CLIMATIC IMPLICATIONS DERIVED FROM THE COMPARISON OF BATHYTHERMOGRAPH (BT) DATA WITH TWO TYPES OF HISTORIC AND MODERN SEA SURFACE DATA

MARGARET K. ROBINSON [1]

INTRODUCTION

In order to study further the climatology of the Pacific Ocean as evidenced in the sea surface temperature record, three sets of historical data have been examined:

1. Sea surface temperature data in the Pacific Ocean taken between the years 1816 and 1889, tabulated by Makaroff (1894).
2. Sea surface temperature data in the Pacific Ocean taken between the years 1867 and 1875 by American ships, on file in the National Archives, Washington, D.C.
3. Sea surface temperature data in the 1-degree square, 37°N, 123°W, collected by ships of all nations in the years 1857–1955, furnished by the U.S. Department of Commerce, Weather Bureau, National Records Center, Asheville, North Carolina.

These three sets of historical sea surface data were compared statistically and graphically with average sea surface temperatures based on modern Bathythermograph (BT) data taken in the years 1941–1952 (Robinson, 1951, 1954, 1957; and Pattullo, Cochrane and Burt, 1950) and also with each other. The data at 37°N, 123°W, were also compared with San Francisco (Fort Point) tide station sea surface temperatures and with San Francisco air temperatures. The results were examined for evidence of the following: Do the 19th century temperatures differ significantly from the BT averages? If these differences are significant, is there geographic and time variation among them? Do trends in the sea surface temperature agree with trends described by meteorologists and other scientists?

The detailed description of the sample data and the methods of statistical analysis are contained in the Appendix. The Makaroff and American ship data were analysed together. However, the data in the Northeast Pacific were segregated from the data in the Marshall Islands area throughout the statistical analysis. The Weather Bureau data at 37°N, 123°W, were analysed and will be discussed separately. Throughout this discussion the signs of the anomalies indicate the direction of departure of the 19th century data from the modern data.

DISCUSSION OF RESULTS

The Makaroff and American ship samples

Figure 1 is a dual purpose location chart of the Makaroff and American ship samples. It shows not only the geographic locations of the observations, but also whether the individual monthly anomalies were positive or negative. When the sample was considered as a whole, the 19th century sea surface temperatures were lower than the BT temperatures. The mean anomaly in the Northeast Pacific was —1.4°F and 70% of the anomalies were negative. The range of the anomalies, however, was very large, from -11.5°F to +7.5°F. While some of the excessively large anomalies may be due to observational error, recent synoptic temperature charts in the North Pacific ocean have shown surface temperature anomalies of comparable magnitude (McGary et al., 1957, 1958, 1959).

The mean anomaly for the Marshall Islands portion of the sample was -0.8°F and 81% of the anomalies were negative. The range of the anomalies was much smaller, from -4.0°F to +2.5°F.

The frequency distributions of the anomalies were found to be approximately normal. If the BT average temperatures and the 19th century average temperatures were the same, we would expect in a random sample of this size the mean anomaly to be zero. The negative mean anomalies for both the Northeast Pacific and the Marshall Islands samples are significantly different from zero with probabilities of such results occurring by chance being less than .0001.

Rms deviations of the anomalies were computed for both samples. For the Northeast Pacific sample the value was 2.8°F, and for the Marshall Islands sample it was 1.2°F. These values are consistent with the variability found in BT data in these same areas.

There were no systematic differences in the sizes of the anomalies when the Northeast Pacific data were divided into subsamples longitudinally or latitudinally. In the Marshall Islands sample the size of the anomalies increased with distance from the equator. The mean anomaly for the data between 15° and 20°N, -1.3°F, was only 0.1°F less than the mean anomaly for the Northeast Pacific sample, but considerably smaller than those of the areas closer to the equator -0.2°F to 0.6°F.). No longitudinal differences could be noted.

Table 1 summarizes the statistics for the Northeast Pacific sample when the anomalies were segregated into time intervals of months and years, and Table 2 similar statistics for the Marshall Islands sample. When the sample was subdivided by months and years, it was found that the positive and negative mean anomalies were not randomly distributed in time. In the Northeast Pacific the mean anomalies were negative and statistically significant in 26 of

[1] Contributions from the Scripps Institution of Oceanography, New Series.

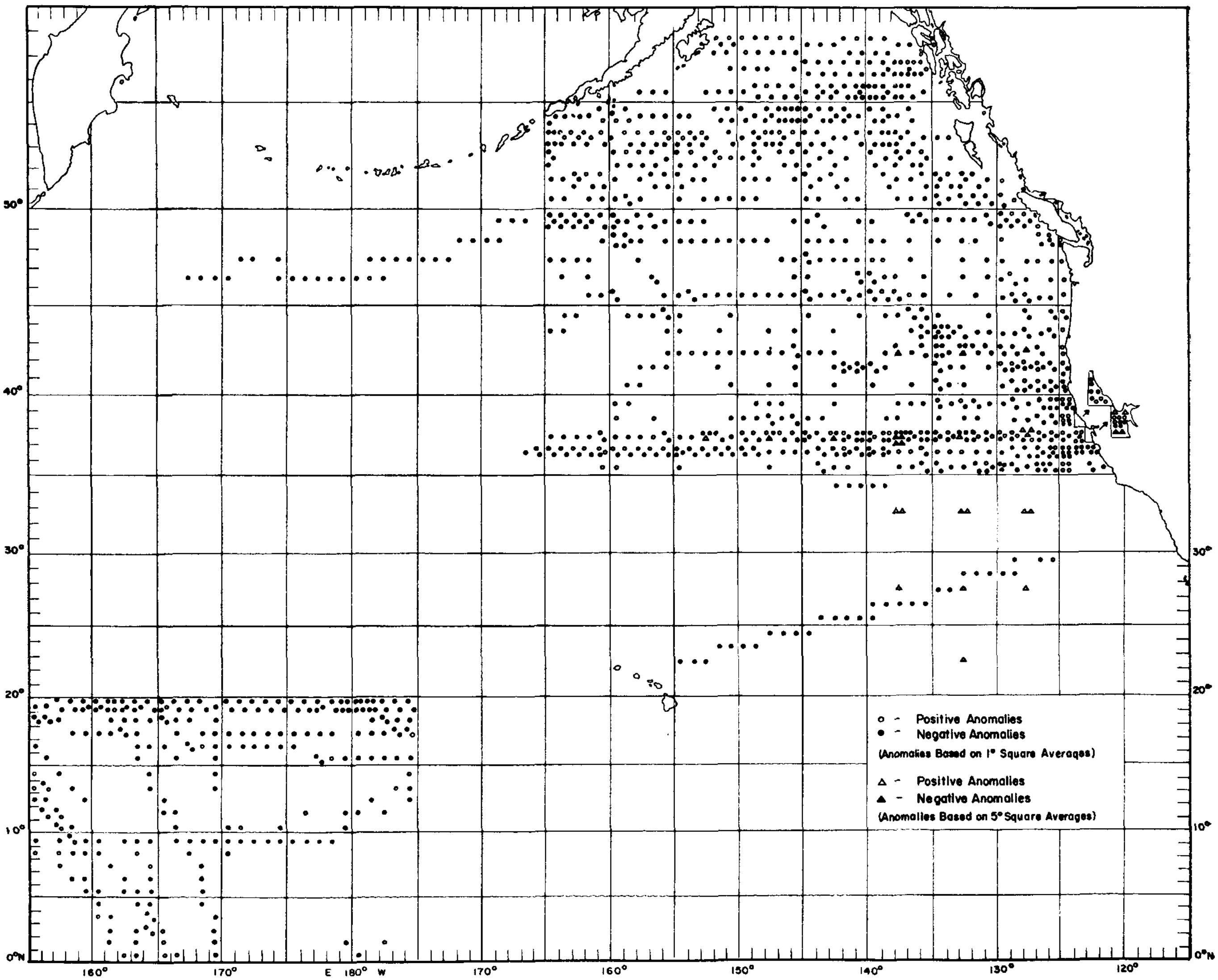

FIGURE 1. Location chart for Makaroff and American ship samples.

65 subsamples by two significance tests (see Appendix), and in 11 additional cases by one test: September 1816; September 1817; August 1824; August 1825; October and November 1826; October and November 1829; April, May, June, October and November 1848; July, September and October 1862; May, June, July, September and October 1863; April and July 1864; September 1867; June and September 1871; July, September, October and November 1873; January, February, April, July and September 1874; July 1875; and June 1889. The mean anomalies were positive and statistically significant in seven cases by both tests and in two cases by one test: December 1848; March and June 1864; February 1870; August 1873; August and October 1874; April and May 1889.

In the Marshall Islands sample, the mean anomalies were negative and statistically significant in 8 of the 23 subsamples by two tests, and in 7 additional cases by one of the tests, as follows: January, March, April and November 1817; May 1824; October 1825; May and December 1826; June 1829; October and November 1862; April 1863; May 1880; April 1887; and May 1888. In May 1863, the mean anomaly was positive and statistically significant.

The more frequent occurrence of positive anomalies between 1863 and 1889 is in agreement with the findings of Hubbs (1948) and Willett (1951).

There were eight instances in the Northeast Pacific (none in the Marshall Islands area) where results indicated that the 19th century temperatures were approximately the same as the BT averages: October 1816; September 1826; December 1829; August 1864; June, July and December 1873; and November 1874.

In Tables 1 and 2, the means of all anomalies in a given year are listed. In only two cases was there a .95 of better probability that this mean was a good estimate of the true annual anomaly: –3.3°F in

TABLE 1
SUMMARY OF STATISTICS FOR NORTHEAST PACIFIC DATA

YEAR		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	N_y	$\bar{D}_y$	rms_y	% N_y Negative	No. of Ships
1816	$\bar{d}$ / n									-1.8 / 6	-0.9 / 15	+3.0 / 1		22	-1.0	1.9	68	1
1817	$\bar{d}$ / n									-1.1 / 21				21	-1.1	1.7	76	1
1824	$\bar{d}$ / n								-1.6 / 7					7	-1.6	1.7	100	1
1825	$\bar{d}$ / n								-1.4 / 9	-2.3 / 3				12	-1.6	1.4	92	1
1826	$\bar{d}$ / n									-0.8 / 28	-6.1 / 15	-6.5 / 11		54	-3.5	4.1	61	1
1829	$\bar{d}$ / n										-5.2 / 11	-1.8 / 37	+0.4 / 14	62	-1.9	2.6	76	1
1846	$\bar{d}$ / n						-2.0 / 1							1	-2.0	---	100	1
1848	$\bar{d}$ / n				-1.1 / 26	-1.7 / 16	-5.8 / 17				-6.1 / 29	-2.7 / 23	+2.2 / 4	115	-3.3	2.8	90	1
1862	$\bar{d}$ / n							-8.0 / 1		-1.5 / 37	-4.4 / 6			44	-2.0	1.6	100	2
1863	$\bar{d}$ / n			+1.5 / 1	+3.5 / 1	-3.7 / 31	-1.0 / 34	-5.2 / 3		-4.2 / 4	-2.3 / 88	-1.5 / 1		163	-2.3	2.3	83	3
1864	$\bar{d}$ / n			+2.7 / 11	-0.7 / 55	-2.0 / 3	+4.1 / 5	-3.1 / 28	+0.3 / 12					114	-0.7	2.7	61	2
1867	$\bar{d}$ / n									-1.8 / 5*				5*	-1.8	1.4	100	1
1870	$\bar{d}$ / n	+1.0 / 2*	+2.5 / 4*							-0.7 / 8*				14*	+0.4	2.0	36	3
1871	$\bar{d}$ / n						-2.5 / 27			-1.2 / 52				79	-1.6	2.9	71	2
1872	$\bar{d}$ / n				-0.9 / 5*	+0.9 / 4*								9*	+0.9	1.5	22	2
1873	$\bar{d}$ / n						+0.1 / 25	-0.2 / 40	+1.9 / 4	-1.3 / 63	-4.9 / 44	-2.2 / 9	-0.2 / 20	205	-1.6	2.9	68	2
1874	$\bar{d}$ / n	-0.5 / 47	-1.4 / 21		-0.8 / 44		-0.2 / 5*	-0.8 / 43	+3.2 / 36	-2.8 / 25	+2.6 / 23	+0.8 / 38		282	0.0	2.4	55	3
1875	$\bar{d}$ / n							-0.8 / 22*						22*	-0.8	1.8	82	2
1889	$\bar{d}$ / n				+3.0 / 5	+5.2 / 8	-2.2 / 43							56	-0.7	3.3	64	1
														N 1287	$\bar{D}$ -1.4	rms 2.8	% of N Negative-70%	Total Ships 21

* Data tabulated by 5-degree squares.
Single underline indicates .95 significance by percentage test.
Double underline indicates .95 significance by standard deviation of mean test.

Circles indicate .95 significance by both tests.
See Appendix for identification of symbols.

1848 in the Northeast Pacific and –0.9°F in 1817 in the Marshall Islands area. For all other years the monthly samples were too few to justify the assumption that the mean of all anomalies within a given year represents a true annual anomaly.

Further consideration of the locations of the very large positive and negative mean monthly anomalies belies what at first appears in Figure 1 to be a random distribution in space, even as Tables 1 and 2 revealed that positive and negative anomalies are not randomly distributed in time. High positive anomalies were localized in August 1874, near the Aleutians; in October 1874, in the Gulf of Alaska; in June 1864, near 47°N, 140°W; and in May 1889, along the coast between San Francisco and Vancouver Island. The occurrence of the very high temperatures in August 1874, reported by the U.S.S. *Tuscarora* south and east of the Aleutians, were substantiated by data collected by the U.S.S. *Portsmouth* in October 1874, in the Gulf of Alaska. It is of interest to note that the temperatures reported by both of these ships were approximately the same as those recently reported in these areas and months during the warm years of 1957–1959 (McGary et al., 1957, 1958, 1959).

Large negative anomalies were localized in current regions: the California Current—November 1826, October 1829, and October 1873; the Alaskan Current—October 1826 and 1829; and the Aleutian or Subarctic Current—June and October 1848.

Anomalies based on data collected by the Russian ship *Krotkiy,* which sailed south from Sitka through the Alaskan Current to 35°N at about 135°W in October and November 1826, were the largest of the negative anomalies. Seventeen anomalies fell between –6.0°F and –11.7°F. In September 1826, the *Krotkiy* had crossed the Gulf of Alaska from the west to Sitka, and the mean anomaly of their September data was only –0.9°F. The mean anomaly for October 1826 was –6.1°F, and for November 1826, –6.5°F. If these *Krotkiy* data are, in fact, true ocean tempera-

TABLE 2
SUMMARY OF STATISTICS FOR MARSHALL ISLANDS DATA

YEAR		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	N_y	$\bar{D}_y$	rms_y	% N_y negative	No. of Ships
1816	$\bar{d}$ / n					+0.5 / 1								1	+0.5		0	1
1817	$\bar{d}$ / n	-0.5 / 15	-0.5 / 2	(-1.1 / 4)	-3.3 / 4							-0.8 / 18		43	(-0.9)	1.0	77	1
1824	$\bar{d}$ / n					-2.0 / 2								2	-2.0	2.0	100	1
1825	$\bar{d}$ / n				+1.9 / 1						-4.0 / 1			2	-1.0	4.3	50	1
1826	$\bar{d}$ / n					-1.9 / 8							(-1.8 / 29)	37	(-1.8)	1.2	92	1
1827	$\bar{d}$ / n			+0.1 / 2										2	+0.1	0.7	50	1
1829	$\bar{d}$ / n						(-1.0 / 21)							21	(-1.0)	0.7	95	1
1858	$\bar{d}$ / n									0.0 / 2				2	0.0	0.3	50	1
1862	$\bar{d}$ / n										(-1.0 / 11)	(-1.2 / 18)		29	(-1.1)	0.9	93	1
1863	$\bar{d}$ / n				-0.3 / 17	(+0.8 / 18)								35	-0.2	1.0	48	2
1880	$\bar{d}$ / n					(-0.9 / 26)								26	(-0.9)	1.1	100	1
1887	$\bar{d}$ / n				(-2.2 / 8)	+1.2 / 1								9	(-1.9)	1.5	89	2
1888	$\bar{d}$ / n					(-0.6 / 44)	-0.2 / 4							48	(-0.5)	0.8	77	2
														N 257	$\bar{D}$ (-0.8)	rms 1.2	% of N Negative 81%	Total Ships 11

Single underline indicates .95 significance by percentage test.
Double underline indicates .95 significance by standard deviation of mean test.

Circles indicate .95 significance by both tests.
See Appendix for identification of symbols.

tures, the fall of 1826 must truly have been a remarkably cold period.

In general, widespread geographic coverage adds insight to the significance of small samples. Generalizations concerning year-to-year differences or climatic trends are not warranted when a sample is limited to a few months within a year. Thus, the conclusions which may be drawn from the Makaroff and American ship samples are limited to specific times and small areas.

Weather Bureau sample, data at 37°N, 123°W.

The 98-year record of sea surface temperatures at 37°N, 123°W, was approached from a different point of view than the Makaroff and American ship samples, primarily because the temperature means for each month based on the entire record are a better frame of reference for climatic purposes than are the BT data from the years 1941–1952 in the same area. This can best be seen in Figure 2 which summarizes in frequency diagrams the monthly means and the extremes of the Weather Bureau sample and the BT data.

It was found that the monthly extremes of all Weather Bureau data for all months with the exception of February, March and December maxima, occurred after 1941. Thus, a second maximum for each of those three months from the post 1941 data was added to the chart for better comparison in time with the BT data. It is a surprising and puzzling fact that all but three monthly extremes in the Weather Bureau data should have occurred in the post–1941 period. While some of the extremes may have been errors, it would be highly coincidental if all were. However, it may be due to larger numbers of observations in the post–1941 sample, since one would expect the range of temperatures to increase with increase in number of observations. No estimate of this effect could be made since the numbers of observations were not listed for the pre–1941 Weather Bureau data.

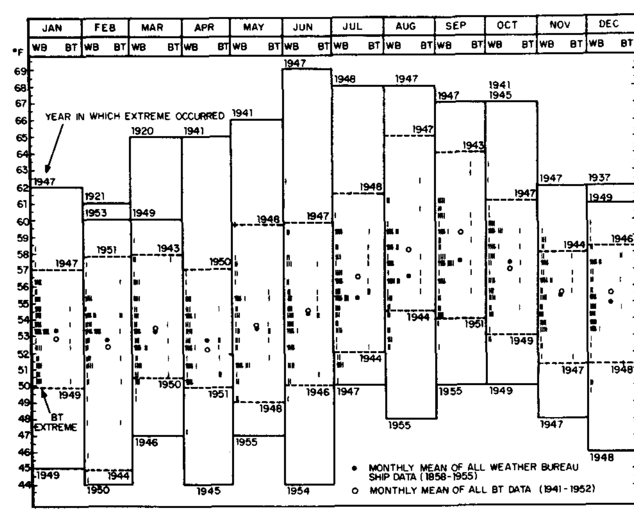

FIGURE 2. Summary of monthly means and extremes of Weather Bureau ship data and BT data at 37°N, 123°W.

It is obvious from Figure 2 that year-to-year differences are large. The BT 1941–1952 mean monthly sea surface temperatures were higher in 8 months and lower in 4 months than the long-period Weather Bureau means. This is evidence that during the period 1941–1952, most of the temperatures in this region were higher than those of a great part of the previous 84 years. (See also Figures 3, 5, and 6.)

Table 3

MONTHLY STANDARD DEVIATIONS AT 37°N, 123°W

(Estimated from Range)

	Jan.	Feb.	Mar	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Average All Months
Weather Bureau data 1941–1955	2.2	1.9	1.8	2.4	2.2	2.9	2.8	2.9	2.7	2.6	2.1	1.4	2.4°F
BT Data 1941–1952	1.9	3.8	2.0	1.9	2.6	2.5	2.4	2.9	2.4	2.1	2.0	2.8	2.4°F

While the range of temperatures within individual months was greater in the Weather Bureau sample than in the BT data, standard deviations (see Table 3) show variability, in general, to be approximately the same in both samples. It has been previously shown from an investigation of shore station temperatures along the West Coast between Alaska and Southern California that between 1948 and 1955 variability in sea surface temperatures was lower than average in this region (SIO Ref. 60–30, 1960).

Figure 3 presents the chronological anomalies of the Weather Bureau sample computed from the long-period monthly means of the sample. Different symbols are used for each season in order to draw attention to seasonal differences, and to the occurrence of persistence of positive or negative anomalies. While much of the month-to-month variation appears random in size and sign, there are numerous periods where there is evidence of persistence in the signs of anomalies over periods of several months. In 1941–1942 sixteen consecutive positive anomalies can be seen, and in 1916–1917, fourteen consecutive negative anomalies. Roden and Groves (1960), have found evidence of persistence of from four to six months in sea surface temperature data in two locations in the North Pacific. Robinson (1960), showed occasional periods of persistence up to eighteen months in length in the Pacific Coast shore station sea surface temperature data of Alaska, Canada and the United States.

Weather Bureau tabulations did not include the number of observations on which the monthly means were based for the period prior to 1941. It was thus impossible to compute the significance of the monthly mean anomalies for the period prior to 1941. Table 4 presents the monthly mean anomalies for the period 1941 to 1955. Seventy-nine of the one hundred and forty monthly means are significantly different from the all-data means; of these fifty-four were higher than the all-data means.

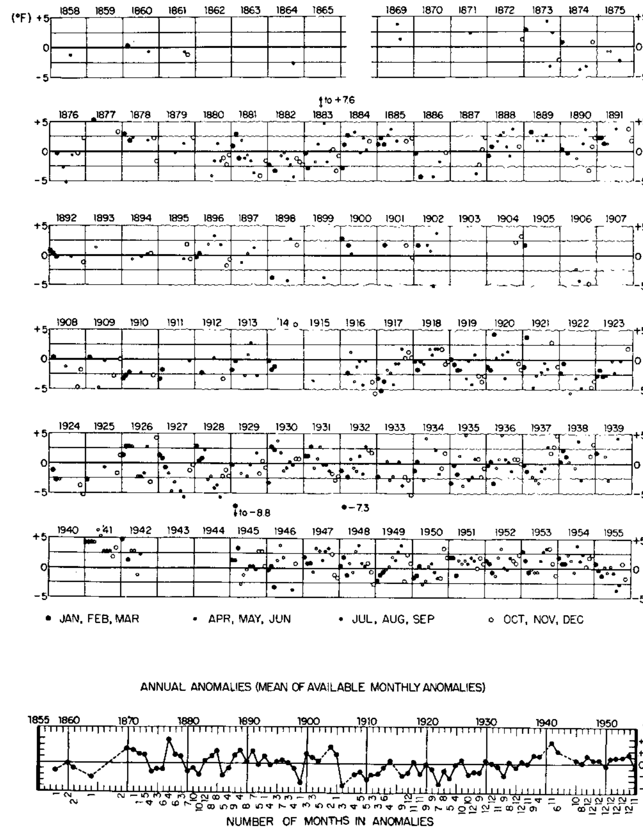

FIGURE 3. Top: Monthly anomalies 1858–1955 at 1-degree square, 37°N, 123°W, plotted to show seasonal relationships. Bottom: Annual anomalies.

Along the bottom of Figure 3 the means of the available monthly anomalies as an estimate of the annual anomalies are presented. Prior to 1920, the number of years with data in most months is rather small; thus, only general trends in these anomalies may be considered to be real. During the period 1870 to 1905, there are more frequent positive than negative anomalies; whereas from 1906 to 1935 negative anomalies predominated, and from 1936 to 1955 positive anomalies were again the most frequent.

In the following years there is a probability of .05 or less that the number of positive or negative monthly anomalies could have occurred by chance: positive anomalies—1885, 1891, 1941, 1947, 1951, and 1954; and negative anomalies—1882, 1886, 1910, 1916, 1919, 1922, 1923, and 1927. The probability that the sign of the mean of the monthly anomalies would be the same as the sign of the true annual mean was .95 in the following years: warm years—1878, 1888, 1889, 1938 and 1942; and cold years—1876, 1921, 1929, and 1933.

These findings agree, in general, with the trends in air temperatures described by Willett (1950), Kincer (1946) and with trends in the Atlantic sea surface temperatures described by Smed (1952).

The years 1926 and 1931, which are remarkably warm in Canadian and American Pacific shore station data, are warm peaks within the cold period, but

TABLE 4

ANOMALIES FROM ALL-DATA MONTHLY MEANS

1-degree square, 37°N, 123°W

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1941	+4.1	+4.2	+4.2	+4.1	+6.0	+5.1	+2.5	+2.5	+2.5	+1.8	+3.4	
1942	+4.6		+1.3	+2.5	+2.5	−1.4	+2.2					
1945		+1.2	+3.3	−2.8	−1.2	−0.3		+0.4	−0.4	+2.5	+2.5	+0.1
1946	−0.4	+0.3	−3.0	+1.4	+3.5	+1.6			−3.5	+0.6		
1947	+1.6	+0.5	+0.8	−0.8	+3.2	+2.7	+1.3	+2.8	+3.3	+2.2	−1.0	−1.6
1948	+0.1	+1.8	−1.0	+0.7	−0.9	+2.7	+3.7	+0.5	+0.4	+0.9	−0.8	−2.5
1949	−2.2	−1.2	−0.9	−0.3	+0.3	+1.5	+1.4	+2.5	+3.6	−2.0	+2.2	+0.7
1950	−1.8	−1.2	+0.2	−2.5	−2.4	+0.1	+0.6	−0.7	−1.5	−1.9	+3.3	+1.5
1951	+1.6	+1.5	−1.3	+1.0	+0.5	+1.3	+0.7	+1.6	+1.3	0.0	+1.7	+0.5
1952	+1.0	+0.9	−0.6	−1.4	+1.8	+3.4	0.0	−0.3	+1.9	+1.1	+0.6	+2.0
1953	+2.7	+1.3	−0.5	−0.3	−0.5	−0.5	+1.3	+2.6	+3.3	+3.1	+0.8	−1.4
1954	+1.9	+0.8	+0.6	+2.1	+1.0	−0.8	+3.8	+1.1	+2.0	+0.1	+1.9	+2.3
1955	+0.5	−0.2	−1.0	+0.1	−0.9	+0.2	−0.7	−3.5	−2.7	+0.6	−1.6	

Underlined values exceed $\frac{\sigma}{\sqrt{n}}$ at .05 or less probability level.

the number of positive anomalies is not significant in these years. The significantly cold years of 1922 and 1933 are in agreement with the Pacific Coast shore station data (SIO Ref. 60–30, 1960).

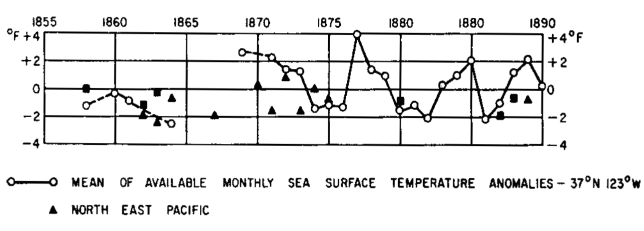

FIGURE 4. Comparison of annual sea surface temperature anomalies at 37°N, 123°W and in the Northeast Pacific Ocean and Marshall Islands area.

The climatic relationship between the Weather Bureau data and data from other sources is shown in Figures 4, 5, and 6. In Figure 4, the Weather Bureau mean anomalies for the years 1858 to 1889 are compared with the mean anomalies of the Makaroff and American ship samples during the same period, but in different areas. The sign of the annual anomalies is the same in only half of the comparisons. This result is not surprising since as shown above for the Makaroff and American ship sample, in only a few cases was it probable that the sum of the individual anomalies in a given year was a good estimate of the true annual anomaly.

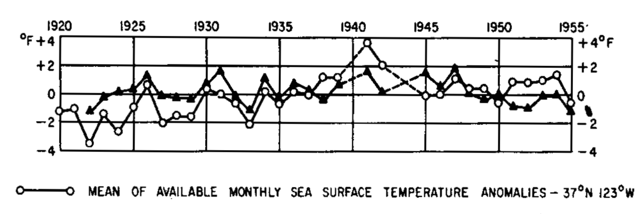

FIGURE 5. Comparison of annual sea surface temperature anomalies at 37°N, 123°W and at San Francisco (Fort Point), California.

In Figure 5, the annual anomalies at 37°N, 123° W, for the Weather Bureau sample are compared with the annual anomalies for the San Francisco (Fort Point) sea surface temperature data for the years 1922–1955. The reference base, for the computation of the anomalies, was the long-period mean for the period 1922–1955 for both sets of data.

There is good agreement between the sign of the anomalies and the direction of change of the anomalies from year to year at the two locations, with the exception of the period 1949–1954.

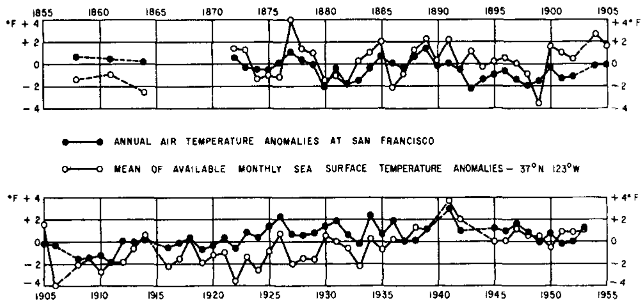

FIGURE 6. Comparison of annual sea surface temperature anomalies at 37°N, 123°W and air temperature anomalies at San Francisco, California.

In Figure 6, Weather Bureau annual sea surface temperature anomalies at 37°N, 123°W, are compared with annual air temperature anomalies at San Francisco, for those years between 1858 and 1953 that data exist at both places. The long-period means used as the basis of reference for computing the anomalies include only those data common to both. However, the annual air temperature anomalies are based on data in all twelve months. Those at 37°N, 123°W, are the means of available data within each year.

This figure shows evidence of a correlation between ocean temperatures and air temperatures. There is general agreement in the signs of the anomalies, with notable exceptions. There is closer agreement, however, in the trends of the anomalies from year to year at the two locations.

In order to evaluate quantitatively the relation between offshore oceanic sea surface temperature anomalies and onshore sea surface and air temperature anomalies, the correlation coefficients shown in Table 5 were computed. Also listed are the probabilities of obtaining these results by chance.

Highly significant positive correlations between *monthly* anomalies of *sea* surface temperature at 37°N, 123°W, and those at San Francisco (Fort Point) were found in the months November to June. In July, the correlation was negative and not significant, probably because of upwelling along shore.

A highly significant positive correlation was also found when *annual sea* surface temperature anomalies for the offshore and onshore stations were compared. A further significant positive correlation was found between *annual sea* surface temperature anomalies at 37°N, 123°W, and *annual air* temperature anomalies at San Francisco.

For comparison, Table 5 includes the highly significant correlation between *annual sea* surface temperature anomalies at San Francisco (Fort Point) and *annual air* temperature anomalies at San Francisco previously reported by Hubbs (1948), and the much lower but still significant correlation between the *monthly* BT *sea* surface temperature anomalies at 37°N, 123°W, and *monthly sea* temperature anomalies at San Francisco from Robinson (1957).

TABLE 5

CORRELATION COEFFICIENTS (r) AND PROBABILITIES OF THEIR OCCURRENCE BY CHANCE

A. Sea Surface Temperatures 37°N 123°W (WB) vs. San Francisco (Fort Point)

1. Between Monthly Anomalies, by months, (1922–1954)

	Jan.	*Feb.*	*Mar.*	*April*	*May*	*June*
r	.597	.619	.548	.609	.521	.400
n	26	25	22	27	22	26
Prob.	.001	<.001	.006	.001	.009	.033

	July	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
r	.051	.562	.422	.382	.603	.632
n	21	24	25	23	24	22
Prob.	----	.003	.025	.063	.001	.001

2. Between Monthly Anomalies, all months, (1922–1934)

r	.527
n	287
Prob.	≪.001

3. Between Annual Anomalies (1922–1953)

r	.486
n	29
Prob.	.005

B. Sea Surface Temperatures 37°N 123°W (WB) vs. Air Temperatures Francisco

1. Between Annual Anomalies (1858–1953)

r	.390
n	78
Prob.	.003

2. Between Annual Anomalies (1922–1953)

r	.477
n	29
Prob.	.006

C. Sea Surface Temperatures, San Francisco (Fort Point) vs. Air Temperatures, San Francisco

1. Annual Anomalies (1922–1953)

r	.801
n	29
Prob.	≪.001

D. Sea Surface Temperatures 37°N 123°W (BT) vs. San Francisco (Fort Point)

1. Monthly Anomalies, all months, (1941–1952) from Robinson (1957)

r	.273
n	75
Prob.	.022

CONCLUSION

Let us return to the questions raised in the introduction:

1. Do the 19th century temperatures differ significantly from the BT averages? Yes. The mean of the Makaroff and American ship sample temperatures was less than that of the BT averages in the same locations. In some months of some years, the 19th century temperatures were higher than the BT averages.
2. If these differences are significant, is there geographic and time variation among them? A large part of the differences was significant. The differences varied with geographic location. Anomalies were small in equatorial regions, and large in high latitudes and in current regions. The anomalies also varied with time. The significant

anomalies were negative prior to 1864. Between 1864 and 1889, there were both significant positive and negative anomalies, though negative anomalies were more frequent.

3. Do trends in the sea surface temperature agree with trends described by meteorologists? Yes. The occurrence of the significant positive anomalies between 1864 and 1889 in the Makaroff and American ship samples, and the occurrence of a majority of positive anomalies between 1870 and 1905, a majority of negative anomalies between 1906 and 1935, and a majority of positive anomalies from 1936 to 1955 in the Weather Bureau sample are examples of agreement of the trends in sea surface temperatures with those in air temperatures described by meteorologists.

The correlation of offshore and onshore sea and air temperatures demonstrated in this paper further serves to point up the fact that the inter-relationship between air and sea surface temperatures needs further investigation in the open ocean. Such an investigation would expand our knowledge of the climatic history of the Pacific Ocean. Those years for which there are also historic weather maps (1889–1955) deserve special emphasis with the ultimate objective of forecasting sea surface temperatures and long-range weather.

ACKNOWLEDGMENTS

This paper represents results of research carried out by the University of California, under contract with the Office of Naval Research. Reproduction in whole or in part is permitted for any purpose of the U.S. Government.

This research also received support from the California Cooperative Oceanic Fisheries Investigations, a project sponsored by the Marine Research Committee of the State of California.

REFERENCES

Fisher and Yates, 1948. *Statistical tables for Biological Agricultural and Medical Research.* 3rd Ed. Oliver and Boyd, London, England. p 46.

Hoel, Paul G., 1947. *Introduction to Mathematical Statistics.* John Wiley and Sons, Inc., N.Y., 246 pp.

Hubbs, Carl L., 1948. Changes in the fish fauna of western North America correlated with changes in ocean temperature. *J. Mar. Res.* **7**: 459–482.

Kincer, J. B., 1946. Our climate change. *Transactions Am. Geo. Un.* **27** (3) : 342–347.

Makaroff, S., 1894. *Le Vitiaz et l'Ocean Pacifique* **I** and **II**. St. Petersbourg, Russie, 848 pp.

McGary, James W., Calloway, R. J. and Mendiola, E. W., 1957, 1958, 1959. Synoptic sea surface temperature charts. Fish. and Wild. Serv., Pac. Oce. Fish. Invest. (Honolulu Biological Laboratory, B.C.F.)

Pattullo, June, Cochrane, John D. and Burt, Wayne V., 1950. Sea temperature in the Aleutian Islands area. Univ. Calif. Scripps Inst. Oceanogr., *Oceanographic Rept.* **24** (Mimeo.).

Robinson, Margaret K., 1951. Sea temperature in the North Pacific area, 20°–40°N, 125°–155°W. Univ. Calif. Scripps Inst. Oceanogr. *SIO Ref.* **51-20.** 14 (Mimeo).

Robinson, Margaret K., 1954. Sea temperature in the Marshall Islands area, Bikini and nearby atolls. *Geol. Survey Prof. Papers* **260D**, 10.

Robinson, Margaret K., 1957. Sea temperature in the Gulf of Alaska and in the Northeast Pacific Ocean, 1941–1952, *Bull. Scripps Inst. Oceanogr.* **7** (1) : 98.

Robinson, Margaret K., 1960. The use of a common reference period for evaluating climatic coherence in temperature and salinity records from Alaska to California. *Marine Research Committee, Calif. Coop. Oceanic Fish. Invest. Rept.* **VIII**. Sacramento.

Roden, Gunnar and Groves, Gordon C., 1960. On the statistical prediction of ocean temperatures. *J. Geo. Review* **65** (1): 249–263.

Smed, Jens, 1952. Variation of the surface temperature in the northern North Atlantic during 1876–1952. Conseil Permanent International pour l'Exploration de la Mer. *Annales Biologiques* **9** : 19–21.

Smithsonian Institution, 1927, 1934 and 1947. *Smithsonian Misc. Coll.* **79, 90** and **105.** Smithsonian Institution, Wash. D.C.

Tippett, L.H.C., 1925. On the extreme individuals and the range of samples taken from a normal population. *Biometrica* **17** : 364–387.

U.S. Coast and Geodetic Survey, 1956. Surface water temperatures at tide stations, Pacific coast *Special Publication* **280.**

U.S. Weather Bureau, 1952. *Climatological Data California.* **45-56.** 1941–1952.

University of California, Scripps Institution of Oceanography, 1960. Temperature and salinity anomaly charts for 24 Canadian and American shore stations based on a common reference period. *SIO Ref.* **60-30.**

Willett, H. C., 1949. Long-period fluctuation of the general circulation of the atmosphere. *J. Met.* **6,** No. 1.

Willett, H. C., 1950. Temperature trends of the past century. *Centenary Proceedings of the Royal Met. Soc.* : 195–206.

Willett, H. C., 1951. Extrapolation of sunspot-climate relationships. *J. Met.* **8** (1) : 1–6.

APPENDIX

DESCRIPTION OF SAMPLE DATA

Makaroff's (1894) tabulations of Pacific Ocean sea temperature data included all observations known to him which had been collected between 1816 and 1889. From his collection only those data were selected for this analysis that were in areas where BT temperature data had already been analyzed and results published (Robinson, 1951, 1954, 1957; and Pattullo, Cochrane and Burt, 1950).

Table 6 lists the number of observations from the Makaroff collection in the Northeast Pacific Ocean by year, month, and by ship's name. There were 885 observations selected for analysis in this area. Of this total, 671 were collected by 11 Russian ships, 202 by *USS Tuscarora* and 12 by *HMS Challenger*. These data were taken in 15 of the years between 1816 and 1889.

TABLE 6

MAKAROFF SHIP LIST

Gulf of Alaska Observations

Year	Ship	Month	Observations
1816	Rurik	September	6
		October	15
		November	1
1817	Rurik	September	21
1824	Predpriatie	August	7
1825	Predpriatie	August	9
		September	3
1826	Krotkiy	September	28
		October	15
		November	11
1829	Krotkiy	October	11
		November	37
		December	14
1846	Herald	June	1
1848	Atcha	April	26
		May	16
		June	17
		October	29
		November	23
		December	4
1862	Abrek	September	37
		October	6
	Rynda	July	1
1863	Abrek	March	1
		October	51
	Rynda	April	1
		May	31
		June	34
		July	3
		November	1
	Bogatir	September	4
		October	37
1864	Abrek	March	11
		April	55
		June	5
		July	28
		August	12
1873	Tuscarora	August	4
		September	19
		October	34
		November	9
		December	20
1874	Tuscarora	January	37
		July	43
		August	36
	Gaydamik	May	3
1875	Challenger	July	12
1889	Kreisser	April	5
		May	8
		June	43
		TOTAL	885

Table 7 similarly lists the observations in the Marshall Islands area. Here there were 257 observations collected in 13 of the years between 1816 and 1888. Of this total 255 were taken by 10 Russian ships and 2 by *HMS Blossom*. In eight of the years, there were data in both areas.

TABLE 7

MAKAROFF SHIP LIST

Marshall Islands Observations

Year	Ship	Month	Observations
1816	Rurik	May	1
1817	Rurik	January	15
		February	2
		March	4
		April	4
		November	18
1824	Predpriatie	May	2
1825	Predpriatie	April	1
		October	1
1826	Krotkiy	December	29
1827	Blossom	March	2
1829	Krotkiy	June	21
1858	Novara	September	2
1862	Abrek	October	11
		November	18
1863	Abrek	April	7
		May	11
	Bogatir	April	10
		May	7
1880	Djiguit	May	26
1887	Vitiaz	April	8
	Rynda	May	1
1888	Razboinik	May	39
		June	4
	Rynda	May	5
	Total		257

The unpublished American ship data were obtained from the National Archives, Washington, D.C. The data, totalling 402, are listed in Table 8 by date and by ship's name. All data were in the Northeastern Pacific and were collected in seven of the years between 1867 and 1875.

Both the Makaroff collection and the American ship data were tabulated by 1-degree squares and were segregated by months and by years, with the exception of 43 of the American ship observations which were tabulated by 5-degree squares (see Table 8).

There were only 8 instances where 2 ships took observations in the same month and year, and even in these cases none were within the same 1-degree square but only in the same general area. It was therefore possible to verify results in only 8 cases by comparing data from different sources. (Fortunately verification, not disproval, did result from these comparisons).

The third sample selected for analysis was obtained from the U.S. Department of Commerce, Weather Bureau, National Records Center, Asheville, North Carolina.

These data include tabulations of monthly means and range of sea surface temperature for the 1-degree square, 37°N, 123°W. The IBM print-outs of

TABLE 8
AMERICAN SHIP LIST
Northeast Pacific Area

Year	Ship	Month	Observations
1867	Jamestown*	August	5
1870	Jamestown*	January	2
	Saginaw*	February	4
	Kearsarge*	September	8
1871	Cyane	June	27
	Jamestown	September	52
1872	Mohican*	April	5
	Pensacola*	May	4
1873	China	June	25
		July	40
		September	44
		October	10
1874	China	January	10
		February	21
		April	44
	Portsmouth	September	25
		October	23
		November	38
	Pensacola*	June	5
1875	Portsmouth*	July	10
	Total		402

* Data tabulated by 5-degree squares.

these data listed monthly means in 83 of the 98 years between 1857 and 1955, and in 564 individual months of the 996 months during these 83 years. The number of different ships collecting the data in each month was not listed. Most unfortunate for statistical purposes, the number of observations on which the monthly means were based was omitted for the years prior to 1941, severely limiting the statistical usefulness of the data between 1857 and 1941.

The Weather Bureau sea surface temperature data were compared with BT temperature data in this area analyzed by Robinson (1957). Additional data used in this analysis were: 1) sea surface temperatures collected at San Francisco (Fort Point), California tide station (U.S.C.G.S., 1956) and 2) air temperatures, San Francisco weather station, (Smithsonian Institution, 1927, 1934, 1947, and U.S. Weather Bureau, 1952.)

RELIABILITY OF THE SAMPLE DATA

It is difficult to evaluate the reliability of the individual 19th century observations. Surely the positions of the observations were accurate within a unit area of 1° of latitude and longitude. Nineteenth century sailors were expert navigators and they would have been able to make corrections for periods when they sailed by dead-reckoning. Fahrenheit had invented the mercury thermometer in 1714. By 1816, accurate mercury thermometers must have been available. Observers' errors in reading thermometers or in transcribing data are always possible. For this reason, single observations should be accepted with caution, or, at times, even those taken by a single ship. We can never be sure how many times an untrained observer lifted a thermometer from a bucket of sea water, raised it to eye-level to read, but left the wet mercury bulb to the mercy of the wind.

However, Makaroff did critically evaluate the data which he tabulated. He spent an entire year examining ships' logs and published accounts of expeditions for description of methods, instruments and thermometer calibrations. He published only those data which he believed to be sufficiently accurate for scientific purposes (Makaroff, 1894, pp. 235–238).

The author transcribed the American ship data from the original ships' logs. Nothing was listed in these ships' deck logs concerning thermometer calibrations, but the data were accepted if the variation of temperature from observation to observation along the ship's track was consistent with that found in our modern temperature charts. That is, it was accepted if a rapid increase or decrease of temperature occurred when the ship sailed in the direction of the temperature gradient and little change of temperature when it sailed normal to the gradient.

The reliability of the Weather Bureau sample is unknown. It is made up of data from sources similar to the American ship sample. It is not known if any screening or evaluation of the data was done by the Weather Bureau. The mean temperatures, however, are based on data from numerous ships and the effect of random errors should be at a minimum.

It is equally difficult to evaluate the reliability of the BT smoothed averages. The root mean square difference of the BT smoothed monthly average contoured isotherms from the BT raw averages in the Northeast Pacific was 1.7°F with a mean difference of —0.05°F, based on 3,438 comparisons. These figures imply that no bias was introduced by the smoothing. They do not indicate the reliability nor accuracy of the BT average contours. For the purposes of this study we will assume that they are climatically representative means for the period for which BT data were analyzed—i.e., 1941–1952 for the Northeast Pacific; 1941–1949 in the area south of 35°N between San Francisco and Hawaii; 1942–1948 in the Aleutian Island area; and 1942–1951 in the Marshall Islands area.

The variability of sea-surface temperature can best be demonstrated by computations of standard deviations from their monthly means of individual observations taken in different years at a single location. In the Northeast Pacific, on weather stations and at other locations with numerous BT data, standard deviations for surface temperatures segregated by months range from 0.8°F to 3.8°F. At Eniwetok, in the Marshall Islands, the standard deviations for surface temperatures range from 0.6°F to 1.6°F (Robinson, 1951, 1954, 1957).

METHOD OF ANALYSIS

The Makaroff and American ship data were analyzed together. These samples consist of individual observations widely and erratically distributed in space and time. From each of the sample temperatures the BT smoothed average monthly temperature for corresponding 1-degree (or 5-degree) square was subtracted. Thus a negative anomaly indicates that the sample temperature was lower than the BT average.

The anomalies were tabulated into frequency distributions as follows: (a) 0.5°F class interval; (b) the total sample; (c) subsample by area: Northeast Pacific and Marshall Islands; (d) each area subsample was further subdivided by: 10-degree bands of longitude, 10-degree bands of latitude for the Northeast Pacific, by 5-degree bands of latitude in the Marshall Islands area; (e) subsample by time intervals of years and of months.

Table 9 lists symbols and equations used in statistical analysis of the frequency distributions of the anomalies.

TABLE 9

SYMBOLS AND EQUATIONS USED IN STATISTICAL ANALYSIS

t = Sample temperature, 1 month, 1 year, unit area.*

$\bar{t}_{BT}$ = Average BT temperature, corresponding month, year and area.

n = Number of observations in 1 month, 1 year, all areas.

N_y = Number of observations in all months, 1 year, all areas.

N = Total sample, all months, years, areas.

d = $(t - \bar{t}_{BT})$, anomaly, 1 month, 1 year, unit area.

$$\bar{d} = \frac{\Sigma_A (t - \bar{t}_{BT})}{n}$$, anomaly, 1 month, 1 year, all areas.

$$\bar{D}_y = \frac{\sum_1^{N_y} d}{N_y}$$, anomaly 1 year, all areas.

$$\bar{D} = \frac{\sum_1^{N} d}{N}$$, anomaly all months, years, areas.

$$rms_y = \frac{\sqrt{\sum_1^{N_y} (t - \bar{t}_{BT})^2 - (\bar{D}_y)^2}}{N_y - 1}$$, root mean square deviation all months, *1 year*, all areas.

$$rms = \frac{\sqrt{\sum_1^{N} (t - \bar{t}_{BT})^2 - (\bar{D})^2}}{N - 1}$$, root mean square deviation, all months, all years, all areas.

* Unit area is 1-degree square of latitude and longitude, except where values are starred in Table 2. Here unit area was 5-degree square. In only one case were anomalies based on 1-degree and 5-degree square averages combined. This was in July, 1875 where 10 of the 22 values were based on 5-degree square averages.

The statistics of the anomalies were tested in the following way: (a) The frequency distributions were tested for normalcy. (b) The mean anomalies of total samples and all subsamples were tested to see if they departed significantly from zero, using $\sigma\sqrt{n}$ as the significance criteria, assuming that the rms value computed for the total sample is a good estimate of σ. (c) The probabilities were computed that the given percentage of positive and negative anomalies could have occurred by chance, assuming that the BT mean temperatures and the 19th century mean temperatures were the same. The following method was used:

p = probability of obtaining negative anomaly = ½
q = probability of obtaining positive anomaly = ½
n = number of observations
$\sigma = \sqrt{npq}$

$$M = \frac{n}{2} = \text{mean}$$

X = observed number of negative (or positive) anomalies

$$t = \frac{X - M}{npq}$$

For given values of t, the probability of obtaining such distributions is given in Table 1 of Hoel (1947). (d) The probability was computed that the observed distribution of monthly anomalies $(\bar{d})$ might have occurred by chance, and the probability that the sign of the mean of the monthly anomalies $(\bar{D}_y)$ is the same as the true annual anomaly, assuming that the sign of each month's anomaly and the sign of each year's anomaly is an independent event.

The frequency distributions of the total samples were found to be leptokurtic; i.e. symmetrical but more sharply peaked and longer tailed than a normal distribution. The departure from normality was not great enough, however, to invalidate the probabilities which were computed on the assumption of normal distributions.

The Weather Bureau sample was treated in a somewhat different fashion. This sample consists of data limited in space to a 1-degree square of latitude and longitude. The data are not continuous for the total period of time between 1857 and 1955, although after 1916 there are data in almost all months of all years except for 1940, 1943 and 1944, where no data at all were listed.

The analysis of these data was based on the following statistics:

(a) The long-period monthly means and annual mean were computed. These were used as the base to compute monthly anomalies. The average of the available monthly anomalies in a given year was computed and assumed to be a best estimate of the annual anomaly for the given year.

(b) In the portion of the sample in the years 1941–1955, the standard deviation of individual observations was computed from the range (Tippett, 1925). This was possible because the range of the individual temperature values, and the number of observations on which the sample mean was based, was listed for this portion of the Weather Bureau sample. The values obtained for each month for the 14-year period were averaged, and these average monthly deviations are compared with the standard deviations computed in the usual manner, for each month for the BT data in Table 3.

(c) The significance of the monthly anomalies ($\bar{d}$), assuming normal distribution, was tested; also, the probabilities were computed that the signs of the $\bar{D}_y$'s were the same as the signs of the true annual anomalies.

(d) Correlation coefficients were computed between the Weather Bureau sea surface mean temperature anomalies, representing offshore oceanic conditions and San Francisco shore station mean sea surface temperature anomalies for both monthly and yearly periods.

(e) Correlation coefficients were computed between the Weather Bureau annual sea surface mean temperature anomalies and San Francisco annual air temperature anomalies.

(f) The significance of the computed correlation coefficients was tested using tables published by Fisher and Yates (1948).

o

37439—800 1-65 3,500

printed in CALIFORNIA OFFICE OF STATE PRINTING