ANOMALIES OF MONTHLY MEAN SEA LEVEL ALONG THE WEST COASTS OF NORTH AND SOUTH AMERICA

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INTRODUCTION

Measurements of mean sea level provide a source of long-term information concerning ocean processes. The data series of hourly tidal height measurements are unique among marine data series, in that they have been obtained inexpensively, over relatively long periods, at many fixed locations worldwide.

Many investigators have examined fluctuations of sea level at single stations, or relationships among small groups of stations. Roden (1960, 1963, 1966) used spectral and statistical methods to examine the interrelationships among sea level, temperature, and atmospheric pressure at selected stations along the west coast of North America. Saur (1972) examined sea level differences between the Hawaiian Islands and the California coast as an index of broad-scale changes in geostrophic flow in the California Current system. For fisheries assessment purposes, however, monitoring of ocean changes requires groups of stations covering larger areas. The stations examined in this report extend along the west coasts of North and South America from Massacre Bay, Attu, in the Aleutian Islands, to Caldera, Chile.

DATA

Most of the monthly mean sea level data in our data base were obtained from the University of Hawaii.[2] These data were updated

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[2]We thank K. Wyrtki and B. Kilonsky, Department of Oceanography, University of Hawaii, who assembled these data and provided us with a tape copy.

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and expanded with data from other sources.[3] All data were converted to centimeters.

For this report, tide stations most representative of open ocean conditions were selected. Although many tide gage stations examined in this report are located on piers in sheltered coastal harbors, stations subject to highly variable local tidal conditions common to large river mouths (such as Astoria, OR), large shallow bays (such as Alameda, CA), and straits or sounds (such as Ketchikan, AK), were generally not included. Additional criteria for station selection were a long, continuous data record, a constant tidal reference datum, and an even distribution of stations with distance along the coast. The stations selected and their locations are shown in Figure 5.1.

The processes affecting sea level are complex. In addition to the well-understood tidal or astronomic forces, sea level is affected by:

1. Changes in the average density of the water column.

2. Changes in distribution of atmospheric pressure over the ocean surface (resulting, in part, in variations in large scale wind patterns).

3. Variations in speed of alongshore components of ocean currents.

4. Changes in total mass of ocean water resulting from accretion or melting of glaciers.

5. Subsidence or emergence of the land upon which the gage is located.

The relative importance of these processes varies from station to station.

For ocean monitoring in support of fisheries assessment, we are interested in fluctuations with periods of months to years. For this reason the data are presented in terms of monthly means which remove the principal diurnal and semidiurnal periodicities from the data. Fluctuations with periods longer than months or years can be reduced by comparing the data with a 19-yr mean. This compensates for the nodal tide, which results from the changing declination of the moon over a period of 18.61 years. The nodal tide has a much greater "potential," or effect, than do

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[3]Permanent Service for Mean Sea Level, Berkenhead, U.K., and National Ocean Survey, NOAA, Washington, DC 20852.

other long-period, astronomically induced, harmonics observed in tidal data (Lisitzin 1974). We did not, however, remove very long-period fluctuations such as those caused by isostatic glacial responses (as at Yakutat, AK) or fluctuations related to land subsidence or uplift (such as at Balboa, CZ).

Our objective is to compare temporal fluctuations of sea level along much of the eastern Pacific coast for eventual comparison with fishery fluctuations. In order to allow comparison between stations and to flag unusual events, the data are presented as monthly mean anomalies or departures of a given month from its long-term mean. The long-term means used in this report were for the 19-yr period, 1949-67. The tidal reference datum differs from station to station. Computation of anomalies at each station allows comparison in time between stations having different datum levels.

Pattullo et al. (1955) found that in temperate and tropic latitudes (between about 40N and 40S) changes in the specific volume of the water column were responsible for most of the nontidal variation in recorded sea level. Atmospheric pressure effects were found to account for only a small part of the recorded changes in sea level. This situation is not true, however, in higher latitudes. Lisitzin and Pattullo (1961) found that north of 40N much of the variation in sea level results from changes in distribution of atmospheric pressure over the ocean. This "inverted barometer" effect can be removed from the data in high latitudes by adjusting sea levels for departures of atmospheric pressure from a long-term mean.

There is evidence that fluctuations in atmospheric pressure are quickly followed by compensating changes in sea level so that the total pressure on the sea floor remains very nearly constant. This isostatic adjustment is thought to occur over a range of several thousand miles and within a time span of several days. Thus, the ocean can be considered to approach isostatic equilibrium with atmospheric pressure for periods of a month or more. Assuming the average pressure over the oceans remains constant, if the pressure difference between two stations changes, the sea surface slope will change to compensate for this difference so that there will be no net change in the distribution of pressure on the sea floor (Pattullo et al. 1955; Saur 1972).

Pressure effects were removed from the data by correcting sea levels to a long-term mean atmospheric pressure in the vicinity of the tide gage. This compensates for both the normal seasonal cycle and the monthly pressure anomaly. Monthly mean sea level pressure data were obtained from the World Weather Record series, Monthly Climatic Data for the World, from CCEA,[4] or computed from monthly mean pressure fields obtained from FNWC.[5]

Normal atmospheric pressures at each station were obtained by averaging monthly pressures for the entire period of record. The effects of monthly variations from this long-term pressure mean were removed from sea level measurements by applying a correction of 1 cm in sea level for each millibar deviation in atmospheric pressure. Sea level data for all stations north of Mazatlan were corrected in this manner, with resultant small decreases in the range of sea level anomalies. Pressure deviations south of Mazatlan were on the order of one millibar or less, not large enough to warrant correction because sea level measurements have a typical error of about 1 cm.

DISCUSSION

The anomalies of corrected monthly mean sea level (Figs. 5.2-5.6) exhibit remarkably coherent patterns in time and space. Perhaps the most striking feature of the time series is the long-term persistence and wide distribution of high sea level during the period 1957-59. Evidence of anomalously high sea level extends from Caldera, Chile, to Adak, AK. Similar periods of anomalously high sea level can be seen in 1940-41 and 1971-73, and to a lesser extent in 1951-52 and 1965-66.

The simultaneous occurrence of these changes over such vast distances suggests a relation to large-scale oceanic or atmospheric disturbances. The periods of anomalously high sea levels were also periods of anomalously warm sea surface temperatures and are associated with El Nino occurrences in the eastern tropical Pacific (Quinn 1976, 1978).

Such environmental changes can have dramatic effects on marine fisheries. Along the coast of Peru, for example, large changes in the distribution and abundance of anchoveta result from adverse oceanographic conditions associated with El Nino periods. These conditions, combined with heavy exploitation, have resulted in a decline of the fishery and have had major economic impact. Radovich (1961) documented many changes in the distribution of marine populations along the coast of California during the warm water periods 1940-41 and 1957-59 which were associated with high sea levels. He found a general northerly shift of southern

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[4]Center for Climatic and Environmental Assessment, Environmental Data Service, NOAA, Columbia, MO 65201.
[5]Fleet Numerical Weather Central, U.S. Navy, Monterey, CA 93940.

species and an increase in yellowtail and bonito populations off California. Changes of sea level related to fluctuating coastal circulation may be associated with variations in year class strengths of marine populations due to changes in larval transport.

In his investigation of low frequency sea level oscillations, Roden (1966) found a high coherence in sea level fluctuations measured by tide gages located within similar macroenvironments, such as those located within the Gulf of Alaska or within the California Current area. Even stations with dissimilar exposure, such as those with gages located on the open coast compared to those with gages located in enclosed bays, yielded similar results if the stations were within the same macroenvironment. We now examine fluctuations of sea level in groups of stations having similar oceanographic environments.

Aleutian Islands

Sea levels in this area are quite variable. Significant long-term lower sea levels can be seen at Adak (1943-51) and Attu (1952-53). In contrast to the low sea levels observed at Adak and Attu in 1952-53, Unalaska, Kodiak, and Yakutat show anomalously high values, with a peak in early 1953. There seems to be little correlation between Attu and neighboring stations. This suggests that sea level at Attu, which is located in an area of relatively free exchange between the Pacific Ocean and Bering Sea, may respond to a different combination of environmental processes than sea level at Adak, Unalaska, or Kodiak. It is interesting to note that Attu is the only station of the 25 examined that did not show anomalously high sea levels in 1957-59. Unalaska had small anomalies through 1956 and strong positive anomalies during 1957-59. In contrast, the periods 1964-67 and 1971-74 exhibit strong negative anomalies. This suggests long-term fluctuations in the ocean environment near Unalaska.

Gulf of Alaska - Pacific Northwest

Kodiak has the shortest record of observations in the series. It was included to fill a gap between widespread stations. It shows surprisingly small variations in sea level with extremes in 1957-58 and 1961-62. A weak positive anomaly with a peak in early 1958 is evident.

The Yakutat gage, located in a harbor, is subject to salinity changes due to increased river runoff during summer months (Favorite 1974). The trend of decreasing sea level seen in the series for this station results from land uplift due to isostatic glacial rebound. Strong negative anomalies are evident during 1955-56, 1961-62, and 1971-72. Surprising small positive anomalies are seen during 1958. Favorite (1974) has shown that annual mean sea level anomalies at Yakutat were well correlated with mean annual wind stress transport anomalies in the Gulf of Alaska during the period 1950-59.

Fairly persistent long-term sea level anomalies with short-term fluctuations can be seen at Sitka, Prince Rupert, Tofino, Neah Bay, and Crescent City. Sea level fluctuations are remarkably coherent among these stations, considering the 1800 km along the coast between Sitka and Crescent City. Major periods of high sea level are seen during 1940-41 and 1957-59. Low sea level periods include 1955-56, late 1961-early 1962, and 1964. A significant period of anomalously low sea level is evident at Prince Rupert between the years 1947 and 1951.

California Current

Sea level data from San Francisco, Avila Beach, Los Angeles, and La Jolla also exhibit similar fluctuations. Periods of high sea level are noticeable during 1941, 1951-52, 1957-59, and 1972-73 at all stations. Periods of high sea level during 1969 were observed at San Francisco and Avila. Periods of low sea level occurred at all stations during 1955 and early 1956 and during 1964. A strong trend of rising sea level in relation to land occurred at all stations in this group.

Mexico - Central America

Mazatalan, Manzanillo, Acapulco, Balboa, La Union, and Buenaventura show similar patterns of sea level fluctuations. Periods of high sea level correspond very well with El Nino conditions (Quinn 1976, 1978). All stations exhibit very high sea levels during 1941-42, 1957-59, and, to a lesser extent, 1965-66. Extremely high levels were noted during 1972-73. The anomaly at Manzanillo for December 1972 measured 28.8 cm, one of the largest in the entire series. Anomalously low sea levels were seen in 1949-50, 1955, and 1967. The station at Balboa shows a trend of rising sea level which Roden (1963) attributed to land subsidence.

Peru Current Region

Talara, Callao, Matarani, Antofagasta, and Caldera also show remarkably coherent fluctuations in sea level. Like the group of stations to the north, periods of high sea level correspond well with El Nino conditions. The 1941-42 period of high sea levels is evident at Matarani. The 1957-59 and 1965 periods of high sea levels are seen at all stations in this region. During 1972, a period of extremely high sea levels occurred at Talara peaking at 36.5 cm in December 1972. A maximum anomaly of 34.4 cm was measured at Talara during November 1974. It is interesting to note the sharp spike of extremely low sea level that occurred just before the 1974 period of high sea level at Talara. Anomalously high sea levels are also evident at Callao during 1972. Periods of low sea level occurred at all stations in this group during 1949-50, 1954-56, and 1966-67.

CONCLUSION

Anomalies of monthly mean sea level observations along the west coast of North and South America persist for periods ranging from several months to two years or longer and are coherent in space for hundreds of kilometers. Anomalous "events" can be traced along the coast from Chile to Alaska and may be related to coastal circulation processes which may in turn affect larval drift and reproductive success of marine organisms. Certainly the major periods of anomalously high sea level during 1941-42, 1957-59, and 1972 were associated with unusual changes in the abundance or distribution of many marine species. It is hoped that further research on the factors affecting sea level will lead to a better understanding of ocean circulation processes and their effects on populations of marine organisms.

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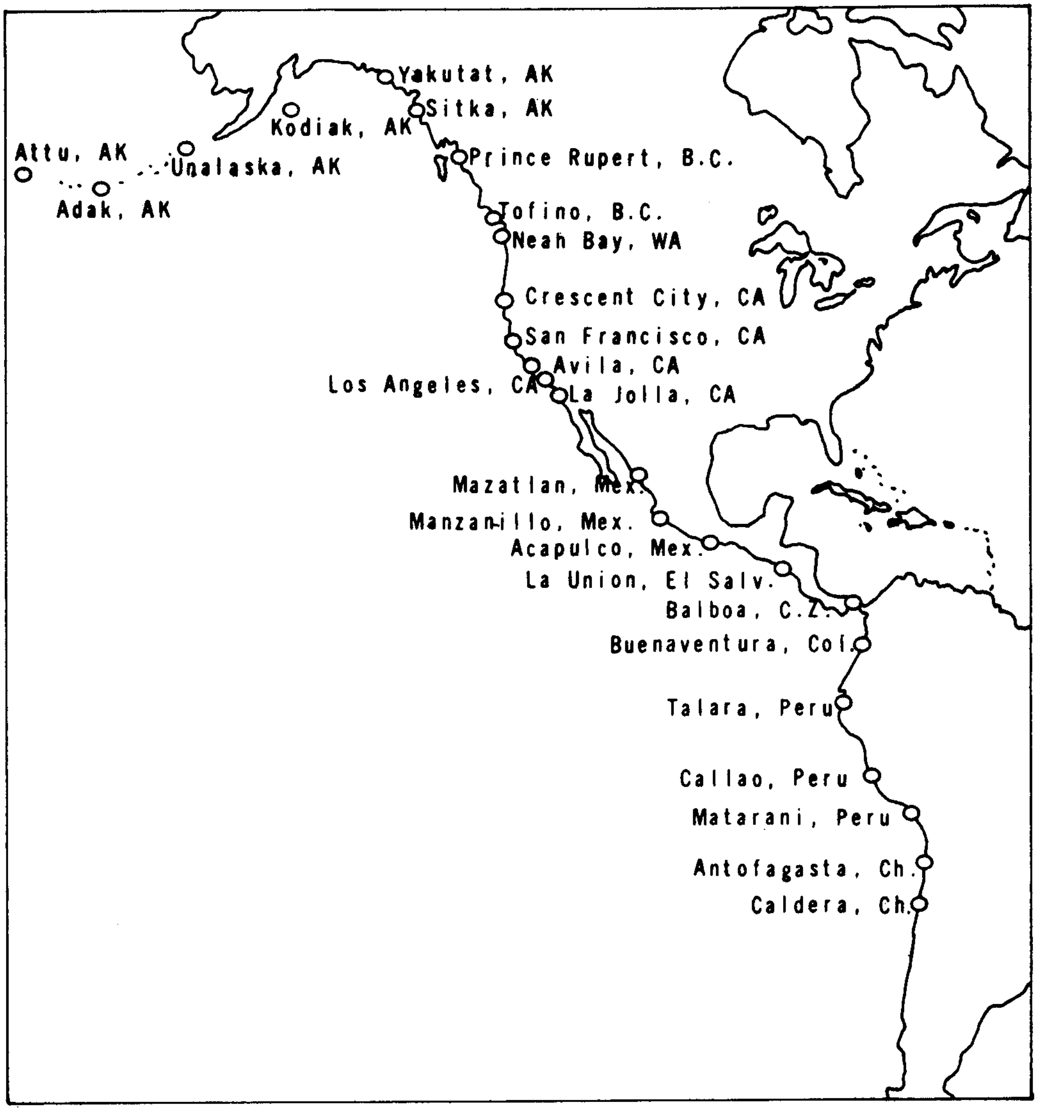

Figure 5.1.—Selected tide stations along the west coast of North and South America.

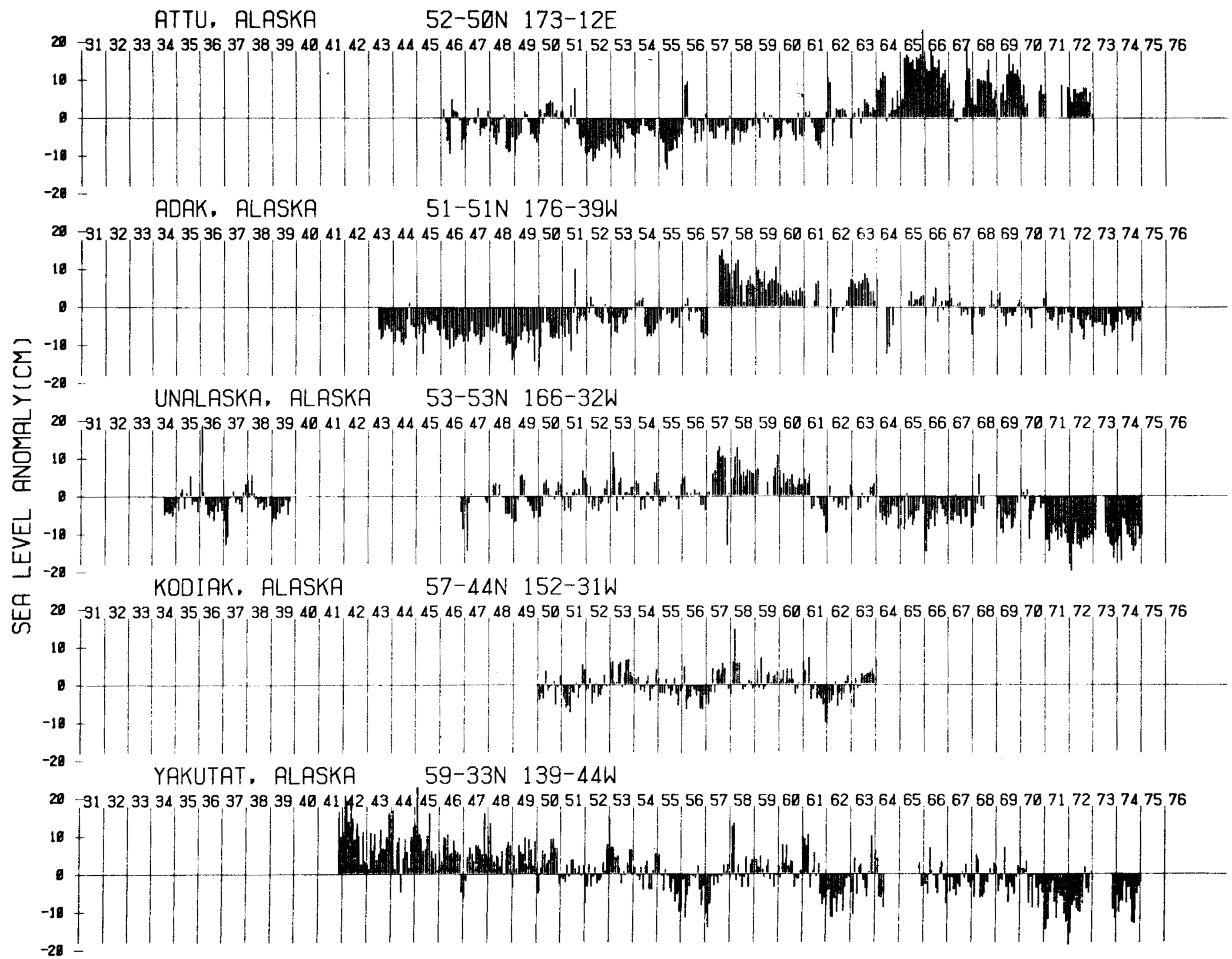

Figure 5.2.—Anomalies of mean sea level for stations in the Aleutian Islands and Gulf of Alaska.

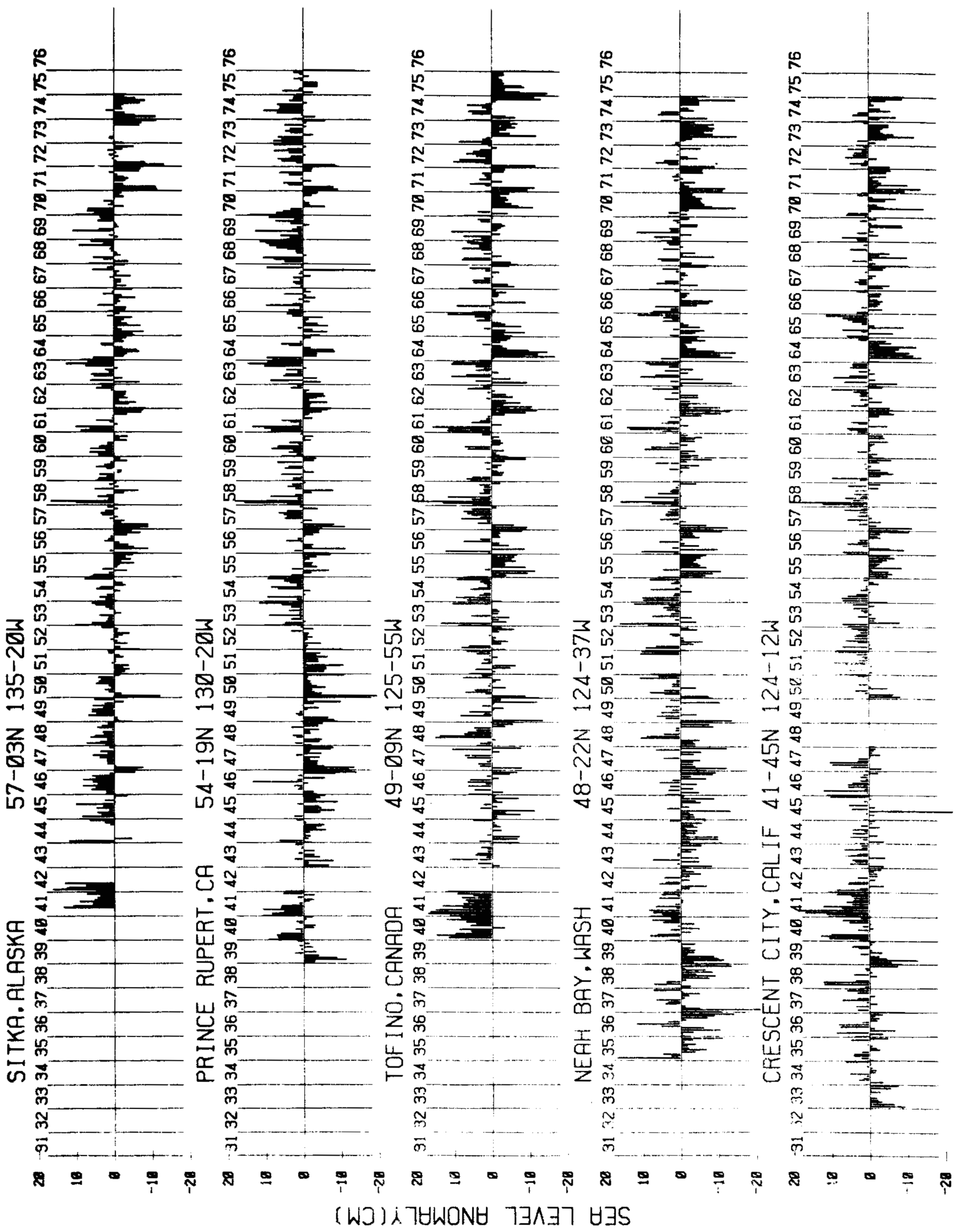

Figure 5.3.--Anomalies of mean sea level for stations in the Gulf of Alaska and Pacific Northwest.

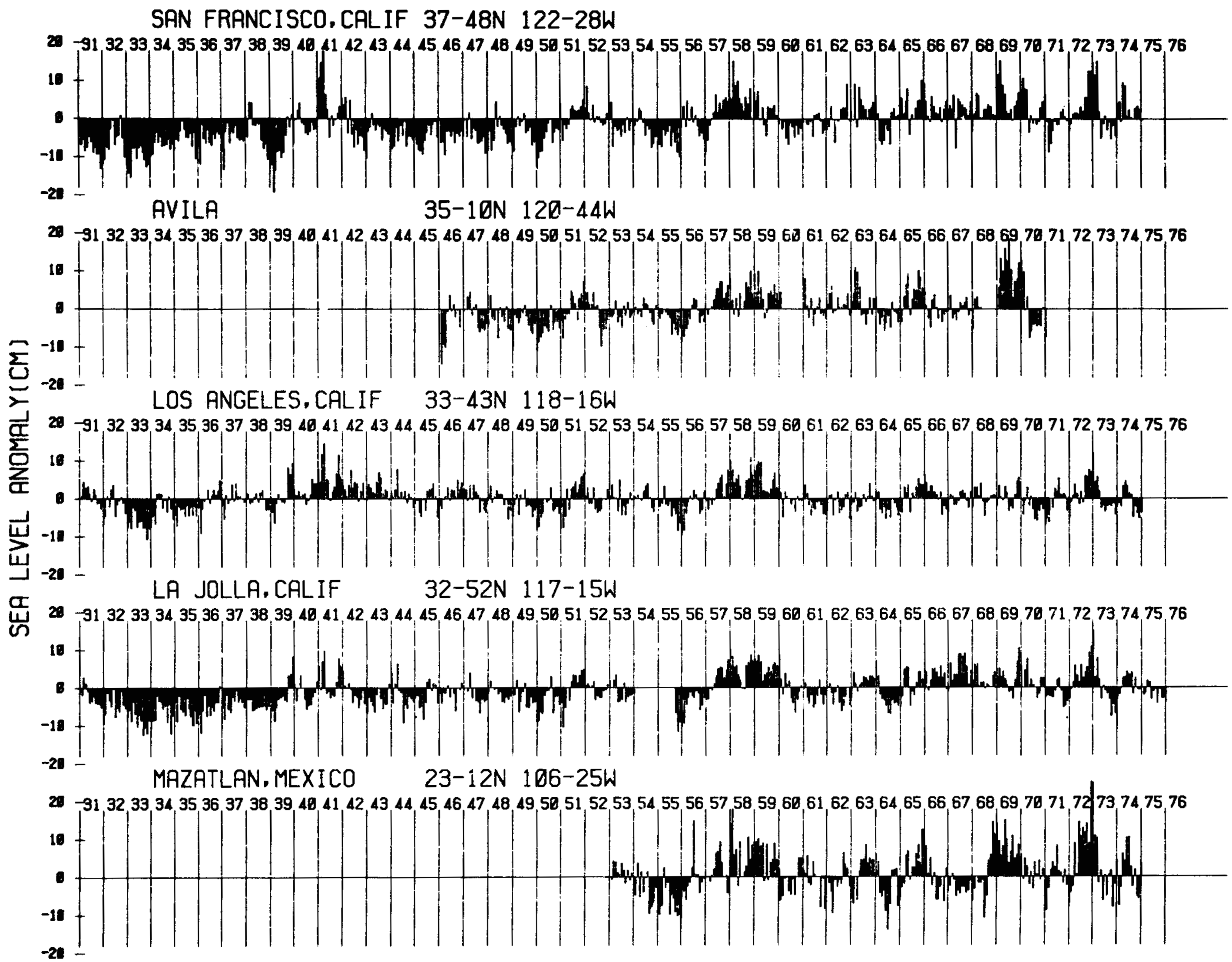

Figure 5.4.—Anomalies of mean sea level for stations in the California Current area and northern Mexico.

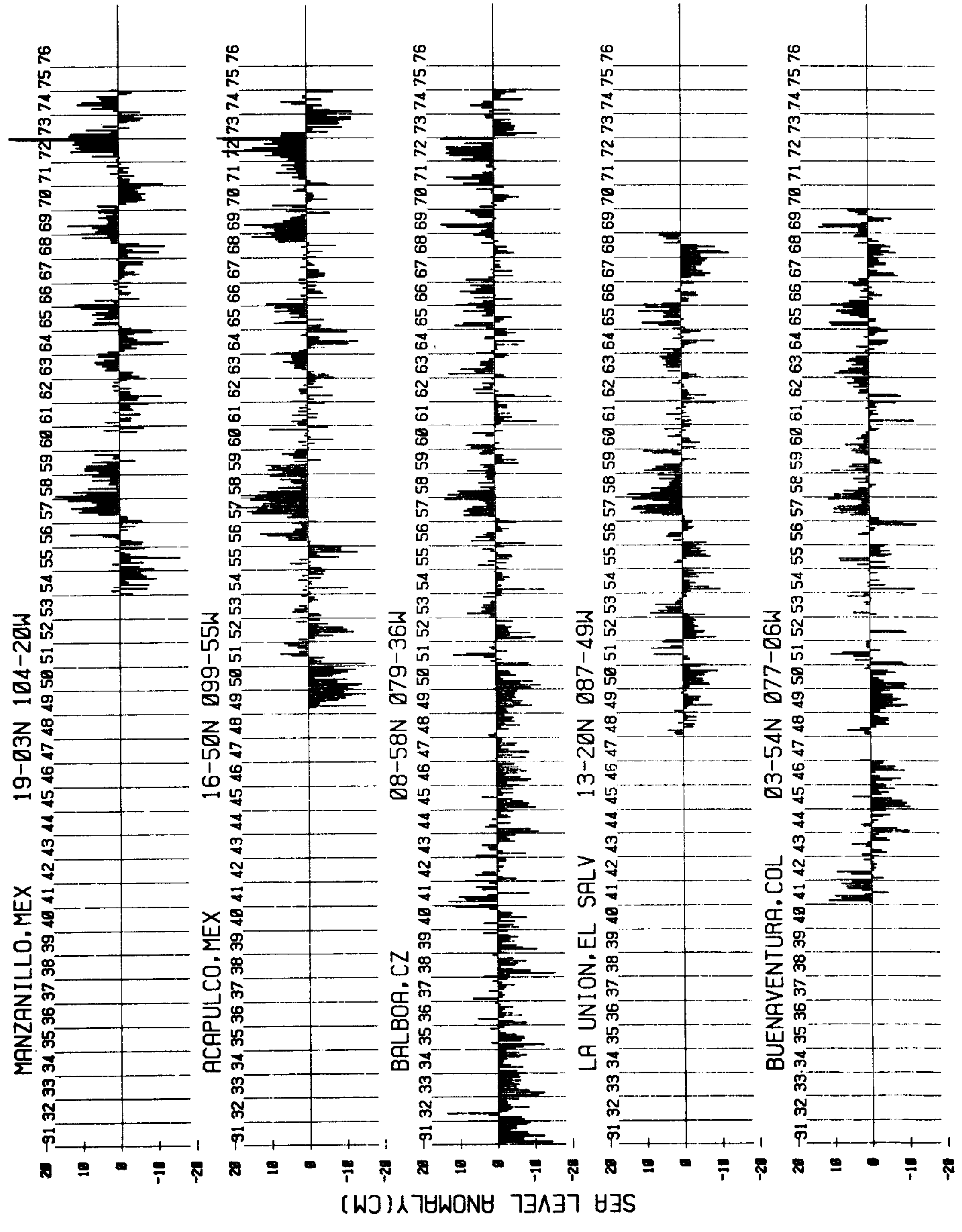

Figure 5.5.—Anomalies of mean sea level for stations in Mexico and Central America.

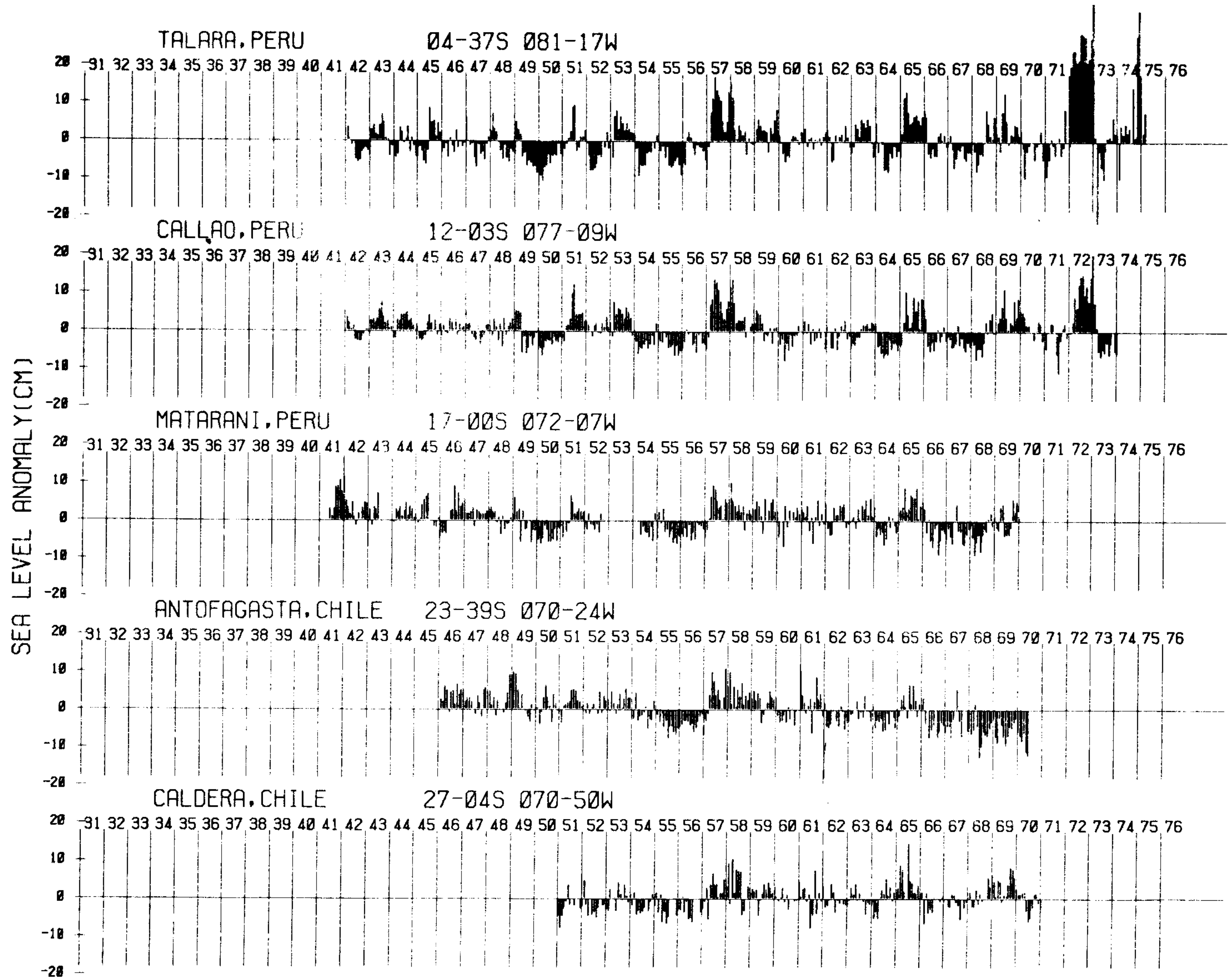

Figure 5.6.—Anomalies of mean sea level for stations in the Peru Current area.