MONTHLY SEA LEVEL DIFFERENCES BETWEEN THE HAWAIIAN ISLANDS AND THE CALIFORNIA COAST

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ABSTRACT

Time series of monthly sea level differences, adjusted for linear trends and the isostatic effect of atmospheric pressure, are computed for Honolulu-minus-San Francisco (1905-69) and Hilo-minus-Avila (1947-59 and 1961-67) as an index to broad scale changes in current around the eastern limb of the North Pacific anticyclonic current gyre.

The normal seasonal cycle of sea level differences imply a net southeastward surface current that is strongest from April through October and weakest from December through February and the range is about 20% of the average. Nonseasonal differences for Honolulu-minus-San Francisco and Hilo-minus-Avila show a highly significant correlation over the 240 months of coincident records. Inferences regarding nonseasonal large-scale long-term changes in geostrophic current are drawn from the 65-year Honolulu-minus-San Francisco smoothed monthly anomalies in which variability of less than 6 months was suppressed, as follows: 1) nonseasonal changes in current speed exceed ± 10% of the normal current over one-third of the time and range up to 54% of the normal monthly current, 2) the periods 1922-38 and 1950-54 were eras of low variability as compared with greater variability in the rest of the record, and 3) periods of weakest circulation were in 1911, 1918, 1941, 1957-58, and 1967, and of strongest circulation in 1915, 1920-21, 1943-44, 1948-49, and 1959.

For more than a decade there has been a rapidly growing interest of fishery scientists and biological oceanographers in the role of the environment in fishery problems. One objective is to include environmental effects in models of population dynamics and in fishery forecasting procedures. However, to do this, environmental characteristics which are significant to fisheries must be determined and set forth in quantitative form. One empirical approach to these complex environmental problems is to compile historical oceanic and atmospheric data into time series to gain a knowledge of the mean seasonal cycles and variability, identify periods of highly anomalous environmental conditions for further study, and seek an understanding of cause-effect relations which bring about the observed changes. Such an understanding would be useful for efficient monitoring of the oceanic environment and in predicting environmental conditions.

Oceanographic data with good time and space distribution for time-series studies of environmental changes of a few months to several years are woefully scarce. Only sea-surface temperature observations taken by ships as a part of the marine weather observations have long-term continuity in time as well as oceanwide distribution. As a result, these have been used extensively in air-sea interaction studies and to indicate oceanic changes.

To augment the sea temperature data, mean sea levels compiled from continuous tidal records at coastal and island stations provide another source of long time-series data on ocean variability. The statistical characteristics and interrelations of the sea levels, atmospheric pressure, and temperature of many coastal and island stations in the Pacific have been described in several papers by Roden (1960, 1963, 1966) using autocorrelation, spectral, and coherence techniques.

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The data have been less utilized in the study of specific oceanographic changes. Stewart, Zetler, and Taylor (1958) pointed out the rise in sea level along the west coast of North America during the warming period of 1957-58. Bjerknes (1966) also noted changes in sea levels along the equator during El Niño, i.e., warming which occurs off the Pacific coast of South America, during the same 1957-58 period.

In this paper the use of sea level information in the northeast Pacific Ocean to augment inferences about oceanographic changes is explored. The geostrophic equation requires that the speed of the surface current be proportional to the transverse slope of the sea surface. Thus time series of differences in sea level between the Hawaiian Islands and the California coast could be an index to broad-scale changes in surface current in the eastern North Pacific Ocean. Some earlier exploratory work on sea level differences between Honolulu and San Francisco through 1962 was reported orally at meetings of the American Geophysical Union (Saur, 1966). These preliminary results indicated that a pronounced weakening of the strength of the south flowing current around the eastern limb of the North Pacific current gyre was associated with the warm winters of 1940-41 and 1957-58, which have been reported for the California Current region (Reid, 1960; Robinson, 1961). The occurrence of El Niño in these same periods (Bjerknes, 1961, 1966) further indicated the possibility of a relaxation in strength of ocean current systems in the eastern Pacific on a broad scale.

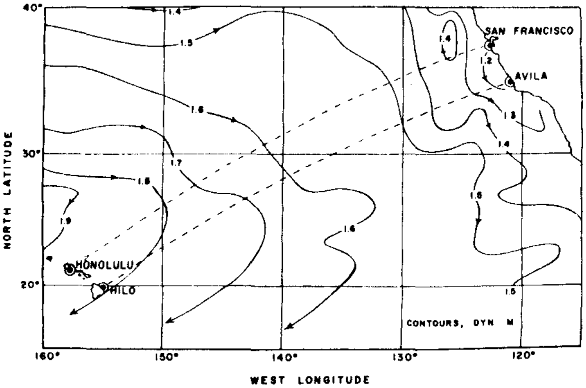

FIGURE 1.—Station locations and general pattern of surface currents (solid contours: geopotential anomaly at the sea surface relative to the 1,000 db surface, in dynamic meters) after the NORPAC Atlas (Oceanic Observations of the Pacific, 1960) but modified near the Hawaiian Islands per Reid (1961) and Seckel (1962). Dashed lines are great circles joining pairs of tide stations for which sea level differences are calculated.

No time series of direct observations of ocean conditions exist to study such broad-scale changes in current, and certainly not of the continuous nature of sea level data. In this paper therefore, the normal seasonal cycles of sea level differences between the Hawaiian Islands and the California coast are presented and some inferences are drawn from the 65-year record of Honolulu-minus-San Francisco differences about the character of changes of surface current in the region.

EARLIER STUDIES

Montgomery (1938) was the first to use the cross-current difference in sea level in the geostrophic equation to estimate the range of fluctuation of ocean current. Using changes in sea level difference between Charleston, S.C., and Bermuda, he found the range of seasonal variation was about 32% of the average difference. Stommel (1953) used fluctuations in cross-current sea level differences between Havana and Key West and between Cat Key and Miami as a measure of current in developing a model of the structure of the Florida Current. More recently, Wunsch, Hansen, and Zetler (1969) measured statistical variability of the Florida Current by spectral and coherence analyses of longer sea level records at the same four stations. They found that the apparent seasonal variation of the Florida Current accounts for only about 10% of the root-mean-square modulations for periods from 2 days to 1 year. They further concluded that monthly mean sea levels could be used to indicate long-period fluctuations.

Changes in mean sea levels at shore stations have been favorably compared by other investigators with changes in geopotential height of the sea surface in deep water offshore as traditionally determined from observed subsurface distribution of density of the water column. Montgomery (1938) cautioned that he had only a meager number of hydrographic stations for this, but other studies since that time tended to confirm his results.

For the southern California coast, LaFond (1939) found good agreement between weekly sea level and contours of dynamic height (0/500 db) extrapolated to the tide station. Special observations of sea level and temperature structure were carried out at many island stations during the International Geophysical Year from which Lisitzin and Pattullo (1961) concluded that in the open ocean most of the deviations from mean sea level can be explained by combined atmospheric pressure effects and steric effects, the latter being defined as those due to changes in the specific volume of the water column, i.e., those measured by dynamic height anomalies. Shaw and Donn (1964) had 173 hydrographic stations, taken approximately biweekly by the *Panulirus* off Bermuda over a period of nearly 7½ years, to compute steric levels for comparison with sea levels. They found that about 80% of the variance of raw sea levels, which included the seasonal cycle, resulted from a combination of the atmospheric pressure effect, which was weak, and the steric effect, which was dominant.

Sturges (1966) has shown high correlations between steric levels and mean sea level at two Pacific coast locations. The least squares regression of steric levels computed for the coast against 3-day sea level (adjusted for atmospheric pressure) for Neah Bay, Wash., was 0.97 with a standard error of estimate of 4.1 cm and a correlation of 0.904. The regression coefficient at San Diego, Calif., was only 0.61 with a standard error of estimate of 2.2 cm and a correlation of 0.914. Theoretically, for variations of sea level adjusted for pressure to agree with steric level, the slope of the regression should be unity. Sturges also estimated the wind set-up effect at Neah Bay, which has a narrow continental shelf, to be negligible.

Such studies indicate, as summarized by Donn, Pattullo, and Shaw (1964), that the combined atmospheric pressure and steric effects account for most of the sea level variations of periods longer than a few months. Thus, the interpretations made here assume that sea level differences, suitably adjusted for trends and atmospheric pressure, are a reasonable measure of changes in broad-scale geostrophic currents.

SURFACE CURRENTS OF THE REGION

Our area of interest is shown in Figure 1. Sea level differences between Honolulu and San Francisco and between Hilo and Avila are to be studied. The great circles joining each pair of stations span the same region of the eastern North Pacific Ocean.

The currents in the region are part of the eastern limb of the major anticyclonic current gyre of the North Pacific Ocean. The general pattern is shown in Figure 1 by the 0/1,000 db contours of dynamic height anomaly. The surface current is generally to the southeast, nearly normal to the great circles over most of the distance. At these latitudes the California Current extends from the California coast to about long 130°W, or somewhat farther, and about one-half of the change in geopotential anomaly takes place across this current, i.e., in less than one-third the distance between the stations. As a typical eastern boundary current (Wooster and Reid, 1963), it is broad, sluggish, and reinforced by coastal upwelling during the spring and summer months. During the winter months, December through February, a narrow north flowing countercurrent, often referred to as the Davidson Current, frequently occurs at the surface along the central California coast.

The California Current feeds into the North Equatorial Current, the axis of which lies south of lat 20°N (Seckel, 1962) so that there is generally a southward component across the great circle near the Hawaiian Islands. Occasionally, however, there is a west-northwestward flow along the east side of the islands, as evidently occurred at the time of the 1955 Norpac survey (Oceanic Observations of the Pacific, 1960). Corresponding to this return flow across the great circle, the sea levels at the Hawaiian stations would be lower than sea level northeast of the islands. Such localized conditions cannot be revealed by the sea level data, and thus are one source of "noise" in the data.

DATA AND PROCEDURES

Monthly mean sea levels were obtained from the National Ocean Survey[2] which has for many years compiled these data for its tide stations. The coincident period of record for Honolulu and San Francisco is 65 years, 1905-69. The coincident period for Hilo and Avila is 20 years, 1947-59 and 1961-67. It is broken and shortened because of incomplete records at Avila. However, Avila was selected among other California stations to pair with Hilo, so that the great circle between them would be close to that joining Honolulu and San Francisco and would cross essentially the same currents.

All of the tide gauges have moderately good exposure. Hilo and Avila are small coastal harbors protected by artificial breakwaters. The Honolulu gauge is in the outer of two harbor areas just inside of the entrance channel. The San Francisco gauge is at Fort Point just below the Golden Gate Bridge on the south side of the entrance to San Francisco Bay. Depths of 100 fm (183 m) are less than 10 km offshore from Hilo and Honolulu tide gauges, less than 20 km off Avila, and about 55 km off San Francisco.

ELIMINATION OF TRENDS

The sea level observations refer to the level of the ocean surface relative to the adjacent land. The annual mean sea levels at each of the four stations increase irregularly with time as shown in Figure 2. Such long-term trends as are due to a combination of change in the total mass of ocean water by melting (or accretion) of glaciers and of local subsidence (or emergence) of the land on which the gauge is located (Hicks and Shofnos, 1965), need to be eliminated from the data.

The linear trends determined by least squares regression, of 0.17 cm/year at Honolulu and 0.20 cm/year at San Francisco (Figure 2) are essentially the same as reported by Hicks and Shofnos (1965) for sea levels through 1962 at the same stations. The trend of 0.24 cm/year at Avila is only slightly larger than the first two, but the trend of 0.57 cm/year at Hilo is well over twice as large. In a computer analysis of the tide records at five stations in the Hawaiian Islands, Moore (1971) found a pattern of near zero trend at the older islands to the northwest increasing consistently toward the southeastern younger islands. Moore attributes the greater trend at Hilo to subsidence caused by loading of the crust by active volcanism. An interesting study by Apple and MacDonald (1966) of archeological features—native bait cups, net tanning tubs, and playing boards—carved into a newly submerged reef at Honaunau, Hawaii, further indicates a century of subsidence like that indicated by the recent tide gauge records.

By an indirect method using the decay constant of the autocorrelation coefficient Roden (1966) examined the consistency of trends for moving 30-year periods in the longer records at Honolulu and San Francisco. He found that the 30-year trends at Honolulu varied irregularly from 0.12 cm/year to 0.25 cm/year. At San Francisco the trends were low (about 0.05 cm/year) for the 1904-35 period, rising gradually and leveling off at about 0.25 cm/year for 30-year periods starting after 1915. Since not enough is known about the possible meteorological and oceanographic contributions to these trends, only the long-term linear trends shown in Figure 2 have been eliminated.

ADJUSTMENT FOR ATMOSPHERIC PRESSURE

There is general agreement that for periods of 1 month or more the ocean maintains an isostatic equilibrium with changes in atmospheric pressure. Assuming the average pressure over the whole ocean to be constant, if the pressure difference between two locations changes, the elevation of the sea surface changes in a compensatory manner so that there is no change in distribution of pressure on the sea floor. There is no balancing current associated with this portion of the slope of the sea surface which is balanced by the atmospheric pressure gradient. There-

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[2] Formerly the Coast and Geodetic Survey, Environmental Science Services Administration.

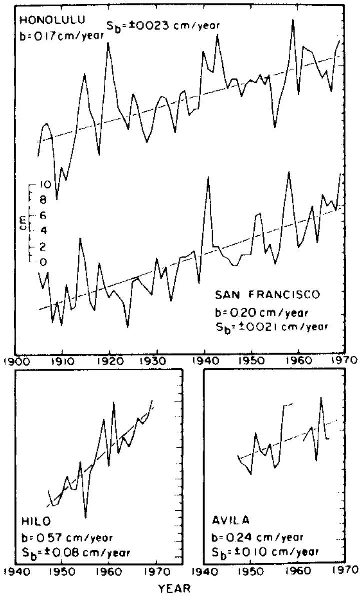

FIGURE 2.—Changes in annual mean sea level at four tide stations and linear trends determined by least squares regression. Slope of regression, *b*, and standard error of regression, s_b, are shown.

fore, an adjustment for this "inverted barometer" effect is made by correcting the sea levels to a "normal" atmospheric pressure which compensates for both the normal seasonal cycle and the monthly anomaly of atmospheric pressure at the station. For our purpose a correction of 1 cm in sea level for 1 mb change in atmospheric pressure is sufficiently accurate. Adjustments of less than 1 cm for monthly deviations of mean atmospheric pressure over the world oceans reported by Pattullo et al. (1955) have not been made to the individual station data reported here, because they are small and would have no effect on sea level differences.

Monthly mean atmospheric pressure reduced to sea level from weather observations of the National Weather Service at Honolulu, San Francisco, Hilo, and Santa Maria (less than 20 nautical miles from Avila) were obtained mainly from published sources. The World Weather Record series (Clayton, 1944a, 1944b; Clayton and Clayton, 1947; U.S. Weather Bureau, 1959, 1965, 1968) contain climatological data, including monthly atmospheric pressure, through 1960. Monthly mean pressures for first order weather stations are included in the monthly issues of Climatological Data, National Summary, U.S. Environmental Data Service, published since January 1950. Some manuscript records obtained directly from the Weather Service offices were helpful in standardizing all pressure data to sea level.

NORMAL SEASONAL CYCLES OF SEA LEVEL AND SEA LEVEL DIFFERENCE

The *normal* monthly sea levels are obtained by averaging the monthly sea levels[3] for a given month from all years of record. Because the zero level for the scale on the tide gauge is arbitrary at each station the normal monthly sea levels are shown in Table 1 in terms of departure from the long-term mean for all months and years. The standard deviations for given months in Table 1 are measures of the year-to-year variability of monthly sea level for the given month. From these one can compute that the 95% confidence limits on the monthly normals for Honolulu and San Francisco are 0.8 cm or less, and 1.4 cm or less for Hilo and Avila.

We are interested in the real differences in normal monthly sea level between stations as a base against which to measure the variability. For continental stations it is possible to determine this difference of long-term mean sea level between two stations by reference to the geodetic leveling network,[4] but no such reference leveling exists between the continent and Hawaiian Islands. As described in the next section, the long-term sea level difference has been estimated using oceanographic data.

COMPUTATION OF LONG-TERM MEAN SEA LEVEL DIFFERENCE

The long-term mean sea level differences between Honolulu and San Francisco and between

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[3] Monthly sea level with trend removed and adjusted to normal atmospheric pressure is hereafter implied.

[4] From oceanographic data, however, Sturges (1966) suggests there may be some systematic north-south leveling error.

TABLE 1.—Departures of normal monthly sea level, $\bar{h}$, *from the long-term mean at each tide station*; normal monthly sea level difference, $\bar{d}$; and standard deviations, s, of monthly values for total years of record, in centimeters. Honolulu and San Francisco, 1905-69; Hilo and Avila, 1947-59 and 1961-67.

Month	Honolulu		San Francisco		Honolulu-San Francisco		Hilo		Avila		Hilo-Avila	
	$\bar{h}$	s_h	$\bar{h}$	s_h	$\bar{d}$	s_d	$\bar{h}$	s_h	$\bar{h}$	s_h	$\bar{d}$	s_d
Jan.	−1.9	4.4	5.4	5.3	50.6	6.9	−2.0	4.2	4.6	4.4	46.0	4.2
Feb.	−1.7	4.4	4.4	6.3	51.9	6.8	−3.1	3.7	1.1	4.3	47.6	4.4
Mar.	−1.7	5.1	−1.1	6.0	57.4	7.6	−2.9	5.1	−4.6	3.8	53.3	6.3
Apr.	−2.8	5.3	−5.1	4.6	60.3	7.2	−2.2	4.2	−6.9	3.5	56.6	6.0
May	−2.6	5.1	−6.3	3.4	61.7	5.8	−3.5	5.3	−6.6	3.6	55.7	5.6
June	−2.0	5.6	−4.6	2.6	60.6	6.3	−2.5	5.9	−4.3	2.9	53.9	6.0
July	0.3	5.8	−1.3	2.8	59.6	6.4	0.9	5.0	0.0	3.6	53.3	5.2
Aug.	2.6	5.5	−0.5	2.8	61.1	5.8	4.0	4.6	2.2	3.6	53.9	4.7
Sept.	3.7	4.7	1.0	3.2	60.8	5.7	4.4	4.7	3.2	3.7	53.1	6.4
Oct.	3.7	4.7	1.0	3.7	60.7	6.1	4.1	3.5	3.2	4.4	52.9	4.5
Nov.	2.1	3.9	2.3	4.4	57.8	5.8	2.8	4.3	3.8	3.7	50.6	4.8
Dec.	0.1	4.5	4.6	4.9	53.5	6.3	0.0	5.1	4.4	5.1	47.0	5.5

Note: Long-term mean differences, Honolulu-minus-San Francisco and Hilo-minus-Avila, have been adjusted to 58 cm and 52 cm, respectively, by *reference to 0/1,000 db dynamic heights, as described in text.*

Hilo and Avila have been estimated from 0/1,000 db dynamic height anomalies. Reed (1970) has shown that the real topography of the 1,000 db surface between Honolulu and San Francisco is probably 1 cm or less.

The dynamic height anomalies were obtained from listings of hydrographic station data supplied by the National Oceanographic Data Center and data reports of the Trade Wind Zone Oceanography (TWZO) Program (Charnell, Au, and Seckel, 1967a, b, c, d, e, f).

Information on the number of stations, location, and average dynamic height anomalies is given in Table 2. The locations of the hydrographic stations relative to the tide stations are shown in Figure 3. Frequent observations made since 1949 by the California Cooperative Oceanic Fisheries Investigations (CalCOFI) made it possible to get a good sampling of stations very near the two California tide stations. The density of sampling was much lower near the Hawaiian Islands, so observations over broader geographic regions were used. The mean dynamic height anomalies were computed for several independent sets of observations in the vicinity of Honolulu and Hilo to reveal the extent of island effects, but no large differences were found in the averages.

All oceanographic stations were taken since 1947. Sampling of different months throughout the year was good. Long-term mean Honolulu-minus-San Francisco sea level difference was found to be 58 cm and the Hilo-minus-Avila difference was 52 cm. The normal monthly sea level differences in Table 1 reflect the adjustment of long-term mean sea level differences to these values.

HONOLULU-MINUS-SAN FRANCISCO

The seasonal variation of the normal monthly sea level difference for Honolulu-minus-San Francisco sea level difference is shown in the upper part of Figure 4. The cycle is asymmetric about the mean level. The monthly difference is high, forming a plateau, in the months from April through October, and a sharp minimum occurs from December through February. March and November are transitional months. The range of the normal seasonal cycle is 11 cm or 19% of the long-term mean difference of 58 cm.

The lower part of Figure 4 shows how the normal seasonal cycles at each station contribute to the seasonal cycle of the difference. The monthly normal at San Francisco is lowest in May, early in the upwelling season. The Honolulu sea level is also at its minimum, but the magnitude of the negative departure at San Francisco is more than double that at Honolulu and the normal cycle of sea level difference is at its maximum. Both station curves rise at nearly the same rate from June to October. A somewhat more rapid rise in July at San Francisco,

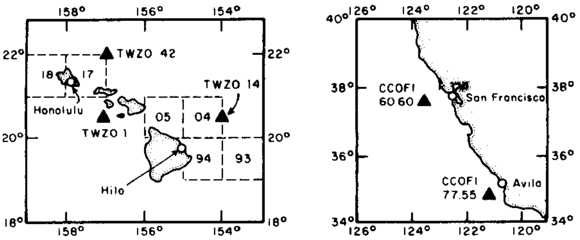

FIGURE 3.—Locations of hydrographic station data used to determine long-term differences in sea level as referred to in text and in Table 2. CCOFI = California Cooperative Oceanic Fisheries Investigations. TWZO = Trade Wind Zone Oceanography program. Two-digit numbers are 1-degree square (dashed lines) identification used in National Oceanographic Data Center listings of hydrographic station data.

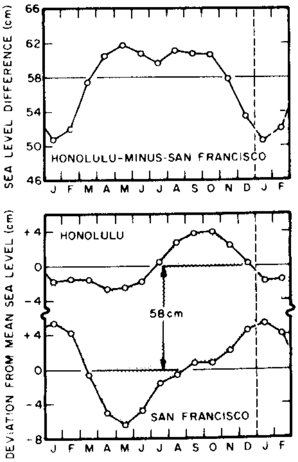

FIGURE 4.—Seasonal deviations of 65-year normal (1905-69) monthly sea levels (trend removed and adjusted to normal pressure) from long-term mean, Honolulu and San Francisco (below). Seasonal cycle of normal monthly sea level difference (above). Difference of long-term mean sea level of 58 cm was determined from hydrographic station data (see text).

probably due to heating, giving way to a more gradual rise into autumn, results in a slight dip during July in the plateau of the difference. The sea level at Honolulu drops rapidly from October to January. At San Francisco, however, the sea level continues to rise from November to its highest value in January. Some of this rise is undoubtedly the result of the frequent occurrence of the north-flowing coastal countercurrent in these months (Reid, Roden, and Wyllie, 1958), while some may be due to decrease in the speed of the south-flowing current offshore. The proportions cannot be determined from the sea level data. The combined changes at Honolulu and at San Francisco result in a sharp winter minimum in the normal cycle of sea level difference.

HILO-MINUS-AVILA

The seasonal variation of the normal monthly sea level difference for Hilo-minus-Avila (Figure 5) is similar to that for Honolulu-San Francisco. A winter minimum occurs in December-February, and the maximum occurs in the spring. However, after a decrease of a few centimeters to July the normal difference remains at a nearly constant level through October rather than rising again as it did for Honolulu-San Francisco. March and November are transitional months except that March has a normal difference as high as those for late summer. The range of the normal seasonal cycle

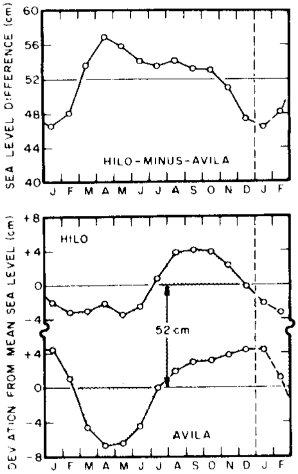

FIGURE 5.—Seasonal deviations of 20-year normal (1947-59, 1961-67) monthly sea level (trend removed and adjusted to normal pressure) from long-term mean, Hilo and Avila (below). Seasonal cycle of normal monthly sea level difference (above). Difference between long-term mean sea level of 52 cm was determined from hydrographic station data (see text).

is 10.6 cm, or 20% of the long-term mean sea level difference of 52 cm.

The seasonal cycle for Hilo is very much like that at Honolulu. The slight peak in April at Hilo, which does not occur at Honolulu, combined with the April minimum at Avila causes the maximum in the sea level difference to occur 1 month earlier for Hilo-Avila than for Honolulu-San Francisco. The normal seasonal cycle at Avila tends to lead that at San Francisco by 1 month. A stronger rise occurs at Avila in June-August than at San Francisco, which may be a heating effect because Avila is at a lower latitude.

DISCUSSION

The characteristics of the normal seasonal cycles of sea level difference for both pairs of stations are in agreement with each other and in accord with our knowledge from other sources of the oceanography of the northeast Pacific and California Current. The geostrophic equation requires that the speed of the surface current be proportional to the transverse slope of the sea surface. From the sea level difference we can infer that the average current normal to the great circles between the Hawaiian Islands and the California coast is southeastward throughout the year. It is strongest in the upwelling and summer season when the North Pacific atmospheric high pressure cell is best developed. It is weakest during the winter season.

Using an average latitude between stations and the long-term differences in the geostrophic equation, the average current to the southeast is 2.0 cm/sec for the Honolulu-San Francisco difference and 1.9 cm/sec for the Hilo-Avila difference. The range of the normal seasonal cycle, as noted earlier, is 20%.

It must be kept in mind that the sea level difference indicates only the average geostrophic surface current normal to the line between the two stations. For the California Current the contours of 0/500 db dynamic height anomaly in the CalCOFI Atlas No. 4, Geostrophic Flow (Wyllie, 1966) indicate that the speed averaged over a distance of 1,000 km is about 5 to 10 cm/sec, whereas there may be narrow regions about 100 km in width with current of 25 cm/sec, or greater.

COMPARISON OF MONTHLY SEA LEVELS WITH STERIC LEVELS

Monthly sea level differences are to be used to estimate the slope of the sea surface and draw inferences regarding month-to-month and year-to-year changes in current from the geostrophic equation. Traditionally the slope is estimated indirectly by computing geopotential heights, or steric levels. Therefore, the agreement between monthly sea levels and steric levels at nearby offshore locations was investigated using hydrographic station data, employed earlier to establish the long-term mean differences in sea level between pairs of stations. Correlation coefficients between the monthly sea levels, linearly interpolated to the date of each hydrographic station, and the steric levels are given in the last column of Table 2. For San Francisco and Avila, where a large number of hydrographic stations were made within a small area at nearby locations, the correlation coefficients are 0.54 and 0.57 respectively. Both coefficients are considerably higher than the 1% level of significance.

For Honolulu the correlations from four sets of data from different areas are quite consistent, ranging from 0.54 to 0.65. These coefficients are as large as those for San Francisco and Avila, but because of the smaller sample sizes are statistically significant only at the 5% level.

For Hilo the correlations for three different sets of steric levels are less consistent. A high correlation, $r = 0.78$, which is significant at the 1% level, was obtained with Hilo monthly sea levels only from the set of 10 steric levels from observations in 1-degree squares 04 and 05 immediately northeast of Hilo. Dynamic topography charts in TWZO data reports (Charnell et al., 1967a, b, c, d, e, f) reveal that the presence of an anticyclonic eddy or ridge northeast of Hilo at TWZO station 14 during 5 of the 16 observational periods caused the lower correlation of data from that station with Hilo sea levels. One suspects some similar local effect as

TABLE 2.—Determinations of long-term mean sea level differences from 0/1,000 db geopotential (steric) anomalies at nearby offshore locations. Correlations, r, of monthly sea levels with geopotential anomalies.

Shore station	Data source	Location of hydrographic stations (see Figure 3)	Distance from shore station (km)	No. of observations	Average steric anomaly, 0/1,000 db (dyn cm)	Correlation, r steric vs. sea level
Honolulu	NODC	1-degree square 17, Marsden square 088	10-100	10	[1] 182.4	0.65*
	NODC	1-degree square 18, Marsden square 088	30-120	12	[1] 182.2	0.64*
	TWZO	Station 1	100	16	184.3	0.60*
	TWZO	Station 42	120	15	184.0	0.54*
San Francisco	NODC	CalCOFI 60.60	105	52	[2] 125.2	0.54**
		Long-term mean sea level difference, Honolulu-minus-San Francisco = 58 cm				
Hilo	NODC	1-degree squares 04, 05, Marsden square 088	10-150	11	[1] 179.5	0.78**
	NODC	1-degree squares 93, 94; Marsden square 052	20-200	10	[1] 179.3	0.48
	TWZO	Station 14	140	16	181.1	0.42
Avila	NODC	CalCOFI 77.55	50	42	[3] 127.5	0.57**
		Long-term mean sea level difference, Hilo-minus-Avila = 52 cm				

[1] 0/500 db average plus 49.0 dyn cm for 500/1,000 db average, based on TWZO data and 1,000 m stations.
[2] 0/500 db average plus 45.9 dyn cm for 500/1,000 db average, based on 37 stations in same 1-degree square.
[3] 0/400 db average plus 57.9 dyn cm for 400/1,000 db average, based on 25 stations in same 1-degree square.
* Correlation significant at 5% level.
** Correlation significant at 1% level.

the cause of the lower correlation for observations in 1-degree squares 93 and 95.

The correlations between monthly sea levels and offshore steric levels for the four stations in this study are less than anticipated from the results reported by other investigators, e.g., Shaw and Donn (1964) and Sturges (1966), as noted in the section, Earlier Studies. It is suspected that the lower correlations for the four Pacific stations in the present study may be due in part to comparison of a monthly sea level with a steric level from a single hydrographic observation on a given day. Present available steric data explain only about 40% of the variance of monthly sea levels from which the trend has been removed and which have been adjusted to normal pressure. As suggested by Stommel (1958) in relation to sea level at Bermuda, the possibility exists that geostrophically balanced barotropic currents exist which would also affect the monthly mean sea levels. When time series of frequent hydrographic observations or long-term observations from buoys become available to give a better estimate of continuous changes in steric level, we may then be able to attain a better understanding of the causes of sea level variations. For the present the unexplained variability may limit the use of sea levels and sea level differences to interpretation of broad-scale, highly anomalous oceanic changes.

NONSEASONAL SEA LEVEL DIFFERENCES

The monthly sea level differences used in this study are given in Appendix Tables 1 and 2 for Honolulu-minus-San Francisco and Hilo-minus-Avila, respectively. For each station the linear trends were removed and values adjusted to normal atmospheric pressure. The monthly differences reflect the adjustment, previously discussed, of the long-term mean sea level difference for all months and years to a mean difference determined from 0/1,000 db geopotential heights.

VARIABILITY

The nonseasonal variations are represented by the monthly anomalies, defined as the difference between the value for the month and the normal for the same month. The standard deviations in Table 1 for given months at individual stations exhibit the same characteristics as those reported in an earlier study (Saur, 1962) for six Pacific

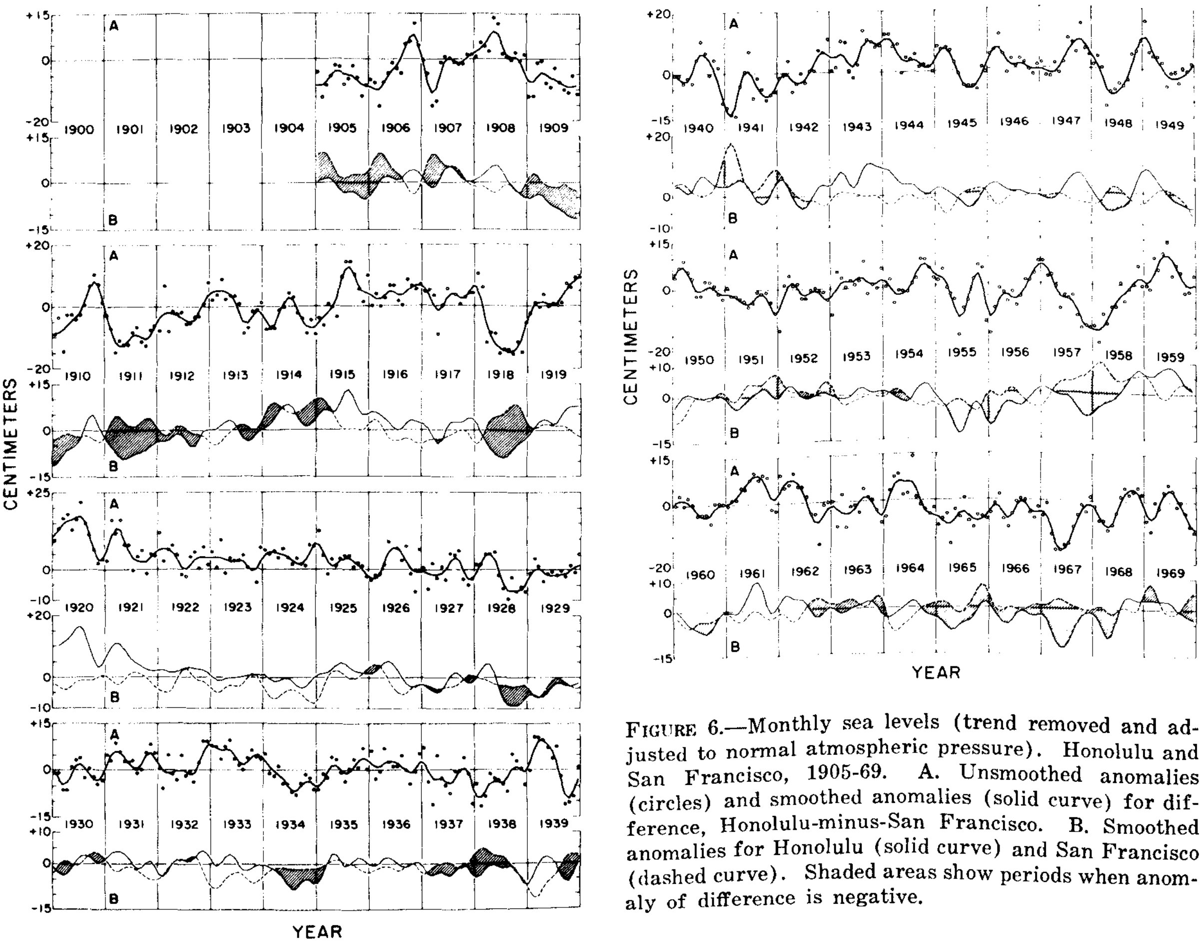

FIGURE 6.—Monthly sea levels (trend removed and adjusted to normal atmospheric pressure). Honolulu and San Francisco, 1905-69. A. Unsmoothed anomalies (circles) and smoothed anomalies (solid curve) for difference, Honolulu-minus-San Francisco. B. Smoothed anomalies for Honolulu (solid curve) and San Francisco (dashed curve). Shaded areas show periods when anomaly of difference is negative.

stations, two of which were Honolulu and San Francisco. Standard deviations in the former study were slightly larger because trends were not eliminated. At San Francisco, a coastal station at mid-latitude, the standard deviations show a seasonal change, attaining values near 6 cm in the late winter but decreasing to less than 3 cm in summer. At the other stations they vary less with season and those at the island stations generally lie in the range between 4.0 and 5.5 cm.

The standard deviations of the monthly sea level differences (Table 1) do not vary greatly throughout the year. The Honolulu-minus-San Francisco values are slightly larger than those for Hilo-minus-Avila because "climatic" changes, to be discussed later, appear in the longer Honolulu-San Francisco records.

The time series of the anomalies of monthly sea level difference are shown by open circles in Figure 6 for Honolulu-minus-San Francisco and in Figure 7 for Hilo-minus-Avila. The variability indicated by the standard deviations is evident. To suppress the shorter period variability and aid in detecting underlying longer period changes the time series have been smoothed, as indicated by the solid curves.

A simple 5-point smoothing operator with weights of $-1/16$, $1/4$, $5/8$, $1/4$, $-1/16$ was selected for the smoothing. This is a particular case of one-dimensional, two-element smoothers described by Shapiro (1970). It is a low-pass filter with a response function:

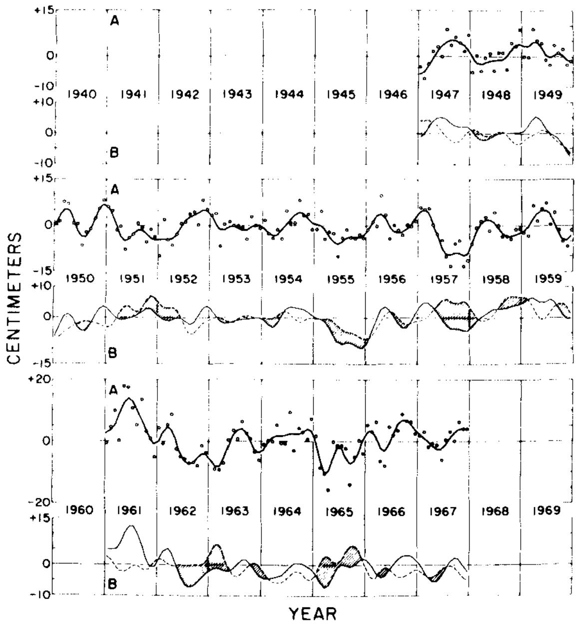

FIGURE 7.—Monthly sea levels (trend removed and adjusted to normal atmospheric pressure). Hilo and Avila, 1947-59 and 1961-67. A. Unsmoothed anomalies (circles) and smoothed anomalies (solid curve) for difference, Hilo-minus-Avila. B. Smoothed anomalies for Hilo (solid curve) and Avila (dashed curve). Shaded areas show periods when anomaly of difference is negative.

$$R(n) = 1 - \sin^4 \frac{\pi}{n}$$

where n is the number of data intervals in the Fourier component being smoothed. In our case n is also the wave period in months. Periods of 2 months are eliminated completely in one application of the smoother. Repeated applications of the smoother eliminate or reduce progressively longer periods. The response is a positive value between zero and one for all finite wave periods, so no 180° phase shift nor amplification occurs. The filter can be applied to the individual station anomalies followed by computation of the difference, or applied directly to the time series of the difference anomalies with the same end result.

The smoothed anomalies of monthly sea level for each station and of sea level differences in Figures 6 and 7 were obtained by applying the smoother eight successive times. The 50% level for the response function lies between periods of 5 and 6 months, and the response is 85% at 8 months.

CORRELATIONS BETWEEN HONOLULU-MINUS-SAN FRANCISCO AND HILO-MINUS-AVILA ANOMALIES

There are no independent data against which to check the anomalies of sea level differences as an index of nonseasonal variations in current. Since the two sets of differences span very nearly the same current region, the consistency between them is examined in this section to see if they agree reasonably well.

The correlations by month for both unsmoothed and smoothed anomalies are listed in Table 3. A general improvement of the correlations, particularly in winter, occurs as a result of smoothing to suppress the short-period variability. The effect of different scales of wind systems can be recognized by the seasonal pattern of correlations, especially in the smoothed anomalies. In the months from April through November when the subtropical high dominates the atmospheric pressure pattern over the North Pacific Ocean, all the correlations of smoothed anomalies are significant at the 1% level. In the months from November through March when meso-scale cyclonic and anticyclonic

TABLE 3.—Correlations of monthly sea level differences, by month Hilo-minus-Avila versus Honolulu-minus-San Francisco; $n = 20$ years.

Month	Unsmoothed anomalies	Smoothed anomalies
January	0.37	0.45*
February	0.37	0.44*
March	0.40	0.48*
April	0.56**	0.54**
May	0.45*	0.58**
June	0.63**	0.63**
July	0.64**	0.63**
August	0.41	0.69**
September	0.74**	0.68**
October	0.53**	0.56**
November	0.32	0.51*
December	0.57**	0.49*

* Correlation significant at 5% level ($r \geqslant 0.42$).
** Correlation significant at 1% level ($r \geqslant 0.54$).

wind systems move through the region, the correlations are somewhat lower, but still significant at the 5% level.

For the entire 20 years of concurrent records for Hilo-minus-Avila and Honolulu-minus-San Francisco, the correlation of unsmoothed anomalies is 0.49 and for smoothed anomalies it is 0.55. The 1% level of significance for the correlation coefficient of a sample of 240 months is 0.17, so these values are highly significant.

A visual comparison of the data in Figures 6 and 7 reveals the agreement evidenced by the correlation coefficients. Smoothed anomalies of the same sign tend to occur at the same time. For the most part the oscillations of the smoothed anomalies of sea level difference are in phase. Oscillations are noticeably out of phase in the periods October 1950-February 1951, March 1952-January 1953, September 1955-June 1956, and January-July 1958. In the last 18 months of the Hilo-minus-Avila record (July 1966-December 1967) the changes are similar to those for Honolulu-minus-San Francisco, but the smoothed anomaly of the difference is positive rather than strongly negative. Except for the 1955 periods, the nonagreement of the anomalies during these periods results mainly from a rise in sea level at San Francisco as opposed to a drop at Avila. These periods comprise only 20% of the total 20-year coincident records. In the remaining 80% the correlation coefficient for unsmoothed anomalies is 0.65 and for the smoothed anomalies it is 0.76. Both are significant well beyond the 1% level of 0.186 for a sample of 190.

CURRENT CHANGES INFERRED FROM SEA LEVEL DIFFERENCES

In this section some characteristics of the 65-year record of anomalies of sea level differences, Honolulu-minus-San Francisco are described with emphasis on their implications regarding changes in surface currents. Because the smoothed anomalies minimize local effects near the station, such as the set-up by wind and eddy systems passing near the Hawaiian Islands, they will be used as more realistic estimates of the larger scale and longer term changes in circulation. The term *current index* will be applied to this usage.

The discussion will follow the basic premise in this paper, that the currents are geostrophically related to the sea level difference so that a positive current index indicates above normal current, i.e., stronger flow to the south around the eastern limb of the anticyclonic gyre of the North Pacific Ocean. Conversely, negative current indexes indicate a below-average slope of the sea surface and proportionally weaker circulation.

Three tables have been compiled to show the characteristics of the current indexes. Table 4 gives statistical data regarding the current indexes by month. The data describe the year-to-year variations that occur. The normal monthly sea level differences, *d*, (of unsmoothed data) are repeated from Table 1 as a reference against which to measure the ranges and standard deviations of the current indexes.

Visual inspection of the time series (Figure 6) indicates that there are a number of different "climatic periods" in the record, i.e., periods characterized by the variability and the mean level of the current index during the period. Table 5 identifies seven such periods, into which I have subjectively divided the time series, and gives the mean and the standard deviation about that mean for each period. Obviously, other investigators might well select different climatic periods based upon other criteria related to their work.

In Table 6, highly anomalous periods have been identified on the basis of a criterion that the magnitude of the current index exceeded 10 cm for two or more consecutive months. As well as information on the dates, sign, magnitude, and duration of the current index, data are also given on the sign, magnitude, and date of the largest monthly sea level index at Honolulu and San Francisco which coincided with the current index greater than 10 cm.

Some observations which may be made about the Honolulu-minus-San Francisco differences and the information in these tables are given below.

1. The standard deviations of year-to-year changes for a given month (Table 4) vary from

TABLE 4.—Variability of current index (smoothed anomaly of sea level difference), Honolulu-minus-San Francisco, by months. $N = 65$ years. Standard deviation (s); largest positive and negative departures (Max and Min) and year of occurrence; Range (R) in centimeters and in percent of normal monthly sea level difference, $\bar{d}$ (from Table 1).

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
s (cm)	5.7	6.0	6.2	6.0	5.7	5.5	5.4	5.2	5.1	5.2	5.3	5.4
Max (cm)	11.2	13.5	15.3	16.0	16.5	17.4	17.7	15.8	11.4	10.3	9.5	10.6
Year	1920	1920	1920	1920	1920	1920	1920	1920	1920	1943	1943	1948
Min (cm)	−14.7	−14.4	−13.0	−14.0	−16.1	−15.4	−14.2	−14.6	−14.5	−13.5	−13.7	−14.4
Year	1958	1958	1958	1967	1967	1967	1918	1918	1918	1918	1957	1957
R (cm)	25.9	27.9	28.4	30.1	32.6	32.7	31.9	30.4	25.9	23.8	23.2	25.0
$R/\bar{d}$, (%)	52	54	49	50	53	54	53	49	43	39	40	47
$\bar{d}$ (cm)	50.6	51.9	57.4	60.3	61.7	60.6	59.6	61.1	60.8	60.7	57.8	53.5

5.1 cm in September to 6.2 cm in March. The seasonal change is due to greater winter-time variability at San Francisco (Saur, 1962) probably caused by year-to-year differences in weather conditions. A range of two standard deviations is nearly the same as the 11 cm range of the normal seasonal cycle. Long-term non-seasonal changes exceed ± 10% of the normal over one-third of the time.

2. The range between extremes (Table 4) in any given month varies from 23.2 cm for November to 33.7 cm in June. These are 39% and 54%, respectively, of the normal sea level differences for these months.

3. The minimum current index was —16.1 cm in May 1967 and the maximum was + 17.7 cm in July 1920. The range between the extremes of the current index is 58% of the long-term mean sea level difference of 58 cm for Honolulu-minus-San Francisco, and it is three times as large as the range of the normal seasonal cycle.

4. The periods 1905-15, 1939-41, and 1955-69 were characterized by large changes between positive and negative values of current index over periods up to a few years, but on the average the indicated current is weaker than normal (Table 5).

5. During the periods 1915-25 and 1942-49, the current index implies moderate to large changes in current over periods of several years but indicates on the average a current stronger than normal. Except for large negative values in 1918, the current index indicates almost continuously stronger-than-normal circulation from mid-1915 through 1925.

6. The current changes during the periods 1926-38 and 1950-54 were relatively small as compared to the rest of the records. The current index did not exceed 8.5 cm and was nearly evenly distributed between negative and positive values.

7. The sea level records imply that unusually weak currents (negative anomalies in Table 6) occurred in 1911, 1918, 1941, 1957-58, and 1967, and that the periods of unusually strong currents occurred in 1915, 1920-21, 1943-44, 1948-49, and 1959.

8. During 7 of the 10 highly anomalous periods in Table 6, the absolute value of the monthly sea level anomaly at Honolulu is much larger than that at San Francisco. This indicates that significant changes in physical conditions which affect circulation occur in the central water of the current gyre as well as in the boundary current itself.

CONCLUDING REMARKS

For the investigation of historical changes in the ocean environment two notable observational deficiencies are apparent: the paucity of time-series subsurface data and the lack of information on changes in current of periods from a few months to several years. This study has attempted to develop some information on the normal seasonal cycle and the nonseasonal change of ocean currents in that part of the eastern

TABLE 5.—Mean current index, $\bar{\Delta}d$, and standard deviation, s, Honolulu-minus-San Francisco, for selected "climatic" periods (see text).

Years	Number of months	$\bar{\Delta}d$ (cm)	s (cm)
1905-14	120	−3.0	5.3
1915-25	132	3.5	6.1
1926-38	156	0.2	3.6
1939-41	36	−1.2	6.3
1942-49	96	2.6	4.8
1950-54	60	0.1	3.4
1955-69	180	−1.9	5.6

North Pacific Ocean which includes the California Current, using the most appropriate long-term records of sea level available.

Monthly sea level differences for a 65-year period (1905-69) between Honolulu and San Francisco and for 20 years (1947-59, 1961-67) between Hilo and Avila were computed to indicate the strength and fluctuations in the monthly geostrophic current around the eastern limb of the anticyclonic gyre of the North Pacific Ocean. The premise is that through the geostrophic relationship the nonseasonal variations of sea level difference indicate proportional changes in the current.

The distance between tide stations in each pair is about 3,900 km. The current structure is not uniform across the geographic region. Variability in the records is introduced by local conditions, and smoothing has been used to minimize these effects. Therefore, the sea level differences presented here can be indicative of only large-scale changes in circulation and conclusions regarding the circulation have been confined to periods of the more persistent highly anomalous periods in the sea level differences. In the tropical and western North Pacific where islands are more suitably located with respect to the currents the procedures followed here might be used to study variations in the Equatorial Currents and the Kuroshio.

In the Northeast Pacific there is no independent set of long-term observations to substantiate the inferences regarding current changes that have been drawn and no other islands for improving the network of tide stations. This lack emphasizes the desirability of frequent sections of subsurface observations between Cali-

TABLE 6.—Highly anomalous periods of sea level difference Honolulu-minus-San Francisco, 1905-69, identified by current index magnitude greater than 10 cm for at least two consecutive months.

Difference[1]										
1. Sign of anomaly	Negative	Positive	Negative	Positive	Negative	Positive	Positive	Negative	Positive	Negative
2. No. of months, magnitude of anomaly >10 cm	4, (1)[2]	3	7	9, (3)	3	2, (2)	2	6	2	4
3. Dates, magnitude of anomaly >10 cm	Mar.-June 1911 (Oct. 1911)	July-Sept. 1915	May-Nov. 1918	Jan.-Sept. 1920 (Feb.-Apr. 1921)	Jan.-Mar. 1941	Sept.-Oct. 1943 (Jan.-Feb. 1944)	Dec. 1948-Jan. 1949	Oct. 1957-Apr. 1958	May-June 1959	Apr. 1967-July 1967
4 .Largest anomaly, cm	−12.8	+12.9	−14.6	+17.7, (+13.7)	−13.6	+11.2 (+11.2)	+10.9	−14.7	+10.3	−16.1
5. Total months duration, anomaly of same sign	22	23	11	80	23	32	8	18	19	45
6. Inclusive dates for 5	Jan. 1911-Oct. 1912	May 1915-Mar. 1917	Mar. 1918-Jan. 1919	Feb. 1919-Oct. 1925[3]	Oct. 1940-Aug. 1942[4]	Sept. 1942-May 1945	Oct. 1948-May 1949	Apr. 1957-Sept. 1958	Oct. 1958-Apr. 1960[5]	Sept. 1964-June 1968
Honolulu[1]										
7. Sign of anomaly	Negative	Positive	Negative	Positive	Positive	Positive	Positive	Negative	Positive	Negative
8. Largest anomaly, cm, during 3 above	−9.4	+13.1	−9.2	+16.6 (+11.0)	+5.0	+10.6 (+8.5)	+7.8	−7.6	+9.2	−12.4
9. Date of largest anomaly	May 1911	Aug. 1915	July 1918	July 1920, Mar. 1921	Mar. 1941	Sept. 1943, Jan. 1944	Jan. 1949	Nov. 1957	June 1959	May 1967
San Francisco[1]										
10. Sign of anomaly	Positive	Positive	Positive	Negative	Positive	Negative	Negative	Positive	Negative	Positive
11. Largest anomaly, cm, during 3 above	+4.6	+0.4	8.6	−4.2, (−2.7)	+17.7	0, −3.3	−3.8	+10.0	−1.6	+3.7
12. Date of largest anomaly	Mar. 1911	Sept. 1915	Oct. 1918	Mar. 1920, Mar. 1921	Feb. 1941	Sept. 1943, Feb. 1944	Dec. 1948	Feb. 1958	May 1959	May 1967

[1] All data refer to the smoothed anomalies depicted in Figure 6.

[2] ( ) secondary maximum or minimum in the same period.

[3] Ignores −0.4 cm in October 1923.

[4] Ignores +0.9 in June 1941.

[5] Ignores −0.3 cm in November 1959.

fornia and Hawaii. One would like information on the strength of the California Current, on the role of upwelling in the variations of the current, about the movement of the boundary or transition zone between the central water mass and the waters of the California Current, and about the interconnection between the California Current and the North Equatorial Current. The large changes in sea level at Honolulu as compared to San Francisco during periods of strong anomalies in the sea level difference (Table 6) raise the question as to how the California Current may vary in strength or width in relation to changes in the central water mass and position of the eastern North Pacific anticyclonic current gyre. Such environmental information has important applications for advisory services and forecasting for fisheries along the west coast of the United States.

One consequence of the preliminary work with sea level differences (Saur, 1966) mentioned earlier was the start of a pilot program of expendable bathythermograph observations between Honolulu and San Francisco aboard a merchant ship (Saur and Stewart, 1967) in June 1966, which continued at a frequency of up to 20 sections per year through 1970. Although the period of observation is very short as compared to the sea level records, it is hoped that the analysis of these observations can better define conditions related to the anomalous weak circulation in 1967 inferred from the sea level records, and shed light on the more specific problems mentioned above.

ACKNOWLEDGMENTS

It is a pleasure to submit this contribution honoring Dr. O. E. Sette, a great scientist, associate for many years, and friend. This exploratory investigation of sea level differences is one outgrowth of many stimulating discussions with him on environmental variability and its implications to fisheries.

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APPENDIX TABLE 1.—Honolulu-minus-San Francisco, 1905-69. Monthly sea level difference (linear trend removed and adjusted to normal atmospheric pressure at each station) in centimeters. The long-term mean difference for all months and years has been adjusted to 58 cm, as explained in text, by reference to 0/1,000 db geopotential heights.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1905	46.7	39.5	48.6	54.7	59.6	58.2	51.5	54.8	58.6	54.9	45.9	45.2
1906	43.8	44.1	42.1	52.9	(57.3)[1]	59.2	56.6	56.3	65.9	66.6	69.4	58.1
1907	50.2	47.1	42.3	46.8	60.5	61.5	59.6	59.6	58.9	59.0	59.4	55.1
1908	51.5	57.6	61.5	62.8	75.1	72.0	61.1	61.5	60.2	62.8	56.9	54.8
1909	38.4	39.9	56.0	59.6	53.7	51.3	56.6	54.2	50.7	49.7	52.4	41.9
1910	41.8	48.8	43.0	58.0	59.4	56.6	57.3	61.8	67.2	71.4	65.4	54.7
1911	48.0	44.7	42.6	49.7	49.2	48.5	51.7	54.7	49.3	48.0	50.4	47.6
1912	42.8	58.9	49.3	59.0	59.4	59.1	54.0	55.9	57.7	57.9	58.9	61.6
1913	52.8	55.9	66.5	62.7	65.4	64.1	60.6	52.4	54.0	59.4	56.8	55.0
1914	43.3	45.0	50.5	59.3	61.6	65.3	62.7	58.9	56.9	51.9	53.7	44.4
1915	47.2	45.7	58.2	59.9	58.2	69.2	74.2	75.5	70.4	66.5	59.2	63.6
1916	50.7	56.2	57.1	63.0	68.6	67.5	61.2	61.0	69.4	67.3	63.2	60.7
1917	55.3	57.5	60.7	51.2	62.0	66.5	64.3	64.8	61.3	63.7	62.3	57.7
1918	61.3	58.2	45.5	51.9	52.7	45.3	45.8	47.2	45.3	49.4	43.0	48.0
1919	48.5	53.2	56.9	64.3	61.4	61.6	59.8	62.2	68.4	66.8	67.3	62.8
1920	60.4	65.5	73.9	78.4	74.5	76.6	81.6	76.1	72.1	67.5	59.8	56.9
1921	53.4	68.0	68.7	76.6	69.6	68.6	59.1	65.2	67.0	59.1	62.9	57.6
1922	62.6	54.4	63.8	68.3	66.3	58.7	57.1	65.0	66.4	60.8	65.1	54.7
1923	56.3	52.3	66.9	58.8	65.1	63.2	62.2	65.6	61.0	60.8	53.3	60.5
1924	56.7	56.6	63.2	63.7	68.4	64.3	60.9	64.6	62.1	61.6	65.8	60.8
1925	63.0	56.3	55.5	63.7	62.5	64.1	64.0	65.3	61.3	62.8	58.7	51.1
1926	46.9	50.0	55.7	61.9	70.6	67.7	66.3	63.7	68.3	59.1	50.4	59.8
1927	51.0	45.4	59.3	57.3	62.5	57.1	64.7	65.5	66.9	57.5	52.6	50.5
1928	52.2	53.7	62.3	65.6	67.4	58.8	53.2	51.4	58.1	53.4	52.2	46.1
1929	49.3	55.6	58.2	56.2	60.2	59.9	57.4	60.7	58.1	62.0	56.5	58.4
1930	49.5	51.1	50.7	53.8	62.7	63.9	63.7	58.4	61.3	58.3	53.1	50.2
1931	55.7	54.8	66.2	66.5	64.3	63.0	62.8	59.8	61.0	66.5	66.4	58.9
1932	50.9	45.9	62.3	58.9	58.3	65.5	57.6	60.8	56.8	63.1	67.4	62.7
1933	58.5	59.6	60.7	68.1	71.6	64.1	61.2	61.0	64.6	67.4	62.0	57.0
1934	56.1	50.8	55.3	61.7	57.2	56.4	52.6	53.0	56.7	59.4	55.2	47.3
1935	44.2	50.8	54.7	64.6	65.0	60.1	56.0	61.6	64.4	61.4	65.3	53.7
1936	57.2	49.0	57.0	67.7	64.2	61.8	61.0	66.0	60.3	56.2	57.3	59.0
1937	58.3	48.3	46.3	65.4	59.2	55.6	52.0	60.9	60.4	65.0	56.6	42.6
1938	46.5	40.3	49.1	59.4	58.9	57.4	55.1	54.2	66.3	63.6	58.4	48.8
1939	50.7	63.1	68.0	70.3	69.2	64.5	67.7	59.1	49.7	50.5	49.5	54.6
1940	50.0	51.3	53.9	58.9	58.4	65.0	70.3	67.8	60.0	65.1	59.6	43.6
1941	39.1	38.2	43.1	56.0	62.1	67.6	51.5	59.5	55.6	51.8	50.6	47.3
1942	49.0	51.2	61.2	54.0	58.1	60.2	56.3	61.6	61.2	68.2	64.3	64.4
1943	51.1	53.7	67.7	70.2	62.3	58.9	62.2	74.7	71.4	70.4	66.1	62.3
1944	63.0	64.3	65.6	69.5	61.2	65.4	63.6	67.0	62.3	63.2	59.1	53.2
1945	59.0	59.2	65.3	67.1	64.4	58.5	54.7	55.8	55.6	54.2	58.7	52.4
1946	55.6	58.5	68.7	65.4	60.3	64.1	60.3	64.3	62.6	60.0	55.5	54.5
1947	52.5	49.2	54.4	61.9	59.8	62.5	69.3	69.3	65.9	75.3	64.4	57.9
1948	51.9	56.2	57.5	48.3	54.4	54.2	55.1	55.6	57.4	65.9	64.1	63.0
1949	66.7	57.7	61.6	64.4	63.8	55.5	58.8	60.3	56.5	61.6	57.5	55.7
1950	54.5	58.9	66.5	65.9	65.0	58.3	57.3	63.6	63.0	61.8	56.0	49.9
1951	51.3	49.4	54.8	57.0	57.3	54.5	55.0	60.2	59.1	59.7	53.7	45.2
1952	37.0	53.3	61.5	61.3	63.4	57.4	56.3	60.7	61.0	59.6	56.5	49.5
1953	41.8	57.3	60.6	60.7	64.2	61.7	62.0	69.8	58.6	61.8	57.4	59.5
1954	50.6	54.4	51.6	59.1	59.9	58.7	60.4	63.5	69.7	69.4	63.0	55.7
1955	52.1	57.2	56.5	57.1	56.6	44.0	51.6	55.8	62.2	66.9	62.9	41.3
1956	34.5	43.9	55.9	57.7	55.8	58.2	52.5	57.1	62.0	61.7	61.2	61.0
1957	58.2	54.1	60.2	59.5	53.6	57.1	54.9	57.5	50.3	46.6	44.8	39.7
1958	37.6	33.3	47.9	47.8	54.6	53.5	60.5	55.7	59.6	61.2	64.2	53.4
1959	50.8	50.7	66.7	65.4	72.5	75.2	62.9	68.1	65.0	58.6	56.2	56.7
1960	50.3	55.2	57.0	62.9	62.0	56.9	55.8	58.0	54.4	61.3	58.3	53.5
1961	49.9	53.3	58.8	65.6	66.2	68.4	69.9	68.7	70.3	69.3	55.8	50.8
1962	59.9	56.7	63.2	70.2	66.6	65.8	61.4	57.2	56.7	46.9	56.9	53.5
1963	50.8	43.7	59.7	51.8	59.9	59.4	55.9	65.1	61.8	61.0	54.7	46.2
1964	45.5	55.1	65.1	69.0	63.2	62.7	73.8	61.9	59.2	(57.6)[1]	53.2	51.1
1965	42.3	45.9	52.9	45.9	58.6	54.7	60.2	54.0	51.5	55.7	52.2	47.0
1966	46.4	50.6	59.0	54.0	52.8	56.3	59.1	61.5	60.6	56.6	51.8	51.3
1967	45.5	51.0	46.1	44.2	45.6	46.2	45.8	52.5	56.0	59.3	54.1	54.9
1968	48.7	45.4	50.9	50.7	53.9	56.8	61.1	65.3	62.6	63.7	62.3	55.6
1969	44.3	42.1	57.3	58.0	64.8	66.4	63.3	59.5	60.9	57.2	49.8	43.5
N	65	65	65	65	64	65	65	65	65	64	65	65
MEAN	50.6	51.9	57.4	60.3	61.7	60.6	59.6	61.1	60.8	60.7	57.8	53.5

[1] Missing value was estimated by interpolation of anomalies.

APPENDIX TABLE 2.—Hilo-minus-Avila, 1947-59 and 1961-67. Monthly sea level difference (linear trend removed and adjusted to normal atmospheric pressure at each station) in centimeters. The long-term mean difference for all months and years has been adjusted to 52 cm, as explained in text, by reference to 0/1,000 db geopotential heights.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1947	42.4	40.0	50.9	58.1	58.8	53.7	62.2	57.3	59.5	57.1	52.0	54.1
1948	40.8	47.9	48.5	56.0	56.7	49.2	54.4	54.9	48.7	57.2	53.6	55.9
1949	45.9	47.1	62.5	61.8	59.9	52.8	50.4	57.6	54.2	55.2	47.7	45.7
1950	46.5	48.6	60.9	63.2	55.8	54.1	46.3	51.6	51.7	54.8	56.1	55.1
1951	52.0	52.1	51.5	56.1	47.4	49.8	50.3	54.5	52.0	47.0	49.1	43.1
1952	35.7	49.2	48.3	49.7	52.6	54.3	54.2	57.5	57.4	52.7	58.8	52.1
1953	49.0	51.2	46.3	56.8	56.6	53.5	52.8	52.8	48.3	55.5	50.1	45.7
1954	47.5	44.7	48.7	55.1	51.0	58.6	53.8	54.4	61.2	55.7	54.2	45.4
1955	44.8	52.3	48.7	54.4	52.9	43.6	48.7	52.6	49.0	48.4	47.7	42.6
1956	45.0	48.8	52.7	66.2	58.9	49.4	53.4	52.3	49.8	53.1	50.0	48.3
1957	52.0	52.7	59.1	56.5	52.6	49.2	42.9	40.7	47.2	48.0	37.2	35.7
1958	40.7	47.0	54.9	59.5	53.9	58.4	53.2	50.4	49.7	48.4	49.5	46.1
1959	43.6	44.3	60.2	58.0	61.3	61.5	53.5	58.3	52.0	47.5	43.6	45.7
1960	--	--	--	--	--	--	--	--	--	--	--	--
1961	45.5	52.1	63.3	56.6	73.6	71.3	63.9	59.0	66.6	56.0	51.4	41.8
1962	50.4	46.6	58.7	65.4	53.0	48.9	47.4	46.6	46.3	44.8	49.2	43.3
1963	(39.5)[1]	38.3	43.8	49.4	55.9	57.5	53.8	60.3	55.5	53.6	47.0	40.7
1964	45.0	47.8	53.1	61.9	54.9	53.1	62.8	51.0	57.3	55.8	51.1	54.3
1965	47.9	38.8	42.8	40.9	55.7	52.6	52.0	51.7	39.1	48.0	51.1	43.1
1966	51.6	50.7	59.8	50.1	47.5	58.6	55.1	57.4	62.0	59.5	56.9	49.4
1967	47.8	50.8	51.5	56.1	54.4	47.9	53.9	57.1	53.0	59.3	54.5	51.2
N	19	20	20	20	20	20	20	20	20	20	20	20
MEAN	46.0	47.6	53.3	56.6	55.7	53.9	53.3	53.9	53.0	52.7	50.5	47.0

[1] Missing value was estimated by interpolation of anomalies.