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Key Points:

- Multidecadal variability in ISOW vigor persisted over the past ~600 years
- Atlantic wide climate (AMV) and ISOW varied with similar frequencies
- Empirical support for a link between deep circulation and AMV

Supporting Information:

- Text S1, Figure S1–S5 captions, and Table S1–S4 captions
- Text S1, Table S1–S3 captions, and Figure S1–S5 captions
- Figure S1
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Multidecadal changes in Iceland Scotland Overflow Water vigor over the last 600 years and its relationship to climate

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Abstract Changes in the Atlantic Meridional Overturning Circulation (AMOC) have commonly been invoked to explain the low-frequency climate changes evident over millennial-multidecadal timescales during the Holocene period. While there is growing evidence that deep ocean circulation varied on millennial timescales, little is known about ocean variability on shorter timescales. Here we use a marine sediment core (GS06-144-09MC-D) recovered from a high accumulation rate site on the Gardar Drift in the Iceland Basin (60°19′N, 23°58′W, 2081 m) to reconstruct decadal-centennial variability in the vigor of Iceland-Scotland Overflow Water (ISOW) with the paleocurrent proxy "sortable silt" mean grain size ($\overline{SS}$). Our $\overline{SS}$ record reveals that changes in ISOW vigor have occurred on multidecadal-centennial timescales over the past ~600 years; similar timescales as documented in Atlantic Multidecadal Variability observations and reconstructions. Our findings support a link between changes in basin-wide climate and deep ocean circulation.

1. Introduction

The Atlantic Meridional Overturning Circulation (AMOC) is widely hypothesized to affect climate variability over millennial [e.g., *Bianchi and McCave*, 1999; *Bond et al.*, 1997; *Hall et al.*, 2004; *Oppo et al.*, 2003] to multidecadal timescales [*Knight et al.*, 2005; *Sutton and Hodson*, 2005; *Zhang et al.*, 2007]. There is substantial empirical evidence documenting millennial scale variability in deep circulation and properties of the Atlantic Ocean during the Holocene [*Chapman and Shackleton*, 2000; *Hall et al.*, 2004; *Manighetti and McCave*, 1995; *Oppo et al.*, 2003] and past interglacial periods [*Hodell et al.*, 2009]. Reconstructions using the paleocurrent proxy "sortable silt" mean grain size (hereafter $\overline{SS}$, i.e., *McCave and Hall* [2006] and *McCave et al.* [1995]) reveal that variations in the vigor of Iceland-Scotland Overflow Water (ISOW), an important constituent of the AMOC [*Dickson and Brown*, 1994; *Hansen and Østerhus*, 2000], have occurred throughout the Holocene period on multimillennial to centennial timescales [*Bianchi and McCave*, 1999; *Hoogakker et al.*, 2011; *Kissel et al.*, 2013; *Thornalley et al.*, 2013]. However, much less is known about the natural variability of ISOW on multidecadal to centennial timescales beyond the last two centuries [i.e., *Boessenkool et al.*, 2007a]. These higher frequency changes are particularly relevant for contextualizing the current ocean and climate changes and evaluating the wide range of AMOC variability exhibited by (unforced and forced) model simulations.

An example of high-frequency climate variability is the Atlantic Multidecadal Variability (AMV), a basin-wide change in the spatial pattern of sea surface temperature's (SST) of the North Atlantic, which is thought to impact Sahel and North American rainfall patterns and drought [e.g., *Enfield et al.*, 2001; *Goldenberg et al.*, 2001; *Knight et al.*, 2006], as well as the variability in Arctic sea ice [*Miles et al.*, 2014]. AMV reconstructions based on tree ring chronologies [*Gray et al.*, 2004a] and multiproxy studies [*Mann et al.*, 2009; *Svendsen et al.*, 2014] reveal that the AMV has been a consistent feature of the climate system for the past 1500 years and perhaps persisted throughout the past 8000 years [*Knudsen et al.*, 2011]. While a number of studies have suggested a potential AMOC link, either as an important driver of [*Delworth and Mann*, 2000; *Knight et al.*, 2005; *Vellinga and Wu*, 2004; *Wei and Lohmann*, 2012] or responder to AMV changes [*Clement et al.*, 2015], empirical support for changes in ocean circulation related to AMV has been lacking.

Another important climate change driver on decadal timescales is the atmospheric pattern known as the North Atlantic Oscillation (NAO [*Hurrell*, 1995]), which is the most prominent atmospheric pattern in the Atlantic region. Modern observations support a link between the NAO and the lower limb of the AMOC through formation of Labrador Sea Water (LSW), due to deep winter convection in the Labrador Sea [e.g., *Dickson et al.*, 1996; *Visbeck et al.*, 2003; *Yashayaev et al.*, 2007]. A reconstruction of ISOW flow speed changes

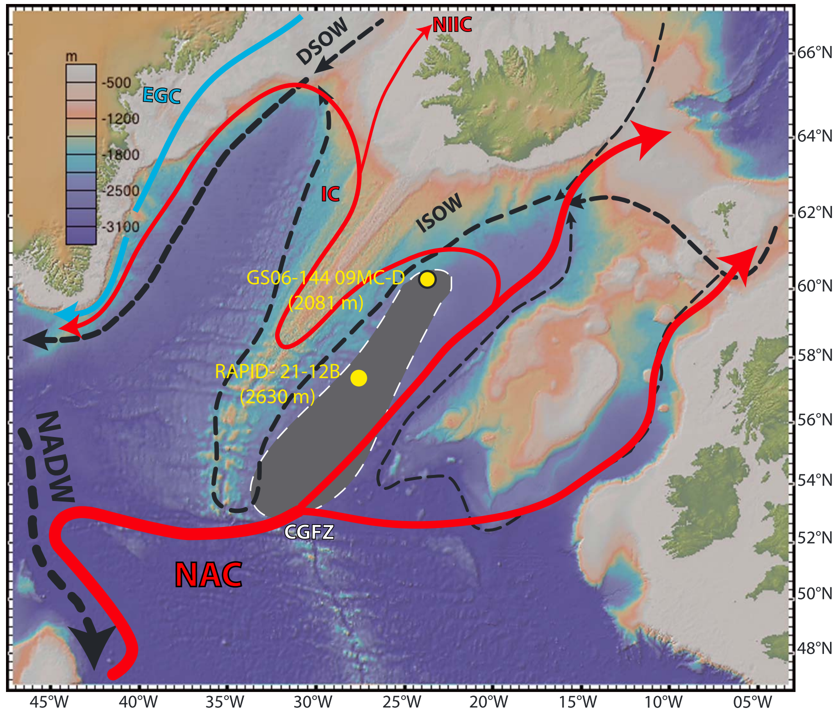

Figure 1. Bathymetric map over the North Atlantic basin with arrows indicating the schematic circulation and spreading pathways of the different branches of inflowing (solid lines) and outflowing (stippled lines) water from the Nordic Seas that forms a portion of the Atlantic Meridional Overturning Circulation. The approximate extent of the Gardar sediment drift is marked with gray shading (and stippled white outline). The location of core GS06-144-09MC-D (60°19 N, 23°58 W, 2081 m water depth) is marked with a yellow circle, as is the other core used in this study; RAPID 21-12 B (57°27.09′N´, 27°54.53′W, 2630 m water depth) after *Boessenkool et al.* [2007b]. (NAC: North Atlantic Current; IC: Irminger Current; NIIC: North Icelandic Irminger Current; EGC: East Greenland Current; ISOW: Iceland-Scotland Overflow Water; DSOW: Denmark Strait Overflow Water; NADW: North Atlantic Deep Water; CGFZ: Charlie-Gibbs Fracture Zone) The bathymetric map was generated with GeoMapApp (http://www.geomapapp.org) using the base map of *Ryan et al.* [2009].

using the paleocurrent proxy $\overline{SS}$ has revealed an inverse correlation with the NAO during the past ~230 years, where the reduced (increased) ISOW during a positive (negative) NAO phase was suggested to reflect increased (decreased) entrainment of LSW into ISOW [*Boessenkool et al*., 2007a]. While revealing, little more than two centuries of ISOW variability is not sufficient to fully evaluate whether such decadal-scale changes in overflow vigor are reflecting changes in ISOW or NAO induced changes in LSW; thus, longer records of ISOW variability are needed in order to address this potential mechanism properly.

To investigate multidecadal to centennial variability in the vigor of ISOW and evaluate its relationship to climate during the past ~600 years, we use a core recovered from the northern part of the Gardar Sediment Drift (Figure 1). The Gardar Drift is an elongated contourite, deposited under the influence of ISOW as it flows as a deep (western) boundary current along the eastern flank of the Reykjanes Ridge in the Iceland Basin [*Faugères et al*., 1999; *Kidd and Hill*, 1987; *Ruddiman*, 1972; *Wold*, 1994]. The surface waters of the Iceland Basin are influenced by the Subpolar Front, which separates the cold and fresh surface waters of the Subpolar Gyre from the warmer and more saline subtropical waters, associated with the North Atlantic Current (NAC) [*Bersch*, 2002; *Lacan and Jeandel*, 2004].

2. Materials and Methods

The chronology for the 44 cm long multicore GS06-144-09MC-D is based upon ^{210}Pb excess dates from the topmost 7.25 cm and two accelerator mass spectrometry (AMS) ^{14}C dates measured on monospecific samples of *Neogloboquadrina incompta* (previously *Neogloboquadrina pachyderma dextral*, i.e., *Darling et al*. [2006]) at 11.5 cm and 30 cm down core. The two AMS ^{14}C dates are calibrated using the Marine 13 calibration curve [*Reimer et al*., 2013] assuming a standard reservoir age correction of 400 years, and the age-depth model for the full record is constructed using a smoothed spline curve through the ^{210}Pb and AMS ^{14}C dates calculated at $\pm 1\sigma$ confidence ranges using "clam" software [*Blaauw*, 2010], operated through the open-source statistical software "R" [*R Core Team*, 2014]. The average dating uncertainty of the core is ± 40 years, with lower uncertainties in the upper (7.25 cm) ^{210}Pb dated interval (less than ± 3 years) and higher uncertainty below (±49 years). However, true uncertainty could be larger due to uncertainty in the underlying assumptions (e.g., constant reservoir age and constant ^{210}Pb flux without bioturbative redistribution). Based on this chronology, the average sedimentation rate of the core is 77 cm/1000 years, providing a sample spacing of 7 years between every 0.5 cm sample (see supporting information for more details about how the age model is constructed).

We reconstruct changes in the vigor of ISOW from size variations in the sediment proxy $\overline{SS}$. The $\overline{SS}$ paleocurrent proxy is based on the sedimentary characteristics of the 10–63 μm fraction of terrigenous silt particles [*Bianchi et al*., 1999; *McCave and Hall*, 2006; *McCave et al*., 1995], with increases (decreases) in mean grain size indicating relatively higher (lower) bottom velocities. The $\overline{SS}$ was measured on a Beckman Coulter Multiziser 3, Coulter Counter® (the analytical precision is better than 4% [*Bianchi et al*., 1999; *Hall et al*., 2004]). Here we report averages of duplicates (see supporting information). The signal, or range of grain size variability down core (~2.5 μm), exceeds the average standard error of the mean (±0.31 μm) for the record.

3. Results and Discussion

Our $\overline{SS}$ reconstructions reveal that the near-bottom flow speed across the Gardar Drift has varied on decadal-centennial timescales throughout the past ~600 years (Figure 2). For instance, there are four prominent multidecadal to centennial scale cycles between 1530–1605 A.D., 1605–1730 A.D., 1855–1940 A.D., and 1940–2006 A.D. Although our record represents the flow speed variability in only one locality along the flow path of ISOW, it captures the main variability observed in the shorter $\overline{SS}$ record collected more than 100 km further south on the central Gardar Drift and more than 600 m deeper [*Boessenkool et al*., 2007a, 2007b], suggesting a common element of large-scale changes in bottom water flow speed (Figure 2a). Although the two $\overline{SS}$ records are only weakly correlated ($r = 0.41$, at zero years lead/lag, see Figure S5 in the supporting information), they show a clear in-phase relationship during the twentieth century when our age models are most certain. Any offsets prior to the midnineteenth century could be the result of age model uncertainties (on average ± 49 years), migrations in the flow path of ISOW relative to one of the core sites, or competing local influences. We suggest that variability in ISOW vigor [or density cf., *Langehaug et al*., 2016], which influences sediment deposition at both of these locations, is the most likely cause for this common signal. Thus, our record effectively reproduces and extends the *Boessenkool et al.* [2007a] decadal-centennial record of ISOW variability through the past ~600 years.

Direct comparison between our $\overline{SS}$ record with instrumental and reconstructed AMV reveals clear similarities, with periods of strong ISOW associated with Atlantic-wide warmth (Figure 2b). During the past two centuries there is a strong correlation between our reconstructed ISOW changes and the instrumental AMV record ($r = 0.68$–0.79 [*Enfield et al*., 2001], see supporting information Figure S5) as well as AMV reconstruction based upon marine multiproxy records ($r = 0.71$–0.65 [*Svendsen et al*., 2014]) when ISOW lags behind the AMV by 0–20 years. The relatively short time lag of ISOW behind AMV may reflect the response time of the overflow to ocean surface changes. The 0–20 year lag by ISOW behind basin-wide Atlantic climate is also observed between the $\overline{SS}$ record and the AMV reconstructions constructed from tree ring chronologies gathered from locations around the rim of the Atlantic that are known to be strongly affected by Atlantic SSTs ($r = 0.35$–0.41 [*Gray et al*., 2004b]), as well as from the 1500 year long AMV global multiproxy reconstruction by *Mann et al.* [2009] ($r = 0.41$ when $\overline{SS}$ lags by 19 years).

While the SS AMV comparison reveals that the deep ocean flow clearly varies on similar timescales as the basin wide climate (AMV), it is important to note that the precise phasing is difficult to determine given that the cumulative effect of age model uncertainties (e.g., analytical, initial assumptions, and reservoir changes) at any given point are likely more than half of the duration of any individual AMV oscillation. Prior to 1900 A. D., this is certainly the case as the nominal uncertainty for this interval is ± 49 years; typical to AMS ^{14}C-based chronologies. Despite the absolute age uncertainties, it is encouraging that the bottom flow signal $(\overline{SS})$ is reproduced at two independently dated Gardar Drift study sites (Figure 2a), demonstrating the same signal and timing is reproducible at widely spaced localities. Thus, while our results suggest that AMV and deep

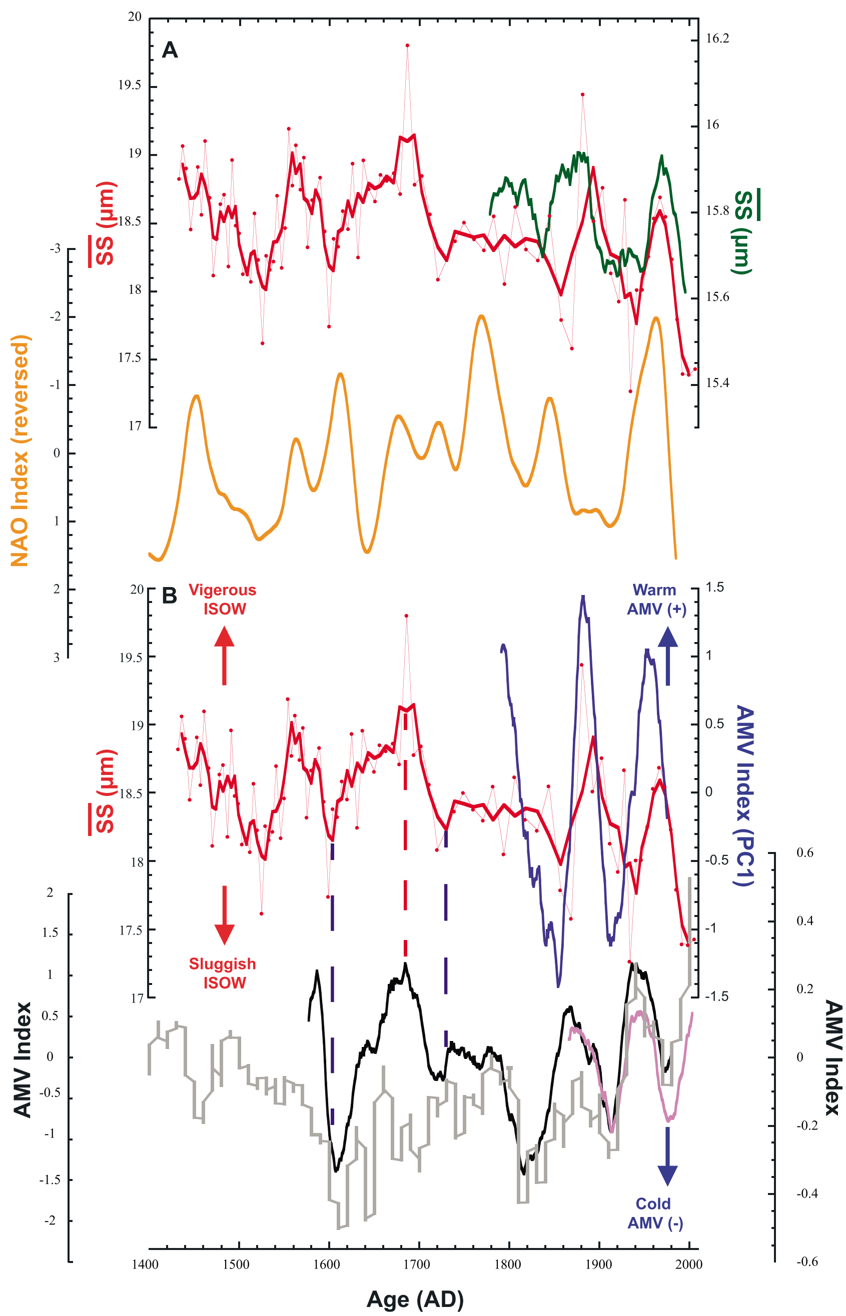

Figure 2. (a) Raw (thin red) and 3-point smooth (thick red, ~20 year running average) $\overline{SS}$ data from core GS06-144-09MC-D (2081 m water depth) plotted against a ~20 year running average (9-point smooth) of *Boessenkool et al.* [2007b] $\overline{SS}$ data from core Rapid-21-12B (green, 2630 m water depth), as well as 20 year running average (20-point smooth) of the winter North Atlantic Oscillation Index (NAO, orange curve) of *Trouet et al.* [2009]. (b) The raw (thin red) and smoothed (thick red) $\overline{SS}$ record from core GS06-144 09MC-D plotted against a 20 year running average of the marine-based multiproxy AMV reconstruction by *Svendsen et al.* [2014] (blue curve, 20-point smooth) based upon principal component analysis, a 20 year smooth of the detrended instrumental AMV record (purple curve, 20-point smooth [*Enfield et al.*, 2001]; gathered from the Kaplan SST database http://www.esrl.noaa.gov/psd/data/timeseries/AMO/), a 20 year smooth of the detrended AMV reconstruction by *Gray et al.* [2004b] (black curve, 20-point smooth) based upon tree ring chronologies, and a ~23 year smooth of the detrended multiproxy AMV reconstruction by *Mann et al.* [2009] (gray curve, 9-point smooth) based upon principal component analysis.

ocean circulation varied on similar timescales over the past 600 years, determining the precise phasing will ultimately require independent and absolute age control points.

Our bottom flow reconstructions demonstrate that at least one major branch of the AMOC, the ISOW, was actively varying on AMV timescales over the past ~600 years. In the most general sense, this supports the suggestion that variations in AMOC could be sensitive to multidecadal climate variability as found in forced and unforced model simulations [*Delworth and Mann*, 2000; *Kerr*, 2000; *Knight et al.*, 2005; *Sutton and Hodson*, 2005]. However, in simulations the shallower overturning component associated with LSW formation is typically the most sensitive to both internal [*Delworth and Mann*, 2000; *Jungclaus et al.*, 2005; *Langehaug et al.*, 2012] and external forcing (e.g., volcanic and solar: *Otterå et al*. [2010] and *Swingedouw et al*. [2011]). *Boessenkool et al.* [2007a] observed that ISOW was inversely correlated to NAO during the instrumental period, suggesting that the overflow was sensitive to synoptic scale atmospheric forcing. We find from comparison between our $\overline{SS}$ record and a reconstructed winter NAO index covering the last millennium [*Trouet et al.*, 2009] that the inverse relationship is only apparent during the twentieth and fifteenth century (Figure 2a, see also Figure S5 in the supporting information), suggesting that the relationship between the NAO and ISOW during the past 600 years is more complex than the simple linear relationship observed during the instrumental period. *Boessenkool et al.* [2007a] proposed that this antiphasing between NAO and ISOW was due to the moderating influence of LSW formation and its effect on entrainment and/or hydrographic pressure gradients across the Greenland-Scotland Ridge (GSR). While extended high-resolution records of LSW formation are required in order to evaluate the role of LSW as a mediator of ISOW vigor, models suggest a number of additional alternatives for how synoptic scale atmospheric forcing could alter exchanges across the GSR. For example, NAO changes affect both a rapid barotropic response (NAO induced changes in wind stress—increased inflow through the Faroe Shetland Channel leads to decreased overflow through the Faroe Shetland Channel and increased overflow through the Denmark Strait, i.e., *Sandø et al*. [2012]) and a more gradual response via its influence on convection in the Greenland and Iceland Seas [*Jungclaus et al.*, 2008]. In addition to NAO, other atmospheric forcing could also alter GSR density gradients. For example, the Scandinavian and East Atlantic Patterns have both been suggested to influence exchange across the GSR [*Langehaug et al.*, 2012; *Medhaug et al.*, 2012].

Regardless of how the changes in deep circulation vigor are ultimately triggered, our results suggest that at least one major branch of the AMOC is active on multidecadal timescales. There is both model and observational evidences suggesting that the Upper North Atlantic Deep Water, fed by convection in the Labrador and Irminger Seas, has been particularly sensitive to climate and buoyancy forcing [*Danabasoglu et al.*, 2012; *Dickson et al.*, 2002; *Yashayaev et al.*, 2008]. Our records suggest that the flow of a major constituent of lower NADW (the ISOW) has also been actively varying during the multidecadal climate variability in the Atlantic over the past half millennium. The observation that at least one of the GSR overflows is variable on multidecadal timescales is significant, as together, these overflows and their entrained components ultimately comprise the vast majority of newly ventilated deep water in the North Atlantic (~70% of NADW [*Dengler et al.*, 2006; *Haine et al.*, 2008; *Schott et al.*, 2004]). This persistent multidecadal variance in the lower branch of the overturning circulation (ISOW) supports the notion that the overturning either drove [e.g., *Delworth and Mann*, 2000; *Knight et al.*, 2005; *Vellinga and Wu*, 2004; *Wyatt et al.*, 2011] or provided inertia to [e.g., *Knudsen et al.*, 2011; *Wei and Lohmann*, 2012] the climate system on multidecadal timescales. With similar constraints on Denmark Strait Overflow Water vigor, it may eventually be possible to characterize the multidecadal variance in both major constituents of southward flowing lower NADW. Given the recent decadal-scale decline observed in lower NADW transport [*Robson et al.*, 2014; *Smeed et al.*, 2014], such proxy-based records are sorely needed in order to place these recent ocean trends in context and understand their relationship to natural and anthropogenic climate changes.

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