**Reconsidering the relationship between Gulf Stream transport and dynamic sea level at U.S. East Coast**

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Key Points:

- Gulf Stream transport variability decorrelates rapidly with distance downstream of Cape Hatteras.
- Gulf Stream transport downstream of Cape Hatteras is not correlated with sea level on the U.S. East Coast.
- Correlations between the Gulf Stream transport and sea level at Middle Atlantic Bight are results of their concurrent responses to wind.

**Abstract**

The relationship between Gulf Stream (GS) transport and coastal sea level is investigated using monthly GS transport between 1993−2019 at Florida Straits and ten 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 both the South Atlantic Bight (SAB) and Middle Atlantic Bight (MAB). However, the significant correlations in MAB are due to their concurrent response wind on the shelf—the correlation becomes insignificant once the influence of local winds is removed. North of Cape Hatteras, the influence of GS transport on sea level is mostly over the deep ocean and rarely on the shelf, indicating that there is no dynamic link between the GS transport and coastal sea level in this region.

**Plain-Language Summary**

Sea level on the U.S. East Coast north of Cape Hatteras rose rapidly in recent decades. Some previous studies attributed this sea-level rise to a decline in the Gulf Stream (GS) transport next to it. In this study, we investigate the relation between them from in-situ and remote 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 previously reported relationship between the GS transport and coastal sea level is due to their concurrent responses to winds. 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.

# Introduction

Sea level rise on the U.S. East Coast, especially in the Middle Atlantic Bight (MAB), has accelerated over the last few decades and at a rate higher than the global ocean (Boon, 2012; Davis and Vinogradova, 2017; Ezer et al., 2013; Kopp, 2013; Park and Sweet, 2015; Sallenger et al., 2012). Records from tide gauges also show large interannual fluctuations in coastal sea level and the rate of sea level rise (Andres et al., 2013; Ezer, 2013; Goddard et al., 2015). The sea level rise has caused an increase in the number of minor tidal flooding days on the East Coast (Ezer and Atkinson, 2014) and may lead to more frequent extreme high-water events in the future (Tebaldi et al., 2012). It is already a real threat to communities near the coast and has attracted much concern.

Some studies have reported that the Gulf Stream (GS) has weakened in the past two decades (Caesar et al., 2018; Ezer, 2015; Ezer et al., 2013; Smeed et al., 2018), and that changes in GS transport have contributed to both the long-term trend and the interannual fluctuations in sea level along the U.S. East Coast. A weakened GS should be accompanied by a reduction in cross-stream sea level drop due to geostrophy—it has been suggested that this mechanism drives coastal sea rise to the west of the GS (Ezer, 2015; Ezer et al., 2013; Goddard et al., 2015; Yin and Goddard, 2013). This mechanism has also been adopted to explain how a decline in the Atlantic meridional overturning circulation (AMOC) may have contributed to sea level rise on the U.S. East Coast based on the assumption that fluctuations in AMOC transport drive downstream fluctuations in GS transport (Ezer, 2015; Ezer et al., 2013; Ezer and Atkinson, 2014; Goddard et al., 2015; Hu and Bates, 2018; Yin et al., 2010, 2009).

However, Rossby et al. (2014) and Chi et al. (2021) found no significant trend in GS transport from in-situ measurements and altimetry records, respectively, and 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 altimetry records and also found no link with coastal sea level. 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). 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.

In this study, we revisit direct links between GS transport and dynamic sea level at U.S. East Coast. We first derived the GS transport at Florida Straits and 10 satellite altimeter tracks from the Florida Straits to the south of Newfoundland Island. It is found that GS transport does not vary consistently along its path. Then, the relationship between coastal sea level and GS transport at different locations is investigated. We find no significant relationship between GS transport and coastal sea level north of Cape Hatteras once their simultaneous response to wind forcing is accounted for.

## Data and Methods

The GS transport through Florida Straits, also known as the Florida Current transport (FCT), has been measured by underwater cables for decades (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).

The 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). 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. The GS transport from altimetry is given in units of Sv km$^{-1}$ (= $10^3$ $m^2 s^{-1}$) and is proportional to the sea level difference between the two zero velocity points. A decrease of 1 Sv km$^{-1}$ in GS transport corresponds to a decrease 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 ADCP measurements at the Oleander transect (Chi et al., 2021).

Monthly mean coastal sea level from tide gauges are extracted from the Permanent Service for Mean Sea Level (PSMSL) (Holgate et al., 2013; PSMSL, 2019). Details of the tide gauges are listed in Table 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.

Results in this study are based on monthly mean data. The annual cycle is removed from both sea level and GS transport by subtracting climate monthly means from the time series. Any trends in sea level and GS transport were not removed in the calculations presented in this paper. We repeated the calculations after removing linear trends, and the results were substantially the same. Statistical significance of correlations is estimated by 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.

# Result and discussion

3.1 Streamwise correlations of GS transport

Figure 2 shows correlations between monthly GS transport at different locations. GS transports at different locations are significantly correlated upstream of Cape Hatteras; however, the correlation coefficients are less than 0.5, so less 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, most correlations of GS transport between neighboring tracks are insignificant. These results show that GS transport varies independently at different locations along its 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). This is consistent with the result reported by Sanchez-Franks et al. (2014) that GS transport at Florida Straits and the Oleander transect are not correlated with each other.

With more water joining the GS from recirculation gyres north and south to it, the magnitude of its transport increases dramatically from ~32 Sv at Florida Straits (Meinen et al., 2010) to 85–102 Sv at the Oleander transect (Sanchez-Franks et al., 2014). Thus, recirculation gyre variability likely has a larger impact on GS transport variability downstream of Cape Hatteras 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 GS is not a river of hot water flowing through the ocean.” 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 Coastal sea level and GS transport at Florida Straits

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 west of the GS upstream of Cape Hatteras and on the shelf (marked by 1000-meter isobath) in the MAB. This result appears to be consistent with previous studies arguing that the sea level rise 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. To further investigate whether the coastal sea level in the MAB and FCT are linked by ocean dynamics or atmospheric circulation, we follow Piecuch et al. (2019) and decompose sea level into a local wind-driven component and a residual component, $h_{\mathrm{res}}$. First, the wind direction explaining the largest fraction of local sea level variance is determined by linearly regressing the local wind stress vector against the sea level; then, sea level is regressed against wind stress in that direction. Figure S1 shows that the sea level at all the tide gauges is significantly correlated with the local wind stress. The direction of greatest correlation is approximately alongshore at most tide gauges from South Atlantic Bight (SAB) to GoM (Figure S1). Sandstrom (1980) suggested that the Coriolis term in alongshore current forced by alongshore wind (and bottom friction) should be balanced by a transverse sea level drop, thus the coastal sea level at the East Coast should be positively correlated with the southwestward alongshore wind. Piecuch et al. (2019) also found that alongshore wind drives local sea level variability on the New England Coast from New York to the GoM, while the influence from cross-shore wind is negligible.

We find that after removing effects of local wind, FCT is significantly correlated with residual sea level at tide gauges only in the SAB (Figure 4a). Thus, the significant correlations between FCT and sea level in the MAB result from their concurrent response to wind. The significant correlation from altimetry next to the coastline around New York City may not be reliable since none of the three tide gauges in the same region show significant correlations.

3.3 Coastal sea level and GS transport derived from along-track ADT

According to geostrophic balance, GS surface transport is proportional to the sea level drop across it; however, significant correlations between transport and sea level do not necessarily extend to the coast. Upstream of Cape Hatteras, the relationship between coastal sea level and GS transport is similar to its relationship with FCT. GS transport at tracks 254 & 76 is negatively correlated with coastal sea level in the SAB and part of the MAB (Figure 3b & Figure S2a).[1] The correlations with tide gauges in the MAB become insignificant once the local wind effects are removed (Figure 4b & Figure S3a).

North of Cape Hatteras, the significant correlations between GS transport and sea level are limited to the deep ocean and rarely appear on the shelf (Figure 3 & Figure S2). The only exception is track 202, where GS transport is correlated with sea level along the slope off MAB after local wind effects are removed (Figure 4d). This may be due to its distinct location—track 202 is located between the Northwest Recirculation Gyre (NWRG, 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. This effect can be seen in Figure S4, which shows that sea level changes associated with GS transport extend further north at track 202 than other tracks. GS transport at track 202 is also correlated with sea level near Cape Cod (Figure 4d). However, the small and insignificant correlations between the GS transport and sea level at the three tide gauges near Cape Cod suggest that its influence on coastal sea level is negligible.

With local wind effects removed, GS transport downstream of Cape Hatteras

[1] Only results for FCT and GS transport at every other track from altimetry are presented in Figure 3 to keep each panel large enough to be read easily. Results from the remaining tracks are given in the Supporting Information.

is not systemically correlated with sea level at the tide gauges. At the 95% confidence level adopted here, one in twenty correlations are expected to be significant by random chance. With 20 tide gauges shown in Figure 4 and Figure S3, we can expect one significant correlation for each track even if no true correlations exist. We therefore conclude that GS transport downstream of Cape Hatteras is not a major driver for coastal sea level north of it.

The above conclusion is reasonable since a large part of the GS transport downstream of Cape Hatteras is from recirculation gyres instead of basin scale circulations described in classic theories. It is the sea level at centers of the recirculation gyres, which is also the edge of GS, that matters for GS transport. Sea level variations at centers of the recirculation gyres are not necessarily related to sea level variations at their edges, or at the coastline. Composites of sea level profiles across the GS (Figure S4) show that the sea level rise (decrease) north of the GS associated with decreased (increased) 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 S5. The significant positive correlations between mean sea level from tide gauges at MAB (GoM) and gridded sea level from altimetry are restricted to the shelf.

Overall, the GS transport only affects coastal sea level south of Cape Hatteras. North of Cape Hatteras, its influence on sea level is mostly over the deep ocean and does not reach the coastline.

## Summary

The Gulf Stream (GS) transport during 1993−2019 from underwater cables at Florida Straits and satellite altimeters at 10 descending tracks from Florida to Canada coast are investigated in this study. Only a few statistically significant correlations between GS transport at different locations are found. Correlations, even where significant, are less than 0.5, implying that more than 75 percent of variations of 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.

The relationship between GS transport along its path and sea level at the U.S. East Coast during 1993−2019 was examined. South of Cape Hatteras, coastal sea level is significantly anti-correlated with adjacent GS transport, indicating that a decrease in GS transport can lead to sea-level rise to its west via geostrophy. This mechanism has been adopted in some previous studies (Ezer, 2013; Ezer et al., 2013; Yin et al., 2009) to suggest that a decrease in GS transport will affect sea levels along the U.S. East Coast. However, north of Cape Hatteras—which is a “hotspot” of sea level rise in recent decades—the GS’s transport influence on sea level is restricted to the deep ocean. The coastal sea level in this region is rarely correlated with GS transport, which indicates that the above mechanism is not generally applicable. Even though significant correlation can be found between the GS transport near Florida Straits and sea level in Middle Atlantic Bight (MAB), such correlations become insignificantly small when local wind effects are removed, indicating the significant correlations are due to their concurrent responses to wind rather than a direct dynamic link.

Some previous studies suggested that a decrease in GS transport, accompanied by a weakened AMOC, contributed to the rapid sea level rise in MAB and further north (Ezer, 2015, 2013, 2001; Ezer et al., 2013; Goddard et al., 2015; Yin et al., 2009; Yin and Goddard, 2013). However, the lack of direct link between the GS transport and coastal sea level north of Cape Hatteras presented in this study indicates that this is unlikely to be true. 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. This is also confirmed by 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 sea level rise at U.S. East Coast. The horizontal resolution of most numerical models in previous studies is 1° or coarser. Chi et al. (2018) showed that such coarse resolution models cannot reproduce the GS structure and recirculation gyres north of the GS correctly. Also, the shelf off the U.S. East Coast is about 100~200 km in width, which is only 1~2 grid points in the models. Thus, the models are not expected to simulate the processes on the shelf accurately.

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. 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.

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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 are extracted from *ERA5 Monthly Averaged Data on Single Levels from 1979 to Present* via Copernicus Climate Change Service Climate Data Store (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means?tab=overview).

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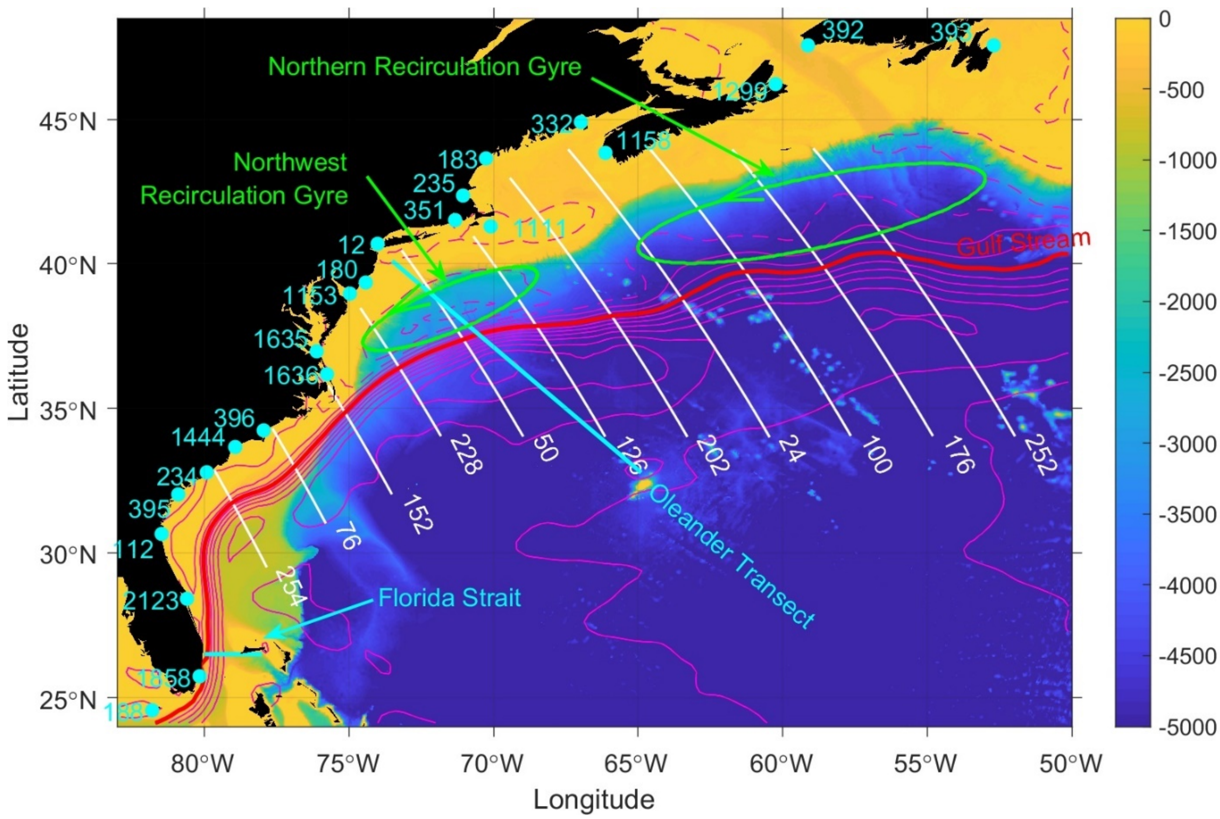


Figure 1: (Background shading) Topography of the northwest Atlantic. The solid (dashed) purple lines are contours for positive (negative) absolute dynamic topography (ADT) with a 10-cm interval during 1993-2019. The mean GS path is marked by the thick red line. Satellite tracks are marked by white lines and tide gauges used in this study are marked by cyan dots. The Track 152 is not used in this study since the northern edge of the GS is too close to the coastline.

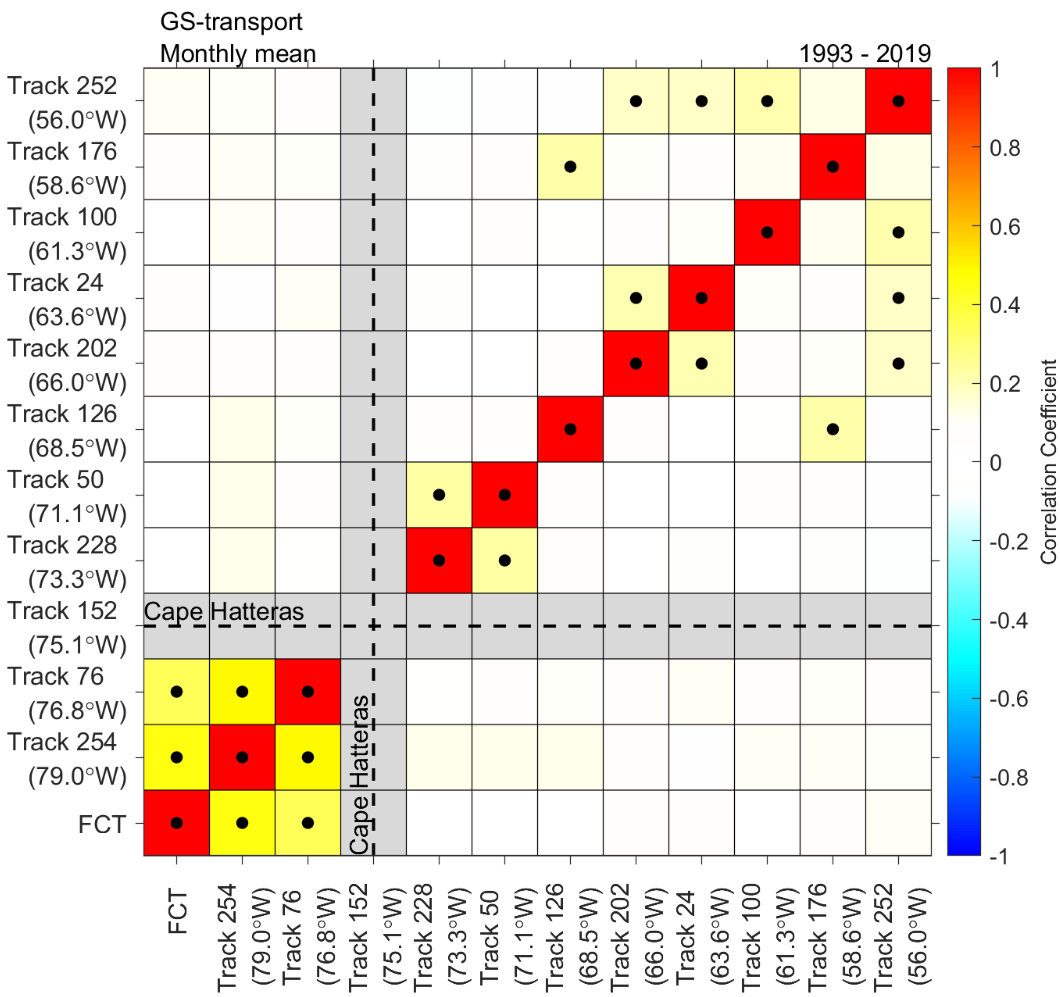


Figure 2: Correlation coefficients between monthly mean GS transport at locations. The correlations significant at 95% level are marked by black dots. Florida Current Transport (FCT) represents the GS transport at the Florida Straits.

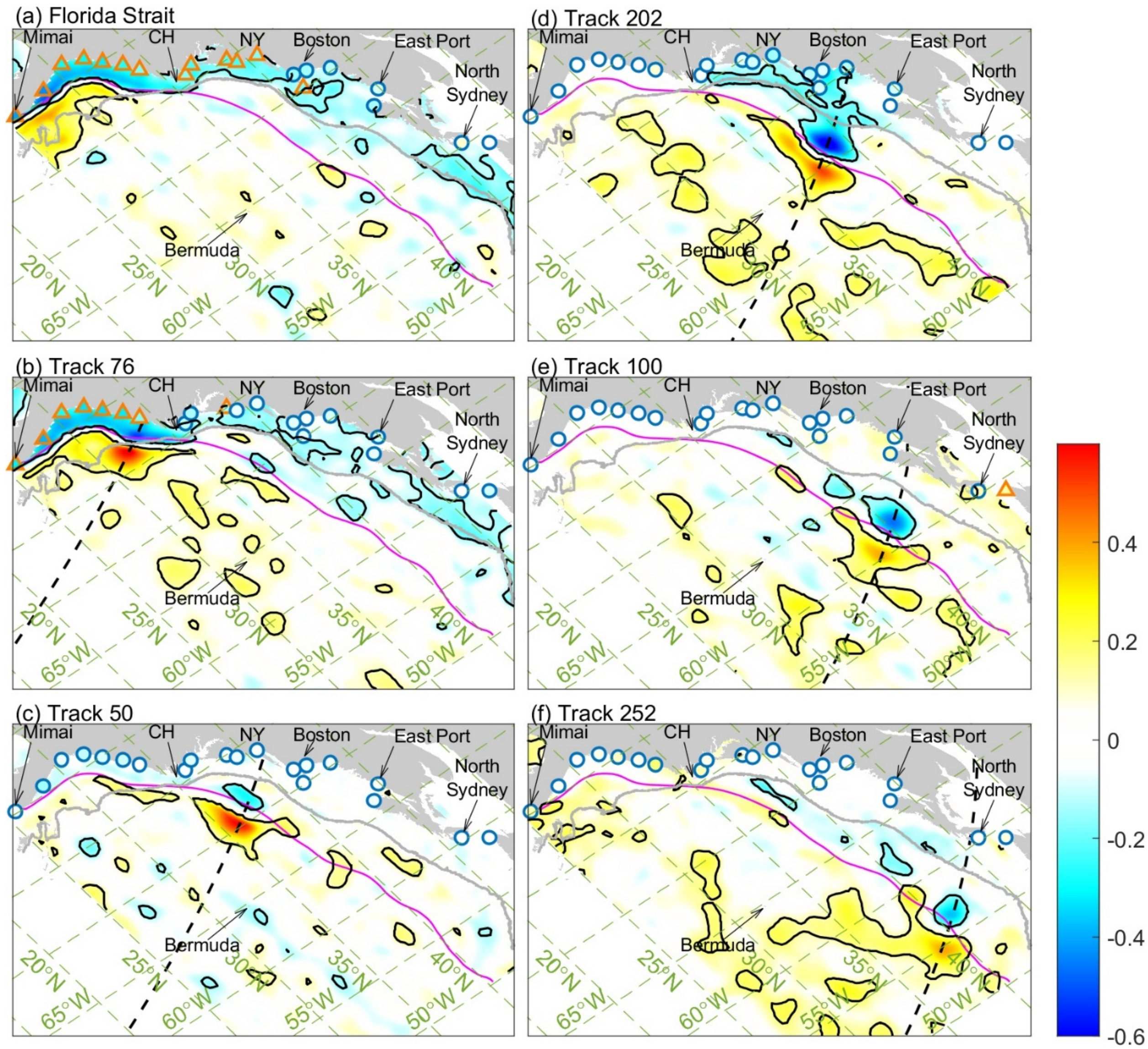


Figure 3: Correlation between monthly averaged ADT and (a) GS transport at Florida Straits, (b-f) surface-layer Gulf Stream transport at altimetry tracks. The correlations significant at the 95% confidence level are bounded by black contours. Locations of tide gauges are marked by circles and correlations between sea level from tide gauges and the Gulf Stream 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. The grey solid line indicates 1000-meter isobath, which is approximately the edge of the

shelf. The plots have been rotated to show the entire U.S. East Coast. Some major landmarks are noted, among which CH indicates Cape Hatteras and NY indicates New York City.

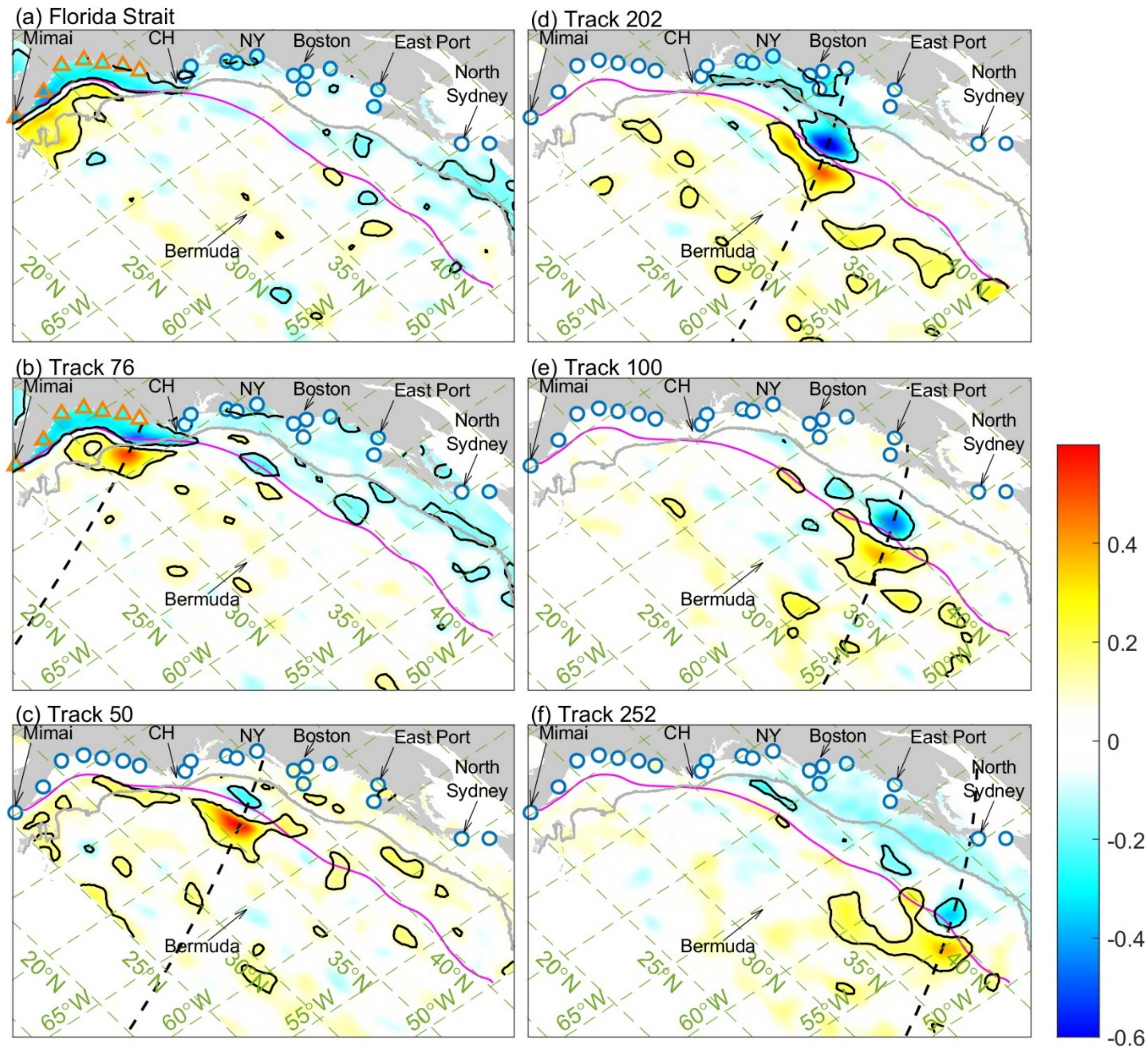


Figure 4: Same as Figure 3 but for residual sea level with local wind effects removed.