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Key Points:

- Gulf Stream (GS) transport decorrelates rapidly with distance downstream of Cape Hatteras
- Monthly sea level variations on the U.S. East Coast are not correlated with GS transport north of Cape Hatteras
- Downstream of Cape Hatteras, onshore-side sea level changes associated with GS transport decay rapidly away from the axis

Supporting Information:

Supporting Information may be found in the online version of this article.

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Reconsidering the Relationship Between Gulf Stream Transport and Dynamic Sea Level at U.S. East Coast

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Abstract The relationship between Gulf Stream (GS) transport and coastal sea level is investigated using monthly GS transport between 1993 and 2019 at Florida Straits and 10 altimeter tracks. The results show that GS transport decorrelates quickly along its path, indicating it is misleading to assume that transport at a particular location represents strength of the GS as a whole. GS transport south of Cape Hatteras is significantly correlated with coastal sea level in South Atlantic Bight from both altimetry and tide gauges. North of Cape Hatteras, sea level changes associated with GS transport decay rapidly away from GS on the onshore side and become negligible approximately 300 km northwest of GS axis. In this region, the correlations between GS transport and sea level are primarily in the deep ocean and rarely on the shelf, indicating that coastal sea level is unlikely to be driven by geostrophic adjustment to changes in GS transport.

Plain Language Summary Sea level on the U.S. East Coast north of Cape Hatteras has risen rapidly in recent decades. Some previous studies attributed this sea-level rise to a decline in the Gulf Stream (GS). Here, we investigate the relationship between them from in situ and satellite observations. The results show that GS transport changes continuously along its path, suggesting that the GS strength cannot be represented by its transport at a particular location. South of Cape Hatteras, the GS transport can impact neighboring coastal sea levels via oceanic links. However, its influence on coastal sea level is negligible north of Cape Hatteras. The above results imply that changes in GS transport are unlikely to be the direct cause of rapid sea-level rise at the U.S. East Coast north of Cape Hatteras.

1. Introduction

Sea level rise (SLR) on the U.S. East Coast, especially in the Mid-Atlantic Bight (MAB), has accelerated over the last few decades at a rate higher than the global ocean (Boon, 2012; Dangendorf et al., 2021; Davis & Vinogradova, 2017; Ezer et al., 2013; Harvey et al., 2021; Kopp, 2013; Park & Sweet, 2015; Sallenger et al., 2012; Yin, 2023). Records from tide gauges on the U.S. East Coast show large interannual fluctuations in coastal sea level and the rate of SLR (Andres et al., 2013; Ezer, 2013; Goddard et al., 2015).

Gulf Stream (GS) is the western boundary current of the North Atlantic subtropical gyre. Its large surface-layer transport is geostrophically balanced by a ∼1 m cross-stream change in sea level (Johns et al., 1989). A reduction in GS surface-layer transport at a specific location is therefore accompanied by a reduction in the cross-stream sea level drop, with increased (decreased) sea level on the inshore (offshore) flank of the GS. It has been suggested that this mechanism drives coastal SLR along the U.S. East Coast on the inshore side of the GS (Ezer, 2015; Ezer et al., 2013; Goddard et al., 2015; Yin & Goddard, 2013). This mechanism has also been adopted to explain how a decline in the Atlantic meridional overturning circulation (AMOC) may contribute to SLR on the U.S. East Coast since fluctuations in AMOC transport may affect GS transport (Ezer, 2015; Ezer & Atkinson, 2014; Ezer et al., 2013; Goddard et al., 2015; Hu & Bates, 2018; Yin et al., 2009, 2010). However, observed reductions in AMOC transport at 26.5°N are primarily due to decreases in upper midocean transport and changes to GS transport at that location are statistically insignificant (Meinen et al., 2010; Smeed et al., 2014).

Previous studies invoking changes to the GS or AMOC to explain SLR on the U.S. East Coast focus on different time periods or geographic locations, making direct comparisons challenging. Here we summarize the most relevant studies for the benefit of readers.

There was a major reduction of about 30% in AMOC transport measured at 26°N during 2009–2010 (Bryden et al., 2014). Goddard et al. (2015) suggested that this AMOC slowdown, coupled with an extremely negative

North Atlantic Oscillation index, was the cause of an unprecedented SLR event on the Northeast Coast of North America. The proposed mechanism was that the AMOC reduction reduced the sea level gradient across the GS and thus lifted sea level along the coast. However, Bryden et al. (2014) reported that the reduction of GS transport accounted for only 0.8 Sv years (1 Sv = 1×10^6 m^3/s, 1 Sv year ≈ 32,000 km^3) of the AMOC slowdown of 6.3 Sv years. This reduction in GS transport is within its normal interannual variation, so it is unlikely to be the direct cause of the SLR event.

Ezer et al. (2013) used Empirical Mode Decomposition and spectral coherency to relate monthly sea level at 10 tide gauges in the MAB with the sea level gradient (proportional to surface transport) across the GS in that region during 1996–2011. While there were several isolated frequencies with significant coherence between coastal sea level and the GS sea level gradient, only one (at 6 months) corresponds to peak in sea level variability and 2–3 (confidence intervals not given) of the six peaks lack the antiphase relationship expected from geostrophic balance.

Little et al. (2019) reviewed the relationship between coastal sea level at the U.S. East Coast, GS, and AMOC in recent studies, pointing out that "the causal relationships between different observational metrics, AMOC, and sea level are often unclear," even though robust correlations can be found. The GS is flanked by recirculation gyres on the seaward side upstream of Cape Hatteras and on both sides downstream of Cape Hatteras. The presence of these recirculation gyres presents a significant complication in relating GS transport to directly coastal sea level since GS transport is also affected by changes in the recirculations.

Moreover, Chi et al. (2021) and Rossby et al. (2014) found no significant trend in GS transport from in-situ measurements spanning 1992–2012 and altimetry records spanning 1993–2018, respectively. The lack of a long-term trend makes changes in GS transport a poor explanation for a long-term trend in sea level. Dong et al. (2019) examined the GS transport from gridded altimetry records and found no link with coastal sea level averaged between Cape Hatteras and Cape Cod on the interannual time scale. Other studies have suggested that local wind plays an important role in sea level fluctuations and correlations between the AMOC, GS and the coastal sea level are due to their concurrent response to large-scale atmospheric circulations (Andres et al., 2013; Piecuch et al., 2019; Valle-Levinson et al., 2017; Woodworth et al., 2014).

In this study, we revisit direct links between GS transport and dynamic sea level at U.S. East Coast. We first derive GS transport at Florida Straits and 10 satellite altimeter tracks from Florida Straits to the south of Newfoundland. Then, the relationship between coastal sea level and GS transport at different locations is investigated. An important result is that GS transport rapidly decorrelates along its path, implying that it is misleading to infer changes to the GS as whole from changes at a few locations, which may explain why inconsistent conclusions about the relationship between coastal sea level and GS transport have been reached in previous studies focused on different regions, such as Dong et al. (2019), and Ezer (2013). Thus, we must consider the possible relationship between SLR and GS transport along its whole length rather than using a single representative transport measurement. We further find no significant relationship between GS transport and coastal sea level north of Cape Hatteras once local wind effects on coastal sea level are accounted for.

2. Data and Methods

The GS transport through Florida Straits, also known as Florida Current transport (FCT), has been measured by underwater cables for decades (Baringer & Larsen, 2001; Meinen et al., 2010). The measurement technique is detailed in Larsen and Smith (1992) and the uncertainty is discussed in Garcia and Meinen (2014) and Meinen et al. (2010). Gaps in the cable records are filled by another dataset derived from sea level differences across the strait (Volkov et al., 2020).

Surface-layer GS transport downstream of Florida Straits is derived from absolute dynamic topography (ADT) at 10 descending tracks that are approximately perpendicular to the GS path (Figure 1). Rossby et al. (2010, 2005) showed that it is proportional to the depth-integrated GS transport. Hereafter, GS transport refers to its transport at the surface layer except for FCT. At each track, cross-track geostrophic velocity is derived from ADT. Then, GS transport is calculated by integrating the geostrophic velocity between the first point where it drops to zero north and south of the GS axis. Since the geostrophic velocity is proportional to sea level gradient, the surface-layer GS transport (T_s) can also be written as a function of cross-stream sea level drop (Δh): $T = g \bullet \Delta h/f$, where f is the Coriolis parameter and g is the gravitational acceleration. The surface-layer GS transport from altimetry is given in units of Sv km^{-1} (=$10^3 m^2 s^{-1}$). A decrease of 1 Sv km^{-1} in the surface-layer GS transport corresponds to a decrease

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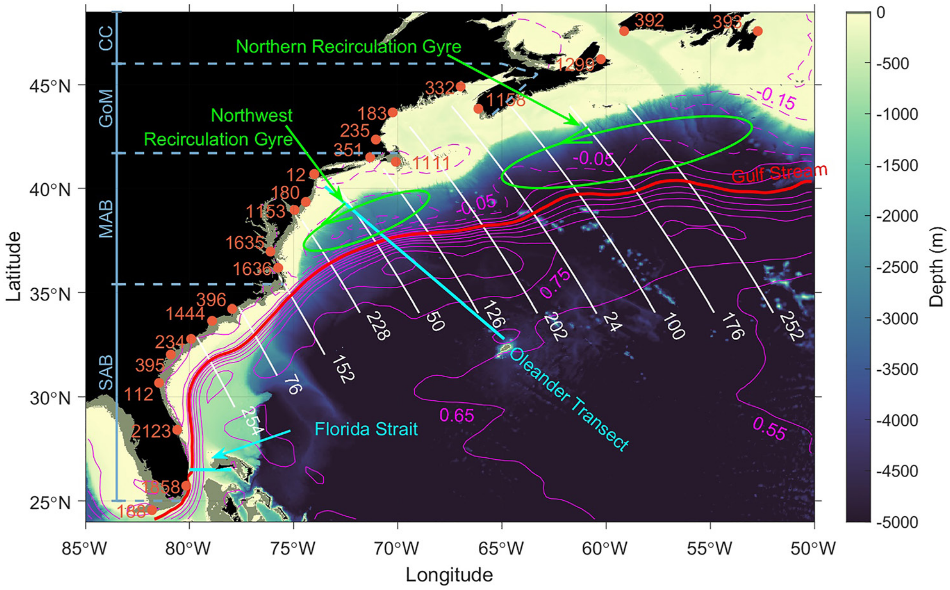

Figure 1. (Background shading) Topography of the northwest Atlantic. The solid (dashed) purple lines are contours for positive (negative) absolute dynamic topography (ADT) with a 10-cm interval during 1993–2019. The red line indicates the mean Gulf Stream (GS) path (i.e., the 25-cm contour of mean ADT during 1993–2019 [Text S1 in Supporting Information S1]). Satellite tracks are marked by white lines and tide gauges are marked by orange dots. Track 152 is not used in this study since the northern edge of the GS is too close to the coastline. SAB, South Atlantic Bight; MAB, Middle Atlantic Bight; GoM, Gulf of Maine; CC, Canadian Coast.

of approximately 0.9 cm in the ADT drop across the GS. The GS transport used in this study is identical to that used in Chi et al. (2021) but extended to 1993–2019. It has been shown that the GS transport from along-track ADT is comparable to *in-situ* acoustic doppler current profiler (ADCP) measurements at the Oleander transect (Chi et al., 2021). That monthly estimates of GS transport can be consistently estimated from satellite measurements that have a ~10 days interval is demonstrated in Figures S1 and S2 in Supporting Information S1 using FCT as an example. Further details about how GS transport is calculated can be found in Text S1 in Supporting Information S1.

Monthly mean coastal sea level from tide gauges are extracted from the Permanent Service for Mean Sea Level (PSMSL) (Holgate et al., 2013). Only tide gauges that face the open ocean directly and that are available during 1995–2016 are selected. If two tide gauges are close to each other, only one of them will be considered. Details of the tide gauges are listed in Table S1 in Supporting Information S1 and their locations are shown in Figure 1. In this study, we focus on dynamic sea level, which is "the local height of the sea surface above the geoid with the inverse barometer (IB) correction applied" (Gregory et al., 2019). The IB effect is removed using monthly mean sea level pressure from ERA5 (Hersbach et al., 2019), which also provides surface wind stress used in this study. Please note that the sea level from tide gauges, after IB effect removed, is dynamic sea level plus a constant offset due to the difference between the true geoid and the datum associated with the tide gauge.

Results in this study are based on monthly mean data. The annual cycle is removed from both sea level and GS transport by subtracting climatological monthly means from the time series. Linear trends are removed from tide gauges, gridded sea level, and GS transport unless otherwise noted. This also removes influences from vertical land movement and glacial isostatic adjustment as these changes are essentially linear on the timescale of this study. Keeping the linear trend or removing global mean sea level does not substantially affect the results. Statistical significance of correlations is estimated using the random-phase method described in Ebisuzaki (1997), in which data are resampled 20,000 times. The 95% confidence interval is adopted to decide whether a correlation is significant.

3. Result and Discussion

3.1. Streamwise Correlations of GS Transport

Figure 2 shows correlations between monthly FCT and the altimetry tracks. The transports are significantly correlated with each other upstream of Cape Hatteras; however, the correlation coefficients are less than 0.5, so less

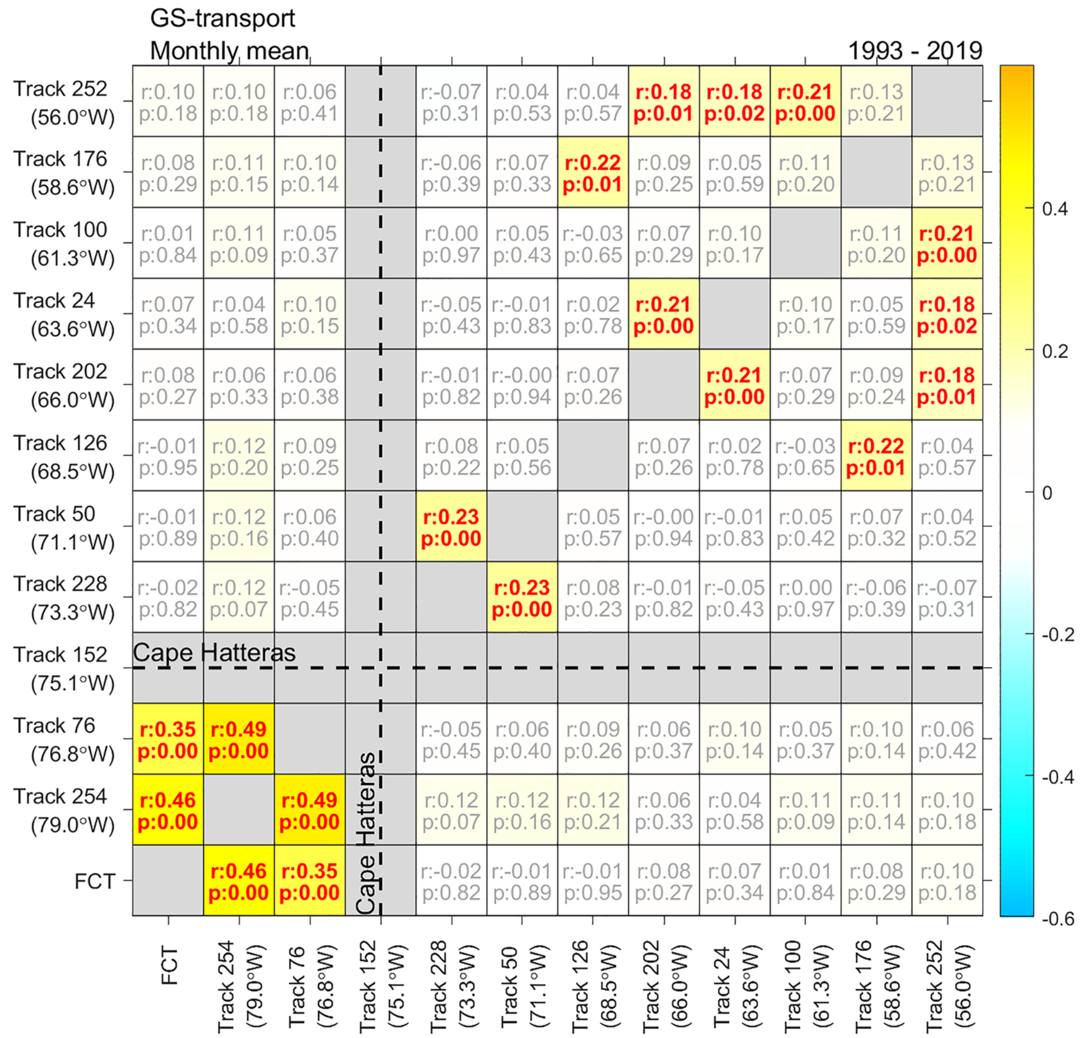

Figure 2. Correlation coefficients (represented by "*r*") and *p* values (represented by "*p*") between monthly mean Gulf Stream (GS) transport at locations. The correlations significant at the 95% level are noted by bold red numbers. Florida Current Transport (FCT) represents the GS transport at the Florida Straits.

than 25% of the GS transport variance at a given track can be explained by the transport at a neighboring track. Downstream of Cape Hatteras, transport at a given track is typically not significantly correlated with the transport at neighboring tracks. These results show that the surface transport varies independently at different locations along the GS path and the monthly mean transport at one transect is not representative of the monthly mean transport at other transects. In particular, the GS transport upstream of Cape Hatteras is not representative of GS transport downstream of Cape Hatteras, where the GS is closest to the MAB and Gulf of Maine (GoM). Similar results can also be found from seasonal and annual FCT (Figures S3 and S4 in Supporting Information S1), indicating that the lack of downstream correlation in Figure 2 is unlikely due to small-scale/fast phenomena such as eddies or rings. Further, retaining or removing the seasonal cycle and/or long-term trend has little effect on the results. This is consistent with Chaudhuri et al. (2011) and Sanchez-Franks et al. (2014), who suggest different behaviors of GS transport upstream and downstream of Cape Hatteras. The disjointed structure of GS is seen also in Figure 3d of Dong et al. (2019). In most of the years sea surface height (SSH) anomaly changes sign within a few degrees of longitude. Even in 2003, when the SSH anomaly is mostly positive, it is not constant with distance and becomes nearly zero at 70°W and 55°W.

GS transport increases dramatically from ~32 Sv at Florida Straits (Meinen et al., 2010) to 85–102 Sv at the Oleander transect (Heiderich & Todd, 2020; Sanchez-Franks et al., 2014) due to recirculation gyres. The variability of these gyres likely has as large or larger impacts on GS transport variability downstream of Cape Hatteras

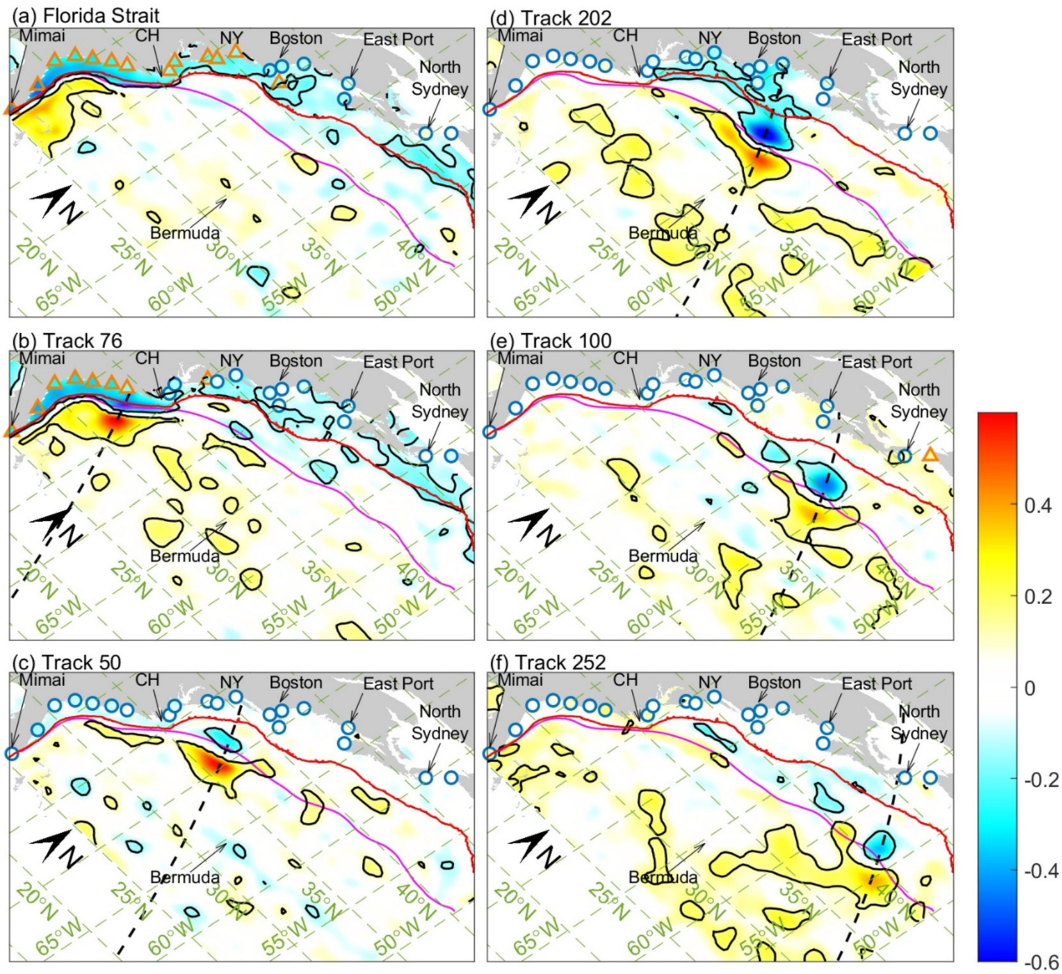

Figure 3. Correlation between monthly averaged absolute dynamic topography and (a) Gulf Stream (GS) transport at Florida Straits, (b–f) surface-layer GS transport at altimetry tracks. The correlations significant at the 95% level are bounded by black contours. Locations of tide gauges are marked by circles and correlations between sea level from tide gauges and the GS transport are indicated by the color inside those circles. Orange (blue) triangles (circles) indicate statistically significant (insignificant) correlations. The violet line indicates the mean GS path, the dashed black line indicates the altimetry track, and the red solid line indicates 200-m isobath. CH, Cape Hatteras; NY, New York City.

than variations in upstream transport. Thus, it is incorrect to attribute a specific fluctuation in transport at a particular location to the GS as a whole. As noted by Stommel (1958), "the Gulf Stream is not a river of hot water flowing through the ocean" (emphasis added). It is a highly turbulent boundary current buffeted by continuously varying topography and instabilities such that its flow decorrelates rapidly as it moves downstream.

3.2. GS Transport Upstream of Cape Hatteras and Coastal Sea Level

Records from both tide gauges and altimetry show that FCT is correlated with sea level along the U.S. East Coast from Florida to Massachusetts (Figure 3a). The significant negative correlations are limited to the west of the GS upstream of Cape Hatteras and on the shelf (marked by the 200-m isobath) in the MAB. Similar correlations can also be found between GS transport at track 254 & 76 and tide gauges, except that the correlations are only significant at one or two of the tide gauges in the MAB.

The significant correlation between GS transport south of Cape Hatteras and sea level in the South Atlantic Bight (SAB) is expected considering geostrophic balance and the proximity of the GS to the coast. Indeed, altimetry records show that, on average, high GS transport south of Cape Hatteras is accompanied by low sea level extending approximately from the GS axis to the U.S. East Coast (Figures 4a and 4b). However, this correlation does not

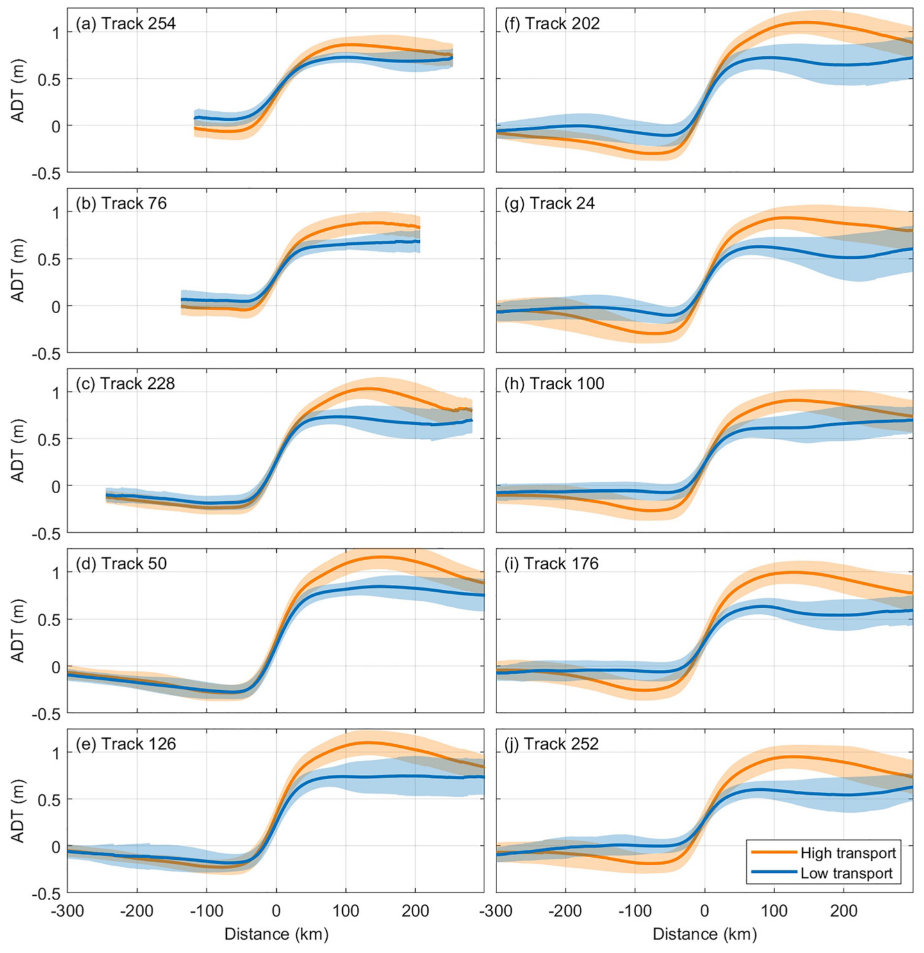

Figure 4. The solid orange (blue) lines show composites of absolute dynamic topography (ADT) when Gulf Stream (GS) transport is greater (less) than one standard deviation above (below) its mean value at the corresponding track. The shading gives the standard deviation of the corresponding composite. The ADT is averaged in stream-following coordinates in which the GS axis is always located at 0 km. Positive (negative) distances indicate locations southeast (northwest) of the GS.

necessarily mean that it is the GS that drives changes to coastal sea level in the SAB. Other effects, like westward propagating signals from the ocean interior (R. Domingues et al., 2016; R. M. Domingues et al., 2019) and large scale atmospheric circulations (Hameed et al., 2021) can also drive FCT by modulating coastal sea level. R. Domingues et al. (2018) reported that the accelerated SLR in the SAB during 2010–2015 are caused by warming in the Florida Current.

The significant correlations between FCT and coastal sea level in the MAB initially appear to be consistent with previous studies arguing that the SLR in the MAB is partly due to a decrease in GS transport (Ezer et al., 2013). However, a significant correlation does not necessarily indicate a causal relationship. For example, Piecuch et al. (2019) showed that the significant correlation between AMOC transport at 26.5°N and New England coastal sea level was due to their mutual correlation with large-scale winds. To determine whether a similar effect explains the correlation between FCT and sea level south of New England, we follow Piecuch et al. (2019) and decompose sea level into a local wind-driven component, h_{wind}, and a residual component by linear regression (detailed in Text S2 in Supporting Information S1). The correlation between h_{wind} and local wind stress are shown in Figures S5 and S6 in Supporting Information S1. The regression coefficients at tide gauges (Figure S7 in Supporting Information S1) is consistent to Piecuch et al. (2019), shown in their Figure S6 in Supporting Information S1, suggesting that the regression coefficients can be primarily explained by the same barotropic model with alongshore wind balanced by bottom friction and geostrophic balance between offshore sea level gradient and alongshore current (Sandstrom, 1980). However, other local and remote forcings, like buoyancy forcings, may also be included in the linear regression.

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We find that after removing local wind effects on coastal sea level, correlations between FCT (and GS transport at the other altimetry tracks upstream of Cape Hatteras) and residual sea level in the MAB become insignificant (Figures S9 and S10 in Supporting Information S1). Thus, the significant correlations between FCT and sea level in the MAB shown in Figure 3a do not necessarily indicate that FCT drives sea level in the MAB by geostrophy, or any other direct links between them. Instead, the significant correlations may result from their concurrent response to the wind, or it is the coastal sea level in the MAB drives FCT. Wind stress anomalies in the MAB can create sea level anomalies, which could propagate to the Florida Straits via coastal trapped waves and affect the transport there. Similar mechanisms have been discussed in Czeschel et al. (2012) and Hameed et al. (2021).

This is consistent to previous studies. R. Domingues et al. (2018) reported a sea level decline north of Cape Hatteras during 2010–2015, suggesting it is mostly due to combined effects of increasing atmospheric pressure and changes in alongshore wind. R. Domingues et al. (2016) and Zhao and Johns (2014) also found negative correlations between FCT and coastal sea level in the SAB. Focusing on different frequency bands, however, they present opposite correlations between FCT and sea level in the MAB, indicating that the relation between FCT and sea level in the MAB is more complex than a geostrophic link.

3.3. GS Transport Downstream of Cape Hatteras and Coastal Sea Level

North of Cape Hatteras, the significant correlations between GS transport and altimetric sea level are limited to the deep ocean and rarely appear on the shelf (Figure 3 and Figure S8 in Supporting Information S1). The only exception is track 202, where GS transport remains correlated with sea level along the slope off the MAB (Figure 3d). This may be due to the distinct location of the track between the Northwest Recirculation Gyre (Andres et al., 2020; New et al., 2021) and the Northern Recirculation Gyre (Hogg, 1992; Hogg et al., 1986) (Figure 1). These recirculation gyres allow signals from GS transport at Track 202 to reach the slope more easily than at other locations. GS transport at track 202 is also correlated with sea level near Cape Cod (Figure 3d). However, the small and insignificant correlations between the GS transport and sea level at the three tide gauges near Cape Cod suggest that altimetry might not be a reliable indicator of coastal sea level at this location.

These results are expected since a large fraction of GS transport downstream of Cape Hatteras is due to recirculation gyres instead of basin scale circulations. It is the sea level at centers of the recirculation gyres, which are also the boundaries of GS, that has the largest effect on GS transport. Sea level variations at centers of the recirculation gyres are not necessarily related to sea level variations at their boundaries, or at the coastline. Composites of sea level profiles across the GS (Figure 4) show that the sea level change north of the GS associated with changes in GS transport decays away from the GS and becomes negligible approximately 300 km north of the GS axis at all tracks downstream of Cape Hatteras. The above result is also consistent with the correlation map shown in Figure S11 in Supporting Information S1. Significant positive correlations between tide gauges north of Cape Hatteras and altimetry sea level are restricted to the shelf.

4. Summary

The GS transport during 1993–2019 from an underwater cable at Florida Straits and satellite altimeters at 10 descending tracks from Florida to Canada coast are investigated in this study. Only 9 out of 55 correlations between monthly GS transport at different locations are significant (Figure 2). Correlations, even where significant, are less than 0.5 (less than 0.25 downstream of Cape Hatteras), implying that more than 75% of the variations in GS transport, even between neighboring locations, are independent of each other. Hence, it is misleading to suggest that transport variations at any particular transect represent the GS as a whole. This results also holds for seasonal and annual mean transport and regardless of whether the seasonal cycle and/or long-term trend has been removed. Importantly, increasing the averaging time scale increases the *values* of the downstream correlations but does not increase their *significance* (i.e., the p-values do not decrease). While it seems likely that the GS transport will exhibit downstream correlation on sufficiently long time scales, the current altimetric record to too short to establish this time scale. Continued monitoring of GS transport at multiple locations is required to better understand how the GS transport evolves downstream of Florida Straits.

The influence of GS transport on sea level is restricted to the deep ocean north of Cape Hatteras and coastal sea level in this region is rarely correlated with GS transport. It is therefore unlikely that coastal sea level variations are driven by geostrophic adjustment to changes in GS transport. Even though significant correlations can be found between FCT and sea level in the MAB, such correlations become insignificant when local wind effects are removed. This suggests that coastal sea level does not respond to changes in GS transport in and of itself, since changes in transport uncorrelated with the wind do not affect coastal sea level. While we do not definitely identify the mechanism connecting sea level, transport variations, and the wind, it seems more likely that the wind is driving both changes in coastal sea level and transport than the GS affecting coastal sea level directly. Removing the global mean sea level instead of linear trends shows similar results (Figures S12–S16 in Supporting Information S1).

While studies have suggested that a decrease in the AMOC would result in a decrease in GS transport, which would result in SLR in the MAB and further north (Ezer, 2001, 2013, 2015; Ezer et al., 2013; Goddard et al., 2015; Yin et al., 2009; Yin & Goddard, 2013), the observed AMOC decreases are associated with a reduction in GS transport that is too small to have a direct influence on coastal sea level (Smeed et al., 2014, 2018). Even during the major AMOC slowdown of 2009–2010 discussed by Goddard et al. (2015) and Yin and Goddard (2013), the decrease in Florida Current was only 0.8 Sv years—not very different from its interannual fluctuations (Bryden et al., 2014).

By analyzing 20-year ADCP measurements at the Oleander transect, Rossby et al. (2014) found that there is no long-term trend in the GS transport at that location. This result has been validated for the length of the GS in two follow-up investigations (Chi et al., 2021; Dong et al., 2019), both of which show stable GS transport west of 70°W. Thus, it is not likely that changes in GS transport contribute to the SLR at U.S. East Coast.

Even though significant correlations between coastal sea level and the GS transport are rarely found north of Cape Hatteras, the GS may still affect the coastal sea level indirectly. Changes in heat transported by the GS may drive steric sea level changes in the northwest Atlantic (R. Domingues et al., 2018; Volkov et al., 2019). The GS may also affect coastal sea level indirectly via its interaction with the Labrador Current near Grand Banks, since Frederikse et al. (2017) and Gonçalves Neto et al. (2021) suggest that the Labrador Current might play a role in sea level variations on the shelf. Wise et al. (2020) also indicated that sea level variability north of Cape Hatteras is driven by the subpolar gyre. Limited by the available data, only the geostrophic component of GS transport is discussed in this study. Little et al. (2019) suggested that the ageostrophic component might be important and worth further investigation. Additional work is needed to better understand the relationship between GS transport and coastal sea level at different locations and their interaction with large-scale ocean/atmosphere circulations.

Data Availability Statement

The tide gauge records were extracted from the revised local reference data of the Permanent Service for Mean Sea Level (PSMSL, https://www.psmsl.org/data/obtaining/complete.php). The along-track absolute dynamic topography was extracted from Global Ocean Along-track L3 Sea Surface Heights Reprocessed 1993 Ongoing Tailored for Data Assimilation (https://doi.org/10.48670/moi-00146), and the gridded absolute dynamic topography was extracted from Global Ocean Gridded L4 Sea Surface Heights and Derived Variables Reprocessed 1993 Ongoing (https://doi.org/10.48670/moi-00148). The Florida Current transport from cable measurements is available from the Atlantic oceanographic and Meteorological Laboratory (https://www.aoml.noaa.gov/phod/floridacurrent/data_access.php). The sea level pressure and surface wind stress were extracted from ERA5 Monthly Averaged Data on Single Levels from 1979 to Present via Copernicus Climate Change Service Climate Data Store (https://doi.org/10.24381/cds.f17050d7).

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