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What caused the accelerated sea level changes along the United States East Coast during 2010-2015?

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Key points:

- Accelerated sea level rise recorded between Key West and Cape Hatteras during 2010-2015 was caused by warming of the Florida Current
- Warming of the Florida Current provided favorable baseline conditions for occurrence of nuisance flooding events recorded in 2015
- Temporary sea level decline in 2010-2015 north of Cape Hatteras was mostly caused by changes in atmospheric conditions

Abstract: Accelerated sea level rise was observed along the U.S. eastern seaboard south of Cape Hatteras during 2010-2015 with rates five times larger than the global average for the same time-period. Simultaneously, sea levels decreased rapidly north of Cape Hatteras. In this study, we show that accelerated sea level rise recorded between Key West and Cape Hatteras was predominantly caused by a ~1°C (0.2°C/year) warming of the Florida Current during 2010-2015 that was linked to large-scale changes in the Atlantic Warm Pool. We also show that sea level decline north of Cape Hatteras was caused by an increase in atmospheric pressure combined with shifting wind patterns, with a small contribution from cooling of the water column over the continental shelf. Results presented here emphasize that planning and adaptation efforts may benefit from a more thorough assessment of sea level changes induced

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by regional processes.

Plain Language Summary: During 2010-2015, sea level rose rapidly along the U.S. East Coast between Key West and Cape Hatteras, causing extensive flooding to large urban areas such as Miami. Simultaneously, sea level was observed to decline north of Cape Hatteras at an accelerated rate. Here, we investigate what caused the rapid sea level changes recorded during 2010-2015 at the U.S. East Coast. In this study, we show that sea level rise recorded between Key West and Cape Hatteras was mostly caused by the warming of waters carried by the Florida Current during 2010-2015, which can raise coastal sea level through thermal expansion of the water column. We also show that sea level decline north of Cape Hatteras was mostly caused by changes in atmospheric conditions, such as by an increase in atmospheric pressure, which affect sea level due to variations in the overall weight of the atmosphere over a certain location, and by changing wind conditions that can pile up, or push ocean water away from the coast.

1. Introduction

The U.S. East Coast includes several areas where sea levels are currently rising faster than the global average [e.g. Sallenger et al., 2012; Sweet et al. 2018, Table S1]. The combined contribution from global and regional drivers can cause sea level to rise above a local threshold value, above which minor flooding conditions may develop. These events are typically referred to as "nuisance flooding". Several East Coast communities are currently affected by recurrent nuisance-flooding events that have been increasing in frequency [Sweet, et al., 2017; Ezer & Atkinson, 2014] and are projected to further intensify [Sweet et al., 2018]. In response to these events and projections, adaptation efforts to improve coastal resilience are already in place or being planned for densely populated urban areas such as Miami [Miami-Dade County ,2010] and New York City [Rosenzweig & Solecki, 2010].

During the satellite altimetry era (1993-2015), global sea level rose at a rate of 3.1 mm year^{-1} (3.3 mm year^{-1} during 1993-2009 reported by Nicholls & Cazenave, [2010]), while areas along the Northeast U.S. Coast showed rates as large as 6.1 mm year^{-1} for the same period. Over shorter timescales, however, temporal acceleration of sea level changes can occur at much larger rates than the long-term trend. During 2010-2015, for example, sea levels increased at rates reaching 25.5 mm year^{-1} between Key West and Cape Hatteras, approximately five times faster than the global average of 4.5 mm year^{-1} estimated for this

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period (Figure 1a,c). Over the same time period, sea level decline at rates reaching -16.9 mm year^{-1} were also recorded north of Cape Hatteras. The accelerated sea level rise observed during 2010-2015 along the Southeast U.S. coast provided the baseline conditions for the occurrence in October 2015 of the worst nuisance-flooding event in Miami during the past 20 years (Figure S1a), which was also favored by offshore conditions associated with Hurricane Joaquin (2015) [Ezer and Atkinson, 2017]. These accelerated changes in sea level along the U.S. East Coast during 2010-2015 were first reported by Valle-Levinson et al., [2017], who attributed them to changes in atmospheric conditions modulated by the North Atlantic Oscillation (NAO) and the El Niño-Southern Oscillation (ENSO). Changes in atmospheric conditions can affect coastal sea level through the inverse barometer effect, shifting wind patterns, and due to changes in storm tracks (e.g. Tropical Cyclones).

In addition to changes in atmospheric conditions, the variability of ocean currents flowing along the U.S. Eastern seaboard can also drive sizeable contributions to regional sea level. The geostrophic component of the Florida Current and Gulf Stream, for example, implies that the intensity of their flow is proportional to cross-current variations in seawater density below the sea surface, and/or to the slope of the sea level at the surface. Because of this dynamical condition, a decline of 1 Sv (1 Sv = 10^6 m^3 s^{-1}) in the Gulf Stream transport, for example, is generally associated with a 0.5–3.0 cm sea level increase along the Northeast U.S. coast [Ezer et al., 2013; Woodworthet al., 2014; Goddard et al., 2015; Ezer, 2016]. Accelerated sea level rise north of Cape Hatteras during 1950-2009 was attributed by Sallenger et al. [2012] to weakening in the Atlantic Meridional Overturning Circulation (AMOC) and Gulf Stream, with this relation being further confirmed by other studies [Ezer et al., 2013; Yin and Goddard, 2013]. Moreover, a combination of a weak AMOC and extreme negative NAO [Piecuch and Ponte, 2015] can also result in short-term elevated coastal sea level and increased flooding along the U.S. East Coast, as recorded, for example, during 2009-2010 [Ezer, 2015; Goddard et al., 2015]. Along the Southeast U.S. coast, widespread nuisance-flooding events commonly coincide with extremely low transport by the Florida Current [Sweet et al., 2016; Baringer et al., 2017], given that variations in the Florida Current transport can amount to ~10 Sv [Schott et al., 1988; Meinen et al., 2010]. In fact, disruption in the Florida Current flow caused by offshore forcing from hurricanes has been acknowledged as a known remote source for elevated sea level events that can threat the Southeast U.S. coast [Ezer and Atkinson, 2017; Ezer, 2018].

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In this study, mechanisms accounting for the accelerated sea level changes observed during 2010-2015 and first reported by Valle-Levinson et al., [2017] are examined in detail. It is shown for the first time that changes in the temperature of the Florida Current can contribute to the occurrence of nuisance flooding along the coast, and that the accelerated sea level rise observed in 2010-2015 south of Cape Hatteras was mostly caused by the warming of this current. It is also reported that these changes are sometimes offset or combined with contributions from interannual changes in atmospheric conditions through the inverse barometer effect and shifting wind patterns.

2. Sea level changes along the U.S. east coast in 2010-2015

Accelerated sea level changes were observed along the U.S. East Coast during 2010-2015 by 43 tide gauges distributed along the region (see Supplemental Information), with sea level rising rapidly south of Cape Hatteras, and sea level decreasing to the north. Before addressing in detail these changes, it is worth emphasizing that these changes are overlaid on the longer-term sea level rise recorded along the entire U.S. East Coast (Figure 1c, Table S1) at rates that are close to the global mean sea level rise [Nicholls & Cazenave, 2010; Cazenave et al., 2014] south of Cape Hatteras, and slightly greater rates up north. Therefore, while short-term reductions in the mean sea level north of Cape Hatteras may have temporarily reduced the risk of nuisance flooding, the present-day sea level is still consistently higher than values recorded a few decades ago everywhere along the U.S. East Coast (Figure 1b).

During 2010-2015, accelerated sea level rise was observed from Key West to Cape Hatteras (Figure 1a,d), with sea levels increasing at rates as large as 25.5 mm year^{-1} at Trident Pier, Florida (28.41°N, Table S1). South of Cape Hatteras, sea level increased at average rates of 19.6 ± 3.6 mm year^{-1}, with significant rates exceeding 20.0 mm year^{-1} consistently observed over the continental shelf (Figure 1a). Off Miami, for example, dynamic sea level rise estimated from altimetry across the entire Florida Straits at 27°N had values of 19.9 ± 1.4 mm year^{-1}. Extensive nuisance-flooding events occurred in September-October of 2015 in Miami [e.g. Sweet et al., 2016], with astronomical tide prediction underestimating sea level by 23 cm in Miami (Figure S1c). Offshore conditions associated with Hurricane Joaquin (2015) also forced a disruption in the Florida Current flow that further favored flooding events of October 2015 [Ezer and Atkinson, 2017]. Flooding events of this magnitude may occur in Miami about every 6 years given matching environmental

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conditions to those observed in September-October 2015, such as near-peak lunar nodal cycle and the reduction of the Florida Current transport by approximately 9 Sv [Sweet et al., 2016].

North of Cape Hatteras, an overall decline in the mean sea level was recorded by 28 tide gauges between 2010-2015 with rates ranging from -3.0 to -16.9 mm year^{-1} (Figure 1d, Table S1), and average rates of -11.6 ± 4.1 mm year^{-1}. This decline was not reflected in satellite altimetry gridded products, which showed smaller and statistically insignificant rates (dotted areas, Figure 1a). The discrepancy is due to temporal changes in atmospheric pressure, which are removed from the gridded altimetry products through the inverse barometer correction. In 2009-2010, atmospheric pressure from the ERA interim reanalysis [Dee et al., 2011] (see Supplemental Information) showed low over Atlantic associated with the extreme negative phase of the NAO [Piecuch & Ponte, 2015; Goddard et al., 2015]. During 2010-2015, average atmospheric pressure conditions shifted from low values in 2010 (Figure 2a) to higher values in 2015 (Figure 2b). Atmospheric conditions in 2015 were associated with the relatively positive phase of the NAO, and the strongly positive phase of the East Atlantic pattern (see http://www.cpc.ncep.noaa.gov/data/teledoc/ea.shtml), which is the second-most prominent mode of low-frequency variability over the North Atlantic and often identified as a southward shifted NAO pattern [e.g. Barnston & Livezey, 1987]. Over the entire U.S. East Coast, an increase in atmospheric pressure from 2010-2015 (Figure 2c) favored a decline of sea level, with stronger changes of 3-5 mbar (which corresponds to a decrease of 3-5 cm in sea level) north of Cape Hatteras.

Overall, rates of sea level decline during 2010-2015 due to increasing atmospheric pressure along the U.S. northeast coast ranged from -1.7 in Key West to -9.2 mm year^{-1} in Cutler Farris Wharf (Table S1). These changes in atmospheric pressure were accompanied by a significant shift in wind patterns, especially in the proximity of Cape Hatteras (Figure 2d). In fact, wind fields from the ERA interim reanalysis (see Supplemental Information) show a decreased of 0.04 N m^{-2} in alongshore winds close to Cape Hatteras during 2010-2015 (Figure S2). Because changes in the alongshore wind conditions are important in the coastal sea level budget, its contribution was quantified here using the method reported by Piecuch et al., [2016] (see Supplemental Information). This analysis shows that shifting winds indeed played a significant role in accounting for the observed sea level changes in 2010-2015. South of Cape Hatteras, statistically significant rates of wind-driven sea level increase ranged from 2.9 mm year^{-1} in Mayport to 8.1 mm year^{-1} in Springmaid Pier (Table S1). Rates

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between Key West and Trident Pier were smaller than 1.6 mm year^{-1} and not statistically significant. North of Cape Hatteras, statistically significant rates of wind-driven sea level decline were only observed north of Chatham, and ranged from -3.5 mm year^{-1} in this location to -7.3 mm year^{-1} in Wells. In fact, north of Chatham the observed sea level decline recorded by the tide gauges is mostly (up to 98%) accounted by the combined contribution of changes in atmospheric pressure and shifting winds patterns. South of Cape Hatteras, however, the observed increase in atmospheric pressure is partially compensated by the decrease in the alongshore winds, and combined changes in atmospheric conditions can only account for up to 25% (in Wrightsville Beach) of the observed sea level increase recorded by the tide gauges.

3. Warming of the Florida Current

The accelerated sea level rise observed between Key West and Cape Hatteras in 2010-2015 cannot be explained by the combined effect of glacial isostatic adjustment and changes in atmospheric pressure and winds, which altogether generally account for less than 25% of the observed changes (Table S1). Here, we discuss the contribution of the Florida Current variability, which has been identified as a key driver for sea level changes along the southeast U.S. coast [e.g. Sweet et al., 2009; Ezer et al., 2013; Ezer, 2016]. In particular, changes in the Florida Current transport can be examined in detail due to the availability of the long-term observations of this current [Larsen & Smith, 1992; Baringer et al., 2017]. The low-pass filtered Florida Current transport estimates obtained from NOAA (see Supplemental Information, Figure S4) during 1995-2016 varied between 29-34 Sv on interannual time-scales, with weaker/stronger Florida Current transports contributing to higher/lower sea level anomalies along the southeast U.S. coast [Sweet et al., 2009; Domingues et al., 2016]. During 2010-2015, even though the Florida Current transport was slightly below the average by ~1 Sv (red shading, Figure S4), a linear trend analysis indicates changes in its flow cannot explain the observed coastal sea level rise recorded south of Cape Hatteras, which increased by 12.0 ± 2.0 cm on average (Table S2).

Because changes in buoyancy play a dominant role in driving sea level variability in the mid-latitudes [Mayer et al., 2001], changes in the temperature of the Florida Current are also evaluated here based on 2,466 hydrographic profiles sampled in the Straits of Florida and made available by NOAA (see Supplemental Information, Figure S3). The Florida Current

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temperature anomalies (Figure 3a) reveal substantial year-to-year temperature variability (seasonal cycle removed and 1-year low-pass filter applied) that can often exceed ±1°C. Most of the time, anomalies are coherent throughout the entire water column (e.g., late 2015, Figure 3a,c), but occasionally (~30% of the time) temperature anomalies above and below 100 m have opposite signs (e.g., early 1997, Figure 3a,b). The thermosteric sea level (due to thermal expansion) estimated here from the depth-integrated ocean temperatures indicates that these changes in temperature may account for sea level changes of ~10 cm on seasonal time-scales (not shown) and ~20 cm on interannual time-scales (Figure 3d). Thermosteric anomalies are significantly ($p<0.1$) larger by ~40% when temperature anomalies have the same sign throughout the water column.

One key finding of this study is that the Florida Current shifted from a cold phase in 2010-2013 to a warm phase in 2014-2015 (Figure 3a), accounting for a sea level rise during 2010-2015 at a rate of 18.9 mm year^{-1} (Figure 3d, Figure S4). This indicates that the thermosteric rise associated with the warming of the Florida Current provided the dominant component that explained about 95% of the dynamic sea level rise observed in the Florida Straits with satellite-altimetry (19.9 ± 1.4 mm year^{-1}), with the remaining 5% possibly associated with mass changes. In fact, the observed thermosteric component accounted for an overall sea level rise of 12.5 cm in the Florida Straits during 2010-2015. This increase largely accounts for the sea level rise of 10.1 cm recorded by the Virginia Key (Miami) tide gauge for the same time period (Figure 1e, Table S2). The 2.4 cm difference between the observed sea level and the thermosteric component can be partly explained by the concurrent increase of atmospheric pressure by about 1.2 mb (Figure 2c, Table S2). During this time period, changes in winds were not statistically significant south of Trident Pier (Table S1), and the Florida Current transport remained relatively constant. Table S2 describes the contribution of some of the key components accounting for the sea level budget in the Florida Straits off Miami during 2010-2015. Warming of the Florida Current was the most important driver for the observed accelerated sea level rise here.

4. Contribution of the upper ocean cooling to sea level decline north of Cape Hatteras

While the decline in sea levels north of Cape Hatteras in 2010-2015 (Figure 1b,d) is largely due to the combined changes in atmospheric pressure and shifting winds between Oregon Inlet and Woods Hole (north of Chatham) (Table S1), SST cooling over the

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continental shelf also occurred during this period at rates of ~ -0.2°C year^{-1} (Figure 4a). Simultaneously, Gulf Stream waters warmed at rates greater than 0.3°C year^{-1}, indicating that warmer Florida Current waters (red line, Figure S4) were advected offshore as the Gulf Stream separated from the coast. The spatially averaged temperature data from 10,375 XBT profiles (displayed as a function of distance from New York City and time, Figure 4b) confirm that the entire water column over the continental shelf (~50 m depth, dashed magenta line) cooled at rates of -0.2°C year^{-1} during 2010-2015.

The cooling of continental shelf water may have contributed to the decline in sea level due to the contraction of the water column. Thermosteric heights and anomalies (Figure 4c,d) estimated here using XBT data reveal, however, that changes in sea level accounted for by temperature conditions rarely exceed absolute values larger than 2 cm given the shallow ~50 m depth of the water column over the shelf. In fact, cooling over the continental shelf during 2010-2015 in the proximity of New York City accounted for only a -3.5 ± 1.5 mm year^{-1} decline in sea level. This decline does not fully account for the decrease in coastal sea levels that reached rates of -14.82 mm year^{-1} in the proximity of New York City (The Battery, Table S1). Therefore, another key finding of this study is that the decline in sea levels north of Cape Hatteras during 2010-2015 was mostly accounted for by the combined effect of increased atmospheric pressure and shifting wind patterns, with a small contribution of cooling over the continental shelf off New York City.

5. Discussion

Accelerated changes in the mean sea level along the U.S. East Coast have been previously attributed to changes in atmospheric conditions due to the NAO and to the ENSO [e.g. Valle-Levinson et al., 2017]. During 2009-2010, for example, the increase in sea levels for areas north of Cape Hatteras (Figure 1b), was attributed to the extreme negative phase of the NAO in 2010 [Piecuch & Ponte, 2015; Goddard et al., 2015] and to the associated weakening of the Atlantic Meridional Overturning Circulation [Ezer, 2015]. During 2010-2015, accelerated sea level decline observed north of Cape Hatteras was also dominated by changes in atmospheric pressure and winds associated with moderate, and extreme positive phases of the NAO, and East Atlantic pattern in 2015, respectively.

A much smaller contribution to lowering sea levels north of Cape Hatteras was accounted for by cooling of continental shelf waters, that explained -3.5 ± 1.5 mm year^{-1}

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during 2010-2015. Cooling of continental shelf waters for areas north of Cape Hatteras was possibly associated with changes in the Northern Recirculation Gyre [Mellor et al., 1982] that separates the Gulf Stream from coastal areas. This enclosed gyre circulation is fed by cold waters carried by the Slope Current [Rossby et al., 2010], which includes an export of cold Coastal Labrador Sea Water into the region. Changes in the strength of the Slope Current [Ezer, 2015] and in the flow of Coastal Labrador Sea Water [Xu & Oey, 2011] have both been shown to play important roles in regional sea levels north of Cape Hatteras. The strength of the Slope Current is also oftentimes anti-correlated with meridional displacements in the Gulf Stream [Ezer, 2015]. In fact, dynamic height estimates derived in this study suggest a southward shift in the Gulf Stream axial position in 2014 (Figure 4c), which was likely associated with the strengthening of the Slope Current. It is, therefore, possible that the cooling reported in our analysis was caused by a stronger Slope Current flow. It should also be considered here that as the Gulf Stream detaches from the coast in the proximity of Cape Hatteras, warming anomalies recorded in the Florida Straits (Figure 3a) were advected offshore by the circulation (Figure 4b). The combination of warming offshore with cooling over the shelf (Figure 4e) implies in more intense frontal gradients and Gulf Stream baroclinic transport, which are further confirmed from sea level trends estimated from altimetry-derived data (Figure S5). Thus, it is likely that temporary downstream intensification of the Gulf Stream transport during 2010-2015 may have further contributed to lowering sea levels north of Cape Hatteras, as demonstrated in previous studies (e.g. Ezer et al., 2013). Future work will include addressing these mechanisms in greater detail.

South of Cape Hatteras, where the Florida Current and Gulf Stream flow accelerated sea level rise during 2010-2015 was largely accounted for by a ~1°C warming of the Florida Current (0.2°C year^{-1}). These changes in temperature conditions translated into a sea level rise of 12.5 cm solely due to thermal expansion. Changes in the temperature of the Florida Current are likely traced to locations upstream from the Florida Straits and southeast U.S. coast. Approximately 80% of the water carried by the Florida Current has its origin in the Loop Current, which transports warm Caribbean water into the Gulf of Mexico, while other sources such as the Northwest Providence Channel contribute to less than 5% of the flow [Johns et al., 2002; Sheinbaum et al., 2002; Beal et al., 2008]. This explains why the accelerated changes in the Florida Straits during 2010-2015 are in good agreement with time-series indicators of upper ocean heat content in the Gulf of Mexico (r = 0.65), Atlantic Warm Pool (AWP, r = 0.70), and Western Hemisphere Warm Pool (WHWP, r = 0.65), which are

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defined as areas within the Florida Straits, Gulf of Mexico, Caribbean Sea, tropical North Atlantic, and east North Pacific with sea surface temperatures (SSTs) warmer than 28.5°C [Wang et al., 2006; Wang & Enfield, 2001]. These three indicators exhibited an accelerated increase in averaged sea level during 2010-2015 (Figure S6). Therefore, the accelerated sea level rise observed during 2010-2015 along the southeast U.S. coast due to warming of the Florida Current was probably part of the large-scale changes (e.g. Figure S5) that occurred in the North Atlantic Ocean.

One key mechanism driving year-to-year SST variability in the Gulf of Mexico, AWP, and WHWP is caused by changes in atmospheric circulation and cloudiness during Pacific Ocean El Niño events [Wang & Enfield, 2001; 2003; Enfield et al., 2006]. Changes in atmospheric circulation such as weakening of the northeastly trade winds result in a warming of the tropical North Atlantic which, in turn, induces the development of an unusually large warm pool through a "tropospheric bridge" that transfers El Niño effects to the Atlantic sector and induces a warming of the AWP. In fact, one study [Enfield et al., 2006] reported that summers following El Niño events from 1950–2000 were characterized by instances of extraordinarily large WHWP averaging about twice their climatological size. The accelerated rates of sea level rise peaking in 2015 along the southeast U.S. coast was locally associated with warming of the Florida Current, and coincided with the strong 2015 El Niño event (www.esrl.noaa.gov/psd/enso/mei/). In contrast, negative thermosteric anomalies were observed in the Florida Straits during the strong 1997/98 El Nino (Figure 3a). This difference is because the timing of such accelerated sea level rise events is mostly determined by El Niño, while the location is largely determined by the NAO [Valle-Levinson et al. 2017]. A recent study by Volkov et al., [2018] also showed that changes in atmospheric conditions associated with the NAO can drive large-scale heat divergence in the North Atlantic, affecting a basin-wide tri-pole mode of sea level variability in the region. In fact, their results confirmed that during 2010-2015 the mid-latitude band of the tri-pole was indeed gaining heat over that period, which is agreement with the warming of the Florida Current, and of the AWP reported here. Hence, it is likely that under favorable NAO and El Niño conditions, warming of the Florida Current reported here can provide a key component linking large-scale changes in atmospheric conditions with regional accelerated sea level rise along the Southeast U.S. coast. Results reported here are therefore complementary to findings of Valle-Levinson et al. (2017) and of Volkov et al., (2018), since they include additional information on the local mechanisms that can account for observed coastal sea level changes.

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In conclusion, the analysis developed in this study used an extensive dataset that included sea level observations from tide gauges and satellites, as well as in situ hydrographic observations of the Gulf Stream and Florida Current, with the goal of enhancing our understanding of the drivers of sea level change along the U.S. East Coast. An analysis of these observations revealed that accelerated sea level rise occurred along the southeast U.S. coast from 2010-2015 were mostly caused by an unprecedented warming of the Florida Current. Warming of the Florida Current during this time period provided a background condition that, when combined with the September-October spring tides, favored the occurrence of extensive flooding in Miami late in 2015. North of Cape Hatteras, however, declining sea levels during 2010-2015 were largely accounted for by a combination of increasing atmospheric pressure, shifting wind patterns, and a small contribution from cooling of the water column over the continental shelf.

This study shows that changes in the temperature of the water carried by ocean currents flowing in proximity to the U.S. East Coast, and that are not considered in typical astronomical sea-level predictions, are relevant drivers of sea level changes in the region. Finally, results reported here illustrate the importance of assessing attributions of sea level changes caused by various components, while addressing the different time scales associated with these driving processes.

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References

Baringer, M. O., Smeed, D. A., Willis, J., Lankhorst, M., Hobbs, W. R., Dong, S., ... & Send, U. (2017). Meridionaloverturning and oceanic heat transport circulation observations in the North Atlantic Ocean [in "State of the Climate in 2016"]. Bulletin of the American Meteorological Society, 98(8), S84-S87.

Barnston, A. G., and R. E. Livezey (1987), Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. Mon. Wea. Rev., 115, 1083-1126.

Beal, L. M., Hummon, J. M., Williams, E., Brown, O. B., Baringer, W., & Kearns, E. J. (2008). Five years of Florida Current structure and transport from the Royal Caribbean Cruise Ship Explorer of the Seas. Journal of Geophysical Research: Oceans, 113(C6).

Cazenave, A., Dieng, H. B., Meyssignac, B., Von Schuckmann, K., Decharme, B., & Berthier, E. (2014). The rate of sea-level rise. Nature Climate Change, 4(5), 358.

Cheng, L., Zhu, J., Cowley, R., Boyer, T., & Wijffels, S. (2014). Time, probe type, and temperature variable bias corrections to historical expendable bathythermograph observations. Journal of Atmospheric and Oceanic Technology, 31(8), 1793-1825.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., ... & Bechtold, P. (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. Quarterly Journal of the royal meteorological society, 137(656), 553-597.

Domingues, R., Baringer, M., & Goni, G. (2016). Remote sources for year-to-year changes in the seasonality of the Florida Current transport. Journal of Geophysical Research: Oceans, 121(10), 7547-7559.

Enfield, D. B., Lee, S. K., & Wang, C. (2006). How are large western hemisphere warm

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pools formed?. Progress in Oceanography, 70(2-4), 346-365.

Ezer, T. (2015). Detecting changes in the transport of the Gulf Stream and the Atlantic overturning circulation from coastal sea level data: The extreme decline in 2009–2010 and estimated variations for 1935–2012. Global and Planetary Change, 129, 23-36.

Ezer, T. (2016). Can the Gulf Stream induce coherent short-term fluctuations in sea level along the US East Coast? A modeling study. Ocean Dynamics, 66(2), 207-220.

Ezer, T., (2018), On the interaction between a hurricane, the Gulf Stream and coastal sea level, Ocean Dynamics, doi:10.1007/s10236-018-1193-1.

Ezer, T., Atkinson, L. P., Corlett, W. B., & Blanco, J. L. (2013). Gulf Stream's induced sea level rise and variability along the US mid-Atlantic coast. Journal of Geophysical Research: Oceans, 118(2), 685-697.

Ezer, T., & Atkinson, L. P. (2014). Accelerated flooding along the US East Coast: on the impact of sea-level rise, tides, storms, the Gulf Stream, and the North Atlantic oscillations. Earth's Future, 2(8), 362-382.

Ezer, T. and L. P. Atkinson (2017), On the predictability of high water level along the U.S. East Coast: can the Florida Current measurement be an indicator for flooding caused by remote forcing?, Ocean Dynamics, 67(6), 751-766, doi:10.1007/s10236-017-1057-0.

Goddard, P. B., Yin, J., Griffies, S. M., & Zhang, S. (2015). An extreme event of sea-level rise along the Northeast coast of North America in 2009–2010. Nature Communications, 6, 6346.

Johns, W. E., Townsend, T. L., Fratantoni, D. M., & Wilson, W. D. (2002). On the Atlantic inflow to the Caribbean Sea. Deep Sea Research Part I: Oceanographic Research Papers, 49(2), 211-243.

Larsen, J. C., & Smith, F. T. (1992). Transport and heat flux of the Florida Current at 27 N derived from cross-stream voltages and profiling data: Theory and observations. Phil. Trans. R. Soc. Lond. A, 338(1650), 169-236.

Mayer, D. A., Molinari, R. L., Baringer, M. O. N., & Goni, G. J. (2001). Transition regions and their role in the relationship between sea surface height and subsurface temperature structure in the Atlantic Ocean. Geophysical Research Letters, 28(20), 3943-3946.

Meinen, C. S., Baringer, M. O., & Garcia, R. F. (2010). Florida Current transport variability:

Accepted Article

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An analysis of annual and longer-period signals. Deep Sea Research Part I: Oceanographic Research Papers, 57(7), 835-846.

Mellor, G. L., Mechoso, C. R., & Keto, E. (1982). A diagnostic calculation of the general circulation of the Atlantic Ocean. Deep Sea Research Part A. Oceanographic Research Papers, 29(10), 1171-1192.

Miami-Dade County (2010). Green Print – Our design for a sustainable Future. Available at: http://www.miamidade.gov/greenprint/home.asp (accessed on 07/01/2018, 15:00 EST)

Nicholls, R. J., & Cazenave, A. (2010). Sea-level rise and its impact on coastal zones. science, 328(5985), 1517-1520.

Peltier, W. R., Argus, D. F., & Drummond, R. (2015). Space geodesy constrains ice age terminal deglaciation: The global ICE-6G_C (VM5a) model. Journal of Geophysical Research: Solid Earth, 120(1), 450-487.

Piecuch, C. G., Dangendorf, S., Ponte, R. M., & Marcos, M. (2016). Annual sea level changes on the North American Northeast Coast: influence of local winds and barotropic motions. Journal of Climate, 29(13), 4801-4816.

Piecuch, C. G., & Ponte, R. M. (2015). Inverted barometer contributions to recent sea level changes along the northeast coast of North America. Geophysical Research Letters, 42(14), 5918-5925.

Rosenzweig, C., & Solecki, W. (2010). Introduction to climate change adaptation in New York City: building a risk management response. Annals of the New York Academy of Sciences, 1196(1), 13-18.

Rossby, T., Flagg, C., & Donohue, K. (2010). On the variability of Gulf Stream transport from seasonal to decadal timescales. Journal of Marine Research, 68(3-4), 503-522.

Sallenger Jr, A. H., Doran, K. S., & Howd, P. A. (2012). Hotspot of accelerated sea-level rise on the Atlantic coast of North America. Nature Climate Change, 2(12), 884.

Schott, F. A., Lee, T. N., & Zantopp, R. (1988). Variability of structure and transport of the Florida Current in the period range of days to seasonal. Journal of Physical Oceanography, 18(9), 1209-1230.

Sheinbaum, J., Candela, J., Badan, A., & Ochoa, J. (2002). Flow structure and transport in the Yucatan Channel. Geophysical Research Letters, 29(3), 10-1.

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Accepted Article

Sweet, W., Dusek, G., Obeysekera, J., & Marra, J. (2018). Patterns and Projections of High Tide Flooding Along the U.S. Coastline Using a Common Impact Threshold. NOAA Technical Report NOS CO-OPS, Vol. 86, National Oceanic and Atmospheric Administration, Silver Spring, Maryland, USA.

Sweet, W. V., Menendez, M., Genz, A., Obeysekera, J., Park, J., & Marra, J. J. (2016). In Tide's Way: Southeast Florida's September 2015 Sunny-day Flood. Bulletin of the American Meteorological Society, 97(12), S25-S30.

Sweet, W., Kopp, R., Weaver, C. P., Obeysekera, J., Horton, R., Thieler, E., Zervas, C. (2017). Global and regional sea level rise scenarios for the United States. NOAA Technical Report NOS CO-OPS, Vol. 83, National Oceanic and Atmospheric Administration, Silver Spring, Maryland, USA.

Sweet, W. W. V., Zervas, C. E., & Gill, S. K. (2009). Elevated east coast sea level anomaly: June-July 2009.

Szuts, Z. B., & Meinen, C. S. (2017). Florida Current salinity and salinity transport: Mean and decadal changes. Geophysical Research Letters, 44(20).

Valle-Levinson, A., Dutton, A., & Martin, J. B. (2017). Spatial and temporal variability of sea level rise hot spots over the eastern United States. Geophysical Research Letters, 44(15), 7876-7882.

Volkov, D. L., Baringer, M., Smeed, D., Johns, W., & Landerer, F. W. (2018). Teleconnection between the Atlantic Meridional Overturning Circulation and sea level in the Mediterranean Sea. Journal of Climate, (2018).

Wang, C., & Enfield, D. B. (2001). The tropical Western Hemisphere warm pool. Geophysical research letters, 28(8), 1635-1638.

Wang, C., & Enfield, D. B. (2003). A further study of the tropical Western Hemisphere warm pool. Journal of climate, 16(10), 1476-1493.

Wang, C., Enfield, D. B., Lee, S. K., & Landsea, C. W. (2006). Influences of the Atlantic warm pool on Western Hemisphere summer rainfall and Atlantic hurricanes. Journal of Climate, 19(12), 3011-3028.

Woodworth, P. L., Maqueda, M. Á. M., Roussenov, V. M., Williams, R. G., & Hughes, C. W. (2014). Mean sea-level variability along the northeast American Atlantic coast and the roles of the wind and the overturning circulation. Journal of Geophysical Research:

Accepted Article

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Oceans, 119(12), 8916-8935.

Xu, F. H., & Oey, L. Y. (2011). The origin of along-shelf pressure gradient in the Middle Atlantic Bight. Journal of Physical Oceanography, 41(9), 1720-1740.

Yin, J., & Goddard, P. B. (2013). Oceanic control of sea level rise patterns along the East Coast of the United States. Geophysical Research Letters, 40(20), 5514-5520.

Zweng, M. M., Reagan, J. R., Antonov, J. I., Locarnini, R. A., Mishonov, A. V., Boyer, T. P., ... & Biddle, M. M. (2013). World ocean atlas 2013. Volume 2, Salinity. In Levitus, S ed. World Ocean Atlas 2013 (WOA13). (NOAA Atlas NESDIS 74) National Oceanographic Data Center, Silver, S pring, MD http://www.nodc.noaa.gov/OC5/woa13/pubwoa13.html

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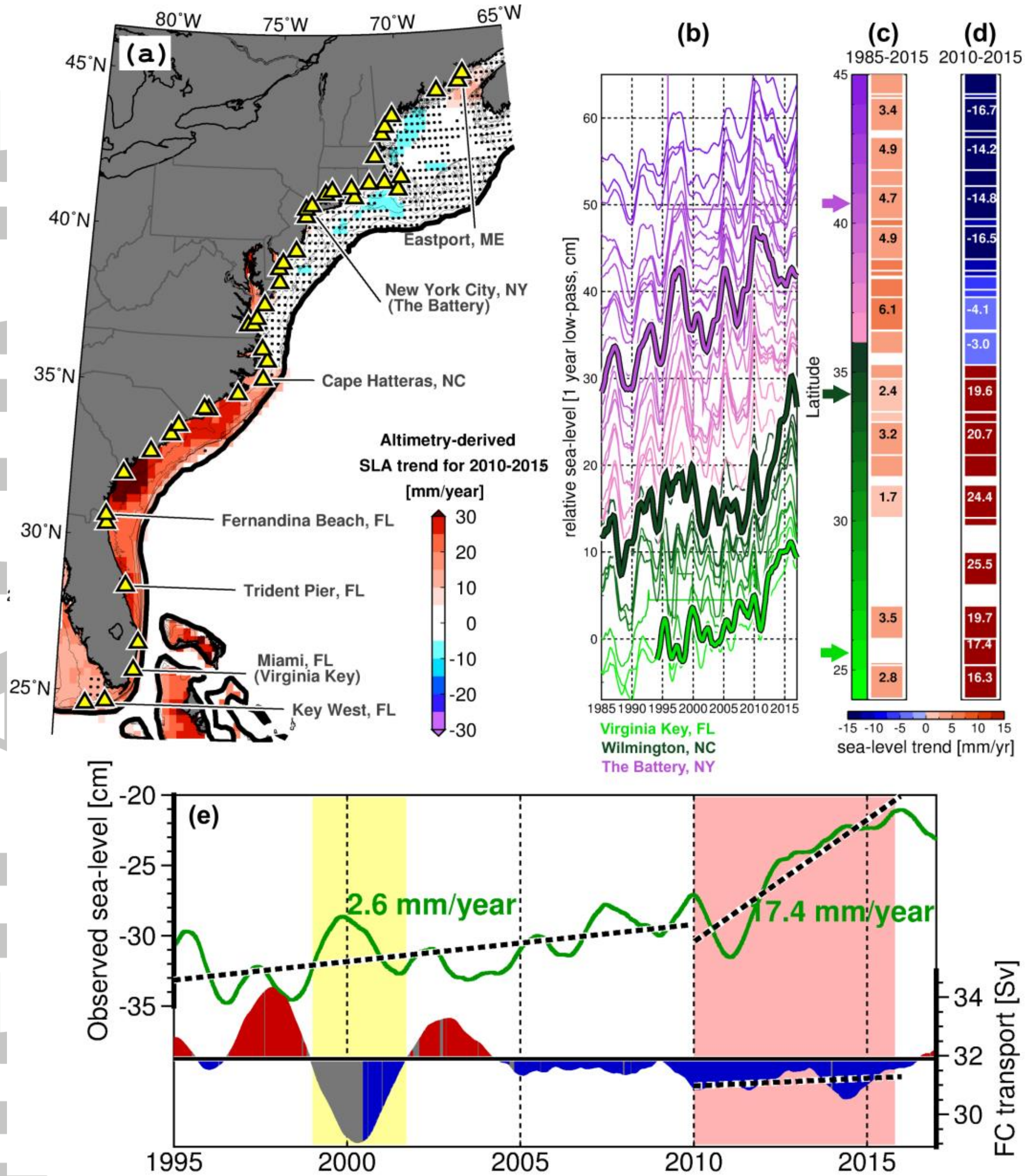

Figure 1 – Sea level changes along the U.S. East Coast during 2010-2015. (a) Location of 43 NOAA tide gauges overlaid on satellite altimetry-derived SLA trends during 2010-2015. Dotted areas emphasize locations where rates of sea level change estimated from satellite altimetry are statistically insignificant, and the black dashed line indicates the 200 m isobath. (b) Sea level time-series from the 43 tide gauges low-pass filtered using a window of 1 year. Time-series are offset by 1.5 cm between consecutive tide gauges for display purposes and color coded as a function of latitude. Linear sea level trends calculated for the periods of (c) 1985-2015, and (d) of 2010-2015. (e) Time-seres of sea level recorded in the Virginia Key tide gauge (Miami) shown in greater detail, and of the Florida Current transport filtered using a one year low-pass filter.

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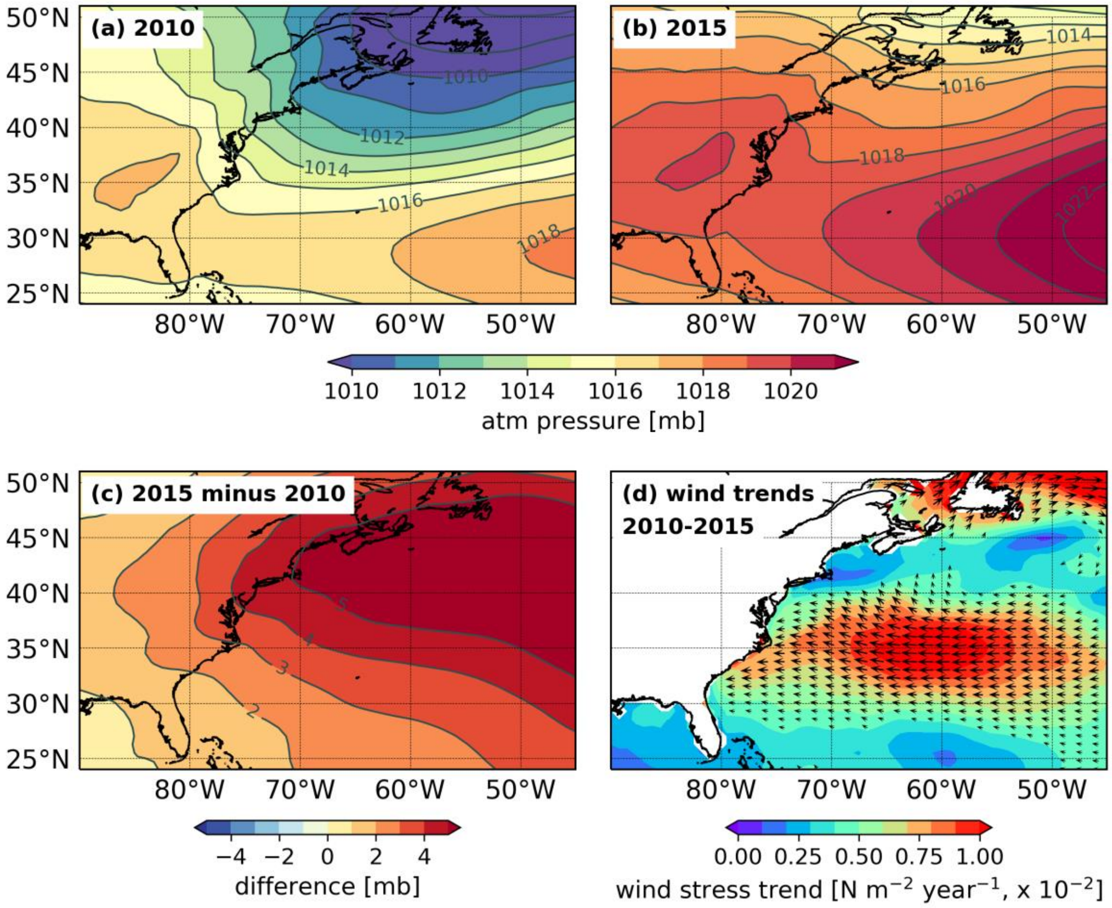

Figure 2 – Surface atmospheric pressure and wind changes during 2010-2015. Surface atmospheric pressure fields from the ERA Interim reanalysis averaged for (a) 2010, (b) 2014, and (c) the difference between 2014 and 2010. (d) Wind trends during 2010-2015 (only statistically significant vectors are shown).

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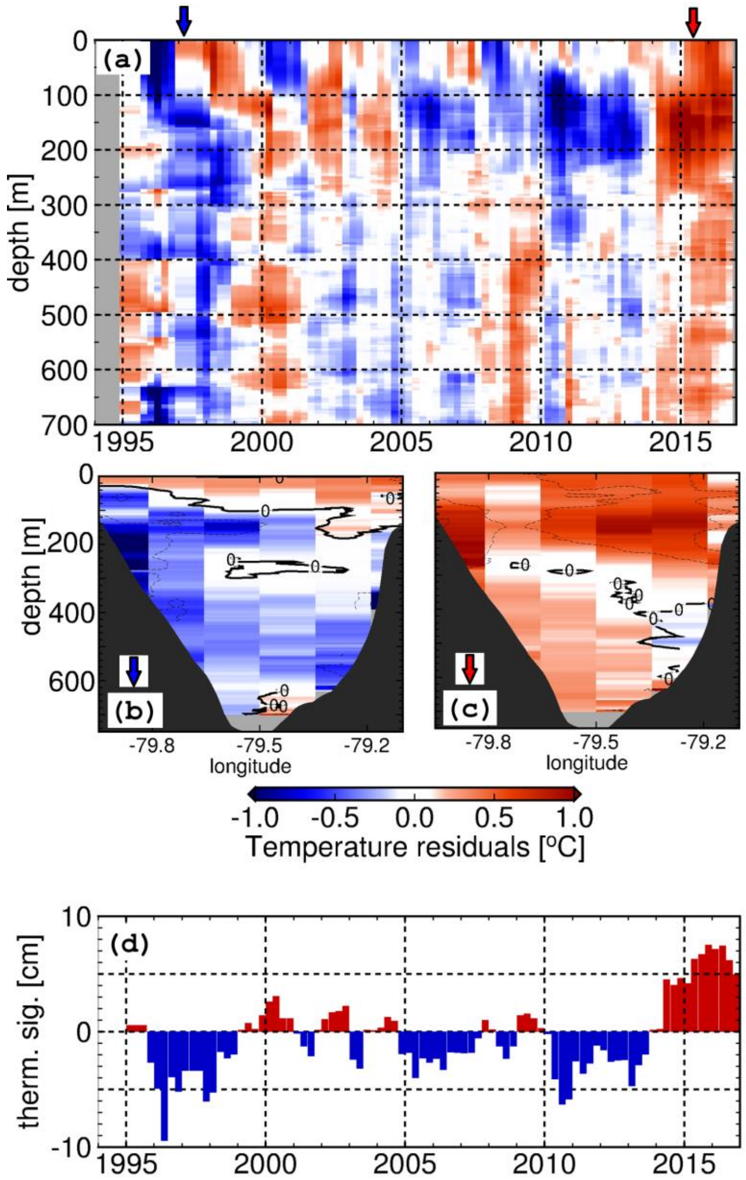

Figure 3 – Year-to-year changes in the Florida Current. (a) Depth-time diagram of the average temperature residuals (seasonal cycle removed) in the Florida Straits using subsurface temperature profile data derived from 1,925 XBT profiles and 541 CTD casts sampled during 1995-2016. Florida Current temperature residuals across the Florida Straits for (b) JFM 1997 and (c) JAS 2015. (d) Thermosteric residuals in the Florida Straits η_{FCtemp} were calculated based on XBT and CTD data.

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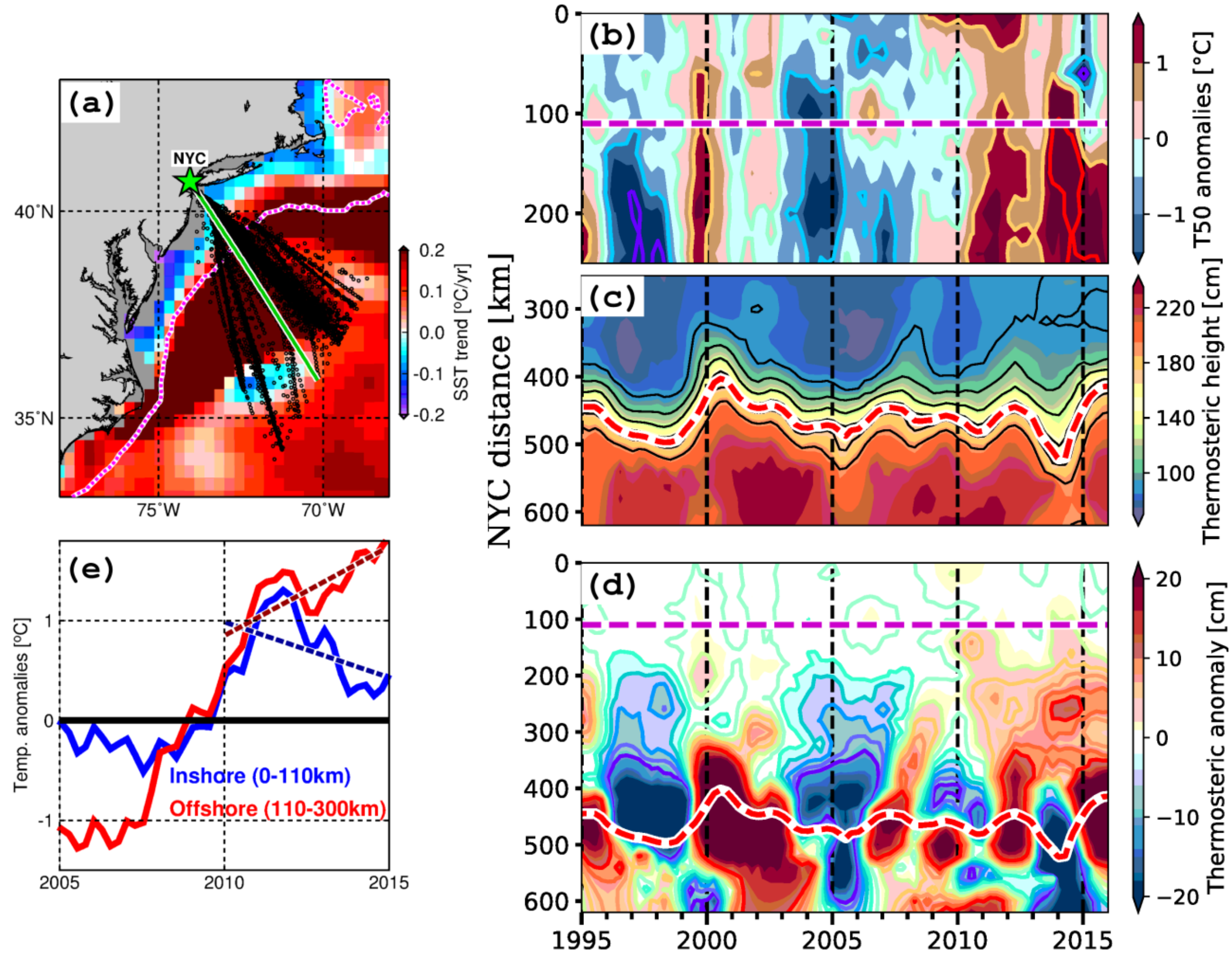

Figure 4 – Temperature changes off the Gulf Stream for coastal areas near New York City (NYC) (a) Location of XBT profile observations overlaid on satellite-derived SST trends for areas north of Cape Hatteras during 2010-2015. Green line indicates the location of the reference transect used. (b) Distance-time diagram of temperature anomalies derived from XBT data for the layer between 0 and 50 m projected along the reference transect (green line, panel a). (c) Distance-time diagram of the thermosteric height derived from XBT observations, and (d) thermosteric anomalies with respect to mean thermosteric height conditions during 1995-2016. The dashed magenta line in (b) and (d) indicates the shelf-break location. (e) Averaged temperature anomalies for the layer between 0 and 50 m for inshore areas (0-110 km from NYC, blue line), and offshore areas (110 - 300 km from NYC, red line). The dashed magenta lines in panels (a), (b), and (d) indicate the location of the 200m isobath. The dashed red line in panels (c) and (d) indicate the mean location of the Gulf Stream jet inferred as the thermosteric height gradient in (c).

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