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Key Points:

- Interannual variations in Florida Current transport are highly correlated with sea level at eastern side of the Florida Straits (SSH_{east})
- Changes in SSH_{east} exhibit a linear link to warming and cooling conditions in the equatorial Pacific
- This connection is through the wind stress curl changes remotely forced from the equatorial Pacific

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Remote Impact of the Equatorial Pacific on Florida Current Transport

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Abstract Satellite and in-situ measurements are used in this study to investigate a possible link between the Florida Current transport (FCT) and temperature changes in the equatorial Pacific. Consistent with the geostrophic nature of the current, the FCT variability shows good correspondence with the changes in sea surface height differences (ΔSSH) between the eastern (SSH_{east}) and western (SSH_{west}) sides of the Florida Straits. While the variability of SSH_{west} is mostly associated with seasonal and shorter timescale fluctuations of ΔSSH and FCT, changes in SSH_{east} are strongly related to the interannual variability of ΔSSH and FCT. A significant correlation is found between the FCT and the Oceanic Niño Index (ONI) on interannual timescales, which explains 21% of the interannual FCT variance. The connection of ONI with FCT is through its impact on SSH_{east}, associated with the anomalous convergence/divergence in the Caribbean region and the Bahamas forced by ONI-induced wind stress curl changes.

Plain Language Summary Variations in the Florida Current transport (FCT) have been linked to widespread weather and climate phenomena. Various driving mechanisms for the FCT variability have been proposed, but none can fully explain its wide spectrum variability. In this study, we analyzed in-situ and satellite observations and found a linear link between the FCT and temperature changes in the equatorial Pacific on interannual timescales. A warming condition in the equatorial Pacific results in low pressure anomalies in the Gulf of Mexico and high pressure anomalies extended into the Caribbean Sea from the tropical Atlantic. This atmospheric pressure pattern is associated with anticyclonic winds over the Caribbean Sea and the Bahamas that drive anomalous oceanic convergence and, therefore, cause higher sea levels in those regions. A higher sea level near the Bahamas often steepens the sea level slope across the Florida Straits, which corresponds to a stronger FCT. A cooling condition in the equatorial Pacific will have the opposite effect, resulting in a reduced FCT.

1. Introduction

The Florida Current (FC), the beginning of the Gulf Stream as it flows through the Florida Straits (FS), has been the subject of numerous studies to understand its transport variability and driving mechanisms on timescales ranging from days to long-term trends (e.g., Wunsch et al., 1969; Schott et al., 1988; Baringer & Larsen, 2001; Beal et al., 2008; Di Nezio et al., 2009; C. S. Meinen et al., 2010; Todd et al., 2018; Piecuch, 2020; Hameed et al., 2021). The broad interest in monitoring the FC is driven by its link to weather, climate, and societal issues, including changes in coastal sea level and flooding events (e.g., Ezer & Atkinson, 2014; Sweet et al., 2016; Domingues et al., 2018). Despite the tremendous efforts from the scientific community, the driving mechanisms for the FC transport (FCT) variability are not fully understood. Previous studies have proposed and investigated many possible mechanisms, and it is believed that multiple drivers are responsible for the observed large variability in FCT.

The majority of earlier studies on FCT has attributed its variability to wind forcing either remotely from upstream or downstream of the FS (Anderson & Corry, 1985a, 1985b; Czeschel et al., 2012) or from ocean interior (e.g., Di Nezio et al., 2009; Domingues et al., 2016), or locally from along-stream winds (e.g., T. N. Lee and Williams, 1988; Schott et al., 1988; Beal et al., 2008). The North Atlantic Oscillation (NAO), eddy activity east of the Bahamas, and the excursions of the Loop Current have also been identified as drivers for the FCT variability (Baringer & Larsen, 2001; C. S. Meinen et al., 2010; Domingues et al., 2019; Frajka-Williams et al., 2013; Hameed et al., 2021; Hirschi et al., 2019; Lin et al., 2009; Mildner et al., 2013).

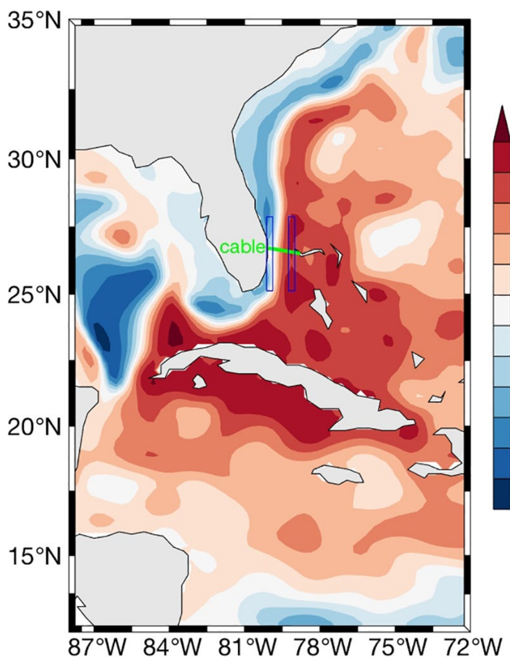

Figure 1. Spatial distribution of the correlation coefficients at zero lag between the Florida Current volume transport (FCT) and sea surface height anomalies on interannual time scales. Green line shows the location of the FCT measurements from submarine cable. The two blue boxes denote the regions where SSH_{west} and SSH_{east} are defined.

The FCT response to the NAO is rather complex, with various NAO-related mechanisms that may impact the FCT at different time lags. Baringer and Larsen (2001) showed that the interannual FCT variations over the period 1982–1996 were anti-correlated with NAO at an 18-month lag. This anti-correlation was linked to the propagation of the first mode baroclinic Rossby waves forced by NAO-induced wind stress curl changes in the ocean interior (Di Nezio et al., 2009). However, C. S. Meinen et al. (2010) found that this mechanism only holds during the period 1984–1998. Hameed et al. (2021) examined the wintertime FCT and the NAO during 1983–2017 and found no significant correlation between the two. However, their analysis suggested that the zonal migrations of the Azores High are associated with alongshore wind stress changes close to the North America coast. The alongshore wind generates coastal sea level anomalies which propagate as coastal trapped waves to the FS and affect the FCT within the same season. They also suggested that wind stress curl changes induced by the meridional migrations of the Azores High and the Icelandic Low pressure centers can result in the FCT changes 4 years later through the Rossby wave propagation mechanism.

The impact of El Niño/Southern Oscillation (ENSO), warming and cooling conditions in the tropical Pacific, on global ocean via atmospheric bridges has been well known (e.g., Alexander et al., 2002; S. K. Lee et al., 2008), including the impact on the western boundary currents, such as the Kuroshio (e.g., Jacobs et al., 1994; Kawabe, 2000, 2001; Kuo & Tseng, 2021) and Agulhas current (Paris et al., 2018; Putrasahan et al., 2016; Trott et al., 2021). However, the impact of ENSO on the FCT has not yet been explored. The objective of this study is to investigate the potential connection between ENSO and the changes in FCT on interannual timescales through analyzing satellite and in-situ measurements during 1993–2020.

2. Data and Method

The daily Florida Current volume transport (FCT) at 27°N has been monitored nearly continuously since 1982 with submarine telecommunication cables (Figure 1). Voltage measured on the cable is calibrated into transport using ship-borne measurements at nine stations across the FS at 27°N (Larsen & Sanford, 1985). Approximately 12–14 cable calibration and validation cruises are conducted per year. The daily FCT cable record has a number of gaps due to recording system failures as well as logistics and/or operational issues, ranging from days to the longest 17-month gap between October 1998 and March 2000. The transport estimates from the calibration/validation cruises are used to fill in the gaps in the cable record whenever possible. The daily FCT is averaged to monthly. Because this study focuses on the interannual variations in the FCT, a monthly climatology is removed and a lowpass filter is applied to exclude signals with periods shorter than 1 year. A linear trend during the study period (January 1993 – December 2020) is also removed. The same data processing procedure is applied to all variables described in this section. The degrees of freedom for estimating the significance of correlations between variables are determined assuming the decorrelation time scale of 1 year.

The FC is approximately in geostrophic balance, such that the FCT changes are reflected in the sea level slope across the FS. Previous studies have used sea level differences between the eastern and western sides of the Straits measured from tide/pressure gauges (Maul et al., 1985, 1990; C. S. Meinen et al., 2021) and satellite altimetry (D. L. Volkov et al., 2020) to approximate the FCT. Delayed-time monthly satellite altimetry fields of sea surface height anomaly (SSHA) from January 1993 to December 2020 processed and distributed by the Copernicus Marine and Environment Monitoring Service are used in this study to reveal a possible mechanism driving interannual changes in the SSHA and the FCT. This delayed-time SSHA on a 0.25° × 0.25° grid is derived by merging data from all altimetry satellites available at a given time (Pujol et al., 2016). Consistent with earlier studies, the correlation map between the low-pass filtered FCT and SSHA at each grid point (Figure 1) shows positive values on the eastern side of the FS and negative values on the western side. This correlation implies the possibility of using the cross-stream SSHA differences to approximate the FCT on interannual timescales. To reduce noise,

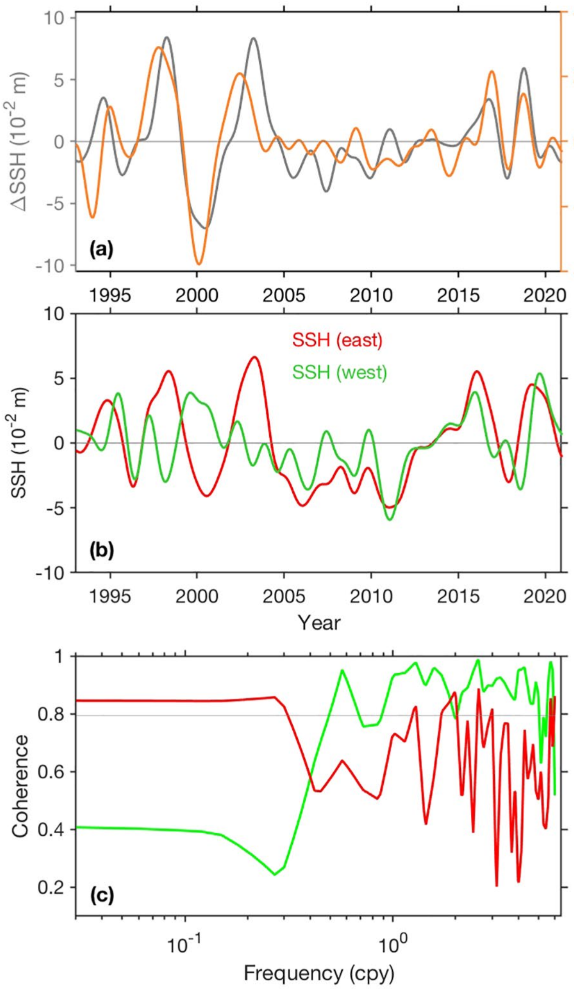

Figure 2. Time series of (a) the Florida Current transport (orange, right axis) and sea surface height difference (ΔSSH) between the eastern and western boundaries of the Florida Straits (FS) (gray, left axis), and (b) SSH near the eastern (red) and western (green) boundaries of the FS. (c) Coherence between ΔSSH and SSH_{east} (red) and between ΔSSH and SSH_{west} (green), with gray line indicating the 95% confidence level.

SSHA was averaged within a 3° latitude band between 25°N and 28°N near 80°W and 79°W (blue boxes in Figure 1) to represent SSH changes at the western (SSH_{west}) and eastern (SSH_{east}) sides of the FS, respectively.

Monthly averages of sea level pressure (SLP) and surface wind stress from the European Centre for Medium-Range Weather Forecasts Reanalysis fifth Generation (ERA5, Hersbach et al., 2020) on a 0.25° × 0.25° grid are used to investigate the possible forcing for the FCT variability. Climate indices, including the NAO and Oceanic Niño Index (ONI), are used to explore their relationship with the FCT and SSHA. The NAO index, defined as the normalized SLP difference between the Azores High and the Icelandic Low pressure centers (Hurrell & Deser, 2009), is the dominant mode of climate variability in the North Atlantic. The ONI, defined as sea surface temperature anomaly in the Nino 3.4 region (5°N to 5°S, 170°W to 120°W), measures the departure from the normal sea surface temperature in the east-central Pacific Ocean (Glantz & Ramirez, 2020).

3. FCT Interannual Variability

The interannual variability of the FCT shows large amplitudes between 1993 and 2004, with strong positive anomalies in 1997–1998 and 2002 and negative anomalies in 1993–1994 and 1999–2000 (Figure 2a). The maximum positive anomalies of about 3.0 Sv occurred at the end of 1997 and in 2003, and the largest negative anomaly was observed at the beginning of 2000 with a value of −3.7 Sv. The FCT variability between 2004 and 2013 was weak, mostly within ±0.5 Sv. Since 2014, its variability has strengthened with positive anomalies peaking around 2.1 Sv and negative anomalies peaking around −1.1 Sv, but it is still relatively weak compared to the variability during 1993–2004.

The variability of sea surface height difference ($\Delta SSH = SSH_{east} - SSH_{west}$) between the eastern and western boundaries of the FS is very similar to the FCT variability (Figure 2a) with anomalies ranging from −6.9 to 8.4 cm. The correlation coefficient between the low-pass filtered FCT and ΔSSH is 0.71 (95% confidence level of 0.37) for the entire study period. This result is consistent with D. L. Volkov et al. (2020) who used the along-track altimetry data and found a correlation of 0.67 between the yearly averages of the FCT and ΔSSH during 2005–2020. For the same time interval, the correlation between the low-pass filtered FCT and ΔSSH derived from the gridded product is 0.66. This suggests that fluctuations in ΔSSH are representative of about half of the variance in the FCT on interannual timescales.

One interesting question is why there was a drastic change in the FCT and ΔSSH variability starting around 2005. The SSH anomalies at either side of the FS do not demonstrate such large change, although the SSH_{east} anomalies during 2005–2014 (up to −4.9 cm) are somewhat weaker than the anomalies before 2005 (up to 6.6 cm; Figure 2b). Before 2005, changes in SSH_{west} were often opposite to those in SSH_{east} except during 1996. This opposing change in SSH_{west} and SSH_{east} explains the large variability in the ΔSSH and FCT. Whereas since 2005, the SSH_{west} has been mostly co-varying with SSH_{east}, both increasing and decreasing simultaneously, which explains the reduced amplitudes in ΔSSH. To examine the contributions of SSH_{west} and SSH_{east} to ΔSSH variability, we performed a coherence analysis of ΔSSH with SSH_{east} and SSH_{west} (Figure 2c). The unfiltered SSH anomalies are used in the coherence analysis. The coherence between ΔSSH and SSH_{west} is high at frequencies greater than 0.5 cycles per year, but their coherence is not significant at lower frequencies. On the contrary, the coherence between ΔSSH and SSH_{east} exceeds 95% confidence level at lower frequencies (less than 0.35 cycles per year), but mostly below 95% confidence level at higher frequencies. This suggests that at higher frequencies, the energy in ΔSSH primarily comes from SSH_{west}, whereas at lower frequencies SSH_{east} dominates the energy in the ΔSSH.

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4. Relationship of Florida Current Transport With Climate Indices

4.1. Impact of North Atlantic Oscillation on Florida Current Transport

Previous studies (e.g., Baringer & Larsen, 2001; C. S. Meinen et al., 2010) have associated the interannual variations in the FCT with the NAO. However, as noted in C. S. Meinen et al. (2010), significant anti-correlation between the two can only be seen between 1984 and 1998. After 1998, there is no statistically significant relationship between the two. Consistent with earlier studies, we find some correspondence between the FCT and the NAO during the time period 1993–2000 with a negative correlation of −0.48, but their anti-correlation during the entire study period 1993–2020 is statistically insignificant with the maximum negative value of −0.18 when the NAO leads by 14 months. Nevertheless, the lagged correlation analysis gives a significant (marginal at 95% confidence level) positive correlation of 0.39 when the NAO leads the FCT by 44 months.

Similar to the FCT, the correlation between SSH_{east} and the NAO ($r = 0.31$, with the NAO leading by 9 months) is not significant (Figure 3d). However, the SSH_{west} is significantly correlated with the NAO, with a correlation coefficient reaching 0.57 (significant at 95% confidence level) when the NAO leads by 10 months (Figures 3e and 3f). This suggests that a positive NAO is associated with a higher SSH at the western side of the FS, which reduces cross-stream SSH gradient and, therefore, a weaker FCT about a year later. However, because SSH_{west} plays a secondary role in the interannual variability of the FCT compared to SSH_{east}, the significant correlation between SSH_{west} and the NAO does not translate into a significant correlation between the low-pass filtered FCT and NAO. Near the 4-year leading time, the NAO shows a peak correlation with both SSH_{east} ($r = 0.31$, Figure 3d) and SSH_{west} ($r = -0.28$, Figure 3f), but in the opposite sense. The positive correlation between NAO and SSH_{east} indicates an increase in SSH_{east} corresponding to a positive NAO, whereas the negative correlation between NAO and SSH_{west} indicates a decrease in SSH_{west} corresponding to a positive NAO. Although both correlations are below 95% confidence level, the opposing responses in SSH_{east} and SSH_{west} enhance changes in the FCT, which explains the stronger link between NAO and FCT at a 44-month lag.

4.2. Impact of Equatorial Pacific on Florida Current Transport

Examination of the low-pass filtered FCT and ONI shows a correlation of 0.46 between the two (significant at 95% confidence level) when the ONI leads the FCT by 3 months (Figures 3a and 3b). Correlation analysis of SSH_{east} and SSH_{west} with the ONI gives the maximum correlation of 0.64 between SSH_{east} and the ONI, with the ONI leading by 3 months (Figures 3c and 3d), but the correlation between SSH_{west} and the ONI is statistically insignificant ($r = 0.18$ at zero lag; Figure 3d). This suggests that the connection between the ONI and the FCT is mainly through the impact of the ONI on SSH_{east} near the Bahamas, although its weak correlation with SSH_{west} reduces its overall influence on the FCT.

A regression analysis between the ONI and SSHA at each grid point in the North Atlantic between 5°N and 60°N is performed to examine the large-scale impact of the ONI, where SSHA is regressed onto the ONI with a 3-month lag. Positive regression coefficients exceeding 95% confidence level are observed in a broad region within 90°W-60°W, 10°N-25°N, including the Caribbean Sea and the Bahamas (Figure 4a). The response of the SSH to the ONI strengthens eastward in the FS at 27°N, with the regression coefficients increasing from 0.005 m/°C at 80°W to 0.033 m/°C at 79°W. This suggests that a 1°C increase in the ONI would induce a 0.028 m increase in ΔSSH. Linear regression of the FCT onto ΔSSH gives a 27 Sv change in the FCT associated with a 1 m change in ΔSSH. Therefore, a 1°C anomaly in the ONI can result in a 0.76 Sv change in the FCT.

To further look into the forcing mechanisms, we regressed SLP and surface wind stress fields onto the ONI (Figure 4b). The SLP anomalies associated with the ONI show low pressure centered around 30°N, 85°W, which extends from the Gulf of Mexico toward the northwestern subtropical North Atlantic. High pressure anomalies centered at 15°N, 35°W extend into the Caribbean Sea. This pressure pattern induces anticyclonic circulation in the Caribbean Sea and the Bahamas, coinciding with the region where a significant association between SSHA and the ONI is found (Figure 4a). The anticyclonic wind circulation results in negative anomalies of wind stress curl in the region (Figure 4c), which in turn drives oceanic convergence, therefore, higher sea level. The 3-month delay in sea level changes is likely due to the oceanic response time to the momentum flux, similar to the response time of the tropical Atlantic sea surface temperature to surface heat flux anomalies forced by El Niño events (e.g., S. K. Lee et al., 2008).

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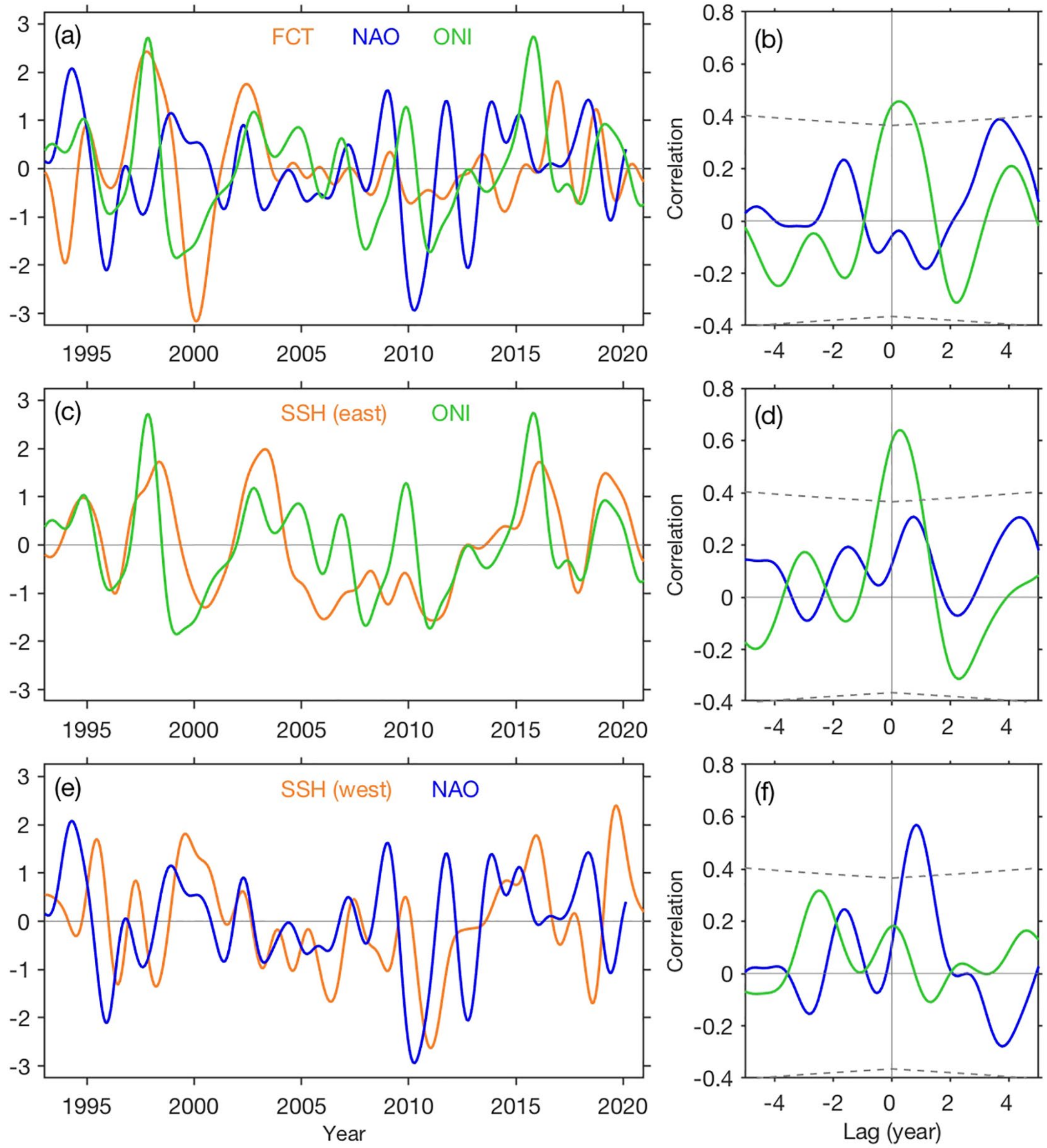

Figure 3. Time series of (a) the Florida Current transport (FCT) (orange) and North Atlantic Oscillation (NAO) (blue) and Oceanic Niño Index (ONI) (green) indices, (c) SSH (orange) at the eastern side of the Florida Straits (FS) and ONI index (green), and (e) SSH (orange) at the western side of the FS and NAO index (blue). All variables are standardized by dividing values by their standard deviation. Lead-lag correlations of the FCT (b) and SSH at the eastern (d) and western (f) boundaries of the FS with NAO (blue) and ONI (green) indices, respectively. Dashed gray lines in (b), (d), and (f) indicate 95% confidence level.

Changes in SSH_{east} can be local responses to the ONI-induced wind anomalies or signals propagated from the Caribbean Sea and/or north of Cuba. Our preliminary lagged correlation analysis between SSH_{east} and SSH at each grid point shows high correlations within the region surrounding Cuba and in the Caribbean Sea with time lags of 1–3 months (not shown). Although the propagation scenario is consistent with the high correlation between the FCT and SSH variations in the Caribbean Sea and to the north of Cuba on interannual timescales (Figure 1), further study is needed to investigate this propagation possibility and potential physical mechanisms for the propagation.

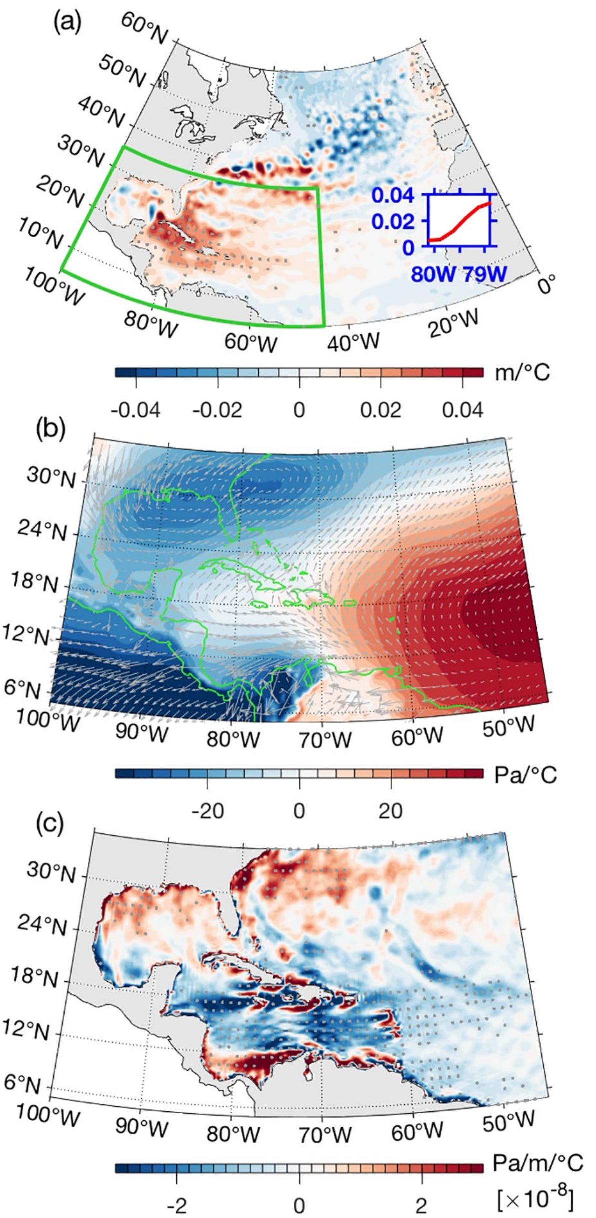

Figure 4. Spatial distribution of linear regression coefficients of (a) SSHA onto Oceanic Niño Index (ONI) at 3-month lag, (b) sea level pressure (color shading) and surface wind stress (gray arrows) onto ONI, and (c) wind stress curl onto ONI. The inset plot in (a) shows the regression coefficients across the Florida Straits at 27°N. Gray dotted areas in (a) and (c) indicate regions where regression coefficients are significant at the 95% confidence level. The green box in (a) indicates the region for (b) and (c).

5. Discussion

The FCT variability and its forcing mechanisms are complex and vary on different time scales. By analyzing SSH near the eastern and western boundaries of the FS we gain more insight into the forcing mechanisms on interannual timescales. Our results indicate that the dominant forcing for SSH_{east} and SSH_{west} is different. Although both the NAO and the ONI impact SSH across the FS, the NAO has a stronger impact on SSH_{west}, whereas the ONI dominates changes in SSH_{east}. Not only the magnitudes of the NAO and the ONI anomalies are important, the phase relationships between these climate indices are also critical for the FCT variability. We showed that the large FCT anomalies between 1997 and 2004 (Figure 2a) are linked to the opposing anomalies in SSH_{east} and SSH_{west}. These opposite changes are likely due to the fact that the NAO and ONI indices tend to be out of phase during this period (taking into account the lead-time of both indices to SSH changes). Since 2005, the NAO and ONI indices tend to be more in-phase, which results in coherent changes in the SSH_{west} and SSH_{east}. Consequently, despite the large anomalies in SSH on both sides of the FS, variations of the FCT are relatively small.

Although no significant anti-correlation between the FCT and NAO was found during 1993–2020, NAO has a strong impact on interannual sea level changes on the western side of the FS, such that a positive NAO anomaly induces a higher sea level 10-month later, and vice versa. The response of sea level on the eastern side to the NAO changes is similar, but weaker. The coherent response of SSH_{west} and SSH_{east} to the NAO is probably associated with the leading EOF (empirical orthogonal function) mode of the interannual SSH variability in the North Atlantic, which displays a tripole pattern with the SSH in the subtropical region varying out of phase with both the tropical and the subpolar regions (D. L. Volkov et al., 2019). D. L. Volkov et al. (2019) found that the interannual changes of SSH in the subtropical region lag the interannual changes of the NAO index by 9 months, which is consistent with the leading time of the NAO to SSH_{east} and SSH_{west} shown in Figures 2d and 2f. The higher positive correlation between SSH_{west} and the NAO is also consistent with the finding of D. L. Volkov et al. (2019) that the interannual SSH variance explained by the tripole mode is greater in the western part of the FS than in the eastern part (see their Figure 1e). D. L. Volkov et al. (2019) showed that the North Atlantic SSH tripole reflects changes in oceanic heat content and the adjustment of the large-scale horizontal and overturning ocean circulation to the NAO-induced changes in surface buoyancy and wind forcing. Further investigation is needed to understand the interplay of different forcing mechanisms on the FCT and SSH changes.

The positive correlation between the FCT and NAO index when NAO leads by 44 months from our analysis of the monthly data during 1993–2020 is somewhat different from Hameed et al. (2021), who did not find a strong relationship between the wintertime FCT and NAO index during 1983–2017. However, they found that wind stress curl changes over the ocean interior induced by the meridional migrations of the Azores High and the Icelandic Low pressure centers can result in FCT changes 4 years later through the Rossby wave propagation mechanism. The small difference in the time lag is probably because we used monthly instead of wintertime data as in Hameed et al. (2021). When we use the wintertime (DJF) FCT and NAO during 1993–2020, the correlation between them becomes 0.27 at 4-year lag. Same as previous studies, the observed time lag is probably due to the propagation of baroclinic Rossby waves forced by NAO-induced wind stress curl changes in the subtropical North Atlantic.

6. Summary

In this study, we advanced our understanding of the interannual variations of the Florida Current volume transport by linking its variability to processes in the equatorial Pacific. We found that sea level changes near the eastern and western boundaries of the FS control the cross-stream sea level gradient on different time scales, with SSH_{west} dominating on seasonal and shorter time scales and SSH_{east} dominating on interannual-to-longer time scales. As a result, the variability in SSH_{east} has a larger impact on interannual variations of the FCT, whereas the FCT variability on seasonal and shorter time scales is strongly linked with changes in SSH_{west}.

Consistent with previous studies, we did not find a significant anti-correlation between the NAO and FCT after the year 2000. However, a significant positive correlation was found when the NAO leads the FCT by 44 months. This relationship may be linked to the propagation of baroclinic Rossby waves forced by the NAO-induced wind stress curl changes in the subtropical North Atlantic. Although the ENSO teleconnection and its global impact have been known for decades, here for the first time we demonstrated its connection with the FCT. We found a significant positive correlation between the FCT and ONI on interannual timescales, with the ONI leading by 3 months. The link between the FCT and ONI is mainly through the ONI's impact on the SSH changes in the eastern part of the FS. Further analysis indicated that a positive ONI, corresponding to warming condition in the equatorial Pacific, is associated with low pressure anomalies in the Gulf of Mexico and high pressure anomalies extended into the Caribbean Sea from the tropical Atlantic. This pressure pattern drives anticyclonic circulation anomaly over the Caribbean Sea and the Bahamas, which induces oceanic convergence and, hence, higher sea levels in those regions. Higher sea levels on the Bahamas side correspond to the stronger FC. A negative ONI will have the opposite effect, resulting in a weaker FC. The established relationship gives some predictability of the FCT and coastal sea level changes with a 3-month lead time, which can benefit coastal communities, particularly during strong El Niño and La Niña events.

Data Availability Statement

The Florida Current cable and section data are made freely available on the Atlantic Oceanographic and Meteorological Laboratory web page (www.aoml.noaa.gov/phod/floridacurrent/) and are funded by the DOC-NOAA Climate Program Office – Ocean Observing and Monitoring Division. Satellite altimetry products were produced by the Copernicus Marine and Environment Monitoring Service (CMEMS) and can be found at https://resources.marine.copernicus.eu/product-detail/SEALEVEL-GLO_PHY_L4_MY_008_047/INFORMATION (https://doi.org/10.48670/moi-00148). The Oceanic Niño Index (ONI) from NOAA's National Weather Service is available at https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php. The monthly North Atlantic Oscillation index (station-based) is retrieved from https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based. The monthly sea level pressure and surface wind stress from the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis fifth Generation (ERA5) is available at https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means?tab=overview.

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