Drivers of US East Coast sea-level variability from years to decades in a changing ocean—What do we know and what do we need to know?

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Sea level varies over all time scales. At shorter periods, from minutes to months, are the familiar sea-level fluctuations due to waves, tides, storms, tsunamis, and the seasons, which have been documented by coastal populations for millennia. At longer periods, from centuries to millennia and longer, are sea-level changes tied to such global climatic and geologic phenomena as the waxing and waning of the great ice sheets, plate tectonics, and convective flow within Earth's mantle, which have been the subject of scientific inquiry for more than a century (Carlson et al. 2019; Khan et al. 2019). In between, at periods of years to decades, are more subtle sea-level variations mainly related to ocean dynamics and regional climate. Understanding sea-level variations at these intermediate time scales is informative for inferring past changes in ocean currents and anticipating future coastal hazards (Burgos et al. 2018; Piecuch 2020). Here, I review recent progress on understanding past observed sea-level variability on interannual and decadal time scales along the US East Coast—a coastline of millions of people and homes vulnerable to sea-level rise and coastal flooding (Strauss et al. 2012; Kulp and Strauss 2019). In this context, "sea level" is used to mean relative sea level, which is the height of the sea surface relative to Earth's crust, as measured by a tide gauge.

Large-scale ocean circulation

Climate models predict that the US East Coast will experience greater-than-average sea-level rise during the next century related to changes in ocean circulation and climate (Yin et al. 2009; Landerer et al. 2007; Little et al. 2019). Over the past decade, numerous studies have used observations to test this hypothesis from models that US East Coast sea-level changes are related to changes in various components of the North Atlantic Ocean circulation, such as the Florida Current, Gulf Stream, and Atlantic meridional overturning circulation (Bingham and Hughes 2009; Boon 2012; Ezer and Corlett 2012; Sallenger et al. 2012; Ezer 2013, 2015, 2019; Ezer et al. 2013; Kopp 2013; Yin and Goddard 2013; Kenigson et al. 2014; Rossby et al. 2014; Thompson and Mitchum 2014; Woodworth et al. 2014; Goddard et al. 2015; McCarthy et al. 2015; Park and Sweet 2015; Domingues et al. 2016, 2018; Frederikse et al. 2017; Valle-Levison et al. 2017; Dong et al. 2019; Little et al. 2019; Piecuch et al. 2019a; Volkov et al. 2019; Ezer and Dangendorf 2020). A clear relation is observed between changes in the Florida Current—the Gulf Stream at Florida Strait—and coastal sea level along the South Atlantic Bight at various time scales, including interannual and decadal, such that sea level rises when the Current weakens or warms. Less clear (and more subject to debate) is the nature of any direct causal links between coastal sea level along the Mid-Atlantic Bight or Gulf of Maine and measures of the general circulation such as the latitude, width, speed, and transport of the Gulf Stream at various longitudes downstream of Cape Hatteras. To aid interpretation, analytical theories have been formulated for the connection between coastal sea level and open-ocean circulation, based on geostrophy and mass conservation in a boundary layer; these theories describe coastal sea level on a western boundary in terms of the superposition of signals propagating from upstream along coastal waveguides and along planetary potential vorticity contours, and possibly modified by friction (Thompson and Mitchum 2014; Minobe et al. 2017; Wise et al. 2018, 2020). Many questions remain regarding how sea level at the coast "feels" ongoing changes over the deep open ocean.

Local forcing and coastal processes

One reason it has been difficult to identify the "signal" of any link between US Northeast Coast sea level and measures of large-scale general circulation is the "noise" of local forcing over the shelf near the coast (Woodworth et al. 2014; Little et al. 2019). Anomalous onshore winds can raise coastal sea level through a wind setup, whereas anomalous alongshore winds (alongshore in the counterclockwise sense of coastal-wave propagation in the Northern Hemisphere) can also increase sea level and drive an alongshore flow at the coast through frictional dynamics. According to the inverted barometer effect, lower barometric pressure forces sea level to rise isostatically (without any accompanying change in ocean circulation), while higher barometric pressure drives a corresponding sea-level fall. And it follows from Knudsen's hydrographical theorem and thermal wind balance that an increase in the volumetric rate of freshwater runoff from a river at the coast drives an increase in coastal sea level in the far field downstream of that river source, in concert with a buoyant alongshore flow. Such locally forced coastal ocean processes account for a large portion of the variability in tide-gauge sea-level records along the US East Coast north of Cape Hatteras on interannual and decadal periods (Andres et al. 2013; Li et al. 2014; Woodworth et al. 2014; Piecuch and Ponte 2015; Piecuch et al. 2016, 2018a, 2019b; Frederikse et al. 2017; Kenigson et al. 2018; Domingues et al. 2018; Chen et al. 2020). For example, Piecuch et al. (2019b) estimate that barotropic response to wind and pressure accounts for 20-50% of the interannual-to-decadal variance in US Northeast Coast tide-gauge data, but <20% of the data variance along the US Southeast Coast during the past century.

Redistribution of ice and water

Other studies emphasize the influence of ice and water mass redistribution on US East Coast sea level. When water mass is redistributed at the surface and exchanged between the ocean and other components of the climate system, Earth's crust, gravity field, and rotation vector are perturbed, leading to spatial patterns of sea-level change (Gregory et al. 2019). Davis and Vinogradova (2017) determine that ice melt from Greenland and Antarctica accounts for most of the sea-level acceleration observed in tide-gauge records along the US Southeast Coast since the 1990s. Frederikse et al. (2017) estimate that present-day mass redistribution related to the melting of ice sheets and mountain glaciers and the building of dams explains ~30% of the acceleration observed in sea level from Virginia to Maine during 1965-2014. Karegar et al. (2016) identify the role of groundwater extraction in determining variable rates of sea-level change seen along the US Southeast Coast between South Carolina and Virginia in recent decades, revealing that rates of vertical land motion can change by ~1 mm/year on decadal time scales in response to changes in groundwater levels. These and other studies (Karegar et al. 2017; Johnson et al. 2018) demonstrate that ice and water mass redistribution, and resulting gravitational, rotational, and deformational effects, are important contributors to US East Coast sea-level changes on quasi-decadal time scales over the past century.

Questions, challenges, and opportunities for the future

These recent studies have improved our understanding of changes in US East Coast sea level on interannual and decadal time scales. They also point to new questions, challenges, and opportunities to be addressed in the future. I briefly mention some possibilities below.

How did US East Coast sea level vary during earlier time periods?

Much of our knowledge of US East Coast sea level comes from tide-gauge records, many of which only span the past century, which is a short period relative to Earth's long climate history. To determine how representative these data are of interannual and decadal sea-level variability more generally, **future studies should interrogate US East Coast sea-level variability for earlier time periods**. Newly available instrumental and proxy data records, which extend the record of interannual and decadal sea-level variability centuries (Talke and Jay 2013; Talke et al. 2018) and millennia (Kemp et al. 2014, 2015) into the past, will be helpful to this end. A fuller portrait in space and time could be painted by applying spatiotemporal models to these new data (Cahill et al. 2015, 2016; Piecuch et al. 2017; Ashe et al. 2019; Walker et al. 2020). For example, Gehrels et al. (2020) apply probabilistic models to salt-marsh-sediment-based sea-level reconstructions, and find that there was a period of rapid multi-decadal sea-level acceleration on the US Northeast Coast in the 1700s, which was almost as rapid as accelerations observed during the twentieth century. Such studies provide a basis for evaluating whether the basic characteristics of sea-level variability will be the same or different under climate change.

What is the spectrum of vertical land motion along the US East Coast?

Since the advent of continuous Global Positioning System (GPS) monitoring, the community has increasingly recognized the importance of vertical land motion to coastal sea-level change (Blewitt et al. 2016; Hamlington et al. 2016; Wöppelmann and Marcos 2016; Santamaria-Gomez et al. 2017). While it has long been established that vertical land motion related to glacial isostatic adjustment (Earth's ongoing response to the last deglaciation) is a crucial large-scale, long-term control on sea-level trends (Love et al. 2016; Frederikse et al. 2017; Caron et al. 2018; Piecuch et al. 2018b), it has grown clear that high-frequency, short-scale crustal motions also contribute importantly to coastal sea-level changes (Featherstone et al. 2015; Frederikse et al. 2017; Johnson et al. 2018). It remains to fully characterize the frequency-wavenumber spectrum of vertical land motion and identify the mechanisms responsible for crustal motion at short periods and small scales along the US East Coast in the context of sea level and coastal flooding. Recent papers focusing on Norfolk, Virginia and Miami Beach, Florida use GPS records alongside remotely sensed data from interferometric synthetic aperture radar to map vertical land motion on local spatial scales (Bekaert et al. 2017; Buzzanga et al. 2020; Fiaschi and Wdowinski 2020). For example, Buzzanga et al. (2020) use Sentinel-1 data from the past five years to show that the mean rate of subsidence in Hampton Roads, Virginia is ~-4 mm/year, but that there is substantial spatial variation such that rates can vary by ~+/-3 mm/year over short spatial scales of kilometers to tens of kilometers. Such studies serve as potential templates towards more complete mapping of the drivers of coastal sea-level change and vulnerability of US East Coast communities to future flood hazards.

How are high-frequency statistics of US East Coast sea level changing at low frequencies?

In addition to year-to-year and decade-to-decade variations in US East Coast mean sea level, there are low-frequency modulations of high-frequency variations in tides, storms, and seasonality. The amplitude of the sea-level annual cycle on the US Southeast Coast varies on decadal time scales, reflecting a dynamic ocean response to wind forcing over the western subtropical North Atlantic (Wahl et al. 2014; Domingues et al. 2016; Calafat et al. 2018). The statistics of sea-level extremes along the US East Coast, fluctuating at decadal periods, vary in tandem with large-scale climate modes like the North Atlantic Oscillation, Arctic Oscillation, and Atlantic Multidecadal Variability (Wahl and Chambers 2015, 2016). Long tide-gauge records along the US East Coast show changes in tidal range, from more minor gradual oscillations to major abrupt changes (see recent reviews by Talke and Jay 2020; Haigh et al. 2020). **More work is needed to establish how and why such modulations and changes in tides, surges, and seasonality occur along the US East Coast, whether they are independent or covary, and the consequences for the statistics of sea-level extremes and high-tide flooding** (Ray and Foster 2016; Sweet et al. 2016; Burgos et al. 2018).

What is the origin of the spatial covariance structure of US East Coast sea level variability?

There is a peculiar spatial structure to sea-level variability along the US East Coast: sea levels north of Cape Hatteras vary coherently along the coast from Virginia to Maine, but are uncorrelated with sea-level variations south of Cape Hatteras from Florida to Virginia (Thompson and Mitchum 2014; Woodworth et al. 2014; McCarthy et al. 2015; Piecuch et al. 2016; Calafat et al. 2018). This "break" in covariance is surprising given a basic expectation for coastal sea level to be coherent over thousands of kilometers due to boundary waves (Hughes and Meredith 2006; Hughes et al. 2019). Hypotheses have been submitted, some having to do with ocean currents (Thompson 1986; Thompson and Mitchum 2014; McCarthy et al. 2015), others with the geometry of the coast and bathymetry (Meade and Emery 1971), but **the origin of this spatial-covariance structure in US East Coast sea level remains to be established**. Such knowledge will be important for evaluating climate models and assessing whether such covariance structure is a permanent feature of coastal sea level or if a distinct structure will emerge in the future under climate change.

How will new altimetry data change our understanding of US East Coast sea level variability?

Tide gauges provide long records of sea level at the coast, but these data have shortcomings. For example, they are spatially "one dimensional," in the sense that networks of tide gauges observe changes in the alongshore direction, but are "blind" to the structure of sea level offshore. Conventional satellite-altimetry data products have, in the past, not been helpful in this regard, since the quality of the data can be degraded near the coast due to errors in the instrumental measurement itself as well as uncertainties in the geophysical corrections. **Newly reprocessed, dedicated coastal altimetry products and the upcoming Surface Water and Ocean Topography wide-swath altimeter mission promise to change the game, and revolutionize our view of sea level and land-ocean interactions along the US East Coast as well as over the global coastline** (Passaro et al. 2015; Birol et al. 2017; Morrow et al. 2019).

Are ongoing changes in the western North Atlantic Ocean affecting US East Coast sea level?

Relationships between coastal sea level and large-scale ocean circulation remain an important topic of future investigation (Ponte et al. 2019). Noteworthy in this context are the remarkable changes ongoing in the western North Atlantic Ocean. In recent decades, the Gulf of Maine has warmed much faster than the global average (Pershing et al. 2015), marine heat waves have grown longer and more frequent (Oliver et al. 2019), the Gulf Stream has grown increasingly unstable (Andres 2016), warm core rings have been shed more often from the Gulf Stream and lived longer than previously (Gangopadhyay et al. 2019), and intrusions of warm, salty slope and Gulf Stream waters onto the continental shelf have become more frequent (Ullman et al. 2014; Zhang and Gawarkiewicz 2015; Gawarkiewicz et al. 2018). **It remains to establish if any of these regional oceanographic changes are relevant to US East Coast sea level**. The interested reader is directed to Little et al. (2019) for more general future research directions on this topic.

Conclusion

Sea level is a "whole-Earth" process, and sea-level changes reflect myriad geologic and climatic processes acting across space and time. Here I have reviewed recent progress on understanding drivers of observed year-to-year and decade-to-decade US East Coast sea-level change. I mainly emphasize observational studies published during the past decade, and focus largely on the relevance of large-scale circulation, locally forced processes, and surface mass redistribution. I also point to some opportunities for future research, highlighting new technologies and data as well as pressing changes ongoing in the ocean. I hope this short review (see Little et al. 2019 for a more detailed treatment) motivates future research and is informative to both scientific and non-scientific audiences, serving as a jumping-off point for a deeper dive into the literature.

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