The Journal of Marine Research, one of the oldest journals in American marine science, published important peer-reviewed original research on a broad array of topics in physical, biological, and chemical oceanography vital to the academic oceanographic community in the long and rich tradition of the Sears Foundation for Marine Research at Yale University.

An archive of all issues from 1937 to 2021 (Volume 1–79) are available through EliScholar, a digital platform for scholarly publishing provided by Yale University Library at https://elischolar.library.yale.edu/.

Requests for permission to clear rights for use of this content should be directed to the authors, their estates, or other representatives. The Journal of Marine Research has no contact information beyond the affiliations listed in the published articles. We ask that you provide attribution to the Journal of Marine Research.

Yale University provides access to these materials for educational and research purposes only. Copyright or other proprietary rights to content contained in this document may be held by individuals or entities other than, or in addition to, Yale University. You are solely responsible for determining the ownership of the copyright, and for obtaining permission for your intended use. Yale University makes no warranty that your distribution, reproduction, or other use of these materials will not infringe the rights of third parties.

This work is licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License. https://creativecommons.org/licenses/by-nc-sa/4.0/
A comparison of transport and position between the Gulf Stream east of Cape Hatteras and the Florida Current

by A. Sanchez-Franks1,2, C. N. Flagg1, and T. Rossby3

ABSTRACT

The Florida Current (FC) transport and Gulf Stream (GS) transport and position have been measured almost continuously for many decades in the Florida Straits at ~27° N and for the last 20 years at ~38° N along the Oleander line, respectively. Variations in both currents have been linked to the North Atlantic Oscillation (NAO). Here we show five different proxies for the position of the GS near the Oleander line and find all five measures internally consistent. Further, using a zonally averaged index, the local measurements prove to be good representatives of overall meridional shifting of the current (between Cape Hatteras and the New England Seamounts). The second part of the study shows that the statistical relationship between the GS position proxies and the GS and FC transports, in turn, is inversely correlated with r values of approximately −0.30, significant at the 85% level. The GS and FC transports themselves, on the other hand, are not significantly correlated. Although both position and transport for the GS are shown to be linked to the NAO, the lack of a robust relationship between the GS and the FC transports indicates that the FC does not have a detectable interannual signal downstream in the GS.

Keywords: Gulf Stream, Florida Current, North Atlantic Oscillation, Interannual variability, transport

1. Introduction

The Gulf Stream (GS) is the western boundary current flowing north along the U.S. eastern seaboard. At its southernmost end, it is known as the Florida Current (FC) emerging from the Florida Straits. Farther north, the GS veers eastward at Cape Hatteras beyond which it becomes a zonal-flowing meandering jet. East of ~50° W, the GS splits in several directions with the northern branch known as the North Atlantic Current that continues the warm water transport toward Europe. These currents are components of (or links in) the Atlantic meridional overturning circulation (AMOC) responsible for transferring heat from low to high latitudes, a process of fundamental climatological and ecological importance to the North Atlantic and the surrounding landmasses.

© 2014 A. Sanchez-Franks, C. N. Flagg, and T. Rossby.

1. School of Marine and Atmospheric Sciences, Stony Brook University, Stony Brook, NY 11790-5000.
2. Corresponding author e-mail: alejandra.sanchezfranks@stonybrook.edu
3. Graduate School of Oceanography, University of Rhode Island, Kingston, RI 02881.
East of Cape Hatteras, the GS experiences two modes of variability: meanders and lateral shifts (Lee and Cornillon 1995). The meanders are characterized by wavelike perturbations in the GS’s path, whereas the lateral shifts are the large-scale migration, or deviation from the mean, of the path itself (Lee and Cornillon 1995). The lateral shifts have been shown to account for most of the GS’s low-frequency variability (Frankignoul et al. 2001; DeCoëtlogon et al. 2006) and have been linked to atmospheric forcing (Kelly et al. 1996; Joyce, Deser, and Spall 2000; Frankignoul et al. 2001). Several studies found the GS shift correlated to the North Atlantic Oscillation (NAO) with a 2-year lag (Taylor and Stephens 1998; Hameed and Piontkovski 2004), and the GS northward (southward) displacement of the current associated with an increase (decrease) in transport, using a model (DeCoëtlogon et al. 2006), dynamic height (Rossby and Rago 1985), and GEOSAT data (Kelly and Gille 1990; Kelly 1991). As westward Slope Sea transport decreases, the GS is positioned farther north and the Slope Sea’s sea surface temperature (SST) and salinity increase (Schollaert, Rossby, and Yoder 2004; Rossby, Flagg, and Donohue 2005). Here we reexamine GS position and transport using more than 20 years of direct observations (among other data sets) to determine if the results from previous studies are consistent over time and for in situ measurements.

Among data sets available for investigating GS variability, one of the longest records comes from the 
Oleander project. The 
Oleander project is a long-term observational program that has provided expendable bathythermograph (XBT) sections since 1977 and more than 20 years (starting in 1992) of upper ocean velocity and SST data covering the continental shelf, the Slope Sea, GS, and the Sargasso Sea on a line between New York and Bermuda (Fig. 1). The main objective of the 
Oleander project has been to monitor seasonal to long-term variability of the GS and western North Atlantic.

Similar to the GS east of Cape Hatteras, the GS farther south (hereafter referred to as the FC) is also an integral part of the North Atlantic subtropical gyre. The Yucatan Channel provides the primary source of flow for the FC, which then pours out through the Florida Straits flowing northward, along the east coast of Florida. Historically, measurements of this current have been taken at 27° N (Peng et al. 2009), where numerous studies have tracked the FC transport’s variability and its connection to atmospheric forcing (e.g., Baringer and Larsen 2001; DiNezio et al. 2009; Meinen, Baringer, and Garcia 2010). In particular, Baringer and Larsen (2001) found that a high negative correlation between the FC transport and the NAO existed for a time period from 1982 to 1999. Subsequently, DiNezio et al. (2009) showed that these results did not hold for longer periods of time and suggested a connection between FC transport and the NAO via regional wind stress curl instead. They posited that Rossby waves were the underlying mechanism between the current’s variability and atmospheric forcing. The majority of the aforementioned studies linking the FC transport to atmospheric forcing, wind stress curl, and the NAO (DiNezio et al. 2009; Meinen, Baringer, and Garcia 2010) have been based on the Western Boundary Current Time Series (WBTS) project (e.g., Baringer and Larsen 2001). The primary objective of the WBTS is to archive the continuing changes of the western boundary current at the latitude of the Florida Straits.
Meinen, Baringer, and Garcia (2010) merged historical and modern observations of the FC into a 40-year record permitting longer-term statistical analysis of the current’s annual and interannual variability. Here we combine those long-term transport data from the FC with indices of GS position and transport to examine the extent to which the GS and FC are correlated and what this can tell us about the underlying processes involved. Section 2 summarizes the data and methods used in this study. The principal findings are given in Section 3, followed by a discussion and concluding remarks in Sections 4 and 5. Given the continuity between the GS and the FC, and the connection between these currents and the larger-scale North Atlantic gyre and AMOC, we hope to better understand the interrelationship between the prominent features of the western North Atlantic.

2. Data and methods

Position and transport are the two measures of GS variability used here to characterize the GS’s behavior. GS position is described using several proxies, remote and local, whereas GS
ocean transport at 38° N and 27° N (FC) is estimated directly from acoustic Doppler current profiler (ADCP; upper ocean only) and cable measurements, respectively. Measures for GS position are computed using data from the Oleander project, satellite SST, and satellite sea level anomaly (SLA).

The instruments installed and operated on the Oleander include an ADCP, an XBT, and a thermosalinograph (TSG). Since the Oleander program was first initiated, two different ADCPs have been in use, both of which also collect near-surface temperature data. The first ADCP installed, a 150 kHz RD Instruments ADCP, ran from 1992 to 2004 yielding velocity profiles down to 250–400 m (Flagg et al. 1998). In 2005, the 150 kHz ADCP was replaced with the currently running 75 kHz RD Instruments Ocean Surveyor, increasing the depth of the velocity profiles to 500–600 m depth. To obtain absolute current measurements, the Oleander is also equipped with a global positioning system (GPS) continuously recording precise estimates of the ship’s heading and position. Final current velocity is acquired by subtracting the Oleander’s GPS velocity from the ADCP-derived current velocity. The resulting velocity’s accuracy is \( \text{\sim} 0.05\, \text{m s}^{-1} \). The Common Ocean Data Access System is the ADCP software package, developed at University of Hawaii (Firing, Ranada, and Caldwell 1995), used to process and store the final data, which are served on the Oleander website (http://po.msrc.sunysb.edu/Oleander). For this study, the surface temperature and velocity ADCP data used were from 1993 to 2013. The velocity was extracted from the 55 m layer (data are binned in 8 m steps), and at least 60 profiles and gaps no larger than 20 km in the GS region were required for every transect. Technical difficulties in data collection arose primarily from bubble entrainment. During poor weather and particularly on return trips northward when the ship is more lightly loaded, bubbles are more easily swept down under the vessel, impeding good data coverage (Flagg et al. 1998). In addition, the Oleander was taken out of service for a major overhaul in winter/spring 2011. Difficulties with the ADCP during the following start-up led to a significant absence of data coverage for that year.

The Oleander also hosts an XBT program run by the Northeast Fisheries Science Center. Since 1977, the XBT program has been accumulating surface salinity from bucket samples and temperature data from XBTs deployed monthly from the Oleander. The XBT sections generally covered most of the continental shelf, slope, and the GS. Starting in 2008, the Oleander project contributed XBTs to extend coverage through and south of the GS into the Sargasso Sea. The data are processed at the National Oceanic and Atmospheric Administration (NOAA) Northeast Fisheries Science Center Narragansett Lab and can be obtained from the Oleander website (http://po.msrc.sunysb.edu/Oleander/XBT/NOAA_XBT.html).

Another source of GS position information is from the Canadian Marine Environmental Data Service (MEDS) data set, which from 1966 to the present has provided the mean monthly position of the northwall (i.e., the northern edge of GS marked by a sharp drop in temperature) from frontal maps constructed using satellite advanced very high resolution radiometer (AVHRR) SST imagery. The maps cover the area between 75° W and 50° W and 34° N and 44° N, although here we focus only on the SST anomaly
found along 71° W. The SST data are mostly from NOAA and the Naval Oceanographic Office and can be found online (http://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/azmp-pmza/climat/gulf-golfe/slope-plateau-eng.htm).

The second satellite-based data set is the along-track SLA from the Radar Altimeter Database System (RADS). RADS is a product of the Delft Institute of Earth Observation and Space Systems and is currently supported by both NOAA and Delft University of Technology (John Lillibridge, pers. comm.). Measurements can be acquired from the website (http://rads.tudelft.nl/rads/rads.shtml). Here, for a section covering 36°–39° N, data from the European Remote Sensing 2 (ERS-2) satellite track 0693 are used, operational from 1995 to 2011. Latitude, longitude, and sea level (anomaly) measurements are obtained using the geoid height, from the Earth’s gravitation model (Pavlis et al. 2012) as a reference level. Figure 1 shows the region of interest and highlights the track used in this study.

Finally, the WBTS project, funded by NOAA, is used for its long-term measurements on the FC. The WBTS has collected data centered on 26.5° N using submarine cable voltages and dropsondes or lowered ADCPs (LADCPs) since 1982. The transport time series presented here is obtained from cable measurements that have been recorded daily, and dropsondes/LADCPs come from cruises taken throughout the year since the start of the project. The WBTS project has almost complete coverage for the duration of the time period, except for the year 1999, which has almost no coverage due to technical difficulties the project experienced that year. All data were collected from the same line (Fig. 1) found on the website (http://www.aoml.noaa.gov/phod/floridacurrent/data_access.php).

For comparison purposes, all GS and FC time series are presented with the same time step. One of the difficulties in defining a common time base is that each subset of data has different types of coverage and gaps in the sampling. To deal with the different issues in temporal and spatial data coverage, we constructed annual averages, in which 12 months was the averaging interval with 6-month steps, in order to make comparisons between the time series. Although the interannual signal was the focus of this study, the GS and FC’s annual cycle was also considered (for further details, see Appendix). In particular, we found that removing the seasonal variations from the original data before applying a moving average had a negligible effect on the overall results.

3. Results
a. Overview

Two parameters have been used over the years to describe GS variability east of Cape Hatteras, namely the lateral shifting of the GS and the upper ocean transport (or sea level difference across the current). The position of the GS and its relation to the NAO have been quantified in several studies (e.g., Taylor and Stephens 1998; Hameed and Piontkovski 2004; Peña-Molino and Joyce 2008), although significant questions about the mechanisms by which the NAO affects the position of the GS remain. Because FC transport has also been linked to the NAO (Baringer and Larsen 2001), it is of interest to investigate whether the
GS’s variability shows any similarities to the Florida Straits. In the following, we present results for the following two objectives: (1) to evaluate the various possible GS position measures to determine which yields the most robust measure and (2) to compare those measures to the GS and FC transports to establish a connection between lateral position and along GS transports.

b. GS position proxies

To define the GS’s position or path variability, a number of proxy measures have been used over the years. Here six of those measures are reviewed: (1) the 15°C isotherm at 200 m (the classic measure), (2) the GS’s position via the northwall (indicated by the 2°C drop in surface temperature northward from the location of maximum velocity), (3) the position of the velocity maximum at 55 m (from the Oleander transects), (4) the SST anomaly along 71° W from satellite imagery, (5) the location of the maximum along-track gradient in SLA, and (6) the zonally averaged SST gradients from Taylor and Stephens (1998). The principal variables used will be velocity and temperature from the Oleander project, frontal data from the MEDS data set, and the altimeter-derived along-track SLA from the ERS-2 satellite (RADS), all of which have been annually averaged in 6-month steps. All the time series are processed this way to overcome spotty data issues and to focus on the longer interannual time scales. The objective of creating this database of GS parameters was to assess the connection between the different time series and their effectiveness at following the GS’s interannual migration, using and contrasting in situ and satellite measurements. The sixth proxy (i.e., the Taylor index) is not shown or discussed again until Section 4.

First, the structure of the GS’s velocity and its variability over space and time were investigated. Thanks to the Oleander’s 20-year (and running) program, the position of maximum velocity is tracked using direct measurements (Fig. 2). Here we take the position of velocity maximum at 55 m to be our “true” estimate of GS position, from which we can determine how well the other indices approximate the GS’s path. Even though the maximum velocity has embedded small-scale eddy variability, this gets reduced by the running mean and as such serves as our best measure of GS position at the Oleander line. The 55 m depth for the position of maximum velocity is chosen for two reasons: (1) it is the layer closest to the surface with a high degree of coverage, important for comparisons with the ADCP’s surface temperature measurements (see 2°C drop measure), and (2) for consistency with the GS layer transport, also measured at 55 m. The position of the GS’s lateral velocity maximum is unchanging with depth within the first couple of hundred meters (results not shown), thus the 55 m choice of depth is as good a representative as any of the GS’s position of maximum upper level velocity (the minimum depth sampled by the ADCP is 22 m).

Before satellite or ADCP data became available, a widely used characterization of the GS northwall position was the 15°C isotherm at 200 m (e.g., Fuglister and Voorhis 1965; Cornillon and Watts 1987) using XBTs or the earlier mechanical bathythermographs. Another metric that was developed for comparison with satellite thermal imagery was the location
where SST had dropped 2°C from its maximum in the current (Rossby and Gottlieb 1998). These metrics can be estimated from the Oleander’s XBT and ADCP data sets, respectively, and compared with the location of maximum velocity.

The position of maximum velocity in the GS (Fig. 2) indicates that the most significant southward shifts occurred in 1998, 2004, and 2011, and the northward shifts during mid-1995, 2000, and 2012. Similarly, the 15°C isotherm at 200 m and the 2°C temperature drop (where available) indicate a northward shift in the mid-1980s, 1991, and, more markedly, 2000. As expected, both temperature proxies for GS position are located north of the GS’s maximum velocity because the position of maximum velocity is in the GS’s core, whereas
the temperature drop occurs where the GS’s warm water meets the Slope Sea’s cold water north of it. Overall, the time series data indicate periods of quiescence mostly between 1982 and about 1996, and then again from 2003 to about 2011. The highly active periods when the GS shifts south occur, data permitting, for 1981 and then 1998 to 2002. These time periods correspond with the two strongest El Niño episodes recorded in the last century (Fedorov and Philander 2000). The mean standard errors of the ADCP-derived GS position are significantly smaller than the GS’s displacement, especially for the maximum velocity and the $2^\circ$C drop measures. Notable exceptions occur in the $15^\circ$C isotherm at 200 m index for 2008–2009 and 2011. The XBT time series is less complete in 2009, and the ADCP data are spotty during 2011. Despite some interruptions in the record, there is no discernable trend in any of the Oleander position indicators over the 30-year record.

The other measures of GS position near the Oleander line come from satellite data. MEDS records the northwall position from satellite SST anomalies. The MEDS GS position index is then obtained by tracking its latitude from the SST anomalies at longitude $71^\circ$ W. Similar to MEDS, data from the ERS-2 satellite are used to estimate the latitudinal position of the maximum SLA gradient, representative of the GS’s maximum geostrophically balanced velocity.

In the MEDS index, the most abrupt southward shifts occur during the mid- to late 1990s, and then again in 2004 and 2011 (Fig. 2). The northward shifts occur in the early 1990s, 2001, 2007, and 2012. Likewise, the ERS-2 shows the position of the GS to be more northerly during 1995, 2001, and 2009, and more southerly during 1998, 2004, 2006, 2008, and 2010. The positional accuracy of the MEDS index is on par with the ADCP-derived GS position measures as its standard error bars appear considerably smaller than the GS’s displacement about its mean. The ERS-2 index, on the other hand, has slightly larger standard errors, but again, these are smaller than the indicated GS movements. The large magnitude of the 2011 error bar is consistent with the lack of data points from that year due to the early termination of the satellite mission. Similar to the Oleander data, the satellite data also show the late 1990s to be the most active period, which coincides with the 1998 El Niño episode.

Overall, both in situ and satellite observations agree very well for large-scale variations and (to a certain extent) for small-scale variations as well. In particular, all position measures are found to be highly correlated, significant at the 99% level (Table 1; see Section 4). The most active time periods, reflected in all the proxies during the early 1980s and late 1990s, coincide with the two strongest El Niño episodes documented in the last 100 years (Fedorov and Philander 2000). We have also found, using TSG data (not shown here), that salinity proxies are in phase with results presented in this study. This is expected because large temperature excursions are associated with water mass changes.

c. GS and FC transport estimates

The GS transport is obtained from the Oleander’s ADCP following Rossby, Flagg, and Donohue (2010) methods wherein layer transport is calculated at the 55 m depth across the
width of the GS along the Oleander line. The transport is then generated by integrating the velocity normal to the Oleander’s track between the two points whose downstream velocity goes to zero on either side of the GS’s center. The downstream direction is determined by the direction of the maximum observed velocity. The layer transport is the 12-month running mean average, estimated at 6-month intervals (Fig. 3).

The GS layer transport at the Oleander section ranges between 0.122 and 0.146 Sverdrup (Sv) m\(^{-1}\), or from 85 to 102 Sv using a scale factor of 700 (Rossby et al. 2014). The overall mean for this 20-year record is 0.134 Sv m\(^{-1}\) (with a ±9% peak-to-peak range), similar to past studies (e.g., Rossby, Flagg, and Donohue 2010). The figure does not suggest any overall trend, but quite high transport values occur in 1993, 2001, and 2003, and lower transports in 1994–1995 and 2007.

The FC transport shows much greater variability for the first half of the time series (1982–2000), ranging between transport values of 29 and 34.6 Sv, whereas the second half of the time series appears to be more or less restricted to between 30 and 34.2 Sv. The overall mean transport, 31.93 Sv, agrees with estimates previously reported by Baringer and Larsen (2001) and Meinen, Baringer, and Garcia (2010).

To summarize, GS layer transport shows a 9% peak-to-peak range and a 4.6% standard deviation over the 20-year period. The GS’s transport is highest during 1994 and 2004 and lowest during 1995, 2000, and 2008. The FC transport shows much greater fractional transport variability (overall range is about ±8%) for longer time periods during the first half of the time series (1982–2002) compared with the second half (2002–2012). A visual inspection of the two transport estimates (Fig. 3) shows no evident pattern common to both currents.
Table 1. Cross correlations between all Gulf Stream (GS) position and transport time series and the Florida Current (FC) transport. Values that are statistically significant at the 99% level are in bold. The rest are significant at the 85% level, at least. ERS-2, European Remote Sensing 2; MEDS, Marine Environmental Data Service.

<table>
<thead>
<tr>
<th></th>
<th>15°C at 200 m</th>
<th>Maximum velocity</th>
<th>2°C drop</th>
<th>MEDS</th>
<th>ERS-2</th>
<th>Taylor index</th>
<th>GS transport</th>
<th>FC transport</th>
</tr>
</thead>
<tbody>
<tr>
<td>15°C at 200 m</td>
<td>1</td>
<td>0.67</td>
<td>0.69</td>
<td>0.75</td>
<td>0.81</td>
<td>0.64</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Maximum velocity</td>
<td>1</td>
<td>0.94</td>
<td>0.90</td>
<td>0.85</td>
<td>0.70</td>
<td>–0.25</td>
<td>–0.44</td>
<td></td>
</tr>
<tr>
<td>2°C drop</td>
<td>1</td>
<td>0.83</td>
<td>0.82</td>
<td>0.59</td>
<td>–</td>
<td>–0.48</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MEDS</td>
<td>1</td>
<td>0.81</td>
<td>0.67</td>
<td>–0.34</td>
<td>–</td>
<td>–0.21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ERS-2</td>
<td>1</td>
<td>0.79</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Taylor index</td>
<td>1</td>
<td>–0.30</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–0.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GS transport</td>
<td>1</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FC transport</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4. Discussion

Cross correlations are used here to establish whether there are links between the various GS position indices and the two transport measurements. The position measures and transports calculated previously are also compared with the zonally averaged Taylor and Stephens (1998) index (hereafter referred to as the Taylor index). The Taylor index is computed by taking the first principal component of the position of the maximum SST gradient at six different longitudes between 79° W and 65° W. This is followed by an analysis of the relationship between both currents and the NAO index.

Table 1 shows cross correlations between the six GS position measures, the GS transport, and the FC transport. Zero lag correlations show the best results. This is expected as any lag between these two currents would likely not be longer than a few months, due to their physical proximity. All correlation coefficients between the position indices were found to be significant at the 99% level, whereas the correlation coefficients between position and transports were significant between the 85% and 95% levels.

When comparing correlation coefficients between the position proxies, the highest $r$ values correspond to correlations between the maximum velocity vector, 2°C drop, MEDS, ERS-2, and the Taylor index. The high agreement of the satellite (ERS-2 and MEDS) and temperature front indices with our “true” estimate of GS position, maximum velocity, shows that the various local measures of GS position are internally consistent. Given the stiff structure of the GS (Rossby 1999; Rossby and Zhang 2001; Rossby, Flagg, and Donohue 2005), this is not unexpected. The advantage of the Taylor index is that it is a zonal average and has been shown to be closely linked to the NAO (Taylor and Stephens 1998). Despite this high correlation, the maximum velocity index shows a smaller amplitude than the Taylor index. This may be because the Oleander line crosses the GS where the meandering envelope is near a minimum (Lee and Cornillon 1996). Nonetheless, the high correlation shows that even the local measurements of GS position along the Oleander line can represent the low-frequency shifting of the stream as a whole quite well.
In Figure 4, the maximum velocity and Taylor indices are considered, along with both transport data sets and the NAO index, where the NAO is the leading variable. As noted earlier, the position indices are significantly correlated, but the GS and FC transports by themselves are poorly correlated. Further, the noticeable southward shift of the GS position in the mid- to late 1990s is not at all reflected in the GS transport, but the time series suggests that when the GS shifts north, the transport decreases temporarily and vice versa: in 1994 and 1999, northward GS shifts and decreases in transport are visible; whereas in 2001 and 2003, the corresponding southward shifts and increases in transport occur. Curiously, the (negative) correlation of GS position with FC transport looks stronger (e.g., 1996–2001); however, both transports exhibit more rapid variability than does position.

The NAO index shows agreement with the position proxies and an inverse correlation with GS transport, significant at the 95% level (Table 2). Analysis indicates that the NAO can account for 13% of the maximum velocity position with a 1.5-year lag and 20% of the Taylor index with a 1-year lag. For transports, a correlation of $-0.37$ was found between the NAO and GS at a 1-year lag. This indicates that during high NAO, the GS position is shifting north, taking corresponding lags into account. We note that it is reasonable for the Taylor index to be more highly correlated with the NAO than the maximum velocity because the zonally averaged index covers a much wider region in comparison with the Oleander’s ADCP line, which reflects more local variability. No statistically significant relationship between the FC transport and the NAO could be established.
Table 2. The sample size (n) and cross correlations between position measures and transports with the North Atlantic Oscillation (NAO) as the leading variable. Values that are statistically significant at the 99% level are in bold. The rest are significant at the 85% level, at least. MEDS, Marine Environmental Data Service.

<table>
<thead>
<tr>
<th>Variable</th>
<th>n</th>
<th>0</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
<th>2.5</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum velocity</td>
<td>37</td>
<td>-0.39</td>
<td>-</td>
<td>-</td>
<td>0.37</td>
<td>0.34</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>MEDS</td>
<td>92</td>
<td>0.20</td>
<td>0.34</td>
<td>0.43</td>
<td>0.40</td>
<td>0.32</td>
<td>0.31</td>
<td>0.28</td>
</tr>
<tr>
<td>Taylor</td>
<td>92</td>
<td>-</td>
<td>0.26</td>
<td>0.45</td>
<td>0.44</td>
<td>0.39</td>
<td>0.35</td>
<td>0.29</td>
</tr>
<tr>
<td>GS transport</td>
<td>37</td>
<td>-</td>
<td>-0.36</td>
<td>-0.37</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>FC transport</td>
<td>60</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.19</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Both GS position and transport have been shown to have significant regional impact as the GS’s latitudinal migration has been connected to North Atlantic atmospheric storm tracks (Joyce, Deser, and Spall 2000), plankton abundance (Planque and Taylor 1998; Jennings and Allot 2006; Borkman and Smayda 2009), and the mid-Atlantic Bight shelfbreak currents (Bane et al. 1988). However, caution is advised when interpreting estimated correlations—a high correlation does not prove causality. This is illustrated very effectively by the fact that the FC transport exhibits its highest correlation with the position based on the 2°C drop, higher than with the velocity or Taylor indices; there is no physical basis for this that we can see.

There is some indication that when the GS shifts to the north, the transport decreases temporarily, but position and transport do not appear to covary in a consistent fashion. Rossby, Flagg, and Donohue (2010) showed that variations in westward flow in the Slope Sea north of the GS are much smaller than those in the GS. The Sargasso Sea exhibits large variations in westward transport, comparable to those in the GS, but they have not yet been shown to covary (Rossby, Flagg, and Donohue 2010). Thus, GS transport comprises not only the “throughput” of the large-scale GS, but also transport associated with recirculations, some involving the full southern recirculation gyre (Worthington 1976) and some associated with the meandering structure of the GS (e.g., McGrath, Rossby, and Merril 2010).

The mechanism responsible for the lateral shifting of the GS, on the other hand, likely has its origins to the north through variations in the Slope Sea probably due to a variable outflow from the Labrador Sea (Peña-Molino and Joyce 2008). When the NAO is in a strong positive phase (very cold winters), large volumes of water are exported to the east as dense intermediate water (Bersch, Yashayaev, and Koltermann 2007); however, when the NAO is in a negative phase, this intermediate water production is sharply curtailed or ceases, and instead, export tends to take place to the west along the continental shelf and slope (Bersch, Yashayaev, and Koltermann 2007). It is this increased westward flow that leads to a southward displacement of the GS, hence the poor correlation between the GS position measures and the FC.
5. Concluding remarks

Although it would seem that the FC transport has no detectable signal downstream in the GS, several studies, consistent with results presented here, have linked both currents to the NAO. Here we have tested for and have not been able to establish a direct correlation in transport variability between the FC and the GS. The reason we suggest is that the correlation with the NAO comes along different physical pathways.

The GS position has been linked to the NAO with correlations of $\sim 0.6$ following a 1- to 2-year lag in various studies (e.g., Taylor, Jordan, and Stephens 1998; Taylor and Stephens 1998; Joyce, Deser, and Spall 2000; Hameed and Piontkovski 2004). At $27^\circ$ N, Baringer and Larsen (2001) found that for a time period ranging from 1992 to 1998, the FC was inversely correlated with the NAO with an $r$ value of $-0.5$. DiNezio et al. (2009) found results consistent with a mechanism where the NAO affects the current via Rossby waves forced from the wind stress curl for a time period in the range of 1982 to 2007. Some differences in results could be attributed to the fact that we used year-round data for the NAO, instead of the NAO’s active (winter) months.

For the GS position, Rossby (1999) and Rossby, Flagg, and Donohue (2005) suggested that the process linking the GS and NAO is likely through an increased westward transport of shelf and slope water, which then pushes the GS offshore (to a more southerly position), while a decrease or retreat in transport allowed the GS to shift northward. During years of low NAO, winters are milder in the Labrador Sea, and dense water production ceases. This evidently forces an increased Labrador Sea water transport south and west into the slope region; however, when the NAO is high, winters are colder and transport from the Labrador shelf decreases (Rossby and Benway 2000; Smith et al. 2001; Rossby, Flagg, and Donohue 2005). Thus, based on our results and past studies, we posit that the GS east of Cape Hatteras does not have a robust connection with waters upstream from it, and that its connection to the NAO is via buoyancy forcing from the north. We also note that, contrary to previous literature mentioned here (e.g., Kelly and Gille 1990; Kelly 1991; DeCoëtlogon et al. 2006), the GS position and transport do not necessarily covary nor appear to be forced by the same mechanisms. This requires further investigation.

Acknowledgments. The research presented here is the result of long-standing permission from the Bermuda Container Line to operate an ADCP onboard the CMV Oleander. Their support is gratefully acknowledged. We thank Ms. S. Anderson-Fontana for her excellent support and processing of the ADCP data. This project was supported by NOAA and Office of Naval Research (ONR) in its early years, and since 1999, by the National Science Foundation to the University of Rhode Island and Stony Brook University. Additionally, the FC cable and section data are made freely available on the Atlantic Oceanographic and Meteorological Laboratory web page (http://www.aoml.noaa.gov/phod/floridacurrent/) and are funded by the NOAA Climate Observation Division. We thank two anonymous reviewers and the editor for their helpful comments and suggestions.
Figure A1. Annual cycle of the Gulf Stream (GS) and Florida Current (FC) volume transport. The amplitude of the least-squares fit to the data is 0.006 Sverdrup (Sv) m$^{-1}$ (4.51 Sv) for the GS, and 1.12 Sv for the FC. The scatter is 15.5% and 10.2% of the mean for each current, respectively.

APPENDIX

The question addressed here is the seasonal cycle in transport and whether its removal alters the transport correlation estimates. To do this, we use a least-squares sinusoidal fit to transport measurements to determine the annual cycle of transport in the Gulf Stream (GS) east of Cape Hatteras and the Florida Current (FC) at 27° N. We found that removal of the annual cycle from the data had a negligible effect on the correlation estimates. This is not surprising for two reasons: first, the seasonal amplitude is not large (discussed in next paragraph), and second, the 1-year boxcar average averages over a complete annual cycle.

For the time period 1993–2013, from the Oleander data, and the period 1982–2012, following Western Boundary Current Time Series data, the amplitude of the annual cycle is 0.006 Sverdrup (Sv) m$^{-1}$ (4.51 Sv), or 4.7% of the mean flow for the GS, and 1.12 Sv, or 3.5% of the mean flow for the FC (Fig. A1). Instantaneous measurements of the GS transport have a scatter around the sine curve of 15.5% (as a percentage of mean) with the annual cycle peaking in the fall months. In contrast, the FC has a lower scatter of 10.2%, with a peak around the end of the summer months.

REFERENCES


Received: 18 April 2014; revised: 6 October 2014.