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Authors
Flick, R E
Murray, J F
Ewing, L C

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Trends in United States Tidal Datum Statistics and Tide Range

Reinhard E. Flick[1]; Joseph F. Murray[2]; and Lesley C. Ewing, M.ASCE[3]

Abstract: Yearly tidal datum statistics and tide ranges for the National Oceanic and Atmospheric Administration/National Ocean Service long-term stations in the United States tide gauge network were compiled and used to calculate their trends and statistical significance. At many stations, significant changes in the tide range were found, either in the diurnal tide range [mean higher high water (MHHW) − mean lower low water (MLLW)], or mean tide range [mean high water (MHW) − mean low water (MLW)]. For example, at San Francisco, the diurnal tide range increased by 64 mm from 1900 to 1998, while at Wilmington, N.C., the mean tide range increased at a rate of 542 mm per century from 1935 to 1999. This analysis suggests that any studies concerned with present or future water levels should take into account more tidal datum statistics than just mean sea level (MSL). For example, coastal flooding and storm damage studies should consider trends in high water levels, since it is the peak values that cause flooding and determine the design of coastal structures. For habitat restoration planning, mean low water and tide range changes should be considered.

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Introduction

Is the mean high tide rising as fast as the mean sea level? This seemingly simple question led to this study of long-term trends in the tidal data statistics. Yearly tidal datum statistics and tide ranges for the National Oceanic and Atmospheric Administration/National Ocean Service (NOAA/NOS) long-term stations in the U.S. tide gauge network were compiled to calculate their trends and determine if they were statistically significant. The standard set of published tidal datum statistics include: highest water, mean higher high water (MHHW), mean high water (MHW), mean sea level (MSL), mean tide level (MTL), mean low water (MLW), mean lower low water (MLLW), and lowest water. [See Hicks (1989), or the on-line Web version (http://co-ops.nos.noaa.gov/tideglos.html), for definitions of the various NOAA/NOS tidal datum readings and statistics.] The statistics were calculated from monthly data published on the NOAA/NOS Web site (NOAA 2002). This study has been facilitated by the Internet, which has made U.S. water level data much more widely and easily available. Nevertheless, comprehensive overviews of the trends revealed by these measurements, other than those for mean sea level (MSL), have been lacking.

San Francisco was selected for the initial examination of tidal datum statistics because it has the longest continuous tidal record in North America and may be representative of water level fluctuations over broad areas (Bromirski et al. 2003). Tidal records at this station showed a rise in MSL of 22 cm/century since 1900. However, MHHW and MHW actually rose about 19% faster than MSL owing to mean and diurnal tide range increases of about 60 mm/century. All but one (Crescent City) of the long-term open-coast tide stations on the West Coast show an increase in tide range over the available record. Identification of these trends in the tidal records for West Coast stations led to an examination of all tidal records published by NOAA.

The time-series of the various U.S. tidal datum statistics were found to be highly variable, and different from one another. The 18.6-year lunar node cycle represented the largest component of the variability in the tidal datum statistics and tide ranges at many stations. However, of the 62 U.S. stations with significant trends in mean tide range (MHW—MLW), 38 showed an upward trend and 24 showed a downward trend. Some geographical patterns in tide range trends were also evident, especially on the Atlantic and Pacific coasts.

The present analysis focuses on the observed trends in tide range, and on the trends in high water, especially relative to MSL, both subjects of strong interest to coastal engineers. Several stations showed rates of increase of MHW that were about twice those of MSL. Interesting cases of secular change in tide regime were also revealed. At Galveston, Tex. for example, the diurnal inequality seems to have decreased. At Anchorage, Alaska, the tide range increased, but the low tides tended downward much faster than the high tides tended upward (both absolutely and relative to MSL), leading to a falling MTL, even as MSL increased.

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[1] Oceanographer, California Dept. of Boating and Waterways, Scripps Institution of Oceanography, La Jolla, CA 92093-0209. E-mail: ref@coast.ucsd.edu

[2] Graduate Researcher, Integrative Oceanography Division, Scripps Institution of Oceanography, La Jolla, CA 92093-0209. E-mail: jfm@coast.ucsd.edu

[3] Senior Coastal Engineer, California Coastal Commission, 45 Fremont St., Ste. 2000, San Francisco, CA 94105. E-mail: lewing@coastal.ca.gov

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Prior Work

Many published investigations discuss MSL changes over various time scales, spanning the longest geological records, down through the century-scale, to the El Niño related interannual variability along the Pacific Coast of the Americas, and extending to the shortest storm-surge related fluctuations. Bloom (1979) published an ‘‘Atlas of Sea-Level Curves’’ containing all published MSL curves that were known to the writers. Recent developments in remote sensing and crustal rebound modeling may reduce the uncertainty in translating discreet, relative MSL measurements to global absolute sea level changes. For reviews, see Pugh (1987) and Warrick et al. (1993), and references therein.

Hicks and Crosby (1974) provided a graphical compilation of U.S. MSL trends, and Hicks et al. (1983) and Lyles et al. (1988) published compilations of U.S. mean sea level data. The later two volumes focused, respectively, on trends and variability of MSL at 67 and 78 permanent U.S. tide gauge stations, with graphs of annual mean values and selected monthly data and monthly means. They also include extensive appendices containing tables of the NOAA/NOS monthly MSL values through 1980 and 1986, respectively.

Few studies have been published that analyze changes in tide range, and none could be found for U.S. coasts. Bowen (1972) reviewed previous work and examined long-term trends in the Thames River. The study suggested that the observed increase in tide range in the upper Thames estuary was caused mainly by bank raising and river channelization. Amin (1983), also in a study of the Thames estuary, found that tide range had increased between 1929 and 1979, due to increases in the semidiurnal tides. Cartwright (1972) analyzed sea level observations made between 1711 and 1936 at Brest, France, and found a 1% per century decrease in semidiurnal tidal amplitude. This study could not determine whether the changes were oceanic, or due to local coastal modifications, but it eliminated harbor development at Brest as a major factor.

Data and Methods

For the present analysis of temporal change in tide range, data were downloaded from www.opsd.nos.noaa.gov/data_res.html, the NOAA/NOS World Wide Web site. This Web site routinely publishes a suite of monthly average tidal datum statistics (highest water, MHHW, MHW, MSL, MTL, MLW, MLLW, and lowest water) from NOAA’s network of U.S. tide gauge stations and from some locations in other countries. All available, verified, monthly water level data were downloaded. Data from each station were screened only on the basis of record length, and all marine stations with published data records of 20 years or longer were analyzed and included in this paper.

Water level data were downloaded relative to each location’s ‘‘station datum’’ by choosing this option. Relevant data in this paper are displayed relative to this datum for each respective station. This was done to avoid complications and confusion from inevitable future updates of the National Tidal Datum Epoch, and the consequent numerical changes of the various interrelationships between tidal datum planes. Presumably, each station’s datum of tabulation will remain unchanged as long as the station remains fixed and active.

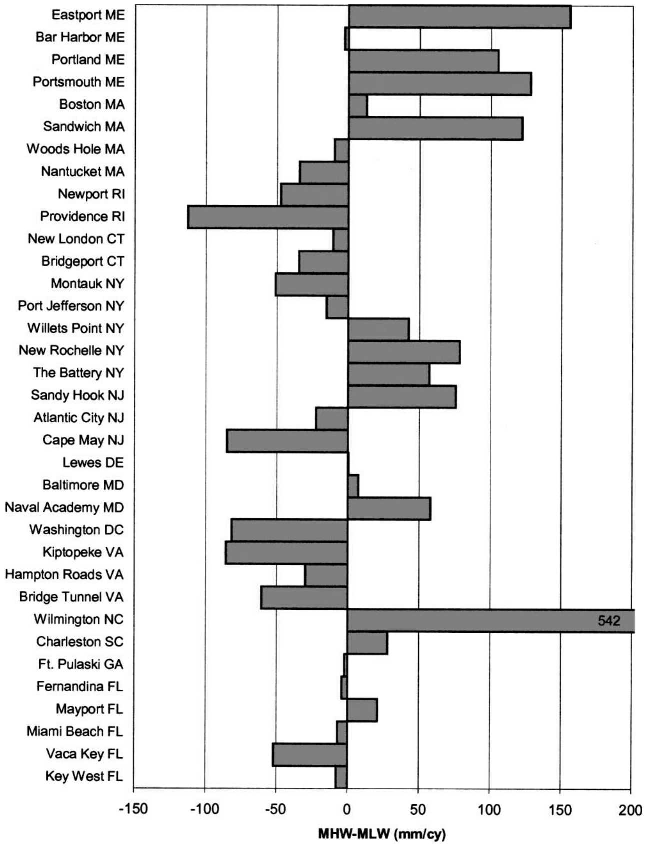

Fig. 1. East Coast mean tide range trends

Data from about 400 stations were reviewed, and measurements from 90 stations were analyzed. The monthly statistics for MHHW, MHW, MSL, MTL, MLW, and MLLW were averaged to obtain yearly values. Years with fewer than 9 months of data were rejected from the analysis. Differences between each statistic and MSL, as well as the diurnal and mean tide ranges, were calculated as follows: highest−MSL, MHHW−MSL, MHW−MSL, MTL−MSL, MLW−MSL, MLLW−MSL, lowest−MSL, MHHW−MLLW, and MHW−MLW. The complete set of summary tables and plots for all stations are presented in Flick et al. (1999). The relevant changes in tide range (mean or diurnal) are summarized for each geographic region as follows:

- East Coast (MHW−MLW), Fig. 1;
- Gulf Coast (MHHW−MLLW and MHW−MLW), Figs. 2 and 3;
- West Coast (MHHW−MLLW), Fig. 4;
- Alaska (MHHW−MLLW), Fig. 5; and
- Pacific Islands (MHHW−MLLW), Fig. 6.

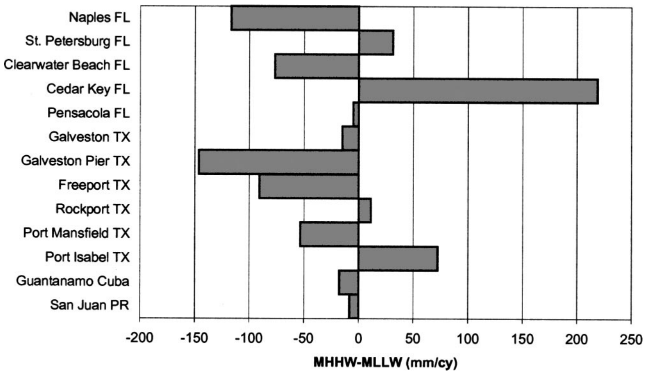

Fig. 2. Gulf Coast diurnal tide range trends

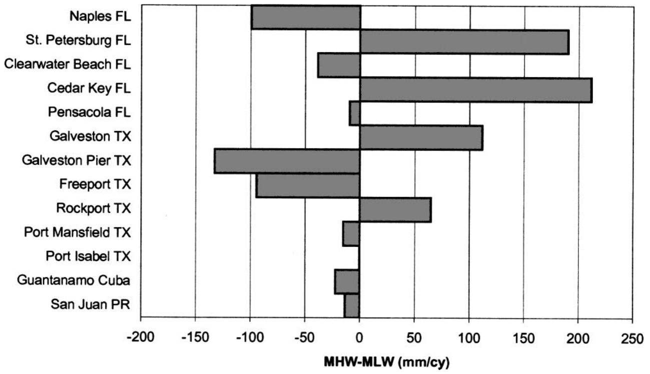

Fig. 3. Gulf Coast mean tide range trends

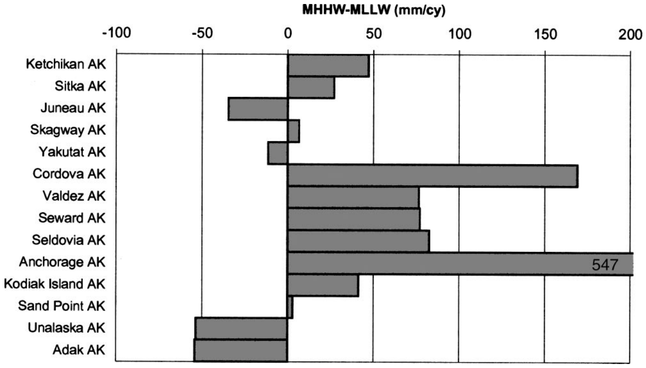

Fig. 5. Alaska diurnal tide range trends

Detailed plots are also given for Wilmington, N.C. (Fig. 7), and San Francisco (Fig. 8).

In order to identify upward or downward trends, a least-squares regression model was used to fit each set of data and differences. The fit parameters included the mean, a linear trend, and an 18.6-year period sinusoid to account for the lunar node cycle (Pugh 1987), which appears prominently in many of the parameters and differences considered. The regression curve is displayed in each plot (solid line) of Figs. 7 and 8, and the value of the linear trend (mm/century) is noted in the lower right corner. Statistical significance at each station was determined with two one-tailed hypothesis tests (trend >0 and trend <0) (Mendenhall and Sincich 1995) applied to MSL, diurnal tide range (MHHW$-$MLLW), and mean tide range (MHW$-$MLW). Of the 90 stations analyzed, 62 showed statistically significant mean tide range trends, and 48 showed statistically significant diurnal tide range trends at the 5% confidence level.

The trend and hypothesis testing results and other information summarizing the results of the present study for MSL and the diurnal and mean tide ranges and their trends are presented in Table 1. Column 1 gives the station name, followed in Column 2 by a somewhat subjective designation of ‘‘O’’ indicating an open ocean station or ‘‘B’’ for stations in bays or harbors (‘‘X’’ designates stations where no information could be found). Columns 3 and 4 show the start and end dates of each record analyzed. Columns 5, 6, and 7 show, respectively, the MSL trend, the number of years suitable for analysis, and whether the resulting trend is statistically significant. In Column 7, the trend direction is labeled ‘‘Up’’ for increasing, ‘‘Down’’ for decreasing, or ‘‘Not’’ if the trend was not significant. Columns 8 and 13 show, respectively, the average diurnal and mean tide range in meters at each station. Columns 9 and 10 and columns 14 and 15, respectively, present the numerical values (mm/century) and the percentage (%/century) relative to the average diurnal and mean tide ranges. Columns 11 and 12 and columns 16 and 17 list the number of years analyzed and the sense of any statistically significant trends in the diurnal and mean tide ranges at each station. Finally, Column 18 provides each NOAA designated station identification number for reference.

Discussion

Inspection of Table 1 and Figs. 1–6 suggest several geographical patterns in the trends of tide range at the NOAA/NOS stations studied, although most regions showed almost as many stations with increasing ranges as decreasing. The following discussion summarizes the regional observations, generally following the regional designations developed by NOAA/NOS.

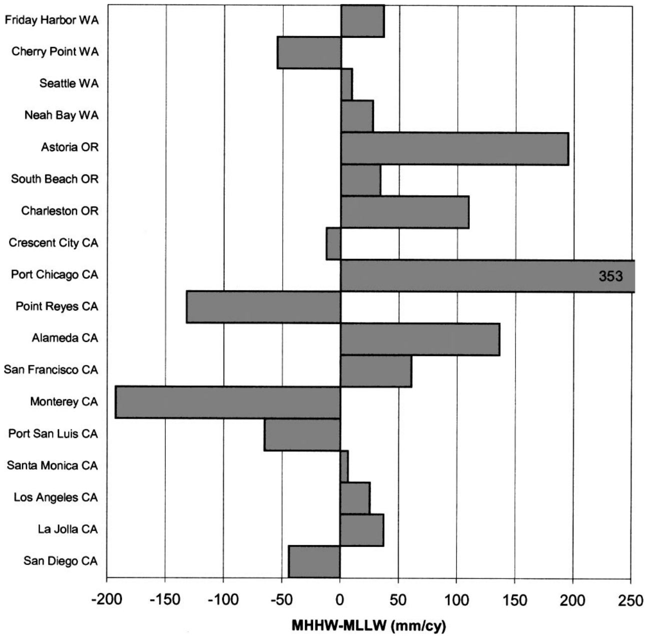

Fig. 4. West Coast diurnal tide range trends

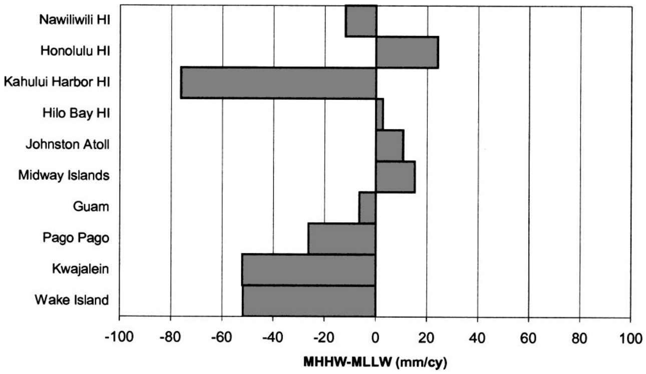

Fig. 6. Pacific Islands diurnal tide range trends

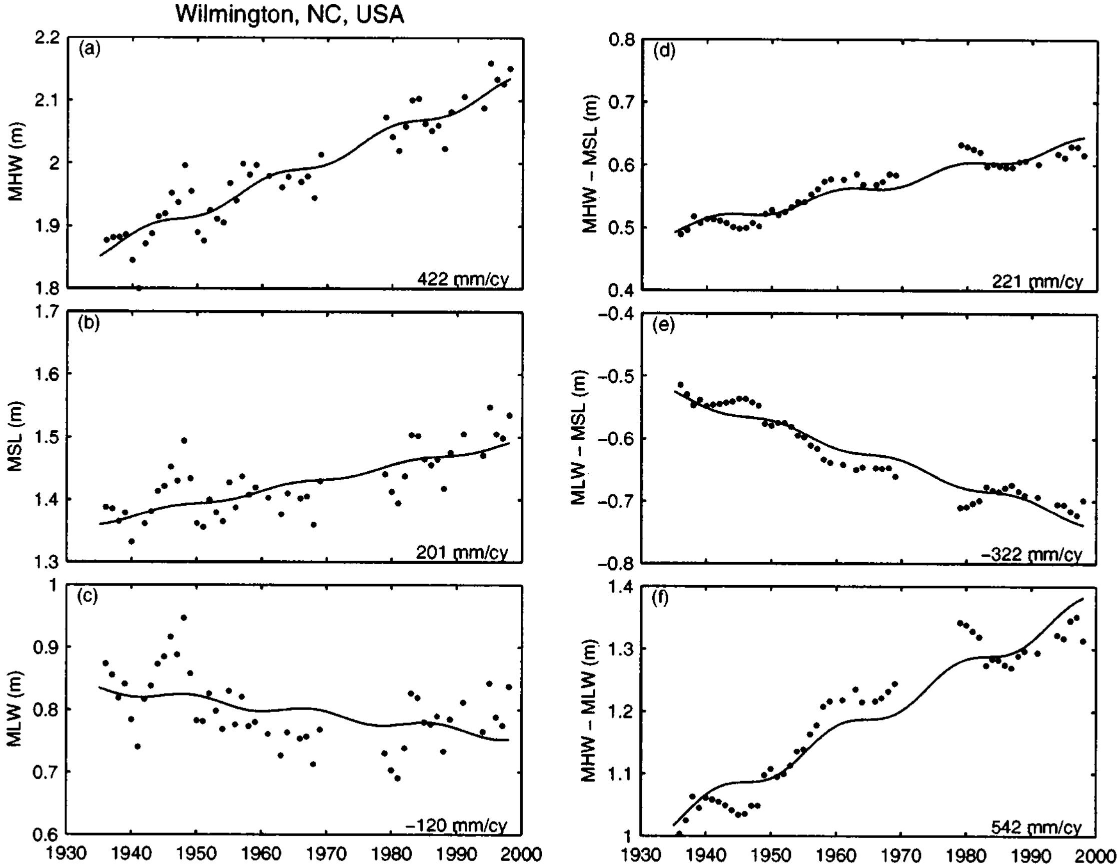

Fig. 7. Yearly averages of (a) MHW; (b) MSL; (c) MLW; (d) MHW−MSL; (e) MLW−MSL; (f) mean tide range MHW−MLW at Wilmington, N.C. (rates of linear trend fits shown in lower right corner)

East Coast

Tides on the East Coast are semidiurnal, with two nearly equal daily high tides and two nearly equal daily low tides. For this reason, MHW and MLW statistics have traditionally been computed by NOAA/NOS since the beginning of each station's record. MHHW and MLLW have only been calculated since the late 1970s, presumably to begin standardizing the nation's chart datum to MLLW on all U.S. coasts. The data records for diurnal range (MHHW−MLLW) were often not sufficiently long to provide statistically significant trend results, while those for mean range (MHW−MLW) were. This may account for the apparent inconsistency of an increase in one and a decrease in the other at some locations. For example, at The Battery, N.Y., the diurnal range seems to have decreased, while the mean range increased. So, while Table 1 provides information on both the mean and diurnal tide ranges for the East Coast sites, none of the diurnal changes were considered further. Similarly, Fig. 1 only shows the mean tide range trends.

The mean tide range generally decreases from north to south, from a high of about 5.5 m in Maine, to a low of about 0.30 m in the Florida Keys, with secondary maxima and minima in between. Along the open Atlantic coast from Maine to Massachusetts, the mean tide range at each location has shown a long-term increase. In contrast, along the south-facing coast from Woods Hole, Mass. (Vineyard Sound–Buzzards Bay), into Long Island Sound to Port Jefferson, N.Y., the tide range trend at each location was downward. The tide range trend increased again in the area around New York City, from Willet's Point at the western end of Long Island Sound to Sandy Hook, N.J. The mean tide range at Sandy Hook increased at a rate of 76 mm/century from 1932 to 2003. MSL at Sandy Hook also showed a relatively high rate of rise (397 mm/century), while MHW rose at a rate of 419 mm/century, or about 6% faster. Stations in the upper portions of Chesapeake Bay, notably Baltimore and Annapolis, Md., showed an upward trend in tide range. The stations on the lower portion of the bay and the riverine station at Washington, D.C., showed a downward trend. Trends in tide range at each station along the Southeast Coast were small, except at Wilmington, N.C. An explanation for this geographic variability has not yet been determined.

At Wilmington, N.C., MSL rose at a rate of 201 mm/century between 1935 and 1999. However, MHW rose at 422 mm/century, a rate more than twice as fast. The mean tide range increased at a rate of 542 mm/century, a rate much higher than that of any other East Coast station (Figs. 1 and 7). While the cause of this sharp increase is not known, this station provides an excellent example of how caution must be used in choosing the appropriate tidal datum statistic for the problem at hand. Furthermore, care must also be exercised when using results from stations like Wilmington, N.C., at adjacent areas where they may not apply.

Gulf Coast

The Gulf of Mexico coast presents a complicated tide regime. It is mixed but dominantly semidiurnal on most of the east coast of Florida, turns dominantly diurnal at the Florida Panhandle through Alabama, is strongly diurnal at the Mississippi River Delta, becomes mixed in western Louisiana, and finally switches

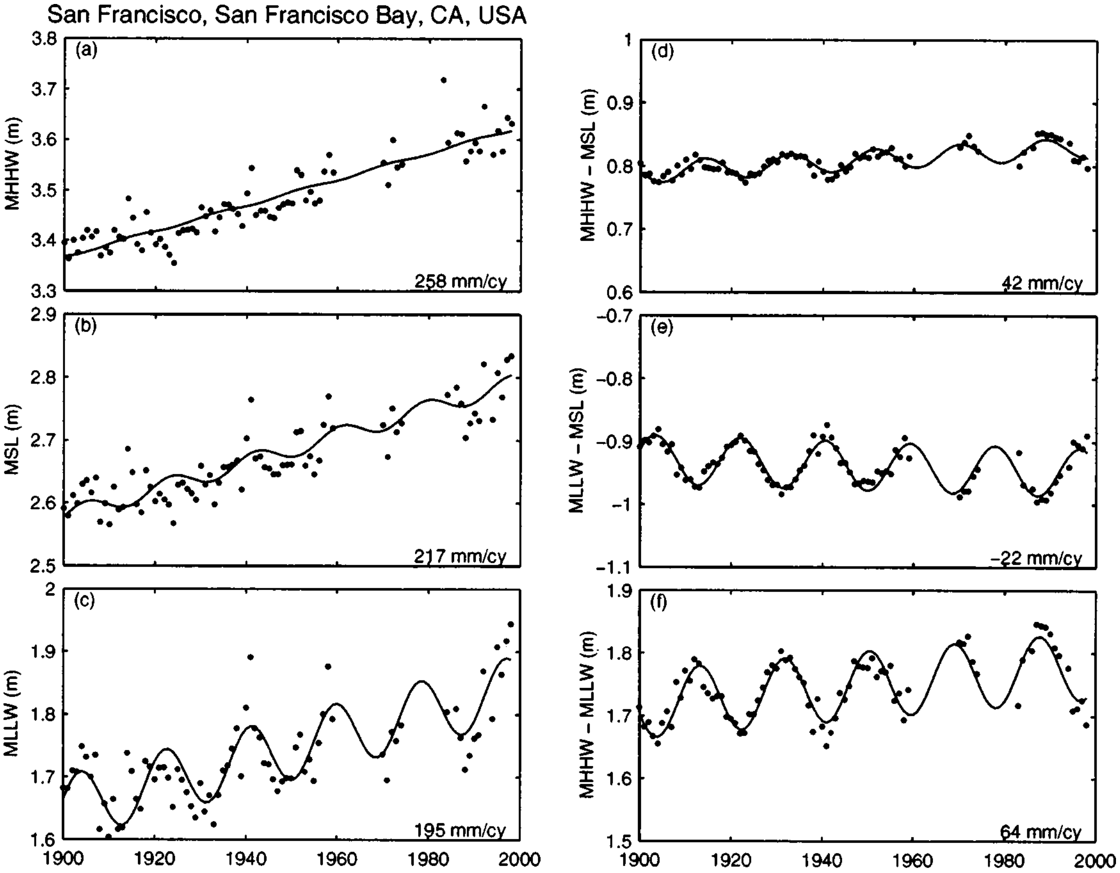

Fig. 8. Yearly averages of (a) MHHW; (b) MSL; (c) MLLW; (d) MHHW−MSL; (e) MLLW−MSL; (f) diurnal tide range MHHW−MLLW at San Francisco (rates of linear trend fits shown in lower right corner)

to dominantly diurnal through most of south Texas and the Yucatan. Tide ranges in the Gulf are generally smaller than those found on the East and West Coasts and vary from about 0.5 m at most open-coast stations from Florida through Texas, to only about 0.03 m (or less) at bay sites, such as Rockport, or Port Mansfield, Tex. Station data published by NOAA from Guantanamo, Cuba, and San Juan, Puerto Rico, was also included in this group.

Only 13 Gulf stations, including five in Florida, six in Texas, and two in the Caribbean, had records over about 20 years long. Of these, three showed an increase in diurnal range, six indicated a decrease, and four were not significant. Figs. 2 and 3, respectively, present plots of the rate of change of the diurnal and mean range at each station. MSL increased at all Gulf stations except Port Mansfield inside the Laguna Madre, where the change was not statistically significant.

At St. Petersburg, Fla., MHW rose at a rate of 316 mm/century, or about 32% faster than MSL. At Cedar Key, Fla., MHW rose at a rate of 255 mm/century, or 86% faster than MSL. The mean tide range at both stations increased at a rate of about 200 mm/century over the past approximately 40 years. In sharp contrast, the tide range trend at Pensacola, Fla., was small and not significant, and MHW increased at about the same rate as MSL. The cause or causes of the sharp increases seen at St. Petersburg and Cedar Key, Fla., are also not known, but these three stations provide additional examples of how caution must be used in choosing the appropriate tidal datum statistic and the area over which it is applied.

At Galveston, Tex., the diurnal tide range showed a small downward trend (−15 mm/century), while the mean range trended upward at a much higher rate (112 mm/century). Inspection of the data suggests that the tide regime at Galveston has changed over time. Since MHHW decreased relative to MSL while MHW increased, the diurnal inequality likely decreased. Further investigation of this apparent regime shift is warranted.

The tide ranges at Guantanamo, Cuba, and San Juan, Puerto Rico, are about 0.3 m, with no statistically significant trends observed.

West Coast

The Pacific Coast of the United States has a mixed-tide regime, with two (usually) unequal daily high tides and two unequal daily low tides. Zetler and Flick (1985a,b) discussed the influence of this mixed-tide system on the pattern of peak high tides, while Flick (2000) showed how it determined their time of day. Table 1 indicates that both the diurnal and mean tide ranges generally decrease from north to south along the West Coast. Furthermore, Puget Sound, San Francisco Bay, and San Diego Bay exhibit higher tide ranges than the corresponding adjacent open-coast areas.

Of the 18 West Coast stations considered in the present study, nine were at open-ocean locations. Of these nine, three of the four stations with long records, namely, San Francisco, Los Angeles, and La Jolla, showed a significant upward trend in diurnal tide range. The fourth, Crescent City, showed no significant trend

Table 1. Mean Sea Level and Tide Range

				MSL			MHHW−MLLW					MHW−MLW					
Location		Start	End	(mm/century)	Years	Trend	(m)	(mm/century)	(%/century)	Years	Trend	(m)	(mm/century)	(%/century)	Years	Trend	Station
(a) East Coast																	
Eastport, Me.	O	1929	1999	224	62	Up	5.87	−172	−3	18	Not	5.55	156	3	62	Up	8410140
Bar Harbor, Me.	O	1947	1998	219	46	Up	3.47	−98	−3	19	Not	3.22	−3	0	46	Not	8413320
Portland, Me.	B	1912	1999	194	87	Up	3.03	−77	−3	22	Not	2.75	105	4	87	Up	8418150
Portsmouth, Me.	B	1926	1998	169	46	Up	2.71	−441	−16	7	Not	2.47	128	5	47	Up	8419870
Boston	B	1921	1999	269	73	Up	3.14	−88	−3	35	Down	2.89	13	0	73	Not	8443970
Sandwich, Mass.	X	1955	1977	80	20	Not	NA	NA	NA	NA	Not	2.67	122	5	21	Up	8447180
Woods Hole, Mass.	O	1932	1999	262	61	Up	0.67	−7	−1	19	Not	0.55	−10	−2	63	Not	8447930
Nantucket, Mass.	O	1965	1999	315	23	Up	1.09	−81	−7	12	Not	0.93	−34	−4	23	Down	8449130
Newport, R.I.	B	1930	1999	255	44	Up	1.18	−104	−9	17	Not	1.07	−48	−4	44	Down	8452660
Providence, R.I.	B	1938	1999	217	37	Up	1.47	−24	−2	9	Not	1.38	−113	−8	37	Down	8454000
New London, Conn.	B	1938	1999	208	57	Up	0.93	−38	−4	19	Not	0.79	−11	−1	57	Down	8461490
Bridgeport, Conn.	B	1964	1999	244	32	Up	2.23	53	2	21	Not	2.05	−35	−2	32	Down	8467150
Montauk, N.Y.	B	1947	1999	248	46	Up	0.77	−73	−9	18	Not	0.64	−51	−8	46	Down	8510560
Port Jefferson, N.Y.	B	1957	1992	215	33	Up	2.17	238	11	13	Not	2.01	−15	−1	32	Not	8514560
Willets Point, N.Y.	B	1931	1999	243	64	Up	2.37	108	5	17	Not	2.17	42	2	64	Up	8516990
New Rochelle, N.Y.	B	1957	1990	−57	21	Not	2.42	121	5	2	Not	2.22	78	4	21	Up	8518490
The Battery, N.Y.	B	1920	1999	319	73	Up	1.55	−112	−7	28	Down	1.37	57	4	73	Up	8518750
Sandy Hook, N.J.	O	1932	1999	397	59	Up	1.58	34	2	26	Not	1.41	76	5	59	Up	8531680
Atlantic City, N.J.	O	1922	1999	415	70	Up	1.41	−89	−6	19	Not	1.24	−23	−2	70	Dri	8534720
Cape May, N.J.	O	1965	1999	365	28	Up	1.66	−51	−3	20	Not	1.49	−85	−6	31	Down	8536110
Lewes, De.	O	1919	1999	304	32	Up	1.43	−33	−2	24	Down	1.26	0	0	32	Not	8557380
Baltimore	B	1902	1999	313	95	Up	0.51	−54	−11	19	Not	0.34	7	2	95	Up	8574680
Naval Academy, Md.	B	1928	1999	374	51	Up	0.44	−188	−43	8	Not	0.28	58	21	51	Up	8575512
Washington, D.C.	B	1931	1999	308	67	Up	0.96	−2	0	20	Not	0.86	−82	−10	67	Down	8594900
Kiptopeke, Va.	B	1951	1999	367	35	Up	0.89	67	7	8	Not	0.81	−86	−11	35	Down	8632200
Hampton Roads, Va.	B	1927	1999	435	62	Up	0.85	−73	−9	30	Down	0.75	−30	−4	60	Down	8638610
Bridge Tunnel, Va.	O	1975	1999	744	24	Up	0.89	−74	−8	23	Down	0.79	−61	−8	24	Down	8638863
Wilmington, N.C.	B	1935	1999	201	48	Up	1.43	−78	−5	17	Not	1.19	542	46	48	Up	8658120
Charleston, S.C.	B	1856	1999	318	75	Up	1.77	−98	−6	23	Down	1.59	28	2	82	Up	8665530
Ft. Pulaski, Ga.	B	1935	1999	297	53	Up	2.29	1	0	14	Not	2.11	−2	0	53	Not	8670870
Fernandina, Fla.	B	1938	1999	216	47	Up	2.01	56	3	21	Up	1.85	−4	0	47	Not	8720030
Mayport, Fla.	B	1895	1999	234	69	Up	1.50	−182	−12	25	Down	1.37	21	2	72	Up	8720220
Miami Beach, Fla.	O	1931	1981	218	44	Up	0.83	−39	−5	11	Not	0.77	−7	−1	44	Not	8723170
Vaca Key, Fla.	O	1971	1999	227	24	Up	0.30	−103	−35	24	Down	0.21	−52	−24	19	Not	8723970
Key West, Fla.	O	1926	1999	192	52	Up	0.55	−8	−1	52	Not	0.39	−8	−2	52	Down	8724580

Table 1. (*Continued*)

				MSL			MHHW−MLLW					MHW−MLW					
Location		Start	End	(mm/century)	Years	Trend	(m)	(mm/century)	(%/century)	Years	Trend	(m)	(mm/century)	(%/century)	Years	Trend	Station
(b) Gulf Coast																	
Naples, Fla.	O	1965	1999	133	32	Up	0.89	−117	−13	32	Down	0.63	−100	−16	32	Down	8725110
St. Petersburg, Fla.	B	1947	1999	239	50	Up	0.69	31	5	50	Up	0.46	190	41	50	Up	8726520
Clearwater Beach, Fla.	O	1973	1999	269	20	Up	0.84	−77	−9	20	Down	0.58	−39	−7	20	Not	8726724
Cedar Key, Fla.	O	1938	1998	137	37	Up	1.11	219	20	37	Up	0.81	212	26	37	Up	8727520
Pensacola, Fla.	B	1923	1999	214	74	Up	0.38	−5	−1	74	Not	0.36	−9	−3	37	Not	8729840
Galveston, Tex.	O	1908	1999	653	89	Up	0.43	−15	−3	89	Down	0.28	112	40	67	Up	8771450
Galveston Pier, Tex.	O	1957	1999	708	35	Up	0.64	−146	−23	35	Down	0.44	−133	−30	20	Down	8771510
Freeport, Tex.	B	1954	1999	1099	44	Up	0.55	−91	−17	44	Down	0.41	−94	−23	21	Not	8772440
Rockport, Tex.	B	1963	1999	564	23	Up	0.11	11	10	23	Not	0.11	65	60	17	Not	8774770
Port Mansfield, Tex.	B	1970	1997	−213	22	Not	0.08	−53	−65	21	Down	0.08	−15	−20	21	Not	8778490
Port Isabel, Tex.	B	1944	1999	327	31	Up	0.41	72	18	31	Up	0.35	0	0	15	Not	8779770
Guantanamo, Cuba	X	1937	1997	285	32	Up	0.39	−18	−5	5	Not	0.30	−22	−7	32	Not	9731158
San Juan, Puerto Rico	B	1962	1999	152	20	Up	0.48	−8	−2	15	Not	0.34	−13	−4	20	Not	9755371
(c) West Coast																	
Friday Harbor, Wash.	B	1934	1999	138	32	Up	2.33	37	2	32	Up	1.40	190	14	32	Up	9449880
Cherry Point, Wash.	B	1973	1999	189	26	Up	2.76	−55	−2	26	Not	1.73	56	3	26	Not	9449424
Seattle	B	1899	1999	212	100	Up	3.45	9	0	100	Up	2.33	5	0	100	Up	9447130
Neah Bay, Wash.	O	1937	1999	−103	37	Down	2.42	27	1	37	Not	1.68	−4	0	37	Not	9443090
Astoria, Ore.	B	1925	1999	6	57	Not	2.55	195	8	57	Up	2.01	141	7	57	Up	9439040
South Beach, Ore.	B	1967	1999	369	32	Up	2.54	34	1	32	Up	1.91	26	1	32	Up	9435380
Charleston, Ore.	B	1970	1999	207	28	Up	2.31	110	5	28	Up	1.73	90	5	28	Up	9432780
Crescent City, Calif.	O	1933	1999	−50	59	Down	2.10	−12	−1	59	Not	1.54	−30	−2	59	Down	9419750
Port Chicago, Calif.	B	1976	1999	727	22	Up	1.49	353	24	22	Up	1.11	288	26	22	Up	9415144
Point Reyes, Calif.	O	1975	1999	405	24	Up	1.75	−132	−8	24	Down	1.20	−140	−12	24	Down	9415020
Alameda, Calif.	B	1939	1999	81	48	Up	1.98	136	7	48	Up	1.45	125	9	48	Up	9414750
San Francisco	O	1855	1999	145	123	Up	1.75	61	3	81	Up	1.22	59	5	81	Up	9414290
Monterey, Calif.	O	1973	1999	302	25	Up	1.63	−193	−12	25	Down	1.09	−152	−14	25	Down	9413450
Port San Luis, Calif.	O	1972	1999	196	27	Up	1.62	−65	−4	27	Down	1.10	−80	−7	27	Down	9412110
Santa Monica, Calif.	O	1933	1999	161	55	Up	1.65	7	0	54	Not	1.14	26	2	54	Up	9410840
Los Angeles	O	1923	1999	91	75	Up	1.67	25	2	75	Up	1.16	34	3	75	Up	9410660
La Jolla, Calif.	O	1924	1999	229	69	Up	1.62	37	2	69	Up	1.12	47	4	69	Up	9410230
San Diego	B	1926	1999	231	71	Up	1.75	−44	−3	71	Down	1.24	−32	−3	71	Down	9410170
(d) Alaska																	
Ketchikan, Alaska	B	1919	1999	−4	70	Not	4.69	47	1	70	Up	3.95	22	1	70	Up	9450460
Sitka, Alaska	O	1938	1999	−211	59	Down	3.02	27	1	59	Up	2.35	13	1	59	Up	9451600
Juneau, Alaska	B	1936	1999	−1248	48	Down	4.98	−34	−1	48	Down	4.20	−40	−1	48	Down	9452210
Skagway, Alaska	B	1944	1999	−1636	32	Down	5.07	7	0	39	Not	4.28	5	0	39	Not	9452400

Table 1. (*Continued*)

				MSL			MHHW−MLLW					MHW−MLW					
Location		Start	End	(mm/century)	Years	Trend	(m)	(mm/century)	(%/century)	Years	Trend	(m)	(mm/century)	(%/century)	Years	Trend	Station
Yakutat, Alaska	O	1940	1999	−552	53	Down	3.07	−11	0	53	Not	2.39	−16	−1	53	Down	9453220
Cordova, Alaska	B	1964	1999	706	31	Up	3.82	169	4	32	Up	3.09	109	4	32	Up	9454050
Valdez, Alaska	B	1973	1999	5	23	Not	3.70	77	2	23	Up	2.97	48	2	23	Up	9454240
Seward, Alaska	O	1925	1999	2069	57	Up	3.23	77	2	30	Up	2.53	46	2	30	Up	9455090
Seldovia, Alaska	O	1964	1999	−997	32	Down	5.49	83	2	32	Up	4.73	54	1	32	Up	9455500
Anchorage	B	1964	1999	381	20	Up	8.83	547	6	28	Up	7.91	473	6	28	Up	9455920
Kodiak Island, Alaska	O	1949	1999	NA	NA	NA	2.67	41	2	27	Up	2.06	16	1	27	Not	9457292
Sand Point, Alaska	O	1972	1999	108	25	Not	2.20	3	0	25	Not	1.59	9	1	25	Not	9459450
Unalaska, Alaska	O	1955	1999	−565	31	Not	1.15	−53	−5	31	Down	0.87	124	14	23	Up	9462620
Adak, Alaska	O	1943	1999	−60	47	Not	1.11	−54	−5	47	Down	0.71	109	15	20	Not	9461380
(e) Pacific Islands																	
Nawiliwili, Hawaii	B	1955	1999	162	36	Up	0.56	−12	−2	36	Not	0.36	27	7	25	Not	1611400
Honolulu	B	1911	1999	129	87	Up	0.58	24	4	86	Up	0.39	18	5	86	Up	1612340
Kahului Harbor, Hawaii	B	1951	1999	234	22	Not	0.70	−76	−11	44	Down	0.47	48	10	33	Up	1615680
Hilo Bay, Hawaii	B	1946	1999	340	52	Up	0.74	3	0	52	Not	0.51	31	6	42	Up	1617760
Johnston Atoll	O	1950	1999	55	33	Not	0.68	11	2	33	Not	0.57	12	2	33	Not	1619000
Midway Islands	O	1947	1999	8	34	Not	0.38	15	4	23	Up	0.26	14	5	35	Not	1619910
Guam	B	1949	1999	−36	44	Not	0.72	−6	−1	44	Not	0.50	−12	−2	44	Not	1630000
Pago Pago	B	1948	1999	199	20	Up	0.82	−26	−3	19	Not	0.76	−9	−1	20	Not	1770000
Kwajalein	O	1946	1999	87	42	Up	1.21	−52	−4	42	Down	1.06	−47	−4	42	Down	1820000
Wake Island	B	1950	1999	155	37	Up	0.73	−52	−7	39	Down	0.63	−37	−6	39	Down	1890000

(Table 1 and Fig. 4). The results for mean tide range trend were similar, except that Crescent City indicated a small but significant downward trend. No other obvious tide range trend patterns appear in the West Coast data, either in trend direction or in magnitude.

Data from San Francisco, showed an upward trend in both diurnal and mean tide range of 64 and 60 mm/century, respectively, since 1900 (Fig. 8). Smith (1980) and Hicks (1981) trace the history of tide gauge measurements at San Francisco. Data were collected at several locations east of the Golden Gate: Fort Point (June 1854–November 1877), Sausalito (February 1877–September 1897), and The Presidio (July 1897–2003). Leveling to established benchmarks from San Francisco to Sausalito shows no elevation change at Sausalito from 1877 to 1977, indicating that the tide gauge stations are referred to a common reference and that relative height comparisons are consistent. The MSL trend at San Francisco since 1900 has been 217 mm/century, although it was only 145 mm/century from 1855 to 1999 (Flick 1998). Over the same period, MHHW rose at 258 mm/century and MHW rose at 250 mm/century, which is about 16% faster than the rate of MSL rise.

Port Chicago, Calif., located at the eastern end of San Francisco Bay, showed the largest magnitude (upward) trend in tide range of any West Coast station (Fig. 4). However, it must be discounted, because the record there is only about 22 years long and contains a strong nodal component. At Alamada, Calif., also inside San Francisco Bay, MSL rose at a rate of 81 mm/century over the 60-year record from 1939–1999. However, MHHW rose at 155 mm/century, 92% faster than MSL, and MHW rose at 145 mm/century, 80% faster than MSL. This pattern is again attributable to the increase in both the diurnal and mean tide ranges, which rose at about 130 mm/century over the same period, and once more suggests that caution should be used in choosing the proper tidal datum statistic and area of application.

Alaska

Diurnal tide ranges in Alaska vary widely from a high of 8.8 m at Anchorage to a low of about 1.1 m at Unalaska and Adak. The diurnal tide range increased at eight Alaska stations. Decreases in diurnal tide range were observed at Juneau, Unalaska, and Adak (Fig. 5). Trends at Skagway, Yakutat, and Popof Island were small and not statistically significant.

Interesting trend patterns are evident at Anchorage, where MSL rose at 381 mm/century and MHHW and MHW increased at a rate of about half that. However, the diurnal and mean tide ranges at Anchorage both increased, because MLLW and MLW had a relatively large downward trend, both absolutely and especially relative to MSL. This too suggests a tide regime shift that warrants further investigation.

Hawaii and Pacific Islands

This group has a modest tide range of between 0.4 and 1.2 m. Data for Honolulu showed clear and statistically significant upward trends in both diurnal and mean tide range of (respectively) 24 and 18 mm/century over the past 87 years (Table 1 and Fig. 6). MHHW and MHW rose, respectively, at rates about 11 and 7% faster than the 129 mm/century rate of MSL rise. The data from the other three stations in Hawaii are mixed. Tide range changes observed at Kauai (Nawiliwili Harbor) were not statistically significant. At Maui (Kahului Harbor), the diurnal range decreased, while the mean range increased. At Hilo the mean range increased, but the diurnal range change rate was not significant.

In the central and western Pacific, Kwajalein and Wake showed downward trends in tide range of 4–7%/century. The variability was substantial, especially at Guam, and there were data gaps, especially at Pago Pago. At Wake Island, the diurnal and mean tide ranges showed downward trends of 52 and 37 mm/century, respectively. While MSL rose at a rate of 155 mm/century, MHHW and MHW rose, respectively, at rates of 20 and 12% more slowly.

Summary

Most studies of water level have concentrated on trends in MSL. However, because of substantial variability and trends in tide range observed at many U.S. coastal stations, the present analysis suggests that any studies concerned with current or future water levels should take into account more tidal datum statistics than just MSL. For example, coastal flooding and storm damage studies should consider trends and fluctuations in high water levels, because it is the peak values that cause flooding and determine the design of coastal structures. For habitat restoration planning, mean low water and tide range changes may be most important. Individual stations with unusual tide range trends, such as Galveston, Tex., Anchorage, Alaska, and Wilmington, N.C., should be studied more carefully to determine the underlying causes for the possible anomalies in these records. Finally, new research proposes that cyclical changes in tide potential may modulate Earth's climate on short and long time scales (Keeling and Whorf 1997, 2000). Summaries of actual tide range measurements should be important in verifying this mechanism.

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