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Nineteenth-Century Tides in the Gulf of Maine and Implications for Secular Trends

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Key Points:
- Nineteenth-century water-level measurements have been recovered for Eastport, Portland, and Pulpit Harbor, Maine
- Large twentieth century trends in tidal amplitudes do not extend back into the nineteenth century
- Tidal trends are coincident with modern rates of sea level rise at Boston and Portland but changing stratification is likely important

Supporting Information:
- Supporting Information S1

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Nineteenth-Century Tides in the Gulf of Maine and Implications for Secular Trends

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Abstract Since the early twentieth century, the amplitudes of tidal constituents in the Gulf of Maine and Bay of Fundy display clear secular trends that are among the largest anywhere observed for a regional body of water. The M_2 amplitude at Eastport, Maine, increased at a rate of 14.1 ± 1.2 cm per century until it temporarily dropped during 1980–1990, apparently in response to changes in the wider North Atlantic. Annual tidal analyses indicate M_2 reached an all-time high amplitude last year (2018). Here we report new estimates of tides derived from nineteenth century water-level measurements found in the U.S. National Archives. Results from Eastport, Portland, and Pulpit Harbor (tied to Bar Harbor) do *not* follow the twentieth century trends and indicate that the Gulf of Maine tide changes commenced sometime in the late nineteenth or early twentieth centuries, coincident with a transition to modern rates of sea-level rise as observed at Boston and Portland. General agreement is that sea level rise alone is insufficient to cause the twentieth-century tide changes. A role for ocean stratification is suggested by the long-term warming of Gulf of Maine waters; archival water temperatures at Boston, Portland, and Eastport show increases of ~2 °C since the 1880s. In addition, a changing seasonal dependence in M_2 amplitudes is reflected in a changing seasonal dependence in water temperatures. The observations suggest that models seeking to reproduce Gulf of Maine tides must consider both sea level rise and long-term changes in stratification.

1. Introduction

One of the first published reports of a secular change in the tides was based on measurements taken at St. John, New Brunswick, Canada, located along the Bay of Fundy. Doodson (1924) analyzed a time series covering the period 1894–1916 and concluded that the amplitude of M_2 was decreasing with time. Doodson was aware of an unusual lunar nodal modulation at St. John, yet it—or perhaps simply inadequate measurements—led him astray, because a longer time series showed M_2 to be increasing rather than decreasing with time (Godin, 1992, 1995). Tidal changes at a single location are not all that unusual (e.g., Woodworth, 2010), but they are often caused by local effects such as instrumentation problems, harbor changes, river dredging, or other changes. The St. John results grew more intriguing once it was realized that similar tidal changes were occurring at stations throughout the whole of the Gulf of Maine (Ray, 2006).

The tidal changes in the Gulf of Maine and Bay of Fundy (see map in Figure 1) are unusual owing to both the regional nature of the changes and to their large magnitude. Flick et al. (2003) reported that during the twentieth century, mean tidal range (MTR) increased at rates exceeding 10 cm per century at three locations there, rates surpassed by only a handful of other stations in their (U.S.-only) compilation; all other locations with large rates were either individual, isolated stations or were based on very short time spans. (The largest MTR change found by Flick et al. was over 50 cm per century at Wilmington, North Carolina, but that gauge sits well up into the Cape Fear River and is now understood to have been caused by extensive dredging; Familkhalili & Talke, 2016.) From the global compilation by Woodworth (2010), focusing on only his longest time series (his set A), one finds that Gulf of Maine stations comprise three of the largest eight trends in M_2 amplitudes (and one of those eight is again Wilmington). Along the North American east coast, aside from Wilmington, comparably large twentieth-century trends are observed at the Sandy Hook (New Jersey) and New York City (Battery) tide gauges (Talke et al., 2014, Figure S20), but those large trends are thought to be primarily local (Ralston et al., 2019); trends to the north at Montauk and to the south at Atlantic City are not comparable. Farther south, the M_2 tide at Charleston, South Carolina, displays a moderately large positive trend of 3 cm per century (Müller, 2011; Ray, 2009).

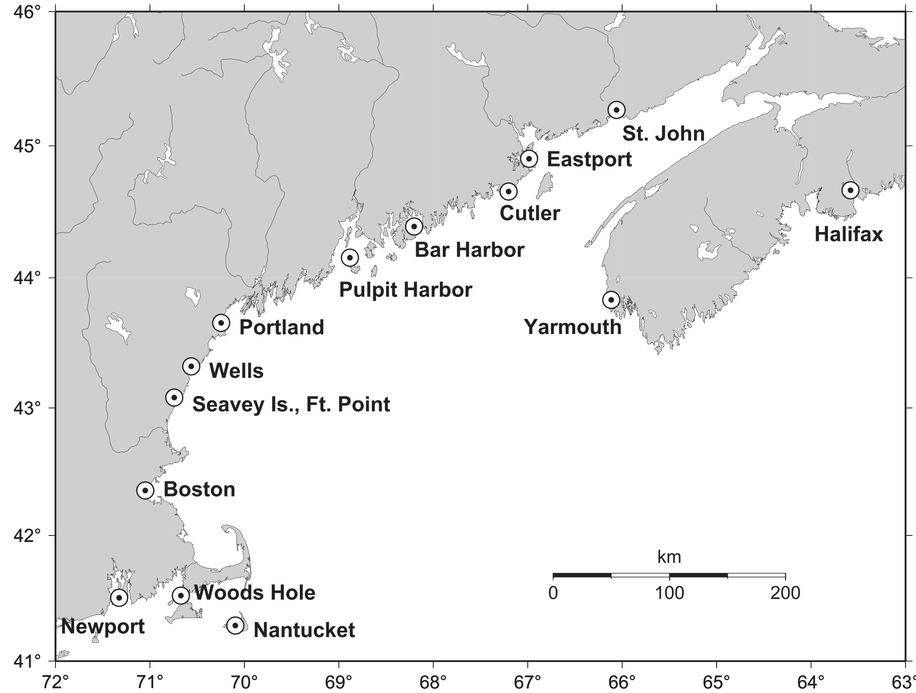

Figure 1. Major tide gauges in and around the Gulf of Maine and Bay of Fundy.

A satisfactory explanation for the secular changes in Gulf of Maine tides is still lacking. Part of the change may be attributed to the ongoing rise in mean sea level. As is well known, the tides in the gulf, and especially the Bay of Fundy, are in resonance, with a natural resonance frequency sitting near or just below the frequency of the N_2 tide (Garrett, 1972; Godin, 1993). Tides are therefore expected to be sensitive to small changes in basin shape, depth, or friction that might modify the resonance. Over the twentieth century, the mean sea-level rise in the gulf has been slightly larger than the global mean; values range between 1.8 mm/year at Portland to 2.9 mm/year at St. John. Several numerical ocean models have been employed to examine how sea-level rise of this magnitude affects the gulf tides. Both global models (e.g., Müller et al., 2011; Schindelegger et al., 2018) as well as a high-resolution local model implemented with a wetting/drying algorithm (Greenberg et al., 2012) have been used. None can fully explain the observed trends in M_2 amplitudes, although all models do predict increasing amplitudes. (Greenberg et al. could match observed trends but only by invoking an unphysically large subsidence rate, centered at the shelf break, to their adopted bathymetry.) It seems likely that additional factors (e.g., Hill, 2016), perhaps related to secular changes in ocean stratification (Müller, 2012), may be playing a role.

In order to understand the causative mechanism(s) more clearly, it would be useful to know when the present-day observed secular trends in the Gulf of Maine tides began. Are they strictly of twentieth-century origin, or were the changes also ongoing during the nineteenth century? The present paper addresses this question. We have located within the U.S. National Archives (College Park, Maryland) historical water-level measurements from the nineteenth century at Eastport, Portland, and Pulpit Harbor (all within the state of Maine), and we attempt here to deduce what these data reveal about secular tidal changes. One of us has also examined in some detail historical water-level measurements at Boston (Talke et al., 2018), but those data are less useful to answer the question posed here because of the extensive harbor and land reclamation changes that have occurred in and around Boston.

In section 2, we update time series of tidal estimates for the modern (post-1900) era at five of the longest-running tide gauges of the Gulf of Maine and Bay of Fundy. The following sections then discuss the nineteenth century data at three stations, followed by a brief discussion of possible explanations for these observed changes. All uncertainties quoted below represent 1σ standard errors.

2. Reexamination of Modern Data

In this section we reexamine modern Gulf of Maine hourly tide-gauge data and extend forward the time series of estimated tidal coefficients since previous work by Ray (2006), Müller (2011), and Greenberg et al. (2012). "Modern" in this context means post-1900. Hourly time series have been obtained from the U.S. National Oceanic and Atmospheric Administration (NOAA) Center for Operational Oceanographic Products and Services and the Canadian ministry Fisheries & Oceans Canada, Marine Environmental Data Section. Major tide gauges in and near the region of interest are listed in Table 1. We concentrate here on the five most complete and longest-running stations: St. John, Eastport, Bar Harbor, Portland, and Boston. The long time series near Portsmouth, New Hampshire (at Seavey Island and Fort Point), requires special handling (see Appendix A). See also the additional Figure S1 in the supporting information to this paper for information on seven other stations.

Each time series was initially analyzed in a multidecade time span with high frequency resolution, and the residual spectra carefully studied to attempt to incorporate all significant spectral lines into the tidal analysis. A smaller subset of constituents, appropriate for a year-long time series and generally numbering around 60–70 frequencies, was then used to estimate tidal coefficients for every year. The multidecade analyses provide a useful context for the subsequent yearly analyses; for example, they reveal when significant lines exist with frequencies closer than 1 cpy which can lead to modulations of annual estimates (particularly noticeable for degree-3 tides; see below). Standard errors were estimated by computing spectra of residuals and scaling formal error covariances by the background spectral density surrounding each estimated constituent. For the spectral densities to properly reflect noise levels, it is important to avoid neglecting small lines at nearby frequencies. For M_2 in this region, this would include seasonally induced sidelines MA_2 and MB_2 (the nomenclature comes from older, mainly British, work—e.g., Amin, 1985), plus two small gravitational constituents 2 cpy from M_2 (usually denoted Γ_2 and δ_2, the former being near the compound MSK_2 and the latter being coincident with MKS_2). Monthly tidal solutions are often helpful for identifying suspect data, and at Eastport, they revealed M_2 amplitudes anomalously offset by roughly 10 cm from late 1971 through August 1972; these data have been discarded. All data from St. John during 2014 are also anomalous and were discarded. The St. John data have other problems: Greenberg et al. (2012) write that "there were siltation problems influencing the St. John water-level data for several years starting around 1980," which is consistent with the "deterioration of the tide gauge" reported by Godin (1992). Moreover, in 1999, the gauge was relocated a short distance, to the other side of the St. John River and farther downstream, and unfortunately, this shows up clearly in Figure 3 below. These problems force us to truncate the St. John time series at 1980 for trend estimation.

Annual estimates of M_2 amplitudes for the five selected tide gauges are shown in Figure 2. Standard nodal corrections have not been applied, since they are known to be inapplicable inside the Gulf of Maine (Ku et al., 1985; Ray, 2006), so the figure is obviously dominated by 18.6-year sinusoids. Figure 3 show the same data with nodal modulations removed by empirical least-squares fits to the yearly estimates. Linear secular trends, simultaneously estimated with the nodal terms, are given in the figures and also summarized in Table 2. Coefficients for the 18.6-year nodal terms, which are needed below, are given in Table 3 in the form α_f, α_u where amplitude and phase corrections are expressed in the usual form

$$f = 1 + \alpha_f \cos N; \qquad u = \alpha_u \sin N, \tag{1}$$

where N is the mean longitude of the moon's ascending node. Note that within 2σ, the phase modulations u agree with theoretical expectations; it is only the amplitude modulations f that are anomalous (the exception is Pulpit Harbor, discussed below).

It is clear from Figures 2 and 3 that standard errors in the U.S. data are smallest after around 1990. The improvement surely owes to instrumentation improvements, especially timekeeping. But the standard errors are not necessarily largest for the oldest data. In fact, consistent with a pattern we have observed elsewhere in U.S. tide records, the errors often appear to be greatest during a roughly two-decade period from early 1960s to mid-1980s; this applies to both Eastport and Bar Harbor, although the Portland and Boston errors are also relatively large during the 1950s. In an analysis of historical Pacific island gauges, Zaron and Jay (2014) found interesting cases where secular increases in amplitude could be explained by long-term decreases in noise in

Table 1
Gulf of Maine Tide Stations With Time Series Exceeding 10 Years[a]

Station	Approximate location		Time span(s)
St. John, NB	45°15.1′N	66°3.8′ W	1893–present[b]
Eastport, ME	44°54.2′N	66°59.1′W	1861–1864, 1929–present
Cutler, ME	44°39.4′N	67°12.3′W	1979–present[c]
Bar Harbor, ME	44°23.5′N	68°12.2′W	1947–present
Pulpit Harbor, ME	44°9.4′N	68°53.2′ W	1870–1888, 1945–1946, 1983, 1985
Portland, ME	43°39.3′N	70°14.8′W	1853, 1864–1866, 1910–present
Wells, ME	43°19.2′N	70°33.8′W	2005–present
Seavey Island, ME	43°4.8′N	70°44.5′W	1926–1935, 1940–1987, 2000–2002
Fort Point, NH	43°4.3′N	70°42.6′W	2003–present
Boston, MA[d]	42°21.2′N	71°3.0′W	1825–1833, 1847–1877, 1897–1911 1921–present
Yarmouth, NS	43°50.0′N	66°7.0′W	1900, 1956–57, 1965–present
Nantucket, MA	41°17.1′N	70°5.8′W	1965–present

[a]Listed time spans may include possible gaps of several years. [b]Most pre-1905 data at St. John not available in digital form. Gauge was relocated in 1999. [c]Gauge at Cutler was relocated in 2010. [d]See Talke et al. (2018) for details and analysis of Boston data.

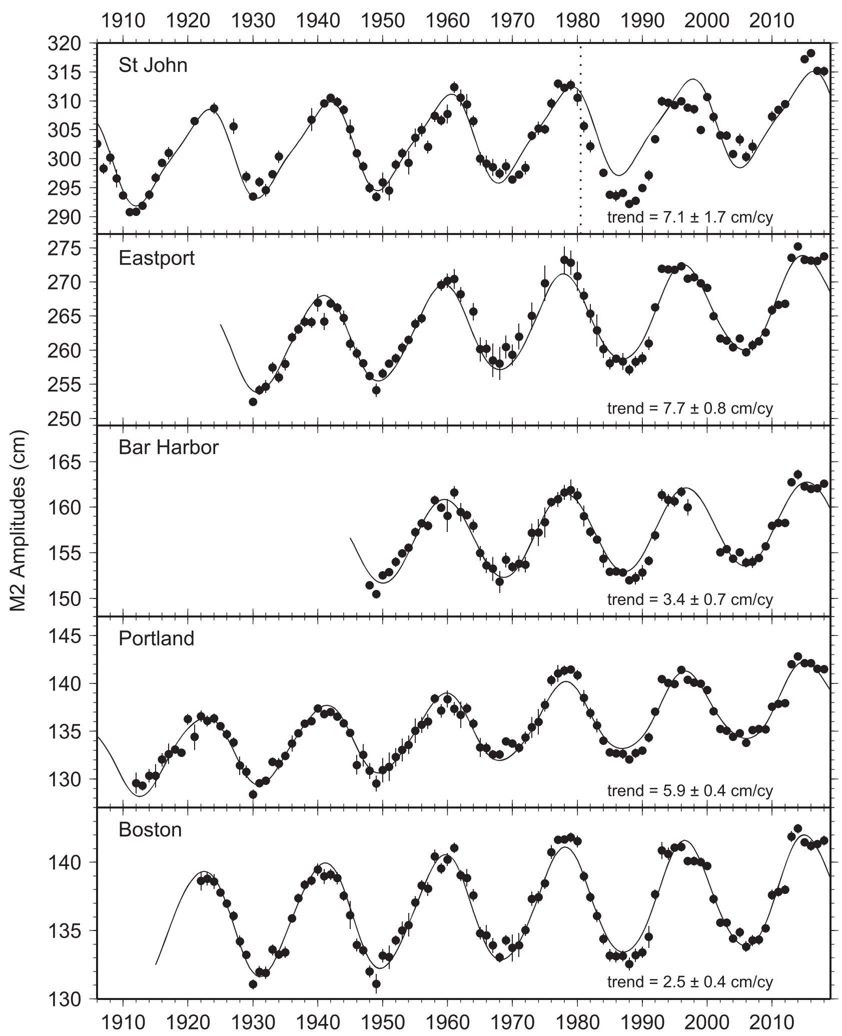

Figure 2. Annual estimates of the amplitudes of the M_2 tide at five stations with the longest, most complete time series. No "nodal corrections" were applied during the tidal analyses, since standard corrections are inapplicable in this region (Ku et al., 1985; Ray, 2006), so all series are dominated by the 18.6-year nodal modulation. Error bars represent one standard error and are based on spectral analysis of tidal residuals. For trend estimation, the St. John time series was truncated at 1980 owing to gauge problems reported by Greenberg et al. (2012).

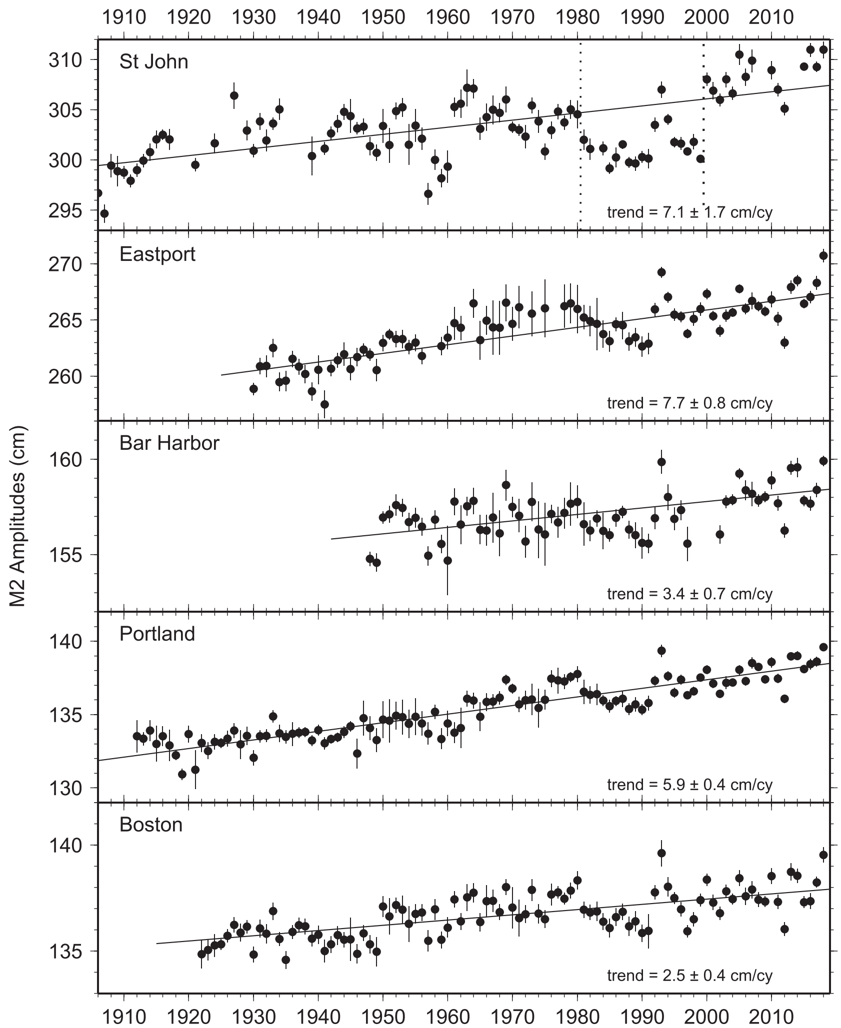

Figure 3. As in Figure 2 but after nodal modulations have been empirically estimated and removed from the time series. For trend estimation, the St. John time series was truncated at 1980 owing to gauge problems reported by Greenberg et al. (2012); the dotted line at 1999 marks when the tide gauge was relocated, which appears to have resulted in an M_2 offset of several centimeters.

Table 2
Tidal Trends in Amplitude H and Phase lag G, post-1900

Station	H (cm)	M_2 $\dot{H}$ (cm per cy)	$\dot{G}$ (° per cy)	M_2 (pre-1980) $\dot{H}$ (cm per cy)	Mean tidal range (cm per cy)
St. John (1906–1980)	302	7.1±1.6	0.5°±0.5°	7.1±1.6	20.6±3.3
Eastport (1930–2018)	263	7.7±0.8	−0.4°±0.3°	14.1±1.3	15.5±1.9
Bar Harbor (1948–2018)	156	3.4±0.7	0.2°±0.7°	5.7±1.9	6.2±1.7
Portland (1912–2018)	135	5.9±0.4	−0.7°±0.3°	7.6±1.1	10.3±0.8
Seavey Is. (1940–2001)	119	5.0±1.1	−0.6°±0.6°	8.2±1.3	5.5±2.0
Boston (1922–2018)	136	2.5±0.4	−1.3°±0.3°	4.3±0.6	2.4±0.9
Nantucket (1965–2018)	43	2.4±0.5	−4.3°±1.0°	—	4.5±1.4
Halifax (1920–2014)	63	−0.9±0.3	−0.9°±0.4°	−0.1±0.3	−3.1±0.7
Newport (1931–2018)	51	−1.1±0.2	0.9°±0.6°	−0.8±0.3	−2.8±0.4

Note. Amplitudes H taken as the 1960 values determined from least-squares fits. St. John series truncated at 1980 owing to instrument problems reported by Greenberg et al. (2012). cy = century.

Table 3
Empirically Estimated 18.6-Year Nodal Modulations

	M_2		N_2	
Station	*f* coefficient	*u* coefficient	*f* coefficient	*u* coefficient
Theoretical[a]	−0.0373	−2.14°	−0.0373	−2.14°
St. John	−0.0240±0.0016	−2.30°±0.22°	−0.0212±0.0029	−2.37°±0.26°
Eastport	−0.0249±0.0011	−2.25°±0.09°	−0.0238±0.0022	−2.36°±0.27°
Bar Harbor	−0.0279±0.0013	−2.17°±0.22°	−0.0270±0.0029	−2.34°±0.33°
Pulpit Harbor	−0.0215±0.0020	−1.45°±0.26°	−0.0257±0.0038	−1.49°±0.24°
Portland	−0.0277±0.0011	−2.03°±0.13°	−0.0257±0.0027	−2.11°±0.28°
Boston	−0.0288±0.0010	−2.28°±0.10°	−0.0257±0.0018	−2.26°±0.17°

[a]Pugh and Woodworth (2014, p. 70) and Doodson (1928, Table XXVI).

the tidal band, presumably from improvements in timekeeping; there is no indication that occasional clock errors are biasing long-term trends in the Gulf of Maine stations. Given the disparity of standard errors in the estimated annual harmonics, we have used weighted least squares to estimate nodal modulations and trends.

For the five time series of Figures 2 and 3 and Table 2, all trends are significantly positive, and three of the five are unusually large. Boston, sitting in the southernmost part of the gulf, displays the smallest trend, and Bar Harbor, from a comparatively short time series, also has a trend smaller than its two neighboring stations. In terms of percentage rates, the amplitude changes for the five stations (north to south) are 2.4%, 2.9%, 2.2%, 4.4%, and 1.8% per century, respectively. Reflecting these large trends, Figure 3 shows that the largest M_2 amplitude of the modern era was experienced last year (2018) at Eastport; the year 2018 was also the highest, or tied for highest, at the four other stations.

Table 2 also includes a few trend estimates from stations just outside the Gulf of Maine. The two longest and most complete time series are from Newport and Halifax. The M_2 trends at both are slightly negative at approximately 1 cm per century. The large secular increase in M_2 amplitude is thus confined to the gulf, with the largest increases in the north, as has been reported earlier (Müller, 2011; Ray, 2006).

A short discussion concerning the empirical removal of the nodal modulations in Figure 2 is necessary. The initial functional form of the least-squares fits to the annual amplitude (and phase) estimates included a bias, trend, and the 18.6-year sinusoid. For N_2, it is necessary (see below) to include an additional sinusoid of period 8.85 years which accounts for the presence of a constituent arising from the third-degree term in the astronomical potential, a point also made by Doodson (1924) in his early study. The notation for degree-3 tides has never been standardized; we employ here a leading superscript “3,” with the understanding that no superscript denotes a standard degree-2 constituent. Based on the astronomical potential (Cartwright & Tayler, 1971), the largest degree-3 semidiurnal tides are $^3N_2$, $^3L_2$, $^32N_2$, and $^3M_2$, in that order. All of them differ in frequency from the degree-2 constituents by one cycle in 8.85 years, which is the period of the Moon's perigee precession. $^3N_2$ is resonantly enhanced in the Gulf of Maine for the same reason that N_2 is; its amplitude at St. John is approximately 4.2 cm.

The constituent $^3M_2$ is very small, especially when compared with M_2. Nonetheless, the 18.6-year sinusoids for M_2 are slightly asymmetrical, suggesting the presence of the additional frequency. We therefore included an 8.85-year amplitude modulation for both M_2 and N_2. Note that for M_2 (and N_2 too), there is a second harmonic of the nodal sideline (corresponding to Doodson number 255.535), which, in principle, can cause a modulation of 9.3-year periodicity. But that term is extremely small, nearly 2 orders of magnitude smaller than the main nodal sideline (Cartwright & Tayler, 1971), so it is surely the third-degree constituent that is effective here and not the second nodal line, which can be safely ignored.

Annual results for N_2, which is the second-largest tidal constituent in the Gulf of Maine, are shown in Figure 4. Here the presence of $^3N_2$ is very clear. Time series of N_2 amplitudes with the modulations empirically removed are shown in Figure 5.

Figure S5 shows results for the much smaller constituent $2N_2$. Noise levels for $2N_2$ are such that no statistically significant trends are found, but the constituent is nonetheless interesting because of the complicated

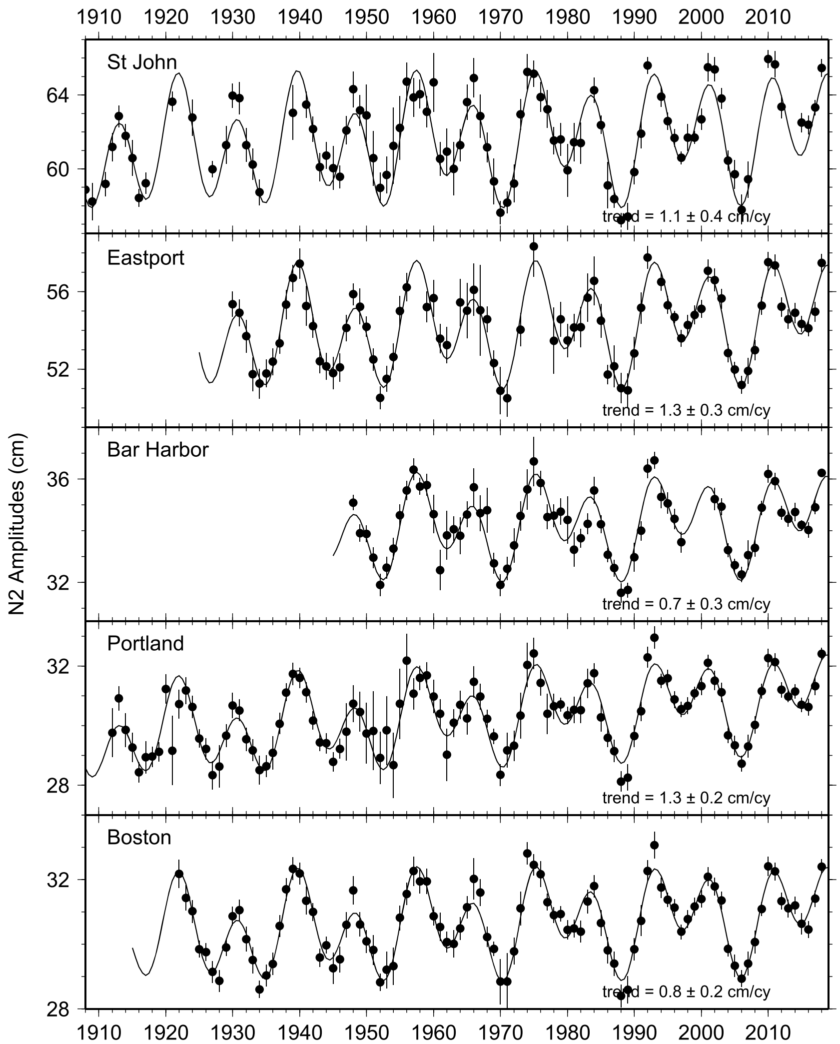

Figure 4. Annual estimates of the amplitudes of the N_2 tide. Here the amplitude modulations are caused by (a) the 18.6-year nodal regression and (b) a significant degree-3 tide, ${}^3N_2$, which induces a 8.85-year modulation. Time series of N_2 amplitude with these modulations removed are shown in Figure 5.

interference from additional nearby frequencies—not only a degree-3 line but also the compound $2MK_2$, and even the compound tide's nodal modulation.

Diagrams similar to Figures 2 and 4 for constituents K_1, O_1, and S_2 are shown in Supporting Information S1. All constituents save S_2 display a positive secular trend in amplitude, although some of the diurnals are not statistically significant. The amplitude of S_2 is decreasing for all stations. Godin (1992) first reported the decrease in S_2, at St. John. He thought N_2 was also decreasing, probably because his time series was short, with interference from ${}^3N_2$. Godin attributed the decrease in S_2 amplitudes to frictional interaction with the increasing M_2. Such interaction does occur and presumably explains a small 18.6-year nodal modulation of S_2, which is out-of-phase with the M_2 modulation (see Figure S4), something observed in many other places (e.g., Feng et al., 2015). Godin's frictional mechanism, however, is insufficient to fully explain the S_2 secular decay (in percentage terms, the S_2 nodal modulation is only half the M_2 modulation, but the magnitude of the S_2 secular trend is twice the M_2 trend). In fact, the anomalous S_2 behavior stems primarily from the fact that S_2 amplitudes in the twentieth century have been decreasing throughout the wider northwestern Atlantic Ocean (Ray, 2009), for reasons unknown, and S_2 interior to the gulf simply reflects this exterior forcing. If an S_2 "admittance" for a gulf station is formed by computing the ratio between observed S_2 and the value observed at a station just outside the gulf, such as at Halifax, then that admittance is found to be

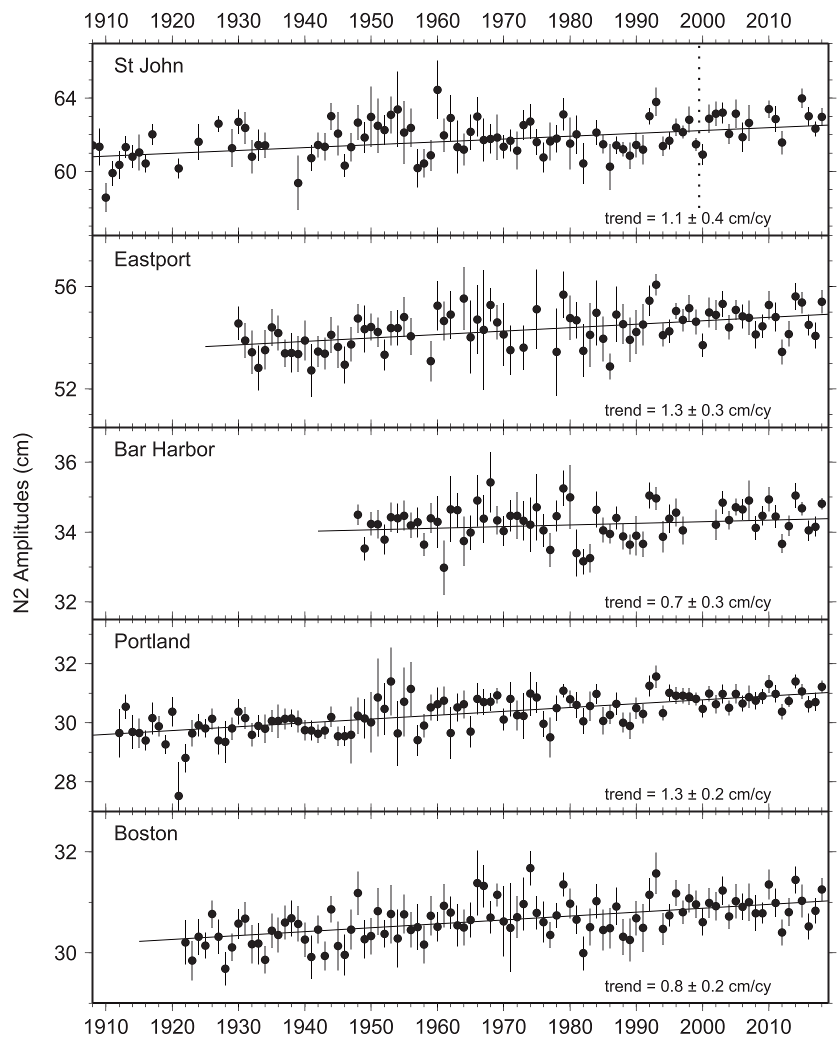

Figure 5. As in Figure 3 but for the N_2 constituent.

increasing with time, not decreasing, and thus similar to all other semidiurnal constituents (Ray, 2009, Fig. 3). In other words, S_2 is decreasing in the Gulf of Maine only because of decreased forcing at the mouth of the gulf; it would otherwise be increasing, as all other semidiurnals are.

In Figure 3 the secular trends are evident, but the figure also displays interesting interannual variability that is surprisingly consistent among the stations. All five M_2 time series show a significant decrease in amplitude beginning in 1980 and continuing to about 1990. In fact, that decade-long decrease is large enough to have affected the overall estimated secular trends; Table 2 includes a column with amplitude trends for just the pre-1980 data, and those trends are all much larger than for the whole time series, with Eastport displaying an unusually large trend of 13.7 cm per century (cf. Greenberg et al., 2012). The 1980–1990 amplitude drop in Figure 3 is followed by a pronounced Λ-shaped feature, with a local maximum in 1993, again seen clearly in each time series. Even the small decreases over the 3-year interval 2010–2012 are evident in all five series. Close examination of the past few years of N_2 estimates (Figure 5) reveals similar consistent interannual variations. The large M_2 amplitude decrease beginning in 1980 appears to reflect a change in M_2 over a much wider region than just the Gulf of Maine (Müller, 2011); the other interannual changes evident in Figure 3 are less apparent elsewhere. These consistent interannual tidal signals are very intriguing, but they are not the main focus of this paper, so we move on to a discussion of the nineteenth-century data and their implications for the secular trends observed in Figures 2-4.

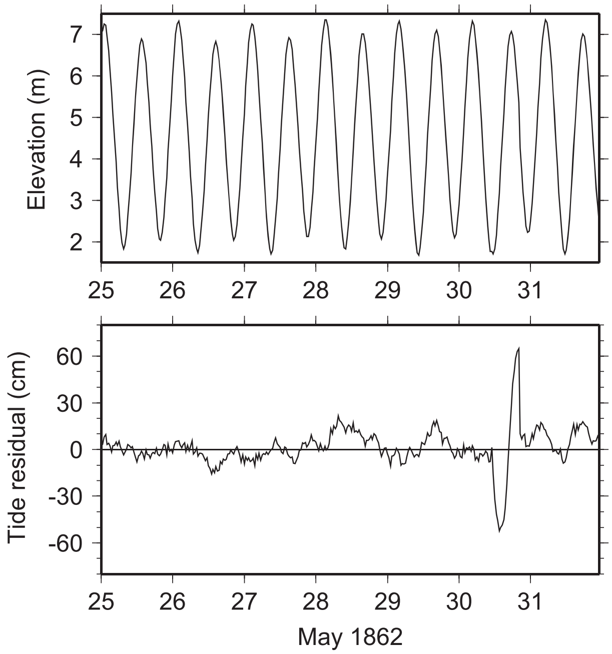

Figure 6. Example of a short section of spurious data from late May 1862. (top) Observed data, nominally satisfactory. (bottom) Residuals from an initial tidal analysis revealing spurious data on the 30th.

3. Eastport

A self-registering tide gauge was established at Eastport, Maine, in early January 1860. Data were collected almost continuously for 4.5 years until July 1864 when the tide gauge was moved to Portland. From the U.S. National Archives (College Park), we recovered many pages of handwritten tabulations that list times and elevations of high and low water for this entire time period as well as 30-min elevation readings for all of 1862 and the first 3 months of 1863. There are also some water level data collected during a few months of 1887 and a few weeks of 1890; we have not examined those later data since the series are so short. In the archived documents (for 1862), the tide gauge location is listed as 44°N 54′N, 66°59′W and the time as "mean local civil," which we take to be mean time at the 66°59′W meridian. Marmer (1922) displayed a single day of the 30-min 1862 data in his descriptive survey of the Bay of Fundy tide and its resonance.

Handwritten notes accompanying the tabulations from early 1860 are rather alarming because of repeated entries concerning irregularities of the clock. Evidently the clock was running "fast" anywhere from 2 to 19 min in seemingly erratic fashion. Fortunately, by mid-February these large clock errors seem to have settled down. Even so, the clock remained troublesome; for example, there were periods noted when it simply stopped, repeatedly in both March and June of 1860.

Here we report primarily results from our analysis of the 30-min Eastport readings of 1862. Our extraction of tides from the high and low water readings for other years leads to consistent results for the M_2 constants, but the residuals display monthly oscillations that are inconsistent year to year, leading to inconsistent N_2 constants. Therefore, we defer discussion of estimated constituent amplitudes and phases from the high-low data pending further study of that problem. Nonetheless, the high-low data can still presumably be safely used to estimate annual MTRs. Note that some of the tabulated high-low data—not raw observations but partially reduced data—employed apparent rather than mean time (the difference being given by the Equation of Time; Meeus, 1998); the timing system will not impact estimates of MTR.

An initial tidal analysis of the 30-min readings from 1862 revealed a number of spurious data. Software that analyzes fourth differences (e.g., Hamoudi et al., 2011; Hood et al., 1979) of these initial tidal residuals was used to automatically identify 36 single-point outliers and replace them in the elevation data by linear interpolation. Most outliers were around 10 cm, but a few were near 60 cm. Three longer patches such as seen in Figure 6 were handled by simply discarding the spurious data.

For the 1862 data, we solved for the same number of tidal constituents used in the yearly analyses of the modern Eastport data (63, including 7 long-period tides and 25 compound tides). The root-mean-square residual was 11.3 cm, which is comparable to the residuals obtained for the 1930s data and considerably better than that obtained for the 1970s data. The estimated M_2 constants are: amplitude H=262.3±0.6 cm, Greenwich phase lag G=97.7°±0.2°. These are again without nodal corrections. Were standard corrections applied, the results would be 261.3 cm, 99.9°. Using the empirical (modern) nodal corrections of Table 3 leads to M_2 constants of 261.7 cm, 100.0°. By happenstance, the term cos$N$ in 1862 was close to zero and f thus close to 1 (actual value: 1.0037), so in the end, the M_2 constants with standard nodal corrections are close to those based on empirical corrections, with amplitudes differing by only 0.4 cm.

During our searches of the Eastport material at the National Archives, we came upon a Coast & Geodetic Survey form listing harmonic constants for this same year, 1862. The form is dated 15 March 1904 and is signed by Paul Schureman. The listed constants for M_2 are amplitude 8.576 feet and phase 326.1°, where the latter is in the "κ phase convention" which is relative to transit of the mean moon across the local meridian rather than across Greenwich (Schureman, 1940, p. 76). Conversion into our convention yields 261.4 cm, 100.1°. There is no reason to suspect that Schureman would not have employed standard nodal corrections, and indeed, the agreement with our constants above is very good, differing only by 0.1 cm and 0.2°. The close phase agreement also implies our interpretation of the 1862 time convention is consistent with Schureman's.

Figure 7 shows the 1862 M_2 estimates plotted alongside the modern Eastport data with all data adjusted by the nodal modulation coefficients of Table 3. Also shown is the least-squares linear extrapolation, based solely on the modern data, back to 1860. The gray shading is the 1σ uncertainty propagated from the error covariance of the linear fit. The 1862 amplitude does not agree with the linear extrapolation; the phase does (with a difference of about 1σ).

For N_2 the linear trend in amplitude (1.3±0.3 cm per century) is sufficiently uncertain that when extrapolated back to 1862 it cannot be statistically distinguished from an extrapolation with zero trend before 1930. Moreover, the uncertainty of the 1862 amplitude estimate also overlaps (at 2σ) both trend extrapolations. Hence, the N_2 constituent is not informative, and the main conclusion regarding the Eastport analysis must rest with the largest constituent, M_2.

A single estimate from one year cannot be definitive—one need only examine how often later annual estimates in Figure 7 fall outside the shaded region. Nonetheless, the 1862 offset of M_2 from the linear trend is greater than that seen for any other year.

As Table 2 suggests, analysis of changes in MTR, which is the difference between Mean High Water and Mean Low Water, are also useful. In this case, we computed annual estimates of MTR using the high-water and low-water tabulations we found for years 1860–1863. For the modern era, we computed high and low water levels from hourly data by identifying local maxima and minima in each half day and then fitting a (slightly taut) cubic spline to the neighboring 4 data points; the spline is then used to find the time and elevation of each maxima. The annual MTR data, both modern and from the 1860s, are shown in Figure 8 (top panel for Eastport). The solid curve in the figure is based on a weighted least-squares fit of a linear trend plus an 18.6-year sinusoid to the modern data. The dotted curve is a sinusoid with identical amplitude, but with zero trend, intersecting with the solid curve at 1930. Three of the 1860s values fall on the dotted curve, not the solid curve; the value for 1864 falls between the curves. Thus, in keeping with the results from our analysis of M_2 alone (Figure 7), the data suggest that the MTR was fairly constant during the nineteenth century and probably began its modern increase sometime in the early twentieth century.

Finally, the 1862 tidal analysis has implications for the anomalous S_2 constituent. As noted above, S_2 amplitudes are decreasing at all stations, which reflects decreased forcing exterior to the gulf. The S_2 trend at Eastport (see Figure S4) is relatively large: −2.27±0.25 cm per century, even larger in magnitude that the positive trend for N_2. As noted above, the time series of annual estimates from the twentieth century displays an apparent 18.6-year nodal modulation of approximately 1.3% (cf. Müller, 2011), even though S_2 is a solar constituent, with a theoretical nodal modulation of only 0.22% (Cartwright & Tayler, 1971); the large modulation is presumably caused by frictional suppression by the large, modulating M_2. The S_2 estimates are also unusually noisy (see Figure S4). However, neither noise nor nodal modulation hides the large negative amplitude trend, which if projected back to 1862 would give an amplitude slightly greater than 45 cm, whereas the present-day amplitude is about 41.8 cm. The estimated S_2 amplitude from the 1862 data is 42.5±0.5 cm, which is not only markedly lower than the projected value but is also lower than the amplitudes observed during the 1930s (see Figure S4). So even though S_2 reflects a tidal phenomenon from the wider northwest Atlantic (Ray, 2009), while M_2 is reflecting changes mostly confined to the Gulf of Maine and Bay of Fundy, the twentieth-century trend in neither constituent carries back into the nineteenth.

4. Portland

At Portland, Maine, we have recovered hourly water-level tabulations from 1 August 1864 through the end of 1865, a total of 17 months. In addition, we found high and low water tabulations for 1866 through the end of October. The location of measurements was at the “Central Wharf,” near the present-day location of the tide gauge. There are also about 5 months of earlier tabulated high and low waters from 1853, but we have not examined those data.

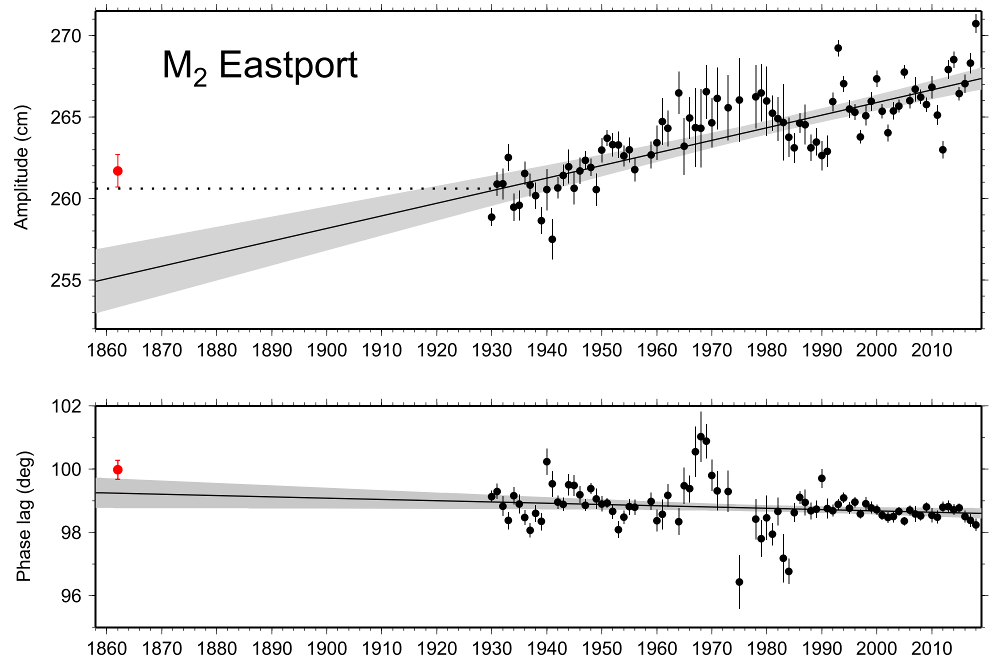

Figure 7. Annual estimates of M_2 amplitudes and phase lags at Eastport. Red points are based on tidal analysis of 30-min readings from 1862. Solid lines are based on weighted least-squares fits to the modern (post-1920) data, with gray shading marking expected 1σ error bounds based on error covariance of the fit. Both the modern and the 1862 M_2 estimates have been adjusted by the empirical nodal factors of Table 3. The 1862 data, although based on only a single year, suggest that the Eastport secular trend in M_2 amplitude does not extend back into the middle nineteenth century. The post-1990 amplitude estimates look somewhat erratic, given their small error bars, but Figure 3 shows that these data are reliably depicting interannual variability throughout the gulf; the data in the 1960–1980 interval are dubious in comparison.

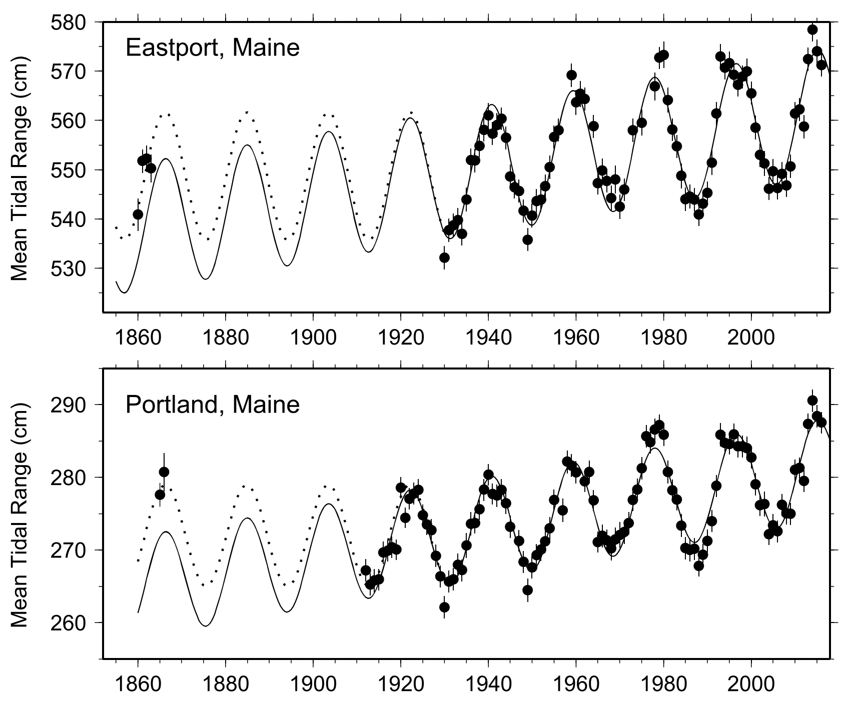

Figure 8. Annual estimates of Mean Tidal Range at Eastport (top) and Portland (bottom). The solid curves are fits (18.6-year sinusoid plus trend) to the modern data alone. The dotted curves extend the fitted sinusoids, with zero trend, backward from 1930.

Initial analysis of the hourly tidal residuals for 1864–1865 revealed that much of December 1864 was suspect, partly from large weather-related offsets and partly from simply spurious readings; these data were discarded. Most of August 1864 may have had a timekeeping error of roughly 5 minutes, but since these data formed only a small subset of all the hourly data, no clock adjustment was attempted.

Similar to the Eastport analysis, we estimated 63 constituents for the 17-month period of hourly data, and as a check, we also ran monthly analyses. The root mean square residual for the full period was 13.1 cm; this is on the high side of the twentieth century annual solutions, 80% of which had rms residuals between 11.0 and 13.5 cm. The estimated M_2 constants (without nodal adjustment) are amplitude H=137.3±0.4 cm and Greenwich phase lag G=103.0°±0.2°. Applying nodal adjustments from Table 3, we obtain H=134.1 cm and G=104.0°.

The combined nineteenth- and twentieth-century M_2 estimates are shown in Figure 9. Consistent with the results from Eastport, the 1864–1865 amplitude estimate falls well above the linear extrapolation of the twentieth century trend.

We computed high-water and low-water elevations from the 17 months of hourly data by the same method applied to modern hourly data. When combined with the additional 8 months of high-water and low-water tabulated elevations, we have two full years from which to compute two annual estimates of MTR. These are shown, along with the modern data, in Figure 8 (bottom). The figure again suggests little tidal change before the modern time series begins.

5. Pulpit Harbor

The Pulpit Harbor measurements form our most extensive nineteenth century data set (excepting Boston), with a time series of hourly (and later 30-min) measurements spanning a complete lunar nodal cycle, from January 1870 until March 1888. The 30-min data sheets have headings that give the gauge location as 44°9′ 26″N, 68°52′ 47″W and the time as “mean local time.” The series is surprisingly complete aside from a short section of 14 missing days in early 1886 and a few short gaps in the winter of 1886–1887, the latter prompting some interesting correspondence between the field and home office (Appendix B). We have also recovered and digitized hourly data from July 1945 through December 1946; those data were obtained through NOAA's Climate Database Modernization Program.

Pulpit Harbor sits on the north side of North Haven, Maine, which is a small island in the center of Penobscot Bay. The harbor lies behind a narrow entrance, with nowadays only residential traffic. (Note that another NOAA station has the name “North Haven”; it sits on the opposite side of the island and obtained data for only about 2 months in 1985.) Unfortunately, as Table 1 indicates, no modern data are being collected at Pulpit Harbor, and the few short segments in the twentieth century from 1945–1946, 1983, and 1985 are inadequate to allow any determination of a change in secular trends. Data are being collected, however, at Bar Harbor, 60-km distant. There are two short series of simultaneous measurements at Pulpit Harbor and Bar Harbor from 1983 and 1985 which conceivably allows the two time series to be tied together. This is hardly a substitute for having a modern time series at the old Pulpit Harbor site, but it is a reasonable alternative given the data in hand.

Examination of Pulpit Harbor tidal residuals indicates a large number of suspect data, some of which were data-entry errors. We have again used automated software to identify and correct single-point outliers; there were 361 of these over the 19 years. Possible level shifts were also identified, which required manual examination, as did generally anomalous spans in the tidal residuals. A total of 29 segments, most no more than a few hours, was eliminated.

Annual tidal estimates were used to solve for empirical nodal modulations, which are listed in Table 3. The amplitude modulations are reasonably comparable to other stations, but the phase modulations are smaller. Whether this is caused by the relative shortness of the Pulpit Harbor time series or has a physical explanation is unknown. We thus applied different nodal adjustments at Pulpit Harbor and Bar Harbor.

To tie the two time series of estimated tides, we used the short overlapping segments from 1983 and 1985, each about 3 months long. Given the Pulpit Harbor data, we extracted identical time spans from the Bar Harbor data and then estimated tidal constants from each in identical fashion. The M_2 constants obtained are (amplitude, phase, and standard error)

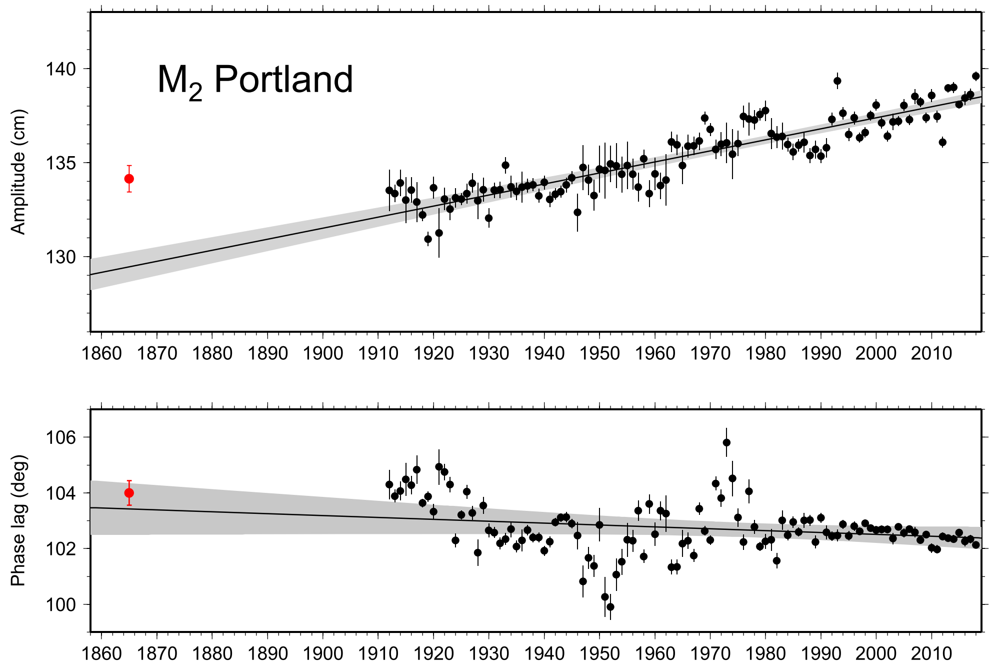

Figure 9. Annual estimates of M_2 amplitudes and phase lags at Portland. Red points are based on tidal analysis of hourly readings from 1865 and part of 1864. Solid lines are based on weighted least-squares fits to the modern (post-1910) data, with gray shading marking expected 1σ error bounds based on error covariance of the fit. Some of the early and mid-twentieth century phase data are remarkably erratic, which is reflected (partially) in the inflated error bars during those years.

Pulpit Harbor	149.60 cm, 98.2°,	0.54 cm
Bar Harbor	157.75 cm, 92.2°,	0.83 cm

The procedure then adopted to tie the M_2 time series was to scale the Bar Harbor amplitudes by 0.948 and increase the phase lags by 6.0°. The resulting combined time series is shown in Figure 10, with the Pulpit Harbor estimates in red and adjusted Bar Harbor estimates in black. (The figure shows the 1983–1985 Pulpit Harbor estimate but not the corresponding Bar Harbor subset estimate. The figure also shows as a single dot a Pulpit Harbor estimate from the 16-month series in 1945–1946, a segment having a considerable number of outliers in the hourly data and some short spans of a few days with evident clock errors.)

Of our three main results, shown in Figures 7-10, the Pulpit Harbor-Bar Harbor result must be considered the least reliable because of the uncertainties associated with combining the two tidal series. Nonetheless, the three figures point to an identical conclusion: The secular trends in the M_2 amplitudes of the Gulf of Maine do *not* extend back into the nineteenth century.

6. Discussion

Our three results at Eastport, Portland, and Pulpit/Bar Harbor consistently show that significant twentieth-century trends in M_2 amplitudes do not extend back into the nineteenth century. The long time series collected at Boston since 1825 (Talke et al., 2018) is consistent with the three time series examined here, in the sense that Boston's MTR began increasing sometime in the early twentieth century, with a rate of about 2 cm per century according to Table 2. Before 1920, however, the Boston series (collected not at the present-day site but at the Charlestown Navy Yard on the other side of Boston proper, a few kilometers away) gives an opposite trend: a remarkably large secular decrease in tidal range of about 20 cm per century (Figure 4 of Talke et al., 2018). In keeping with suggestions noted long ago by Freeman (1903, Appendix 20), we suspect that such large changes in tide are related to large-scale landfill (e.g., the extensive reclamation around Bass River and South Boston) and harbor changes that occurred at and around the Navy Yard (Seasholes, 2003).

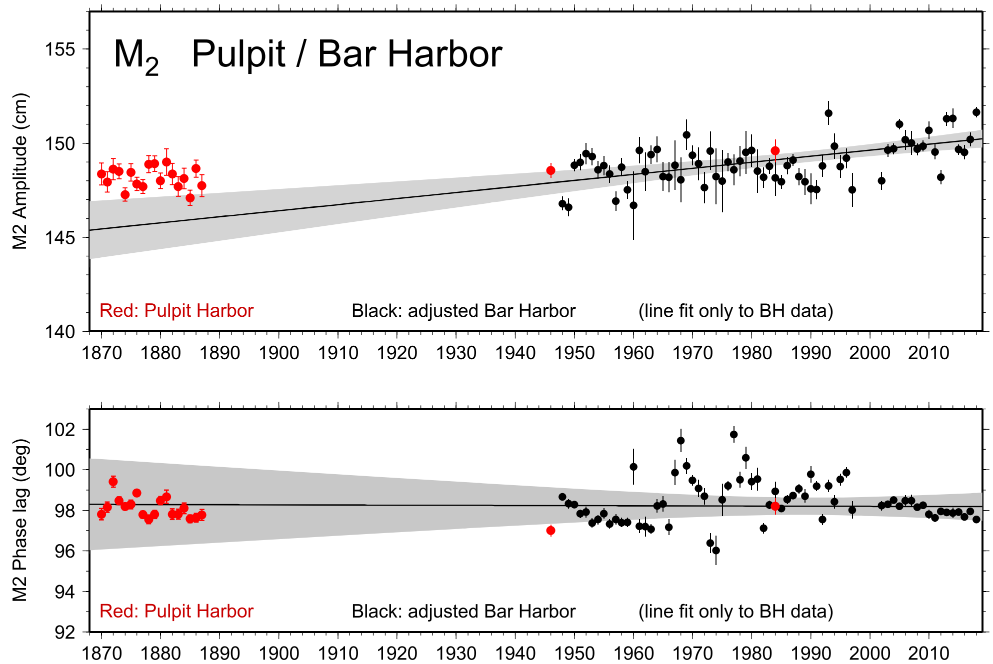

Figure 10. Annual estimates of M_2 amplitudes and phase lags at Pulpit Harbor (red) and at Bar Harbor (black), where the Bar Harbor data have been adjusted so that tidal constants from the 1983 and 1985 overlap agree for the two gauges. A single point is here plotted at 1984 for Pulpit Harbor; the usual annual estimates are plotted for Bar Harbor. Solid lines are based on weighted least-squares fits to the adjusted Bar Harbor data, with gray shading marking expected 1σ error bounds based on error covariance of the fit.

We suspect the pre-1920 tide changes in Boston are primarily a local effect. To our knowledge, no similar large-scale reclamation and/or harbor changes have occurred at Portland or Eastport.

To understand the underlying cause(s) of spatially coherent changes in semidiurnal tides, as presented above, requires development of a comprehensive numerical model of this region, which is outside the scope of the present paper. And in any event, numerical modeling may still fail to clarify all the physical processes behind these changes, since modeling alone cannot compensate for lack of observations and inadequate general knowledge about nineteenth- and early twentieth-century regional oceanography. Nonetheless, the changes in tides beginning in the twentieth century correlate with other changes in the physical and geomorphic properties of the Gulf of Maine, and these merit brief discussion.

6.1. Connection to Mean Sea Level

A small or insignificant tidal trend during the nineteenth century, followed by a significant trend in the twentieth, underscores the likely connection to mean sea level, which has undergone similar changes in trend. The longest instrumental sea-level record in the region, from 1825 to present, is for Boston (Talke et al., 2018). Beginning in 1825 and for about a century thereafter, sea level at Boston was nearly constant, but sometime around 1925 there was a clear "change point" with sea level rising approximately 2.5 ± 0.2 mm/year to the present. A similar change point of 1920–1930 was obtained by Gehrels and Woodworth (2013) based on proxy and instrumental records from Connecticut, outside the Gulf of Maine but near the lower left corner of Figure 1. The annual mean sea level determinations of Talke et al. (2018) are reproduced here in Figure 11.

We can now add to those data the results of our historical mean sea-level determinations at Portland, which are far less complete but nonetheless broadly consistent with the Boston results in showing a very small pre-1930 trend. (The datum tie between the 1860s and 1930s is based on archival benchmark sheets, which show that Benchmark 31, the primary benchmark of the entire modern Portland time series, is 25.972 feet above the 1864–1866 staff zero.) We cannot include an Eastport time series of mean sea level because the 1860 benchmark was destroyed in the 1870s. Pulpit Harbor, of course, has no modern sea-level data to compare against.

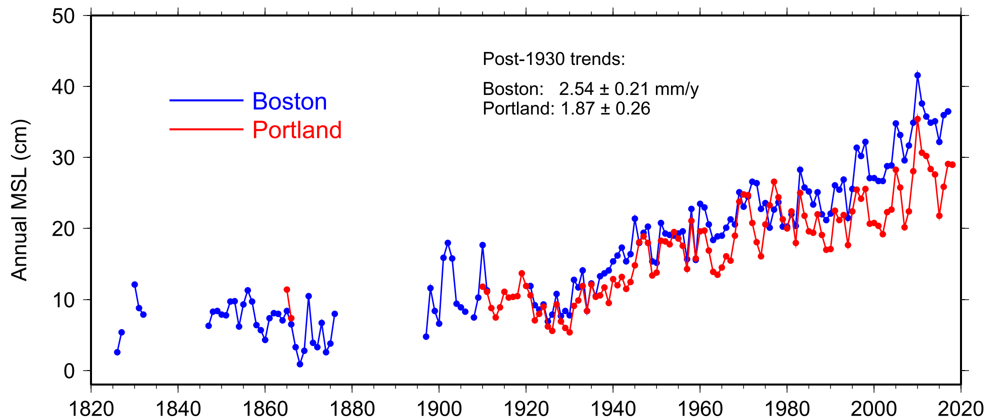

Figure 11. Annual mean sea levels at Boston and Portland, with Boston data extracted from Talke et al. (2018). The two curves are aligned at year 1910. The Boston rate is higher than the Portland rate partly because of different rates of glacial isostatic adjustment: 0.51 and 0.18 mm/year, respectively, according to Peltier et al. (2015).

While the qualitative correspondence between sea level and tidal range—no significant trend before the early twentieth century and significant trends afterward—is compelling, we noted in section 1 that previously published modeling exercises have failed to explain the tidal changes as strictly caused by sea level rise. The modeled signs of tidal trends are correct, but their magnitudes do not match observations (e.g., Greenberg et al., 2012; Müller et al., 2011; Pelling & Green, 2013; Schindelegger et al., 2018). For example, Schindelegger et al. report that their modeled trend is less than 20% of the observed trend at Portland. Pelling and Green, who stress that results depend on how their model handles flooding versus no-flooding, see almost no M_2 changes at Portland even with a 1-m sea level rise (their Figures 6a,6b), although their amplitudes clearly increased to the north of Portland. So the rise in mean sea level provides only a partial explanation for the observed secular tide changes.

6.2. Connection to Stratification: A Seasonal Analog

As in many other locations (e.g., Müller et al., 2014), the M_2 tide in the Gulf of Maine has a significant seasonal variation in both amplitude and phase. The seasonal amplitude changes are shown in Figure 12 for four stations, plus Newport and Halifax outside the gulf. The results are based on monthly response analyses (Munk & Cartwright, 1966), subsequently averaged over all months of two different epochs, one early in the modern time series and one late. (A response analysis is a preferable methodology for this, because it will automatically account for small 1-cpy and 2-cpy sidelines around M_2 that exist in the tidal potential but are of no interest here because they do not reflect environmentally driven changes in M_2. It will not, however, automatically account for the possible presence of the compound MSK_2, 2 cpy from M_2, but we found this constituent to be less than 1 cm at all ports.)

The amplitude offsets between epochs in Figure 12 (i.e., biases between red and blue curves) reflect mostly the secular increase in M_2 amplitudes or the small decreases at Newport and Halifax (see Table 2 and Figure S1). At all stations inside the gulf, M_2 attains maximum amplitude in mid-year, July at St. John and April to July at Portland and Boston. There are two important points to draw from Figure 12: (1) For the four stations inside the gulf, the seasonal cycle in M_2 has changed. The curve offsets are noticeably greater during the beginning of the year and smallest during late summer. For example, at Portland, the January difference is 5.2 cm, whereas the September difference is 2.7 cm. Moreover, for the three northernmost stations, the seasonal cycle has weakened over time: the red curves have lower variance than the blue. This is not the case at Boston, however, nor for the stations outside the gulf; Newport and Halifax appear to have relatively unchanged seasonal cycles. Hence, some factor is modulating tidal amplitudes inside the gulf on a seasonal scale, and that factor has changed between the early twentieth century and today. (2) The seasonal changes in M_2 in both early and late epochs are comparable to or larger than the secular changes in M_2. Could the causes of seasonal and secular changes be similar?

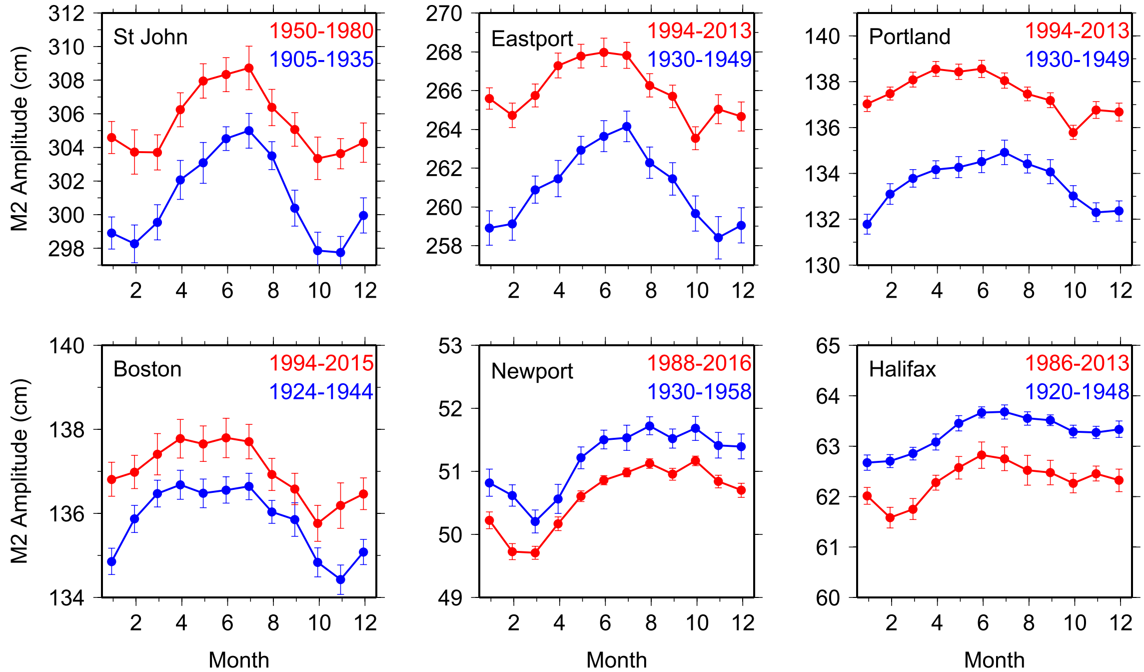

Figure 12. Seasonal dependence of the amplitude of the M_2 tide at six ports, including two (Newport and Halifax) outside the Gulf of Maine. Mean values for each month of the year were calculated for the listed epochs, one earlier (blue) and one later (red). The amplitude offsets between different epochs reflect mostly the secular changes in amplitude (which are decreases at Newport and Halifax; see also Figure S1). The seasonal cycle in M_2 has weakened for the three stations farthest in the interior (top panels). The late (red) epoch at St. John is actually midcentury in order to avoid the gauge problems there in 1980 and afterwards.

Consider first the seasonal dependence on sea level. In this region the mean seasonal changes in sea level can be adequately approximated by the range of the tidal constituent Sa, which is fairly small ("range" is twice the amplitude). We estimated Sa ranges as follows (north to south): 3.0 cm at St. John, 1.2 cm at Eastport, 3.8 cm at Bar Harbor, 5.6 cm at Portland, and 7.8 cm at Boston. These numbers are smaller (very much smaller at Eastport) than the mean sea level rise over the twentieth century (e.g., Figure 11). Because the secular change in water level is, according to models cited above, insufficient to explain secular changes in tides, the same mechanism, given an even smaller change in water level by season, is also by itself evidently insufficient to explain the seasonal changes in tides. Moreover, the seasonal cycle in sea level has changed little over time at these ports (see Figure S6).

A dependence on stratification, either within or just outside the gulf, is likely playing a significant role. Indeed, the region around Georges Bank is a known source of energetic internal tides (Brickman & Loder, 1993), and the barotropic-to-baroclinic conversion there must depend on changing stratification. Energy extracted from the barotropic tide around Georges Bank would be reflected in the tidal amplitudes subsequently observed throughout the interior of the gulf. In addition, changing stratification in shallow water may directly affect barotropic transports by modifying the amount of tidal kinetic energy lost to turbulence (Müller, 2012).

Using a numerical model of the Gulf of Maine and the wider New England Shelf, Chen et al. (2011) found that "stratification has limited impact on tidal elevation." They quote a standard deviation difference of 1.5 cm for M_2, although the spatial pattern of this change is not presented or described. Since much of their domain covers the broader New England Shelf, a domain-average statistic can be expected to be small, and it is unlikely to characterize the coastal region of the upper gulf. In a more recent modeling effort, Katavouta et al. (2016) investigated effects of seasonal changes in stratification on M_2 elevations and currents. They too found small (order 1 cm) changes in M_2 amplitudes over their whole domain, but they noted much larger changes within just the Gulf of Maine (5–10 cm) and even larger changes in the Bay of Fundy (greater than 10 cm). More specifically, at Eastport for the year 2010, their model gave summer-winter changes in M_2 amplitude of 17 cm, somewhat larger than in the observed tide, and changes in phase of 1° (Anna

Katavouta, personal communication, 27 November 2018). The authors attribute part of the changes to reduced vertical viscosity in summer-stratified water, which is similar to the Müller (2012) mechanism noted above. In any event, these seasonal changes in the Eastport tide are larger (in amplitude) or comparable (in phase) to the M_2 secular changes observed at Eastport (Figure 12).

The results of Katavouta et al. (2016) clearly show that Gulf of Maine tides are sensitive to changes in ocean stratification. If salinity and/or temperature patterns have changed on a secular time scale, some of the long-term changes in tides can thus plausibly be linked to corresponding changes in stratification. But is there evidence for secular changes in stratification? The details of the region's stratification, and how it varies geographically and temporally, even for the present day, are complex (Li et al., 2015; Richaud et al., 2016). There are hints of long-term changes in salinity, including inferences from changes in the zooplankton community (e.g., Kane, 2007), but better evidence exists for long-term changes in water temperature.

In a comprehensive compilation of historical and modern (1875–2007) sea surface temperature (SST) data along the U.S. east coast, Shearman and Lentz (2010) have found that coastal temperatures in the Gulf of Maine have increased by 1.0±0.3° per century. According to their time series (see their Figure 8), the temperature increases were minimal until mid-twentieth century, somewhat analogous to our results for M_2. (Aside from these long-term trends, however, the shorter period, or decadal, fluctuations show no direct relationship; e.g., a very large SST anomaly centered at 1950 has no analog in our tide series). In addition, Shearman and Lentz found that most of the warming in the Gulf of Maine occurs during wintertime, with long-term winter trends about 0.5° per century greater than summer trends. This is again analogous to the changes in seasonality of M_2 (Figure 12).

In the context of our tide work at Eastport, Portland, and Boston, we can supplement somewhat these results of Shearman and Lentz (2010). At these three tide gauges, water temperature measurements have been routinely made by NOAA since 1997. A longer time series exists for Boston, and Maul et al. (2001) used such data over 1921–1994 to compute a temperature trend at Boston of 3.6° per century, which is an unusually high value, as those authors noted. In addition, we have located similar water temperature measurements—possibly also employed by Shearman and Lentz—that were collected during 1881–1890 by the U.S. Signal Service when it was branch of the Army. Archival records explicitly state that the Portland measurements were collected at the Customs House Wharf; presumably, the Boston and Eastport measurements were similarly near the tide gauges. Water temperature measurements during this era were collected at the three ports every day at 2:00 p.m. We have sampled the modern data also at 2:00 p.m. to be consistent. We removed obvious outliers (e.g., unphysical day-to-day jumps or unrealistic temperatures) and computed from both data sets a long-term climatological average for each day of year, subsequently smoothed by a 30-day running mean. The mean SST data for both modern and historical eras are shown in Figure 13.

Results show that water temperature has increased an average of 1.8 to 2.2 °C at the three ports. These values are larger than the average trends for the whole gulf found by Shearman and Lentz (2010) but smaller than the 1921–1994 Boston value of Maul et al. (2001). Our estimates are larger than those of Shearman and Lentz in part because of very large temperature increases in the Gulf of Maine since 2000 (Pershing, 2015). (We also did not apply a bucket correction as did Shearman and Lentz, which slightly raises our estimates of total temperature change.) At Boston and Portland, the largest changes in water temperature are observed during late autumn and winter, with the minimum change occurring from June to August. Eastport is an outlier, however, with a near-constant increase of 1.8 °C observed throughout the year. At least for the southernmost ports, the seasonal cycle in SST has weakened, with most of this weakening due to a rise in SST during colder seasons, which is consistent with the results for M_2 tidal amplitudes in the gulf. Interestingly, this correlation is in keeping with the mechanism discussed by Müller (2012) whereby a more stable wintertime water column, as suggested by the higher modern winter SST values, acts to reduce the tidal kinetic energy lost to turbulence (cf. Müller et al., 2014, Figure 14), thus increasing tidal amplitudes observed at the coast.

Aside from these surface temperature measurements, we are unaware of historical water-column measurements comparably old, which would be needed to constrain quantitatively any changes in stratification. Moreover, Li et al. (2015) emphasize that in the eastern Gulf of Maine, stratification is mostly controlled

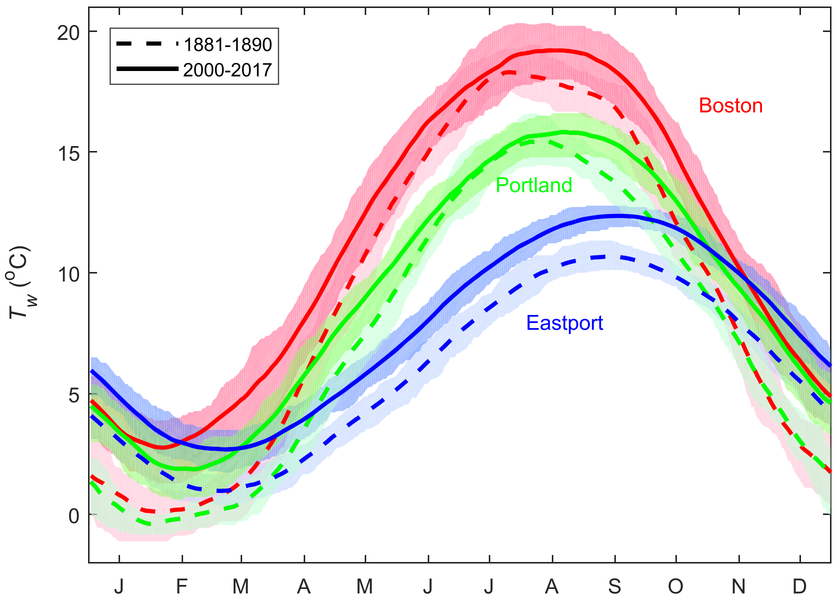

Figure 13. Mean sea surface temperatures at Boston, Portland, and Eastport. Dashed lines were computed from historical measurements made by the U.S. Signal Service (1881–1890); solid lines were computed from modern data collected by NOAA (2000–2017). The shadings denote the 25th to 75th percentile of measurements and provide an estimate of interannual variability relative to long-term changes. The secular sea surface temperature changes suggest the possibility of secular stratification changes along the coast and conceivably in other areas of the gulf as well.

by haline processes, and there is even less historical information on salinity. Nonetheless, the large changes in SST constitute a plausible link to stratification, and since modeling work (Katavouta et al., 2016) has already established the importance of stratification to seasonal changes in M_2, it is not unreasonable to infer that stratification is also playing an important role in secular changes.

Finally, in addition to secular changes in sea level and stratification, other possible environmental factors, some anthropogenic, may have influenced tidal properties over the past century or more. There have been decreases in the length of tributary estuaries; for example, three were shortened by up to 30 km in the 1960–1970 era by road and causeway construction, with subsequent formation of large mudflats on the seaward side (Daborn & Dadswell, 1988). As is typical for a system near resonance (Talke & Jay, 2020), the Gulf of Maine may be quite sensitive to changes in length and energy dissipation over shallow water (see also Holleman & Stacey, 2014). Environmental (and ecological) changes caused by trawling (Kenchington et al., 2007) may have exerted a not-yet-explored, system-scale impact on seabed roughness and frictional dissipation. Tidal changes from these processes would be expected to occur either episodically or mostly during recent decades, and they cannot, by themselves, explain the relatively steady, secular rates seen in Figure 3. They may well help explain some short-term fluctuations, and perhaps, they have contributed to the somewhat erratic M_2 behavior seen at St. John (Figure 3, top panel, although that behavior has also likely been influenced by the St. John River). Lastly—on the topic of rivers—long-term changes in discharge into the gulf could conceivably play a role, but the recent compilation of discharge data by Piecuch et al. (2018) indicates a negligible trend in annual water level exported to the Gulf of Maine; it is possible that the seasonal cycle has shifted, as it has in other locations such as the Hudson River (Ralston et al., 2019).

7. Summary

All three nineteenth-century tide-gauge time series suggest that the large post-1900 secular trends in M_2 observed in the Gulf of Maine do not extend into the previous century. As was stressed in section 1, any tidal change observed at a single station must be treated skeptically because of the high likelihood of changes in the local environment or instrument. Thus, to obtain consistent results at three locations lends some confidence that the conclusions apply to the regional tide throughout the whole Gulf of Maine.

It is a pity that modern measurements do not exist at Pulpit Harbor. Even a few years would add considerably to the few months of data from 1983 and 1985 that we had to rely on to tie the time series with Bar Harbor. Obtaining enough years to span a full nodal cycle, which would complement the full cycle obtained in 1870–1888, would eliminate the need to tie the series to a separate station. The Pulpit Harbor measurements could then stand on their own, which would be highly desirable.

A small or insignificant tidal trend during the nineteenth century, followed by a large trend in the twentieth, again underscores the likely connection to mean sea level, which has undergone similar changes in trend (Figure 11, also Talke et al., 2018). Large seasonal changes in the tide, in both observations (Figure 12) and modeling studies (Katavouta et al., 2016), suggest the importance of stratification to the barotropic tide, as has been pointed out in other contexts or locations (e.g., Kang et al., 2002; Müller, 2012), and historical and present-day SST observations (Figure 13) hint that stratification may well have changed on secular time scales in the Gulf region. These gross similarities in the patterns of changes in tides, sea levels, and ocean temperatures provide an attractive, first-order target for future detailed tide and climate modeling studies. Further efforts in data archaeology which could constrain such modeling efforts would be welcome.

Appendix A: Seavey Island Tide Gauge

For a large fraction of the twentieth century (1926–2002), a tide gauge was maintained at the Portsmouth Naval Yard, on Seavey Island, which sits in the Piscataque River on the boundary between Maine and New Hampshire. Beginning in July 2003, a new tide-gauge station was established at Fort Point, New Hampshire, a site farther downstream and more directly open to the sea. The M_2 amplitude is approximately 9 cm larger at Fort Point than at Seavey Island, and the M_2 phase lag is approximately 7° earlier, so without direct overlap, the two time series cannot be easily combined to study secular trends. Therefore, we focused on Seavey Island data alone.

Data problems often become more transparent in a time series of monthly, rather than annual, tidal estimates. Figure A1 shows such estimates, for the amplitudes of M_2 and M_4, for the whole 1926–2002 time span. The calculations are based on a response tidal analysis, relative to the equilibrium tide, so a small residual 18.6-year nodal modulation can be expected. The figures show some obvious problems—abrupt jumps—which are suggestive of tide gauge relocations. Metadata located within NOAA archives confirms the tide gauge was relocated a number of times, although always on Seavey Island. Unfortunately, the listed positions are often either inaccurate or simply too imprecise to recover definite locations (e.g., some coordinates correspond to the middle of the island). An undated handwritten note was found that reads: "Station moved May 23, 1973, to the other side of island. It is near but not at the old (prior ′69) site." We are thus confident that the large M_2 offsets over 1969–1973 are from measurements obtained on the north side of the island (the so-called Back Channel of the Piscataque), whereas all other measurements were obtained on the southwest side, or possibly west side, in the main branch of the river. From the M_2 diagram, one might suspect that the 1940–2002 data, excepting the short 1969–1973 data, were obtained in approximately the same location, but the M_4 amplitudes are clearly inconsistent over that time span.

If we assume that the Seavey Island measurements over the 1940–2002 interval (again excepting 1969–1973) were sufficiently close to allow an analysis for M_2 tidal changes, then we obtain over that interval a linear trend in amplitude of 5.4±0.8 cm per century, which is only slightly smaller than the trend observed at Portland to the north. But the Figure A1 offsets in M_4 suggest that this Seavey Island trend estimate must be treated with caution.

Appendix B: Letter From Pulpit Harbor

As noted above, the nineteenth-century tide records collected at Pulpit Harbor are unusually complete, with only a few noteworthy gaps. A number of minor gaps occurred in the winter of 1886–1887. These hardly affect any analysis of the data, and the tidal residuals from this period appear of similar quality to the other data. Nonetheless, the gaps prompted some correspondence between the field and home office. We think modern readers will find one of these letters especially revealing. It gives us some inkling of what was endured to obtain good observations on an isolated island during a nineteenth-century Maine winter.

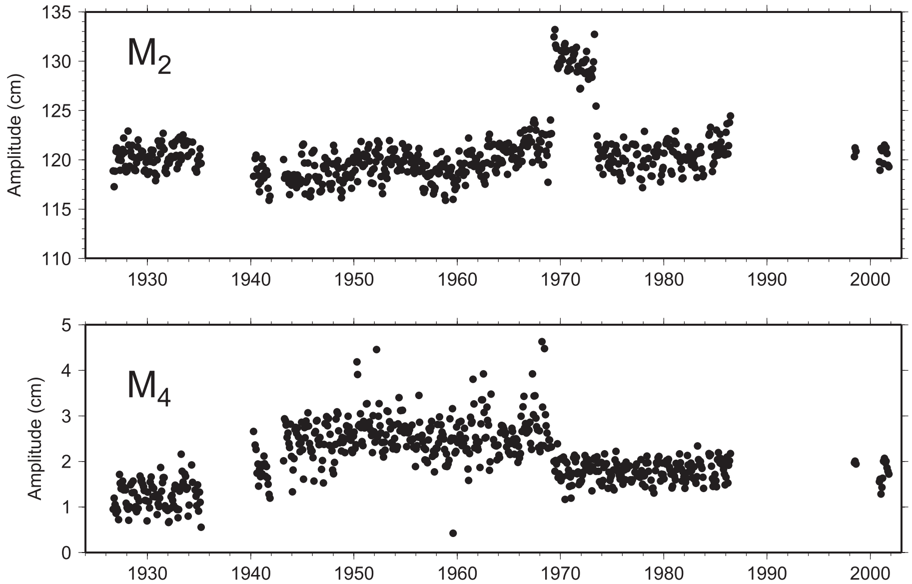

Figure A1. Monthly estimates of M_2 and M_4 amplitudes computed from hourly data collected on Seavey Island, a small island which sits in the Piscataque River separating Maine from New Hampshire. The evident offsets in monthly estimates are caused by relocations of the tide gauge, always on the island and thus not far (the island is less than 1 km across), but the movements were evidently sufficiently distant to spoil any attempt to estimate real changes in the tides.

The letter is dated 1 April 1887 and is addressed to the Washington office of the U.S. Coast and Geodetic Survey. We quote here nearly the whole letter, omitting only a few extraneous sentences:

Dear Sir:

> Your letter of March 23rd, acknowledging receipt of records from this station has been received. I will be careful in future to make the dates inclusive, in my statement of tabulations. It was accidental that they were not so stated in my last.
>
> You do me an injustice in presuming that I have allowed the gauge to freeze up. It has not frozen up – the float has been entirely free from ice without a single exception. All the breaks in the curves were occasioned by the stopping of the clock. This clock has been in constant use at this station since Nov. 5, 1872, and has not been in the hands of a jeweler for repairs or even cleaning once during the whole period. I have usually taken it apart and cleaned it about twice a year, seldom stopping the clock more than two hours for the purpose, and taking observations from the staff to cover this. The stopping of the clock has not been occasioned by any lack of care on my part. I have given it more care and attention during the past winter than at any other time, for the reason that it was stopping. I started my fire in the tide house Nov. 14, and since the latter part of November the fire has not been out only just long enough to clear out the stove and build a new fire. I seldom leave the tide house earlier than 10 or 11 o'clock at night, and in the worst weather frequently go again before morning. …
>
> I will make comparison of benchmarks and staff and send results to Office as soon as ice is out of the cove, and there comes a good tide and smooth water. I established a new benchmark May 11th, 1886. It coincides with 17.49 feet on staff. I examined it a few days ago and could detect no changes. The tide just covers the mark when the staff indicates 17.49 ft. …
>
> I failed to notice the distortion of curves by earthquake tremors, which you mention. Accept thanks for calling my attention to this. Will you do me the favor to send me a tracing of the curves in question, with date[?]… I would like a new clock and a couple of rollers for the tide gauge, but if not convenient to send them I will do my best to get along without them. I thought once I had discovered and removed the principle cause of the clock stopping, but it has stopped once since, and for this reason I fear it may again. I shall be obliged to continue the fire some two or three weeks longer.

Very Respectfully,

J. G. Spaulding

Tide Observer

Acknowledgments
We are all indebted to J. G. Spaulding (see Appendix) and the many generations of similarly dedicated tide-gauge operators. The nineteenth-century tide records are stored at the U.S. National Archives (College Park, Maryland), under accession 370-89-009, Record Group 370, National Ocean Service, "Tide Staff Readings, 1835–1943." We thank several archivists at the National Archives for help finding these records. Modern U.S. tide gauge data were obtained from NOAA's Center for Operational Oceanographic Products and Services, through their website (http://tidesandcurrents.noaa.gov). Modern Canadian tide gauge data were obtained from the Canadian Hydrographic Service, Department of Fisheries and Oceans Canada (http://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/twl-mne/index-eng.htm). The nineteenth-century water temperature measurements are available from 19th Century Forts and Voluntary Observers Database (FORTS) at the University of Illinois (https://mrcc.illinois.edu/data_serv/cdmp/cdmp.jsp). Thanks to Thomas Wahl for comments and Hannah Baranes for useful discussions of data problems in the modern gauge data. This work was supported by the U.S. National Aeronautics and Space Administration, the National Science Foundation (Career Award 1455350 to PSU), and the U.S. Army Corps of Engineers (Award W1927N-14-2-0015 to PSU).

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