

Eddy impacts on the Florida Current

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The Gulf Stream in the Atlantic carries warm water northwards and forms both the return closure of the subtropical gyre as well as the upper limb of the meridional overturning circulation. Recent time series recorded east of the Bahamas at 26°N indicate that from May 2009–Apr 2011, in contrast with past observations, the northward flowing Antilles Current covaried with the Gulf Stream in the Florida Straits—the Florida Current—even though the Florida and Antilles Currents are separated by banks and islands spanning 150 km. The peak-to-trough amplitude of transport variations during this period was $15 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ for the Florida Current and $12 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ for the Antilles Current, at timescales of 50 days to a year. From satellite observations, we show that the fluctuations in both the Florida and Antilles Currents between May 2009–Apr 2011 are driven by eddy activity east of the Bahamas. Since the Florida Current time series is a critical time series for the state of the oceans, and often compared to climate models, this newly identified source of variability needs careful consideration when attributing the variability of the Florida Current to changes in the larger scale circulations (e.g. gyre and overturning) or wind forcing.

1. Introduction

The Gulf Stream is the primary northward meridional flow in the top 1000 m of the North Atlantic, carrying warm subtropical waters to higher latitudes where they cool, giving off their heat to the atmosphere. As the western boundary intensification of the subtropical gyre, the strength of the Gulf Stream transport (measured in $10^6 \text{ m}^3 \text{ s}^{-1} = 1 \text{ Sv}$) depends on the basin-wide wind stress curl which forces the gyre circulation. However at 26°N, where the Gulf Stream is confined between Florida and the Bahamas islands, the northward transport of the Gulf Stream—at this latitude, called the Florida Current (FC)—is nearly twice the southward thermocline flow (32 Sv vs. 18 Sv). Due to mass balance constraints, the remainder of the southward flow balancing the northward Florida Current as well as northward surface Ekman transport (3 Sv), is found below 1000 m as the lower layer of the meridional overturning circulation (MOC, roughly 18 Sv). By this simplification—where the

sum of gyre flows and the overturning transport is equal to the northward FC transport—variations in FC transport may be associated either with variability of the horizontal gyre or the MOC.

At 26°N in the Atlantic, an observational program has shown that the FC projects its variability directly onto the MOC, independently of other components [Kanzow et al., 2010, @]. A parallel investigation into ocean heat transport demonstrated that the transport of the MOC rather than the gyre dictates oceanic heat transport [Johns et al., 2011, @; Hall and Bryden, 1982, @]. These results highlight the significance of the MOC variability in the oceans role in climate, and reinforces the significance of the FC in MOC variability.

Extensive investigations into the FC variability have been made from a cable time series of transport, available since 1982 (to follow). Fluctuations in the FC have been primarily associated with wind forcing, on a range of timescales. On short timescales up to 20 days (the “weather band”) and at seasonal timescales, the FC is coherent with local winds [Schott et al., 1988, @; Atkinson et al., 2010, @; Rousset and Beal, 2011, @]. At seasonal timescales however, the annual cycle comprises only 10% of the variance [Meinen et al., 2010, @]. On interannual timescales (3–12 year timescales), variations can be attributed to changes in the large scale wind forcing associated with the North Atlantic Oscillation (DiNezio et al., 2009 [@] and references therein). A particular gap in the coherence between the FC and wind stress was noted between 20-days and seasonal timescales [Schott et al., 1988, @]—a range of timescales associated with the mesoscale field in the ocean.

The Antilles Current (AC), another western-intensified current in the Atlantic, is located on the other side of the Bahamas from the Florida Straits. In contrast to the FC, AC variability has been associated with the mesoscale eddy field [Gunn and Watts, 1982, @; Lee et al., 1996, @; Johns et al., 2008, @]. However, observations indicate that northward AC transport must supplement FC transport in order to balance the theoretical Sverdrup transport strength (Lee et al., 1996 [@], and references therein). Numerical simulations of ocean circulation suggest that the AC is part of the wind-driven circulation: when an overturning circulation was present, the AC was stronger (than in a case with no overturning) and primarily contained gyre flow, while the FC carried the northward MOC transport [Johns et al., 2002, @]. While the AC and FC together may form the western boundary closure of the Atlantic subtropical gyre, previous calculations showed no statistical correlation between the AC and FC transports [Meinen et al., 2004, @], suggesting separate forcings of their variability.

Here, we present observational evidence from mid-2009 to mid-2011, indicating that the FC transport fluctuations were correlated with those of the AC. We also show that during mid-2009 to mid-2011, both AC and FC variability were associated with mesoscale eddies east of the Bahamas, and discuss the implications for our understanding of Gulf Stream variability.

2. Methods

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Data were obtained from measurements in the Florida Straits and east of the Bahamas. The former data are from a submarine telephone cable which uses the principles of magnetic induction to deduce a transport estimate of the FC [Larsen and Sanford, 1985, @]. These observations have been made nearly continuously since 1982 and calibrated with frequent hydrographic measurements [Meinen et al., 2010, @]. The records are 3-day low pass filtered, then provided on as a daily transport time series. Here, we used the data from Apr 2004–Apr 2011, and linearly-interpolated daily transport values over gaps in the record (4.2% of the records from Apr 2004 to Apr 2011). Gaps of longer than 45-days are noted in the figures. These gaps in the record influence our ability to diagnose mesoscale variability at similar timescales to the gap duration.

East of the Bahamas, the AC transport is estimated from current meters on taut-wire subsurface moorings (Fig. 1a), as part of the RAPID-WATCH/MOCHA and WBTS programs (hereafter, 26°N array, see Rayner et al., 2011 [@]). Current meter records from Apr 2004–Mar 2011 are used to estimate meridional transport of the AC in the top 1000 m between the coast of Abaco (about 77°W) and a mooring 25 km offshore called WB₂ (76.75°W). Details of data processing and transport calculations can be found in Johns et al., 2008 [@]. While the core of the AC is between 200–800 m deep and northward, we have not removed transport above 200 m (which is occasionally southwards) as it does not substantially change the variability. Here, we call the Antilles Current the integrated transport out to 76.75°W (Fig. 1b) which is smaller than the total northward transport out to WB₃ at 45 km offshore (76.5°W), but the two estimates of transport are significantly correlated ($r = 0.95$). Using either WB₂ or WB₃ does not change the results (of a correlation between the FC and AC); we use WB₂ as it is easier to see the correlation by eye in the figures.

Sea surface height (SSH) anomaly data were obtained from AVISO (information online at www.aviso.oceanobs.com). The data were used during the RAPID measurements from Apr 2004–Apr 2011, and have a nominal resolution of $1/3^\circ$ in space and weekly in time. We use the DT-REF product: reference, delayed-time maps of sea level anomalies, with the raw data coming from TOPEX/Poseidon, Jason-1, ERS-2 and Envisat. While altimeter estimates of SSH are subject to degradation near coasts, previous results showed that SSH anomalies near the Bahamas agreed with dynamic height estimates from *in situ* moorings [Kanzow et al., 2010, @]. When a single time series is used (as in Fig. 1b), it is the time series of SSH anomaly time series at 26.57°N and 76.67°W, the grid point closest to the mooring used to define the outer edge of the Antilles Current, which is also the location where the SSH anomaly has the strongest correlation with the FC.

During processing, the cable data were filtered with a 3-day lowpass filter, while the current meter records were filtered with a 2-day lowpass filter to remove tides, before calculating transports. Here, both Florida and Antilles Current transports were further filtered with a 7-day boxcar filter, then subsampled onto the weekly time grid for comparison to the SSH data. For visualisation in Fig. 1b, all three time series were additionally filtered with a 30-day lowpass Tukey filter. The FC transport time series (Fig. 1b) was offset by -30.4 Sv and SSH by -3 cm, to highlight covariability at the frequencies of interest during May 2009–Apr 2011. While SSH anomaly data are available since 1992 and FC transport data since 1982, we will focus primarily on the period from 2004–2011, when all three data sources are available.

3. Results

Over Apr 2004–Apr 2011, the transports of the FC and AC were 31.6 ± 3.1 Sv (mean \pm std) and 1.2 ± 2.5 Sv, respectively (Fig. 1b). From May 2009 to Apr 2011, transport

anomalies were correlated with zero lag (Fig. 2a). In particular, the maximum correlation was $r = 0.66$ (99% significance) at zero lag. In contrast, there was an insignificant correlation for the period from Apr 2004–Apr 2009 ($r = 0.04$). During the latter period, the peak-to-trough fluctuations in transport were 15.4 Sv for the FC and 11.7 Sv for the AC. In general, when the FC was 3 Sv stronger northward, the AC was 3 Sv stronger than its mean. Because the transport time series varied in phase, the net northward fluctuations of their combined transports were greater than transport variations in either individual record. While the period under consideration is short (roughly 2 years), a linear relationship between the AC and FC transports explained more than 43% of the variance of the FC transports from May 2009 to Mar 2011.

Since the AC has previously been associated with the mesoscale eddy field, SSH anomalies at a point east of the Bahamas (76.67°W and 26.5°N) were compared to the AC transport anomalies and found to correlate for the whole duration of the record, 2004–2011 ($r = 0.71$, 99% significance). In particular, low values of AC transport are related to negative SSH anomalies (depressions), while high values were associated with positive anomalies (elevations). To determine the spatial structure of the SSH anomalies responsible for the fluctuations in the AC, we calculated maps of the regression slope between the AC transport and SSH anomalies. At zero lag (Fig. 3c), the regression map highlights a closed region in the SSH anomalies, with a region of significance 200–300 km diameter. This means that when the SSH is higher east of the Bahamas, it is higher not just at a single location, but is associated with an anticyclonic eddy (circulation in the clockwise sense) with northward flow adjacent to the Bahamas. The lagged regression maps for SSH anomalies preceding AC transport anomalies (Fig. 3a, b) further show that these anomalies originated east of the coast, in line with the westward propagating anomalies highlighted in Kanzow et al., 2009 [@]. This is relevant because it shows that the anomalies in SSH, AC and FC measures were preceded by an open-ocean anomaly in sea surface height, rather than all locally forced by winds or other processes. At the Bahamas, as a consequence of the presence of this eddy, the measured AC transport is stronger, since the current meter observations are in the northward part of the eddy (between about 77°W and 75°W). Similarly, when the SSH is lower, as associated with a cyclonic eddy, southward flow is adjacent to the Bahamas and the measured AC is weaker and occasionally reversed.

While the AC transport fluctuations are correlated with SSH anomaly time series for the duration of the AC records, the AC and FC time series were only correlated from May 2009–Apr 2011. To investigate the relationship between the SSH anomalies and FC transport during the RAPID period and in this shorter period of AC-FC correlation, we calculate the coherence and phase between the FC transport time series and SSH anomalies (Fig. 2b and c). High coherence is present in the band from about 50 to 150 days (Fig. 2a). While the 2009–11 period shows higher coherence in this band, the longer 2004–11 period also shows relatively high coherence in this band even though the overall correlation for the longer period is almost zero. The phase offset is less than seven days, with the SSH anomalies leading the FC transport anomalies (Fig. 2c). While the lag appears to be longer than in the case of the FC and AC lag correlations, between the filtering applied during processing of the FC and AC, and the actual repeat timing of satellite altimeters used to create the SSH product, time variations on timescales shorter than seven days cannot be resolved. The coherence indicates that while there was some coherence in the period 2004–2009 between the FC transports and SSH anomalies, it is much greater ($\gamma^2 > 0.6$) during the later time, May 2009–Apr 2011, at around 100-day timescale. In turn, it could be inferred that the impact of these mesoscale features on both the AC and FC is larger during this period, and would stand out more clearly with respect to other processes that could drive transport fluctuations of FC.

4. Discussion

While the SSH anomalies are consistent with transport estimates of the AC, they do not immediately explain the covariability with the Florida Current, nor the nonstationarity of the covariability. During May 2009–Apr 2011, there appeared to be larger amplitude elevations and depressions in the SSH anomalies east of the Bahamas than prior to it (Apr 2004–Apr 2009). This is shown in Fig. 4, where the rms-amplitudes of sea surface height anomaly are averaged for the two periods: Apr 2004–Apr 2009 and May 2009–Apr 2011. While the first period is of longer duration than the latter, the results are not sensitive to this choice. For any two year period between Apr 2004–Apr 2009, the maximum rms-amplitude of SSH anomaly between 74–76°W was 12.6 cm, while for May 2009–Apr 2011, it was 15.6 cm. This suggests that the eddies east of the Bahamas, associated with the anomalies in the SSH time series, had larger amplitude than previously.

In an idealised analytical and numerical study, Simmons and Nof, 2002 [20] simulated an encounter between an anticyclone and a gap in a meridional wall. Their results indicate that when intense eddies encounter gaps, they are drained by wall jets on either side of the gap (east and west) until the eddy can squeeze through the gap. The lagged regression between SSH anomalies and AC transports in Fig. 3 was extended in time, to see how SSH anomalies change following the AC transport anomalies. At 21 days past AC variations, we found that the eddy at the Bahamas had shrunk and moved closer to—and partially through—the gap, though significance is reduced. In addition, both at zero lag and 21 days lag, elongated anomalies in the regression slope are found west of the Bahamas, aligned with the Florida Straits (Fig. 3d), suggestive of the wall jets in Simmons and Nof, 2002 [20]. However, in the observations, both cyclones and anticyclones encountered the Bahamas, and were associated with a response in the Florida Current. The real ocean has more complicated topography (Fig. 1a) than the simple meridional wall of Simmons and Nof, 2002 [20]. As well, the gap itself is a narrow zonal channel some 150 km long, and while the water is full depth (4000 m) east of the gap, west of the gap it is less than 1000 m deep. While results are qualitatively promising, there are substantial differences between the idealised model and observations presented here.

5. Conclusions

In contrast to previous studies, the FC and AC transport time series were shown to be correlated from May 2009 to Apr 2011. Coincident with the fluctuations in the AC and FC transports, closed contours of SSH anomalies east of the Bahamas were identified, with diameters of roughly 200–300 km and amplitudes of ± 15 cm. These results indicate that the fluctuations in the AC are governed by mesoscale eddy activity east of the Bahamas, where the SSH anomalies and *in situ* instruments were located, consistent with previous research (e.g. Lee et al., 1996 [21]). While the AC transport appears to be controlled by the eddy activity throughout the record, 2004–2011, the FC variability was most clearly influenced by the eddies from May 2009 to Apr 2011. During this 2009–11 period, the fluctuations in the AC transport west of 76.75°W were equal in magnitude to the fluctuations in the FC transport. If the AC were considered to be part of the western boundary current, as suggested by Thomas et al., 2012 [22], then the combined fluctuations of the AC and FC in 2009–11 would double in range relative to considering the FC alone.

Lagged regression maps between the AC and SSH anomalies further show that the SSH anomalies responsible for AC transport anomalies originated east of the Bahamas, though

significance is reduced with distance offshore (Fig. 3a–c). These are consistent with observations from all ocean basins of mesoscale eddies and waves propagating westward. Here, this result supports the idea that these eddies can be an important, or sometimes even dominant, source of variability for both the FC and AC in addition to their forced response to local and regional winds.

As the Gulf Stream is a major artery of the global ocean circulation, and transport estimates in the Florida Straits are one of the longest, high-temporal resolution time series of a western boundary current, understanding sources of variability of the Gulf Stream is important. The cable observations are regularly used to validate numerical models, or are compared with climate indices to improve our understanding of the ocean-atmosphere system. Particularly when most climate models do not include the mesoscale physical processes we expect here, this new source of variability may inform our interpretation of agreement or disagreement between observations and models. Even in models which resolve eddies, these eddy impacts would not be expected to occur at the same times as in the real ocean, due to the stochastic nature of eddies.

While the simple relationship (FC=gyre+MOC) and past results from observations of the MOC [Kanzow et al., 2010, 20] suggested that the Gulf Stream variability should project onto large scale circulations, we have shown that some FC variations reflect local, stochastic, and internal-ocean forcing by mesoscale eddies from the Atlantic. The transmission of eddy variability through the Bahamas Banks from the Antilles to Florida Currents presents a new source of variability to the FC not previously explored. Indeed, without the array east of the Bahamas, relating the transport variability of the FC and AC would not be possible.

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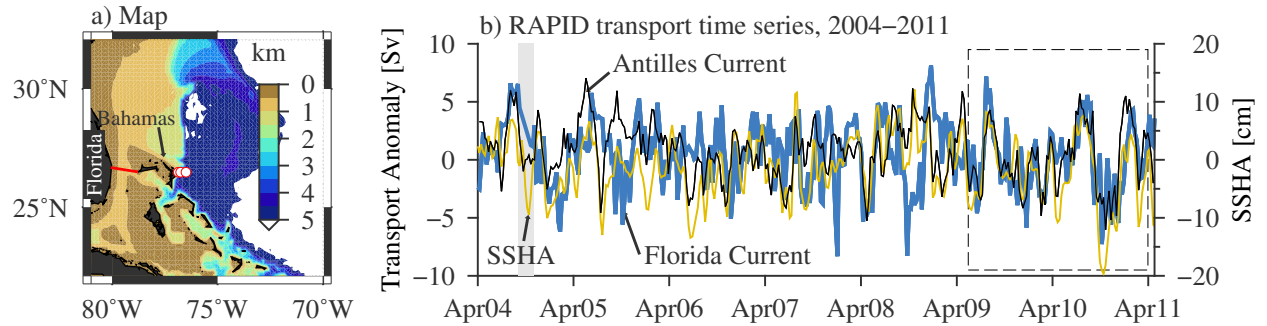


Figure 1. a) Map of the region with land in black and bathymetry shaded at 500 m intervals. Moorings used to estimate the AC transport are given by the red open circles, WB₂ and WB₃ at 76.75°W and 76.5°W, respectively, and 26.5°N. Additional moorings used are between WB₂ and the Bahamas, and are indistinguishable at this scale. The SSH anomaly time series at 26.57°N, 76.67°W is between the centres of the two visible white dots. The FC cable position is given by the red line between Florida and the Bahamas islands. (b) Florida Current (thick blue) and Antilles Current transport anomalies (thin black) for the period Apr 2004–Apr 2011, with amplitudes on the left y-axis. Also plotted are SSH anomalies at 26.57°N, 76.67°W, with the seasonal cycle removed (yellow). The roughly 2-month period from Sep 2004–Oct 2004 is shaded in grey indicating a gap in the FC cable data. The box (black, dashed) shows the period where the FC and AC are correlated.

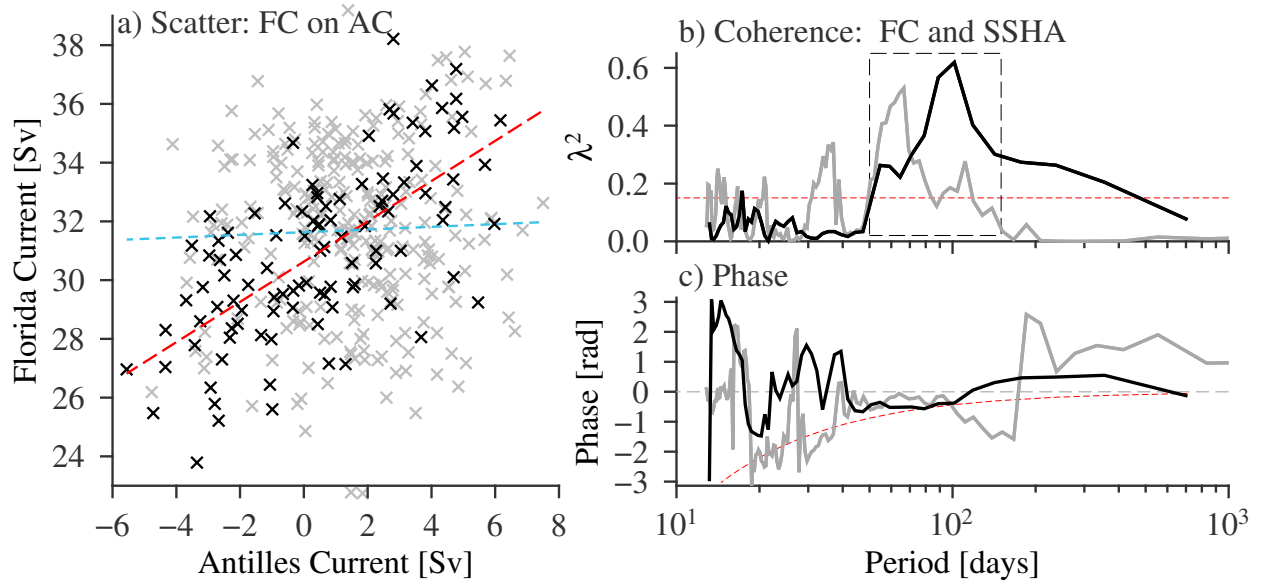


Figure 2. (a) Scatter plot of transport time series for the FC and AC, for Apr 2004–Apr 2009 (grey) and May 2009–Apr 2011 (black), with the best fit regression lines in blue and red, respectively, and correlation coefficients $r = 0.04$ (not significant) and $r = 0.66$ (99% significant), respectively. (b) Magnitude squared coherence between the FC transport and the SSH anomaly time series, for the same periods, and colours as in (a). Areas above the red, dashed curve are significant. The box (black, dashed) indicates the mesoscale timescales (50–150 days). (c) Phase in radians, where a 7-day lag (SSH leading) is in red, dashed.

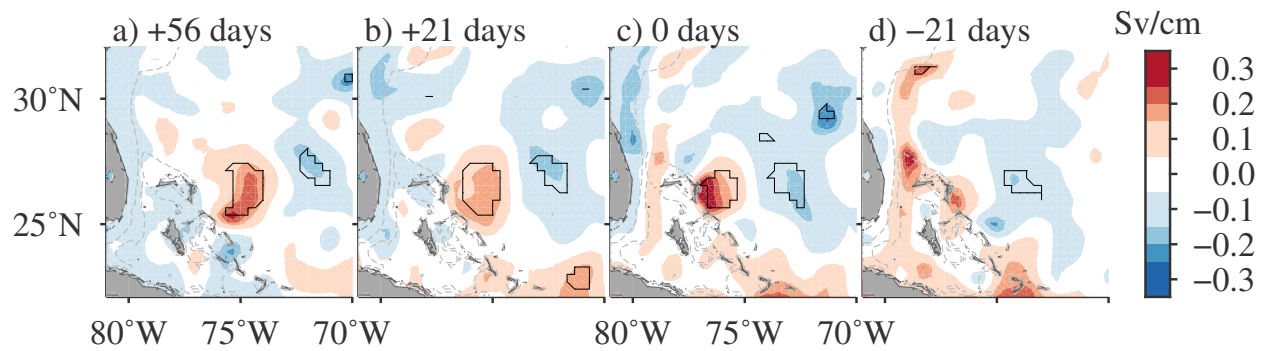


Figure 3. Lagged regression maps between the AC transport and SSH anomalies for the time period May 2009–Apr 2011, where the SSH time series has had its seasonal cycle removed. The slope of the regression is plotted in color for lags of (a) 56, (b) 21, (c) 0 and (d) -21 days. Positive lags indicate that the SSH anomalies precede the AC transport anomalies. Significant regions at the 95% level are contoured in black. The 800 m bathymetric contour is also contoured with dashed grey.

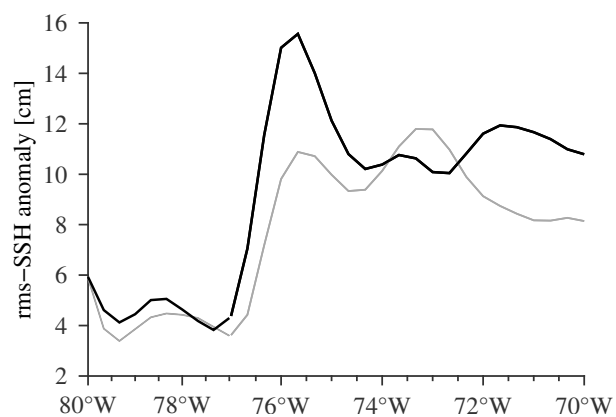


Figure 4. Root-mean-square amplitude of SSH anomalies along 26.58°N for the intervals Apr 2004–Apr 2009 (solid grey line) and May 2009–Apr 2011 (solid black line), as in Kanzow et al., 2009 [20], Fig. 6.