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Gulf Stream Variability in the Context of Quasi-Decadal and Multidecadal Atlantic Climate Variability

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Key Points:
- On quasi-decadal timescales, NAO varies in phase with GSNW and in antiphase with Atlantic SSTs
- On multidecadal timescales, NAO continues to vary in phase with GSNW, but the relationship to Atlantic SSTs has changed
- The weakening and broadening of the Gulf Stream is consistent with increased instability since 2005 and not with a northward shift

Supporting Information:
- Supporting Information S1

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Abstract

The Gulf Stream plays an important role in North Atlantic climate variability on a range of timescales. The North Atlantic is notable for large decadal variability in sea surface temperatures (SST). Whether this variability is driven by atmospheric or oceanic influences is a disputed point. Long time series of atmospheric and ocean variables, in particular long time series of Gulf Stream position, reveal differing sources of SST variability on quasi-decadal and multidecadal timescales. On quasi-decadal timescales, an oscillatory signal identified in the North Atlantic Oscillation (NAO) controls SST evolution directly via air-sea heat fluxes. However, on multidecadal timescales, this relationship between the NAO and SST changes, while the relationship between the NAO and Gulf Stream position remains consistent in phase and resonant in amplitude. Recent changes in the Gulf Stream Extension show a weakening and broadening of the current, consistent with increased instability. We consider these changes in the context of a weakening Atlantic overturning circulation.

Plain Language Summary

The North Atlantic Ocean is a region of remarkable variability in surface temperatures on timescales of decades and longer. Much debate surrounds whether this variability is driven by the atmosphere or by ocean currents, such as the Gulf Stream, moving heat around. In this study, we show that on timescales around 10 years, the atmosphere is the likely cause of Atlantic temperature variability but that this changes when multidecadal variability is considered. Changes ongoing in the Gulf Stream coincide with changes in the broader Atlantic—changes that imply a relatively cooler Atlantic in the coming decades.

1. Introduction

The Gulf Stream is a western boundary current, the conduit of warm, upper-ocean (<1,000 m) water from the subtropical to the subpolar North Atlantic. The balance between these warm, shallow, northward-flowing Gulf Stream waters and cold, deep, southward return flow describes the Atlantic meridional overturning circulation (AMOC), which carries 90% of the heat in the North Atlantic and leads to the largest heat transport of any ocean (Johns et al., 2011), and is a major driver of subpolar heat content changes. In contrast to the AMOC, for which direct observations only exist since 2004, long time series of the path of the Gulf Stream, known as the Gulf Stream North Wall (GSNW), exist back to 1955 (Joyce et al., 2000) and 1966 (Taylor & Stephens, 1980) that allows the study of decadal and multidecadal ocean circulation variability in the context of Atlantic changes.

Decadal and multidecadal variability is a notable feature of North Atlantic sea surface temperatures (NASST), with multidecadal variability being larger than interannual and shorter timescale variability (Sutton et al., 2017). This Atlantic multidecadal variability (AMV) consists of multiple decades of anomalously warm or cool NASST relative to background global warming and is most intense in the subpolar gyre. AMV is linked with global and regional temperature and precipitation variations, hurricane activity, and sea level fluctuations (Buckley & Marshall, 2016). A leading explanation of the mechanism controlling NASST variability on multidecadal timescales is that the heat transported by the ocean into the subpolar gyre, through control of subpolar heat content, governs the phases of AMV (Delworth & Mann, 2000). We refer to this as internal ocean-driven variability. However, external factors have also been proposed, including the effect of atmo-

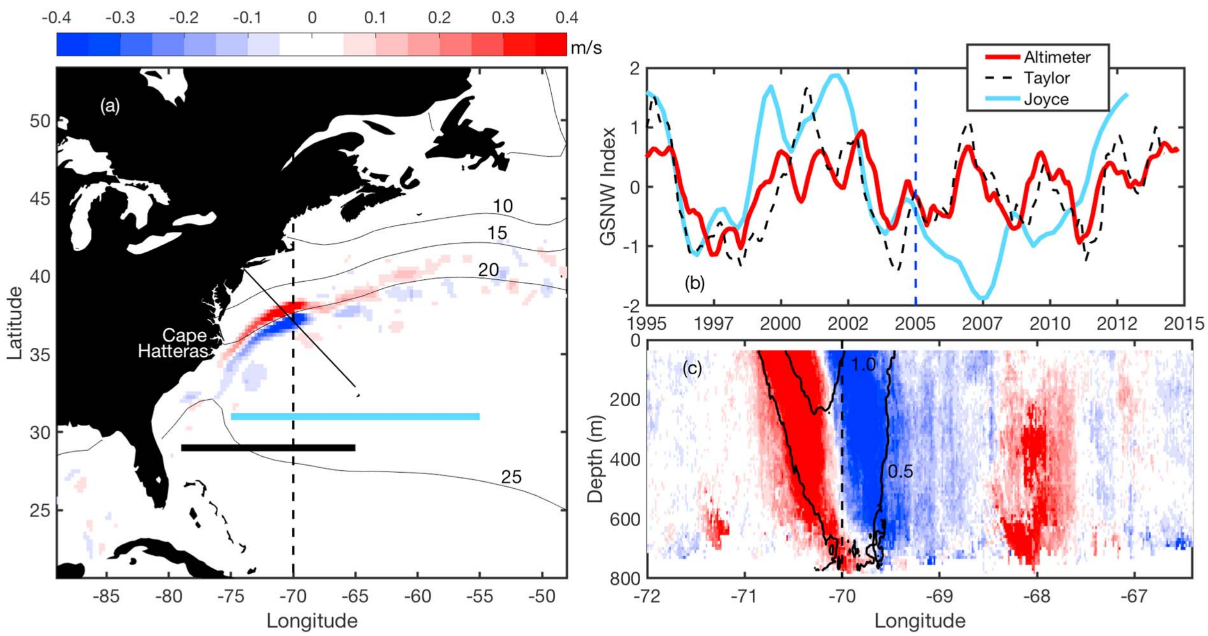

Figure 1. (a) Composites of AVISO satellite-based surface velocity (1993 to 2015) and (c) *Oleander* ADCP subsurface velocity magnitude (169 transects from 2005 to 2015) constructed by subtracting periods when the GSNW altimetric index is negative from periods when it is positive. (b) GSNW time series derived from altimeter measurements (red), surface temperatures as defined by Taylor and Stephens (1980; black, dashed) and 200-m temperatures as defined by Joyce et al. (2000; light blue). (c) The mean location of the Gulf Stream is indicated by the black contours which denote the average position of the jet core in metres per second. (a) The black line from New Jersey to Bermuda denotes the path of the *Oleander*. Horizontal bars denote the longitudes over which the Taylor (black) and Joyce (light blue) GSNW indices are calculated. Contours of mean sea surface temperature in degree Celsius (thin, black) are overlaid. GSNW = Gulf Stream North Wall.

spheric aerosols and greenhouse gases (Bellomo et al., 2018; Booth et al., 2012). In particular, Clement et al. (2015) propose that AMV could be generated as a response to natural atmospheric variability.

Atmospheric variability plays a role in Atlantic variability on multiple timescales, with the leading mode described by the North Atlantic Oscillation (NAO). The NAO is characterized by fluctuations in the strength of the Azores high-pressure and the Greenland low-pressure patterns. Prominent modes of NAO variability at quasi-decadal and multidecadal timescales have been identified (Årthun et al., 2017; Da Costa & Verdiere, 2002; Gray et al., 2016). The impact of the NAO on Atlantic SST patterns via air-sea heat exchange gives a characteristic tripole pattern, with, for example, a positive NAO resulting in cold subpolar and tropical SSTs and a warm band of subtropical SSTs (Hurrell et al., 2003), and can thus play a direct role in NASST evolution.

Here we look at three variables to consider the role of the Gulf Stream in North Atlantic climate: NAO, GSNW, and NASST.

2. The GSNW

The Gulf Stream flows northward, close to the North American coast, from the Straits of Florida to Cape Hatteras (33° N, 75° W). There, it leaves the coast, becoming a separated western boundary current, flowing eastward as the Gulf Stream Extension and, from approximately 55° W, as the North Atlantic Current. The Gulf Stream Extension marks a transition from warm subtropical to cold subpolar waters known as the GSNW (Figure 1). The subpolar region north of the Gulf Stream Extension is known as the Northern Recirculation Gyre as distinct from the broader subpolar gyre north and east of the Grand Banks.

GSNW variability can be seen in satellite-derived surface velocities (Figure 1a) as meridional shifts in the path of the Gulf Stream after Cape Hatteras. Figure 1a shows a composite of surface velocity magnitude corresponding to a GSNW index based on the velocity difference between the locations of maximal variance along a transect from Elisabeth, New Jersey, to Bermuda (Figure 1b). This transect is the path of the *Oleander* container ship that has been fitted with a 75-kHz Acoustic Doppler Current Profiler that provides velocity data to a depth of approximately 800 m since 2005. A composite of these subsurface velocity magnitudes (Figure 1c) shows that surface variations in the GSNW extend to over 700 m — the full depth of the Gulf Stream.

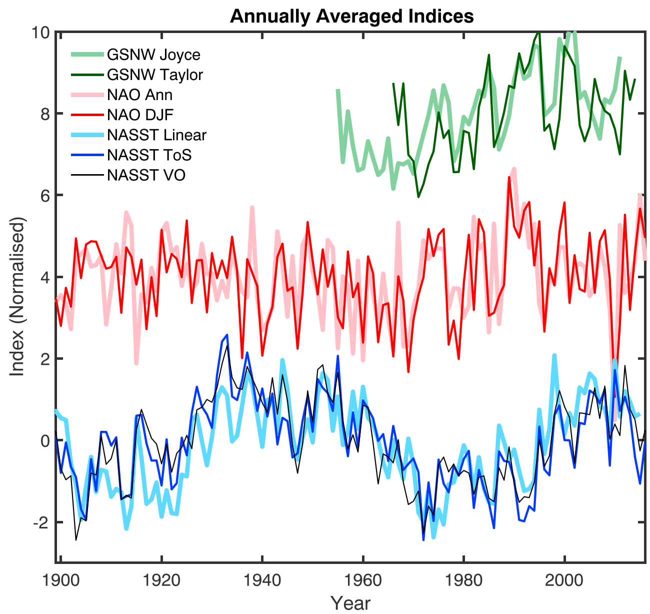

Figure 2. GSNW indices of Joyce (light green) and Taylor (dark green). NAO indices: annual averaged (pink) and DJF (red). All NAO indices are principal component-based (Hurrell et al., 2003). NASST: linearly detrended NASST index from NOAA (light blue), Van Oldenborgh et al. (2009, VO) index (navy blue), and Trenberth and Shea (2006; ToS black) indices. All time series have been normalized and arbitrarily offset. GSNW = Gulf Stream North Wall; NAO = North Atlantic Oscillation; NASST = North Atlantic sea surface temperatures.

We consider the GSNW indices of Taylor and Stephens (1980) and Joyce et al. (2000). The Taylor index is based on the identification of a surface temperature front associated with the Gulf Stream in a longitude range between 79°W and 65°W, from which the latitude of the GSNW is determined using principal componentanalysis. The Joyce index is based on the location of the intersection of the 15° C isotherm and the 200-m-depth level in a longitude range from 75° W to 55° W from which the latitude of the GSNW can be determined. We also define an altimetric index for the GSNW to coincide with the *Oleander* transect. Two peaks in variance of surface velocity are found along the transect at longitudes of 70.0° and 70.6° W. We define our index as the difference in surface velocity between these two locations and is very similar to that of Pérez-Hernández and Joyce (2014). All three indices are shown in Figure 1b. There is a high degree of correlation between the altimetric index and the Taylor index ($r = 0.75$) through the whole time series, with more variation in the two surface indices (Pérez-Hernández & Joyce, 2014). However, the Joyce index visibly diverges from the other two indices in 2005, which can be attributed to substantial differences in GSNW position between 75–70° W (positive) and 70–55° W (negative), as discussed in more detail later.

3. Quasi-Decadal Variability

Figure 2 shows annually averaged indices of GSNW, NAO, and NASST time series. The Taylor and Joyce GSNW indices are significantly correlated for the period 1970 to 2005, with a zero-lag correlation of 0.65 (sig. > 99%; significance in this study was estimated according to the random phase test of Ebisuzaki, 1997). Disagreement between the two time series occurs prior to 1970 and post-2005, causing the correlation and significance to drop to 0.43 (sig. ≈ 60%), when the full overlapping time period from 1966 to 2011 is considered (Figure 2). The data used to compute both indices prior to 1970 were sparser in comparison with the present day. However, as already noted, the time series diverge post-2005 when data coverage was good, meaning that divergence that is not an artifact of sparse data is a possibility. The December-January-February (DJF) and annual Principal Component (PC)-based NAO time series (Hurrell et al., 2003) are significantly correlated ($r = 0.65$, sig. > 99%), with zero time lag reflecting the wintertime dominance of the NAO (Figure 2). Finally, Figure 2 shows three NASST indices: the linear NASST is constructed from the Kaplan data set from 0° to 70° N with a linear trend removed; the Van Oldenborgh et al. (2009) NASST index is constructed from NASSTs in the domain 25–60° N, 7–75° W minus a regression on global temperatures; and the Trenberth and Shea (2006) NASST is constructed from SSTs in the domain 0–60° N, 0–80° W minus SST 60° S to 60° N. Both of these latter indices are based on the ERSST data set. We note that all of these were calculated as indices of AMV, but as we are analyzing timescales shorter than multidecadal, we refer to them as NASST indices. While the NASST indices are subtly different, they capture the same variability with the correlation between each pair of indices never dropping below $r = 0.74$, sig. > 99%, and with multidecadal variability having a magnitude notably larger than shorter timescale variability (Figure 2).

The NAO, GSNW, and NASST time series show variability on multiple timescales, but a consistent signal emerges when the time series are 5–20-year band-pass Tukey filtered (Figure 3a). Spectra were calculated for each time series using the maximum size Hanning window that allowed for a 50% overlap. Peaks were evident in the 5–20-year band above the 90% confidence level for the associated red noise spectrum (Figure 3b). These peaks were robust to the choice of window length and overlap. Overlapping windows were not employed in analysis of GSNW time series due to the shorter length of the time series. Spectral peaks were found with maxima between 8.3 and 9.5 years. The half power spectral width is estimated at 3 years; hence, we refer to a quasi-decadal band of variability rather than a 9-year band explicitly. Variability in the NAO at these periods has been previously noted at 8 years (Årthun et al., 2017; Da Costa & Verdiere, 2002) and 11 years (Gray et al., 2016; Tourre et al., 1999). Likewise, variability in the GSNW and NASST at decadal timescales has been noted by Nigam et al. (2018). The quasi-decadal peak is present in each index when the full time period of each index is considered as well as when the overlapping period since 1955 is considered alone. Power in

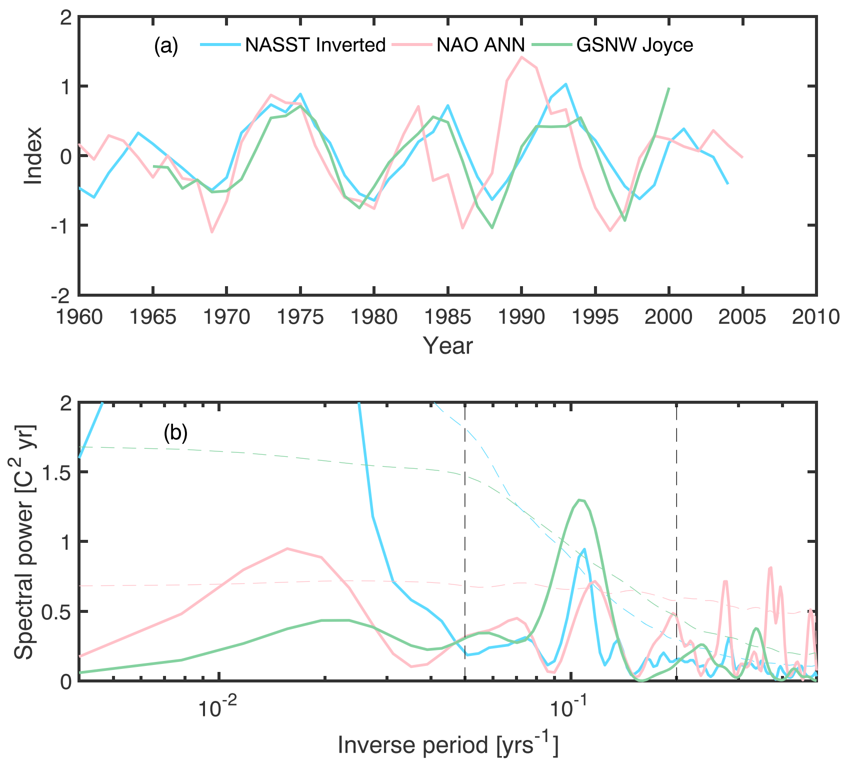

Figure 3. (a) Inverted NASST index (light blue), NAO annual index (pink), and the GSNW index (light green). All time series have been annually averaged and band-pass filtered in the 5–20-year band. (b) Spectrum of unfiltered time series. The full time period of each time series is considered for calculating spectra. Black, dashed, vertical lines indicate the 5–20-year band of interest. Estimates of 90% confidence interval based on red noise spectra for each time series are included (dashed, colors). GSNW = Gulf Stream North Wall; NAO = North Atlantic Oscillation; NASST = North Atlantic sea surface temperatures.

the NAO during this period is diminished prior to 1955 as noted by Tourre et al. (1999); however, the peak is still significant. The width of the resolved peaks in this instance encompasses the 8–11-year band of variability. In this period of overlap, the choice of version for each time series is irrelevant, with each showing similar properties and relationships with one another.

In this quasi-decadal band, the NAO and GSNW covary, while the NASST anti-varies. The covariance between the NAO and GSNW is in line with observational (Frankignoul et al., 2001; Joyce et al., 2000; Nigam et al., 2018; Taylor & Stephens, 1998) and modeling (De Coëtlogon et al., 2006) work on the subject, where the GSNW varies at short lags of the order of 1 year are associated with wind forcing. On the other hand, the inverted relationship between the NAO and NASST on these timescales is indicative of the direct action of air-sea heat fluxes. Positive values of the NAO cool the subpolar North Atlantic through air-sea heat exchange, with this and associated feedbacks leading to the characteristic tripole pattern of SSTs associated with the NAO. The 5–20-year band-pass filtered SST and net heat flux patterns associated with the NAO (supporting information Figure S1). Comparison of the two patterns reveals that regions of surface warming/cooling correspond to weaker/stronger ocean heat loss that is consistent with the SST responding to NAO-driven changes in the air-sea exchanges.

For the overlapping period from 1965 to 2000 considered in Figure 3, we have identified a prominent mode of quasi-decadal variability that links the NAO, Gulf Stream, and North Atlantic SSTs. This quasi-decadal mode of

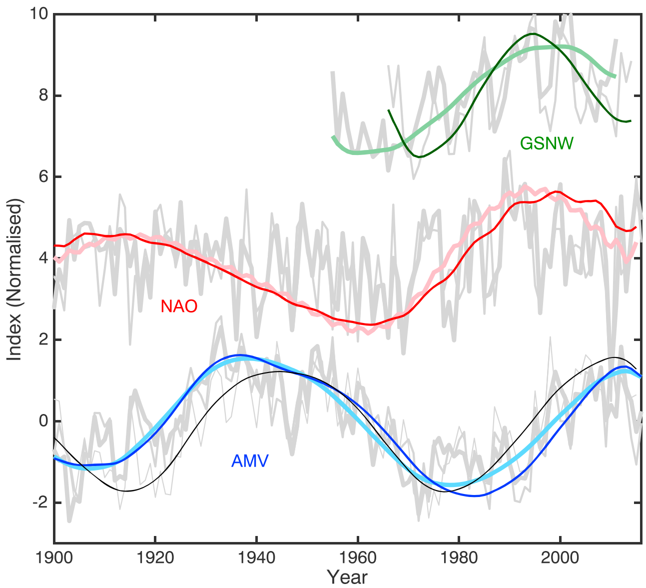

Figure 4. Multidecadal variability in (light blue) van-Oldenburgh, (navy blue) Trenberth and Shea, (black) linear North Atlantic sea surface temperatures, (red) DJF, (pink) annual NAO, and (light green) Joyce and (green) Taylor GSNW indices. Original data from Figure 3 shown in gray, with line widths illustrating the correspondence to each multidecadal component. All time series have been normalized and arbitrarily offset. GSNW = Gulf Stream North Wall; NAO = North Atlantic Oscillation; AMV = Atlantic multidecadal variability.

variability links positive NAO both to northward shifts in the separated Gulf Stream and to negative subpolar SST via air-sea fluxes.

4. Multidecadal Variability

The GSNW time series are shorter than the NASST and NAO but nonetheless show multidecadal variability. Both the Joyce and Taylor time series show increasing trends from 1970 to 2000 and decreasing thereafter (Figure 3). Both are based on temperature, and some of this tendency may be indicative of a long-term warming trend associated with global warming, a northward shift in the GSNW over time, or both (Wu et al., 2012). However, the reversal of trends in recent years indicates that the wider impacts do not project one-to-one and that local dynamics are also important.

We apply Singular Spectrum Analysis (SSA; Ghil et al., 2002) to study longer-term variation in these time series. SSA separates time series into oscillatory modes plus noise. Results of low frequency changes are robust whether SSA or low-pass filtering is applied (Figure S2). SSA allows extrapolation of the multidecadal modes over the full time series, which is relevant for the discussion here. Applying SSA to all time series, we combine the modes that have periods of variability longer than 15 years. Figure 4 shows the multidecadal variability of the NASST, NAO, and GSNW. The positive correlation observed on quasi-decadal timescales between the NAO and the GSNW remains on these longer multidecadal timescales. While the number of degrees of freedom is limited for these low frequency components, the correlation between either NAO estimate and the Joyce (Taylor) indices never drops below 0.94 (0.84), and the level of significance is greater than 95%. However, the relationship between the NASST and both the NAO and GSNW has changed. On long time periods, the NAO and GSNW remain in phase and lead the NASST by approximately 20 years showing that a direct response of NASST mediated by air-sea interaction does not explain the relationship between the NAO and the NASST on multidecadal timescales. Multidecadal variations of the GSNW are larger than the quasi-decadal variations (Figure 4). This is suggestive of ocean circulation resonating to atmospheric forcing at lower frequencies, similar to the NAO-AMOC link discussed by Delworth et al. (2017), and suggestive of an enhanced role for ocean circulation on multidecadal timescales. We note also that the multidecadal pattern of SST variability displays a basinwide mode (e.g., Sutton et al., 2017) and hence differs from the tripole pattern of SST variability associated with NAO heat fluxes. Whether the wind forcing that relates the NAO to the GSNW on interannual to decadal timescales can explain this resonant response at multidecadal timescales is a topic for future research.

5. Ongoing Changes in the Gulf Stream

Figure 5 investigates the change in the Gulf Stream between the periods 1995–2005 and 2005–2015. It has already been noted that during this period, the previously covarying Joyce and Taylor indices for the GSNW began to diverge. Indices of GSNW are not designed to capture broadening or weakening but to capture position; hence, we offer the following explanation for their divergence. From 70°W to 59°W, a broadening of the Gulf Stream extension is evident. Velocity change shows a tripolar pattern in this longitude band indicating, on average, a broader jet from 2005 to 2015 and a narrower jet from 1995 to 2005 and hence supports a broadening of the Gulf Stream Extension in this region. This is consistent with the increased instability in the Gulf Stream Extension noted by Andres (2016). Andres (2016) showed the destabilization point of the Gulf Stream Extension moving from 55°W to 70°W from 1995 to 2014. The increased eddying path changes in this region is consistent with the interpretation of a broadening Gulf Stream presented here. The only region where there is robust support for a northward shift in the Gulf Stream is between 70°W and 75°W. Viewed in sea surface

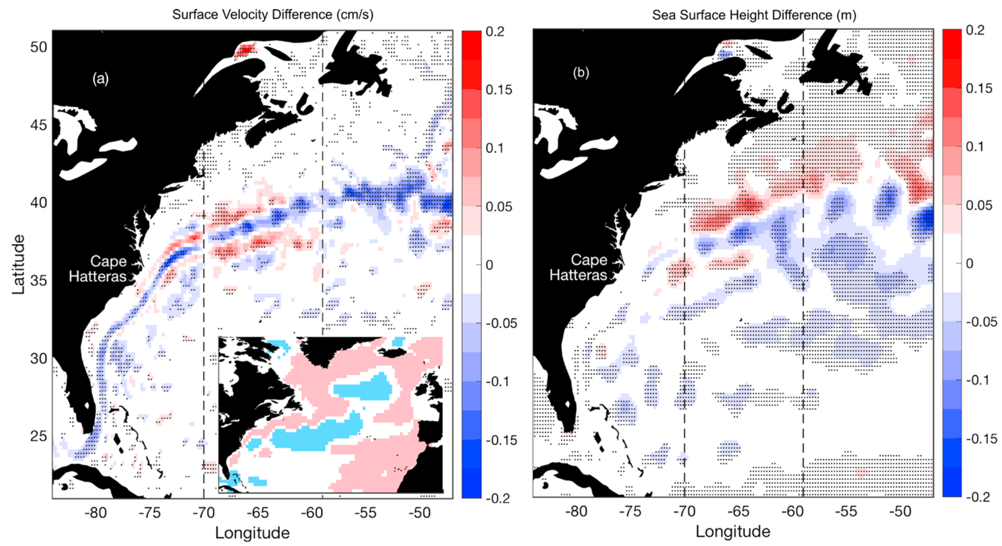

Figure 5. The difference in (a) surface velocity magnitude and (b) sea surface height for the period 2005–2015 minus 1995–2005. Dots indicate regions of change that are greater than 95% significant. (inset) Depth averaged, upper 500 m, temperature change for the same periods. Pink (light blue) indicates a warming (cooling) greater than 0.1° C. Vertical dashed lines indicate longitudes of 70° W and 59° W.

height (SSH) SSH (Figure 5b), the pattern of sea level rise north of the Gulf Stream East of 70W may appear like a northward shift in the Gulf Stream. East of 59° W and west of 75° W from Florida to Cape Hatteras, a pattern of weakening of the Gulf Stream is evident.

The broadening of the Gulf Stream and increase in SSH in the Northern Recirculation Gyre is coincident with widespread changes in the thermal structure. Changes in the depth-averaged temperature in the top 500 m (Figure 5 inset) show a warming in the Northern Recirculation Gyre, cooling south of the Gulf Stream, and cooling in the central subpolar gyre. Again, the velocity magnitude changes suggest that this temperature pattern is not due to a large shift in the path of the Gulf Stream. The pattern of warming in the Northern Recirculation Gyre and cooling in the central subpolar gyre is a fingerprint of a declining AMOC (Caesar et al., 2018; Zhang, 2008) and coincides with a period when direct measurements of the AMOC show it is in a weakened state (Smeed et al., 2018).

6. Discussion and Conclusions

The primary driver of NASST variability changes from quasi-decadal and multidecadal timescales. In both frequency bands, the NAO plays a leading role, but the mechanism of NAO-related air-sea heat flux forcing of SSTs on quasi-decadal timescales does not hold on multidecadal timescales. This is in contrast with the phase locking between the NAO and GSNW indices, which on decadal to multidecadal timescales remain consistent.

A cyclical, quasi-decadal, inverse relationship exists between the NAO and North Atlantic SSTs that is explained by air-sea fluxes. Positive values of the NAO are associated with a tripole pattern of SST anomalies, which constitutes an external (to the ocean), atmospheric driver of SSTs. The inverted relationship between air-sea fluxes and Atlantic SSTs on shorter than multidecadal timescales has been previously highlighted by Gulev et al. (2013) among other authors.

The prominence of air-sea fluxes on quasi-decadal timescales does not mean that there is no response by ocean circulation to the NAO on decadal timescales. The in-phase relationship between the NAO and the GSNW suggests a potential ocean role in setting this timescale due to ocean advection causing shifting of the GSNW (Joyce et al., 2000) or meridional advection of ocean SST signals across the intergyre boundary. Indeed, we identify a quasi-decadal cycle in the NAO and GSNW, which is the same period as that identified in the circulation of Labrador Sea Water (Nigam et al., 2018; Zantopp et al., 2017). However, we conclude that the changes in circulation, on these timescales, do not dominate the SST variability.

The NAO and GSNW remain in phase from quasi-decadal to multidecadal timescales, emphasizing that circulation changes are coincident with NAO variations over both quasi-decadal and multidecadal timescales. The consistent relationship has implications for linking the GSNW to the AMOC. Positive NAO values are generally associated with positive AMOC phases (Delworth et al., 2017), whereas the relationship of the GSNW to the AMOC is disputed with some authors finding an inverted relationship (Joyce & Zhang, 2010; Zhang & Vallis, 2007) and some authors finding a positive relationship (Nigam et al., 2018). We suggest that considering the role of the NAO may be fruitful in future considerations of the relationship between the GSNW and AMOC. It is important to note that, while we have demonstrated the phase locking on decadal and multidecadal timescales, there is little correspondence on shorter than 5-year timescales. The multidecadal variability of GSNW has a magnitude twice as large as that of the quasi-decadal resonating at longer timescales.

A different picture emerges in the relationship between the NAO and SST on multidecadal timescales. The inverse, in-phase relationship between the NAO and NASST disappears, and an approximately 20-year-lagged, positive relationship emerges. The direct action of air-sea fluxes can no longer explain the relationship. A positive, lagged relationship is consistent with the hypothesis of NAO-induced circulation changes impacting subpolar gyre heat content (Delworth et al., 2017; McCarthy et al., 2015).

Changes are ongoing in the Gulf Stream region and in the broader Atlantic. We have presented evidence of the Gulf Stream broadening and weakening from 70° W to 59° W, which we link with increased instability in the Gulf Stream Extension after 2005. The AMOC is weaker than it was in 2005 (Smeed et al., 2018), which has been linked to a predicted decline in the AMV (Frajka-Williams et al., 2017). Here we emphasize that cyclical, quasi-decadal fluctuations in SST are to be expected, superimposed on this multidecadal tendency. This atmospherically driven variability may have a magnitude 50% the size of the multidecadal variations implying that warming or cooling of SSTs for periods of 4–6 years are not sufficiently long enough to identify a multidecadal change in NASST. Indeed, the recent low values in the NASST index (Figure 2) in 2015 are coincident with the quasi-decadal, air-sea interaction driven component of SST variation and not part of the multidecadal decline. The separation of driving mechanisms of NASST between external atmospheric-driven sources and internal ocean processes, including circulation changes, is a key problem in understanding Atlantic SST variability on all timescales and its likely future evolution.

Acknowledgments
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