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Nineteenth Century North American and Pacific Tidal Data: Lost or Just Forgotten?

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ABSTRACT

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Tide data are the oldest and longest oceanographic records and comprise one of the few tools for understanding, quantifying, and separating century-scale human and climate impacts on the coastal zone. Our archival research indicates that continuous measurements of tides began in 1844 in the western Atlantic, 1853 in the Eastern Pacific, and 1858 in the Western Pacific. At least 50 multiyear tide series existed by the year 1900. With few exceptions, however, these 19th and early 20th century measurements have not been analyzed in more than a century and have been forgotten and neglected by the scientific community. This article describes historical tide measurements in the Pacific Ocean and North America, their current status, and ongoing efforts to recover the data. Possible uses of the data include assessing trends in sea level, tidal properties, and river flow, and reanalyzing extreme events such as historical storms and floods. More than 600 years of station data are confirmed to still exist in paper form, out of approximately 1900 years total.

ADDITIONAL INDEX WORDS: *Tide data, mean sea level, tidal dynamics, historical reanalysis, extreme events, hydrological change, data recovery.*

INTRODUCTION

The few available 19th and early 20th century tidal data sets from the Pacific Ocean and North America are most often used to help reconstruct historic mean sea-level (MSL) and estimate MSL acceleration (Church and White, 2011; Hannah, 1990; Jevrejeva *et al.*, 2006; Maul and Martin, 1993). Historic tide data, however, can also help determine trends in tidal range and storminess (Bromirski, Flick, and Cayan, 2003), reconstruct extreme events and storm surge (Woodworth and Blackman, 2002), characterize changes in estuarine processes (Amin, 1983), assess geologic uplift/subsidence (Wood and Elliot, 1979), describe climate cycles such as El Nino/La Nina (Komar, Allen, and Ruggerio 2011), and hindcast historical river flow (Jay and Kukulka, 2003). Extreme water levels depend on changing MSL but also on tidal range and storm impacts, all of which have been increasing in the Eastern Pacific for more than a century (Bromirski, Flick, and Cayan, 2003; Jay, 2009). Long-term changes in tidal constituents worldwide (Jay, 2009; Woodworth 2010) reflect altered oceanic conditions (Colosi and Munk, 2006) but also occur because of local channel modifications, channel deepening, and altered hydraulic roughness (Amin, 1983). Extreme cases are found on the North Sea coast: for example, tidal range in the Ems estuary on the German/Dutch border has increased fivefold because of increasing North Sea tidal range, installation of a weir in 1899 (river km –12.7), and channel deepening/streamlining since 1960 (Figure 1a). A direct consequence of the changed tidal dynamics (Chernetsky, Schuttelaars, and Talke, 2010) is greater sediment trapping and summer time hypoxia (Talke, de Swart, and de Jonge, 2009).

Long tidal records allow analyses of site-specific tidal dynamics, river flow, and coastal upwelling, even if they are not tied to modern benchmarks. This is particularly important when no other hydrographic records exist. For example, San Francisco Bay river flow was hindcast between 1858 and 1930 (Figure 1b), using the observation that increasing river flow alters tidal amplitudes and phases (Kukulka and Jay, 2003). The results suggest a 30% decrease in annual flow since the 19th century and a shift from a snowmelt influenced system to a primarily rain-driven system (Moftakhari *et al.*, 2013). This analysis also suggests that the great 1862 flood was ~25–30% larger than any other flood since 1858.

Determining accurate tidal and MSL trends requires records over a time period greater than sources of variability such as the nodal cycle and Pacific Decadal Oscillation (Woodworth, 2010). In addition, estimates of MSL acceleration are often dependent on the start date (Rahmstorf and Vermeer, 2011), and the uneven spatial distribution of long records complicates estimates of MSL rise and acceleration (Jevrejeva *et al.*, 2006). Hence, one strategy to address the recent controversy regarding MSL acceleration (*e.g.* Houston and Dean, 2011; Rahmstorf and Vermeer, 2011; Watson, 2011) is to increase the number, length, and spatial distribution of historic records. All

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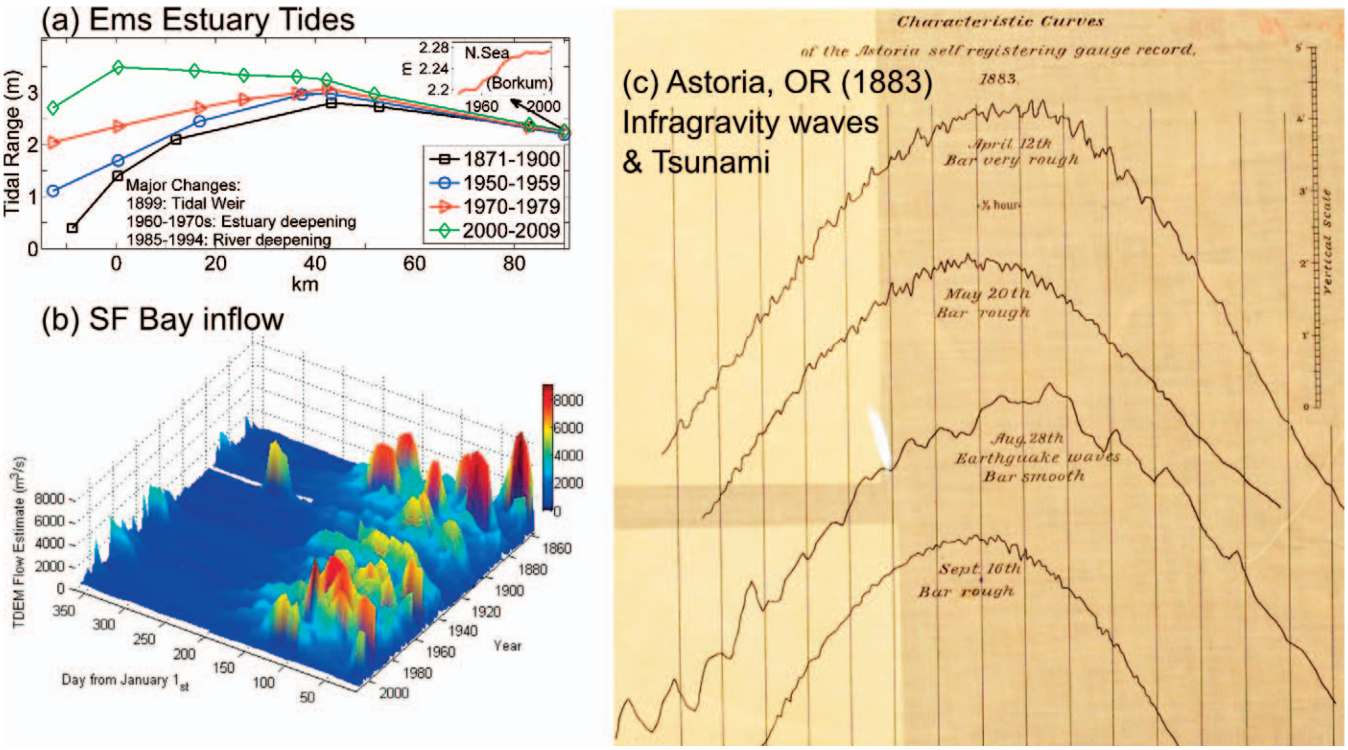


Figure 1. (a) Change in Ems estuary tidal range (pre-1900 from Keller [1901]). (b) Inflow into San Francisco Bay from 1858–1986 using tide data (Moftakhari *et al.,* 2013). (c) Long-period waves (5–30 minutes) and the Krakatoa tsunami measured in Astoria, Oregon (Powell, 1884). Each vertical line denotes half an hour. (Color for this figure is available in the online version of this paper.)

of these examples emphasize the importance and benefits of historic tidal data recovery.

RESULTS OF ARCHIVAL RESEARCH

Memory of most pre-1900 tide records has largely disappeared from the modern scientific literature, despite their potential uses. Data from 33 mid-19th century U.S. gauges, some of which were multiyear series, were last analyzed by Bache (1855). Nineteenth-century MSL in Boston, Massachusetts, from 1847–77 and 1897–1902 was last analyzed by Freeman (1903). Similarly, 19th century Canadian data from as early as 1850 (Halifax) were last referenced by Proudman (1920). On the U.S. west coast, 19th century hourly data for Astoria and San Diego were last referenced (but not used) by Roden (1966), while Wood and Elliot (1979) last analyzed annually averaged 19th century San Diego MSL to estimate vertical crustal movements. Matthäus (1972) last mentioned Australian data from as early as 1858. The only exceptions to this neglect are short segments of marigrams (the original pencil trace on paper produced by a tide gauge), which have been used to reconstruct past tsunamis (*e.g*. Lander, Lockridge, and Kozuch, 1993). Figure 1c shows a trace from the 1883 Krakatoa tsunami, as measured in Astoria, Oregon. Other nontidal, infragravity fluctuations evident in Figure 1c were caused by elevated coastal winds and ocean waves, as described in Powell (1884), and were used by local mariners to assess wave conditions at the Columbia River bar.

Pacific Ocean Measurements

The history of Pacific Ocean tide measurements before 1910 is reconstructed in Table 1 and Table 2 from historic literature and our research in U.S. and Canadian archives. U.S. Coastal Survey annual reports (1854–1876) indicate that self-registering tide gauges were installed in 1853 in Astoria, San Diego, and San Francisco. Continuous measurements began before 1900 in Australia (1858), New Zealand (1883), Japan (1891), and Canada (1893). The French measured tides in Panama (1881–88), and Americans began tidal measurements in Hawaii (1877) and the Philippines (1901). Tide gauges were used for military purposes (Smith, 1997), surveying, and tide predictions, and data were analyzed using specialized machines in Washington, D.C. and England. Station information shown in Table 1 and Table 2 and descriptions of tidal constituents, MSL, data quality, and other observations were found in Ellery (1880), Wharton (1888), Darwin (1891), Russell (1890–1903, annually), Wright (1902), Dawson (1907), Hirayama (1911), Proudman (1920), USACE (1881–1915), IHR (1932), Matthäus (1972), and historic U.S. Coast and Geodetic Survey (USC&GS) (1877–1910) annual reports and USC&GS tide tables.

Of the 27 pre-1900 records listed in Table 1 and Table 2, only two are available pre-1899 as digitized hourly data (San

Table 1. *List of present-day tide gauges in the Eastern Pacific that collected data for four or more years before 1910. Confirmed years have been located in U.S. and Canadian archives by authors.*

Location	Start Date	Confirmed Years Extant in Undigitized Form	Years Unaccounted	Currently Digitized Hourly	Total Years Undigitized
San Francisco, CA[1]	1853	1853	–	1854–pr (present)	1
San Diego, CA[2]	1853	1853–72[R]	–	1906–pr	19
Astoria, OR[3]	1853	1853–76 [R]	1883–1907	1925–pr	45
Port Townsend, WA[4]	1855	1855,[R] 1873–77,[R] 1933–35, 1941, 1952	–	1966, 1972– pr	10
Seattle, WA[5]	1891	1891–92	–	1899–pr	1
Kodiak, AK[6]	1880	1880–91,[R] 1906–09,[R] 1918–20, 1932–39, 1949–74	–	1975–pr	48
Honolulu, HI[7]	1877	1883–84, 1892–99, 1901–04	1900	1877–82, with gaps; 1905–pr	13
Victoria, BC[8]	1893	1905–08	1893–1904	1909–pr	16
Pt Atkinson, BC	1897	1920, 1922–40, 1959–60[IOSA]	1897–1906, 1908, 1910–13, 1941–43, 1945–46	1914–19, 1921–22, 1927, 1933, 1939, 1944, 1947–58, 1961–pr	38
Vancouver, BC	1901	1901, 1905–08, 1924–39, 1940, 1942[IOSA]	1902–04	1909–23, 1941, 1943–pr	25
Tofino, BC	1905	1905–08, 1921–39, 1942, 1944, 1946,1948[IOSA]	–	1909–pr, with gaps	27
Prince Rupert, BC	1906	1906–08, 1920, 1922, 1925–26, 1928–38, 1942[IOSA]	–	1909–pr, with gaps	19
Isle de Naos,[9] PA	1881		1881–88	Nearby Balboa, 1907–pr	8
Total		~ 200 years confirmed	~68 years		~270 years

Abbreviations: R = recovered in paper form by authors; IOSA = data available at Institute of Ocean Sciences (IOS) archives, Sidney, British Columbia (BC). Notes 1–9 are described in the supplementary material. References consulted for this table include Roden (1966), Dawson (1907), and IHR (1932).

Francisco and Honolulu) and only two (San Francisco and Sydney) are used to evaluate 19th century MSL in the Pacific (*e.g*. Church and White, 2011). A subset of the 20th century data has been digitized and made available by government agencies, PSMSL (Permanent Service for Mean Sea Level) and GLOSS/IOC (the Global Sea Level Observing System/ Intergovernmental Oceanographic Commission (Caldwell, 2003; Levitus *et al*., 2005); however, many record segments remain undigitized, particularly between 1850 and 1950. Table 1 and Table 2 document 200 years and 93 years, respectively, of extant, undigitized records and a combined 1273 station years of unaccounted data (likely a mixture of extant data, lost data, and recording gaps). Many marigram and tabulated records are stored by the U.S. National Archives and by the National Oceanographic and Atmospheric Administration (NOAA; Silver Spring, MD). Other records are stored in Australian,

Table 2. *List of present-day tide gauges in (or near) the Western Pacific region that collected data for four or more years before 1910.*

Location	Start Date	Confirmed Years Extant in Undigitized Form	Years Unaccounted	Currently Digitized Hourly	Total Years Undigitized
Fort Denison[1] (Sydney), NSW	1867	1905–13 NSWA, 1910 NARA-CP[R]	1867–1904	1914–pr (present)	47
Newcastle,[2] NSW	1870	1907–09 NSWA	1870–1906, 1910–24	1925–pr	55
Yamba,[5]* NSW (Clarence River)	1900	1946–63 NSWA	1900–45, 1964–83	1984–pr	84
Williamstown,[3] VIC	1858		1858–1965	1966–pr	108
Hobart,*[4]TAS	1889		1889–1959, 1961	1960–pr	72
Ballina,*[5] NSW	1897	1946–63 NSWA	1897–1945 1964–85	1986–pr	89
Brisbane,*[6] QLD	1865		1865–1956	1957–pr	92
Cairns,*[7] QLD	ca. 1890		1890–1959, 1961–65	1960, 1966–76, 1978, 1982–pr	75
Wellington,[8] NZ**	1887	1891–94 (NARA-KC)[R]	1887–90, 1895–1943	1944–pr	57
Lyttleton,[9] NZ **	ca. 1883	**1886–1910 in NZNA (unconfirmed)	1883–1923	1924–pr	41
Dunedin, NZ**	ca. 1883	1898 (NARA-KC)	1883–1897	1899–pr, with gaps	15
Auckland, NZ	1899		1899–1902	1903–pr	4
Westport,[10] NZ*	ca. 1901		1901–81	1982–pr	81
Ayukawa,[11] JP ***	1891		1891–1961	1962–pr	71
Hanasaki, JP***	1895		1895–1963	1964–pr	69
Yokohama, JP***	1899		1899–1960	1961–96	62
Aburatsubo, JP***	1893		1894–1932	1933–pr	39
Kushimoto, JP***	1892		1892–1960	1961–pr	69
Hosojima,[12] JP***	1892		1892–1932	1933–pr	41
Keelung,[13] TW***	1904		1904–79	1980–pr	76
Manila, PH	1901	1901–40 (NOAA/NARA-KC)	1941–47	1948–pr	48
Total		~93 years confirmed	~1202 years		~1295 years

Abbreviations: *Not known if gauge record is uninterrupted. **Unconfirmed old tide data available in NZ national archives. ***84 pre-1940 tide stations are microfiched by the Japan (JP) Oceanographic Data Center and might include these data. NSWA = New South Wales archives; NARA-CP = U.S. National Archive, in College Park, MD; NARA-KC= U.S. National Archive in Kansas City, MO; R = recovered (photographed) by authors. For notes #1–13, see supplementary material. References consulted for this table include AAAS (1913), Chapman (1938), Hannah (1990), Hirayama (1911), Proudman (1920), Richardson (1901), Russell (1885), Russell (1890–1903), USHO (1920), Wharton (1888), Wilson (1938), and Wright (1902).

Table 3. *Tide gauges off the East Coast of North America with at least 4 years of pre-1910 data. Confirmed data has been located (by authors) at U.S. and Canadian archives.*

Station	Start Date	Confirmed Years Extant in Undigitized Form	Years Unaccounted	MSL Data (PSMSL, NOAA)	Hourly Data Available
St. John, NB	1896	1899–1904, 1918, 1922, 1925, 1928, 1935–38	–	1896–pr (present), with gaps	1896–pr, with gaps
Halifax, NS	1851	1896, 1898–1920	1851–52, 1861–62	1897, 1921–pr	1897, 1921–pr
Eastport, ME	1860	1860–64, 1918	–	1930–pr	1930–pr
Pulpit Bay, ME	1870	1870–88	–	1983–85	
Portland, ME	1852	1852–53, 1864–66, 1910–11	–	1912–pr	1912–pr
Boston, MA	1847	1847–77, 1903–11	1897–1902,[D] 1912–28[i,M]	1921–pr	1921–pr
Newport, RI	1844	1844–46, 1892–95	–	1930–pr	1930–pr
Providence, RI	1872	1872–92	1893–1902[M]	1938–pr	1979–pr
Willets Point, NY	1885	1885, 1890–96	–	1930–2000, Kings Pt. 1998-pr	1957–2000
New York, NY	1844	1844–1879, 1885	1886–1920[M] (Port Docks)	1856–78, 1893–pr	1920–pr
Brooklyn, NY	1855	1855–65	–	–	–
Sandy Hook, NJ	1844	1844–46, 1855–58, 1872–93, 1907–09	–	1910–pr	1910–pr
Reedy Island, DE	1896	1896–1903	–	1956–65, 1973–pr	1996–pr
Baltimore, MD[1]	1845	1845,[i] 1853–54,[i]1855–56, 1863,[i] 1866,[i] 1876,[i] 1886,[i] 1898,[i] 1899[i]		1902–pr	1902–pr
Annapolis, MD	1844	1844–47, 1853, 1870, 1888 (intermittent surveys)		1928–pr	1928–pr
Washington, D.C.	1852	1852, 1858–60, 1891–1902, 1925	–	1931–pr	1931–pr
Old Point Comfort, VA[2]	1844	1844–79, 1906, 1907, 1909–10, 1918–19	–	1927–pr[H]	1927–pr
Wilmington, NC	1882	1882, 1887, 1890–91, 1908–11		1930–pr	1930–pr
Charleston, SC[3]	1850	1850–61, 1882–1908, 1910, 1913	–	1856	1921–pr
Fort Pulaski/Tybee Island, GA	1851	1851–52, 1889–92, (1854,[i] 1866,[i] 1897[i])	1894–95,[C] 1903–05,[C] 1911–20[C]	1935–pr	1935–pr
Fernandina, FL (Ft. Clinch)	1855	1855–61, 1869–71,[i] 1878–79	1890–91[C]	1897–1924, 1938–pr	1897–1924 1938–pr
Key West[4]	1847	1847,[i] 1850–52, 1857–59, 1903	–	1913–pr	1913–pr
Cedar Keys, FL	1858	1858–60, 1892–93		1914–25, 1938–pr	1997–pr
Total to recover/digitize		~330–340 years	as much as ~ 95 years		

Notes: I = intermittent survey; C = U.S. Army Corps of Engineers Measurement; D = Deer Island, MA; H = Hampton Roads, VA; M = Municipal (City) gauge. (1) Also Fort Carroll, Fort McHenry; (2) also known as Fort Monroe; (3) Fort Sumter, Castle Pinckney; (4) see Maul and Martin (1993).

Canadian, Japanese, and New Zealand archives (Table 1 and Table 2).

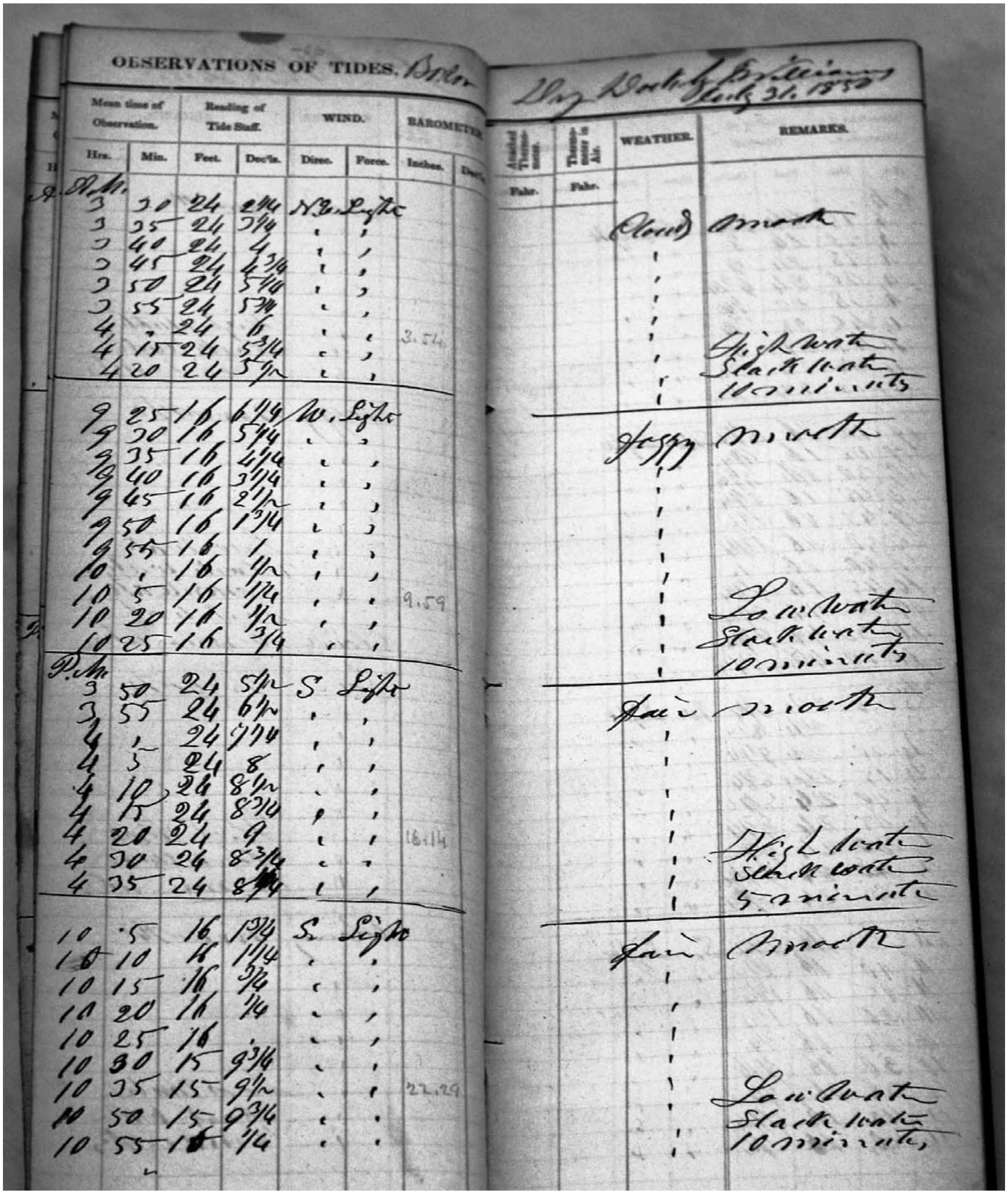
Western Atlantic Measurements

Tidal measurements during the 19th century were also widespread between Florida and New Brunswick on the east coast of North America (Table 3). Continuous tidal measurements began in the 1840s and 1850s, and many multidecade records are extant as tabulated (but not digitized) data or as analog marigrams from locations such as Boston, Sandy Hook, Old Point Comfort, and Charleston. Altogether, more than 330 years of extant, undigitized pre-1920 data have been located for the 23 stations in Table 2. By contrast, only 84 years of pre-1920 hourly data is currently digitized, with the earliest hourly data from 1896–97 (Fernandina; St. John, New Brunswick; and Halifax). Similarly, MSL data are available at PSMSL for only one station pre-1897 (New York, 1856–78, 1893-present). Our research indicates that nearly 100 years of tide data are unaccounted for, primarily measurements by city governments; for example, the Port Docks authority in New York, New York, measured tides continuously at Pier A from 1886 to at least 1920 (Schureman, 1934). As in the Pacific, both long-term trends (tidal, sea level) and information regarding extreme events (extreme water level in Boston in 1851, the 1893 New York hurricane, and the 1893 and 1894 hurricane surge in Charleston) are contained within the undigitized data.

Description of Extant Records

The type of analog records available parallels the historical development of tide predictions and tidal science (Reidy, 2008). Bathymetric surveys by the U.S. Coastal Survey required tidal elevations. These short tidal series (<6 months) from various U.S. coastal locations and colonies are available from 1835–1950 at the U.S. National Archives. Early tidal analysis and tide predictions required the times and heights of high and low water, preferably from long (>1 year) data sets. Therefore, multiyear, hand-measured time series from the 1840s and 1850s typically include 1–2 hours of data around the daily extrema in 10–15 minute increments (Figure 2).

During the early to mid-1850s, the U.S. Coastal Survey began using the Saxton automatic tide gauge, which produced a continuous pencil trace on a ~20 m long scroll on a monthly basis (Figures 3 and 4). In the U.S., these marigram data were reduced to tabulations of high and low water and analyzed by subsequent first and second reductions (see supplementary material). Because the marigram traces contained nontidal



OBSERVATIONS OF TIDES, Boston Dry Dock [illegible] July 31. 1850

Mean time of Observation.		Reading of Tide Staff.		WIND.		BAROMETER.		Attached Thermometer.	Thermometer in Air.	WEATHER.	REMARKS.
Hrs.	Min.	Feet.	Dec'ls.	Direc.	Force.	Inches.	Dec'ls.	Fahr.	Fahr.		
A.M.											
3	30	24	2 1/4	N.E.	Light					Cloudy	Smooth
3	35	24	3 1/4	"	"					"	
3	40	24	4	"	"					"	
3	45	24	4 3/4	"	"					"	
3	50	24	5 1/4	"	"					"	
3	55	24	5 3/4	"	"					"	
4	"	24	6	"	"					"	
4	15	24	5 3/4	"	"	3.54				"	High water
4	20	24	5 1/2	"	"					"	Slack water 10 minutes
9	25	16	6 1/4	W.	Light					Foggy	Smooth
9	30	16	5 1/4	"	"					"	
9	35	16	4 1/4	"	"					"	
9	40	16	3 1/4	"	"					"	
9	45	16	2 1/2	"	"					"	
9	50	16	1 3/4	"	"					"	
9	55	16	1	"	"					"	
10	"	16	1/2	"	"					"	
10	5	16	1/4	"	"	9.59				"	Low water
10	20	16	1/2	"	"					"	Slack water
10	25	16	3/4	"	"					"	10 minutes
P.M.											
3	50	24	5 1/2	S	Light					Fair	Smooth
3	55	24	6 1/2	"	"					"	
4	"	24	7 1/4	"	"					"	
4	5	24	8	"	"					"	
4	10	24	8 1/2	"	"					"	
4	15	24	8 3/4	"	"					"	
4	20	24	9	"	"	16.14				"	High water
4	30	24	8 3/4	"	"					"	Slack water
4	35	24	8 [illegible]	"	"					"	5 minutes
10	5	16	1 3/4	S.	Light					Fair	Smooth
10	10	16	1 1/4	"	"					"	
10	15	16	3/4	"	"					"	
10	20	16	1/4	"	"					"	
10	25	16	"	"	"					"	
10	30	15	9 3/4	"	"					"	
10	35	15	9 1/2	"	"	22.29				"	Low water
10	50	15	9 3/4	"	"					"	Slack water
10	55	16	1/4	"	"					"	10 minutes

Figure 2. Example of manually measured tide data from Boston, Massachusetts, on 31 July 1850.

fluctuations (edge waves, seiching, *etc*.), tabulators (known as computers) sometimes interpolated the approximate time and height of high and low water (see Figure 4). Similarly, when the marigram data was missing, tabulators often interpolated data from high water/low water tabulations or from tide tables (*e.g.* San Francisco in May 1862; see Figure 5) to complete hourly listings and monthly summaries. These examples illustrate the necessity of re-examining the original record for possible errors or bias, particularly for studies examining the nontidal (residual) portion of the historical record.

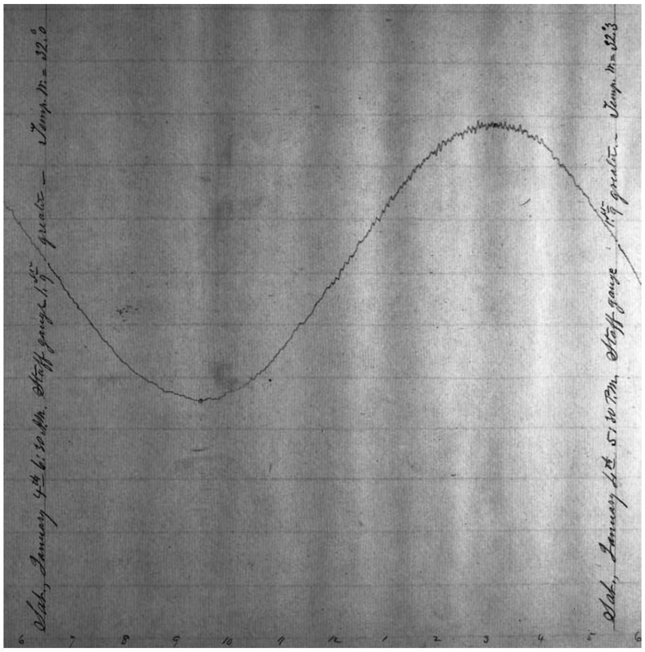


Figure 3. A marigram from a self-registering tide gauge in Astoria, Oregon, on 4 January 1862. Each horizontal line represents approximately 30 cm of water level. Note the extremely cold water temperatures listed for the morning and afternoon gauge check and the infragravity oscillations on the rising tide and near high water.

With the development of harmonic analysis by William Thomson in 1867 (Thomson, 1868) and the advent of tide-predicting machines in 1872 in England (Thomson, 1881) and the early 1880s in the United States (Ferrel, 1882), year long-time series of hourly spaced data became necessary (Figure 5). Around this time, many (but not all) of the pre-1880 U.S. marigrams appear to have been reduced to hourly measurements. These data are stored by either NOAA or the U.S. National archives (*e.g.* Fort Point, California, 1854–77; San Diego, California, 1853–72; Astoria, Oregon, 1870–76; Governor's Island, New York, 1860–79; Boston, Massachusetts, 1869–77; Old Point Comfort, Virginia, 1865, 1874–78). The remaining data is typically available as tabulated high/low data.

Ancillary Data

To compare historical MSL with modern gauges and to assess data quality, benchmark information and ancillary data such as gauge and time checks are also required. As early as the 1850s, it was standard practice for the U.S. Coastal Survey to tie tide gauges to at least one primary benchmark. The benchmark locations and elevation for 12 Atlantic and Gulf Coast gauges were described in the annual *U.S. Coastal Survey Report* (1854). Some early benchmarks (*e.g.* the Astoria 'tidal rock' benchmark from 1853) still exist (Figure 6) and can be resurveyed today, while the elevation of others must be recovered by examining later surveys. For U.S. west coast stations, we have recovered early benchmark data from NOAA in the form of leveling surveys (*e.g.* Astoria, 1887; see Figure 5) or from data contained in hydrographic surveys and available in the U.S. National archives (San Diego, 1898; Kodiak Island, 1920). Multiple benchmarks were typically used in these later surveys and indicate growing sophistication in methods. These late 19th/early 20th century surveys can often be tied to present gauges using the data from periodic resurveys, many of which are cataloged by agencies such as NOAA. Historical publications also describe benchmarks and local datums, for example, in Australia (Ellery, 1880; Russell, 1890–1903) and Canada (Dawson, 1907). Hence, it is probable that other benchmarks from as early as the 1840s can be recovered throughout the Pacific and North America, though local archival research in the country of origin is often required (*e.g.* Hunter, Coleman, and Pugh, 2003, in Tasmania).

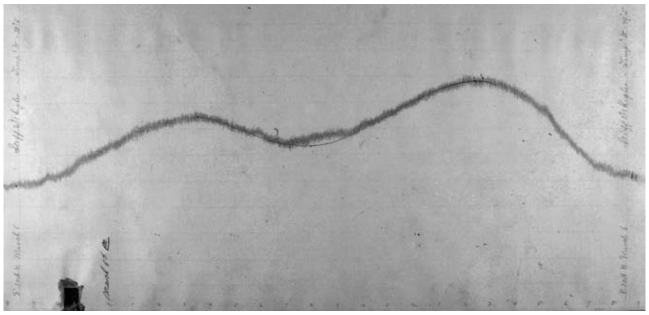
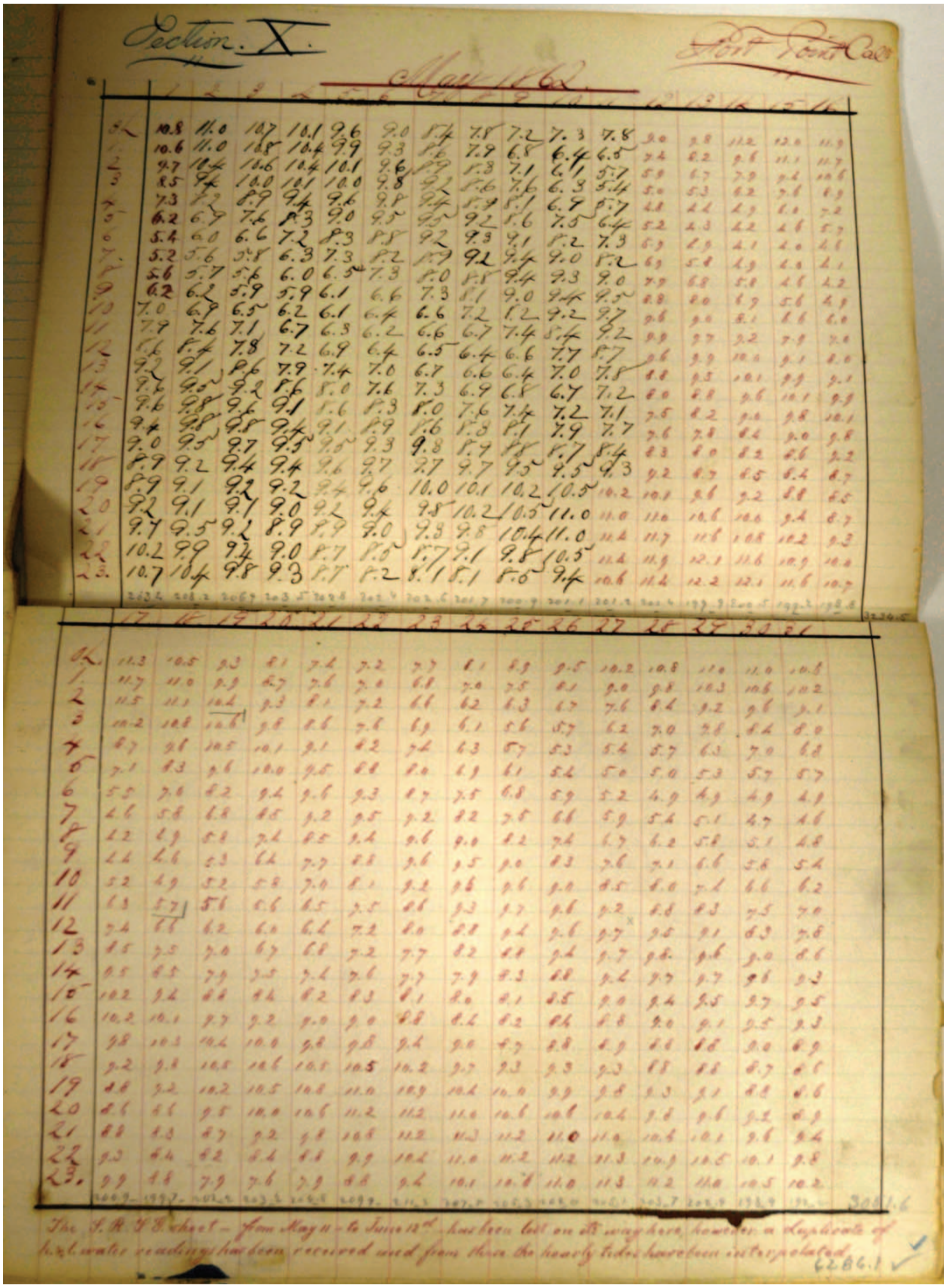


Figure 4. Marigram from 5 March 1862, from San Francisco, California. Nontidal fluctuations are evident and required interpolation by the tabulator to estimate the astronomical low water (see interpolation line and low-water point). The thick pencil line indicates atypical, short (<1 minute) fluctuations caused by a stilling well problem or by dock vibrations after moving the gauge to a new gauge house, which was necessitated by the severe storms of December 1861 to February 1862.

Routine time and elevation checks are also vital to make recovered marigram data useful. For U.S. and Canadian data, ancillary data are stored with the tide tabulations and/or were marked on the original marigrams. For example, the gauge in Astoria, Oregon, was typically checked twice a day (morning and evening), and the difference between the gauge height and a tide staff was tabulated (Figure 3). These measurements were later used to scale the marigram to a tidal height by hand tabulators.

Challenges

A typical problem in many historic tide measurements was occasional sedimentation or clogging of the intake holes in the stilling well (*e.g.* San Francisco in Sept. 1904; see supplementary material). These problems often produce spurious data that contaminate modern tidal analyses (see, *e.g.* Moftakhari *et al.*, 2013). Because time-keeping could also pose a problem, tide-gage keepers also checked their chronometers (clocks) and tabulated (on a monthly basis) the error, which was typically on the order of a few seconds a day but occasionally more (see supplementary material). Because the chronometer was checked at local high noon, most (if not all) of the early tide measurements appear to have been made in local mean city



Section. X.

May 1862

Fort Point Cal

The S.R.T.G. sheet – from May 11 – to June 12th has been lost on its way here, however a duplicate of h.&l. water readings has been received and from these the hourly tides have been interpolated.

Figure 5. Example of a month of hourly tabulated data from San Francisco, California, from May 1862. Times are in the left column, while days are listed horizontally. Sums of the columns were used to check the veracity of the tabulation. Red (lighter colored) tabulations indicate interpolated (rather than actual) data, as explained in the note on the bottom: "The S.R.T.G. (Self Recording Tide Gage) Sheet from May 11 to June 12th has been lost on its way here, however a duplicate of high water readings has been received and from this the hourly tides have been interpolated." (Color for this figure is available in the online version of this paper.)

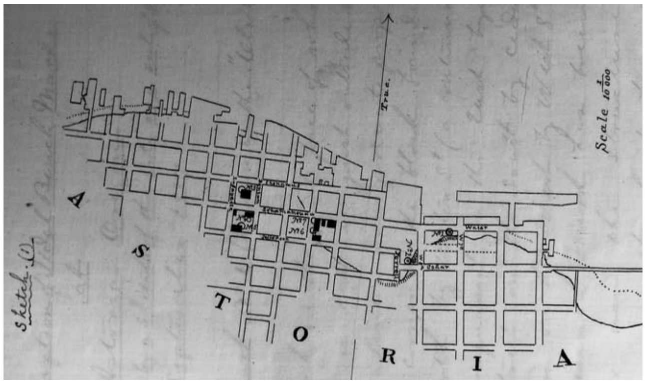


Figure 6. Locations of Astoria, Oregon, benchmarks 1–7 (marked in red) from an 1887 leveling survey by the U.S. Coastal Survey (data at U.S. national archives in College Park, Maryland). The No. 1 benchmark from 1853 still exists. The old shoreline (dotted line) indicates that infilling occurred between 1854 and 1887.

time (standardized time zones did not become common in the United States until the mid-1880s).

Other problems may enter historical records; for example, the wharf in San Francisco subsided by approximately 0.75–0.9 m between July 1854 and April 1858, according to a 19th century reanalysis of data (see supplementary material). Combined with problems with the tide gauge (silting), early San Francisco data from 1854–58 are of questionable utility (see also Bromirski, Flick, and Cayan, 2003). MSL estimates from 1876–81 were also corrected by as much as 0.07 m (0.24 ft) because of tide staff instability (see supplementary material). It is worth noting, however, that most of the issues described previously continued to affect tide measurements for most of the 20th century and have been documented in some cases to bias MSL estimates (see, *e.g*. Agnew, 1986). The example of San Francisco suggests that even well established, long-term tidal data sets might benefit from a careful reanalysis of original meta-data to flag time periods with problems.

Because the 19th century observers lived at or near the tide-gauge house, the marigram records from the 19th century might, in some cases, be superior (and/or more complete than) to 20th century measurements. For example, the tide-gauge observer in Astoria (Louis Wilson) checked the gauge between 50–60 times per month for nearly 20 years. By contrast, our archival research indicates that the San Francisco gauge between 1920–40 was checked only 10–15 times per month, and a similar practice seems to have been in place for west coast gauges in the 1960s and 1970s (Agnew, 1986).

CONCLUSIONS

A first step to spurring international recovery, use, and reanalysis of long-neglected, multiyear tide records from the 19th century is to document their history. Worldwide, early measurements were more widespread than modern compilations would suggest. The Ems estuary alone had multidecadal records from 24 locations by 1900 (Keller, 1901). Storm surge on the Elbe estuary using tide data from 1841–95 was described by Nehls (1896). Tide gauges were operating before 1900 in other European countries (*e.g*. Bouquet de la Gyre, 1901), along U.S. and Canadian coasts, and in colonies such as India, Pakistan, Singapore, Indonesia, and South Africa. Wharton (1888) documented 35 gauges (not including Figure 1c) at which the 1883 Krakatoa tsunami was observed. Therefore, a concerted international effort to document, locate (where possible), and digitize these data is needed (see also Woodworth, 2006). Continued efforts by GLOSS/IOC, the UHSLC, other government agencies, data archeology efforts such as http://ils.unc.edu/~janeg/dartg/, and scientists in various countries are slowly increasing the amount of digitized data (Caldwell, 2003; Hannah, 1990; Marcos *et al*., 2011; Watson, 2011) and might over time address the paucity of available 19th century data.

Across the Pacific basin and throughout North America, extensive, multidecade measurements of tides were made starting in the mid-19th century. At least 50 multiyear tidal data sets were collected by the year 1900, and at least 600 station years of tabulated data are currently unused and stored in national or local archives. Collectively, these data could help address important scientific questions such as secular trends in MSL, tidal range, and the hydrologic cycle and help assess anthropogenic impacts on estuarine dynamics. Because these data document historical tsunamis, storms, and floods, they might also spur reanalysis of extreme events such as the flood of 1862 on the U.S. west coast.

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