



Cold Water in a Warm World: Investigating the Origin of the Nordic Seas' Unique Surface Properties During MIS 11

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Surface waters in the Nordic Seas were colder and fresher throughout the marine isotope stage (MIS) 11 interglacial compared to present day. This has been previously attributed to the continuous delivery of freshwater sourced from large ice structures characteristic of the preceding glacial interval, MIS 12. While it is conventionally believed that high-latitude surface freshening can trigger a reduction of the Atlantic Meridional Overturning Circulation (AMOC), multiple lines of evidence suggest a vigorous AMOC despite elevated freshwater forcing in the Nordic Seas. Here, we review and reanalyze evidence for sea surface properties throughout the Nordic Seas and North Atlantic. We find that surface waters in the Nordic Seas experienced an unusually variable inception of interglacial temperature conditions with multiple high-magnitude cold excursions. While cold events in the North Atlantic were frequently associated with in situ meltwater deposition as reconstructed by ice-rafted debris, this proxy was virtually uncorrelated with cold events in the Nordic Seas. Additionally, stable nitrogen analysis revealed variable levels of nutrient utilization in the Nordic Seas' surface layer throughout MIS 11. This may reflect a dynamic structure of the upper ocean concomitant with an intermittent rate of freshwater delivery. Based on this combination of evidence, we suggest that the colder and fresher surface layer in the Nordic Seas was supplied from higher latitudes, rather than from locally-sourced iceberg meltwater as is characteristic of North Atlantic forcing. Pairing proxy-based evidence with recent numerical simulations further decouples surface freshening in the Nordic Seas and Greenland meltwater input, discrediting Greenland as a source of freshwater to this region during the later phase of MIS 11. Because the origin of freshwater has implications for its rate of delivery, our study might help to explain the active AMOC despite surface freshening during MIS 11 and should be recognized when considering this interglacial as an analog for near-future climate change scenarios.

Keywords: MIS 11, AMOC, North Atlantic, Surface waters, Global change, Paleoceanography

INTRODUCTION

Forecasting future Global changes associated with anthropogenic warming requires a comprehensive understanding of the variables that regulate Earth's climate system. Reconstructing climate variability in the past can help to better characterize impending changes by contextualizing the processes affected by anthropogenic warming. The interglacial period from 424 to 374 ka,

marine isotope stage (MIS) 11, has long been considered a powerful analog for modern climate change because of its apparent orbital (Berger and Loutre, 2002; Loutre and Berger, 2003) and atmospheric (Raynaud et al., 2005) similarities to the pre-industrial Holocene. While some records originally suggested comparable internal climate dynamics between MIS 11 and the present interglacial (e.g., Howard, 1997; de Abreu et al., 2005; McManus et al., 2013), later work revealed key differences in cryospheric activity in addition to atmospheric and oceanic circulation patterns (Dickson et al., 2009; Kandiano et al., 2012, 2016; Droessler et al., 2013; Thibodeau et al., 2017a). Here, we review and reanalyze evidence for stage 11's unique sea surface properties with particular attention given to the Nordic Seas, a critical location involved in driving ocean circulation. We investigate ice sheet demise and subsequent freshwater forcing throughout the high-latitude Atlantic Ocean and discuss potential consequences for overturning circulation. Using a combination of published ice-rafted debris (IRD) records and sea surface temperature (SST) reconstructions, we suggest that surface freshening in the Nordic Seas during MIS 11 originated from an external source rather than from *in situ* meltwater such as is characteristic of North Atlantic forcing. We hypothesize that the observed freshwater was derived from higher latitudes, which may be helpful for informing scenarios of near-future freshening in the region.

The Global temperature optimum of MIS 11 is centered around 405 ka, and occurred late in the stage relative to temperature optima of other quaternary interglacial periods. Most records also indicate that peak interglacial conditions persisted for 25–30 ky, an abnormally long time relative to other quaternary interglacials (McManus et al., 2013; Candy et al., 2014). While evidence from an uninterrupted Lake El'gygytgyn sediment core suggests that stage 11 was characterized by an anomalously warm temperature optimum and uniquely elevated sea levels (Melles et al., 2012), planktic $\delta^{18}\text{O}$ values suggest it was no warmer than other interglacials during the past 450 ka (McManus et al., 1999; Hodell et al., 2000). The continued uncertainties regarding the climatic structure of MIS 11 highlight problems with using stage 11 for contemporary climate predictions. Additional complications are introduced when comparing the nature of the Atlantic Meridional Overturning Circulation (AMOC) between both periods.

The AMOC broadly describes the movement of waters throughout the Atlantic Ocean. In the North Atlantic and Nordic Seas, waters are cooled intensely by winds, lose buoyancy, and sink to form North Atlantic Deep Water (NADW), which is exported southward. NADW is composed of Labrador Sea Water, formed in the Labrador Sea, and denser overflow water masses such as Denmark Strait Overflow Water and Iceland-Scotland Overflow Water (Buckley and Marshall, 2016). Because the subpolar North Atlantic is a locus of NADW formation, this region is important for facilitating the strength of Global ocean circulation. Drivers of the contemporary AMOC include local wind forcing on the intra- and interannual timescale, and a combination of thermohaline and wind-driven mechanisms on the decadal timescale (Buckley and Marshall, 2016). Thermohaline mechanisms influence AMOC strength

via diapycnal mixing, or density-driven heat transfer from the surface to deep water. This occurs as a result of wind and tide action, which produces internal waves. Mixing from these internal waves results in lighter deep ocean waters, which can subsequently rise in low latitudes. On shorter timescales, the AMOC is also influenced via northward movement of waters resulting from westerly circumpolar winds (Kuhlbrodt et al., 2007; Buckley and Marshall, 2016).

Numerical studies utilizing both simple box models and general circulation simulations suggest that NADW formation is sensitive to freshwater forcing at the sea surface. Stommel (1961) developed the first box model to describe the physical properties of overturning circulation and showed that two stable regimes can exist within a theoretical framework of thermohaline flow. This was later validated using a coupled ocean-atmosphere model, which revealed a stable system with and without North Atlantic convection (Manabe and Stouffer, 1988). A direct consequence of Stommel's pioneering work is that there exists a bifurcation point, often referred to as the "Stommel bifurcation point," whereby sufficient surface freshening may induce hysteresis, destabilize contemporary overturning circulation (Rahmstorf et al., 2005), and result in abrupt changes in Global climate (Delworth et al., 2008). This is increasingly relevant for modern warming scenarios, as multiple modeling studies suggest that the strength of the AMOC may be impacted by meltwater derived from the Greenland Ice Sheet (GIS) (Bakker et al., 2016; Böning et al., 2016; Luo et al., 2016; Yu et al., 2016). While AMOC recovery may be possible under practical melting scenarios (Gregory et al., 2005; Jungclauss et al., 2006; Stouffer et al., 2006), more recent work suggests that these studies may have favored an unrealistically stable AMOC (Liu et al., 2017). A multi-proxy statistical index has illustrated a slowdown of the contemporary AMOC since 1975 (Rahmstorf et al., 2015) coherent with reduced convection in the Labrador Sea (Yang et al., 2016; Thornalley et al., 2018) and SST patterns indicative of a shifting Gulf Stream (Caesar et al., 2018), a major wind-driven surface current in the circulation system. These observations coupled with uncertainties characteristic of modeling studies highlight the need for paleoceanographic investigations of high-latitude freshwater forcing in Earth's geological past to more accurately forecast future changes to ocean circulation.

Throughout the previous glacial cycle, geochemical proxies indicate that the AMOC shut down during Heinrich stadials 11, 2, and 1 coincident with extensive fresh meltwater, but remained active during several other Heinrich events (Böhm et al., 2015). Multiple investigations of AMOC dynamics throughout MIS 11 also suggest that overturning circulation remained strong and active during this time. Paired micropaleontological and stable isotope data suggest that the onset of MIS 11 aligned with strong NADW formation (Vázquez Riveiros et al., 2013; Rodríguez-Tovar et al., 2015). Benthic carbon records throughout the Atlantic Ocean further suggest an abrupt strengthening of the AMOC around 415 ka, which was attributed to obliquity-driven heat redistribution (Dickson et al., 2009). The decay of Global interglacial conditions was also marked by a strengthened leakage of waters from the Indo-Pacific Ocean into the South

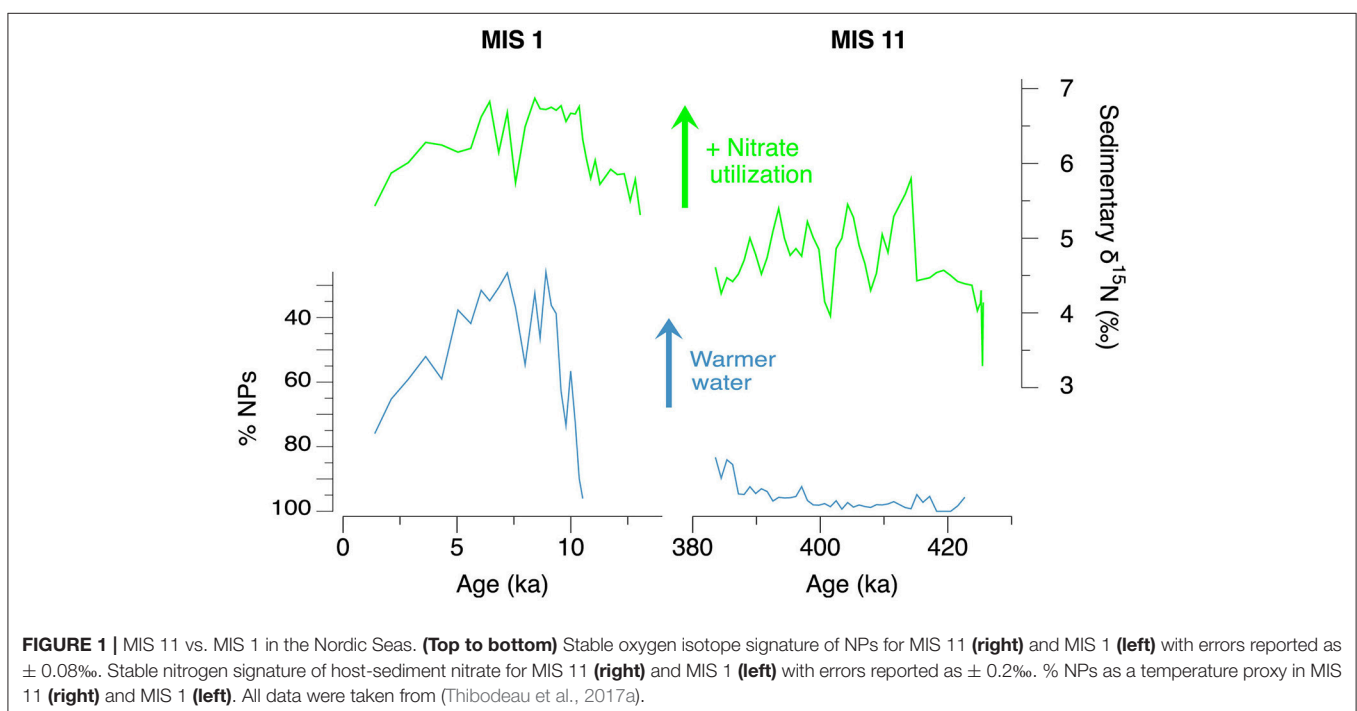
Atlantic, the “Agulhas leakage,” which was hypothesized to drive another increase in AMOC strength around 400 ka and is consistent with reconstructions of European vegetation patterns (Koutsodendris et al., 2014). Interestingly, strengthened circulation occurred despite heightened freshwater forcing in the Nordic Seas (Kandiano et al., 2016; Thibodeau et al., 2017a), which challenges the conventional belief of meltwater-driven AMOC destabilization.

Various lines of evidence point to the extreme melting of the GIS during MIS 11 (Raymo and Mitrovica, 2012; Cronin et al., 2013; Reyes et al., 2014; Hatfield et al., 2016; Schaefer et al., 2016; Robinson et al., 2017), which is commonly invoked as a possible explanation for the cold and fresh surface waters observed in the Nordic Seas relative to the Holocene (Kandiano et al., 2016; Thibodeau et al., 2017a). Evidence for an anomalously cold surface layer is derived from multiple SST records, including the abundance of a polar-indicating foraminiferan, *Neogloboquadrina pachyderma* sinistral (NPs) (Figure 1; Kandiano et al., 2016; Thibodeau et al., 2017a). Salinity reconstructions derived from the hydrogen composition of alkenones further indicate that these waters were unusually fresh during MIS 11 (Kandiano et al., 2016). The relatively colder sea surface conditions in the Nordic Seas contrast with surface conditions elsewhere throughout the North Atlantic, which have been reconstructed as warmer-than-present (Helmke and Bauch, 2003; Kandiano and Bauch, 2007; Kandiano et al., 2012; Bauch and Erlenkeuser, 2013). This may reflect freshwater release sourced from the extended melting of large ice structures left over from the preceding glacial period, MIS 12 (Kandiano et al., 2016). Such long-term meltwater forcing is also supported by bulk $\delta^{15}\text{N}$, a proxy for nutrient utilization and upper-ocean

stratification, which suggests a slow thinning of the summer mixed layer relative to MIS 1 (Figure 1; Thibodeau et al., 2017a). These differences in upper-ocean structure reinforce the notion that sea surface conditions in the Nordic Seas during MIS 11 were considerably different from the Holocene.

Further, the Nordic Seas experienced a unique phasing and variability of sea surface properties during interglaciation, including notable high-magnitude cold anomalies (Kandiano et al., 2016) and delayed peak warming conditions relative to more southern locations (Kandiano et al., 2012). Atmospheric circulation has been previously invoked to explain SST patterns throughout the North Atlantic during the development of MIS 11. Kandiano et al. (2012) hypothesized that stage 11 was characterized by a negative North Atlantic Oscillation (NAO) mode, whereby a decreased atmospheric pressure gradient between the Icelandic low and Azores high suppressed the penetration of North Atlantic warm waters into the Nordic Seas and allowed for more extensive seasonal sea ice cover. However, stable nitrogen evidence indicates a thicker and colder surface mixed layer in the Nordic Seas during MIS 11 relative to the Holocene (Thibodeau et al., 2017a), which may be explained by a continuous input of freshwater from ice melt. The relatively thicker mixed layer implies that the dominance of NPs during MIS 11 does not necessitate the absence of North Atlantic waters, which could still feasibly be advected northward at a greater depth. A strong advection of Atlantic waters would be coherent with the intense AMOC supported by benthic $\delta^{13}\text{C}$ records from Atlantic cores (Vázquez Riveiros et al., 2013).

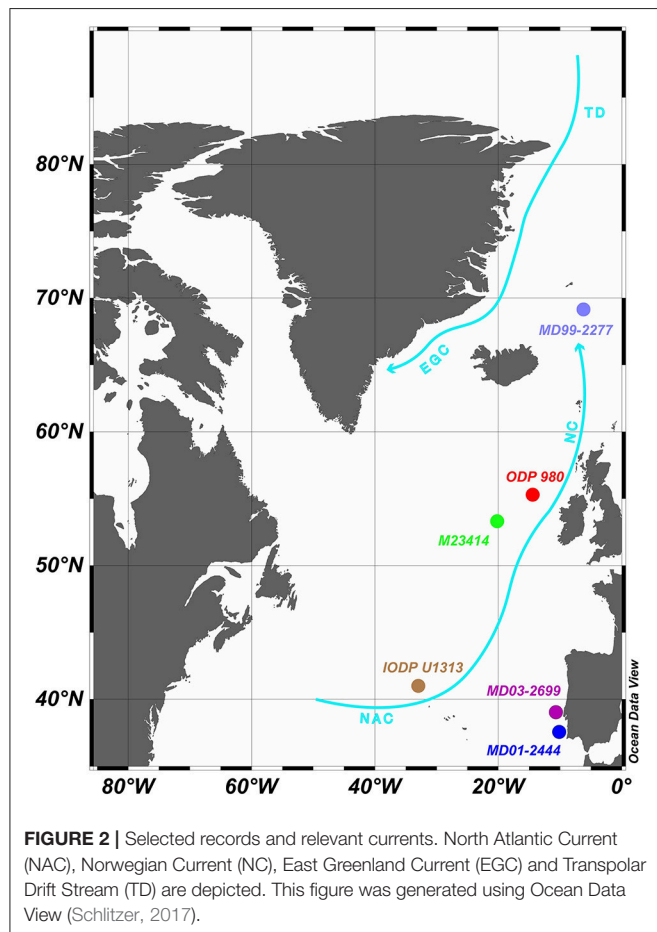
Nevertheless, it is conceivable that NAO could impact the flow of freshwater from the north, as contemporary observations have shown that negative NAO conditions favor the transport of Arctic



freshwater into the Nordic Seas (Morison et al., 2012). Because the source of freshwater would have implications for its rate of delivery into the Nordic Seas, uncertainties surrounding the origin of the fresher sea surface present another challenge with using MIS 11 as an analog for potential near-future freshwater forcing of thermohaline circulation. Below, we consider possible explanations for the source of the colder and fresher sea surface by comparing records from the Nordic Seas to other North Atlantic sites in the context of SST variability and IRD deposition. We find that the freshwater surface layer in the Nordic Seas was likely supplied externally rather than from *in situ* meltwater input. This has implications for reconsidering the flow of freshwater in the high-latitude North Atlantic, which may enhance our understanding of AMOC dynamics during MIS 11.

SELECTED RECORDS: PROXIES AND POSITIONS

In addition to site MD99-2277 in the Nordic Seas, we consider five North Atlantic sites (from higher to lower latitudes, ODP 980, M23414, IODP U1313, MD03-2699, and MD01-2444) for this study (Figure 2). Our analyses are based on independent age models established in previous publications and are not tuned to each other.



Site MD99-2277 (Nordic Seas)

Site MD99-2277 is located at 69° 15' N, 6° 19' W in the central Nordic Seas. Here, data from the nearby PS1243 core (69°22' N, 6°32' W) are also used to describe conditions at this location. The Nordic Seas are predominately influenced by the Norwegian Current, which carries North Atlantic water northward, and the East Greenland Current, transporting Arctic Water southward. At this site, we consider published proxy data describing freshwater volume, SST (Kandiano et al., 2016), IRD (Helmke et al., 2003; Kandiano et al., 2012), and stable nitrogen evidence of nutrient utilization (Thibodeau et al., 2017a). The chronostratigraphy of MD99-2277 presented here was developed in Kandiano et al. (2012) and the age model for PS1243 was supplied by Bauch et al. (2001).

Salinity was derived from the hydrogen isotopic composition of alkenones retrieved from MD99-2277 (van der Meer et al., 2007; Kandiano et al., 2016). SST was reconstructed from foraminiferal census counts, which record temperature in 0–150 m depth of water (Kandiano et al., 2016). IRD grains larger than 250 μm were picked from PS1243 and nutrient utilization was reconstructed from the $\delta^{15}\text{N}$ signal of nitrate in PS1243 sediments (Thibodeau et al., 2017a).

Site ODP 980 (High-Latitude North Atlantic)

ODP Site 980 is located at 55° 29' N, 14° 42' W, positioned in the Feni Drift of the North Atlantic Ocean. This site is north of the Ruddiman IRD belt, where maximum quaternary ice-rafting occurred (Ruddiman, 1977). Its position is on the northern boundary of the northward flowing North Atlantic Current and the southern boundary of the northward flowing Norwegian Current. Here, we consider SST and IRD. The chronostratigraphy presented with these data was developed in McManus et al. (1999).

SST was reconstructed via benthic and planktic foraminiferal stable oxygen isotopes. The $\delta^{18}\text{O}$ signal of the benthic foraminiferan *Cibicides wuellerstorfi* was subtracted from NPs- $\delta^{18}\text{O}$, which removes the effect of ice volume and allows the result to effectively represent SST (McManus et al., 1999). IRD grains from this core were picked at fractions larger than 150 μm (McManus et al., 1999).

Site M23414 (High-Middle-Latitude North Atlantic)

Site M23414 is located southwest of ODP 980 at 53° 32' N, 20° 17' W and is also positioned adjacent to the North Atlantic Current and to the north of the IRD belt. Here, we consider two temperature proxies retrieved from the analog site, GIK23414-8 (54° N, 20° 29' W), one recording SST and the other recording mid-depth (0–200 m) temperature. IRD grains are also investigated. The age model presented for this core was taken from Kandiano and Bauch (2007).

While multiple temperature proxies are available at this site, we chose to represent SST by the average of three foraminifera-derived methods (see Kandiano and Bauch, 2007) for two reasons: they are the highest-resolution temperature records available and, because the MD99-2277 SST record also relies on foraminiferal census data, such a record may be more directly

comparable to the Nordic Seas. The mid-depth temperature was reconstructed via the relative abundance of isoprenoid glycerol dibiphytanyl glycerol tetraethers (GDGTs) in lipids derived from *Thaumarchaeota* (TEX_{86}^L) (Kandiano et al., 2017). IRD grains were picked at fractions larger than $150\ \mu\text{m}$ (Kandiano and Bauch, 2007).

Site IODP U1313 (Low-Middle-Latitude North Atlantic)

IODP Site U1313 is positioned within the Mid-Atlantic Ridge near the southern boundary of the IRD belt at $41^\circ\ \text{N}$, $32^\circ\ 96'\ \text{W}$. Here, we consider an alkenone-based SST record (the alkenone unsaturation index, $U_{37}^{K'}$) and an IRD record with grains larger than $315\ \mu\text{m}$ (Stein et al., 2009; Voelker et al., 2010). Ages reported with this core were derived from Stein et al. (2009)

Sites MD03-2699 and MD01-2444 (Low-Latitude North Atlantic)

Sites MD03-2699 ($36^\circ\ 04'\ \text{N}$, $10^\circ\ 66'\ \text{W}$) and MD01-2444 ($37^\circ\ 34'\ \text{N}$, $10^\circ\ 09'\ \text{W}$) are both located on the western Iberian margin. SST records for both cores were derived from $U_{37}^{K'}$ values (Martrat et al., 2007; Rodrigues et al., 2011). IRD was picked at grains larger than $315\ \mu\text{m}$ at MD03-2699 (Voelker et al., 2010). However, there is no available IRD record at Site MD01-2444. The age model in Voelker et al. (2010) is presented here for MD03-2699, while ages for MD01-2444 were derived from Martrat et al. (2007).

MECHANISMS OF CLIMATE CHANGE

Orbital Configuration and Atmospheric Greenhouse Gas Composition

Variations in insolation driven by orbital parameters are controlled by the phasing of Earth's orbital eccentricity, operating on a 96,000-year cycle, obliquity of Earth's rotational axis, operating on a 41,000-year cycle, and precession of the Equinoxes, operating on a 23,000-year cycle (Hays et al., 1976). The insolation trend during MIS 11 (Figure 3) was most similar to MIS 1 and MIS 19 compared to other quaternary interglacial periods because of reduced eccentricity forcing (Berger and Loutre, 2002; Loutre and Berger, 2003). This feature in combination with the similar atmospheric CO_2 concentrations between stages 11 and the pre-industrial Holocene (Figure 3; Raynaud et al., 2005; Siegenthaler et al., 2005) initially inspired considerations of stage 11 as an analog for Earth's modern climate system.

Ice Volume and AMOC Dynamics

Changes in ice volume, while driven by external forces, also act as a feedback mechanism in the climate system by controlling albedo. Moreover, freshwater forcing of deepwater formation associated with high-latitude ice melt underscores the importance of cryosphere dynamics in the context of Global climate change. Because ice accumulates increased levels of ^{16}O relative to ^{18}O compared to ocean water, ice volume is commonly reconstructed from the stable oxygen signature in benthic foraminifera. The Lisiecki-Raymo stack of globally-distributed

benthic oxygen isotope data, "LR04," is the most comprehensive record of Pleistocene ice volume (Lisiecki and Raymo, 2005), and shows a progressive decline in Global ice cover (lower $\delta^{18}\text{O}$) leading up to the inception of MIS 11 (Figure 3).

In addition to oxygen data, stable carbon isotopes in benthic foraminifera can be used to reconstruct water mass properties, where high $\delta^{13}\text{C}$ values indicate an increased presence of NADW (a strong AMOC) and low values reflect an increase in Antarctic Bottom Water (a weaker AMOC). During MIS 11, a rise in Global benthic $\delta^{13}\text{C}$ suggests a strong overturning circulation (Figure 3). A cross-latitude analysis of stable carbon isotopes suggests an abrupt strengthening of the AMOC approximately 415 ka (Dickson et al., 2009), which is reinforced by empirical orthogonal function analyses of Global sea surface trends (Milker et al., 2013) and may explain the lengthened interglacial temperatures characteristic of MIS 11. This is further supported by subtle SST increases around this time in low-latitude North Atlantic sites IODP U1313 (Stein et al., 2009), MD03-2699 (Rodrigues et al., 2011), and MD01-2444 (Martrat et al., 2007) in addition to the high-latitude North Atlantic site ODP 980 (McManus et al., 1999) and the Nordic Seas record (Kandiano et al., 2016). Taken together, these findings suggest an increase in northward heat transport driven by a stronger circulation (Figure 3).

It is difficult to discern whether this increase also occurs in M23414 as derived from the foraminiferal multi-proxy SST record. The temperature record at this site is further complicated by transient cold excursions recorded in the 0–200 m layer via TEX_{86}^L values (Figure 3). Due to its alignment with a brief decrease in surface salinity and lower ice volume, Kandiano et al. (2017) reasonably attributed the latter cold event to ice melt. However, this trend is not as obviously apparent in the foraminiferal SST record (Figure 4). While the TEX_{86}^L cold excursion may be exaggerated by vertical migration, a separate $U_{37}^{K'}$ record at this site also provides evidence of a cold event around this time, though less dramatic than the one reconstructed from TEX_{86}^L values (Kandiano et al., 2017).

THE UNIQUE NORDIC SEAS OF MIS 11

Full interglacial SST conditions in the Nordic Seas emerged later relative to all other North Atlantic records (Figure 4). Additionally, SST was more variable during the interglacial inception in the Nordic Seas relative to the North Atlantic, marked by higher-magnitude cold anomalies (Figure 5A). While warm anomalies are to be expected during interglaciation, cold excursions require an additional explanatory mechanism. Cold events in the North Atlantic are highly correlated with IRD ($R^2 = 0.76$ in both M23414 and ODP 980 records), likely reflecting the impact of transient *in situ* meltwater on SST at these sites (Figures 5B,C). However, this relationship is virtually nonexistent in the Nordic Seas ($R^2 = 0.03$). While the R^2 -value is identical to two decimal places in both North Atlantic records, methodological differences in SST reconstructions likely make MD99-2277 and M23414 records more directly comparable,

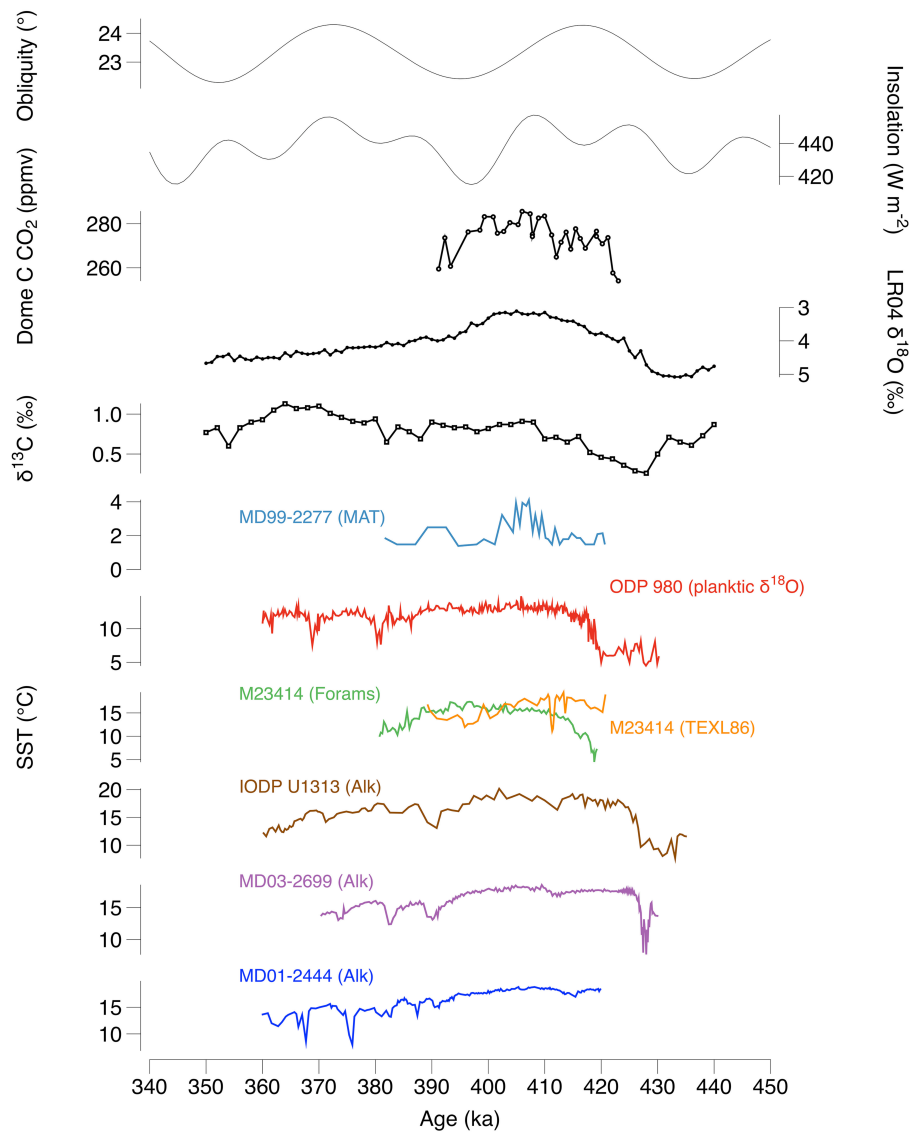
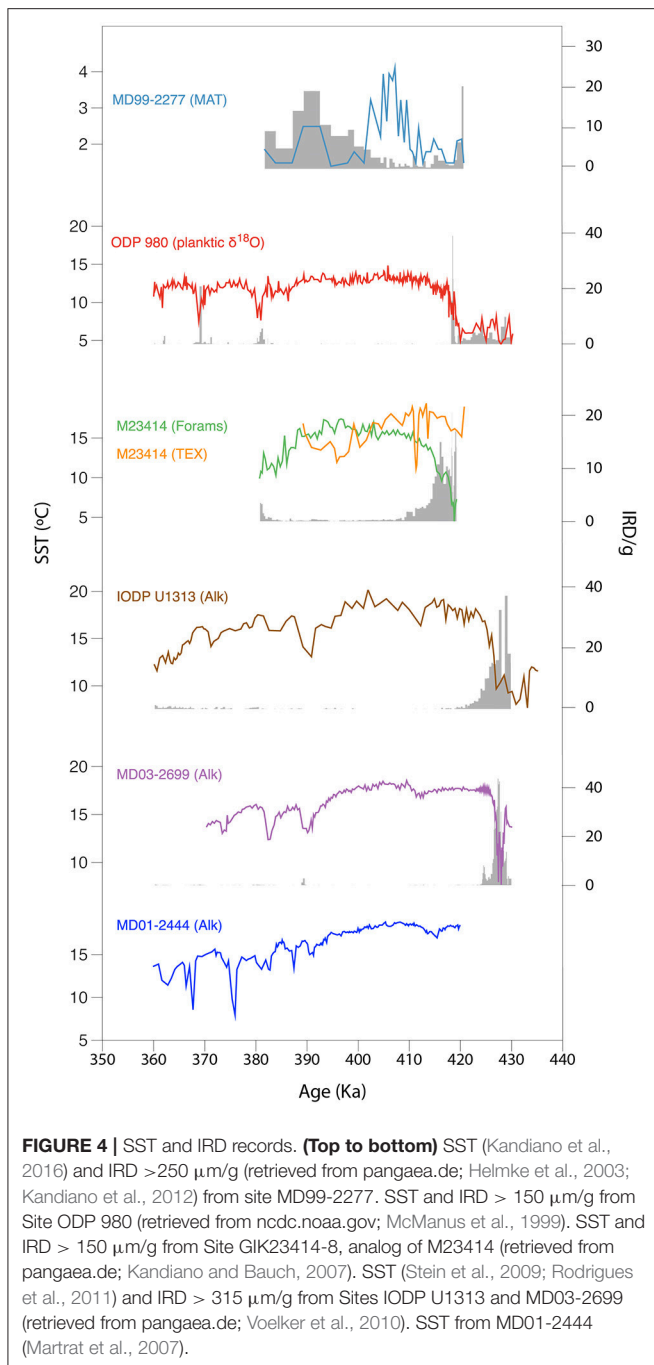


FIGURE 3 | Global signals. **(Top to bottom)** Orbital configurations: obliquity and mid-July insolation at 65°N (retrieved from pangaea.de; Berger and Loutre, 1991). Atmospheric CO₂ concentration derived from the EPICA Dome C ice core record (retrieved from pangaea.de; Siegenthaler et al., 2005). Lisiecki-Raymo (LR04) Global benthic stack of stable oxygen isotopes (retrieved from pangaea.de; Lisiecki and Raymo, 2005). Global stable carbon signal (retrieved from ncdc.noaa.gov; Lisiecki, 2010, 2014). Site MD99-2277 SST data calculated from modern analog technique (retrieved from pangaea.de; Kandiano et al., 2016). Site ODP 980 SST derived from planktic oxygen isotope data (retrieved from ncdc.noaa.gov; McManus et al., 1999). Site M23414 (GIK23414-8) SST data from a combined average of three methods (retrieved from pangaea.de; Kandiano and Bauch, 2007) and 0-200 m TEX_{86}^L -derived temperature (retrieved from pangaea.de; Kandiano et al., 2017). Alkenone-derived SST for sites IODP U1313 (retrieved from pangaea.de; Stein et al., 2009), MD03-2699 (retrieved from pangaea.de; Rodrigues et al., 2011), and MD01-2444 (retrieved from pangaea.de; Martrat et al., 2007).

rather than comparisons between MD99-2277 and ODP 980 (see section Selected Records: Proxies and Positions).

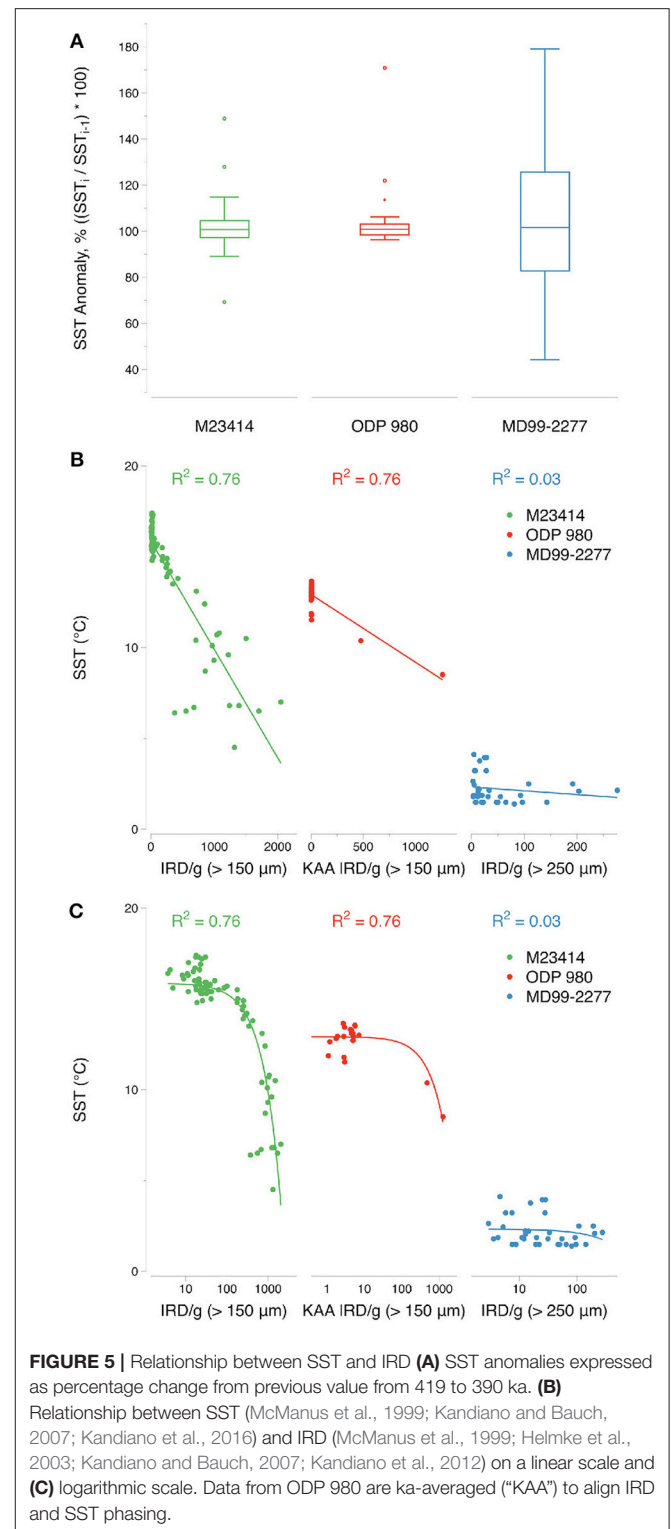
Alkenone-derived hydrogen isotopes suggest a gradual increase in freshwater preceding SST optima in the Nordic Seas and correspond to trivially small IRD values (Figure 6). While the presence of IRD suggests that some minor ice-raftering events must have occurred in the Nordic Seas, such events cannot be realistically invoked as an explanation for the cold and fresh surface conditions reconstructed throughout

MIS 11 (Kandiano et al., 2016). Further, because surface waters in the Nordic Seas are always colder than those in the North Atlantic, larger volumes of low-temperature waters would be required to produce the notable cold excursions in the Nordic Seas. This implies that the temperature-forcing mechanisms were different between the Nordic Seas and the North Atlantic during MIS 11. Whereas cold events in the North Atlantic were predominately associated with iceberg discharge, cold events in the Nordic Seas were likely produced

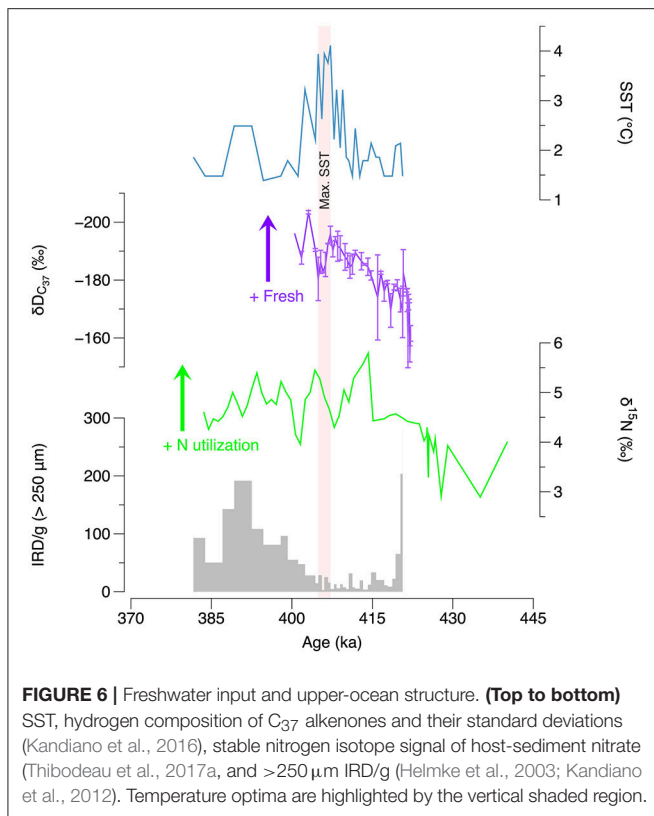


by a massive addition of liquid freshwater or sea ice. This is critical to recognize for paleoceanographic reconstructions of MIS 11.

High variability in the bulk $\delta^{15}\text{N}$ record suggests fluctuating nutrient utilization (Schubert et al., 2001; Ren et al., 2009; Straub et al., 2013; Thibodeau et al., 2017a) characteristic of MIS 11, which may reflect an intermittent rate of freshwater delivery to the Nordic Seas (Figure 6). It has been previously proposed that the prolonged introduction of freshwater to the Nordic Seas during stage 11 resulted in a thicker mixed layer relative to



the Holocene, thereby generating lower $\delta^{15}\text{N}$ values (Figure 1; Thibodeau et al., 2017a). This is caused by an accumulation of buoyant freshwater at the surface that pushes the mixed layer to a greater depth, and is supported by preliminary numerical work

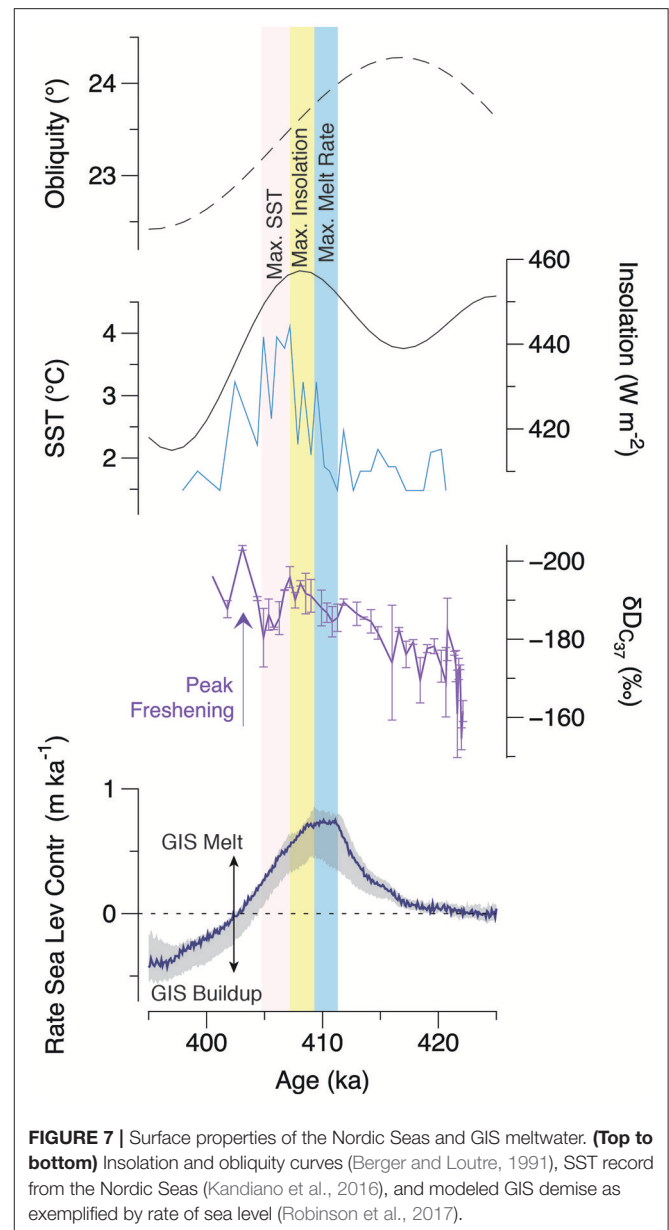


using the intermediately complex OSUVic 2.9 climate model (Thibodeau et al., 2017b, 2018). It therefore appears that surface freshening does not always necessitate upper-ocean stratification, and rather that the duration of freshwater forcing is a driving factor when evaluating the impact of surface freshening on the structure of the surface ocean. While bulk isotope data suggest a volatile mixed layer thickness throughout MIS 11, these values may be further complicated by changes in nutrient supply and primary productivity. Accordingly, more robust biogeochemical techniques such as microfossil-bound $\delta^{15}\text{N}$ (Ren et al., 2009; Straub et al., 2013) are required to unravel nutrient dynamics and upper-ocean structure during this interval.

FRESHWATER SOURCES

A natural question arises regarding the origin of the Nordic Seas' fresher surface layer, for which we consider three possibilities: (1) North Atlantic water flowing northward along the North Atlantic Current, (2) meltwater derived from the demise of the GIS, and (3) waters from higher latitudes including both sea ice export from the Arctic and Eurasian runoff.

Maximum quaternary ice rafting occurred in the North Atlantic (Ruddiman, 1977), and waters from the North Atlantic are transported directly to the Nordic Seas via the Norwegian Current. However, North Atlantic surface waters are considerably warmer than those in the Nordic Seas, and so it is unlikely that freshwater derived from the North Atlantic can



resolve the high-magnitude cold SST anomalies characteristic of the Nordic Seas during MIS 11 (Figure 5A). SST reconstructed by revised analog method showed that the subpolar North Atlantic was 1.19°C warmer during MIS 11 compared to the present, whereas the Nordic Seas were 1.92°C colder on average (Kandiano et al., 2012). The warmer subpolar North Atlantic during MIS 11 might also reinforce stronger AMOC conditions relative to present day. Because there is no evidence of anomalously cold water in the North Atlantic, this further discredits the region as the origin of the fresh and cold surface layer in the Nordic Seas.

The cold and fresh surface layer of the Nordic Seas during stage 11 may also be attributed to meltwater from the GIS. Extreme melting of the GIS during MIS 11 is

supported by terrestrial records that indicate a forested southern Greenland (Willerslev et al., 2007; de Vernal and Hillaire-Marcel, 2008), geochemical and magnetic tracers that suggest minimal southern ice extent (Hatfield et al., 2016), and geomorphological reconstructions that illustrate eustatic sea level changes requiring GIS collapse (Raymo and Mitrovica, 2012; Reyes et al., 2014). Numerical studies also indicate a high sensitivity to warming-induced deglaciation in southern Greenland. However, most of this meltwater would be deposited in the Eirik Drift, which is directly below Greenland's southern tip and distant from the Nordic Seas (Cuffey and Marshall, 2000; Huybrechts, 2002; Tarasov and Peltier, 2003; Lhomme et al., 2005; Reyes et al., 2014). While modeling experiments suggest that early meltwater from the GIS aligns with increased freshwater deposition in the MD99-2277 record (Robinson et al., 2017; **Figure 7**), this initial simulated meltwater likely predominately reflects the demise of southern Greenland, and could therefore not enter the Nordic Seas (Kandiano et al., 2012).

Landscape reconstructions (Bierman et al., 2014) and numerical simulations (Rachmayani et al., 2017; Robinson et al., 2017) indicate that northern Greenland also experienced considerable melting during MIS 11. This increased melting may have been further enhanced by a stronger AMOC responsible for additional northward heat transport (Rachmayani et al., 2017). The deposition of meltwater masses derived from northern Greenland in the Nordic Seas is conceivable under reconstructed atmospheric circulation patterns (Kandiano et al., 2012), and might help to explain the delayed SST optima relative to the insolation peak (**Figure 7**). A rapid increase in salinity concomitant with SST optima immediately follows the peak GIS melt rate, which could reflect either a decrease in colder meltwater or an enhanced influence of Atlantic warm waters at the surface. The latter scenario is supported by nutrient utilization and mixed layer dynamics as reconstructed by an increase in bulk $\delta^{15}\text{N}$ (**Figure 6**), but more robust evidence is required to understand whether this proxy reflects changes in the mixed layer or other phenomena. Interestingly, maximum freshwater input is observed later in the record and aligns with a regrowth of Greenland's ice (**Figure 7**), which suggests that an alternative source must be responsible for the late freshening event in the Nordic Seas.

Arctic sea ice is another potential source of the cold freshwater in the Nordic Seas during MIS 11. Because the freezing of ocean water releases salt, waters that freeze also become relatively fresher. Sea ice is exported from the Arctic to the Nordic Seas via the Transpolar Drift Stream, where its melting may hypothetically result in lower temperatures and freshening in the surrounding waters. However, this would require a sufficiently large volume of sea ice export, and micropaleontological evidence indicates a disappearance of perennial Arctic sea ice

approximately 400 ka aligning with the mid-Brunhes initiation (Polyak et al., 2013; Cronin et al., 2017). It is conceivable that the mid-Brunhes demise of Arctic sea ice, freshwater release, and subsequent export of meltwater could explain the trends observed in the Nordic Seas. Meltwater derived from higher latitudes might alternatively be sourced from Eurasian runoff coherent with observations of negative-mode NAO conditions during MIS 11 (Kandiano et al., 2012; Morison et al., 2012), although this requires further investigations regarding the volume, phasing, and transportation of waters from the north.

CONCLUSIONS

The evidence reviewed here highlights considerable differences in the surface structure of the Nordic Seas between MIS 11 and the Holocene. Because these structural differences may have implications for thermohaline circulation and Global climate, our review suggests exercising caution when making direct comparisons between stage 11 and the current interglacial. Reconciling an active AMOC with continuous and relatively high-volume freshwater forcing in the Nordic Seas remains a challenge in quaternary paleoceanography and may inhibit accurate forecasting of climatic feedbacks associated with GIS demise. Future research is therefore necessary to better assess the location and rate of freshwater input in order to quantify the effect of ice melt on NADW formation and AMOC strength. Our analysis suggests that freshwater in the Nordic Seas during MIS 11 originated from higher latitudes, derived from enhanced Arctic export, elevated Eurasian runoff, and northern Greenland ice melt, rather than from meltwater deposited *in situ* or from southern Greenland. This should be recognized when considering MIS 11 as an analog for near-future perturbations of Earth's climate system.

AUTHOR CONTRIBUTIONS

JD prepared this manuscript. JD and BT generated the figures presented here and co-developed the interpretation of this study.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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