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Recent natural variability of the Iceland Scotland Overflows on decadal to millennial timescales: Clues from the ooze

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How variable is the Atlantic Ocean's Meridional Overturning Circulation (AMOC)? This question has become increasingly important in recent years due to the ocean's influence on climate and potential impacts on future climate development. The northward flow of warm near-surface waters and southward flow of cooler deep water comprising the AMOC redistributes a significant amount of heat within the Atlantic basin (Johns et al. 2011). This influences regional temperature and rainfall patterns (Enfield et al. 2001; Knight et al. 2006), including those on adjacent continents, and helps to ameliorate the human impacts of fossil fuel burning by absorbing CO_2 from the atmosphere and transporting it into the deep ocean (Sabine et al. 2004).

Despite its importance, our understanding of the overturning is far from complete, including its natural variability on various timescales and its sensitivity to increased radiative forcing or surface warming and freshening—each of which appear

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imminent. This uncertainty is apparent when models are used to predict the AMOC response to future conditions. Collectively, the models show AMOC declining when forced by expected changes over the coming century, but there remains a large spread in the individual simulations—ranging anywhere from small changes to more than a 50% reduction when forcing is strong (Schneider et al. 2007; Cheng et al. 2013). Because of this, various communities are racing to better understand and constrain AMOC.

The best way to determine AMOC variability is through direct observation. And after a decade of dedicated efforts, the RAPID program has shown that AMOC is highly variable across a number of timescales, including indications of a long-term decline (Robson et al. 2014), even in the deeper southward flowing components (Smeed et al. 2014). Meanwhile numerous modeling studies have simulated multidecadal AMOC variability (Delworth and Mann 2000; Knight et al. 2005) and suggest a link to the multidecadal climate swings felt throughout the North Atlantic basin over the 20th century, termed Atlantic multidecadal variability (AMV). AMV appears to be a persistent feature of the climate system with evidence that it occurred over at least the last 1500 years (Gray et al. 2004; Mann et al. 2009; Svendsen et al. 2014), if not the last 8000 (Knudsen et al. 2011). Empirical support for AMV-related ocean circulation changes has been missing. Could the recent AMOC decline be akin to what caused these past climate swings or is this something new—perhaps forced by anthropogenic changes? Without extended records depicting the decadal variations in ocean circulation it is difficult to place these current trends in context and test the idea that AMOC has played a role in generating or persisting lower frequency climate swings.

In order to address these questions paleoceanographers have been coring into the seafloor mud and ooze that accumulates over time at the seabed. The recovered layers are analyzed to portray past ocean conditions and water mass properties, such as temperature, salinity, ventilation, nutrient contents, or geostrophic transport and relative vigor of the currents. Traditionally, these archives have been used to study climate and ocean circulation changes over millennia, such as those associated with glacial cycles (cf. review by Stieglitz et al. 2007). In part this is because the sediments normally only accumulate a few centimeters every thousand years, limiting the time resolution possible. The approach that best approximates the AMOC estimates provided by RAPID are the paleo-geostrophic estimates based on cross-Atlantic density reconstructions, which have been used to portray glacial interglacial changes in overturning (Lynch Stieglitz et al. 2007 and references therein). Therefore, ideally, a cross-basin geostrophic approach would be applied at even higher frequencies, but the need for a fairly dense network of sites with appropriate resolution and time control represents a serious challenge for depicting sub-centennial AMOC changes.

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Given the interest in constraining the role of the ocean in higher frequency climate variability, paleoceanographers are actively hunting for those rare archives capable of even higher fidelity to help bridge the gap between the low frequency changes observed in many paleo records and the shorter (and much more complete and dynamically better understood) changes captured by modern observations. Bridging this gap may be beneficial to both communities—providing historical context for modern changes, while the overlap with the modern record can provide the necessary calibration period for moving toward a more quantified and mechanistic understanding of the proxy signals. One initial target has been the sediments that accumulate rapidly due to the lateral transport and focusing by bottom currents. The North Atlantic sediment drifts that accumulate under the influence of the deep overflows from the Nordic Seas have generated intense interest, since here the sediment influx is itself related to key constituents of the deep limb of the AMOC.

Natural variability in Iceland Scotland Overflow Water

Waters overflowing the ridges to the east and west of Iceland are the source of the densest waters contributing to the deep limb of the AMOC. Approximately half of this overflow occurs east of Iceland as Iceland-Scotland Overflow Water (ISOW). Previous reconstructions based on the mean grain size of the sediments sortable silt ($\overline{SS}$), reflecting vigor of near bottom flow (McCave et al. 1995), document multi-millennial to centennial variability along the western boundary guided flow path of ISOW (e.g., Bianchi and McCave 1999; Hoogakker et al. 2011; Kissel et al. 2013; Thornalley et al. 2013). However, it is difficult to achieve higher resolution and close the time gap with the period of modern observations. One notable exception is the work of Boessenkool et al. 2007, whose $\overline{SS}$ record revealed, on decadal timescales spanning the past two centuries, subtle changes in bottom flow that seemed to respond to decadal changes in the North Atlantic Oscillation (NAO) index—the major mode of atmospheric variability and an important forcing in the North Atlantic.

Longer records tracking decadal variability in ISOW bottom flow are now starting to emerge. These both extend and largely support the earlier results. Figure 1 (panel b) shows a new six century long record of bottom flow produced by Mjell et al. (2016) together with the two century record of Boessenkool et al. (2007). The new record has higher mean grain sizes and greater variability suggesting the site, which is shallower and to the north (Figure 1a), may be more strongly influenced by ISOW. Remarkably, despite their distant locations and independent age models, the two locations exhibit similarly timed multi-decadal variations in bottom flow during the period of overlap. This consistency points toward a common influence on bottom water flow—inferred by both studies to be related to changes in the flow of ISOW.

With records spanning many centuries, comparison with extended AMV reconstructions becomes possible. The variations in ISOW have a similar pacing to changes in basin wide climate. At first glance, it appears that periods of Atlantic warmth occur when ISOW is strong and cooling occurs when ISOW is weak—much as one might expect if components of AMOC, and associated heat transports, were spinning up and down on these timescales. Mjell et al. (2016) note that ISOW may lag the AMV by 0-20 years, but caution that the uncertainties in the available reconstructions (e.g., in age models) make this determination of the phasing between ocean circulation and climate highly tentative. Determining this phasing will help delineate the nature of any climate and circulation linkage but will require a concerted effort, using the full toolbox of conventional dating approaches, and likely need to be further refined by absolute age markers such as tephra layers and a better understanding of regional radiocarbon reservoir corrections through time.

Regardless of absolute phasing, at least one major component of the deep overturning circulation (ISOW) may have been persistently varying on multi-decadal timescales over the past 600 years. Yet there is growing evidence that AMV could be an intrinsic feature of the

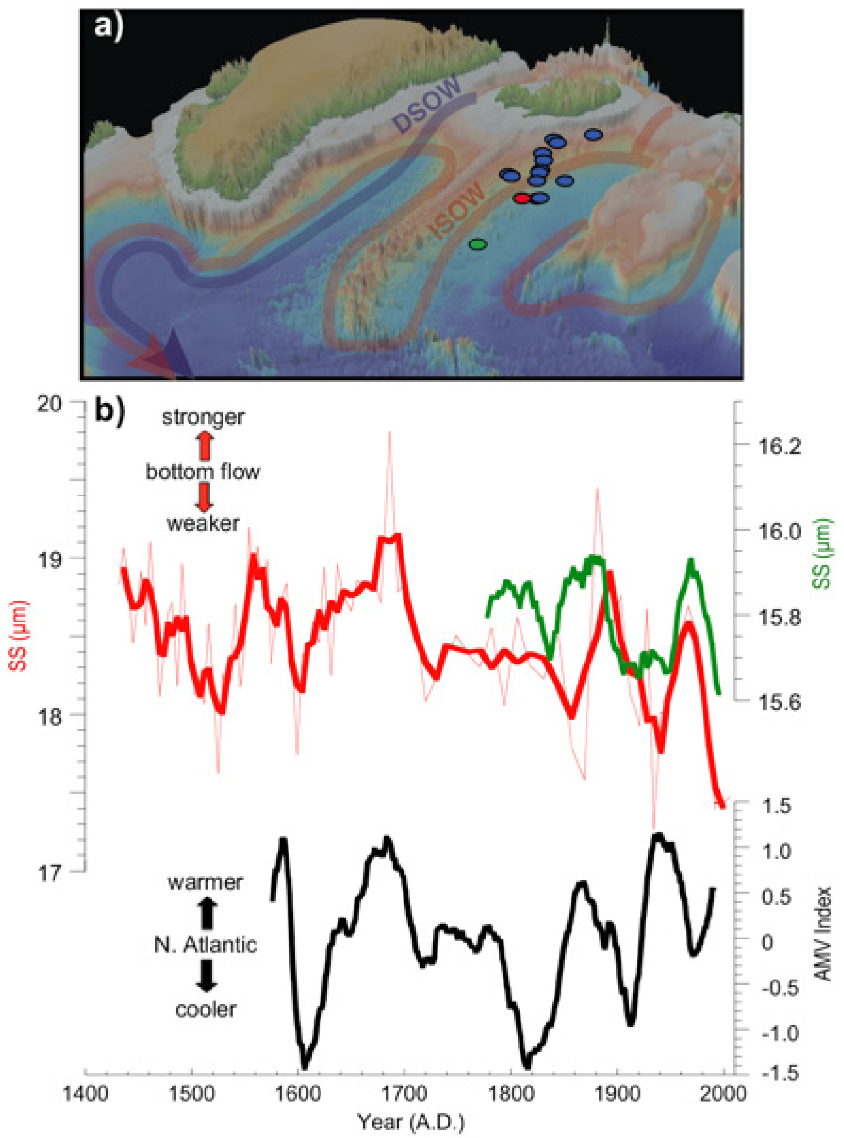

Figure 1 : (a) Top panel is a bathymetric location map of the ISOW reconstructions referred to in the text (bathymetry from Ryan et al. 2009 using http://www.geomapapp.org). The dense overflows from the Nordic Seas, Iceland Scotland Overflow Water (ISOW), and Denmark Strait Overflow Water (DSOW) are schematically illustrated with red and blue arrows. Red and green dots show sites used to reconstruct recent multidecadal changes in near bottom flow (bottom panel), after Mjell et al. 2016 and Boessenkool et al. 2007, respectively. Blue dots mark sites used to reconstruct vertical changes in ISOW through the Holocene (see Figure 2; Thornalley et al. 2013). (b) Bottom panel shows the reconstructed multidecadal variability in the near bottom flow ($\overline{SS}$ μm) over the past ~600 years indicated by the green (Boessenkool et al. 2007) and red (of Mjell et al. 2016) curves plotted together with a proxy reconstruction of Atlantic Multidecadal Variability (black curve, 20-year smooth of detrended AMV from Gray et al. 2004). While similar variability exists, the exact phasing between bottom flow and AMV is difficult to determine precisely due to the current uncertainties (e.g., age model) in the reconstructions.

Atlantic climate for at least the past 8,000 years (Knudsen et al. 2011). Thus, if deep water circulation (e.g., ISOW) is linked intrinsically to AMV, one would expect to see evidence for similar persistence in ISOW variability over this same period. New reconstructions at decadal resolution, spanning several millennia (Mjell et al. 2015; Moffa-Sanchez et al. 2015), suggest that multidecadal variability may indeed be part and parcel of ocean circulation during the current warm interglacial (Mjell et al. 2015). Although, the frequency of this variability may vary through time, warranting further investigation into their robustness and possible climate dependence.

Concerted efforts are also being made to understand the role of ISOW in lower frequency climate oscillations. Recent results have revealed a possible coupling between regional climate conditions, deep water formation in the Nordic Seas, and the strength of the ISOW over the Holocene (Thornalley et al. 2013; Mjell et al. 2015; Hoogakker et al. 2011). An important outcome of this work is the realization that the flow of ISOW migrated vertically through the Holocene (Figure 2), with the deepest flow occurring during the mid-Holocene climatic optimum, when sea-ice cover in the Nordic Seas was at a minimum, thus enabling vigorous ocean convection producing a strong and dense overflow.

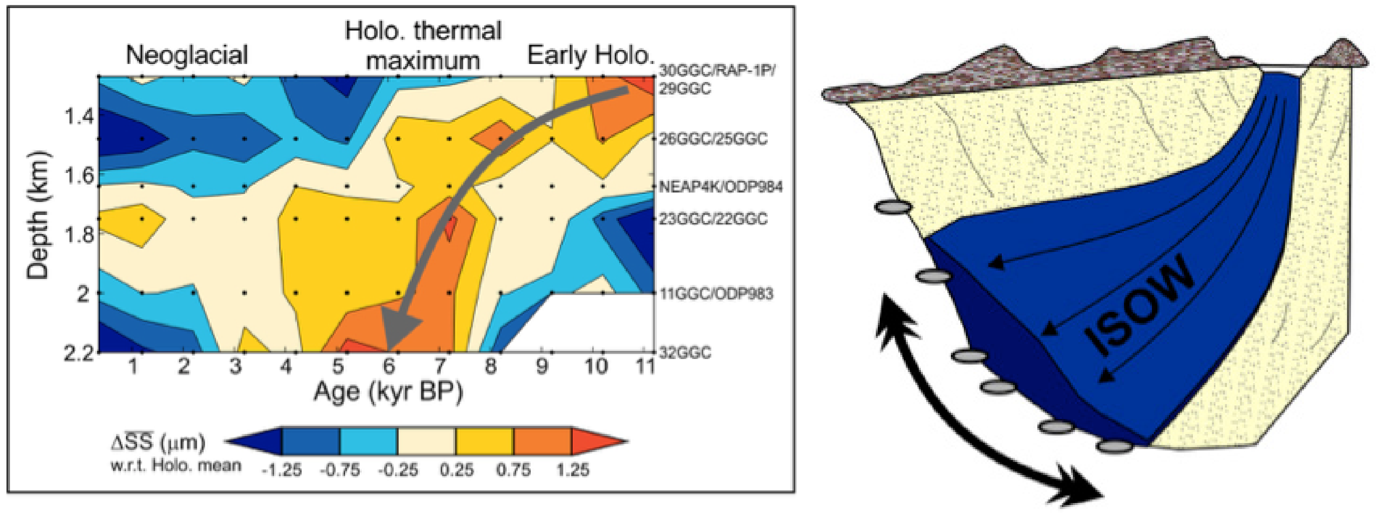

Figure 2: Vertical migration of ISOW. Time-depth contour plot of SS variability (μm) on the South Iceland Rise/Bjorn drift (left panel; modified after Thornalley et al. 2013). The progressive delay in the timing of peak inferred flow speed with increasing water depths has been used to infer a gradual deepening of the main flow path of ISOW during the early-mid Holocene, as sketched in the cartoon (right panel).

Challenges

If such vertical migrations accompanied higher frequency ISOW variations, as a recent modeling study suggests they could as the density and intensity of overflow at the ridge changes (Langehaug et al. 2016), this presents a sobering caveat for attempts to metric ISOW based on a single site. Different locations will have different sensitivities, and potentially even a different sign of response, to vertical changes in ISOW. Further work will ultimately be required to fully elucidate the role of ISOW in multi-decadal, as well as multicentennial, climate events such as the Medieval Climate Anomaly and the Little Ice Age (Bianchi and McCave 1999; Oppo et al. 2003; Hall et al. 2004). Moving forward it will be critical to move from single site characterizations to highly resolved, well-aligned, and long depth transects to portray the non-stationarity in bottom flow. In addition, the newly ventilated deep waters in the North Atlantic have a distinct characteristic in tracers such as $\delta^{13}C$ (Olsen & Ninnemann 2010) relative to ambient deep waters. Co-registered signals of current dynamics and water mass ventilation could be used to build confidence when identifying spatial shifts in water masses. Continuing progress in the calibration of the $\overline{SS}$ proxy, such as the current effort led by Nick McCave (University of Cambridge), will also enable more quantitative reconstructions to be made (e.g., Thornalley et al. 2013).

Despite these promising advancements in our understanding of past ISOW and how to better reconstruct its variability, it is worth remembering that ISOW is only one constituent of the deep limb of AMOC, and compensating rerouting of deep flow between different interior pathways could occur without a change in total overturning. There are hints that such compensation, at least in the vigor of the eastern and western overflows across the Greenland Scotland Ridge, may have occurred on centennial timescales (Moffa-Sanchez et al. 2015). Modeling and paleo-reconstructions also suggest the direct coupling between major constituents of the deep limb of the AMOC, which is likely to complicate efforts to identify the causal mechanisms for the reconstructed variability. Furthermore, the controls on and response of the individual deep AMOC constituents are likely to vary with timescale, different phase relationships between North Atlantic physical properties (heat/salt), and atmospheric forcing on annual to decadal timescales versus those occurring on longer timescales (e.g., greater than decadal). These competing influences on ISOW, and the potentially varying timescale of their dominance, underline the importance of long, well-resolved paleo records for understanding the full spectrum of ocean variability. Existing records have served to demonstrate the importance of ocean variability in the climate system; future, more sophisticated efforts, will strive to quantify its sensitivity to climate and reveal precise forcing mechanisms.

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