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Masked Shoreline Erosion at Large Spatial Scales as a Collective Effect of Beach Nourishment

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Key Points:
- Conventional long-term rates of shoreline change may systematically underestimate erosion hazard
- Beach nourishment since 1960 has delivered enough sand to the U.S. Atlantic Coast to likely account for a trend toward shoreline accretion
- The collective, diffuse effect of beach nourishment on shoreline change may constitute a quantitative signature of coastal geoengineering

Supporting Information:
- Supporting Information S1

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Abstract Sea-level rise along low-lying coasts of the world's passive continental margins should, on average, drive net shoreline retreat over large spatial scales (>10^2 km). A variety of natural physical factors can influence trends of shoreline erosion and accretion, but trends in recent rates of shoreline change along the U.S. Atlantic Coast reflect an especially puzzling increase in accretion, not erosion. A plausible explanation for the apparent disconnect between environmental forcing and shoreline response along the U.S. Atlantic Coast is the application, since the 1960s, of beach nourishment as the predominant form of mitigation against chronic coastal erosion. Using U.S. Geological Survey shoreline records from 1830–2007 spanning more than 2,500 km of the U.S. Atlantic Coast, we calculate a mean rate of shoreline change, prior to 1960, of −55 cm/year (a negative rate denotes erosion). After 1960, the mean rate reverses to approximately +5 cm/year, indicating widespread apparent accretion despite steady (and, in some places, accelerated) sea-level rise over the same period. Cumulative sediment input from decades of beach-nourishment projects may have sufficiently altered shoreline position to mask "true" rates of shoreline change. Our analysis suggests that long-term rates of shoreline change typically used to assess coastal hazard may be systematically underestimated. We also suggest that the overall effect of beach nourishment along of the U.S. Atlantic Coast is extensive enough to constitute a quantitative signature of coastal geoengineering and may serve as a bellwether for nourishment-dominated shorelines elsewhere in the world.

Plain Language Summary Sea-level rise over decades to centuries should, on average, drive shoreline erosion. However, analysis of shoreline change over recent decades along the U.S. Atlantic Coast indicates a pronounced decrease in erosion rates. We examine this enigmatic pattern of shoreline behavior in the context of beach nourishment, which, after 1960, became the predominant form of coastal erosion mitigation in the United States. We find that before beach nourishment became widespread, shoreline change along the U.S. Atlantic Coast was, on average, strongly erosional. We suggest that if coastal erosion has been comprehensively "masked" by beach nourishment, then historical rates of shoreline change, calculated from shoreline surveys prior to 1960, are likely more representative of underlying erosion hazard.

1. Introduction

Along low-lying coasts at passive tectonic margins around the world, sea-level rise should, on average, drive net long-term shoreline erosion over large spatial scales (>10^2 km; FitzGerald et al., 2008; Passeri et al., 2015). Coastal erosion is not necessarily an inevitable consequence of sea-level rise: A variety of natural, dynamic physical factors can influence positive and negative changes in shoreline position over decades to centuries (Cooper & Pilkey, 2004; FitzGerald et al., 2008; Kench et al., 2018; Komar & Holman, 1986; Nicholls & Cazenave, 2010; Passeri et al., 2015; Wong et al., 2014; Zhang et al., 2004). For example, isostacy (regional flexure of the Earth's crust) can exacerbate relative sea-level rise, such as through sediment loading at a major river delta (Syvitski et al., 2009), or effect relative sea-level fall, through long-term rebound after an ice sheet (Dyke et al., 1991; Lambeck & Chappell, 2001; Shennan et al., 2000). Nearshore geology can interact with wave forcing to drive cycles of erosion and accretion at specific reaches, both local (Houser et al., 2008; Lazarus & Murray, 2011) and regional (Valvo et al., 2006). Sediment supply, type, and whether littoral sediment comes from one or a combination of fluvial, offshore, or local (e.g., soft cliff) sources can differentially affect shoreline position (FitzGerald et al., 2008), even within the same littoral cell (Willis & Griggs, 2003). Ecological feedbacks by which coastal vegetation (e.g., marshes and mangroves) or coral systems trap, retain, and create sediment may use relative sea-level rise to drive shoreline advance (Kench

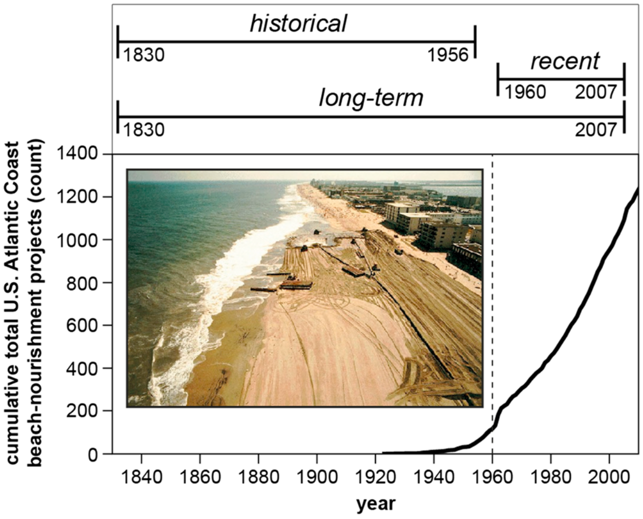

Figure 1. Ranges of survey dates used to calculate historical, recent, and long-term rates of shoreline change (see also Figure S1), with the cumulative number of nourishment projects along the U.S. Atlantic Coast plotted over time. Dashed vertical line marks 1960. Inset photo shows an oblique aerial view of a beach-nourishment project (courtesy of NOAA).

et al., 2018; Kirwan & Megonigal, 2013). Regional wave climates (multiannual to multidecadal distributions of deep-water wave height and direction of travel) reshape coastal planforms by setting up gradients in wave-driven alongshore sediment flux that drive transient spatial patterns of erosion and accretion over large spatial scales (~10^1–10^2 km; Ashton & Murray, 2006a, 2006b; Lazarus, Ashton, et al., 2011; Lazarus et al., 2012). Over time, those spatial patterns of shoreline change may shift with prevailing weather patterns (Thomas et al., 2016; Valvo et al., 2006).

Even in this global context of varied and variable potential responses to environmental forcing, recent trends in shoreline change along the U.S. Atlantic Coast are enigmatic (Hapke et al., 2013). Tide-gauge records show that rates of relative sea-level rise along the U.S. Atlantic Coast vary over time but are increasing (Church & White, 2011; Gutierrez et al., 2011; Hapke et al., 2010; Morton & Miller, 2005). In the northern Mid-Atlantic region, rates of relative sea-level rise have been markedly accelerating (Ezer & Atkinson, 2014; Sallenger et al., 2012). In addition to sea-level rise, observations and modeled hindcasts of deep-water wave conditions in the Atlantic Ocean show a trend of increasing significant wave height over recent decades (Komar & Allan, 2008) and into the past century (Bertin et al., 2013). Greater wave heights will tend to drive larger fluxes of littoral sediment transport (Ashton & Murray, 2006a, 2006b). However, rather than reflecting widespread and intensified erosion, mean rates of recent shoreline change along the U.S. Atlantic Coast show a predominant increase in accretion (Hapke et al., 2010, 2013; Himmelstoss et al., 2010; Miller et al., 2005; Morton & Miller, 2005). What makes the U.S. Atlantic Coast such an exceptional example of this apparent disconnect between environmental forcing and shoreline response is spatial scale. The trends in rates of shoreline change over recent decades are so distorted across such extended length scales (on the order of 10^2–10^3 km) that they appear systemic and indicative of dynamics distinct from natural conditions (Hapke et al., 2013; Johnson et al., 2015; Lazarus et al., 2016; Nordstrom, 2003).

The U.S. Geological Survey (USGS) has previously reported a marked, positive shift (toward accretion) between long-term and short-term rates of shoreline change along much of the U.S. Atlantic Coast north of North Carolina (Hapke et al., 2013). National estimates of U.S. shoreline change are based on composites of shoreline surveys dating back to 1830; these data represent the best available and most comprehensive coverage for such extended spatial and temporal scales (Hapke et al., 2010; Himmelstoss et al., 2010; Miller et al., 2005; Morton & Miller, 2005). National assessments by the USGS include two categorical rates of shoreline change: “long-term” and “short-term” (Hapke et al., 2010, 2013; Himmelstoss et al., 2010; Miller et al., 2005; Morton & Miller, 2005). In a recent analysis, the USGS offers that “a reduction in the percentage of eroding coast in the past two to three decades suggests that human alteration of the coastline is having a measureable impact over large spatial scales” and “even moderate amounts of development are associated with reduced erosion indicating that activities associated with protecting and preserving human infrastructure have a substantial and long-lasting impact” (Hapke et al., 2013).

Natural supply of sandy sediment to much of the U.S. Atlantic Coast is limited to what wave action can rework from patchy, relict deposits on the continental shelf (Meade, 1982; Milliman et al., 1972; Thieler et al., 2014). A possible explanation, then, for the apparent disconnect between sea-level rise and shoreline response along so much of the U.S. Atlantic Coast is the application, since the 1960s, of beach nourishment as the predominant form of mitigation against chronic coastal erosion (NRC, 1995, 2014; Figure 1). Beach nourishment involves importing and redistributing large volumes of sand—typically 10^6–10^7 m^3 (PSDS, 2017)—to widen an eroding beach. From Maine to South Florida, 1,341 nourishment projects have occurred since 1923 and 91% of them after 1960 (PSDS, 2017). An analysis of shoreline change at Cape Fear, North Carolina, suggests that recurrent beach nourishment projects may have cumulatively altered the response of the cape shoreline to natural physical drivers (e.g., wave climate and gradients in alongshore sediment flux) enough to “compensate for — and therefore to mask — natural responses to wave climate change that might otherwise be discernible in patterns of shoreline change alone” (Johnson et al., 2015). Beyond the U.S.

Atlantic Coast, beach nourishment is prevalent in every U.S. coastal state, including the Great Lakes (Trembanis et al., 1999), and is widely applied in Europe (Hanson et al., 2002), Australia (Cooke et al., 2012), and elsewhere in the world (Nordstrom, 2003; Walker & Finkl, 2002).

To examine the potential influence of beach nourishment, specifically, on rates of shoreline change along ~2,500 km of the U.S. Atlantic Coast from Massachusetts to South Florida (Figures 2, S1, and S2 of the supporting information), we use the USGS repository of composite shorelines from 1830–2007 (Himmelstoss et al., 2010; Miller et al., 2005) and the comprehensive data set of beach nourishment projects maintained by the Program for the Study of Developed Shorelines (PSDS, 2017). We treat 1960 as the benchmark year for the onset of beach nourishment as the predominant mitigation response to coastal erosion (Figure 1; NRC, 2014). To distinguish our categorical rates of shoreline change from those reported by the USGS, we define them here as “historical” (pre-1960) and “recent” (post-1960). We make this distinction because the method by which the USGS calculates their long-term rate involves taking a linear regression through all available shoreline surveys at a given location (Hapke et al., 2010, 2013; Himmelstoss et al., 2010; Miller et al., 2005; Morton & Miller, 2005), thus including any effects of nourishment in the result. The historical rate that we calculate still does not represent “natural” shoreline change: human interventions (direct and indirect) in shoreline position along the U.S. Atlantic Coast predate the 1830 shoreline survey (e.g., Kirwan et al., 2011). However, estimating rates of shoreline change prior to the onset of extensive inputs from beach nourishment may yield a more representative assessment of chronic erosion hazard as a component of coastal vulnerability (Thieler & Hammar-Klose, 1999; USGS, 2018).

Three aspects of our analysis differentiate this work from related efforts by the USGS (Hapke et al., 2013). First, where the USGS compared long-term and recent shoreline change for the coastline from southern Maine to Virginia, our investigation extends from Massachusetts to the terminus of South Florida—nearly the double the total distance. Second, by setting 1960 as a reference date for the onset of beach nourishment as a ubiquitous form of mitigation, we isolate a mean historical shoreline-change rate that is significantly higher than USGS calculations of long-term shoreline-change rates that are inevitably moderated by beach nourishment (Figures 1 and 2). Third, we spatially correlate rates of historical and recent shoreline change with records of beach nourishment to isolate and estimate the mean alongshore influence of nourishment inputs, specifically.

Our results suggest that mean rates of shoreline change over the past century (and longer) may be more erosional than previously reported long-term rates would convey. We also estimate that enough sand has been delivered to the U.S. Atlantic Coast since 1960 to likely account for the net positive change in shoreline position overall. Furthermore, we find that a majority of places along the U.S. Atlantic Coast are close enough to beach-nourishment sites to register significant reductions in their local erosion rates.

2. Methods

We calculated rates of shoreline change along the U.S. Atlantic Coast using publicly available shape files of shoreline surveys compiled by the USGS from T-Sheets, aerial photography, and lidar (Himmelstoss et al., 2010; Miller et al., 2005). Because the USGS composite shorelines are stitched together from discontinuous surveys taken in various years, the range of available surveys varies alongshore (Figure S1).

Along the USGS shoreline surveys, we cast shore-normal transects at 1-km spacing (from a 50-m smoothed baseline cast) using the Digital Shoreline Analysis System tool in ESRI ArcGIS (Thieler et al., 2008). At each transect, we found the end-point rate of change in shoreline position for three categories of “end-point rate”: historical (pre-1960), recent (post-1960), and long-term (full span). Start and end dates used to calculate the historical rates of shoreline change range from 1830–1956; recent rates from 1960–2007; and long-term rates from 1830–2007 (for direct comparison to USGS time frames; Figures 1 and S1 and Table S1). We calculated historical rates of shoreline change from the difference in shoreline position between the survey nearest but prior to 1960 and the earliest available survey, divided by the time between surveys (mean time frame ~73 years). We calculated recent rates from the difference in shoreline position between the most recent survey available and the first survey after 1960 (mean time frame ~27 years). We also calculated a long-term rate of change between 1830 and 2007 to match the temporal comparisons by the USGS (Hapke et al., 2010; Himmelstoss et al., 2010; Miller et al., 2005 ; Morton & Miller, 2005); those long-term rates only include start dates prior to 1899 (i.e., 1830–1899) and end dates after 1997 (i.e., 1997–2007). To address especially dynamic

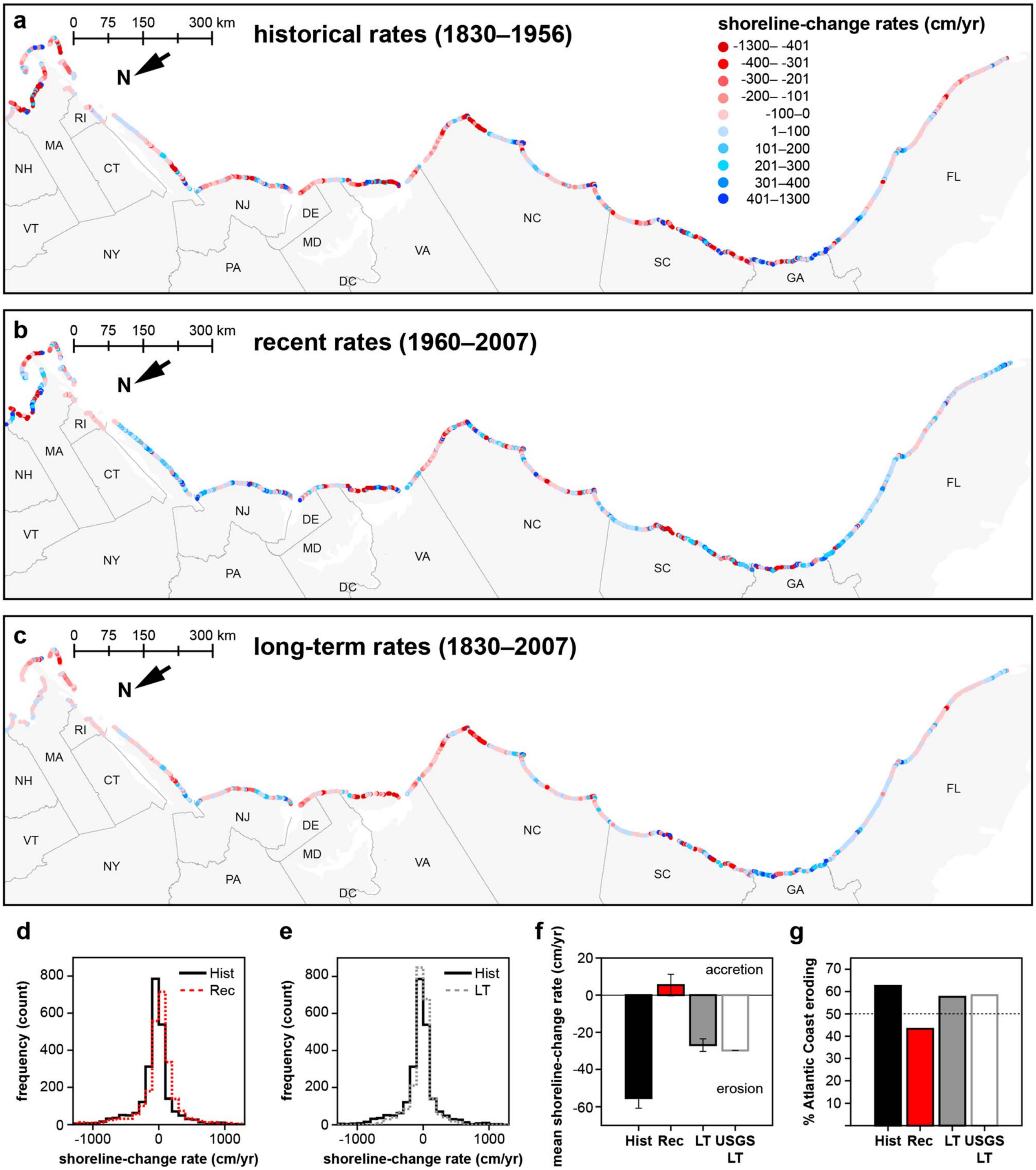

Figure 2. (a) Historical, (b) recent, and (c) long-term rates of shoreline change along the U.S. Atlantic Coast. Color represents the rate (cm/year) at each 1 km alongshore. (Rates are also detailed in Figure S2.) Histograms show the relative distributions of (d) historical (black, solid) versus recent (red, dotted) rates and (e) historical (black, solid) versus long-term rates (gray, dotted). Bar charts compare historical (Hist), recent (Rec), long-term (LT), and the U.S. Geological Survey long-term (USGS LT) rates, for (f) mean erosion rate (cm/year; whiskers ±1 standard error of the mean) and (g) the percentage of the U.S. Atlantic Coast that is eroding. (Descriptive statistics are listed in Table S2.)

sections of shoreline that may have migrated out of (or into) fixed transect positions, resulting in extreme apparent rates of change (Hapke et al., 2010), we included only transects with rates that fall within the 99% distribution (+/−2.58 σ around the mean) of the total data set.

The method we used to calculate end-point rates differs in minor but notable ways from the method used by the USGS. The short-term rates from the USGS are the end-point rate between the two most recent surveys at a given location; their long-term rates are calculated as the linear regression through shoreline position in all available surveys at a given location (Hapke et al., 2010, 2013; Himmelstoss et al., 2010; Miller et al., 2005; Morton & Miller, 2005). The USGS also use a higher sampling frequency, casting a transect every 50 m alongshore to our 1 km.

Despite these methodological differences (including the coarser spacing between transects), the mean long-term rates that we calculate (−27 cm/year) are comparable to those based on the USGS reports (−30 cm/year; Figure 2f and Tables S2 and S3), and the mean percentage of eroding U.S. Atlantic Coast that we calculate is within 1% of the corresponding USGS mean (Figure 2g and Table S3). The mean shoreline-change rate and percentage of eroding coastline that we ascribe to the USGS measurements are summary metrics that we derived from the original USGS reports (Hapke et al., 2010; Himmelstoss et al., 2010; Miller et al., 2005; Morton & Miller, 2005), which list mean rates of shoreline change by state, along with the number of transects used to calculate those means. We weighted those state-by-state means by their number of constituent transects to find what we call the overall "USGS mean" of the U.S. Atlantic Coast.

The USGS national assessments of shoreline change split the U.S. Atlantic Coast into two main regions (Northeast and Southeast); error reporting differs slightly between the respective reports. The report for the Northeast cites an average uncertainty, for lidar surveys, of 2.3 m (Hapke et al., 2010; Himmelstoss et al., 2010). By contrast, the report for the Southeast cites maximum error, which includes large excursions (>20 m) attributed to localized offsets between shoreline records (Miller et al., 2005; Morton & Miller, 2005). We include those error maxima here (Figure S3 and Table S2); error metrics for the Southeast Atlantic surveys continue to be updated (Himmelstoss et al., 2017).

We related spatial patterns of shoreline change to corresponding data for population density (Figures 3a–3e) and beach nourishment projects (Figures 3f–3j). Using population density at the ZIP Code level from 2010 U.S. Census statistics (ESRI, 2012), we spatially joined those data to the shoreline transects. A ZIP Code is an index of local-scale spatial zones (for postal delivery) across the United States. ZIP Code areas are not necessarily the same as municipal boundaries: one or more municipalities may overlap with a given ZIP Code and vice versa. Where publically available digitized maps of local municipal boundaries vary widely in their completeness, ZIP Codes offer complete and continuous spatial coverage of the entire U.S. Atlantic Coast (Armstrong et al., 2016), making them amenable to merging with other spatial data. Locations and counts of beach nourishment projects along the U.S. Atlantic Coast came from the database maintained by the Program for the Study of Developed Shorelines (PSDS, 2017). We excluded any record of beach nourishment prior to 1960 or that postdates the final shoreline survey at a given location. To calculate the proximity of each transect to the nearest beach nourishment project, we used a Geographic Information System (GIS) "near table" and binned the results into bands of 1-km "buffers."

To estimate the approximate total volume of sediment accreted along the U.S. Atlantic Coast since 1960, we used empirical scaling factors relating horizontal shoreline change to beach volume (Farris & List, 2007). We then compared that derived volume to the reported estimated volume of sand delivered from beach nourishment (PSDS, 2017; Table S4).

3. Results

Historical, recent, and long-term shoreline change rates vary spatially along the U.S. Atlantic Coast (Figures 2a–2c and S2). However, comparing the distributions of the categorical rates (Figures 2d and 2e) shows that historical rates of shoreline change are significantly more negative (indicating erosion) than recent (Mann-Whitney $W = 5145138.5$, $p < 0.01$) and long-term rates (Mann-Whitney $W = 5356632.0$, $p < 0.01$). We find the mean historical rate of shoreline change for the entire U.S. Atlantic Coast is −55 cm/year. This rate is 60 cm/year more negative than the mean recent rate of shoreline change (+5 cm/year) and 28 cm/year more negative than the mean long-term rate of shoreline change (−27 cm/

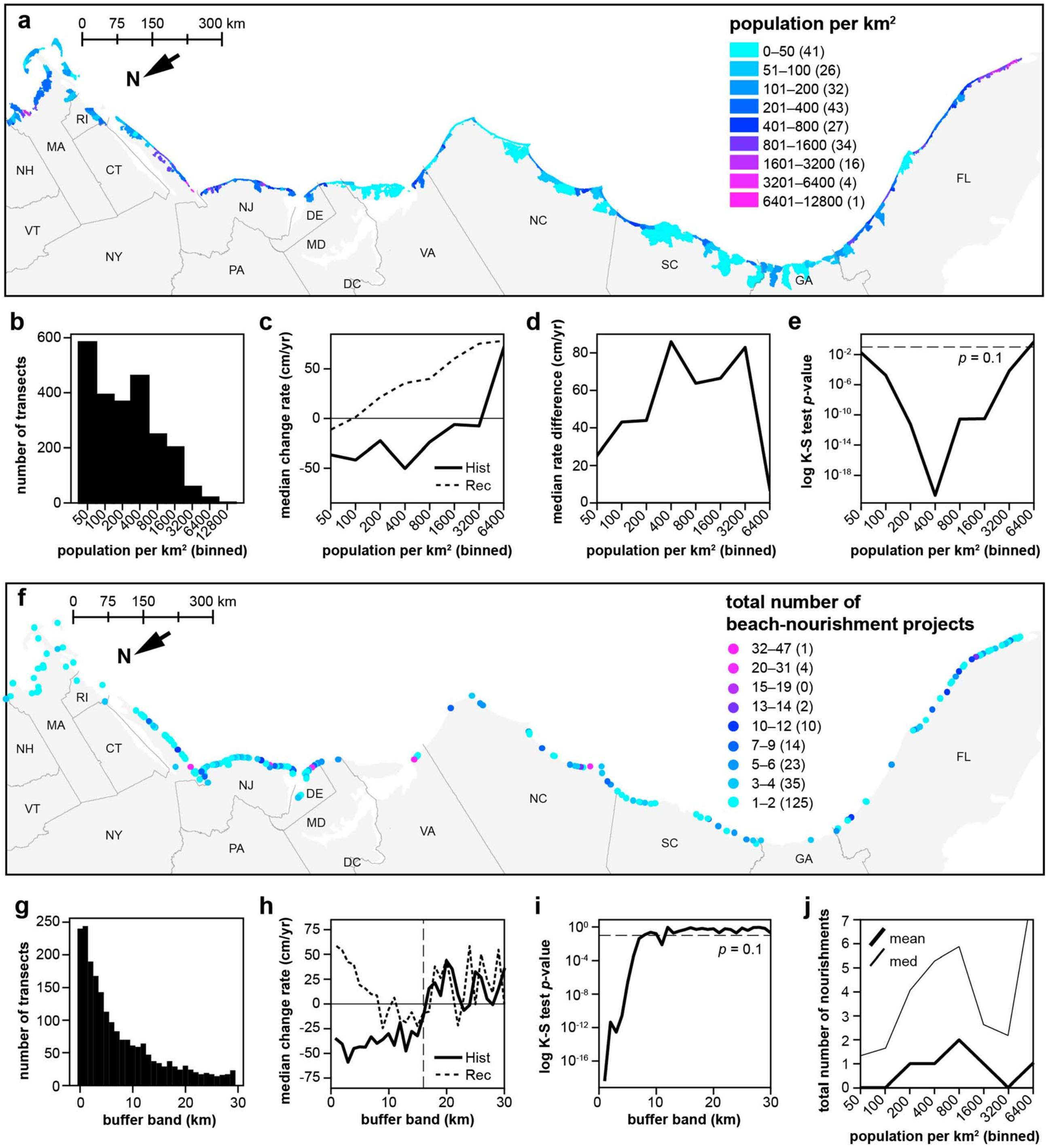

Figure 3. (a) Map of population density (population per km^2) for coastal ZIP Code zones along the U.S. Atlantic Coast. (b) Histogram showing the distribution of transects versus population density (binned). (c) Median historical and recent erosion rates (cm/year) and (d) the difference between them versus population density. (e) Plot of p values from a Kolmogorov-Smirnov test of historical versus recent erosion rates for transects within each population density; values below the dotted line are significant (the relative distributions are quantifiably different from each other) at $p < 0.1$. (f) Map of total number of beach-nourishment projects since 1960 at sites along the U.S. Atlantic Coast. (g) Histogram showing distribution of transects within each 1-km buffer distance from the nearest beach-nourishment site. (h) Median recent and historical erosion rates (cm/year) versus buffer distance (see also Table S5). (i) Plot of p values from a Kolmogorov-Smirnov test of historical versus recent erosion rates for transects within distance buffer bands; values below the dotted line are significant (the relative distributions are quantifiably different from each other) at $p < 0.1$. (j) Mean (thick line) and median (thin line) number of nourishment projects relative to population density, showing a pattern similar to the overall positive differences between recent and historical rates versus population density in (e).

year; Figure 2f). Although our method for calculating rates of shoreline change differs from the one used by the USGS, the mean long-term rate of shoreline change that we determine (−27 cm/year) is comparable to the equivalent rate in USGS reports (−30 cm/year; Hapke et al., 2010; Himmelstoss et al., 2010; Miller et al., 2005; Morton & Miller, 2005; Figure 2f). The proportion of transects at which rates of shoreline change are negative reflects the percentage of the U.S. Atlantic Coast that is eroding: more of the coast appears erosional in the historical rates (63%) than in the recent (43%) and long-term rates (58%; Figure 2g and Table S3).

To test for potential spatial relationships between rates of shoreline change and coastal population pressure (as a proxy for development intensity; NOAA, 2013), we assigned to each transect the population density (people per square kilometer) in the coastal ZIP Code from which it extends (Figures 3a and 3b). We find a positive correlation between the rate of shoreline change (historical and recent) and population density (Figure 3c). Comparing the historical and recent rates relative to population density shows the difference between their trends is greatest (and statistically significant) over the middle range of population density (Figures 3d and 3e). This quantitative result aligns with a classification-based assessment of coastal-development intensity in the Northeast region and the relationship of those class types to rates of shoreline change (Hapke et al., 2013). Assuming that sparsely populated and/or undeveloped shorelines are free to change “naturally” in the absence of direct human intervention, we might expect that their historical and recent trends would, on average, show relatively little difference. That is, the mean historical and recent shoreline-change rates might not be the same, but we would not expect to see an overall reversal from erosion to accretion. Indeed, consistent with Hapke et al. (2013), we find that where population density is low, recent rates are generally less erosional than the historical rates but erosional nonetheless (Figures 3c and 3d). There is a similarly negligible difference between historical and recent shoreline-change rates where population density is highest (Figure 3d), perhaps indicating the sustained maintenance of local shoreline position.

To explore potential spatial effects of beach nourishment (Figure 3f) on proximal rates of shoreline change, at each shore-normal transect, we measured the distance alongshore to the nearest beach-nourishment site. (We consider sites regardless of the number of nourishment projects recorded there or when the site was last active). We refer to these alongshore distances as buffers and binned them into bands 1 km long. We estimate that nearly 74% of the coastline is within ~16 km of a nourishment site (Figure 3g). At the nourishment sites themselves (where buffer = 1 km), historical rates of shoreline change are negative (Figure 3h), consistent with the expectation that beach nourishment after 1960 would occur in zones of chronic erosion. Up to ~16 km alongshore from a nourishment site, historical rates of shoreline change are generally negative—but recent rates (post-1960) are mostly positive, indicating accretion, with the largest positive differences between historical and recent rates at nourishment sites (Figure 3h). With increasing buffer length, the historical and recent rates converge (at least up to ~30 km; Table S5), and >16 km their respective distributions become statistically indistinguishable (Figure 3i). Tellingly, the number of nourishment events relative to population density peaks over the same middle range of population densities (Figure 3j) where the differences between historical and recent rates of shoreline change are greatest (Figure 3d).

We do not ascribe particular mechanistic importance to the alongshore distance of 16 km, but the empirical result is not without physical basis. Beach nourishment projects are typically scrutinized in the cross-shore dimension, for the characteristic way in which wave action will relax a nourishment profile across the local shoreface (Dean & Dalrymple, 2004). But numerical modeling of long-term, nonlocal physical responses to shoreline interventions suggests that alongshore gradients in wave-driven net sediment flux are capable of affecting shoreline changes over several tens of kilometers alongshore (Ells & Murray, 2012; Williams et al., 2013).

Finally, we estimate that the summed total of estimated nourishment volumes since 1960 could account for the 60 cm/year reversal from negative historical to positive recent rates of shoreline change (Table S4). Approximately 95% of nourishment projects between 1960 and 2007 in the PSDS database (as of 2017) include an estimated or reported volume. Since 1960, an estimated ~285 million cubic meters of nourishment sand has been deposited along the U.S. Atlantic Coast (PSDS, 2017)—the equivalent of ~114 m^3/m, were it distributed evenly along the coast. Meanwhile, the summed total of shoreline change, positive and negative, between 1960 and 2007 along the entire U.S. Atlantic Coast is net +54,702 m. Using an empirical scaling factor (c, where $c = 1–3$) relating horizontal to volumetric change for a sandy shoreline (Farris & List, 2007), +54,702 m of shoreline change distributed over 2,339 transects for which there is a historical and recent rate (and assuming the rate per transect is the same as the rate per meter alongshore) equates to between 23 m^3/m ($c = 1$) and 70 m^3/m ($c = 3$). This simplified balance suggests that the total volume of beach nourishment since 1960 could be at least twice (for $c = 3$) the estimated volume necessary to account for net shoreline change in the same period. Even using a large scaling factor ($c = 5$) to generate a deliberately conservative estimate of shoreline-change volume yields 117 m^3/m, within ~3% of the estimated volume from beach nourishment. Of the estimated total 285 million cubic meters in nourishment, approximately 52 million cubic meters (~18%) is attributed to navigational works, such as inlet maintenance (PSDS, 2017). Removing that navigational volume from consideration leaves 232 million cubic meters of sand applied since 1960 or 93 m^3/m—still ~33% more than the estimated volume of net shoreline change (for $c = 3$; increasing the scaling factor to a more conservative value of $c = 4$ results in near equivalency). An alternative calculation of this volumetric comparison, based on shoreline-change rate rather than absolute shoreline change, yields lower but still sufficient nourishment volumes per meter alongshore to account for positive shoreline change since 1960 (Table S4).

4. Discussion and Implications

Our results provide an empirical indication that recent rates of shoreline change along the U.S. Atlantic Coast are, on average, less erosional than historical rates. This shift has occurred despite evidence of intensified environmental forcing, including acceleration in rates of relative sea-level rise and increased significant wave height in offshore wave climates. We suggest that the use, since the 1960s, of beach nourishment as the predominant form of mitigation against chronic coastal erosion in the United States (NRC, 1995, 2014) could explain the unexpected reversal in shoreline-change trends.

Although our analysis uses 1960 as a benchmark date to differentiate historical from recent rates of shoreline change, comparison to previous work (Hapke et al., 2013) suggests that our results are relatively insensitive to the choice of date (Table S3). In the Southeast (North Carolina to Florida), for example, there is a stark gap in surveys between the late 1940s and mid-1960s, leaving no substantively different alternatives for our selection of dates. In the Northeast, the USGS has reported recent rates from the 1970s (Hapke et al., 2013). Scaling those mean recent rates by the lengths of their respective coastal segments yields an overall mean recent rate of +8 cm/year, which the mean recent rate of +5 cm/year that we calculate nearly matches (Table S3).

However, the historical rate of shoreline change that we calculate is, on average, 25 cm/year more erosional than the equivalent mean long-term rate from the USGS (Figure 2f). Because the USGS long-term rates include the potential influence of beach nourishment, they may systematically underestimate the magnitude of “true” coastal erosion as a chronic hazard and component of coastal risk (Thieler & Hammar-Klose, 1999; USGS, 2018). We cannot explicitly disentangle the relative contributions of natural shoreline change, beach nourishment, and other human interventions (e.g., inlet dredging, sea walls, groyne fields, and breakwaters) in the shoreline changes that we examine here. Nevertheless, we know that any effects of beach nourishment on rates of shoreline change would have to influence recent rates more than historical rates (Figure 1), and that no other single form of shoreline-change intervention along the U.S. Atlantic Coast is both so widely used and uniquely capable of the same reversing effect on erosion rates. It is reasonable to infer that the cumulative sediment input from decades of beach nourishment at sites along the U.S. Atlantic Coast could account for a significant proportion of the +60 cm/year difference between recent and historical rates of shoreline change (Figure 2 and Table S4).

We also find that along the full span of the U.S. Atlantic Coast, rates of shoreline erosion may be significantly reduced up to ~16 km from beach-nourishment sites. Even on a segment of coastline where alongshore sediment transport travels in a predominant (net) direction, the effect of a regional wave climate, however asymmetrical, is to move sand laterally in both directions, with nonlocal effects on shoreline position (Ashton & Murray, 2006a, 2006b; Ells & Murray, 2012). This suggests that, in addition to getting redistributed across the shoreface, if some nourishment sand is redistributed laterally by wave-driven gradients in alongshore sediment transport, neighboring coastal communities may benefit from each other's nourishment investments (Lazarus, McNamara, et al., 2011). A community that does not invest in beach nourishment may still benefit from the beach nourishment projects of its neighbors—in resource economics, a dynamic related to the prisoner's dilemma known as “free-riders” and “suckers” (Gopalakrishnan, McNamara, et al., 2016; Williams et al., 2013).

More broadly, if the quantity of beach nourishment in recent decades has been sufficient to mask true rates of shoreline erosion along the U.S. Atlantic Coast and “override the geomorphological signal of shoreline behavior” (Hapke et al., 2013), then our results point to the emergence of a system trap (Lazarus, 2017; Meadows & Wright, 2008). An “addiction” system trap may develop when an intervention to a problem obscures the true system state without addressing the underlying cause (Meadows & Wright, 2008). For example, the prospect of geoengineering the climate through solar radiation management—reducing global temperatures without reducing the amount of carbon dioxide in the atmosphere—would represent a system trap (Royal Society, 2009). Here beach nourishment might reduce apparent erosion rates, but it does not change the climate systems that drive sea-level rise and long-term wave conditions. Moreover, by reducing apparent coastal hazard, beach nourishment may ultimately increase coastal risk by indirectly encouraging more coastal development in hazard-prone settings (Armstrong et al., 2016)—a phenomenon known in land-use planning as the “safe development paradox” (Burby, 2006; Mileti, 1999). By creating a reliance on hazard protection, a safe development paradox may reinforce an addiction trap.

This is not an argument against coastal management: Coastal adaptation is predicted to cost less than doing nothing in response to climate-driven change (Hinkel et al., 2014). Nor do we imply a preference for hard over soft engineering—for seawalls instead of beach nourishment. But our findings do suggest that hazard from shoreline erosion might be stronger than it otherwise appears, placing diffuse but increased pressure on hazard mitigation. We propose that the cumulative, collective effect of beach nourishment on rates of shoreline change constitutes a quantitative signature of coastal geoengineering (Haff, 2003; Lazarus, 2017; Smith et al., 2015). An inclusive definition of geoengineering—one that extends beyond its typical reference to climate—is “the direct, large-scale, purposeful intervention in or manipulation of the natural environments of this planet, e.g., land, lakes, rivers, atmosphere, seas, ocean, and/or its physical, chemical, or biological processes” (Verlaan, 2009). The London Protocol defines “marine geoengineering” as

> a deliberate intervention in the marine environment to manipulate natural processes, including to counteract anthropogenic climate change and/or its impacts, and that has the potential to result in deleterious effects, especially where those effects may be widespread, long-lasting or severe. (Ginzky & Frost, 2014)

A complex aspect of beach nourishment, at least as it manifests in the United States, is that local mitigation actions are deliberate, but their collective consequences are not (Lazarus, McNamara, et al., 2011; Smith et al., 2015). Much like related implications for “termination effects” in climate geoengineering (Royal Society, 2009) were beach nourishment along the U.S. Atlantic Coast to suddenly stop—unmasking true rates of coastal erosion—then the economic effects on the coastal communities that have come to depend on its protection (Gopalakrishnan, Landry, et al., 2016; NRC, 2014) would indeed be deleterious, widespread, long-lasting, and severe. Beach nourishment as a form of geoengineering thus prompts the same question that arises in debates about solar radiation management, regarding how long it can be sustained once underway (Royal Society, 2009). For beach nourishment, however, the question is not hypothetical.

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