Comments on "Reconsidering the Relationship Between Gulf Stream Transport and Dynamic Sea Level at U.S. East Coast" by Chi et al.

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Abstract

Numerous recent studies found significant correlations between weakening of the Gulf Stream (GS) and rising coastal sea level (CSL) along the U.S. East Coast. Based on monthly altimeter data and Florida Current transport, Chi et al. (2023; here, CH23) argued that geostrophic adjustment of the GS is unlikely to drive variations in CSL in the Mid-Atlantic Bight (MAB). It is argued here that this conclusion cannot be universally applicable to all cases, since the monthly data disregard correlations previously found for short time scales based on hourly and daily data; the impact of GS variability on time scales of decades and longer as well as potential time lags between the GS and CSL variability were also not considered by CH23. Examples are given here to demonstrate the important role of the GS in post hurricane coastal flooding.

Comments on "Reconsidering the Relationship Between Gulf Stream Transport and Dynamic Sea Level at U.S. East Coast" by Chi et al.

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Key Points

- Correlations between the Gulf Stream flow and coastal sea level along the U.S. East Coast occur over a wide range of time scales.
- Geostrophic adjustment of the Gulf Stream could not be ruled out as one of the drivers of coastal sea level variability, but this driver may be overlooked in monthly altimeter data.
- The Gulf Stream plays an important role in temporal rise of coastal sea level and unpredictable flooding post hurricanes.

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Numerous recent studies found significant correlations between weakening of the Gulf Stream (GS) and rising coastal sea level (CSL) along the U.S. East Coast. Based on monthly altimeter data and Florida Current transport, Chi et al. (2023; here, CH23) argued that geostrophic adjustment of the GS is unlikely to drive variations in CSL in the Mid-Atlantic Bight (MAB). It is argued here that this conclusion cannot be universally applicable to all cases, since the monthly data disregard correlations previously found for short time scales based on hourly and daily data; the impact of GS variability on time scales of decades and longer as well as potential time lags between the GS and CSL variability were also not considered by CH23. Examples are given here to demonstrate the important role of the GS in post hurricane coastal flooding.

Plain Language Summary

Analysis of monthly altimeter data by Chi et al. (2023) interpreted to show that variations in the Gulf Stream (GS) transport can drive sea level variability only south but not north of Cape Hatteras. In contrast, it is shown here that the Gulf Stream plays an important role in short-term sea level variability, for example, causing an increase in flooding when the GS suddenly weakens following a nearby hurricane. It also should be noted that impact of decadal and longer GS variability could not be inferred from the relatively short altimeter data.

1 Introduction

Numerous studies addressed predicted climate-related weakening in the Atlantic Meridional Overturning Circulation, AMOC, and its potential consequences (Bryden et al., 2005; Ezer 2015; Rahmstorf et al., 2015; Caesar et al. 2018; Smeed et al., 2018; Ezer and Dangendorf, 2020; Pietrafesa et al., 2022). However, direct observations of AMOC are relatively short (<20 years) so studies often used reconstructions, proxies or numerical models to study long-term AMOC trends of the past or future AMOC under climate change scenarios. Since the Gulf Stream (GS) is part of AMOC and provides the main northward transport of mass and heat in the Atlantic Ocean, long-term weakening of the GS would cause significant disruption to weather systems and ocean circulation patterns, and potentially affect coastal sea level (CSL). However, because the GS system is dominated by mesoscale variability, meanders, eddies, and gyres, detecting long-term trends in the GS transport is still quite elusive, and different trends are often found at different locations along the GS path (Andres et al., 2020; Zhang et al., 2020). Sea level rise and increased flooding along the U.S., East Coast of the U.S. is of great concern (Ezer and Atkinson, 2014; Sweet and Park, 2014; Wdowinski et al., 2016), so it is important to assess contribution to CSL from various processes such as AMOC, GS, wind pattern, Rossby Waves, etc. (Sallenger et al., 2012; Ezer and Corlett, 2012; Ezer et al., 2013; Goddard et al., 2015; Ezer, 2015; Ezer and Atkinson, 2014, 2017; Little et al., 2019; Ezer, 2019, 2020a, 2020b; Dangendorf et al., 2021, 2023). These studies indicate relation between different open ocean dynamic processes and the coast, and in particular, many studies found significant GS-CSL correlations on a wide range of time scales from daily to seasonal and decadal. One aspect of the GS-CSL connection is attributed to the geostrophic balance which implies that the sea level slope across the GS is proportional to the flow strength, so weakening GS could reduce the slope and raise CSL along the U.S. East Coast. Therefore, even though detecting long-term trends in the GS flow is challenging with existing data, relation between the GS and CSL on shorter time scales can help us understand the mechanisms involved.

To this end, Chi et al. (2023) (hereafter CH23) analyzed 27 years of monthly Gulf Stream (GS) transport at the Florida Straits and 10 satellite altimeter tracks across the GS and came up with two main conclusions. It is thus important to put their findings in the right perspective with respect to past studies:

1. "…*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*.". This conclusion is consistent with the fact that the GS system includes meanders and gyres, so observations show large differences in sections taken not far apart along the GS path (Andres et al., 2020). However, this result does not contradict any of the studies that found significant GS-CSL correlation, because those studies never used a correlation along altimeter track, as done here, but instead used averaged GS strength over large area from many altimeter tracks that filter out the mesoscale variability (e.g., Ezer at al., 2013; Ezer, 2019; Ezer and Dangendorf, 2020).
2. "*GS transport south of Cape Hatteras is significantly correlated with coastal sea level … North of Cape Hatteras, sea level changes associated with GS transport decay rapidly away from GS on the onshore side … In this region … coastal sea level is unlikely to be driven by geostrophic adjustment to changes in GS transport*." The fact that CSL responds to forcing differently north and south of Cape Hatteras is not new (Valle-Levinson et al., 2017; Domingues et al., 2018; Ezer, 2019), and partly explained by the fact that the GS flows close

> to the coast in the South-Atlantic Bight (SAB) but is separated from the coast in the Mid-Atlantic Bight (MAB). However, there is no evidence in CH23 that geostrophic adjustment does not play a role in CSL variability in the MAB, especially for time scales that were not resolved by CH23 analysis. For example, Ezer (2019) showed that on decadal time scales CSL in the MAB and the SAB are out of phase and may respond to GS variability in opposite way, while on shorter time scales CSL in the MAB and SAB are correlated. In fact, analysis of *daily* variations in the Florida Current transport or *hourly* tide gauge data show highly coherent CSL variations along the entire US East Coast, as seen in observations and in models (Ezer, 2016; Ezer and Atkinson, 2017).

Examples of past studies below demonstrate why the findings of CH23 could not conclusively exclude GS-CSL relation based on geostrophic adjustment. In fact, CH23's statement that "*significant correlations between coastal sea level and the GS transport are rarely found north of Cape Hatteras*" is not accurate given dozens of published papers that did find statistically significant correlations (see many of these examples in: http://www.ccpo.odu.edu/~tezer/FCvsSL/).

2 On the Relation Between the Gulf Stream and Coastal Sea Level

Based on both, tide gauge and altimeter data, Fig. 3a in CH23 shows significant negative correlation between the Florida Current transport (Baringer and Larsen, 2001; Meinen et al., 2010) and CSL along the U.S. East Coast from Florida to Massachusetts. Despite the fact that this result is consistent with many past studies (Park and Sweet, 2015; Ezer, 2016, 2019, 2020a, 2020b; Ezer et al., 2013; Ezer and Atkinson, 2014, 2017; Wdowinski et al., 2018), CH23 tried to argue that mechanisms other than geostrophic adjustment, such as changing atmospheric conditions (Piecuch et al., 2016), may affect both the GS and CSL, so there is not necessarily a cause and effect relation between GS and CSL. It is true that several factors can contribute to CSL variability, but the impact of the GS cannot be dismissed. As a proof that there is a direct impact of the GS on CSL Ezer (2016) conducted controlled numerical simulations with fixed wind and time-dependent oscillations in the Florida Current transport, and the results show response of coherent CSL variations along the U.S. Coast, like those found in tide gauge observations. The simulations show that the response at the coast to wind-driven sea level is fundamentally different than the response to GS-driven sea level. Furthermore, numerical simulations of hurricanes (Ezer et al., 2017; Ezer, 2018; Ezer 2020a; Park et al., 2022) found that in the days after the hurricanes disappeared and wind was no more a factor, CSL remained higher than normal directly due to a weaker GS that has not recovered yet from the disruption caused by the storm. Fig. 1 shows an example of sea level and flooding in Norfolk (North of Cape Hatteras) during and after hurricane Florence passed the region (it did not make landfall in Virginia). In this case, CSL was first raised by wind-driven storm surge (10-Sep-2018), but the hurricane also disrupted the GS flow (transport dropped by ~10sv), which caused CSL to rise again by ~0.5 m and cause tidal flooding two weeks later (25-Sep-2018), driven by the weakening GS.

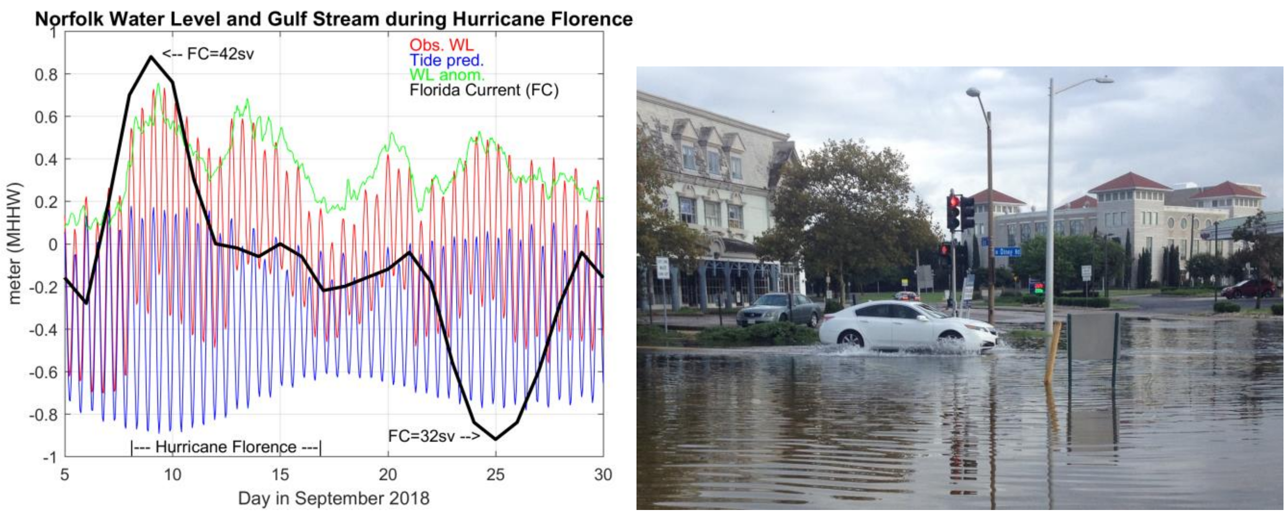

Figure 1. Left: Example of the relation between hourly water level (colored lines) in Norfolk, VA, in the Mid-Atlantic Bight (southern Chesapeake Bay) and daily observed Florida Current (FC) transport (black heavy line), during and after the passage of hurricane Florence in September 2018. Blue, red, and green lines are predicted tides, tide gauge observations and the subtidal anomaly, respectively. Water level (left axis in m) is relative to the Mean Higher High Water (MHHW) and FC transport of maximum and minimum (in Sv; $1Sv=10^6\ m^3\ s^{-1}$) are indicated. Right: Two weeks of "sunny-day" street flooding occurred in Norfolk due to weakening of the GS after the hurricane (picture taken by T. Ezer).

Like Fig. 1, remote GS influence on CSL in the MAB has been recorded after hurricanes Sandy (2012), Joaquin (2015), Mathew (2016) and Dorian (2019). Altimeter data before and after storms show reduction of sea level slope along the entire GS path, which coincides with raised CSL along the entire MAB coast (see Fig. 4 in Ezer, 2018); these observations suggest that geostrophic adjustment to changes in the GS transport may be an important driver of CSL in those cases (though such mechanism cannot be detected by a monthly data, hence the results of CH23). There is also evidence that seasonal variations in the GS transport contribute to the seasonal CSL cycle in the MAB whereas the highest monthly CSL of the year occurs when the seasonal GS has its maximum decline (see the high correlation between the two in Fig. 10c in Ezer, 2020b); since CH23 filtered out the seasonal signal, this contribution could not be captured by their analysis.

Finally, trying to relate simultaneous observations of monthly GS transport and CSL ignores potential lag difference between the two. On interannual to decadal time scales Ezer et al. (2013) found that CSL has higher correlation with *changes* in GS flow ($R=-0.85$, $p<0.001$) than with GS strength itself ($R=-0.58$, $p<0.001$), i.e., CSL rises when the GS flow is in a downward trend, not necessarily when the GS is at its minimum transport. Ezer et al., (2013) also show that a simple solution of the equations of motion points to a mechanism in which *time-changes* in sea level slope across the GS can produce onshore/offshore transports that impact CSL variability. On hourly to monthly time scales Ezer and Atkinson (2017) also found significant correlation between CSL and *changes* in GS transport. The time lag between variations in the GS and the CSL response is near zero in the SAB when the GS is near the coast, but it is larger for the MAB where the GS is far from the coast and the coastal response is less direct (Ezer and Atkinson, 2017). In the MAB, recirculation gyres, the Slope Current from the north and shifting in the GS position, all can affect CSL, so the relation between the GS and CSL is more complex and more difficult to detect, especially with monthly data that ignores the largest instantaneous changes in the GS. Spectral analysis of daily transport of the GS and water level in Norfolk shows statistically significant coherence with near opposite phase (~180°) for several different time scales from few days to months and years (see Fig. 3 in Ezer and Atkinson, 2017), demonstrating the complex nature of the GS-CSL relation, which could not be captured by the monthly analysis of CH23.

In summary, while several offshore dynamic processes can contribute to variations of CSL on a wide range of time and length scales, it is argued that geostrophic adjustment of the GS cannot be ruled out as one of the important factors that impact CSL along the U.S. East Coast (including the MAB). On the one hand the analysis of monthly data in CH23 could not explain correlations on short time scales, as demonstrated here, and on the other hand long-term coastal sea level rise and variability on decadal time scales associated with potential climate-related slowdown of ocean circulation could not be detected in the relatively short altimeter record. The acceleration in flooding due to sea level rise makes attempts to understand all potential forcing more important than ever. Many past events of sea level rise were unexplained by atmospheric forcing alone, pointing to the GS as an important factor that can raise CSL and cause additional flooding when it is weakening (Ezer and Atkinson, 2014). Prediction of potential acceleration of future floods (Ezer, 2022; Sweet et al., 2018) thus should not ignore the contribution of the GS to CSL variability, even if all mechanisms involved are not fully understood. In any case, this area of research should continue with longer data sets as well as models.

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Data Availability Statement

The hourly tide gauges sea level data are available from: (https://tidesandcurrents.noaa.gov/), and the daily Florida Current transport data are available from: http://www.aoml.noaa.gov/phod/floridacurrent/.

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1. "…*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*.". This conclusion is consistent with the fact that the GS system includes meanders and gyres, so observations show large differences in sections taken not far apart along the GS path (Andres et al., 2020). However, this result does not contradict any of the studies that found significant GS-CSL correlation, because those studies never used a correlation along altimeter track, as done here, but instead used averaged GS strength over large area from many altimeter tracks that filter out the mesoscale variability (e.g., Ezer at al., 2013; Ezer, 2019; Ezer and Dangendorf, 2020).
2. "*GS transport south of Cape Hatteras is significantly correlated with coastal sea level … North of Cape Hatteras, sea level changes associated with GS transport decay rapidly away from GS on the onshore side … In this region … coastal sea level is unlikely to be driven by geostrophic adjustment to changes in GS transport*." The fact that CSL responds to forcing differently north and south of Cape Hatteras is not new (Valle-Levinson et al., 2017; Domingues et al., 2018; Ezer, 2019), and partly explained by the fact that the GS flows close

to the coast in the South-Atlantic Bight (SAB) but is separated from the coast in the Mid-Atlantic Bight (MAB). However, there is no evidence in CH23 that geostrophic adjustment does not play a role in CSL variability in the MAB, especially for time scales that were not resolved by CH23 analysis. For example, Ezer (2019) showed that on decadal time scales CSL in the MAB and the SAB are out of phase and may respond to GS variability in opposite way, while on shorter time scales CSL in the MAB and SAB are correlated. In fact, analysis of *daily* variations in the Florida Current transport or *hourly* tide gauge data show highly coherent CSL variations along the entire US East Coast, as seen in observations and in models (Ezer, 2016; Ezer and Atkinson, 2017).

Examples of past studies below demonstrate why the findings of CH23 could not conclusively exclude GS-CSL relation based on geostrophic adjustment. In fact, CH23's statement that "*significant correlations between coastal sea level and the GS transport are rarely found north of Cape Hatteras*" is not accurate given dozens of published papers that did find statistically significant correlations (see many of these examples in: http://www.ccpo.odu.edu/~tezer/FCvsSL/).

2 On the Relation Between the Gulf Stream and Coastal Sea Level

Based on both, tide gauge and altimeter data, Fig. 3a in CH23 shows significant negative correlation between the Florida Current transport (Baringer and Larsen, 2001; Meinen et al., 2010) and CSL along the U.S. East Coast from Florida to Massachusetts. Despite the fact that this result is consistent with many past studies (Park and Sweet, 2015; Ezer, 2016, 2019, 2020a, 2020b; Ezer et al., 2013; Ezer and Atkinson, 2014, 2017; Wdowinski et al., 2018), CH23 tried to argue that mechanisms other than geostrophic adjustment, such as changing atmospheric conditions (Piecuch et al., 2016), may affect both the GS and CSL, so there is not necessarily a cause and effect relation between GS and CSL. It is true that several factors can contribute to CSL variability, but the impact of the GS cannot be dismissed. As a proof that there is a direct impact of the GS on CSL Ezer (2016) conducted controlled numerical simulations with fixed wind and time-dependent oscillations in the Florida Current transport, and the results show response of coherent CSL variations along the U.S. Coast, like those found in tide gauge observations. The simulations show that the response at the coast to wind-driven sea level is fundamentally different than the response to GS-driven sea level. Furthermore, numerical simulations of hurricanes (Ezer et al., 2017; Ezer, 2018; Ezer 2020a; Park et al., 2022) found that in the days after the hurricanes disappeared and wind was no more a factor, CSL remained higher than normal directly due to a weaker GS that has not recovered yet from the disruption caused by the storm. Fig. 1 shows an example of sea level and flooding in Norfolk (North of Cape Hatteras) during and after hurricane Florence passed the region (it did not make landfall in Virginia). In this case, CSL was first raised by wind-driven storm surge (10-Sep-2018), but the hurricane also disrupted the GS flow (transport dropped by ~10sv), which caused CSL to rise again by ~0.5 m and cause tidal flooding two weeks later (25-Sep-2018), driven by the weakening GS.

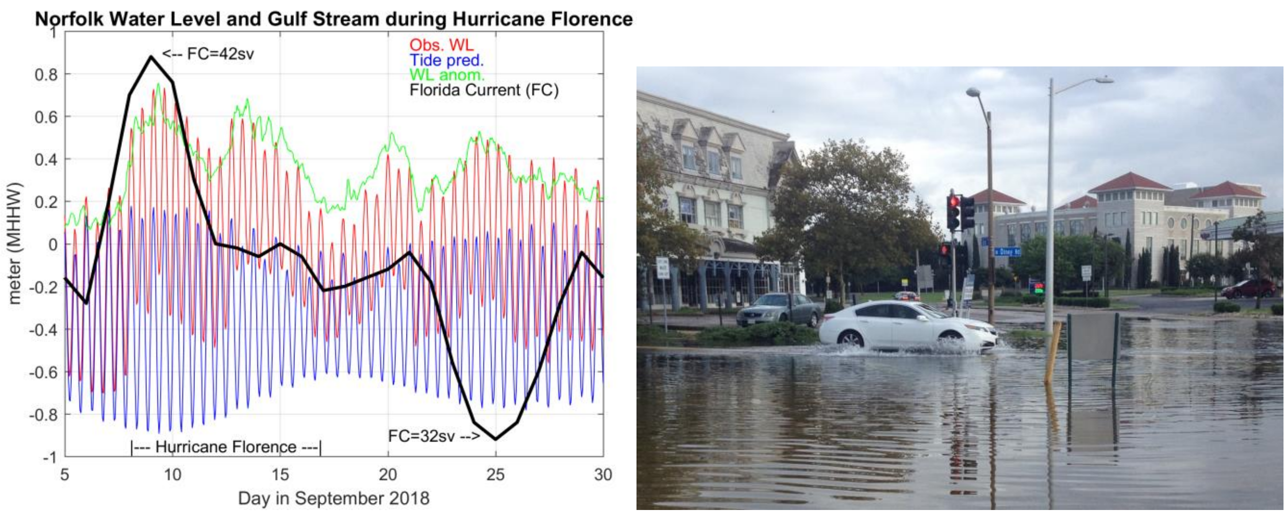

Figure 1. Left: Example of the relation between hourly water level (colored lines) in Norfolk, VA, in the Mid-Atlantic Bight (southern Chesapeake Bay) and daily observed Florida Current (FC) transport (black heavy line), during and after the passage of hurricane Florence in September 2018. Blue, red, and green lines are predicted tides, tide gauge observations and the subtidal anomaly, respectively. Water level (left axis in m) is relative to the Mean Higher High Water (MHHW) and FC transport of maximum and minimum (in Sv; $1Sv=10^6\ m^3\ s^{-1}$) are indicated. Right: Two weeks of "sunny-day" street flooding occurred in Norfolk due to weakening of the GS after the hurricane (picture taken by T. Ezer).

Like Fig. 1, remote GS influence on CSL in the MAB has been recorded after hurricanes Sandy (2012), Joaquin (2015), Mathew (2016) and Dorian (2019). Altimeter data before and after storms show reduction of sea level slope along the entire GS path, which coincides with raised CSL along the entire MAB coast (see Fig. 4 in Ezer, 2018); these observations suggest that geostrophic adjustment to changes in the GS transport may be an important driver of CSL in those cases (though such mechanism cannot be detected by a monthly data, hence the results of CH23). There is also evidence that seasonal variations in the GS transport contribute to the seasonal CSL cycle in the MAB whereas the highest monthly CSL of the year occurs when the seasonal GS has its maximum decline (see the high correlation between the two in Fig. 10c in Ezer, 2020b); since CH23 filtered out the seasonal signal, this contribution could not be captured by their analysis.

Finally, trying to relate simultaneous observations of monthly GS transport and CSL ignores potential lag difference between the two. On interannual to decadal time scales Ezer et al. (2013) found that CSL has higher correlation with *changes* in GS flow ($R=-0.85$, $p<0.001$) than with GS strength itself ($R=-0.58$, $p<0.001$), i.e., CSL rises when the GS flow is in a downward trend, not necessarily when the GS is at its minimum transport. Ezer et al., (2013) also show that a simple solution of the equations of motion points to a mechanism in which *time-changes* in sea level slope across the GS can produce onshore/offshore transports that impact CSL variability. On hourly to monthly time scales Ezer and Atkinson (2017) also found significant correlation between CSL and *changes* in GS transport. The time lag between variations in the GS and the CSL response is near zero in the SAB when the GS is near the coast, but it is larger for the MAB where the GS is far from the coast and the coastal response is less direct (Ezer and Atkinson, 2017). In the MAB, recirculation gyres, the Slope Current from the north and shifting in the GS position, all can affect CSL, so the relation between the GS and CSL is more complex and more difficult to detect, especially with monthly data that ignores the largest instantaneous changes in the GS. Spectral analysis of daily transport of the GS and water level in Norfolk shows statistically significant coherence with near opposite phase (~180°) for several different time scales from few days to months and years (see Fig. 3 in Ezer and Atkinson, 2017), demonstrating the complex nature of the GS-CSL relation, which could not be captured by the monthly analysis of CH23.

In summary, while several offshore dynamic processes can contribute to variations of CSL on a wide range of time and length scales, it is argued that geostrophic adjustment of the GS cannot be ruled out as one of the important factors that impact CSL along the U.S. East Coast (including the MAB). On the one hand the analysis of monthly data in CH23 could not explain correlations on short time scales, as demonstrated here, and on the other hand long-term coastal sea level rise and variability on decadal time scales associated with potential climate-related slowdown of ocean circulation could not be detected in the relatively short altimeter record. The acceleration in flooding due to sea level rise makes attempts to understand all potential forcing more important than ever. Many past events of sea level rise were unexplained by atmospheric forcing alone, pointing to the GS as an important factor that can raise CSL and cause additional flooding when it is weakening (Ezer and Atkinson, 2014). Prediction of potential acceleration of future floods (Ezer, 2022; Sweet et al., 2018) thus should not ignore the contribution of the GS to CSL variability, even if all mechanisms involved are not fully understood. In any case, this area of research should continue with longer data sets as well as models.

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Data Availability Statement

The hourly tide gauges sea level data are available from: (https://tidesandcurrents.noaa.gov/), and the daily Florida Current transport data are available from: http://www.aoml.noaa.gov/phod/floridacurrent/.

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