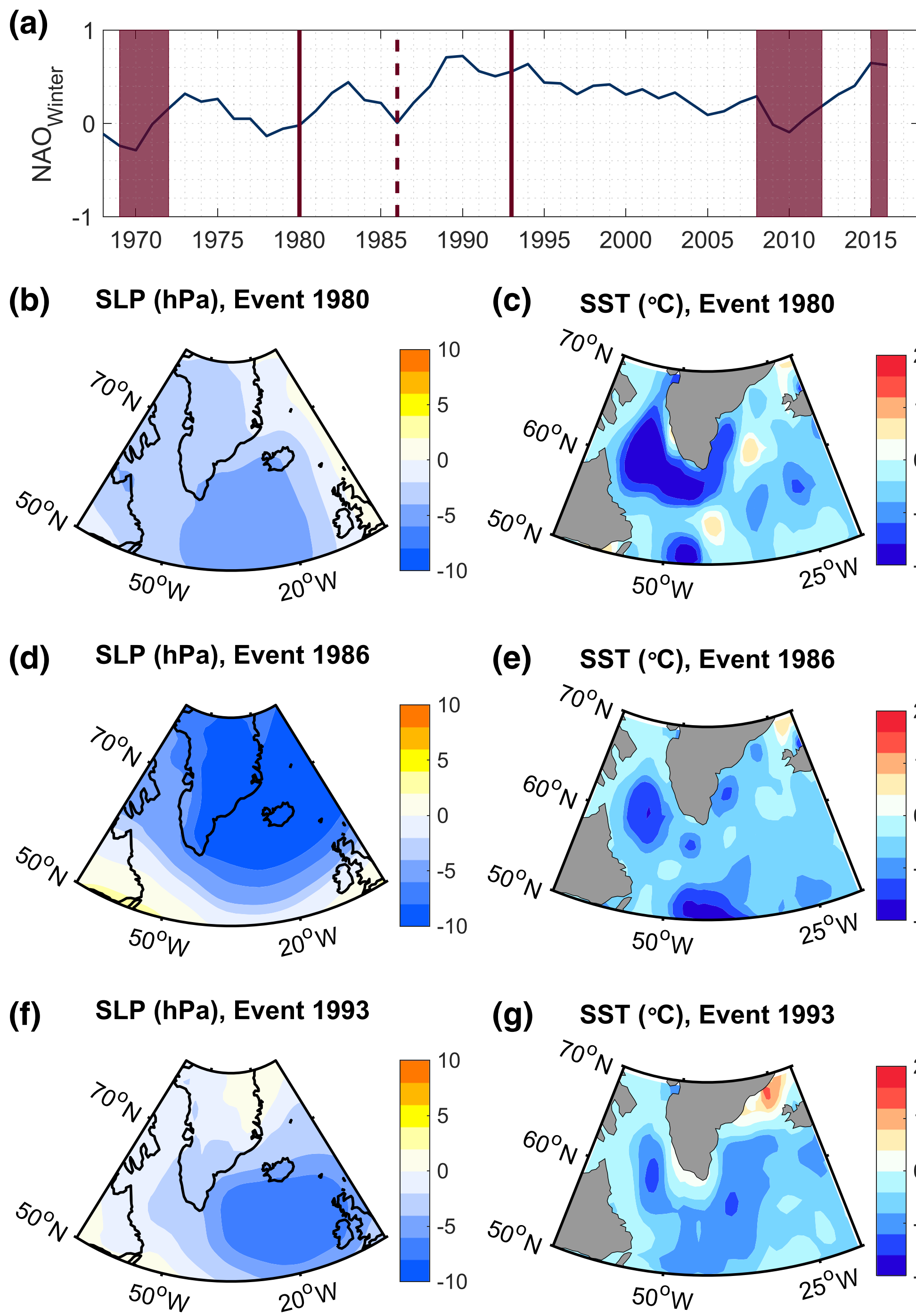

Figure 5. (a) Variability of the three-winter low-pass filtered NAO index. The solid lines and shadings indicate the times of large documented freshwater anomalies, and the dashed line marks the time of an inferred event. (b–g) SLP and SST anomalies following the events in 1980, 1986, and 1993. While the anomalies typically last for several winters, we show them at the time when they reach their maximum amplitude: (b) SLP 1982, (c) SST 1983, (d) SLP 1989, (e) SST 1990, (f) SLP 1994, and (g) SST 1994. All anomalies are with respect to the climatological winter mean.

The detailed evolution of the cold anomaly differed between the investigated freshwater events, which we attribute to variations in the freshwater volumes, their pathways (Belkin et al., 1998), and the strength of the surface fluxes, mixing freshwater down. Also, the event in 1980 preceded an increase in the winter NAO of ~0.46, similar to the other events, whereas the event in 1993 occurred in a phase, in which the winter NAO was already high (Figure 5a). Thus, the subpolar gyre circulation was already intensified (Belkin, 2004) and the maximum SST anomaly was reached sooner (Figure 5g).

Examining the winter NAO more closely, we detect another period of increase starting in 1986 (Figure 5a), concurrent with an elevated value of F_{NA} (Figure 1a). The following winters were characterized by a strongly reduced SLP and a distinct cold anomaly, exceeding approximately −2°C in the Labrador Sea (Figures 5d and 5e). We conclude that, despite differences in their amplitude and detailed evolution, all freshwater events show a link with an enhanced wintertime storminess and the emergence of a cold anomaly. Conversely, all major NAO increases in the last 50 years show a link with a freshwater event.

3. Conclusion

Combining in situ observations with remote sensing and atmospheric reanalysis data, we have shown that enhanced freshening of the subpolar North Atlantic gives rise to an increased surface cooling in fall and winter. Over the last four decades, the freshwater-induced surface cooling has been characterized by a significantly positive trend, reflecting a growing discrepancy between the summer and winter SSTs.

Superimposed on the trend, individual strong freshwater events have triggered pronounced cold anomalies in winter. By increasing the meridional SST gradient, cold anomalies in the subpolar region promote the development of cyclones, which reinforce the cooling by modulating the subpolar gyre circulation. In agreement with this chain of events, past freshwater events were followed by cold anomalies of approximately −2°C and an enhanced wintertime storminess, reflected in increases of the NAO of up to ~0.6 within 3 years.

Our findings suggest that the cold anomaly in winter can be explained by an enhanced surface freshening and the resulting regional atmosphere-ocean interactions, without the need for a buoyancy-driven slowdown of the large-scale overturning circulation. Thus, this study reconciles the proposed inconsistencies between the recent strong convection in the Labrador Sea and the reduced northward heat transport (Lozier et al., 2019). However, the results do not exclude the possibility of a buoyancy-driven slowdown of the overturning on longer time scales.

The identified, freshwater-induced SST pattern resembles the negative phase of the Atlantic Multidecadal Oscillation, which has been found to drive a positive NAO response in winter (Gastineau & Frankignoul, 2015; Peings & Magnusdottir, 2014). Our findings are therefore consistent with earlier studies and suggest that freshwater plays a key role in modulating the low-frequency climate variability over the North Atlantic. In particular, they show that large freshwater events, arising from the most negative NAO summers, were followed by rapid transitions to the most positive NAO phases in winter.

With regard to the influences of the winter NAO on large-scale weather patterns (Hurrell & Deser, 2010), freshwater-induced NAO increases have far-reaching implications. For instance, they can trigger cold spells over Canada (Shabbar & Bonsal, 2004), precipitation events over the United Kingdom (Lavers et al., 2011), and storms over northwest Europe (Feser et al., 2015). Considering the growing freshwater discharges from Greenland (Bamber et al., 2012) and the Arctic (Haine et al., 2015) and the high sensitivity to small variations in the freshwater, when the freshwater concentration is already high, our results raise caution that weather extremes associated with deep cyclones in the subpolar region in winter will increase.

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