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An Average Geopotential Sea Level Series for the United States

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For climate monitoring purposes an average sea level series for the United States, from which a representative curve and a single-value rate were derived, is presented. In addition, the use of dynamic height is introduced in order to take into account the greatly differing latitudes of the tide stations used in the study. The series was obtained by averaging common length uninterrupted sea level elevations reduced from the tide gage measurements of each station. The averaging was by coastal area. The curve, with amplitudes of the averaged meteorological and oceanographic oscillations of periods of less than 5⅛yr attenuated more than 90%, shows the relative apparent secular trend and its changes for the United States as a whole. During the 36-yr period, 1940–1975, sea level rose along the coast of the United States at the average rate of 1.5 dynamic mm/yr.

INTRODUCTION

Many investigators have published glacial eustatic sea level rates. *Munk and Revelle* [1952] created an indirect rate based on variations in the speed of the earth's rotation and the tilting of its axis of instantaneous rotation. Most methods (other than geological), however, have dealt with time series from sea level measurements relative to the adjacent land. By averaging linear approximations of the apparent secular trend (with or without removal of meteorological and oceanographic effects) at, hopefully, representative stations, glacial eustatic rates are stated. These rates are summarized and evaluated by *Lisitzin* [1974]. The numerous problems inherent in the latter methods have also been discussed by *Hicks* [1972]. A far more realistic approach of the latter types has been made by *Fairbridge and Krebs* [1962]. They constructed a glacial eustatic curve by averaging the yearly mean sea level series from selected representative station series over the period 1860 through about 1958.

The study reported here provides a Fairbridge-type curve of the average, representative, relative, apparent secular trend and its variations for the shores of the United States (except Alaska and Hawaii) as a whole during the period 1940–1975. In addition, it attempts to provide a Fairbridge-type series, curve, and rate more closely approaching glacial eustatic characteristics and values than previous investigations.

DATA SERIES

Sea level series are obtained from water elevation measurements conducted at tide stations. The National Ocean Survey operates 29 tide stations that have continuous measurements extending back to 1939 or earlier on the coasts of the United States (except Alaska and Hawaii). Series composed of yearly mean sea level values from 27 of these stations were used in this study. Each value is the arithmetic mean of a calendar year of hourly heights. The hourly heights were either scaled directly from the marigram or obtained from a digital output of the analog tide gage at each tide station. Statistical values and graphs for station series (through 1972 only) are given by *Hicks and Crosby* [1974]. The statistical values are updated through 1975 in Table 1.

Owing to wide differences in the latitudes of the tide station locations, each yearly mean sea level value was converted to dynamic height. To do this, the gravity values, provided by the National Oceanic and Atmospheric Administration's National Ocean Survey (Gravity, Astronomy, and Satellite Branch, National Geodetic Survey), were first reduced to an equivalent value at zero elevation of the National Geodetic Vertical Datum. The values were then converted to the zero on the tide staff via the set of tidal bench marks in the immediate vicinity of each tide station. Finally, the gravity values were adjusted to the mean height of each sea level series.

Each yearly mean sea level value was then multiplied by the single adjusted gravity for its station series, since gravity time series were not available. Observed gravity was used in all cases except Willets Point, New York; New York, New York; Portsmouth, Virginia; and Mayport, Florida, where theoretical gravity (*International Association of Geodesy* [1971], with Bouguer anomalies being used for interpolation) was substituted owing to a lack of observations near the tide stations.

COMPUTATIONS

The coastline of the United States was divided into five areas. The division was based on a subjective balance between series coherence [*Hicks and Shofnos*, 1965], equal coastal lengths, and *Gutenberg*'s [1941] regions. The areas, together with the inclusive stations, are designated by asterisks in Table 1.

Although both Sandy Hook, New Jersey, and Galveston, Texas, have continuous series dating long before 1940, they were not used in this study. Both stations are undergoing anomalous localized subsidence. This is not to say that the other stations are not undergoing subsidence or emergence, only that the two anomalous ones are obviously very different from their area patterns. See *Holdahl and Morrison* [1974], *Cole* [1928], and *Dawson* [1962] for discussion.

For each year at a time the yearly mean sea level values for that year at all stations in an area were averaged. An average series was thus obtained for each of the five areas. Likewise, for each year at a time the average area values for that year for all five areas were averaged. The resulting graph, with straight lines connecting the averaged yearly points, is given in Figure 1. The curve is the result of a seven-point (five and three points near ends) triangular weighting array applied to the averaged yearly points on the graph. The array attenuates the amplitudes of all meteorological and oceanographic oscillations with periods of less than 5⅛yr by more than 90% [*Hicks and Shofnos*, 1965].

Apparent secular trends are not linear or regular and can easily be visually separated into segments of their time series. Thus when results from different stations are compared, it is

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TABLE 1. Trends and Variability of Yearly Mean Sea Level Through 1975 (in ordinary linear measure)

			Entire Series			1940-1975		
Location	Date series began	Dates of missing data	Trend[a]	Standard error of trend[b]	Variability[c]	Trend	Standard error of trend	Variability
			mm yr^{-1}	± mm yr^{-1}	± mm	mm yr^{-1}	± mm yr^{-1}	± mm
			*Northern East Coast to Cape Hatteras					
Eastport, ME	1930	1957,58	3.3	.3	24.6	3.5	.4	26.6
*Portland, ME	1912		2.2	.2	29.1	2.0	.5	29.9
*Seavey I., ME (Portsmouth, NH)[d]	1927	1935-39	2.4	.2	21.4	1.8	.3	20.4
*Boston, MA	1922		2.8	.2	25.1	1.5	.4	22.4
Woods Hole, MA	1933	1965,67-69	3.3	.3	21.0	2.9	.3	20.4
Buzzards Bay, MA	1956	1959	1.0	.9	23.3			
*Newport, RI	1931		3.0	.2	21.2	2.5	.3	20.8
Providence, RI	1939	1947-56,67	2.4	.4	23.0	2.4	.4	23.5
Montauk, NY	1948	1959,72	2.6	.6	24.3			
*New London, CT	1939		2.6	.3	21.0	2.6	.3	21.2
Port Jefferson, NY	1958		3.9	1.3	27.0			
New Rochelle, NY	1958		3.5	1.5	32.0			
*Willets Pt., NY	1932		3.2	.3	26.2	2.9	.4	26.9
*New York, NY[e]	1893		2.9	.1	27.0	3.1	.3	21.4
Sandy Hook, NJ	1933		4.9	.3	23.7	5.0	.4	24.3
Atlantic City, NJ	1912	1921,22,70,71	4.1	.2	28.3	3.9	.5	28.4
Lewes, DE	1921	1923-36, 40-47 50-52	3.7	.4	32.6	3.6	1.0	35.3
Philadelphia, PA	1901	1921,22,59,60	2.8	.2	38.9	2.9	.7	40.5
*Baltimore, MD	1903		3.4	.1	25.7	3.1	.4	25.1
Annapolis, MD	1929	1969	4.2	.3	23.9	3.6	.4	23.0
*Washington, DC	1932		3.4	.4	32.9	3.5	.5	33.9
Solomons, MD	1938	1970	4.0	.4	24.3	4.0	.4	25.0
*Hampton Rds. (Norfolk), VA	1928		4.7	.3	29.6	4.1	.5	29.3
*Portsmouth, VA	1936		4.0	.4	26.1	4.2	.4	27.0
			*Southern East Coast					
*Charleston, SC	1922		3.8	.3	34.9	2.9	.6	37.1
*Ft. Pulaski (Savannah), GA	1936		3.1	.5	33.6	2.9	.6	34.6
*Fernandina, FL	1939		2.4	.5	34.5	2.2	.6	34.7
*Mayport, FL	1929		2.9	.3	32.5	2.3	.5	33.4
*Miami Beach, FL	1932		2.6	.3	22.7	2.3	.4	23.4
			*Gulf Coast					
*Key West, FL	1913		2.3	.2	26.4	1.7	.5	28.4
*Cedar Key, FL	1915	1926-38	2.2	.2	29.6	1.6	.5	31.8
*Pensacola, FL	1924		2.7	.3	37.7	1.8	.6	38.9
Galveston (Pier 21), TX	1909		6.3	.3	49.6	6.3	.8	50.6
			*Southern West Coast to Pt. Arena					
*San Diego, CA	1906		1.9	.2	25.7	1.2	.5	28.3
La Jolla, CA	1925	1954,55	1.7	.3	27.5	1.4	.5	30.1
*Los Angeles (Berth 60), CA	1924		0.5	.2	27.0	-0.5	.4	25.9
*Alameda, CA	1940		0.2	.6	35.3	0.2	.6	35.3
*San Francisco, CA[f]	1860		1.3	.1	39.3	1.5	.5	33.7
			*Northern West Coast					
*Crescent City, CA	1933		-0.7	.4	30.2	-1.5	.5	29.1
*Astoria, OR	1925		-0.1	.4	40.7	-0.7	.6	39.2
*Seattle, WA	1899		1.9	.2	30.3	2.3	.5	28.5
Neah Bay, WA	1935	1959	-1.2	.4	30.7	-1.7	.5	30.6
*Friday Harbor, WA	1934		1.0	.4	29.8	0.6	.5	30.3
			Alaska, Hawaii, and Canal Zone					
Ketchikan, AK	1919		-0.2	.3	35.7	-0.5	.6	40.3
Sitka, AK	1938		-2.5	.4	29.1	-2.5	.5	29.9
Juneau, AK	1936		-13.4	.5	35.5	-13.4	.6	37.2
Yakutat, AK	1940		-5.3	.6	33.6	-5.3	.6	33.6
Honolulu, HI	1905		1.6	.2	35.8	0.3	.5	30.8
Cristobal, CZ	1909	1975	1.3	.2	23.7	1.1	.4	23.7

* Areas and stations used in the averaging computations (see text).

[a] Slope of a least-squares line of regression:

$$b = \frac{\Sigma xy - \frac{(\Sigma x)(\Sigma y)}{n}}{\Sigma x^2 - \frac{(\Sigma x)^2}{n}}$$

Where x = date,
y = height of yearly mean sea level, and
n = number of yearly mean sea-level values.

[b] Standard Error of Slope:

$$s_b = \frac{s_{y.x}}{\sqrt{\Sigma x^2 - \frac{(\Sigma x)^2}{n}}}$$

Where $s_{y.x}$ = Standard Error of Estimate.

[c] Standard Error of Estimate (standard deviation from line of regression).

$$s_{y.x} = \sqrt{\frac{\Sigma y^2 - \frac{(\Sigma y)^2}{n} - b\left(\Sigma xy - \frac{(\Sigma x)(\Sigma y)}{n}\right)}{n - 2}}$$

[d] 1927-1968, Portsmouth Navy Yard, NH;
1969-1972, Back Channel, ME;
1973-1975, Seavey I. (Berth 2), ME.

[e] 1893-1920, Ft. Hamilton;
1921-1975, The Battery.

[f] 1860-1877, Fort Pt.;
1877-1897, Sausalito (two locations);
1897-1975, The Presidio (two locations).

always necessary to use a common series length in the analyses and computations. The common series length, 1940–1975, was an arbitrary subjective choice. The choice was a trade-off between the desire to have as long a time span as possible that would be common to all stations selected and the need to include a sufficient number of stations for a representative coverage of the coast.

Uninterrupted (without breaks due to missing data) series, as well as a series length common to all stations, are also necessary in the averaging computations. Terrestrial leveling has been conducted between most tide stations. However, the connections are usually composed of a network of lines leveled in different years (often in different decades) and adjusted by least squares. Although it is perfectly valid for certain geodetic purposes, this procedure is not applicable to connecting series from different stations at a specific time or even during a relatively short time period. As a result, the averaging must be done each time with the same number of values. Otherwise, the curve would be 'pulled' toward the average of the values that are present for that year.

The slope (trend) of a least squares line of regression was computed for the averaged yearly points in Figure 1. The trend is 1.5 dynamic mm/yr, the standard error of the trend computation amounting to ±0.3 dynamic mm/yr. The standard error of estimate (standard deviation from the line of regression), which quantifies variability, is ±15.9 dynamic mm.

By using the average single-value rate, relative sea level is found to have risen a total of 54 dynamic mm along the coasts of the United States as a whole during the period 1940–1975. The largest excursion of the averaged yearly points was 88.7 dynamic mm, which occurred between 1940 and 1972.

DISCUSSION

The results of this study can be particularly useful in climate monitoring and vertical crustal movement investigations. The curve provides direct monitoring at an extremely critical point in the total hydrologic cycle. Also, the single-value dynamic rate can be converted to a linear scale rate for a particular station location by using observed gravity in the vicinity (corrected for elevation) or gravity (at the latitude) from a theoretical geoid. When it is subtracted algebraically from the observed rate for the station given in Table 1 (1940–1975 column only), a mean tectonic rate (reversed sign) can be approached. The curve likewise can be used for determining time variations in tectonic movement. After conversion to a linear scale the differences from year to year are subtracted from the differences of the corresponding years of the observed series curve. The accuracies of these approximations are subject to the assumptions and procedures of the basic study.

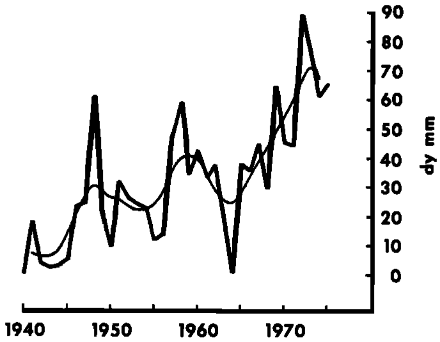

Fig. 1. Average sea level series and curve for the United States (except Alaska and Hawaii).

The degree to which the curve in Figure 1 approaches glacial eustatic characteristics is the degree to which the averaged coast of the United States (as a whole) approaches vertical stability with respect to the center of mass of the earth. Likewise, the degree to which the single-value rate of 1.5 dynamic mm/yr approaches the average glacial eustatic rate from 1940 through 1975 is the degree to which the averaged coast of the United States (as a whole) approaches vertical stability.

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