U. S. DEPARTMENT OF COMMERCE
Sinclair Weeks, Secretary

COAST AND GEODETIC SURVEY
H. Arnold Karo, Director

Recent Increases in Coastal Water Temperature and Sea Level—California to Alaska

H. B. STEWART, Jr., B. D. ZETLER, and C. B. TAYLOR

TECHNICAL BULLETIN NO. 3
May 1958

UNITED STATES GOVERNMENT PRINTING OFFICE WASHINGTON: 1958

For sale by the Superintendent of Documents, U. S. Government Printing Office,
Washington 25, D. C. - Price 20 cents

Technical Bulletin Series

This series of Technical Bulletins is inaugurated to present to the personnel of the Coast and Geodetic Survey and to others the results of research and development in the various fields of the Bureau's activities. It is designed for quick publication and dissemination, and supersedes The Journal of the Coast and Geodetic Survey, the last issue of which was published in October 1957. Since many of the bulletins will deal with new practices and new techniques, the views expressed will be those of the authors and will not necessarily represent final Bureau policy.

Technical Bulletin No. 3 documents the recent increases in sea water temperature and sea level on our west coast with data from Coast and Geodetic Survey tide stations, presents the results of analyses so that they will be available to others working on the problem, and suggests that the increases result from changes in the wind pattern over the eastern North Pacific.

COAST AND GEODETIC SURVEY TECHNICAL BULLETINS

No. 1. Aerotriangulation Adjustment of Instrument Data by Computational Methods. William D. Harris, January 1958 ..... Price $0.05

No. 2. Tellurometer Traverse Surveys. Lieutenant Hal P. Demuth, March 1958 ..... Price $0.15

Coast and Geodetic Survey Technical Bulletins are available from the Superintendent of Documents, Government Printing Office, Washington 25, D. C.

Recent Increases in Coastal Water Temperature and Sea Level—California to Alaska

H. B. STEWART, Jr., B. D. ZETLER, and C. B. TAYLOR, Oceanographers

U. S. Coast and Geodetic Survey

DURING the summer of 1957 wide public interest was attracted by reports of abnormally high water temperatures off the west coast of the United States, Canada, and southeast Alaska. The sport fishing boats operating out of California ports returned with record catches of yellowtail and bonito, and the live-bait fishery reported a northerly extension of the sardine spawning grounds. Probably these were reflections of this same warmer water. In December of 1957, the agencies participating in the California Cooperative Oceanic Fisheries Investigations (CCOFI) issued a preliminary report[1] focusing

Dr. Stewart is Assistant to the Chief, Tides and Currents Division, Mr. Zetler and Mr. Taylor are Chief and Assistant Chief, respectively, of the Currents and Oceanography Branch, Tides and Currents Division.

[1] 1957: The year of warm weather and southern fish, Prelim. Rept. *Calif. Coop. Oceanic Fish. Investigations*, Dec. 19, 1957.

FIG. 1.-Location of stations.

attention on the problem. Although the west coast water temperature observations by the Coast and Geodetic Survey did show values above normal for most of 1957, the anomaly was significantly larger in the last 2 months of 1957 and the first 2 of 1958. Observed tides on the west coast during the same period were considerably higher than predicted, and preliminary investigations indicated that the changes in water temperature and sea level appeared approximately parallel. On the strength of these preliminary results, sea water temperature data and tidal records for the 15 months prior to April 1958 were analyzed for 10 Coast and Geodetic Survey tide stations from southern California to Alaska.

The purposes of this Technical Bulletin are (1) to report the results of these analyses, (2) to present the basic water temperature and sea level data so that other oceanographers concerned with this interesting problem may have them in a ready form, and (3) to suggest that both anomalies are directly related to a shift in the large-scale wind pattern over the eastern North Pacific.

DATA FROM TIDE STATIONS

The 10 tide stations chosen were those most exposed to open ocean conditions; hence, least influenced by the rapid and extreme environmental fluctuations often recorded inside shallow bays and estuaries. Their locations are shown in figure 1. The temperature data were obtained from thermometer readings made in a sample of water drawn by bucket from a foot or two below the surface. Observations were usually made once each weekday at whatever time the observer attended the tide gage, and it may be assumed that in the course of a month or a year the distribution of observations was fairly uniform over all phases of the tide. Sea level data were derived from

Table 1.—Monthly mean temperature and anomaly, La Jolla, Calif., to Sitka, Alaska January 1957—March 1958

(Temperature in degrees Fahrenheit)

	1957												1958		
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.
La Jolla obs	58.6	57.8	58.6	59.5	62.2	66.8	69.6	70.8	66.5	64.6	62.2	61.7	60.9	60.8	59.6
Mean (39 yr.)	57.1	56.9	57.9	59.6	62.7	65.4	68.1	69.3	66.6	64.2	61.2	58.8	57.1	56.9	57.9
Anomaly	+1.5	+0.9	+0.7	- 0.1	- 0.5	+1.4	+1.5	+1.5	- 0.1	+0.4	+1.0	+2.9	+3.8	+3.9	+1.7
Los Angeles obs	58.0	57.8	59.2	58.9	60.2	66.4	69.0	70.2	66.1	65.6	62.6	60.7	60.0	61.1	60.4
Mean (32 yr.)	56.4	56.9	57.9	59.1	61.0	63.6	65.7	66.8	65.4	63.8	61.0	58.3	56.4	56.9	57.9
Anomaly	+1.6	+ 0.9	+1.3	- 0.2	- 0.8	+ 2.8	+ 3.3	+3.4	+ 0.7	+ 1.8	+ 1.6	+ 2.4	+3.6	+4.2	+2.5
Santa Monica obs	57.5	57.1	56.8	57.4	60.5	67.2	69.6	70.3	65.9	64.4	61.8	60.3	60.1	60.9	59.0
Mean (10 yr.)	55.4	55.6	56.6	58.4	60.0	63.6	66.4	66.8	65.3	62.4	59.7	57.1	55.4	55.6	56.6
Anomaly	+2.1	+1.5	+0.2	- 1.0	+ 0.5	+3.6	+3.2	+3.5	+0.6	+2.0	+2.1	+3.2	+ 4.7	+5.3	+2.4
Port Hueneme obs	56.1	55.4	54.3	56.5	58.1	61.9	65.3	64.0	61.9	62.2	61.0	60.3	60.1	60.0	57.7
Mean (36 yr.)	56.1	55.7	55.9	55.9	56.9	58.8	60.8	62.1	62.1	61.2	59.5	57.7	56.1	55.7	55.9
Anomaly	0.0	- 0.3	- 1.6	+0.6	+1.2	+3.1	+4.5	+1.9	- 0.2	+ 1.0	+1.5	+2.6	+4.0	+4.3	+1.8
Avila Beach obs	53.5	53.2	51.6	52.6	55.9	55.9	59.5	59.2	....	....	57.0	56.4	55.1	56.3	55.9
Mean (11 yr.)	53.1	52.9	53.0	53.5	54.3	56.2	58.5	59.2	59.0	57.3	55.9	54.2	53.1	52.9	53.0
Anomaly	+0.4	+0.3	- 1.4	- 0.9	+1.6	-0.3	+1.0	0.0	....	....	+1.1	+2.2	+2.0	+3.4	+2.9
San Francisco obs	49.1	50.0	53.5	53.8	57.1	56.6	58.8	57.5	58.1	60.7	55.8	51.7	52.7	54.2	52.7
Mean (34 yr.)	50.9	51.7	53.2	54.4	55.7	57.4	58.9	59.7	60.3	59.0	55.7	52.6	50.9	51.7	53.2
Anomaly	- 1.8	- 1.7	+0.3	- 0.6	+1.4	- 0.8	- 0.1	- 2.2	- 2.2	+1.7	+0.1	- 0.9	+1.8	+2.5	- 0.5
Crescent City obs	46.4	48.9	51.3	52.9	54.3	58.4	58.6	59.5	60.5	52.6	51.1	51.9	51.9	51.6	52.7
Mean (19 yr.)	49.7	49.9	50.2	51.2	52.6	53.9	55.9	57.0	55.9	53.7	51.7	50.5	49.7	49.9	50.2
Anomaly	- 3.3	- 1.0	+1.1	+1.7	+1.7	+4.5	+2.7	+2.5	+4.6	- 1.1	- 0.6	+1.4	+2.2	+1.7	+2.5
Neah Bay obs	42.4	42.5	45.8	48.8	52.8	53.4	52.5	54.3	52.1	53.0	50.9	49.1	48.2	49.5	49.7
Mean (20 yr.)	45.3	45.1	46.2	48.5	51.1	52.9	53.2	52.7	52.2	51.1	49.1	47.0	45.3	45.1	46.2
Anomaly	- 2.9	- 2.6	-0.4	+0.3	+1.7	+0.5	-0.7	+1.6	- 0.1	+1.9	+1.8	+2.1	+2.9	+4.4	+3.5
Ketchikan obs	39.9	41.0	41.1	42.5	47.2	54.1	56.2	58.0	55.8	49.2	45.7	42.6	42.2	43.4	44.1
Mean (34 yr.)	41.3	41.0	41.7	43.6	48.3	54.3	56.9	57.2	53.8	49.0	44.8	42.3	41.3	41.0	41.7
Anomaly	-1.4	0.0	-0.6	-1.1	- 1.1	- 0.2	- 0.7	+0.8	+2.0	+0.2	+0.9	+0.3	+0.9	+2.4	+2.4
Sitka obs	39.1	38.3	39.6	42.8	47.7	52.4	56.5	59.5	57.3	51.1	47.4	44.7	43.8	42.5	42.2
Mean (14 yr.)	40.2	39.6	39.8	42.2	47.5	52.0	55.8	56.8	53.5	48.7	44.6	42.0	40.2	39.6	39.8
Anomaly	-1.1	-1.3	- 0.2	+0.6	+0.2	+0.4	+0.7	+2.7	+3.8	+2.4	+2.8	+2.7	+3.6	+2.9	+2.4

marigrams obtained from continuously recording tide gages.

ANALYSES

Daily temperature observations at each station were averaged to obtain the monthly mean. Similar monthly temperature data, plus yearly means, extremes, and long-term means, for these and the other west coast stations through 1955 are available.[2] For the 10 stations under consideration, table 1 presents the mean sea water temperatures from January 1957 through March 1958, the monthly mean sea water temperatures for the period of record through 1955, and the deviations of the 1957 and 1958 values from these long-term monthly means. The long-term monthly means are used as the normal temperatures for the month, and the deviations are called the monthly anomalies.

Hourly tidal heights were tabulated from each marigram and averaged to give monthly sea level at each station. These monthly sea levels for the period from January 1957 through March 1958 together with the 19-year mean sea level (where available) for each month at each station and the corresponding monthly sea level anomalies are listed in table 2. In view of the gradual rise in sea level, which Disney[3] has shown to average 0.005 foot per year on the west coast, monthly sea levels in 1957 and 1958 would under normal conditions be 0.05 foot higher than during the median year 1947 of the 19-year (1938-1956) means shown in table 2.

[2]Surface water temperatures at tide stations, Pacific Coast North and South America and Pacific Ocean Islands, Coast and Geodetic Survey. Spec. Pub. 280, *U. S. Govt. Print. Off.* 1956.

[3]Tide heights along the coasts of the United States by L. P. Disney, *Proc. American Society of Civil Engineers*, Vol. 81, Separate 666, 1955.

Table 2.—Monthly sea level and anomaly, La Jolla, Calif., to Sitka, Alaska January 1957—March 1958

(Heights are in feet above original staff zero)

	1957												1958		
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.
La Jolla obs	6.70	6.71	6.56	6.62	6.74	6.97	7.12	7.22	7.14	7.14	7.10	7.19	7.06	6.90	6.83
Mean (18 yr.)	6.67	6.61	6.53	6.49	6.55	6.68	6.84	6.93	7.01	6.89	6.83	6.78	6.67	6.61	6.53
Anomaly	+0.03	+0.10	+0.03	+0.13	+0.19	+0.29	+0.28	+0.29	+0.13	+0.25	+0.27	+0.41	+0.39	+0.29	+0.30
Los Angeles obs	6.46	6.48	6.29	6.30	6.48	6.70	6.86	6.93	6.77	6.83	6.82	6.88	6.75	6.64	6.59
Mean (19 yr.)	6.49	6.42	6.33	6.28	6.35	6.50	6.64	6.69	6.78	6.66	6.61	6.57	6.49	6.42	6.33
Anomaly	-0.03	+0.06	-0.04	+0.02	+0.13	+0.20	+0.22	+0.24	-0.01	+0.17	+0.21	+0.31	+0.26	+0.22	+0.26
Santa Monica obs	5.10	5.12	4.84	4.88	5.06	5.28	5.43	5.48	5.42	5.36	5.41	5.50	5.38	5.30	5.23
Mean (19 yr.)	4.97	4.92	4.86	4.82	4.89	5.04	5.19	5.24	5.30	5.17	5.10	5.06	4.97	4.92	4.86
Anomaly	+0.13	+0.20	-0.02	+0.06	+0.17	+0.24	+0.24	+0.24	+0.12	+0.19	+0.31	+0.44	+0.41	+0.38	+0.37
Port Hueneme obs	6.11	6.10	5.87	6.01	6.11	6.35	6.50	6.55	6.49	6.51	6.49	6.56	6.47	6.39	.....
Mean (16 yr.)	5.96	5.92	5.83	5.78	5.84	5.98	6.11	6.17	6.25	6.15	6.09	6.05	5.96	5.92	5.83
Anomaly	+0.15	+0.18	+0.04	+0.23	+0.27	+0.37	+0.39	+0.38	+0.24	+0.36	+0.40	+0.51	+0.51	+0.47	.....
Avila Beach obs	5.83	5.81	5.62	5.67	5.82	5.95	6.14	6.17	.....	.....	6.06	6.14	5.91	5.80	5.83
Mean (11 yr.)	5.72	5.65	5.55	5.53	5.61	5.70	5.84	5.83	5.94	5.84	5.80	5.76	5.72	5.65	5.55
Anomaly	+0.11	+0.16	+0.07	+0.14	+0.21	+0.25	+0.30	+0.34	.....	.....	+0.26	+0.38	+0.19	+0.15	+0.28
San Francisco obs	8.80	8.91	8.70	8.70	8.93	8.86	9.03	8.97	9.15	9.13	9.01	9.09	9.12	9.56	9.22
Mean (19 yr.)	8.86	8.81	8.68	8.57	8.61	8.70	8.80	8.81	8.90	8.79	8.78	8.86	8.86	8.81	8.68
Anomaly	-0.06	+0.10	+0.02	+0.13	+0.32	+0.16	+0.23	+0.16	+0.25	+0.34	+0.23	+0.23	+0.26	+0.75	+0.54
Crescent City obs	7.40	7.63	7.52	7.14	7.48	7.19	7.40	7.42	7.61	7.78	7.62	7.88	8.16	8.54	7.73
Mean (17 yr.)	7.81	7.69	7.47	7.31	7.26	7.25	7.38	7.43	7.53	7.48	7.62	7.84	7.81	7.69	7.47
Anomaly	-0.41	-0.06	+0.05	-0.17	+0.22	-0.06	+0.02	-0.01	+0.08	+0.30	0.00	+0.04	+0.35	+0.85	+0.26
Neah Bay obs	6.46	6.62	6.78	6.32	6.47	6.15	6.27	6.34	6.45	6.68	6.64	....	.....	7.68	6.85
Mean (18 yr.)	7.01	6.86	6.66	6.42	6.25	6.20	6.18	6.20	6.32	6.57	6.83	7.04	7.01	6.86	6.66
Anomaly	-0.55	-0.24	+0.12	-0.10	+0.22	-0.05	+0.09	+0.14	+0.13	+0.11	-0.19	.....	.....	+0.82	+0.19
Ketchikan obs	13.79	13.96	14.19	13.85	14.02	14.15	14.21	14.12	14.06	14.20	14.53	15.08	15.19	15.06	14.17
Mean (19 yr.)	14.57	14.37	14.20	14.08	13.95	14.00	14.01	13.96	14.11	14.53	14.67	14.74	14.57	14.37	14.20
Anomaly	-0.78	-0.41	-0.01	-0.23	+0.07	+0.15	+0.20	+0.16	-0.05	-0.33	-0.14	+0.34	+0.62	+0.69	-0.03
Sitka obs	9.45	9.76	9.96	9.62	9.75	9.77	9.82	9.83	9.91	10.02	10.37	10.76	10.88	10.79	9.85
Mean (19 yr.)	10.45	10.23	10.08	9.94	9.79	9.78	9.78	9.80	9.98	10.39	10.49	10.58	10.45	10.23	10.08
Anomaly	-1.00	-0.47	-0.12	-0.32	-0.04	-0.01	+0.04	+0.03	-0.07	-0.37	-0.12	+0.18	+0.43	+0.56	-0.23

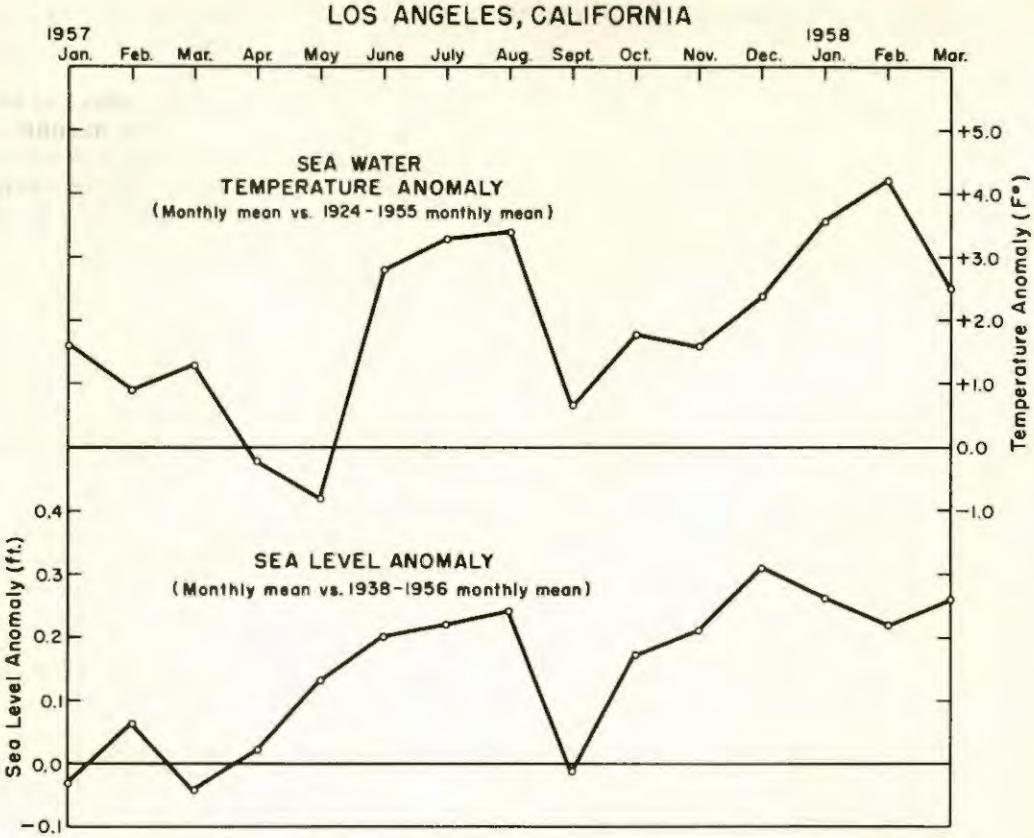

FIG. 2.-Monthly sea water temperature and sea level anomalies, January 1957 through March 1958 at Los Angeles (outer harbor), California.

The results discussed below cannot be considered as seasonal variations in temperature and sea level, for seasonal variations are determined by studying monthly departures from the annual mean. Essentially such variations have been eliminated during the analyses by dealing only with the departure of specific months from the long-term monthly mean.

RESULTS

The monthly anomalies in sea water temperature and sea level at 5 stations from Los Angeles to Sitka in tables 1 and 2 are presented graphically in figures 2 through 6. The anomalies at all 10 stations were averaged by months to present a somewhat generalized picture of the coast as a whole from January 1957 through March 1958. These averages are given in table 3. The outstanding feature of figures 2-6 is the general parallelism of the variations in temperature and sea level anomalies, with the southern stations showing a stronger correlation. This parallelism is even more pronounced in table 3 where differences due to location on the coast are averaged out. The general coastal picture shows that both water temperature and sea level were generally

Table 3.—Monthly averages of sea water temperature and sea level anomalies for ten stations from La Jolla, Calif., to Sitka, Alaska.

January 1957– March 1958

Month	Anomaly	
	Temperature	Sea level
	Degrees F.	*Feet*
1957		
January	-0.5	-0.24
February	-0.3	-0.04
March	-0.1	+0.01
April	-0.1	-0.01
May	+0.6	+0.18
June	+1.5	+0.15
July	+1.5	+0.20
August	+1.6	+0.20
September	+1.0	+0.09
October	+1.1	+0.11
November	+1.2	+0.12
December	+1.9	+0.32
1958		
January	+3.0	+0.38
February	+3.5	+0.52
March	+2.2	+0.22

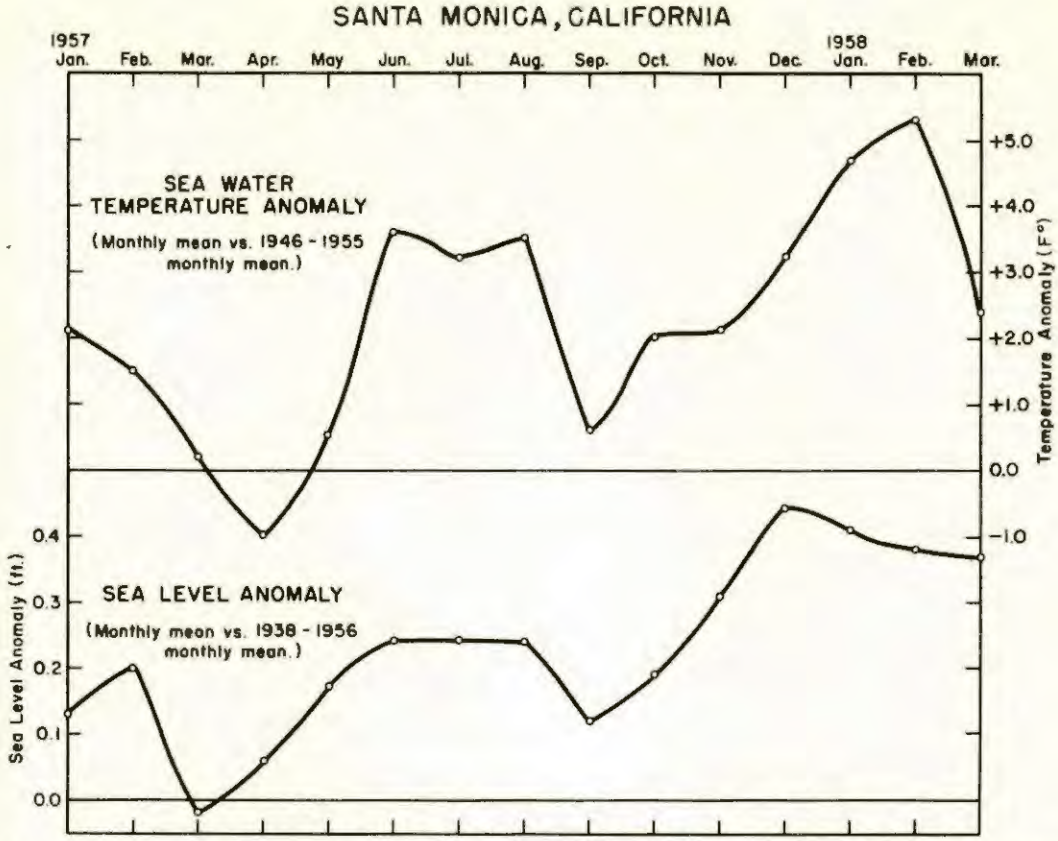

FIG. 3.-Monthly sea water temperature and sea level anomalies, January 1957 through March 1958 at Santa Monica, California.

below normal for the first 4 months of 1957. They rose above normal during May, were high during the summer, and dropped off during September. Values above normal remained relatively constant or increased slightly during October and November. Both anomalies rose rapidly in December, reaching new highs for the year. The sharp rise continued in January 1958; and, for the coast as a whole, the anomalies peaked at exceptionally high values in February before dropping off in March.

The unusual size of the January and February temperature anomalies is apparent when it is realized that during these 2 months, among the stations listed in table 1, 10 records were set for the highest monthly mean water temperature for the period of record. The highest temperature anomaly during the 15 months was recorded in February 1958 at Santa Monica where the monthly mean of 60.9°F was 5.3° above the February mean for the period of record. The highest sea level anomaly during the 15 months was also in February 1958 when sea level at Crescent City was 0.85 foot above the 19-year February mean.

DISCUSSION

The marked similarity of variations in the temperature and sea level anomalies along this coast where upwelling is known to exist suggests that the observed variations are related through the upwelling mechanism to its driving force--the wind. Wind blowing over a body of water in the northern hemisphere tends to generate a surface current moving at an angle approaching 45° to the right of the direction toward which the wind is blowing. Along the west coast of North America this mechanism has been shown by Sverdrup[4], Sverdrup and Fleming[5], and others to cause the upwelling of colder denser water from below to replace the warmer surface water blown seaward by the predominantly northerly winds. The seaward movement of the lighter surface water brings about a redistribution of mass resulting in a south-flowing geostrophic current that augments the lowered temperature by bringing in colder water from the north.

With long-term prevailing winds with a strong northerly component, the upwelling approaches a

[4]On the process of upwelling by H. U. Sverdrup, *Jour. Marine Research.* Vol. 1, pp. 155-164, 1938.

[5]The waters off the coast of southern California, March to July, 1937 by H. U. Sverdrup and R. H. Fleming, Bull. *Scripps Inst. Oceanography,* Univ. of Calif., Vol. 4, No. 10, pp. 261-378, 1941.

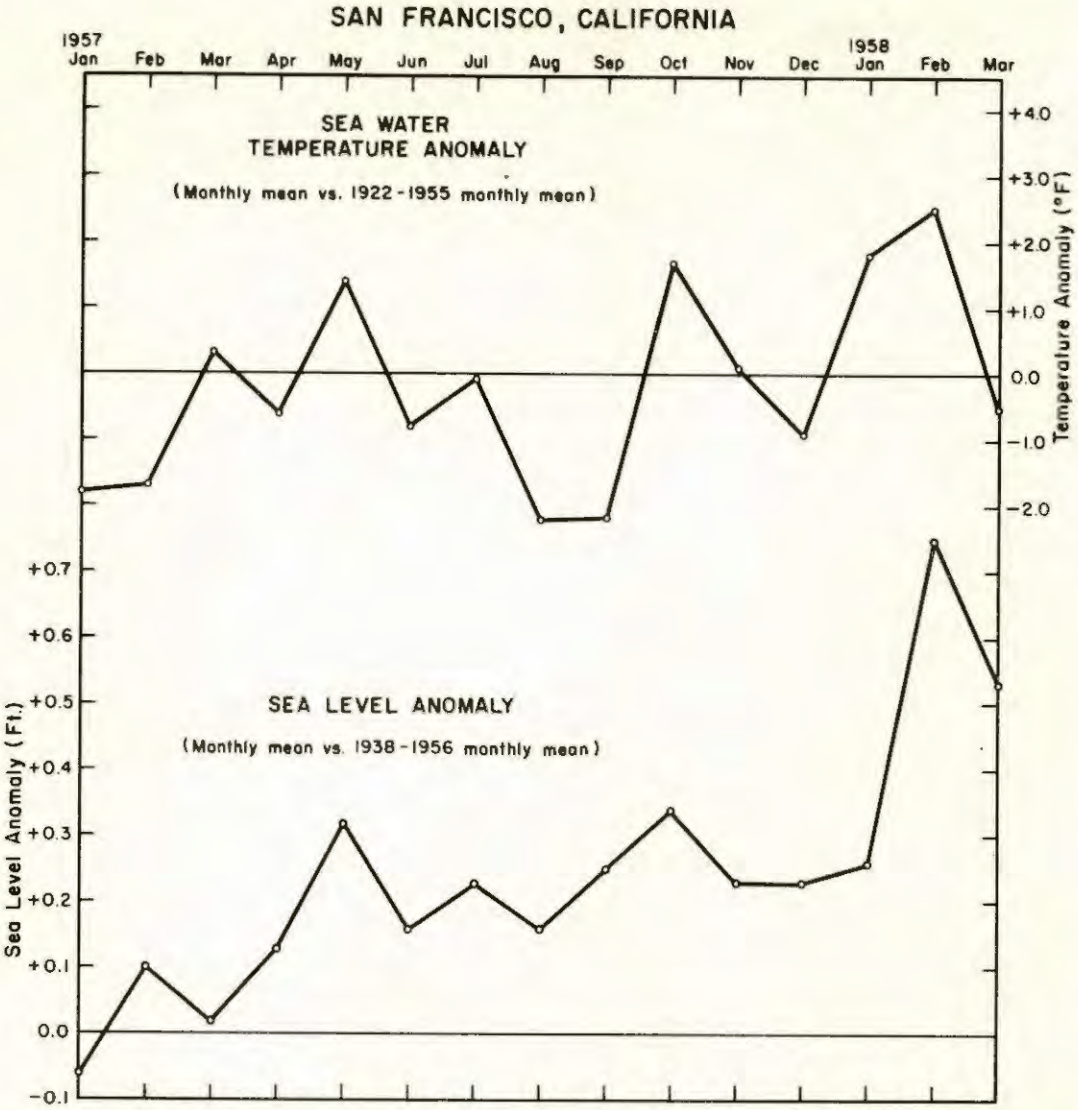

FIG. 4.–Monthly sea water temperature and sea level anomalies, January 1957 through March 1958 at San Francisco (Fort Point), California.

quasi-steady state involving a balance between the wind and the resultant offshore movement of surface water. Given such a condition, the writers hypothesize that sea level near the coast will be maintained at a level lower than that farther from shore. Therefore, the occurrence of a sudden increase in both water temperature and sea level along the coast must reflect the termination of the original steady state condition and the establishment of a new balance that *ipso facto* must be accompanied by a decrease in the northerly component of the wind. Therefore, the variations in the northerly component of the wind were examined. Using monthly mean sea level atmospheric pressure charts supplied by the Weather Bureau, monthly mean geostrophic winds (winds related to the pressure distribution) were computed for each month from January 1957 through March 1958 for three points off the west coast. These points were seaward of Avila Beach, Calif. (at 35°N., 125°W.), seaward of northern Oregon (at 45°N., 130°W.), and off Ketchikan, Alaska (at 55°N., 135°W.). The mean wind for each month at each of these locations was resolved into its north and east components, and the results are given in table 4. Along the coast from California to Washington, positive values in northerly and/or easterly wind components would tend to move water away from the coast; negative values indicating southerly and/or westerly winds would tend to move water toward the coast. In southeast Alaska, due to the orienta-

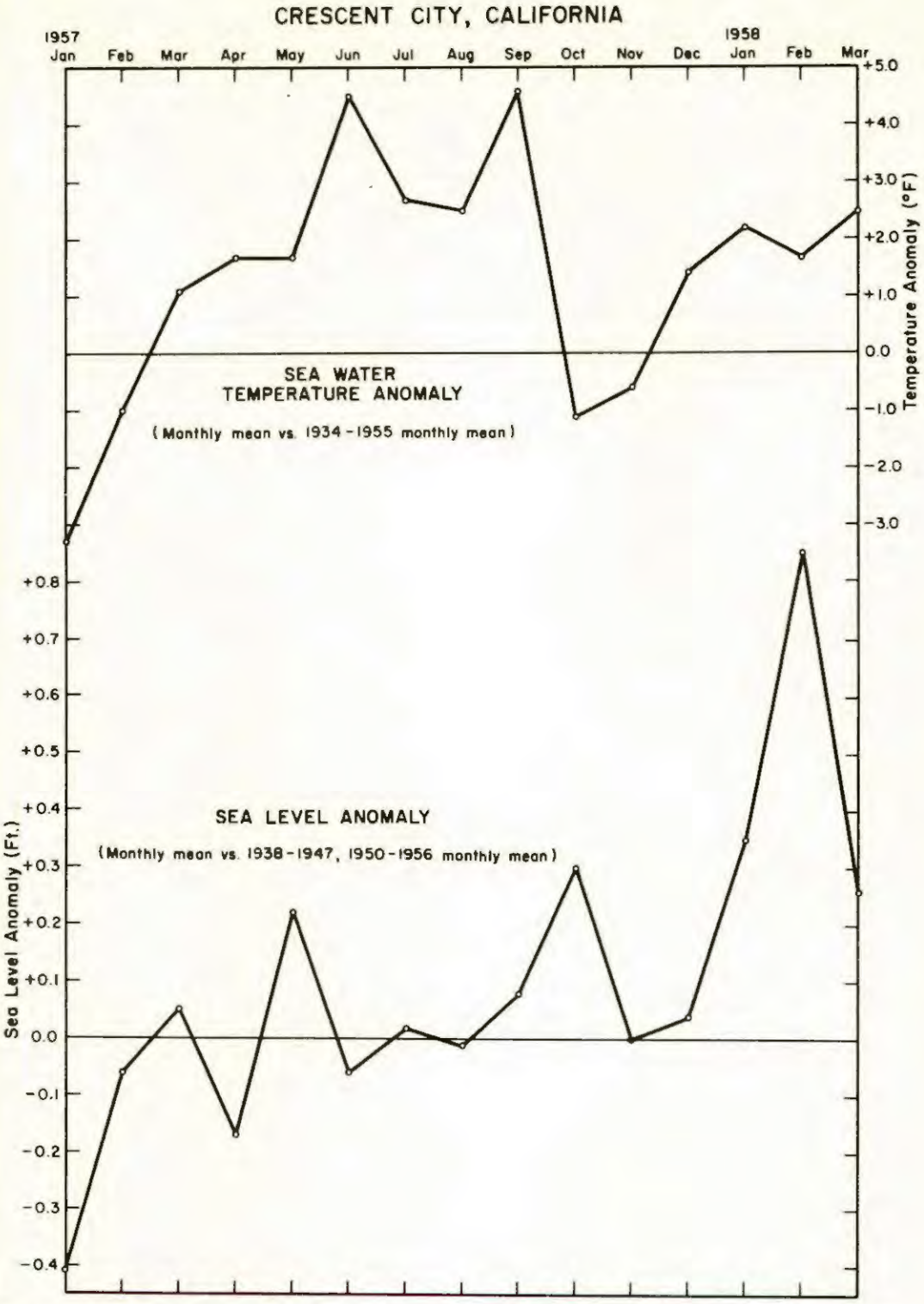

FIG. 5.–Monthly sea water temperature and sea level anomalies, January 1957 through March 1958 at Crescent City, California.

tion of the coastline, only the north component is significant, as east or west winds would move water essentially parallel to the coast.

In January and February 1958, the 2 months in which the high sea level and temperature anomalies were recorded, all three wind stations show

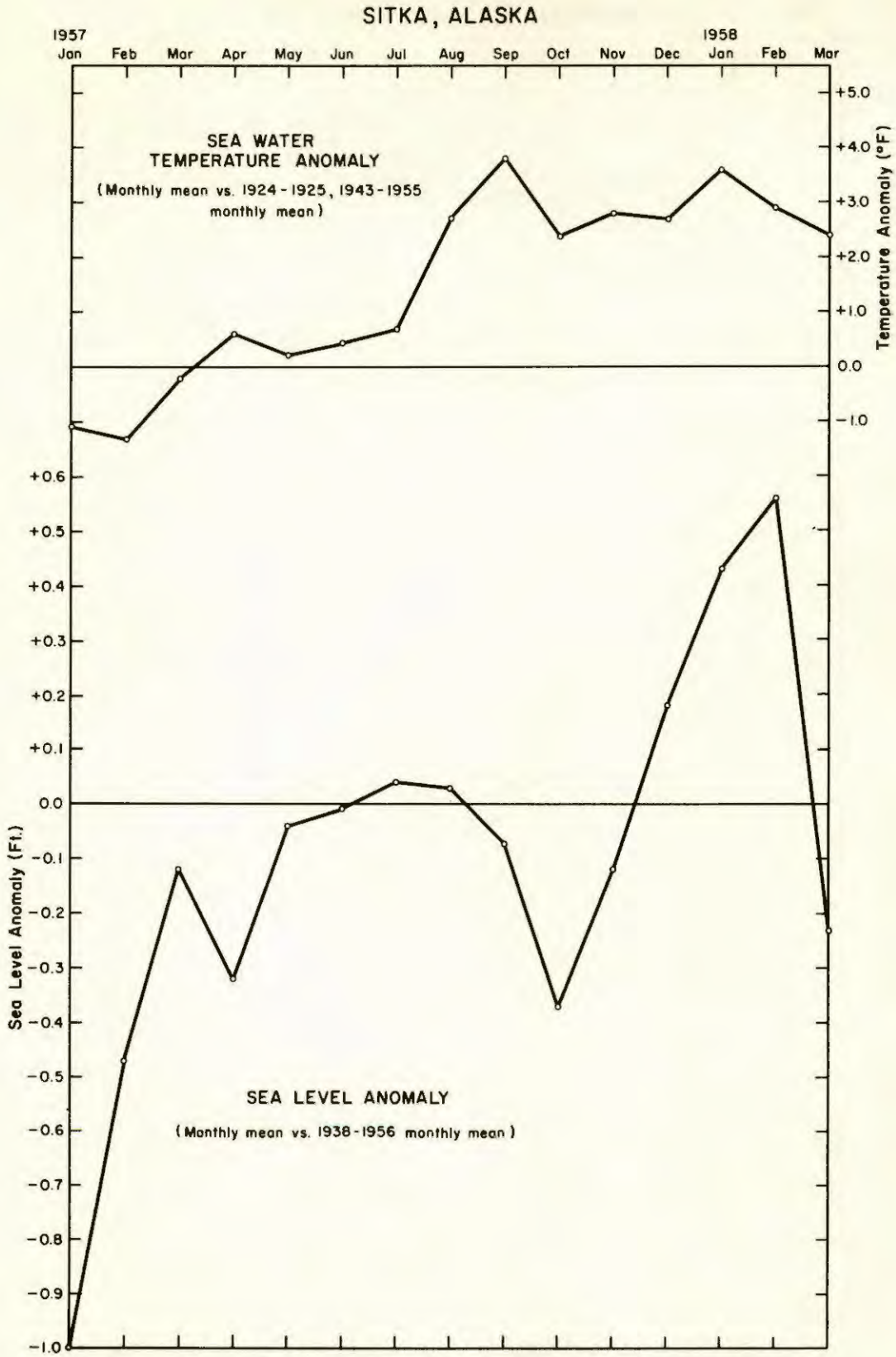

FIG. 6.-Monthly sea water temperature and sea level anomalies, January 1957 through March 1958 at Sitka, Alaska.

the lowest northerly (actually negative or strong southerly) components of the entire period. In addition, the two southernmost wind stations show strong westerly (negative easterly) components during this same period. These winds during January and February 1958 are believed to have diminished or terminated the more normal upwelling by upsetting the existing quasi-steady state condition. This not only resulted in a termination along the coast of the replenishment of colder water from below but also caused a spectacular rise in sea level. The larger range of sea level anomaly at the northern stations during January and February probably is due primarily to stronger onshore winds in this region, but may also be partly due to the configuration of the coast. Sitka and Ketchikan are both near the head of a broad indentation (Gulf of Alaska) and consequently are subject to maximum wind setup.

Similar dependence of variations in water temperature and sea level on variations in upwelling caused by changes in the wind pattern have been found along the east coast of Florida by Taylor and Stewart.[6] Variations in sea level resulting from variations in the wind pattern have been well documented by the studies of De Veaux[7], and Miller[8,9].

Some of the features shown in figures 2-6 can now be explained in terms of the hypothesis presented above. These figures show that the water temperature and sea level anomalies are more or less parallel, and this is brought out even more strikingly in the mean anomalies for the combined 10 stations (table 3). There are several reasons, however, why the correlation between the two, though good, is not the one-to-one correspondence that might be expected if both anomalies are related to the same cause as proposed above.

The progressively stronger correspondence between the two anomalies from north to south is in part a reflection of factors affecting only the temperature. For example, the amount of change in water temperature resulting from a given change in the degree of upwelling is directly related to the difference between the temperature of the upwelling water and the surface water. This difference depends partly on latitude, for the long-term mean surface water temperature decreases steadily from 61.2°F at Los Angeles to 46.9°F at Sitka. Assuming a relatively uniform temperature for the colder water at depth, the temperature differences between the surface and the upwelled water at southerly stations will be greater than at stations farther north. Furthermore, since there will be a seasonal variation in the temperature differences at each station, the response at all stations will be greater in summer than in winter. This may in part explain why correlations appear progressively stronger from north to south and also why, even for the southernmost stations, the fit is better in summer than in winter.

These variations in the range of temperature response refer only to times when upwelling--even though diminished--was taking place, the existing condition during most of 1957. However, in January and February 1958 a strong low pressure area moved into the eastern North Pacific bringing onshore winds over much of the area under consideration. This brought a sharp rise in sea level for all stations from San Francisco north. During this same period, a weak high pressure area off southern California reduced the wind effect in that area, so that the sea level anomaly at stations south of San Francisco--though still high--actually decreased slightly during January and February. The meteorological abnormality of these first 2 months of 1958 is discussed in detail by Teweles and Finger[10],

[6]Summer upwelling along the east coast of Florida by C. B. Taylor and H. B. Stewart, Jr., *Transactions, American Geophysical Union* (in press).

[7]Meteorological trend and the apparent rise in sea level along the South Carolina coast by E. J. De Veaux, *Monthly Weather Review*, Vol. 83, No. 10, pp. 217-224, 1955.

[8]The effect of seatdy winds on sea level at Atlantic City by A. R. Miller, *Meteorological Monographs*, Vol. 2, No. 10, pp. 24-31, 1957.

[9]The effects of winds on water levels on the New England Coast by A. R. Miller, *Limnology and Oceanography*, Vol. 3, No. 1, pp. 1-14, 1958.

[10]An abrupt change in stratospheric circulation beginning in mid-January 1958 by S. Teweles and F. G. Finger, *Monthly Weather Review*, Vol. 86, No. 1, pp. 23-28, 1958.

Table 4.—North and east components of the monthly mean geostrophic wind at three points off the west coast of North America.

January 1957--March 1958

Month	35° N., 125° W.		45° N., 130° W.		55 N., 135° W.	
	N	E	N	E	N	E
	Knots	*Knots*	*Knots*	*Knots*	*Knots*	*Knots*
1957						
January	(*)	(*)	+14	(*)	(*)	(*)
February	(*)	(*)	(*)	(*)	-7	(*)
March	+8	-8	-6	-6	-6	+6
April	+16	(*)	(*)	(*)	(*)	(*)
May	+12	-12	(*)	(*)	-6	+6
June	+22	(*)	(*)	-8	(*)	(*)
July	+20	-8	+7	(*)	(*)	-7
August	+19	-7	+7	(*)	(*)	(*)
September	+6	-6	(*)	(*)	-13	-5
October	+6	-6	(*)	(*)	(*)	(*)
November	+8	(*)	-6	-6	-8	-8
December	(*)	(*)	-8	-20	-15	+15
1958						
January	-6	-16	-21	-21	-23	+9
February	-13	-13	-18	-7	-23	+23
March	+6	-6	+9	(*)	-7	+17

(*) Less than 5 knots.

O'Connor[11], and Klein[12]. Presumably upwelling ceased completely during this period, and with the termination of the usual supply of cooler water from below, the water temperature anomaly rose all along the coast during January and February (table 1). The onshore movement of water, while increasing sea level, would not result in appreciable additional increases in temperature following the postupwelling increase, except for what might be a reflection of a very minor south to north geostrophic flow due to the accumulation of lighter surface waters at the coast. Thus the temperature response to a cessation of upwelling would not be so sharp as the sea level response, and this is shown clearly in the respective anomalies.

Although it appears that change in the atmospheric circulation is the predominant cause for the recent increases in both water temperature and sea level along the west coast, there are other contributing factors that should be considered. These are the effect on sea level of changes in the atmospheric pressure (barometric tides), the possibility that the increase in water temperature was caused hy an increase in air temperature or by solar heating, and the effect on sea level of changes in the density or specific volume of the water (steric tides).

The effects of variations in atmospheric pressure undoubtedly are reflected to some extent in the observed sea level values. However, as pointed out by LaFond[13], seasonal variations in atmospheric pressure at San Diego are relatively small, and year to year differences are even smaller. Thus any correction for the effect of atmospheric pressure would also be small. For the regions off California and off British Columbia, Pattullo et al.[14] show that "correcting" recorded monthly departures from annual sea level for atmospheric pressure effects results in a very small change in range, and the phase is actually changed, indicating a poor correlation between changes in recorded sea level and atmospheric pressure in this area. Since we are dealing here not with the seasonal variation in sea level, but only with the monthly anomaly, the effect of atmospheric pressure on sea level is felt to be relatively small.

Consideration must also be given to the possibility that the increase in water termperature might be related to an increase in the air temperature. The upper surface of the sea is seldom in thermal equilibrium with the bottom of the overlying atmosphere, and heat exchange across the interface attempts to reduce the thermal gradient. Table 5 shows the monthly anomalies

[11]The weather and circulation of January 1958, low index with record cold in southeastern United States by J. F. O'Connot, *Monthly Weather Review*, Vol. 86, No. 1, pp. 11-18, 1958.

[12]The weather and circulation of February 1958, a month with an expanded circumpolar vortex of record intensity by W. H. Klein, *Monthly Weather Review*, Vol. 86, No. 2, pp. 60-70, 1958.

[13]Variations of sea level on the Pacific Coast of the United States by E. C. LaFond, *Jour. Marine Research*, Vol. 2, No. 1, pp. 17-29, 1939.

[14]The seasonal oscillation in sea level by June Pattullo, W. Munk, R. Revelle, and E. Strong, *Jour. Marine Research*, Vol. 14, No. 1, pp. 88-155, 1955.

Table 5.—Monthly mean air temperature and anomaly at five west coast weather stations. Normal temperature is mean for period 1921-1950
January 1957—March 1958

(Temperature in degrees Fahrenheit)

	1957												1958		
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.
Los Angeles Airport obs.	53.9	59.1	59.9	60.1	63.2	69.5	72.3	72.7	69.0	66.2	60.1	60.8	59.3	60.2	57.9
Normal	53.2	54.1	56.5	59.2	62.1	64.7	67.6	68.2	66.7	63.4	59.3	55.6	53.2	54.1	56.5
Anomaly	+0.7	+5.0	+3.4	+0.9	+1.1	+4.8	+4.7	+4.5	+2.3	+2.8	+0.8	+5.2	+6.1	+6.1	+1.4
San Francisco Fed. Bldg. obs.	48.8	54.0	54.2	57.7	57.9	61.4	59.6	59.5	63.6	62.3	56.8	51.5	52.8	56.2	53.1
Normal	50.1	53.0	54.9	55.7	57.1	59.1	58.9	59.3	61.6	61.0	57.2	51.9	50.1	53.0	54.9
Anomaly	-1.3	+1.0	-0.7	+2.0	+0.8	+2.3	+0.7	+0.2	+2.0	+1.3	-0.4	-0.4	+2.7	+3.2	-1.8
Eureka, Calif., obs.	43.3	49.0	49.9	50.6	54.8	57.2	56.7	58.3	59.3	56.2	51.5	49.8	51.2	53.9	47.7
Normal	47.2	48.4	49.1	50.6	52.9	55.6	56.4	57.0	56.2	54.2	51.3	48.6	47.2	48.4	49.1
Anomaly	-3.9	+0.6	+0.8	0.0	+1.9	+1.6	+0.3	+1.3	+3.1	+2.0	+0.2	+1.2	+4.0	+5.5	-1.4
Annette, Alaska, obs.	29.7	32.7	39.3	42.9	50.2	53.2	55.9	59.1	57.7	47.7	42.8	36.6	41.1	40.0	40.6
Normal	34.6	36.1	38.1	42.6	49.0	54.1	56.7	58.0	53.2	46.9	41.0	36.2	34.6	36.1	38.1
Anomaly	-4.9	-3.4	+1.2	+0.3	+1.2	-0.9	-0.8	+1.1	+4.5	+0.8	+1.8	+0.4	+6.5	+3.9	+2.5
Sitka, Alaska, obs.	27.6	31.5	36.8	39.4	46.7	52.2	54.3	58.2	55.3	45.4	42.1	33.0			
Normal	33.3	34.5	36.7	41.0	46.7	52.1	55.1	56.2	52.4	46.0	39.4	34.3			
Anomaly	-5.7	-3.0	+0.1	-1.6	0.0	+0.1	-0.8	-2.0	+2.9	-0.6	+2.7	-1.3			

Data from U. S. Weather Bureau.

in air temperature at five coastal stations as computed from temperature records supplied by the Weather Bureau. This table shows that some increase in air temperature did occur during the times of increased water temperature. Of special significance are the air temperature anomalies for January and February 1958. The air temperature highest above normal for the entire 15-month period occurs during these 2 months at each of the four stations reporting, and the second highest anomalies occur in these same months at three of the four stations. Comparison of tables 1 and 5 shows that for the three weather stations north of San Francisco, water temperatures were higher than air temperatures for 33 of the 42-station-months reporting. Thus the occurrence of the warmer air temperatures is here interpreted as being the result rather than the cause of the warmer ocean waters. Solar heating undoubtedly heated the waters to some extent, but the CCOFI report, mentioned earlier, states that the warming of the waters offshore extended to depths of about 1,000 feet and that approximately 4 times more solar heat than the region actually received would have been needed to cause a change of this magnitude in the water temperature.

Steric oscillations in sea level are those due to changes in the specific volume of the water column. Given two water columns of equal mass, the one with lower density (greater specific volume) will stand at a higher level. Most of the variations in the density of sea water occur in the upper 500 feet, with the density decreasing (specific volume increasing) with increasing temperature and with decreasing salinity. Obviously temperature and salinity measurements for at least the upper few hundred feet are necessary in order to compute steric sea levels, and the present study is limited to surface data at coastal stations. However, LaFond[15] and Pattullo et al.[16] have shown that good agreement exists between seasonal variations in steric and recorded sea levels, but the largest portion of the steric change is related to temperature rather than to salinity changes. Furthermore, on examination of salinity anomalies at the same stations during the same period, little correlation was found between the salinity and either the sea level or the water temperature anomalies. Since the seasonal temperature variation has been removed by the analytical method used, it is only the ***anomaly*** in temperature that could affect the sea level anomaly by its effect on the specific volume. Even if it is assumed that water temperature changes recorded only at the surface reflect changes for the upper 500 feet, the sea level anomalies are too large to be accounted for primarily by steric change. For example, during February 1958 at Crescent City, the recorded temperature anomaly of +1.7°F would have had to extend over a mile in depth in order to account for the observed sea level anomaly of +0.85 foot as a purely steric rise. This is five times the depth to which warming actually occurred.[17] Furthermore, the observed increase in the sea level anomaly from south to north without an accompanying increase in the temperature anomaly militates against changes in the specific volume as the prime reason for the observed conditions.

Although 1957 appears to be somewhat of an exceptional year, Eber and Sette[18] state that the geostrophic winds as a whole during the preceding 10 years had an unusually strong north component. The CCOFI study[19] supports the same concept to the extent that the north component of the wind was reduced during 1957. This 10-year abnormality is found reflected in the water temperatures along the coast, for the averages for the period 1947-1956 are appreciably lower than for 1927-1936 or for 1937-1946.[20] Thus any return to the earlier conditions would appear to be abnormal when referred to the 1947-1956 mean values. A comparison of water temperature anomalies for Los Angeles and nearby Santa Monica (figs. 2 and 3) shows substantially higher anomalies at Santa Monica. This again illustrates the unusual characteristics of the period 1947-1956, since this is approximately the base period for the Santa Monica anomalies, whereas the base period for Los Angeles is considerably longer (1924-1955). The possibility must be considered that rather than being an unusual year, 1957 may in fact herald a return to longer-period average values. January and February 1958 with their exceptionally high anomalies hardly fit this concept; but, inasmuch as they go still further in the direction of the 1957 change, they support the suggestion of a departure from the 1947-1956 conditions.

It must be emphasized that a long-period cyclical variation in geostrophic winds is not proposed nor is the fishing industry advised to anticipate 10 fat years following the past 10 lean years. It is highly desirable that available data on wind, water temperature, and sea level be analyzed for evidence of such cycles.

---

[15]See footnote 13 above.

[16]See footnote 14 above.

[17]See footnote 1 above.

[18]Indices of variations in strength of atmospheric circulation over the Pacific Ocean by L. E. Eber and O. E. Sette, unpublished paper delivered at the Annual Meeting of the *American Geophysical Union*, Washington, D. C., May 1958.

[19]See footnote 1 above.

[20]See footnote 2 above.

☆ U. S. GOVERNMENT PRINTING OFFICE : 1958 O - 474543