AGU100 ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER

10.1029/2018GL081087

**Key Points:**

- Interannual changes in the zonal mean latitude of the separated Gulf Stream can be detected and related to changes in overlying atmosphere
- Northerly GS paths are associated with enhanced storm tracks over Labrador Sea and Greenland, with more zonal storm tracks with southerly GS
- Greenland blocking center expands with a southerly GS path and is reduced with a northerly GS path

**Supporting Information:**

- Supporting Information S1
- Data Set S1

**Correspondence to:**

T. M. Joyce,
tjoyce@whoi.edu

**Citation:**

Joyce, T. M., Kwon, Y.-O., Seo, H., & Ummenhofer, C. C. (2019). Meridional Gulf Stream shifts can influence wintertime variability in the North Atlantic storm track and Greenland blocking. *Geophysical Research Letters*, *46*, 1702–1708. https://doi.org/10.1029/2018GL081087

Received 7 NOV 2018
Accepted 20 JAN 2019
Accepted article online 29 JAN 2019
Published online 11 FEB 2019



# Meridional Gulf Stream Shifts Can Influence Wintertime Variability in the North Atlantic Storm Track and Greenland Blocking

**Terrence M. Joyce[1], Young-Oh Kwon[1], Hyodae Seo[1], and Caroline C. Ummenhofer[1]**

[1]Woods Hole Oceanographic Institution, Woods Hole, MA, USA

**Abstract** After leaving the U.S. East Coast, the northward flowing Gulf Stream (GS) becomes a zonal jet and carries along its frontal characteristics of strong flow and sea surface temperature gradients into the North Atlantic at midlatitudes. The separation location where it leaves the coast is also an anchor point for the wintertime synoptic storm track across North America to continue to develop and head across the ocean. We examine the meridional *variability* of the separated GS path on interannual to decadal time scales as an agent for similar changes in the storm track and blocking variability at midtroposphere from 1979 to 2012. We find that periods of northerly (southerly) GS path are associated with increased (suppressed) excursions of the synoptic storm track to the northeast over the Labrador Sea and reduced (enhanced) Greenland blocking. In both instances, GS shifts lead those in the midtroposphere by a few months.

**Plain Language Summary** Using data from a 34-year period (1979–2012 inclusive), we have examined the relationship between wintertime atmospheric blocking events near Greenland and changes in the synoptic atmospheric storm track with interannual changes in the latitude of the Gulf Stream (GS) in the western North Atlantic Ocean. Results indicate that ocean changes in GS path precede those in the middle of the overlying atmosphere by 1–3 months, with opposite affects upon blocking and storm track. We take this as an indication that GS path shifts can significantly influence climate change in the wintertime atmosphere regionally, especially over the Labrador Sea and Greenland.

## 1. Introduction

Previous studies have convincingly shown that synoptic storm development and the path of the midlatitude zonal jet in the overlying atmosphere throughout the troposphere can be influenced in the time mean sense by the presence and characteristics of the separated Gulf Stream (GS) and that this can be reproduced in atmospheric general circulation models having spatial resolution that can resolve the strong Sea Surface Temperature (SST) gradients associated with GS (e.g., Hoskins & Valdes, 1990; Minobe et al., 2008; Nakamura et al., 2004). We seek to understand further the role that changing locations of oceanic SST fronts, in particular the separated GS in the North Atlantic, can have for the overlying atmosphere. It is motivated by previous studies linking atmospheric variability represented by the North Atlantic Oscillation (NAO) with quasi-decadal changes in the latitude of the separated GS (Gangopadhyay et al., 2016; Joyce et al., 2000). On one hand, one could argue that the separated GS latitude represents the intergyre boundary between the subpolar and subtropical North Atlantic Ocean and responds to quasi-decadal components of surface winds associated with the NAO (Marshall et al., 2001). Periods of high (low) NAO are associated with northward (southward) shifts of the surface westerlies driving the large-scale ocean circulation and the intergyre boundary. Yet time lags between the ocean and atmosphere show that the ocean follows the atmosphere by approximately 1 year, with substantial correlation at zero time lag. The zero lag correlation may reflect a quick Ekman layer ocean response to the local atmospheric variability (Gangopadhyay et al., 1992). However, we also suggest that there may be a ocean-driven effect upon the atmosphere near zero lag, which we want to explore in the present study. It is something entirely missing from ocean forced analyses, as it is a coupled response. The oceanic-forced atmospheric variability could redden the atmosphere as it reinforces the wind-driven forcing, thus creating low-frequency NAO signals, which have been noted in the long-term atmospheric record (e.g., Da Costa & Verdiere, 2002; Deser & Blackmon, 1993; Woollings et al., 2015).

Joyce et al. (2009) showed that observations of the wintertime (January–March, JFM) variance of daily boundary layer winds, vorticity, and meridional temperature fluxes responded with no lag to changing

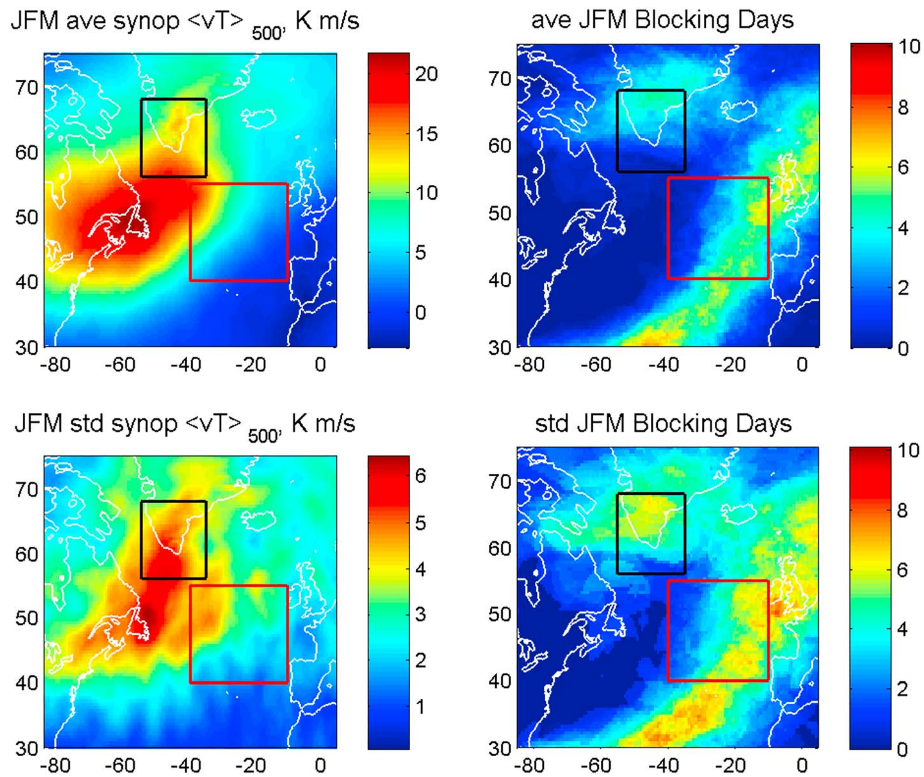


**Figure 1.** Examining 2–8 days, band-passed filtered data at 500 hPa for JFM (1979–2012), we can see the mean position (upper panels) and inter-annual variability (lower panels) of the synoptic storm track as $<v'T'>$ (left panels) and blocking (right panels) over the extratropical North Atlantic Ocean. Kwon and Joyce (2013) showed that the zonal extension of the storm track to the east (red box) was sensitive to shifts in the Gulf Stream path, with Gulf Stream path leading the synoptic variability by about a year and having a negative correlation. In this study we focus on the Greenland blocking region (black box) for the synoptic meridional temperature advection and blocking at the mid-troposphere level. JFM = January–March.

annual variations in wintertime GS latitude, and these changes were widespread at midlatitudes over the western North Atlantic basin. This led to further work (Kwon & Joyce, 2013), seeking changes throughout the overlying atmosphere both leading and lagging the changes in GS latitude. We will follow this course in the study here but focus on midtropospheric measures of wintertime (JFM) synoptic transient eddy temperature advection and blocking, in particular near the eastern coast of North America and south of Greenland. A study of the joint occurrence of North Atlantic blocking and storm track shifts (Booth et al., 2017) has yielded comparable results for the anticorrelation of Greenland blocking and the storm track shifts near Greenland but has also involved storm track variability in the eastern North Atlantic. This differs from our approach since previous findings (Kwon & Joyce, 2013) have shown storm track shifts in the eastern Atlantic follow meridional GS shifts by at least 1 year, in contrast to what we will see here. Recent work by Seo et al. (2017) also examined GS shifts leading atmosphere circulation changes by 1 year, again most relevant to the synoptic meridional temperature advection signal in the eastern North Atlantic. Our focus here is on the region near Greenland.

## 2. Data Sets and Methods

Daily mean variables in winter (JFM) from the Modern-Era Retrospective Analysis for Research and Applications (MERRA; Rienecker et al., 2011) for the recent 34 years (1979–2012) are used in this study. MERRA has 1/2° latitude and 2/3° longitude horizontal resolution, and our analysis is confined to the Northern Hemisphere. In a prior study (Kwon & Joyce, 2013) we examined a number of vertical levels from the surface to the stratosphere. Here we focus on daily geopotential height at 500 hPa (Z500) and synoptic (2–8 days) transient eddy meridional temperature flux $<v'T'(500)>$ for our blocking and storm track

10.1029/2018GL081087

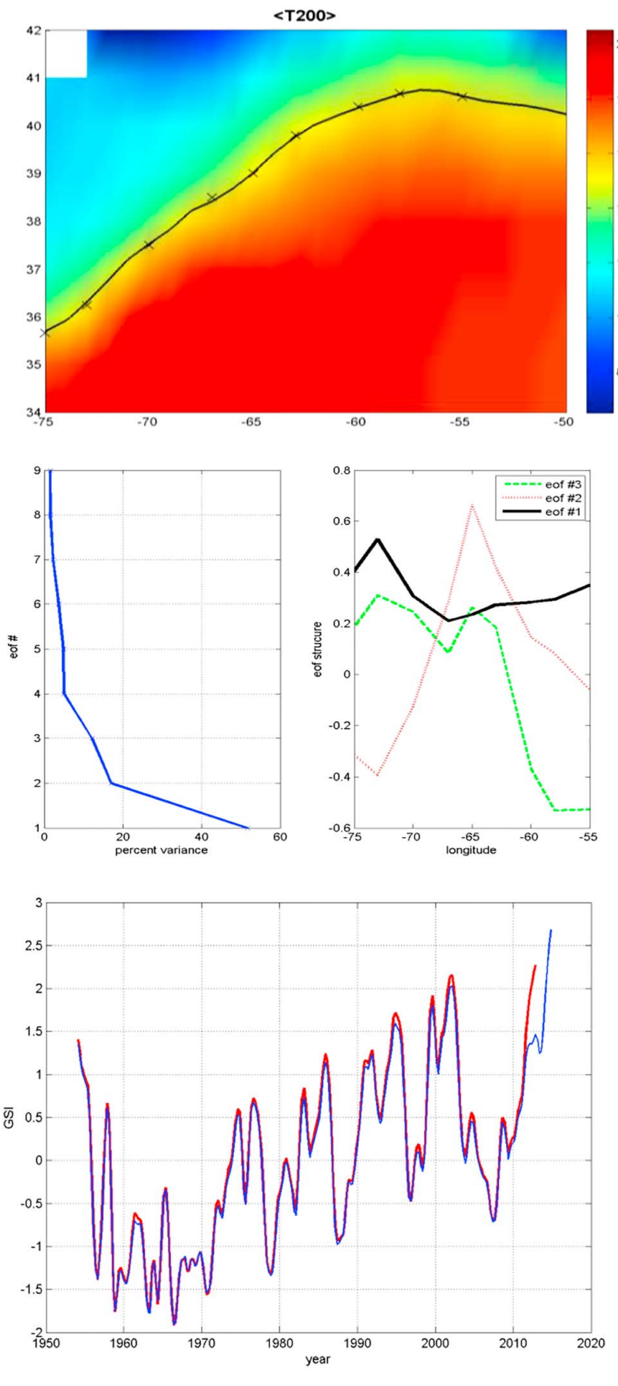


**Figure 2.** The record mean temperature is shown (upper panel) along with the $T(200) = 15$ °C contour (black line), which denotes the mean Gulf Stream North Wall. Nine points along this contour were selected (x's) and used to perform an EOF analysis (middle panels) for the $T(200)$ data through 2013. The first EOF, containing approximately 50% of the variance, was selected to represent a north/south position of the Gulf Stream, as all components of the leading statistical mode of the $T(200)$ covariance matrix had eigenvectors of similar sign for all nine longitudes (middle right, units in degrees Celsius), weighted by the percent of the total variance explained (middle left). The temporal behavior of this mode (PC1, lower panel), shows the temporal shift of Gulf Stream path with a dominant approximately 8- to 10-year periodicity over much of the period. We also show the change after recent data updating of the index from 2013 to 2015 (blue).

variables, respectively. We have followed Scherrer et al. (2006) for our blocking estimation, looking for persistent (>5 days) reversals in the eastward zonal flow or meridional geopotential gradient over 15° of latitude and counting each instance of persistent blocking as one blocking event (for details see Ummenhofer et al., 2017). The total number of days summed up for all the blocking events for each spatial location for the entire winter (JFM) season was tabulated by year and subsequently used. Similarly, daily reanalysis data were high-pass filtered with an 8-day cutoff and the covariance of filtered $v'$ and $T'$ was calculated over a winter season for each location and year (for details see Kwon & Joyce, 2013). At each grid point, we now have shown the mean of the 34 winter seasons as well as the spatial pattern of the interannual standard deviation (Figure 1). While our primary interest is in finding some of the sources for year-to-year variability, it is instructive to examine the mean and standard deviation maps together for each variable.

For completeness, we mention here that location of the GS is accomplished by examining historical ocean temperature data since 1954 (Figure 2, upper panel) along the axis of strong near-surface flow, the 15 °C isotherm at 200-m depth, which marks the "North Wall" of the Gulf Stream (Fuglister, 1955), after it separates from the eastern U.S. coast near Cape Hatteras and becomes a near-zonal front. All available hydrographic, XBT (Expendable Bathythermograph), CTD (Connectivity, Temperature, Depth), and Argo float data have been extracted from NODC (National Oceanographic Data Center) for the study region from the middle of 1954 until 2015 (WOD15). Temperature data have been sorted by latitude, longitude, and time using a resolution of 1° of longitude, latitude, and 3 months of time, respectively, with a Gaussian squared weighting from the selected desired point in a window twice the size of the desired resolution. Editing was used to reject duplicate samples and $3\sigma$ outliers from each selected sample point prior to performing the weighting and averaging; the latter was only carried out when there were at least three data points in the selected interval for each sample point. Typically, 50 or more data values were available. The resulting temperature field was therefore smoothed and has a temporal mean shown in Figure 2, upper panel. Data along the Gulf Stream north wall at nine data points indicated by the $x$'s and black line (Figure 2, upper panel) were used to assemble a spatial/temporal sampling of the $T200$ data along the north wall from 75°W to 55°W. The leading mode of temperature variability of the GS (Figure 2, middle panels) is equivalent to a north-south shift of 50–100 km which is zonally of one sign and amounts to 50% of the seasonal-interannual variance between 75°W and 55°W. The temporal behavior of this mode (PC1, Figure 2, lower panel) shows the temporal shift of GS path with a dominant approximately 8- to 10-year periodicity over much of the period. Without *detrending*, the GS Index (GSI) shows a slight increase over time after 1960, which could be due to long-term changes in $T(200)$ and not the GS path per se. We show the change after recent data updating of the index from 2013 to 2015 (blue). We have used the (detrended) 2013 index for the analyses presented here, except for the cross-correlation analysis for GS leads/lags of $\pm 2$ years, where we required GSI (Gulf Stream Index) estimates as recent as 2015.

The interannual-decadal variability of the GS latitude (Figure 2, lower panel) is shown elsewhere to be closely correlated to changes in NAO and anticorrelated to the basin-wide changes in SST (McCarthy et al.,

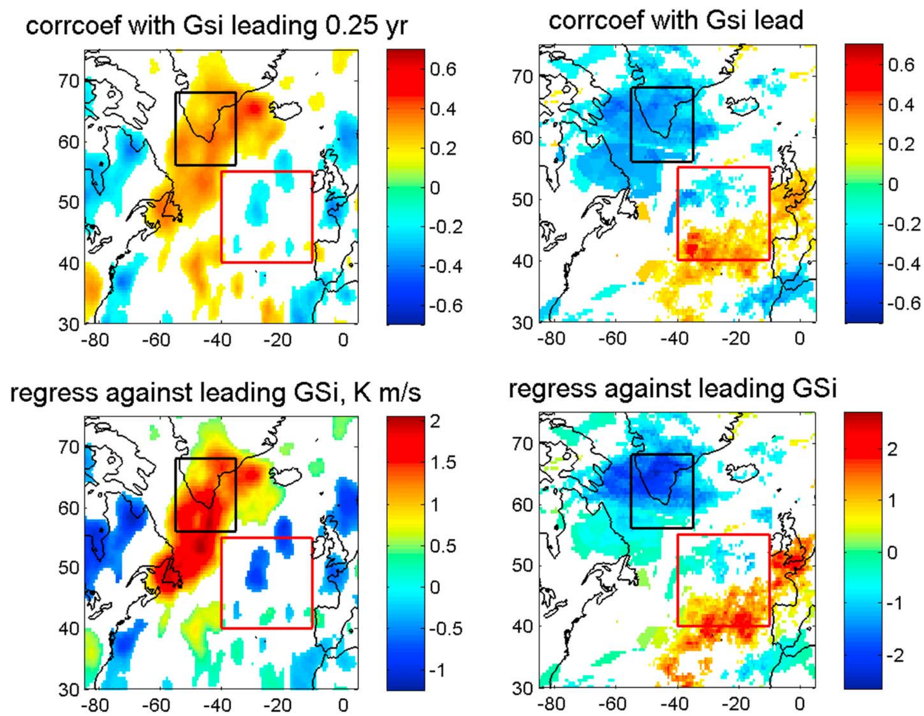


**Figure 3.** The spatial correlation (upper panels) and regression (lower panels) with GSI (Gulf Stream Index) leading by 3 months are plotted for storm track (left panels) and blocking (right panels). When the GSI leads by 3 months and is to the north, the storm track is to the north and blocking is reduced, with opposite behavior when the GS is to the south. Correlation and regression coefficients statistically significant at 90% are plotted. The regressions when GSI leads by 3 months indicate amplitudes of ≈1/3 of the sample standard deviations, which corresponds to normal (±1σ) shifts of the GS path. Blocking units are in days as in Figure 1.

2018). In what follows, we will seek correlated behavior between GS path and wintertime Atlantic storm track/Greenland blocking. In our analyses here, we have linearly detrended this leading index of the GS before comparison with the atmospheric data, which were similarly detrended, for the common period. There was little difference whether the *T*200 temperature data were detrended before or after the EOF (Empirical Orthogonal Function) calculation: the uniform *T*200 shift of the GS north wall remained the leading EOF of the field (see supporting information Figure S1). Our interest here is in the interannual-decadal signals.

## 3. Results: GS and Storm Track Variability Over Southern Greenland

The mean pattern of wintertime synoptic meridional temperature flux at 500 hPa indicates a North Atlantic storm track (Figure 1, upper left panel) and closely mirrors that of the vertically integrated, synoptic eddy temperature flux (Kwon & Joyce, 2013). However, a close examination of the yearly standard deviation of the meridional temperature flux (Figure 1, lower left panel) shows two extensions of higher variance in the downstream continuation of the mean storm track. These are to the east and to the northeast and are indicated by the red and black boxes, respectively (Figure 1). Kwon and Joyce (2013) have shown that the occurrence of the eastward storm track maximum was associated with periods of southward excursion of the GS/low NAO with GS changes leading those in the overlying troposphere by about a year.

We have cross-correlated the synoptic temperature flux with the quarterly record of the GS path using GS data leading by 3 months (Figure 3, upper left panel) after linearly detrending both sets of variables for the common data periods in the 34-year MERRA record. The 3-month lead was motivated by comparisons of synoptic temperature flux and blocking averaged over the Greenland box. We see that for this spatial region, GS variability leads the atmosphere and is most significantly correlated near-zero lag with the maximum found when the GS path leads by only 3 months (Figure 4, upper panel) and is not significant when the GS lags the atmosphere, except for GS lags approaching 2 years. GS data were shifted seasonally by

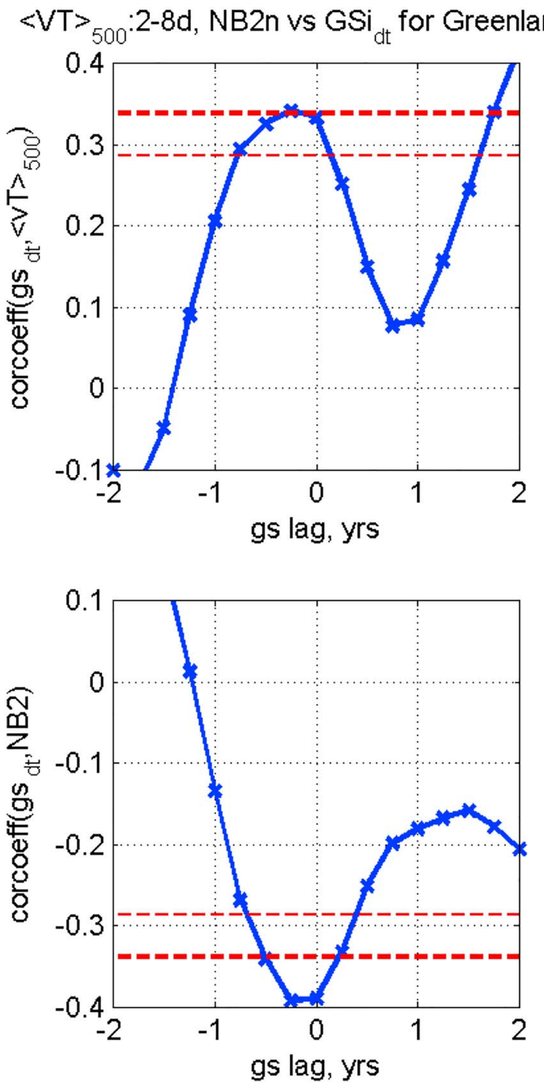


**Figure 4.** Storm track variability (upper) and blocking variability (lower) in the Greenland box were selected, averaged and compared to the Gulf Stream (GS) index for varying lags/leads. GS data were shifted seasonally by utilizing data beyond the regular overlapping period defined by the Modern-Era Retrospective Analysis for Research and Applications data set, keeping the overlapping data window constant for all lags shown for correlation. Cross correlations between the GSI (Gulf Stream Index) and storm track variability (upper) and blocking (lower) had local extrema that were not maxima at zero lags but showed the GS leading by one season, with significant correlations indicated. Since the blocking index (lower panel) is positive definite and the variability non-Gaussian, statistical confidence (90% (95%) shown as thin (heavy) dashed red lines) was estimated from 2,000 randomizations of the blocking time series in the Greenland box.

utilizing data beyond the regular overlapping period defined by the MERRA data set, keeping the overlapping data window constant for all lags shown for correlation in Figure 4. The spatial correlation and regression patterns (Figure 3, upper and lower panels, respectively) show a near-continuous pathway of anomalous winter storm track extension from Newfoundland, over the Labrador Sea to southern Greenland, following one of the preferred mean pathways of high standard deviation for the synoptic temperature flux (Figure 1, left panels). During periods of southward GS path, synoptic variability along this atmospheric pathway is suppressed and wintertime blocking is occurring over southern Greenland, as we will see next. The large positive correlation when GS lags by 2 years reflects the NAO forcing on the GS, especially driven by the Icelandic Low variability (Hameed, 2004; Sanchez-Franks et al., 2016). Therefore, the positive correlation when the GS leads by ~3 months implies a positive feedback from GS to NAO, which may contribute to persistence of the NAO.

### 3.1. GS and Blocking Variability Over Southern Greenland

The mean blocking pattern (Figure 1, upper right) closely follows what has already been studied (Häkkinen et al., 2011; Scherrer et al., 2006), and variability of the Greenland blocking center (Figure 1, lower right) has been associated with phases of the NAO and with the meridional location of the winter midlatitude jet (Davini, Cagnazzo, Neale, & Tribbia, 2012; Woollings et al., 2008). Davini, Cagnazzo, Gualdi, and Navarra (2012) have further pointed out that the Greenland blocking is different from most of the other North Atlantic blocking centers as it is dominated by cyclonic wave breaking and formation of a blocking region located to the north of the midlatitude jet. It is also different in that the GS path has more influence than elsewhere.

In contrast to the synoptic eddy temperature flux, variability of the Greenland blocking region, after detrending, is anticorrelated with GS path with GS path leading by about 3 months (Figure 4, lower panel) and thus anticorrelated with storm track variability (supporting information Figure S2). Because of the non-Gaussian character of the blocking data, we have used Monte Carlo simulation of the blocking data, randomly scrambled, to bootstrap error estimates for the statistical significance. The spatial correlation and regression patterns for blocking anomalies (Figure 3, right panels) show that blocking is enhanced (suppressed) over the Labrador Sea and southern Greenland when the GS path is to the south (north). During southerly GS paths, Greenland blocking is enhanced and storm tracks are guided south of the block. As the GS path and NAO are correlated (Joyce et al., 2000), these results are consistent with previous findings by Woollings et al. (2008) and Davini, Cagnazzo, Neale, and Tribbia (2012) for Greenland blocking and with Hahn et al. (2018) on blocking-related widespread Greenland ice melt and the NAO.

## 4. Discussion

While it may seem surprising that small latitude changes in the GS path are reflected in large meridional changes in the storm track, one must recall that the changes in the GS index are thought to be related to broader changes in the Atlantic Meridional Overturning Circulation (AMOC): periods with a northerly path are thought to be part of reduced AMOC (Joyce & Zhang, 2010), while the GS is shifted to the south when the southward transport of the Deep Western Boundary Current (DWBC) near Cape Hatteras is enhanced by cooling at high latitudes, such as the Labrador Sea. However, our directly observed records of the AMOC at 26°N (Smeed et al., 2014) and just north of the crossover point between the GS and the DWBC near 39°N (Toole et al., 2017) are only 10 years long and barely cover one cycle in the record of observed GS path changes (Figure 2, lower panel) and are thus too short to offer any definitive conclusions at present. The longer records of the GS path, decadal changes in subtropical mode water at Bermuda, and the NAO show strong correlations: with high thickness of mode water at Bermuda in phase with a *southerly* GS path and a *low* NAO, with little phase difference. During *high* NAO periods, the GS is *northerly*, there is enhanced cooling of the Labrador Sea Water, and the storm tracks are northerly (Joyce et al., 2000). We offer in this study two additional pieces of evidence of this ocean influence. First, the shifts in storm track are related to changes in the NAO and thus support an ocean influence on the atmosphere with short (<3 months) time lag, which is the minimum we can resolve with the existing GS data. In particular, the strong asymmetry between the positive and negative lags implies that the zero-lag correlation does not merely reflect the fast ocean response to the local NAO wind forcing but a response of the atmosphere to the ocean with an atmosphere lag of a few months. Next, the development of an atmospheric block amplifies the meridional shift of the storm track by diverting wintertime storms to the south of the Greenland block during periods of southerly GS events: the meridional shift in storm track is thus larger than the meridional shift of the GS itself. The dynamical linkage of this correlative behavior between the atmosphere and ocean is an active area of research, and the present results suggest that the dynamics may couple signals at the ocean surface and in the DWBC with atmospheric variability throughout the troposphere over the maritime region to the east of North America.

We have further examined the robustness of our finding by repeating the lead-lag correlation analyses by substituting the storm track and blocking from MERRA with those from three additional atmospheric reanalyses, that is, the NCEP-NCAR reanalysis I (Kalnay et al., 1996), ECMWF Re-Analysis Interim (Dee et al., 2011), and NOAA twentieth Century Reanalysis (Compo et al., 2011). This sensitivity exercise (not shown) exhibits overall robustness of our conclusions based on MERRA, while we also found some small differences, for example, the exact timing or amplitude of the maximum lag correlations. One noteworthy sensitivity is associated with the analysis period. The two longer reanalyses suggest that relationship between the GS and blocking/storm track may be nonstationary as the lag correlations are very different for the periods before and after the 1970s. Further investigation on this potential nonstationarity is left for a future study. For the convenience of the interested reader, a file containing our GS Index is also included with the supporting information.

**Acknowledgments**
Our research has been conducted with the support of NSF (AGS-1355339, OCE-1419235, and OCE-1242989), NASA (NNX13AM59G), and NOAA CPO Climate Variability and Predictability Program (NA13OAR4310139) grants to the Woods Hole Oceanographic Institution. We also thank three reviewers for their insightful comments on an earlier draft of this manuscript. Quarterly estimates of our Gulf Stream Index are available as a data file in the supporting information.

## References

Booth, J. F., Dunn-Sigouin, E., & Pfahl, S. (2017). The relationship between extratropical cyclone steering and blocking along the North American East Coast. *Geophysical Research Letters*, *44*, 11,976–11,984. https://doi.org/10.1002/2017GL075941

Compo, G. P., Whitaker, J. S., Sardeshmukh, P. D., Matsui, N., Allan, R. J., Yin, X., et al. (2011). The twentieth century reanalysis project. *Quarterly Journal of the Royal Meteorological Society*, *137*(654), 1–28. https://doi.org/10.1002/qj.776

Da Costa, E., & Verdiere, A. (2002). The 7.7-year North Atlantic Oscillation. *Quarterly Journal of the Royal Meteorological Society*, *128*(581), 797–817.

Davini, P., Cagnazzo, C., Gualdi, S., & Navarra, A. (2012). Bidimensional diagnostics, variability, and trends of Northern Hemisphere blocking. *Journal of Climate*, *25*, 6496–6509. https://doi.org/10.1175/JCLI-D-12-00032.1

Davini, P., Cagnazzo, C., Neale, R., & Tribbia, J. (2012). Coupling between Greenland blocking and the North Atlantic Oscillation pattern. *Geophysical Research Letters*, *39*, L16102. https://doi.org/10.1029/2012GL052

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., et al. (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, *137*(656), 553–597. https://doi.org/10.1002/qj.828

Deser, C., & Blackmon, M. L. (1993). Surface climate variations over the North Atlantic Ocean during winter: 1900–1989. *Journal of Climate*, *6*(9), 1743–1753. https://doi.org/10.1175/1520-0442(1993)006<1743:SCVOTN>2.0.CO;2

Fuglister, E. C. (1955). Alternate analyses of current surveys. *Deep Sea Research*, *2*(3), 213–229. https://doi.org/10.1016/0146-6313(55)90026-5

Gangopadhyay, A., Chaudhuri, A. H., & Taylor, A. H. (2016). On the nature of temporal variability of the Gulf Stream path from 75° to 55°W. *Earth Interactions*. https://doi.org/10.1175/EI-D-15-0025.1

Gangopadhyay, A., Cornillon, P., & Watts, D. R. (1992). A test of the Parsons–Veronis hypothesis related to the separation of the Gulf Stream from the coast. *Journal of Physical Oceanography*, *22*(11), 1286–1301. https://doi.org/10.1175/1520-0485(1992)022<1286:ATOTPH>2.0.CO;2

Hahn, L., Ummenhofer, C. C., & Kwon, Y.-O. (2018). North Atlantic natural variability modulates emergence of widespread Greenland melt in a warming climate. *Geophysical Research Letters*, *45*, 9171–9178. https://doi.org/10.1029/2018GL079682

Häkkinen, S., Rhines, P. B., & Worthen, D. L. (2011). Atmospheric blocking and Atlantic multidecadal ocean variability. *Science*, *334*(6056), 655–659. https://doi.org/10.1126/science.1205683

Hameed, S. (2004). The dominant influence of the Icelandic Low on the position of the Gulf Stream northwall. *Geophysical Research Letters*, *31*, L09303. https://doi.org/10.1029/2004GL019561

Hoskins, B. J., & Valdes, P. J. (1990). On the existence of storm-tracks. *Journal of the Atmospheric Sciences*, *47*(15), 1854–1864. https://doi.org/10.1175/1520-0469(1990)047<1854:OTEOST>2.0.CO;2

Joyce, T. M., Deser, C., & Spall, M. A. (2000). The relation between decadal variability of Subtropical Mode Water and the North Atlantic Oscillation. *Journal of Climate*, *13*(14), 2550–2569. https://doi.org/10.1175/1520-0442(2000)013<2550:TRBDVO>2.0.CO;2

Joyce, T. M., Kwon, Y.-O., & Yu, L. (2009). On the relationship between synoptic wintertime atmospheric variability and path shifts in the Gulf Stream and Kuroshio Extension. *Journal of Climate*, *22*(12), 3177–3192. https://doi.org/10.1175/2008JCLI2690.1

Joyce, T. M., & Zhang, R. (2010). On the path of the Gulf Stream and the Atlantic Meridional Overturning Circulation. *Journal of Climate*, *23*(11), 3146–3154. https://doi.org/10.1175/2010JCLI3310.1

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., et al. (1996). The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society*, *77*(3), 437–471. https://doi.org/10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2

Kwon, Y.-O., & Joyce, T. M. (2013). Northern Hemisphere winter atmospheric transient eddy heat fluxes and the Gulf Stream and Kuroshio-Oyashio extension variability. *Journal of Climate*, *26*, 9839–9859. https://doi.org/10.1175/JCLI-D-12-00647.1

Marshall, J., Johnson, H., & Goodman, J. (2001). A study of the interaction of the North Atlantic Oscillation with ocean circulation. *Journal of Climate*, *14*(7), 1399–1421. https://doi.org/10.1175/1520-0442(2001)014<1399:ASOTIO>2.0.CO;2

McCarthy, G. D., Joyce, T. M., & Josey, S. A. (2018). Gulf Stream variability in the context of quasi-decadal and multi-decadal Atlantic climate variability. *Geophysical Research Letters*, *45*, 11,257–11,264. https://doi.org/10.1029/2018GL079336

Minobe, S., Kuwano-Yoshida, A., Komori, N., Xie, S.-P., & Small, R. J. (2008). Influence of the Gulf Stream on the troposphere. *Nature*, *452*, 206–209. https://doi.org/10.1038/nature06690

Nakamura, H., Sampe, T., Tanimoto, Y., & Shimpo, A. (2004). Observed associations among storm tracks, jet streams and midlatitude oceanic fronts. In *Earth climate: The ocean–atmosphere interaction*, *Geophys. Monogr.* (Vol. 147, pp. 329–346). Washington, DC: American Geophysical Union.

Rienecker, M. M., Suarez, M. J., Gelaro, R., Todling, R., Bacmeister, J., Liu, E., et al. (2011). MERRA: NASA's Modern-Era Retrospective Analysis for Research and Applications. *Journal of Climate*, *24*, 3624–3648. https://doi.org/10.1175/JCLI-D-11-00015.1

Sanchez-Franks, A., Hameed, S., & Wilson, R. E. (2016). The Icelandic Low as a predictor of the Gulf Stream North Wall Position. *Journal of Physical Oceanography*, *46*(3), 817–826. https://doi.org/10.1175/JPO-D-14-0244.1

Scherrer, S. C., Croci-Maspoli, M., Schwierz, C., & Appenzeller, C. (2006). Two-dimensional indices of atmospheric blocking and their statistical relationship with winter climate patterns in the Euro-Atlantic region. *International Journal of Climatology*, *26*(2), 233–249. https://doi.org/10.1002/joc.1250

Seo, H., Kwon, Y.-O., Joyce, T. M., & Ummenhofer, C. C. (2017). On the predominant nonlinear response of the extratropical atmosphere to meridional shifts of the Gulf Stream. *Journal of Climate*, *30*(23), 9679–9702. https://doi.org/10.1175/JCLI-D-16-0707.1

Smeed, D. A., McCarthy, G., Cunningham, S. A., Frajka-Williams, E., Rayner, D., Johns, W. E., et al. (2014). Observed decline of the Atlantic Meridional Circulation 2004 to 2012. *Ocean Science*, *10*, 28–38. https://doi.org/10.5194/osd-10-29-2014

Toole, J. M., Andres, M., Le Bras, I. A., Joyce, T. M., & McCartney, M. S. (2017). Moored observations of the deep western boundary current in the NW Atlantic: 2004-2014. *Journal of Geophysical Research: Oceans*, *122*, 7488–7505. https://doi.org/10.1002/2017JC012984

Ummenhofer, C., Seo, H., Kwon, Y.-O., Parfitt, R., Brands, S., & Joyce, T. M. (2017). Emerging European winter precipitation pattern linked to atmospheric circulation changes over the North Atlantic region in recent decades. *Geophysical Research Letters*, *44*, 8557–8566. https://doi.org/10.1002/2017GL074188

Woollings, T., Franzke, C., Hodson, D. L. R., Dong, B., Barnes, E. A., Raible, C. C., & Pinto, J. G. (2015). Contrasting interannual and multidecadal nao variability. *Climate Dynamics*, *45*(1–2), 539–556. https://doi.org/10.1007/s00382-014-2237-y

Woollings, T., Hoskins, B., Blackburn, M., & Berrisford, P. (2008). A new Rossby wave-breaking interpretation of the North Atlantic Oscillation. *Journal of the Atmospheric Sciences*, *65*(2), 609–626. https://doi.org/10.1175/2007JAS2347.1