Sea Level as Affected by River Runoff, Eastern United States

Abstract. *Variations in annual river inflow account for 7 to 21 percent of the total variation in average annual sea level along the Atlantic and Gulf of Mexico coasts of the United States. This compares with 29 to 68 percent of the total variation that can be attributed to the secular rise of sea level, and with 10 to 50 percent of the variation that cannot be attributed to either the river inflow or the secular rise.*

The level of the ocean changes in response to several long-term nontidal factors. Annual average sea levels reveal long-term changes that have been attributed to the secular rise of sea level caused by melting of glaciers and compounded by local effects of coastal emergence or submergence (*1*). Monthly or seasonal average sea levels are higher during summer than during the winter because of the lower density of seawater that results from summer warming and springtime river inflow (*2*). Other variations of sea level have been attributed to exceptionally large or small annual river runoff, as illustrated by low levels and low river flows during the middle 1960's (*3*). Especially large or small river runoffs can produce greater or lesser seaward slopes of the ocean surface, which, in turn, are reflected in faster or slower (or even reversed) coastal currents (*4*). The quantity of river water stored on the continental shelf may be fairly large; for example, the residence time for river runoff on the continental shelf off the Middle Atlantic United States is about 1½ years (*5*). The purpose of our study is to evaluate the proportion of the variation in annual average sea level that can be attributed to variation in annual river inflow.

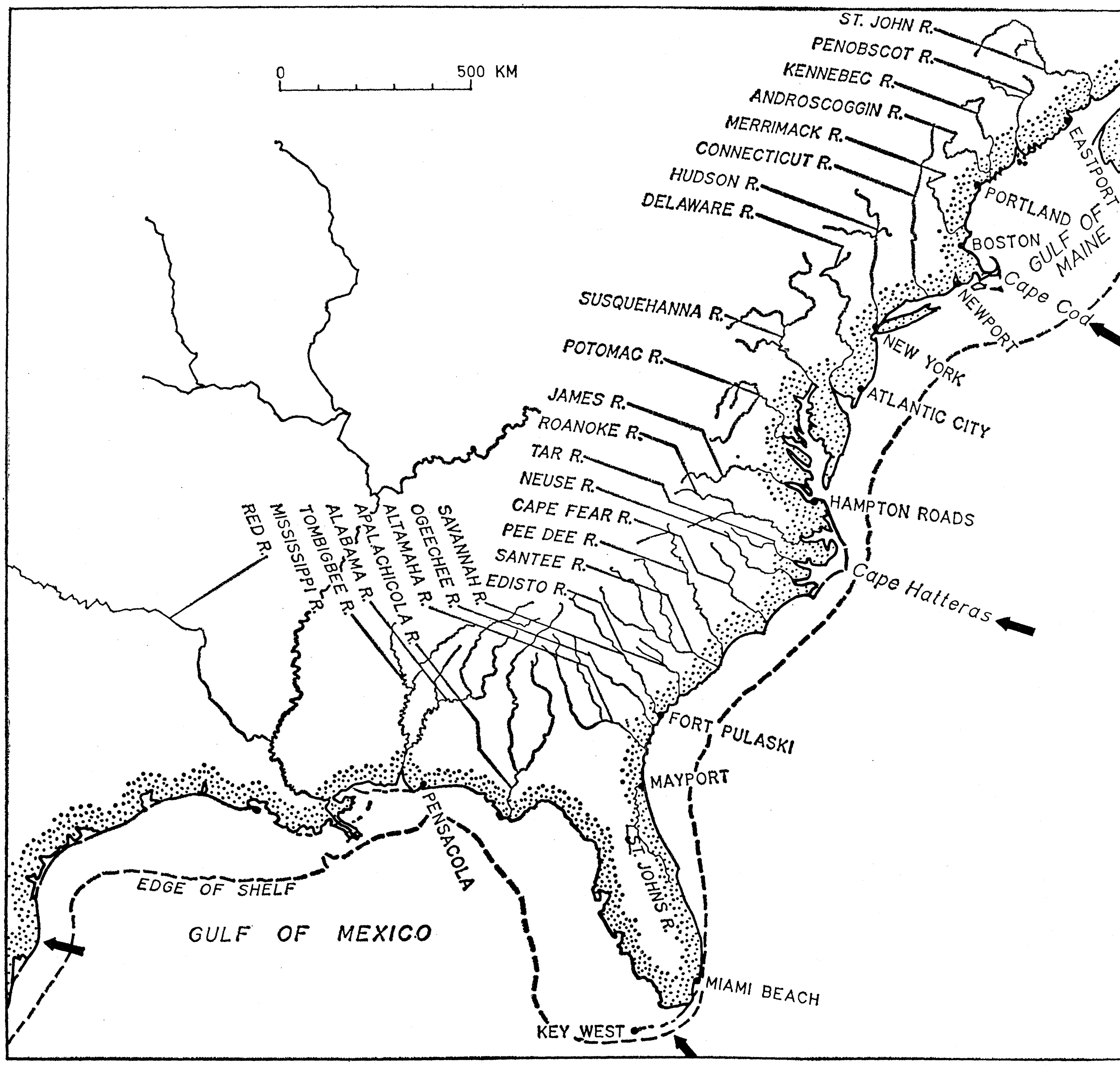

Fig. 1. Map of eastern United States, showing tide stations (black dots) and rivers whose gauged records were used to compute relations between sea level and runoff. Arrows point to boundaries of coastal indentations.

Our study concerns the Atlantic and Gulf of Mexico coasts of the United States. This coastline can be divided into four major coastal indentations: the Gulf of Maine, Cape Cod to Cape Hatteras, Cape Hatteras to Key West, and the Gulf of Mexico (Fig. 1). Each of these indentations tends to behave as an independent unit, because it is separated from the others by coastal projections around which little water moves over the continental shelf. Sea level, as shown by a comparison of tide-gauge records from adjacent stations on both monthly and annual bases, fluctuates rather uniformly within each indentation, but somewhat differently from one indentation to the next.

As sources of data on sea level, we used the published and unpublished records (*6*) collected at tide gauges. These records are reported in the form of monthly and annual average sea levels obtained by averaging the observations recorded at 1-hour intervals; this averaging removes the effects of most short-term tidal variations. After the elimination of tide-gauge stations that have only short or interrupted sequences of records, are too far upstream in rivers, or have been influenced by man-made changes in drainage or by subsidence due to withdrawal of oil or water from underground reservoirs, the remaining acceptable records are from the 12 tide gauges whose positions are shown in Fig. 1. We averaged the annual sea levels on a water-year basis (that is, 1 October through 30 September) for the three acceptable stations in the Gulf of Maine (Eastport, Portland, and Boston), the four stations between Cape Cod and Cape Hatteras (Newport, New York, Atlantic City, and Hampton Roads), the three stations between Cape Hatteras and Key West (Fort Pulaski, Mayport, and Miami Beach), and the two stations in the Gulf of Mexico (Key West and Pensacola). The compilation begins with 1931 because earlier measurements are incomplete for most stations. The data for St. John, Portland, New York, and Key West began earlier, and they indicate that the secular rise in sea level was slower before 1930 than it was after that year.

The average annual sea level in each coastal indentation (Fig. 2) exhibits a general rise that is attributed to secular rise from melting glaciers coupled with regional deformation associated with glacial rebound, sediment loading, or other causes. We believe that the best-fit least-squares straight lines in the upper three graphs of Fig. 2 are the best available indicators of the combination of regional deformation and the secular rise in sea level along the Atlantic coast of the United States for the period 1931 to 1969. During several decades prior to 1931, however, the secular rise was probably slower. Differences in the general trends of the straight lines in the four coastal indentations are due to differences in regional deformation. The many irregularities in each of the sea-level graphs are at least partly due to year-to-year differences in runoff.

As a source of data on river runoff, we used wherever appropriate the information compiled by Bue (*7*) for the Atlantic drainage of the United States.

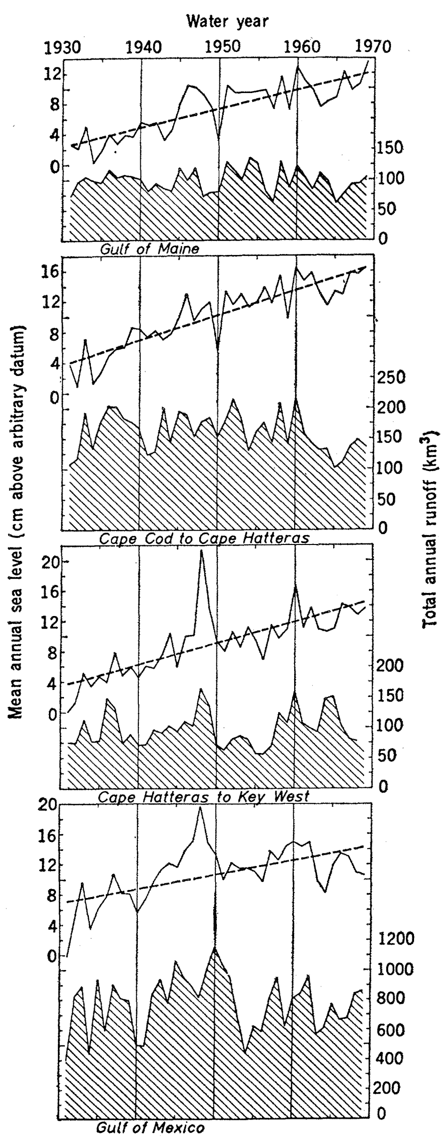

Fig. 2. Variations in mean annual sea level (upper graph of each pair) and annual river runoff (shaded graphs) in four coastal indentations of eastern United States, 1931 to 1969. Dashed lines show best-fit least-squares linear regression lines for secular rise of sea level.

Bue divided the Atlantic coast into ten segments and compiled the total streamflow into each segment for each of the 30 water years from 1931 through 1960. To estimate runoff for the years since 1960 and for part of Canada and the Gulf of Mexico drainage that was not included in Bue's summary, we used records from selected river gauging stations (*8*). For the two coastal indentations from Cape Cod to Cape Hatteras and from Cape Hatteras to Key West, we used Bue's totals for his segments 3 to 6 and 7 to 10, respectively, for the years 1931 to 1960. To extend these totals to include subsequent years through 1969, we used the runoff records from selected long-term gauging stations on the rivers shown in Fig. 1: Connecticut through Neuse rivers for the indentation north of Cape Hatteras, and Cape Fear through St. Johns rivers for the southern indentation. We determined the proportion of the total flow that these gauges collectively measured by comparing their gauged totals with Bue's totals for the years through 1960, and we used the proportions to extrapolate total inflows through 1969. On the basis of comparisons made for the years through 1960, we can expect most of the extrapolated values to be within 10 percent (and all of them to be within 12 percent) of the values that would have been obtained from a continuation of the more laborious compilation procedure used by Bue (*9*). For the Gulf of Maine and the Gulf of Mexico, we used long-term records from five selected gauging stations on the major tributaries to each coastal indentation. Flow past the five selected gauges on the St. John through Merrimack rivers (Fig. 1) accounts for about half the total runoff from Canada and the United States into the Gulf of Maine. Flow past the five selected gauges on the Apalachicola through Red rivers accounts for about 75 percent of the total runoff from the United States into the Gulf of Mexico (*10*). Accordingly, the totals at the selected gauges were multiplied by 2.0 and 1.3, respectively, to obtain the total annual runoff values plotted for the Gulf of Maine and the Gulf of Mexico in Fig. 2. The error in using these index stations as indicators of variations in river runoff rather than compiling the total runoff for these two indentations is probably no greater than 10 percent.

Inspection of the graphs in Fig. 2 reveals that many of the years of especially high or low sea level are ones of high or low runoff. There appears to

Table 1. Statistical summary of sea level variation, eastern United States.

Measurement	Gulf of Maine	Cape Cod to Cape Hatteras	Cape Hatteras to Key West	Gulf of Mexico
Mean annual river inflow, 1931–69 (km^3/yr)	95	160	98	800
Mean annual river inflow per unit coastal length (km^3 yr^{-1} km^{-1})	0.25	0.19	0.07	0.39
Multiple regression of sea level on year (secular trend) and river runoff				
Mean annual rise in sea level (cm/yr)	0.25	0.35	0.26	0.18
Change in sea level due to runoff (cm/km^3 of annual inflow)	.05	.04	.05	.01
Variation in sea level accounted for by secular trend (% of total variation)	68	83	45	29
Variation in sea level accounted for by runoff (% of total variation)	7	7	13	21
Variation unaccounted for by combined secular trend and runoff (% of total variation)	25	10	42	50
Simple linear regression of sea level on year (secular trend)				
Mean annual rise in sea level (cm/yr)	0.24	0.33	0.28	0.18*
Variation in sea level accounted for by secular trend (% of total variation)	66	77	54	31*
Simple linear regression of residual sea level† on runoff				
Change in residual sea level due to runoff (cm/km^3 of annual inflow)	0.05	0.03	0.05	0.01
Variation in residual sea level accounted for by runoff (% of total residual variation)	20	29	28	31

* If simple regression is treated as quadratic rather than linear, the coefficients of the two terms are, successively, 0.84 and −0.017, and the secular trend accounts for 58 percent of the total variation in sea level. † Variation in sea level unaccounted for by linear regression of sea level on year.

be a family resemblance in the fluctuations of sea level and runoff within the two northern coastal indentations. Similarly, the sea levels and runoffs for the two southern indentations resemble each other but are rather different from those for the two northern indentations. Statistical techniques were used to define more specifically the similarities and differences of the data.

Regression analyses, both simple and multiple, were used to assess the amount of variation in sea level that was due to variation in river runoff. This assessment took two forms, both of which were designed to separate the effects of runoff from those of the secular rise in sea level. First, we assessed the two effects in combination by computing the multiple regressions of sea level on the secular trend and the runoff and by observing the proportion of the variation in sea level that pertained to the runoff. Second, we calculated the least-squares line for the secular rise of sea level in each indentation and then compared the residual sea levels (that is, the differences between the observed annual average sea levels and the levels predicted by the least-squares equation) with the runoff. Results of the computations are given in Table 1. All regressions represented in Table 1 are significant at the 99 percent level.

In the three Atlantic coastal indentations, a linear regression equation provides the best fit to the secular rise in sea level. In the Gulf of Mexico, however, a quadratic equation gives a better fit because the rate of sea level rise seems to have decreased somewhat during the period since 1948. The rates of secular rise in all four indentations range from 0.18 to 0.35 cm/year. The rates computed by multiple regression do not differ from the rates computed by simple linear regression by more than 0.02 cm/year. This indicates that the secular trend is essentially independent of variations in runoff, or, to put it another way, that there is no significant secular change in annual runoff that persists during the entire 39-year period.

The change in sea level that can be attributed to changes in runoff ranges from 0.01 to 0.05 cm per incremental cubic kilometer of annual inflow. The change in sea level per unit runoff varies inversely with the total runoff per indentation, but it has no consistent relation to the runoff per unit length of coastline. The effect produced by each incremental cubic kilometer of annual river inflow is of the order of one-tenth or less of the instantaneous increase in sea level that would result from spreading 1 km^3 evenly over the surfaces of the gulfs of Mexico or Maine or the two continental shelf areas between Cape Cod and Key West. This indicates that most of the dynamic adjustment of sea level to increases or reductions in river inflow requires considerably less than 1 year.

The proportion of variation in sea level that is accounted for by runoff ranges from 7 to 21 percent of the total variation and from 20 to 40 percent of the variation that is unattributable to the secular trend. Thus, a tenth to a half of the total variation must be attributed to variations in other factors such as wind, water temperature, currents, atmospheric pressure, experimental error, and random statistical error. The multiple-regression analysis shows that the proportions of total variation attributable to runoff are greater in the two southern indentations than in the two northern ones. As these different proportions are not clearly related to differences in runoff into the indentations (expressed either as total runoff or as runoff per unit length of coastline), we suspect that they are due to differences in the geometry of the indentations or to differences in the dynamic effects imparted to coastal waters by the different components of the oceanic circulation.

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9. In the coastal indentation between Cape Cod and Cape Hatteras, for example, we compared the total of the gauged discharges at 11 stations on the nine largest rivers with the total computed by Bue for his segments 3 to 6 for each of the 29 years from 1932 through 1960. Streamflow at the 11 stations accounted for a mean proportion of 0.551 of the total for segments 3 to 6. This proportion varied from year to year, but it was within 12 percent of the mean value (expressed as percent of the mean proportion of 0.551 rather than as percent of the total inflow to the coastal indentation) during all 29 years, and it was within 10 percent of the mean value in all years but one. To estimate the total inflow to the indentation during the years 1961–69, we totaled the discharges at the 11 selected stations for each year and divided each total by 0.551.
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11. We thank M. A. Rosenfeld, D. W. Spencer, and M. Hunt for their interest and aid in the statistical analyses, and we thank Rosenfeld, D. F. Bumpus, and J. E. Upson for their comments on the manuscript. Contribution 2600 of the Woods Hole Oceanographic Institution. Publication authorized by the director, U.S. Geological Survey.

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Southward Flow under the Florida Current

Abstract. *High-resolution current profiles were obtained in the Florida Straits by means of a new technique. Large temporal variations in the current profiles were observed. At times extensive southward flow, with speeds up to 30 centimeters per second, was recorded in the lower half of the water column.*

The subject of deep-current reversals in the Florida Straits has fascinated oceanographers ever since Pillsbury carried out his classical current observations during the latter part of the last century. On the basis of his measurements in the narrowest part of the Florida Straits between Fowey Rock and Bimini, Pillsbury thought it likely "that at the bottom there is, at times, a current setting to the southward in all parts of the stream, except on the extreme eastern side" (*1*). The temporary existence of a southward bottom current was supported by occasional observations made near the bottom on the western side of the stream. Pillsbury's interpretation was further supported by Wüst (*2*) in an application of the dynamic method in which he used temperature and salinity observations that were made along the Fowey Rock-Bimini section. Forty years elapsed before qualitative evidence for the existence of a deep countercurrent was established by geological observations at the bottom of the straits. Deep-sea photographs by Hurley (*3*) exhibited well-defined current ripple marks on the sandy bottom. These ripples indicated bottom velocities of at least 10 to 30 cm/sec directed toward the south. Direct visual observations (*4*) made from the submersible *Aluminaut* confirmed the findings by Hurley. Bottom-current measurements made with an instrument attached to the submersible yielded southward velocities of approximately 5 cm/sec.

The uncertainty about the precise vertical structure of the Florida Current is due to the lack of adequate observational tools for the extremely difficult conditions in the Florida Straits. Absolute current measurements require the anchoring of a vessel or an unattended mooring, both of which are rather difficult to maintain for any length of time. Furthermore, because the strong flow in the upper layer produces very large angles between the surface and the wires used for mooring and for current meters, the commonly used Savonious rotors are not oriented perpendicular to the flow; this results in intolerable errors. Relative current measurements from a drifting array do not allow a sufficiently high resolution of current velocities in the lower layers, which are generally an order of magnitude smaller than the surface velocities.

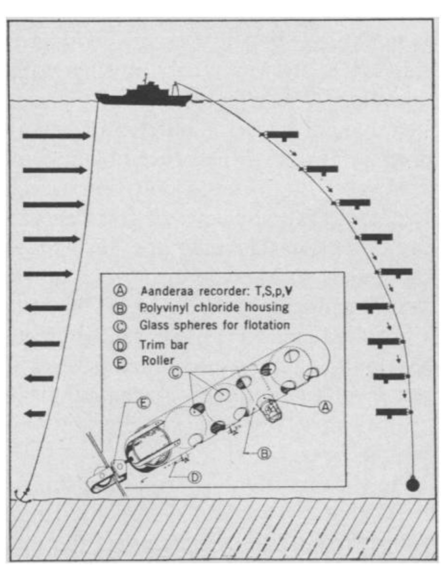

Fig. 1. Principle of current profiling method used in the Florida Current.

Considerable progress was made in the mid-1960's when Richardson and Schmitz (*5*) applied their free instrument technique, which allowed them to determine the vertically integrated net transport. A great number of carefully planned measurements have been made with this method during the last few years. Some results of these studies are described by Richardson *et al.* (*6*). On the subject of the deep southward flow the authors state, ". . . on the average the north component of velocity fills the whole channel. Thus there can be no significant counter-flow beneath the Florida Current in the Straits. . . . We have occasionally observed weak southerly flow in the same region. The origin of this flow is not clear, but our measurements indicate that there cannot be any significant southward transport associated with it."

This finding certainly does not agree with the observations quoted earlier, but it may be that the different results are not comparable. The earlier category of observations constitutes point measurements, whereas the free instrument technique integrates over a water layer with a thickness of several hundred meters. However, the apparent discrepancy points out the need for studies directed toward obtaining velocity profiles of high vertical resolution through the entire water column. A method for obtaining such profiles and initial results are described in the remainder of this report.

The principle of the profiling method is illustrated in Fig. 1. The instrumentation consists of a self-contained Aanderaa (Norway) current meter attached to a cylindrical hull whose density is slightly greater than that of the surrounding water. The Savonious rotor extends out from the bottom side of the cylindrical hull when it is in its horizontal working position. The entire package is attached by a roller to a taut wire suspended beneath an anchored ship; it is allowed to descend slowly through the entire water column.

During our experiment, a complete