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Key Points:

- The location where the detached Gulf Stream's meanders initiate varies by 1500 km and has shifted west (upstream) at ~25 km yr^{-1}
- Gulf Stream troughs and deep cyclones that stir the Deep Western Boundary Current into the deep interior have become more common since 2008
- The detached Gulf Stream's stability may reflect the system's intrinsic variability controlled at the DWBC cross-over near Cape Hatteras

Supporting Information:

- Supporting Information S1
- Figure S1

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On the recent destabilization of the Gulf Stream path downstream of Cape Hatteras

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Abstract Mapped satellite altimetry reveals interannual variability in the position of initiation of Gulf Stream meanders downstream of Cape Hatteras. The longitude where the Gulf Stream begins meandering varies by 1500 km. There has been a general trend for the destabilization point to shift west, and 5 of the last 6 years had a Gulf Stream destabilization point upstream of the New England Seamounts. Independent in situ data suggest that this shift has increased both upper-ocean/deep-ocean interaction events at Line W and open-ocean/shelf interactions across the Middle Atlantic Bight (MAB) shelf break. Mooring data and along-track altimetry indicate a recent increase in the number of deep cyclones that stir Deep Western Boundary Current waters from the MAB slope into the deep interior. Temperature profiles from the Oleander Program suggest that recent enhanced warming of the MAB shelf may be related to shifts in the Gulf Stream's destabilization point.

1. Introduction

The character of the poleward flowing Gulf Stream changes markedly near Cape Hatteras where the current begins to transition from a topographically trapped western boundary current to a vigorously meandering free jet as the continental slope's isobaths diverge from the mean Gulf Stream path (Figure 1). Within 50 km, the Gulf Stream encounters and crosses over the equatorward flowing Deep Western Boundary Current (DWBC) [*Pickart and Watts*, 1990]. The narrow envelope of Gulf Stream paths [*Pickart and Watts*, 1993] gradually widens as the Gulf Stream becomes more contorted downstream [e.g., *Cornillon*, 1986].

Near 70°W, the Gulf Stream mean axis (Figure 1a, yellow line) is separated from the shelf edge by about 250 km. By 60°W this separation has increased to more than 400 km. Between the Gulf Stream north wall and the MAB shelf—within the slope sea—mean flows of the shelf break jet [*Fratantoni and Pickart*, 2007], slope current [*Flagg et al.*, 2006], and DWBC [*Toole et al.*, 2011] are all equatorward. On the MAB shelf, the mean flow is also directed equatorward [*Lentz*, 2008].

With these equatorward currents generally occupying the slope sea, the detached Gulf Stream influences the MAB shelf and slope via occasional extreme diversions in Gulf Stream path [*Gawarkiewicz et al.*, 2012] and, more commonly, via indirect Gulf Stream effects. Indirect effects include pinched-off Gulf Stream rings that flood the slope with warm, salty water [e.g., *Lee and Brink*, 2010] and deep cyclones that spin-up under Gulf Stream meander troughs [*Savidge and Bane*, 1999]. These cyclones stir DWBC waters, with their characteristic high chlorofluorocarbon concentrations, off the continental slope and into the deep interior [*Andres et al.*, 2016].

Mapped and along-track satellite altimetry are analyzed here to demonstrate that the character of the detached Gulf Stream south of New England has changed markedly over the last two decades. The longitude where the detached Gulf Stream "goes unstable" as it transitions from a relatively straight, detached jet to a meandering, convoluted one has moved west (upstream) at a rate of about 25 km yr^{-1}. Early in the 22 year satellite record, path destabilization often occurred at or east of the New England Seamount Chain; however, it is shown here that in 5 of the last 6 years this occurred west of the seamounts. As this destabilization point moves westward, the meandering Gulf Stream comes closer to the MAB and its equatorward currents—both those on the slope (DWBC and slope jet) and those near the shelf edge (shelf break jet and the along-shelf flows). This proximity increases the chance for Gulf Stream-MAB interaction events and may have important consequences beyond a local increase in the Gulf Stream's eddy kinetic energy.

The following describes the method used to identify the detached Gulf Stream's path and determine the mean and time-varying location of its transition to an unstable jet with mapped satellite altimetry. The character of the Gulf Stream downstream of Cape Hatteras is further examined along a satellite altimeter track (# 126).

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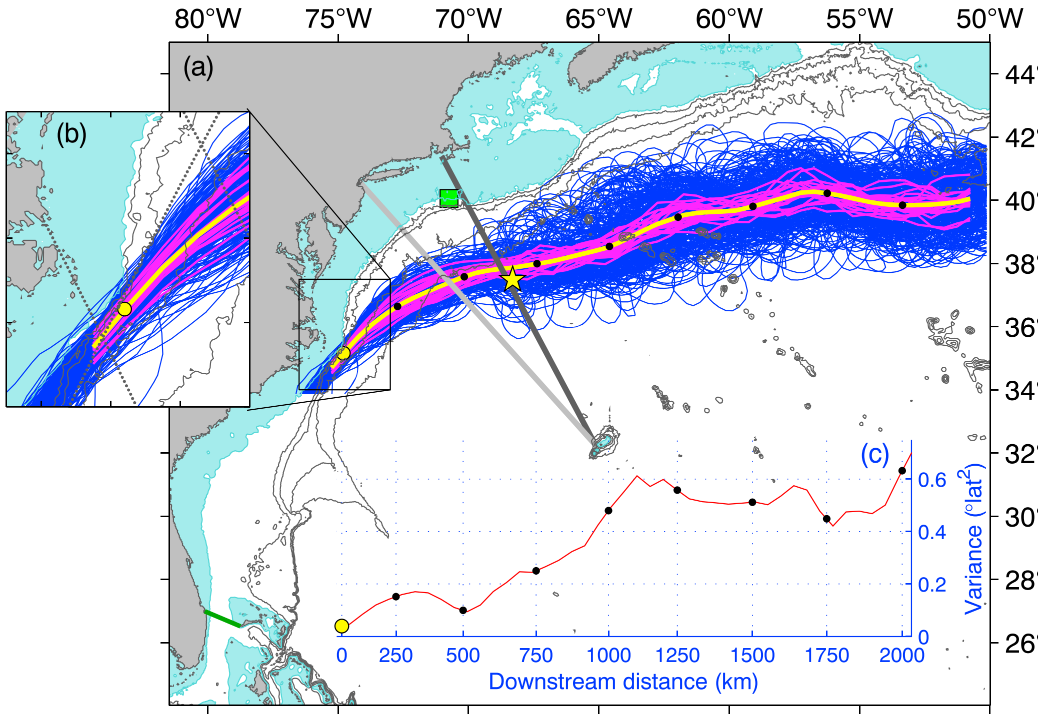

Figure 1. (a) Gulf Stream paths based on the 25 cm SSH contour showing monthly (blue), yearly (magenta), and a 1993–2014 overall (yellow) mean, with downstream distance at 250 km increments (black dots) from 74°48.00′W, 35°8.28′N (yellow dot). Regions <200 m depth are shaded blue; depths contoured at 1000 m interval to 4000 m. Line W (dark gray), mooring w6 (star), Oleander Line (light gray), Pioneer Array (green square), and Florida Strait Transport Time Series (green line) are indicated. (b) Close-up around Cape Hatteras with nearby satellite tracks (dotted lines). (c) Variance in latitudinal position of the monthly mean Gulf Stream paths (1993–2014) as a function of downstream distance (*x* axis aligned to correspond with the longitude axis of Figure 1a).

Finally, interannual Gulf Stream variability downstream of Cape Hatteras is considered in the context of in situ data to investigate possible consequences and causes of the recent Gulf Stream changes.

2. Identifying the Gulf Stream Path and its Transition to an Unstable Jet

Mapped absolute dynamic topography at ¼° resolution is available through Aviso at daily intervals. Daily maps are averaged to produce monthly maps from 1993 to the end of 2014. For each month, the Gulf Stream path is identified with the 25 cm sea surface height (SSH) contour (consistent with *Lillibridge and Mariano* [2013] and *Rossby et al*. [2014]; see also Text S1 in the supporting information for a discussion of different methods to identify the Gulf Stream location with satellite altimetry).

Monthly mean Gulf Stream paths are examined as a group (Figure 1) and separated by year (e.g., Figure 2) to quantify the variability of the Gulf Stream path downstream of Cape Hatteras. In the aggregate (1993−2014), the path in the western part of the domain (i.e., near Cape Hatteras) is stable (low variance), while that in the east is unstable (high variance).

For each year, the 12 monthly mean paths are separated into 0.5° longitude bins and the variance of Gulf Stream position (latitude) in each bin is calculated. In some months the path in a given longitude bin takes a contorted "*S* curve" route. For these months and bins, the most northerly latitude of the 25 cm SSH contour is used in the variance calculation; similar results are obtained from the mean latitude of the 25 cm SSH contour in the bin (though the latter damps the variance somewhat). The downstream distance (longitude) where the latitude's variance first reaches $0.5(°)^2$—equivalent to 6.2×10^3 km^2—is identified as that year's path destabilization point. This is where the Gulf Stream converts from a stable, detached jet to an unstable, meandering detached jet (red dots in Figure 2). The 12 monthly mean Gulf Stream paths are shown for a year with relatively straight paths (1995, Figures 2a and 2b) and a year with contorted paths (2014, Figures 2c and 2d).

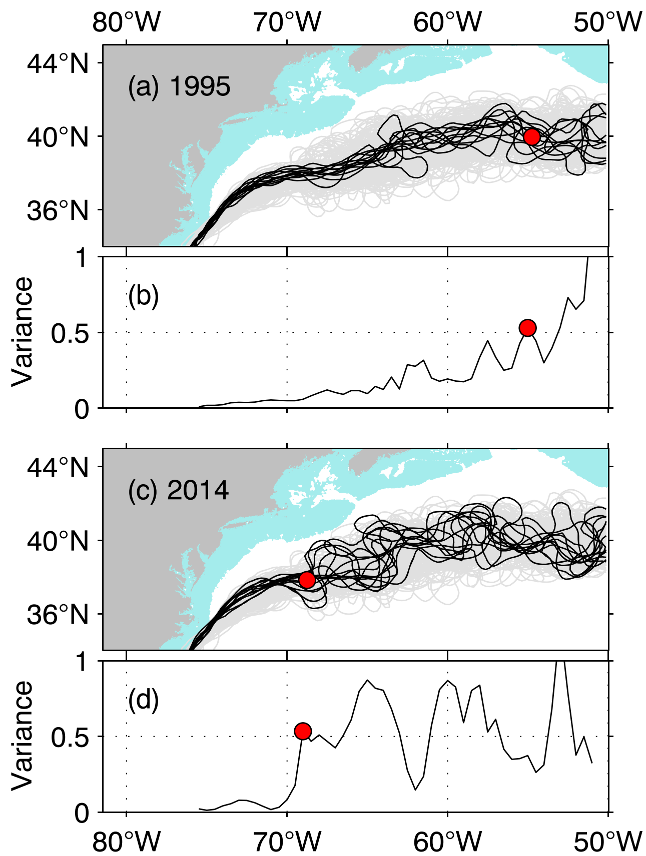

Figure 2. Monthly mean Gulf Stream paths (black) for (a) 1995 and (c) 2014 superimposed on all monthly mean paths (1993–2014, gray envelope). Regions <200 m are shaded blue. (b, d) The respective variances in path position (°latitude) are plotted. Red dots indicate the "destabilization point" where that year's latitude variance first reaches 0.5(°)^2.

Over 22 years (1993–2014) the location of this destabilization point has varied by 1500 km (i.e., between 52.5°W and 69.5°W, Figure 3). In addition to strong interannual variability, there has been a general westward shift of the destabilization point, particularly since 1995 when the jet was in an extremely straight, stable path reaching far downstream of the New England Seamount Chain (Figure 2a).

3. Regional Effects of a Changing Gulf Stream

The westward shift of the path destabilization point has brought the meandering Gulf Stream closer to the MAB shelf and slope and closer to sites where sustained in situ observations are underway or have been completed recently. In situ observations from Line W, the Pioneer Array, and the Oleander Line (Figure 1a) suggest that the Gulf Stream's transition south of the MAB from stable to unstable paths has wide-reaching effects.

3.1. Deep-Ocean Effects

The Line W Program—a decade-long effort (2004–2014) to document changes in the DWBC—included an array of five moorings across the continental slope between the 2200 m and 4100 m isobaths [*Toole et al.*, 2011]. For part of the program an additional mooring, w6, was deployed near the 4700 m isobath (Figure 1a, yellow star). The moorings measured temperature, salinity, and velocity with a combination of profilers and fixed-depth sensors. A second component of the program, repeated shipboard sections, extended the observations from the MAB slope toward Bermuda along satellite track 126 (Figure 1a, dark gray line).

Recent analysis of satellite altimetry maps and the concurrent observations from 18 shipboard sections along Line W–comprising CTD profiles, tracer measurements, and lowered acoustic Doppler current profiler (ADCP) profiles—suggests that DWBC waters are intermittently stirred from the boundary into the interior via deep cyclones that spin-up beneath Gulf Stream meander troughs at Line W [*Andres et al.*, 2016]. Those 18 sections (primarily spanning 2004 to 2014, with two sections from the mid-1990s) sampled through troughs and the associated deep cyclones at Line W for 25% of the transects. A time series of along-track absolute dynamic topography (ADT) from track 126 (described below) and observations from mooring w6 put variability from these 18 shipboard snapshots into a broader context and suggest that these stirring events have become more frequent.

Along-track ADT, with ~10 day temporal resolution and ~6 km along-track spatial resolution, is examined here from 2002 to September 2015 (with the satellite track occupied by Jason-1 until 2008 and Jason-2 thereafter). The unfiltered delayed-time product is first smoothed along the track with a cubic spline, and then along-track sea surface height (SSH) gradient $\delta\eta/\delta x$ is calculated to determine the cross-track component of the surface geostrophic velocity v:

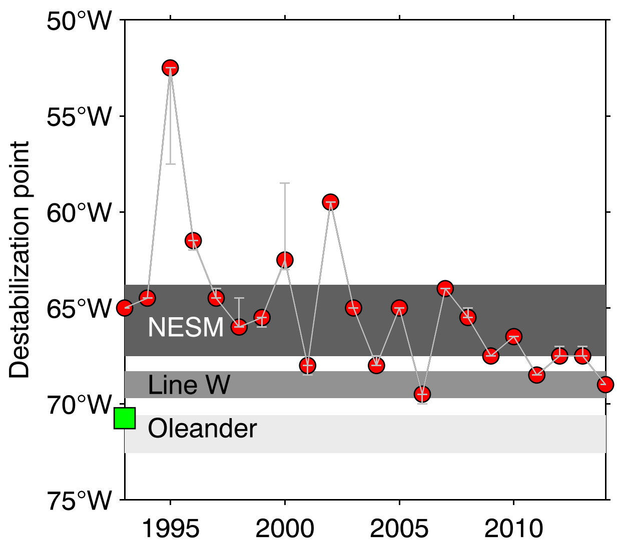

Figure 3. Time series of annual destabilization point location. Error bars represent the destabilization point calculated using variance thresholds of $0.5(°)^2 \pm 10\%$ of the maximum variance reached in Figure 1c (i.e., $0.44(°)^2$ to $0.56(°)^2$). Shaded bands show longitudes spanning the MAB shelf break and mean Gulf Stream path (yellow path in Figure 1) at various features: the New England Seamount Chain (NESM), Line W, and the Oleander Line. The Pioneer Array—located at the MAB shelf break—is indicated with the green square.

$$v = \frac{g}{f}\frac{\partial \eta}{\partial x}. \quad (1)$$

Here f is the local Coriolis parameter, $\delta\eta/\delta x$ is the SSH gradient in the along-track direction, and $g = 9.81\ \mathrm{m\,s^{-2}}$ is acceleration due to gravity. Equation (1) assumes negligible effects due to Gulf Stream curvature.

The time series of v from equation (1) is used to identify the position of the Gulf Stream axis where it crosses Line W. Note that the latitude of maximum v (Figure 4, black curve) tracks the 25 cm SSH contour very closely (see Text S1 and Figure S1). In addition, a Gulf Stream "north wall" is identified with the $0\ \mathrm{m\,s^{-1}}$ isotach shoreward of the Gulf Stream axis (the southern edge of the colored shading in Figure 4). To highlight the character of the flow in the slope sea between the Gulf Stream north wall and the MAB shelf, cross-track velocity is shaded (red and yellow are poleward flow, and blue is equatorward flow).

Satellite-derived v confirms that flow in the slope sea is generally equatorward (toward Cape Hatteras), punctuated with occasional reversals (Figure 4a), often due to anticyclonic warm core rings evident as strong poleward velocity pulses (red shading) onshore of intense equatorward pulses (blue shading). Two notable anticyclones, highlighted with the red arrows, were fortuitously sampled by Line W cruises in May 2006 and September 2009. The first (the strongest in the Jason-1 and Jason-2 records) was a massive 250 km diameter ring with the satellite-derived v suggesting swirl speeds $>1\ \mathrm{m\,s^{-1}}$. The second was a smaller anticyclone but with clear evidence of trapped near-inertial waves (deduced from shipboard data from the Line W cruise and described in *Joyce et al*. [2013]).

In addition to ubiquitous anticyclones in the slope sea at Line W, along-track data discern large offshore meander events, which are evident when the Gulf Stream axis veers more than 80 km offshore of its mean

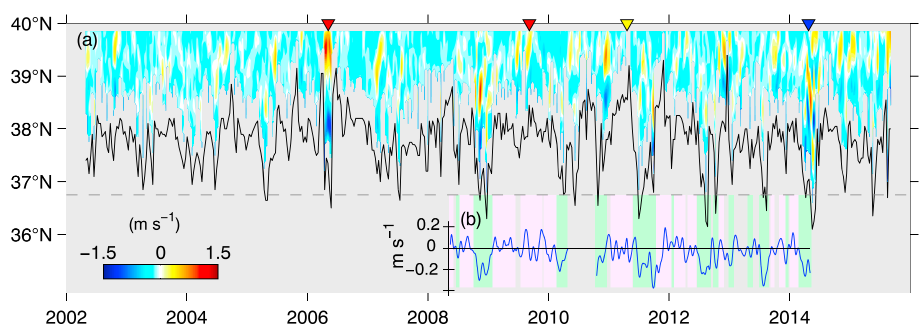

Figure 4. (a) Flow field inferred from along-track altimetry (track 126) at Line W showing Gulf Stream axis position at 10 day interval (black curve) and cross-track velocities between the Gulf Stream north wall and the shelf (blue to red shading). The intervening gray region is the cyclonic side of the meandering Gulf Stream. Arrows indicate events referred to in the text. (b) Concurrent observations from mooring w6 showing 30 day low-pass filtered cross-track velocities at 4000 dbar (blue line); shading highlights times at w6 with warm (>8°C, pink) and cold (<5°C, green) temperature anomalies at 1000 dbar; times with no highlight indicate either a data gap or a period of normal temperatures at w6.

location, past 36°45′N (i.e., when the black curve extends south of the dashed line in Figure 4a). These troughs have become more common: from 2002 to 2007 there were only three large meander events in 7 years (0.4 per year); from 2008 to 2015 there were ~10 such events in 8 years (1.25 per year).

Satellite observations along Line W are complemented by subsurface observations from mooring w6. Mooring data are consistent with the presence of deep cyclones in tandem with the upper ocean meander troughs. Coincident with a large amplitude trough at Line W (evident from the altimetry, Figure 4a), the warm salty Gulf Stream waters retreat from mooring w6. These retreats manifest as cold anomalies measured at w6 at 1000 dbar (green highlighted times in Figure 4b). At the same time, pulses of strong equatorward deep flow—reaching about 20 cm s^{-1}—are measured at depth (~4000 dbar) by w6 (Figure 4b, blue line), presumably as the mooring samples the onshore side of each deep cyclone.

This comparison of Line W mooring observations with concurrent satellite altimetry strongly suggests that deep stirring events—which drive exchange between the DWBC and the deep interior [*Andres et al*., 2016]—have become more common in recent years south of the MAB.

3.2. Upper Ocean Effects

Temperature profiles from expendable bathythermographs (XBTs) have been made regularly since 1977 along the route of the CMV Oleander (Figure 1a, light gray line), a container ship with weekly round-trip crossings between New Jersey and Bermuda [*Sanchez-Franks et al*., 2014]. A node in the envelope of Gulf Stream paths near 68° or 69°W [e.g., *Cornillon*, 1986; *Joyce et al*., 2000] is observed near the Oleander Line, even in 2014 (Figure 2c), when the Gulf Stream's path destabilization point was remarkably far west.

It is not clear whether the Gulf Stream's path destabilization point will continue to migrate westward and across the Oleander Line (eventually erasing the node), but it is possible that the Oleander Program's observations collected on the shelf reflect changes to the east where the Gulf Stream path has already become unstable. Shelf temperature profiles from XBTs launched monthly from the ship suggest that the MAB shoreward of the 80 m isobath has been warming at 0.1°C yr^{-1} since 2002, nearly five times the rate of warming from 1977 to 2013 [*Forsyth et al*., 2015]. This warming is superimposed on strong interannual temperature variability. The cause(s) of this recently enhanced shelf warming trend and of the year-to-year shelf temperature variability remain areas of active research. However, the altimetry observations suggest that interaction events that bring the Gulf Stream's warm, salty waters close to the cooler, fresher waters of the shelf may play a role in driving cross-shelf heat exchange both at the Oleander Line and to the east (with the signals due to the latter then advected to the Oleander Line by the mean equatorward shelf currents).

Around mid-April to mid-May 2011 (yellow triangle in Figure 4a) the cyclonic side of the Gulf Stream overran the continental slope at Line W. During this period, the upper ocean flow on the slope was completely reversed (i.e., all poleward) and there was no evidence of a Gulf Stream north wall (the 0 m s^{-1} isotach was onshore of the shelf break). This suggests that Gulf Stream waters were delivered directly to the outer shelf (in contrast to more typical indirect Gulf Stream influences via the slope sea's anticyclonic rings). How this event manifested itself on the shelf and whether it is captured in data from the nearby Pioneer Array (green square in Figure 1a) remain to be investigated. However, a similar direct intrusion of the Gulf Stream was observed farther east—near 67°W south of Georges Bank—in late 2011 (the along-track data from this region are not shown here). In this case, Pioneer Array measurements of subsurface temperature and salinity, together with a drifter track, strongly suggest that this event delivered Gulf Stream waters directly to the outer shelf and that this warm, salty water was then advected along the shelf break from 67°W to the Pioneer Array [*Gawarkiewicz et al*., 2012].

Another event that stands out in the satellite record at track 126 occurred at the end of April 2014 (Figure 4a, blue triangle). This period coincides with a so-called Pinocchio's Nose Intrusion event which developed due to the direct impingement of ring water past the slope and onto the shelf [*Zhang and Gawarkiewicz*, 2015].

4. Possible Causes of the Gulf Stream Path Destabilization

The shift of the path destabilization point may be forced externally or may reflect intrinsic variability. Neither the large-scale wind field nor the strength of the Gulf Stream (considered below) can be definitively connected to the stability of the Gulf Stream path downstream of Cape Hatteras. Indeed, it is possible that intrinsic (unforced) variability at the Gulf Stream/DWBC crossover plays an important role.

4.1. External Forcing

Annual averages from the Florida Current Transport Time Series (Figure 1a, green line) are examined here as a measure of Gulf Stream strength since 2000 [*Meinen et al*., 2010]. For the common period (2000–2014), transport (not shown) through the Florida Straits and location of the detached Gulf Stream's destabilization point (Figure 3) each have a negative trend and the time series are positively correlated ($r = 0.52$). The detrended time series, however, are only correlated at the 85% significance level ($r = 0.39$). This may suggest that a weaker Gulf Stream goes unstable more readily (i.e., closer to Cape Hatteras) than a strong Gulf Stream. However, Florida Current transport may not be a reliable indicator of transport downstream of Cape Hatteras [*Sanchez-Franks et al*., 2014] and there is not yet clear evidence from in situ observations of a weakening Gulf Stream downstream of Cape Hatteras [*Rossby et al*., 2014]. It is possible that variability in Florida Current transport and in the location of the Gulf Stream path destabilization point, though weakly correlated, may actually respond independently to a separate forcing mechanism without a direct causal link.

The North Atlantic Oscillation (NAO) index represents an atmospheric mode related to the strength and pattern of the North Atlantic wind field [*Hurrell*, 1995]. Annually averaged wintertime (January–March) NAO index is uncorrelated at zero lag with the destabilization point of the detached Gulf Stream. Thus, the large- and regional-scale winds are likely not directly responsible for the stability of the Gulf Stream path south of New England via a remotely forced barotropic response to the winds nor via a local wind-forced response. Once lags are introduced, however, the strongest correlation emerges with NAO leading position of the destabilization point by 5 years. If the trends are not removed, $r = 0.64$; with trends removed $r = 0.46$, significant at the 90% level.

4.2. Intrinsic Variability

In a three-layer, eddy-resolving, primitive equation model with constant forcing, the Gulf Stream/DWBC system oscillates between states due to intrinsic variability [*Spall*, 1996]. The model's upper layer represents the Gulf Stream and is forced by a time-invariant wind stress. Middle and lower layers contain intermediate and deep portions of a DWBC, and these have constant flow rates into and out of the domain.

In the *Spall* [1996] model, the Gulf Stream path oscillates between a stable state (straight path) and an unstable state (convoluted, eddying path). The control on the system comes at the crossover point (analogous to Cape Hatteras) where the Gulf Stream can peel intermediate-layer DWBC waters off the western boundary (producing a stable Gulf Stream path in the upper layer). These waters are first advected off the boundary beneath the Gulf Stream, then are ejected to the interior, and finally rejoin the DWBC south of the model's Cape Hatteras. The alternative at the crossover point occurs when intermediate waters pass directly under the Gulf Stream and continue uninterrupted along the western boundary. This produces an unstable, meandering Gulf Stream. The meandering Gulf Stream produces eddies that advect potential vorticity into a northern recirculation gyre [*Hogg*, 1983], spin-up the gyre, and eventually restabilize the system as intermediate DWBC waters are again entrained under the Gulf Stream at the crossover point.

5. Conclusions

Previous studies have focused on Gulf Stream position, which lags NAO by ~2 years, with path changes attributed to variations in outflow of waters formed by deep convection in the Labrador Sea [e.g., *Peña-Molino and Joyce*, 2008; *Rossby and Benway*, 2000]. In contrast, the focus here is on the *variance* in Gulf Stream position and how this evolves spatially (downstream of Cape Hatteras) and temporally (1993–2014). Consistent with previous studies, the envelope of Gulf Stream paths widens about fivefold downstream of Cape Hatteras. Variance in Gulf Stream latitude increases sharply around 65°W, about 1000 km downstream of the current's separation from the western boundary near Cape Hatteras. A local minimum in variance is evident around 70°W, close to the node reported previously in the literature.

The destabilization point of the detached Gulf Stream's path exhibits a striking, previously unreported shift westward. Irrespective of the cause(s), the consequences of the changing Gulf Stream stability south of the MAB appear to be far reaching and varied. The changes influence both the deep ocean (e.g., via increased stirring of the DWBC into the interior) and the upper ocean (e.g., due to increased events that may drive heat exchange between the upper slope and outer shelf).

The Gulf Stream's destabilization point has not progressed far enough west to induce many direct interactions of the Gulf Stream with the shelf break at the Pioneer Array. However, if the Gulf Stream destabilization point continues to migrate westward, the Pioneer Array will be well positioned to provide subsurface observations during time periods of strong offshore forcing by the Gulf Stream.

Acknowledgments

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