On the Classification and Trends of Long Period Sea Level Series

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INTRODUCTION

The dramatics of surf and longshore currents in the beach erosion process overshadows the small but relentless changes in sea level over years and decades. Yet, these same variations in sea level are the very agents that prevent beach erosion-building equilibria. As such, it behooves those interested in shore and beach preservation to attempt to understand yearly variability and long period trends in sea level and, hopefully, to predict future levels.

The present status of long period sea level studies is: descriptions for many areas including the United States, qualitative understanding of variability, quantitative understanding at selected locations, and quantitative understanding for selected parameters.

This paper presents for the United States: the most recent yearly mean sea level data available (in graphic form), a summary of classifications, and apparent secular trend calculations for the 31-year series, 1940 to 1970 at all stations. It is essentially an updating of the previous *Shore and Beach* paper by Hicks [1968].

DATA

The National Ocean Survey of the National Oceanic and Atmospheric Administration is responsible for monitoring sea level for the United States. The monitoring is accomplished with continuously recording analog tide gages at 115 station locations. A constriction at the bottom of each tide gage float well restricts the flow in and out of the well to the extent that wind waves are effectively damped. Hourly heights are obtained from the recordings and averaged for yearly mean sea level values at each station.

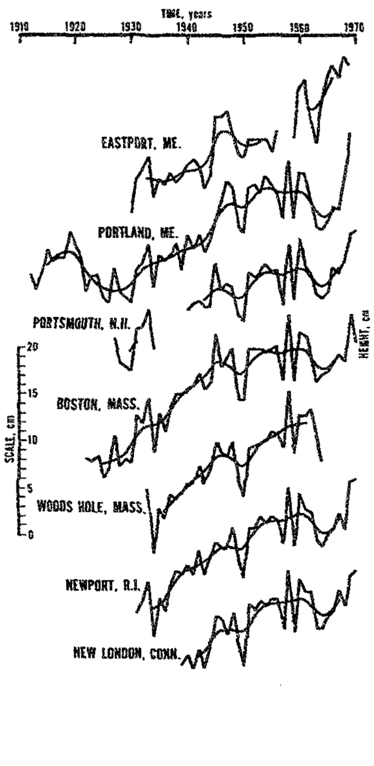

Fig. 1. Change in sea level with respect to adjacent land for stations from Maine to Connecticut. Straight-line segments connect yearly mean sea level values. Curved lines connect yearly values smoothed by weighting array.

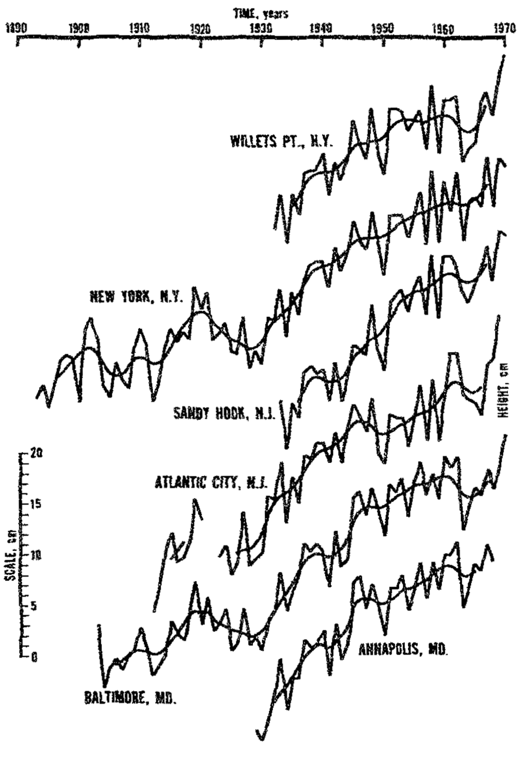

Fig. 2. Change in sea level with respect to adjacent land for stations from New York to Maryland. Straight-line segments connect yearly mean sea level values. Curved lines connect yearly values smoothed by weighting array.

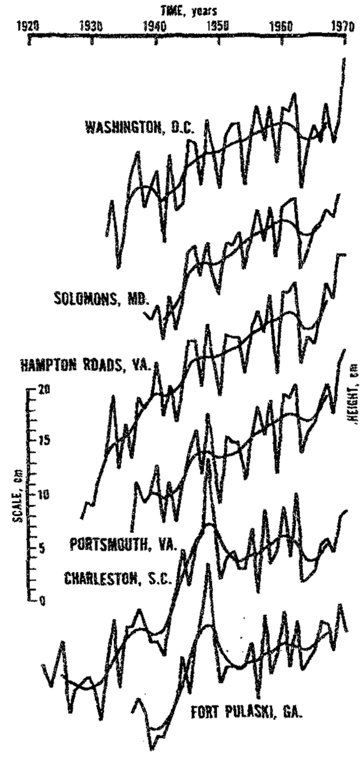

Fig. 3. Change in sea level with respect to adjacent land for stations from the District of Columbia to Georgia. Straight-line segments connect yearly mean sea level values. Curved lines connect yearly values smoothed by weighting array.

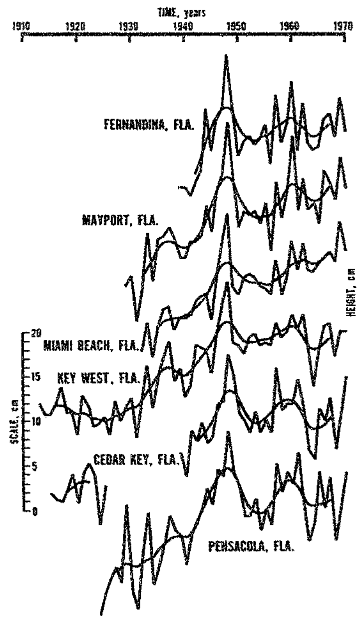

Fig. 4. Change in sea level with respect to adjacent land for stations in Florida. Straight-line segments connect yearly mean sea level values. Curved lines connect yearly values smoothed by weighting array.

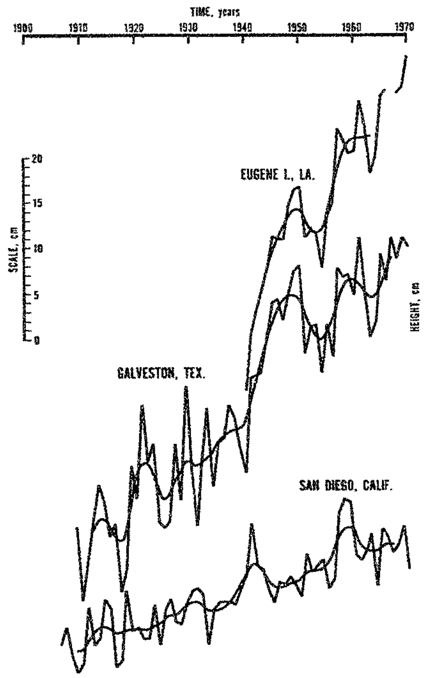

Fig. 5. Change in sea level with respect to adjacent land for stations from Louisiana to California. Straight-line segments connect yearly mean sea level values. Curved lines connect yearly values smoothed by weighting array.

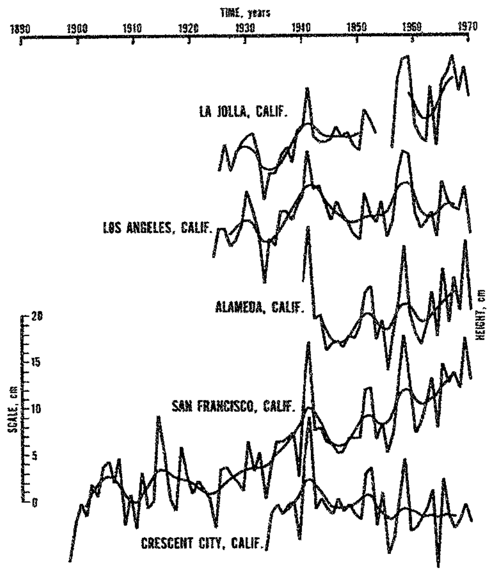

Fig. 6. Change in sea level with respect to adjacent land for stations in California. Straight-line segments connect yearly mean sea level values. Curved lines connect yearly values smoothed by weighting array.

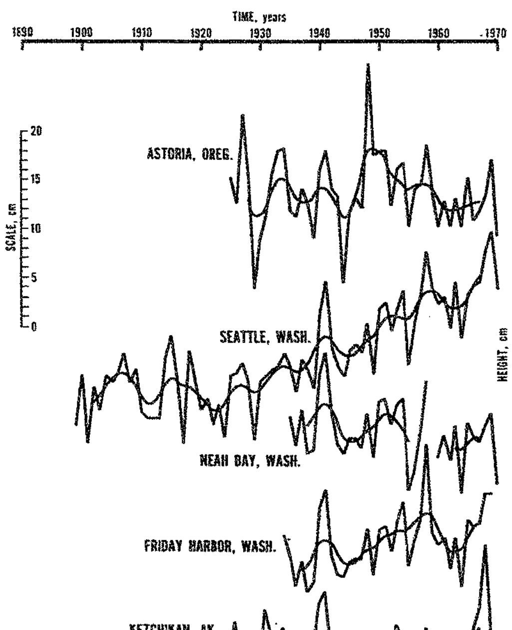

Fig. 7. Change in sea level with respect to adjacent land for stations from Oregon to Alaska. Straight-line segments connect yearly mean sea level values. Curved lines connect yearly values smoothed by weighting array.

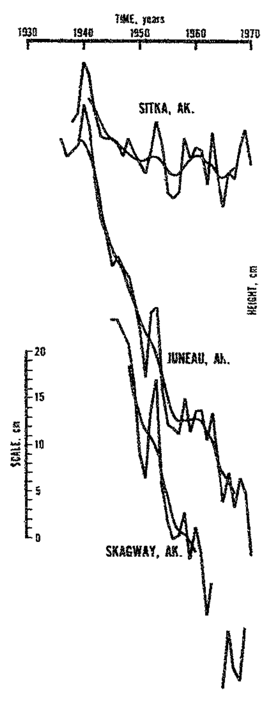

Fig. 8. Change in sea level with respect to adjacent land for stations in Alaska. Straight-line segments connect yearly mean sea level values. Curved lines connect yearly values smoothed by weighting array.

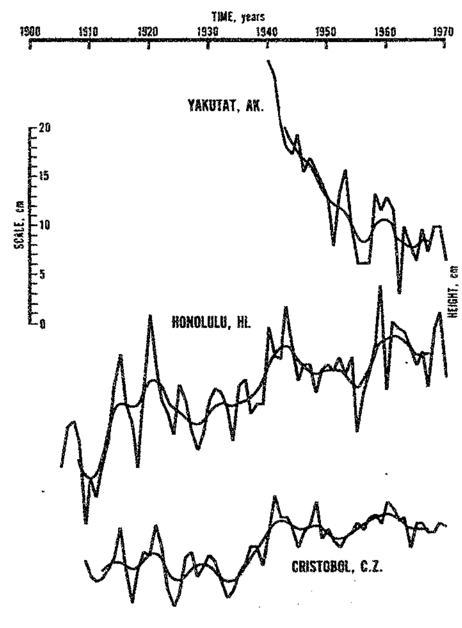

Fig. 9. Change in sea level with respect to adjacent land for Yakutat, Ak., Honolulu, Hi., and Cristobal, C.Z. Straight-line segments connect yearly mean sea level values. Curved lines connect yearly values smoothed by weighting array.

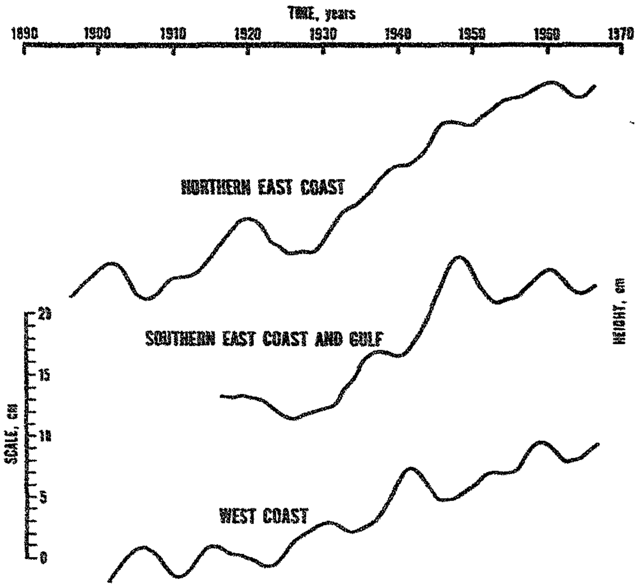

Fig. 10. Averaged damped series classifying United States sea level characteristics into Northern East Coast Area (north of Cape Hatteras), Southern East Coast and Gulf Area (south of Cape Hatteras), and West Coast Area.

When comparing results from different stations, it is necessary to use a common time span for each data series. Since it is desirable to have as long a common series as possible on one hand, and the largest number of stations for the most detailed coverage of the coast possible on the other, a compromise is necessary. By subjectively choosing 1940 or before as the initial date for each series, 43 stations with a common 31-year series become available. It is felt that these stations provide a representative coverage of the coast.

SERIES

The data are plotted in station series in Figures 1 through 9. Each series exhibits yearly variability and an apparent secular trend. Yearly variability is due to variations in the meteorological and oceanographic parameters of wind, direct atmospheric pressure, river discharge, currents, salinity, and water temperature. Apparent secular trends result from glacial-eustatic, tectonic, and both climatological and oceanographic apparent secular trend effects. The term "apparent" is used since it is unknown whether the trends are truly non-periodic or merely segments of very long oscillations.

The curved lines are the result of a triangular (1, 2, 3, 4, 3, 2, 1) weighing array applied to the yearly mean sea level values. The purpose for the application of the array is to dampen the yearly variability so that the nature of the apparent secular trends will become more visible.

The series also contain periodic motion. The 18.61-year nodal period is extremely small in comparison with yearly variability and apparent secular trends. *Hicks* [1969] found, by Fourier analyses, consistently higher than average amplitudes for stations south of Cape Hatteras and along the Gulf Coast at a period of 13.5 years. For stations along the west coast and Hawaii, consistently higher amplitudes were found at 9 years.

CLASSIFICATION

Sea level series could be classified according to the period with the most significant amplitude in a given geographic area, as above. However, the significant amplitudes are so very small in comparison with yearly variability and apparent secular trends that the utility of such a system is precluded.

Hicks and Shofnos [1965b] showed that stations plotted on a graph of apparent secular trend (as measured by a least-squares line of regression) against yearly variability (as measured by the Standard Error of Estimate) formed unique geographical groupings. Although very adequate at the time and based on physical meaning, the continuous lengthening of all series accentuates the non-linearity of the apparent secular trends.

Even though the above systems are valid, the most useful classification is based merely on the areal similarities of the curves from the damped series. The similarities delineating each area are obvious and the differences between areas distinctive; neither requiring statistical correlation.

The station series from each area were averaged. The weighting array was then applied to the averaged series and plotted in Figure 10. The areas are: 1) Northern East Coast Area (north of Cape Hatteras); 2) Southern East Coast and Gulf Area (south of Cape Hatteras); and 3) West Coast Area.

Galveston, Texas and Eugene Island, Louisiana were not included in the Southern East Coast and Gulf Area since they represent locations of marked local land subsidence. In contrast, Yakutat, Juneau, Sitka, Ketchikan, Alaska, and Neah Bay, Washington were not included in the West Coast Area since they cover a region of acute land emergence from local glacial melting [*Hicks and Shofnos,* 1965a]. The series at Astoria, Oregon is dominated by values reflecting variations in river discharge from the Columbia River. Crescent City, California does not fit the West Coast Area classification for a reason yet to be determined. Honolulu, Hawaii and Cristobal, Canal Zone are outside the areas of consideration.

APPARENT SECULAR TRENDS

Apparent secular trends were determined by computing the slope of a least-squares line of regression for the common 1940 to 1970 series at each station. The results are presented in Table 1.

As the level of the sea rises due to a positive apparent secular trend, the shoreline moves inland an amount equal to the product of the rise and the cotangent of the angle of land slope. Similarly, if sea level decreases, the shoreline recedes horizontally by a like amount. The major problem in quantitative

TABLE 1

Apparent Secular Trends for the United States, 1940-70

Location	Series	Missing	Trend 1940-70 ft/yr	Trend 1940-70 cm/yr
Eastport, Me.	1930-69	1957,58,70	.0111	.338
Portland, Me.	1912-69	1970	.0053	.162
Portsmouth, N. H.	1927-70	1935-39	.0054	.165
Boston, Mass.	1922-70		.0035	.107
Woods Hole, Mass.	1933-70	1965,67-69	.0088	.268
Newport, R. I.	1931-70		.0069	.210
New London, Conn.	1939-70		.0075	.229
Willets Pt., N. Y.	1932-70		.0074	.226
New York, N. Y.*	1893-1970		.0094	.287
Sandy Hook, N. J.	1933-70		.0150	.457
Atlantic City, N. J.	1912-69	1921,22,70	.0093	.283
Baltimore, Md.	1903-70		.0085	.259
Annapolis, Md.	1929-68	1969,70	.0094	.287
Washington, D. C.	1932-70		.0080	.244
Solomons, Md.	1938-69	1970	.0107	.326
Hampton Roads, Va.	1928-70		.0105	.320
Portsmouth, Va.	1936-70		.0112	.341
Charleston, S. C.	1922-70		.0059	.180
Fort Pulaski, Ga.	1936-70		.0065	.198
Fernandina, Fla.	1939-70		.0041	.125
Mayport, Fla.	1929-70		.0051	.155
Miami Beach, Fla.	1932-70		.0063	.192
Key West, Fla.	1913-70		.0024	.073
Cedar Key, Fla.	1915-70	1926-38	.0020	.061
Pensacola, Fla.	1924-70		.0013	.040
Eugene I., Fla.	1940-70	1967	.0297	.905
Galveston, Tex.	1909-70		.0141	.430
San Diego, Calif.	1906-70		.0047	.143
La Jolla, Calif.	1925-70	1954,55	.0063	.192
Los Angeles, Calif.	1924-70		—.0014	— .043
Alameda, Calif.	1940-70		.0022	.067
San Francisco, Calif.	1898-1970		.0063	.192
Crescent City, Calif.	1933-70		—.0044	— .134
Astoria, Oreg.	1925-70		—.0030	— .091
Seattle, Wash.	1899-1970		.0085	.259
Neah Bay, Wash.	1935-70	1959	—.0042	— .128
Friday Harbor, Wash.	1934-69	1970	.0029	.088
Ketchikan, Alaska	1919-70		.0010	.030
Sitka, Alaska	1938-70		—.0067	— .204
Juneau, Alaska	1936-70		—.0428	—1.305
Yakutat, Alaska	1940-70		—.0165	— .503
Honolulu, Hawaii	1905-70		.0010	.030
Cristobal, C. Z.	1909-70		.0000	.000

*1893-1920, Fort Hamilton; 1921-1970, The Battery.

determinations of encroachment by the sea is to find out what slope to use (i.e., the "effective" slope).

The slopes of features making up the beach, such as the shore face, low tide terrace, beach face, berms, etc., are maintained in equilibria with the various characteristics of surf, longshore currents, tides, beach material, etc. These slopes, of course, vary continuously with changing conditions, including periodic ones such as the well studied seasonal cycle.

However, these several beach-feature slopes and the mean slope of the entire beach are not a function of the apparent secular trend. As the sea rises due to a positive apparent secular trend and the shoreline moves inland, the beach features will, as a first approximation, move inland maintaining their several slopes. Thus, the effective slope for sea encroachment is the natural slope of the land just inland from the beach.

The above generalization assumes that beach erosion processes leading to equilibria can keep up with or exceed the inland movement of the shoreline demanded by the apparent secular trend and natural slope landward of the beach. If, for example, in the extreme case, a cliff is composed of material that cannot be eroded at the required rate, then the effective slope lies somewhere between that of the top of the cliff landward (if the cliff were erodible at the equilibrium rate) and that of the cliff face itself (if it were not erodible in terms of decades).

With the continuous development of the coastal zone, effective slopes have been artificially changed quite often. Unintentional changes have been caused most frequently by roads and railroad beds paralleling the shore; indirect alterations have been made by such things as the construction of seawalls and hurricane barrier embankments, and by beach nourishment.

CONCLUSIONS AND RECOMMENDATIONS

A. Of the several sea level classifications in extant, a system based on the areal similarities of the curves from damped series is proposed as the simplest and most useful.

B. Three areas are delineated by the above classification system: 1) Northern East Coast Area (north of Cape Hatteras), 2) Southern East Coast and Gulf Area (south of Cape Hatteras), and 3) West Coast Area.

C. Although there was evidence of a reduction in the apparent secular trends during the period 1946 to 1964 in the Northern East Coast Area, data through 1970 indicate a return to rates characteristic of the period 1928 to 1946.

D. Research should be conducted to determine the "effective" slopes for the coasts of the United States in order to quantitatively assess encroachments by the sea.

E. Although the effects of encroachment by the sea do not approach the importance to the North Atlantic Continent as they do to the Netherlands, the results of continuous sea level monitoring show that encroachment determinations can no longer be neglected in beach erosion studies and coastal engineering works in the United States.

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