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The role of sediment compaction and groundwater withdrawal in local sea-level rise, Sandy Hook, New Jersey, USA

Christopher S. Johnson [a, b, *], Kenneth G. Miller [a, b], James V. Browning [a, b], Robert E. Kopp [a, b, c], Nicole S. Khan [d, e, f], Ying Fan [a, b], Scott D. Stanford [g], Benjamin P. Horton [b, d, e, f]

[a] Department of Earth and Planetary Sciences, Rutgers University, 610 Taylor Road, Piscataway, NJ 08854, USA
[b] Institute of Earth, Ocean and Atmospheric Sciences, Rutgers University, 71 Dudley Road, New Brunswick, NJ 08901, USA
[c] Rutgers Energy Institute, Rutgers University, 71 Dudley Road, New Brunswick, NJ 08901, USA
[d] Sea Level Research, Department of Marine and Coastal Sciences, Rutgers University, 71 Dudley Road, New Brunswick, NJ 08901, USA
[e] Earth Observatory of Singapore, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore
[f] Asian School of the Environment, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore
[g] New Jersey Geological and Water Survey, P.O. Box 420, Trenton, NJ 08625-0420, USA

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A B S T R A C T

The rate of relative sea-level (RSL) rise at Sandy Hook, NJ (4.0 ± 0.5 mm/yr) was higher than The Battery, NY (3.0 ± 0.3 mm/yr) from 1900 to 2012 despite being separated by just 26 km. The difference cannot be explained by differential glacial isostatic adjustment (GIA; 1.4 ± 0.4 and 1.3 ± 0.4 mm/yr RSL rise, respectively) alone. We estimate the contribution of sediment compaction to subsidence at Sandy Hook using high-resolution grain size, percent organic matter, and porosity data from three upper Quaternary (≤13,350 cal yr) cores. The organic matter content (<2%) is too low to contribute to local subsidence. However, numerical modeling of the grain size-depth-age-porosity relationship indicates that compaction of deglacial silts likely reduced the column thickness by 10–20% over the past 13,350 cal yrs. While compaction rates were high immediately after the main silt deposition (13,350–13,150 cal yrs BP), rates decreased exponentially after deposition to an average 20th century rate of 0.16 mm/yr (90% Confidence Interval (C.I.), 0.06–0.32 mm/yr). The remaining ~0.7 mm/yr (90% C.I. 0.3–1.2 mm/yr) difference in subsidence between Sandy Hook and The Battery is likely due to anthropogenic groundwater withdrawal. Historical data from Fort Hancock wells (2 km to the southeast of the Sandy Hook tide gauge) and previous regional work show that local and regional water extraction lowered the water levels in the aquifers underlying Sandy Hook. We suggest that the modern order of contribution to subsidence (highest to lowest) appears to be GIA, local/regional groundwater extraction, and compaction of thick Quaternary silts.

1. Introduction

Global, regional, and local processes cause changes in relative sea level (RSL). Global mean sea-level (GMSL) change describes changes in sea surface height averaged over the whole ocean (e.g., Kopp et al., 2015). Due primarily to thermal expansion and shrinking of land ice, GMSL rose at a rate of about 1.3 ± 0.2 mm/yr during the 20th century (Hay et al., 2015; Kopp et al., 2016; Dangendorf et al., 2017), lower than previously published estimates of 1.5–1.9 mm/yr (e.g., Jevrejeva et al., 2008; Church and White, 2011), and has risen at a faster rate of about 3 mm/yr since 1993 (Chen et al., 2017). RSL is the vertical distance between sea-surface height and the solid-Earth surface at a specific location (Kopp et al., 2015). RSL may be falling or rising at a different rate from GMSL and can be used to describe sea-level trends for areas on regional (~100 km^2) and local (single location; ~10 km^2) scales. Comparison of RSL rise at Sandy Hook, which lies on thick compressible sediments, and nearby (26 km) at The Battery tide gauge, New York City, which lies on incompressible bedrock, provides a natural experiment evaluating the natural and

* Corresponding author. Department of Earth and Planetary Sciences, Rutgers University, 610 Taylor Road, Piscataway, NJ 08854, USA.
E-mail address: c.s.johnson@rutgers.edu (C.S. Johnson).

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anthropogenic effects on compaction (Fig. 1).

The increasing availability of tide-gauge records and geologically based reconstructions of past RSL has made it possible to analyze RSL change with finer spatial resolution (e.g., Kopp, 2013; Kemp et al., 2011; Horton and Shennan, 2009). These analyses have shown it is possible, if not common, to have large variations in rates of RSL change over relatively small (a few kilometers) distances. For example, spatio-temporal statistical analysis of tide-gauge records estimated the rate of RSL rise at Sandy Hook between 1900 and 2012 to be 4.0 ± 0.5 mm/yr (Fig. 2). This rate is significantly higher than the 3.0 ± 0.3 mm/yr observed over the same period at The Battery tide gauge, located just 26 km to the northwest (Kopp, 2013).

RSL change can be influenced by many factors, including glacial isostatic adjustment (GIA; Clark et al., 1978), mantle dynamic topography (e.g., Gurnis, 1990), ocean dynamics (Yin et al., 2009), and local processes including active tectonics (Simms et al., 2016), sediment loading, and compaction (Törnqvist et al., 2008; Brian et al., 2015). Both Sandy Hook and The Battery show 20th century rates greater than the 1.3 ± 0.2 mm/yr of GMSL rise (Hay et al., 2015; Kopp et al., 2016). The excess RSL rise above GMSL rise at these two locations is mainly due to GIA (Clark et al., 1978). Kopp (2013) estimated the GIA effect to be 1.3 ± 0.4 mm/yr at The Battery and 1.4 ± 0.4 mm/yr at Sandy Hook.

Accounting for the difference in GIA between Sandy Hook and The Battery leaves a 0.9 ± 0.5 mm/yr difference in RSL change (Kopp, 2013). This difference cannot be attributed to regional processes, but must be due to unquantified local processes. Moucha et al. (2008) showed that there is little or no difference (≤0.003 mm/yr) between Sandy Hook and The Battery in RSL change driven by mantle dynamic topography. Furthermore, changes in ocean dynamics occur over spatial scales too large to affect Sandy Hook and The Battery differently (Yin et al., 2009). Similarly, spatial variation arising from the static-equilibrium (gravitational, rotational, and deformational) effects of shifting mass from land ice to or from the ocean occurs over distances greater than the 26 km between Sandy Hook and The Battery (Kopp et al., 2015). Based on models of long-term thermal subsidence and compaction of pre-Quaternary strata (Kominz et al., 2008), these effects are too low (<0.1 mm/yr difference between sites) to explain the difference (Miller et al., 2013). Thus the 0.9 ± 0.5 mm/yr difference is likely due to sediment compaction.

Here we seek to quantify the sources of local subsidence to account for the high rate of local RSL rise at Sandy Hook. Potential contributors include compaction of organic-rich strata and/or siliciclastic sediments due to natural effects (e.g., Törnqvist et al., 2008) and compaction induced by anthropogenic groundwater withdrawal (e.g., Pope and Burbey, 2004). Locations with high rates of RSL rise (≥~4.0 mm/yr) (e.g., Norfolk, Virginia and Atlantic City, New Jersey) are typically the result of high rates of compaction due to groundwater withdrawal (Pope and Burbey, 2004; Cronin, 2012; Miller et al., 2013). In this study, we assess the RSL contributions from compaction of Quaternary organic material and siliciclastic sediments at Sandy Hook. We conduct sedimentological studies (percent organic matter, grain size, and porosity) on a transect of three cores drilled on Sandy Hook (Fig. 1). We use these data to model the contributions of compaction in young unconsolidated siliciclastic silts to local RSL changes and compare the residual to rates of groundwater withdrawal. Our approach to quantify RSL budgets is applicable to other regions.

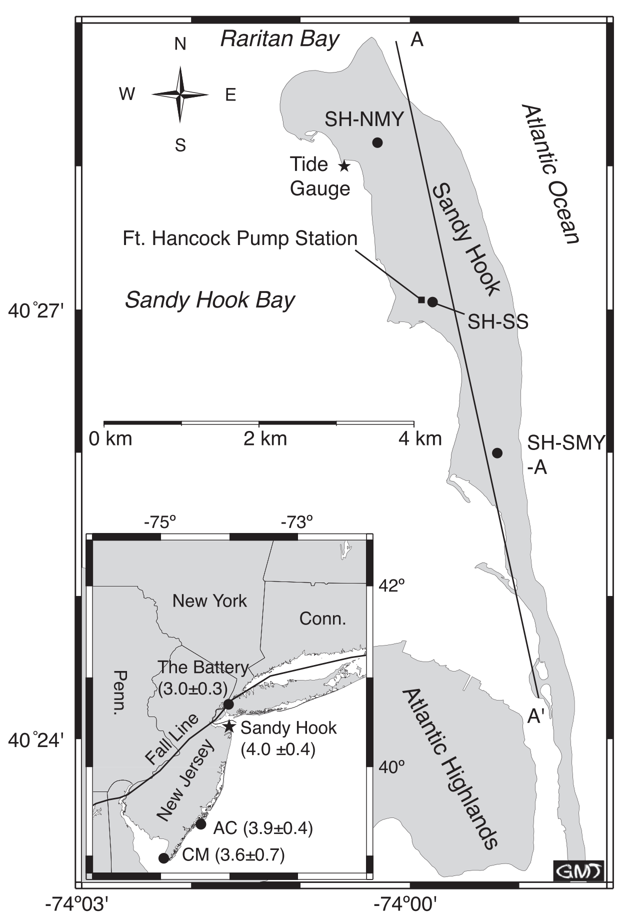

Fig. 1. Sandy Hook Location Map. SH-NMY Sandy Hook North Maintenance Yard Corehole, SH-SS Sandy Hook Salt Shed Corehole, SH-SMY-A Sandy Hook South Maintenance Yard Corehole A. Inset map shows the Fall Line, B = The Battery Tide Gauge, AC = Atlantic City Tide Gauge, CM = Cape May Tide Gauge, and 1900–2012 average rates of sea-level rise at each of those locations including Sandy Hook (Miller et al., 2013). A-A′ is the location of the cross-section in Fig. 3.

2. Study area

Sandy Hook is a sand spit extending 8 km north into Sandy Hook and Raritan Bays between New York and New Jersey, USA (Fig. 1). The spit has been growing northward into Raritan Bay at an average rate of ~8 m/yr over the past two centuries (see supplementary material for calculation). The Sandy Hook tide gauge is located near the NW end of the spit, 26 km southeast of The Battery tide gauge in New York, NY. Sandy Hook and The Battery are in different geologic settings. The Battery is underlain by Paleozoic and Proterozoic crystalline metamorphic bedrock (Lyttle and Epstein, 1987), whereas Sandy Hook, in the New Jersey coastal plain, is underlain by ~300 m of unconsolidated Cretaceous to Holocene marine, near shore, and terrestrial sediments that onlap the bedrock seaward of the fall line (Owens et al., 1998). The fall line, demarcated by a linear series of waterfalls along rivers traversing the line, marks the transition between unconsolidated sediments and more resistant bedrock to the west (e.g., Owens et al., 1998, Fig. 1).

Miller et al. (2013) used tide gauge records to show that the 20th century regional rate of sea-level rise along the fall line and to the west in the Piedmont is ~3.0 mm/yr. Major cities including New York (3.0 ± 0.3 mm/yr), Philadelphia (3.1 ± 0.3 mm/yr), Baltimore (3.1 ± 0.3 mm/yr), and Washington D.C. (3.0 ± 0.5 mm/yr) are located in this region. These rates closely match the sum of GMSL rise and GIA-driven RSL change. Tide gauges located east of the fall line in the coastal plain typically exhibit rates of rise of at least 3.5 mm/yr and can reach rates as high as 3.9 and 4.0 mm/yr in locations such as Atlantic City, NJ and Sandy Hook, NJ, respectively (Miller et al., 2013) and higher in Virginia (Pope and Burbey, 2004).