ON NONSEASONAL TEMPERATURE AND SALINITY VARIATIONS ALONG THE WEST COAST OF THE UNITED STATES AND CANADA

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ABSTRACT

Power spectra of sea surface temperature and salinity anomalies are investigated for the frequency range between zero and six cycles per year. It is found that the power of these anomalies is concentrated at low frequencies and that high frequencies contribute almost nothing to it. The power spectra of temperature anomalies are similar for all 20 stations investigated here, but large regional differences exist in the salinity spectra. The coherence between sea and air temperature anomalies is moderate to good for well exposed stations, and there exists a direct relationship between them. The coherence between salinity and precipitation anomalies is good only for stations along the open coast where there is little river discharge, the anomalies being related inversely to each other. The coherence between salinity and river discharge anomalies is moderate to good for stations at the boundary between river and oceanic water and poor elsewhere. The coherence between surface temperature and salinity anomalies is moderate for light ship and island stations and poor along the continent. The relation between them is mostly an inverse one, as is characteristic of upwelling regions.

INTRODUCTION

For many years careful records have been kept of sea surface temperature and salinity at various stations along the west coast of the United States and Canada. If these records are plotted against time, seasonal as well as nonseasonal variations are obtained. The seasonal variations have been studied by McEwen (1912, 1919, 1929, 1938), and Pickard (1953) and the nonseasonal variations by Hubbs (1948), Reid (1960) and Roden (1958). The particular relation between temperatures and tides was investigated by Herlinveaux (1957), and between salinity and river discharge by Tully (1952).

In this paper the regular seasonal variation is eliminated by taking differences between the monthly mean and the long term mean of the same month. The resulting anomalies are then used to compute the average power contained in each record and also the power spectral density, coherence and phase as defined below. In performing the calculations it has been assumed that the anomaly records are stationary, at least in the wide sense, so that the functions derived depend only upon the sampling interval, and are independent of any origin in time.

The location of tide gage and lighthouse stations is shown on figure 1. Most of them are located in harbors and bays and only few of them are well exposed. Blunts Reef represents a light-ship, anchored a few miles off Cape Mendocino, in the heart of the upwelling region. For meteorological records the nearest meteorological station was chosen. In most cases the tide gage an meteorological stations are located within a radius of 20 km, but in a few instances stations further apart had to be combined. Where the nearest meteorological station was more than 50 km away, no comparisons between oceanographic and meteorological variables were made.

DATA

Sea surface temperatures and salinities were obtained from the U.S. Coast and Geodetic Survey (1956), the Fisheries Research Board of Canada (1958) and the Scripps Institution of Oceanography of the University of California (unpublished). At the Canadian stations the monthly means were computed from daily observations made one hour before the daytime high water. The individual temperature readings are estimated to be accurate within 0.2 C and the individual salinities, determined by a modified Mohr titration, are reported to have an accuracy of $\pm$ 0.06‰. At the United States stations the observations are made at a random hour during each week day, and in many cases the monthly means are computed from less than 20 daily values. The accuracy of individual temperature readings is estimated to be within 0.2 C except for stations in Southern California where the accuracy is somewhat greater, because better thermometers were used. The accuracy there is estimated to be within 0.05 C. The surface salinities up to July 1954 were obtained from density observations by hygrometer at all stations. The accuracy of a single hygrometer reading is not very great, and must very with the individual skill of the observer. In some cases the salinities so determined are probably accurate only within 0.3‰. Since July 1954 the salinities at La Jolla, Balboa, Hueneme, Pacific Grove, SE Farallon Island, and Blunts Reef Lightship are determined by a Knudsen titration, the accuracy of which is about $\pm$ 0.05‰.

Air Temperature and precipitation records were obtained from the U.S. Weather Bureau (1872-1949, 1950-1960, and 1916-1960) and the Canadian Department of Transport (personal communication). The monthly averages of air temperatures are computed from four equidistant daily readings at 0000, 0600, 1200 and 1800 GMT. The accuracy of an individual reading is estimated to be within 0.1 C. The accuracy of rainfall is estimated to be 1% of the total or about 0.3 cm, whichever is the greater.

[1] Contribution from the Scripps Institution of Oceanography.

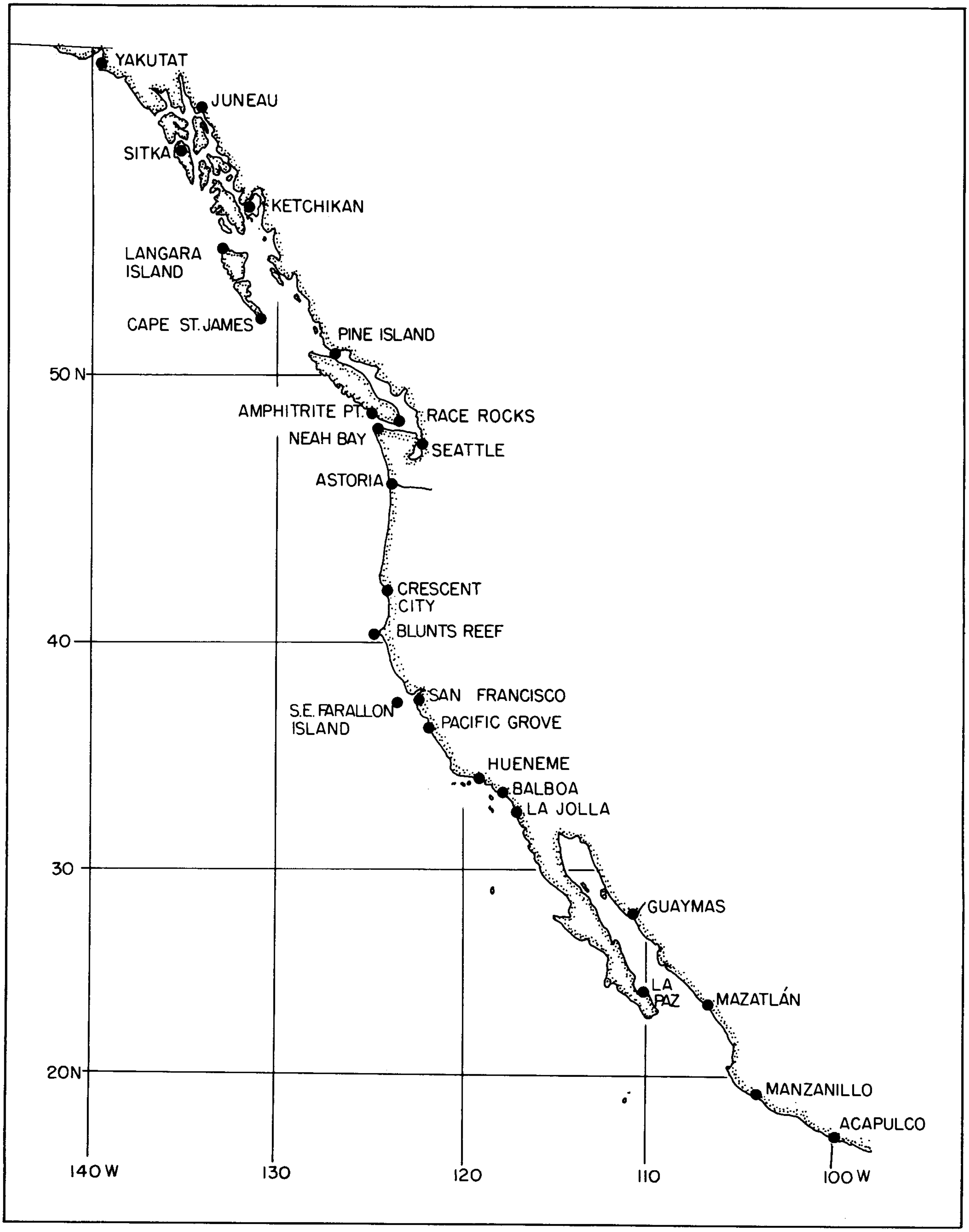

FIGURE 1. Location of stations where temperature and salinity observations are made.

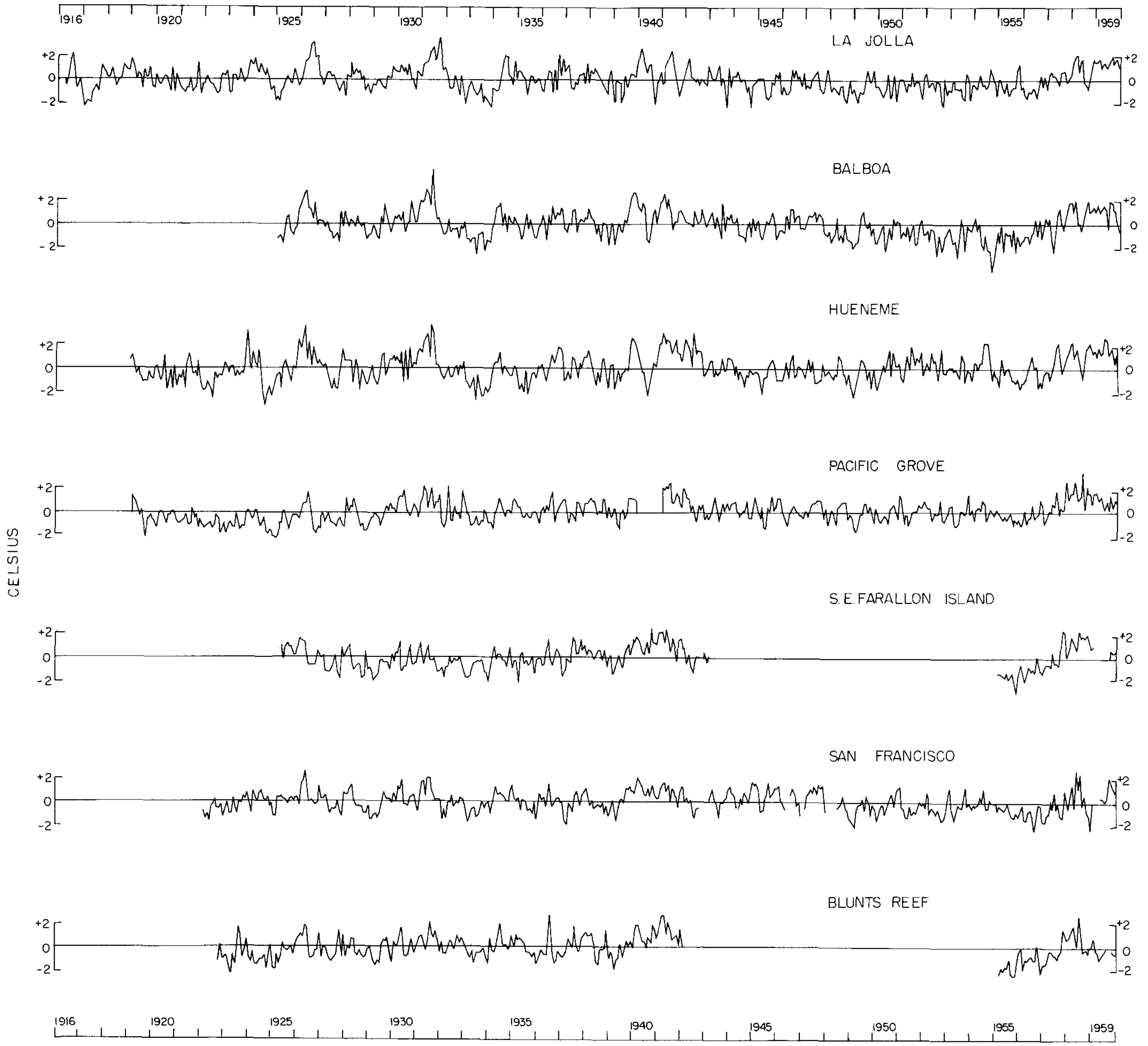

FIGURE 2. Sea surface temperature anomalies at California stations. .

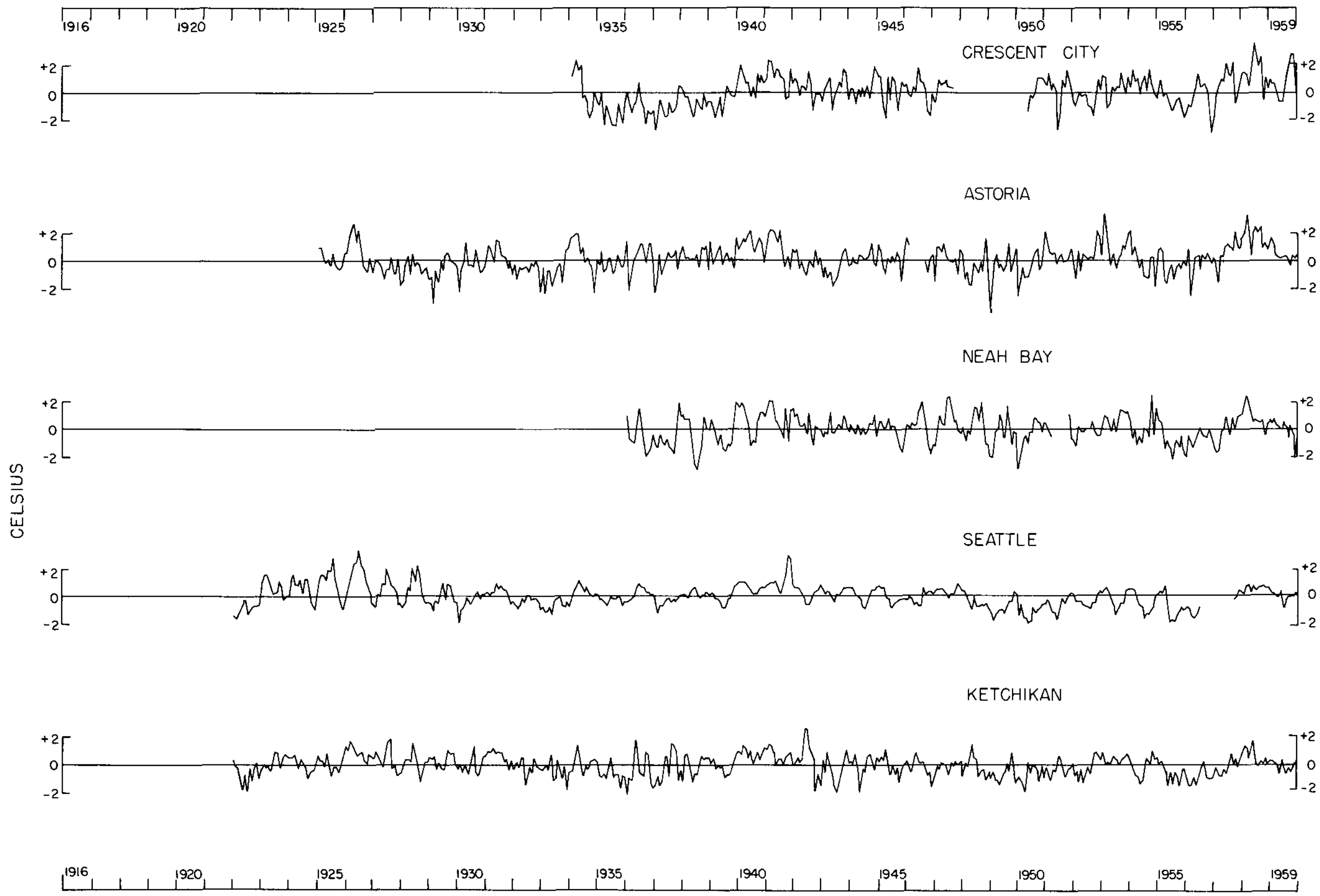

FIGURE 3. Sea surface temperature anomalies at Oregon and Washington stations and at Ketchikan, Alaska.

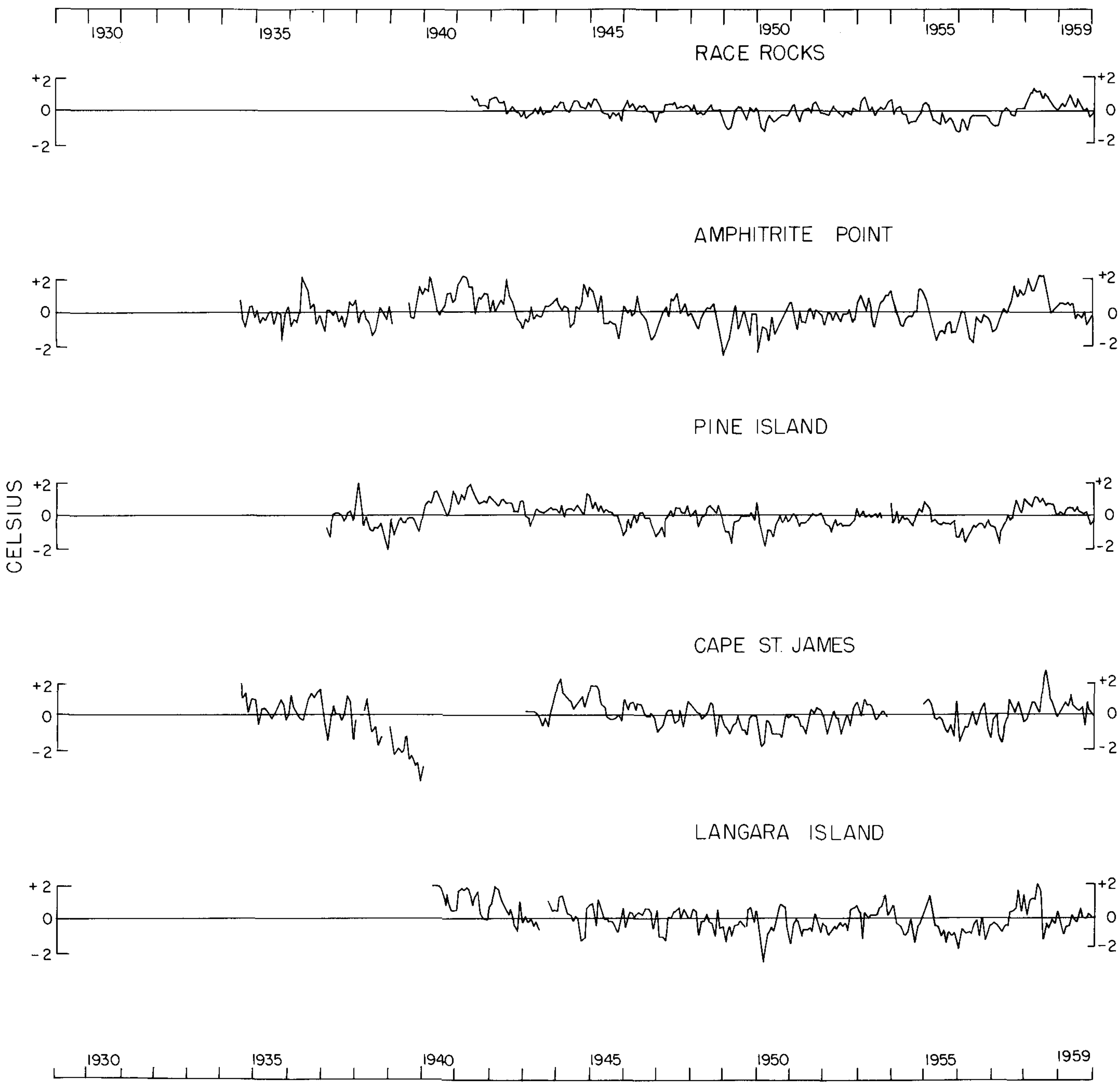

FIGURE 4. Sea surface temperature anomalies at British Columbia stations.

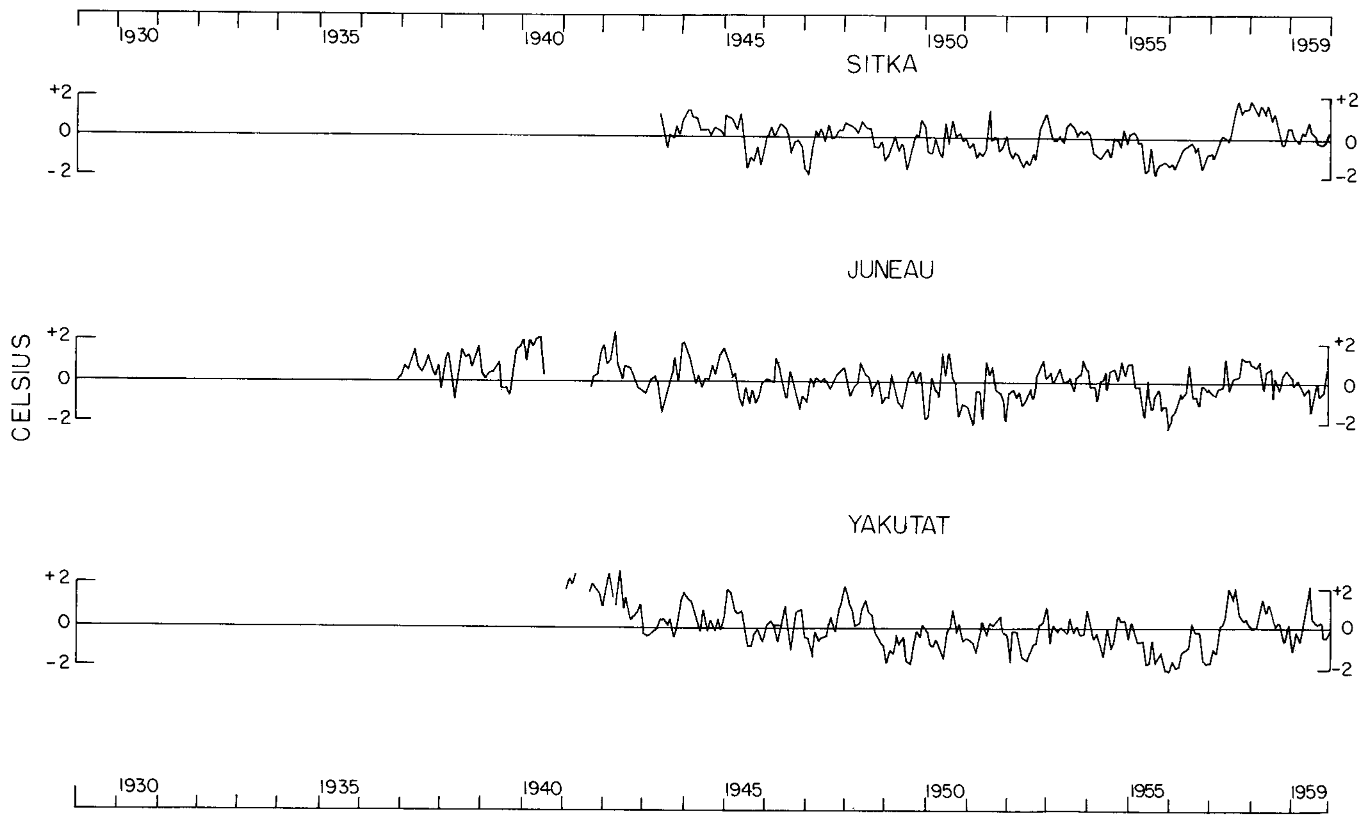

FIGURE 5. Sea surface temperature anomalies at Alaskan stations.

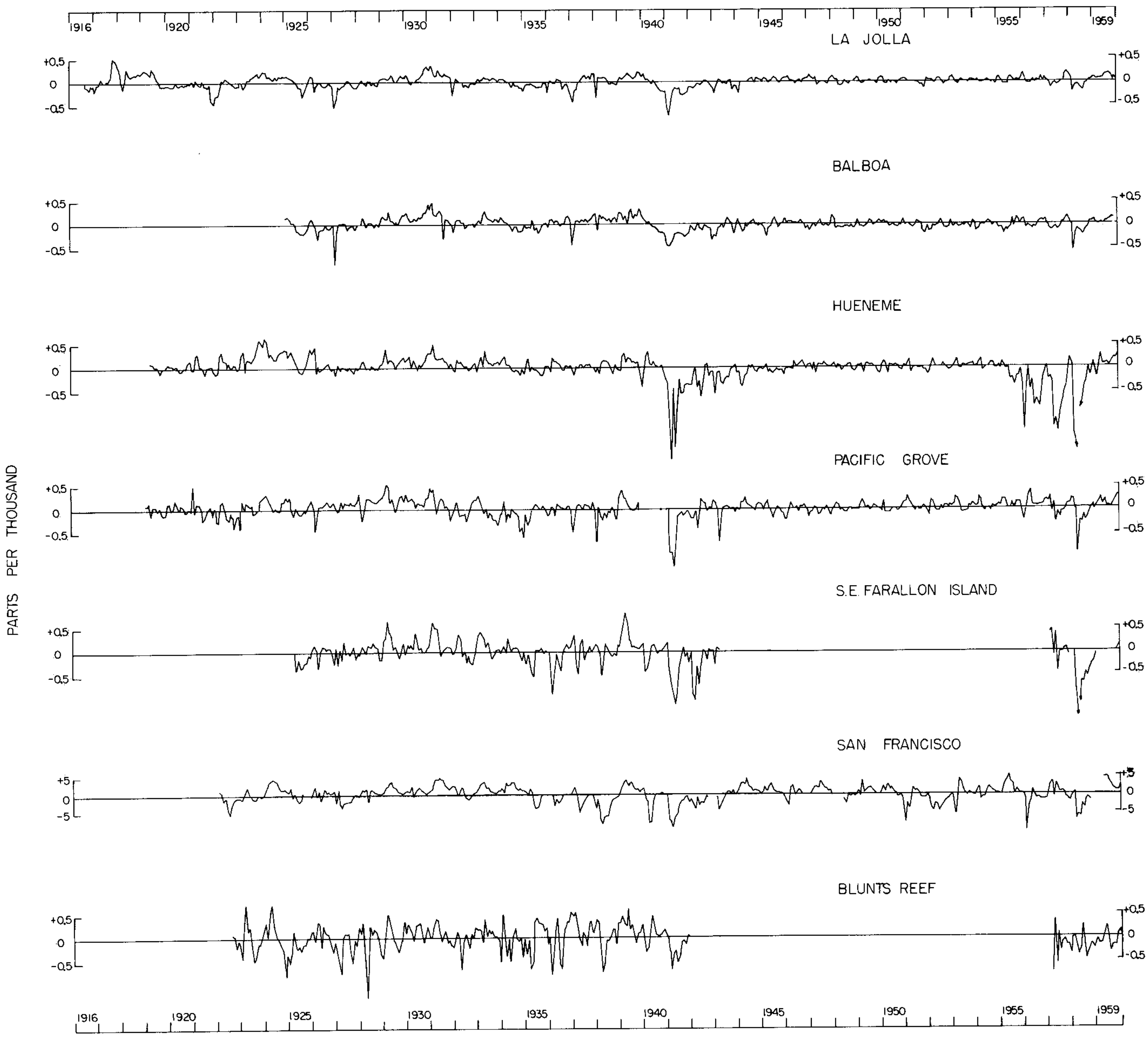

FIGURE 6. Salinity anomalies at California stations. The records for La Jolla, Balboa, Hueneme and Pacific Grove are questionable between 1944 and 1955.

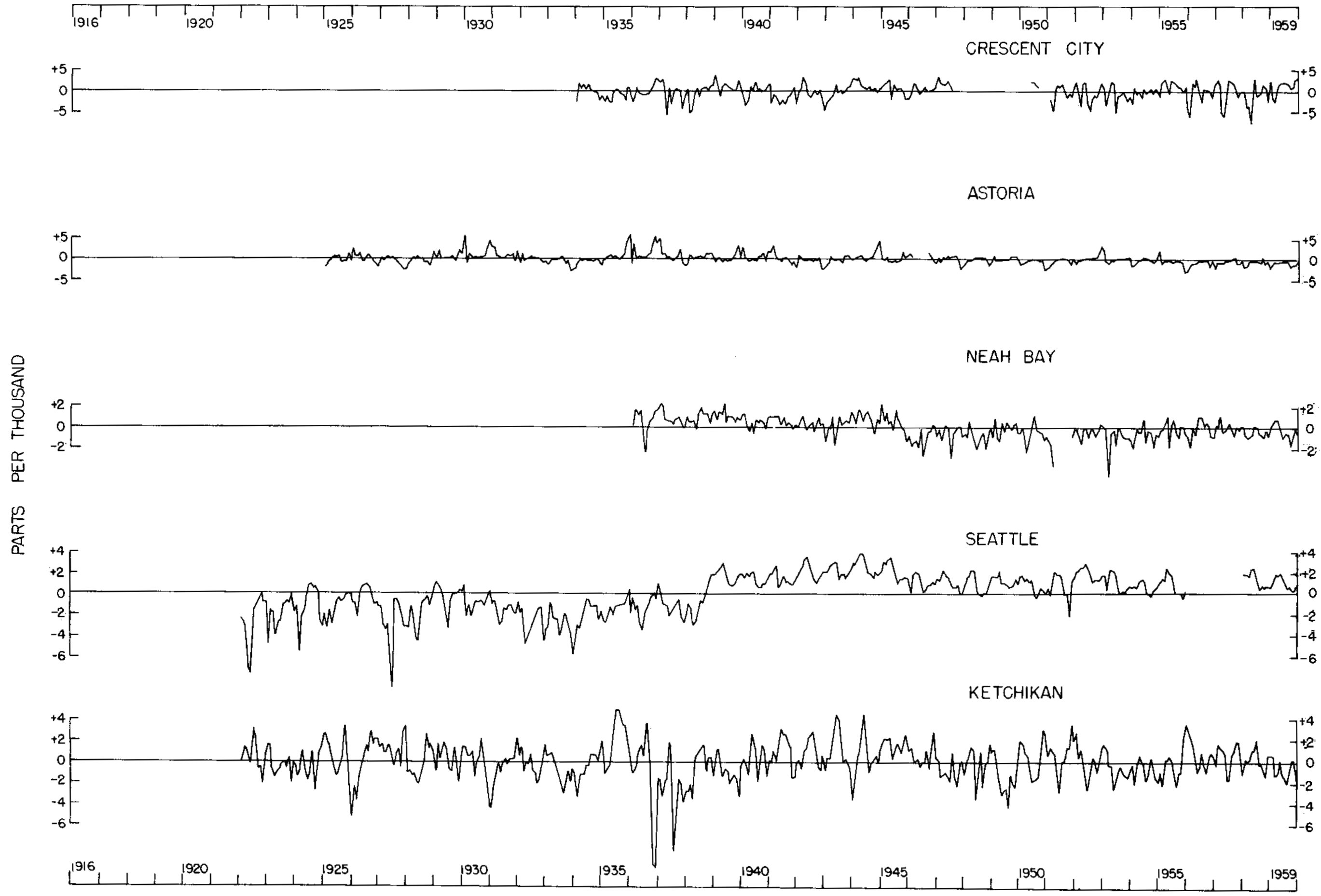

FIGURE 7. Salinity anomalies at Oregon and Washington stations and at Ketchikan, Alaska. The Seattle record is questionable.

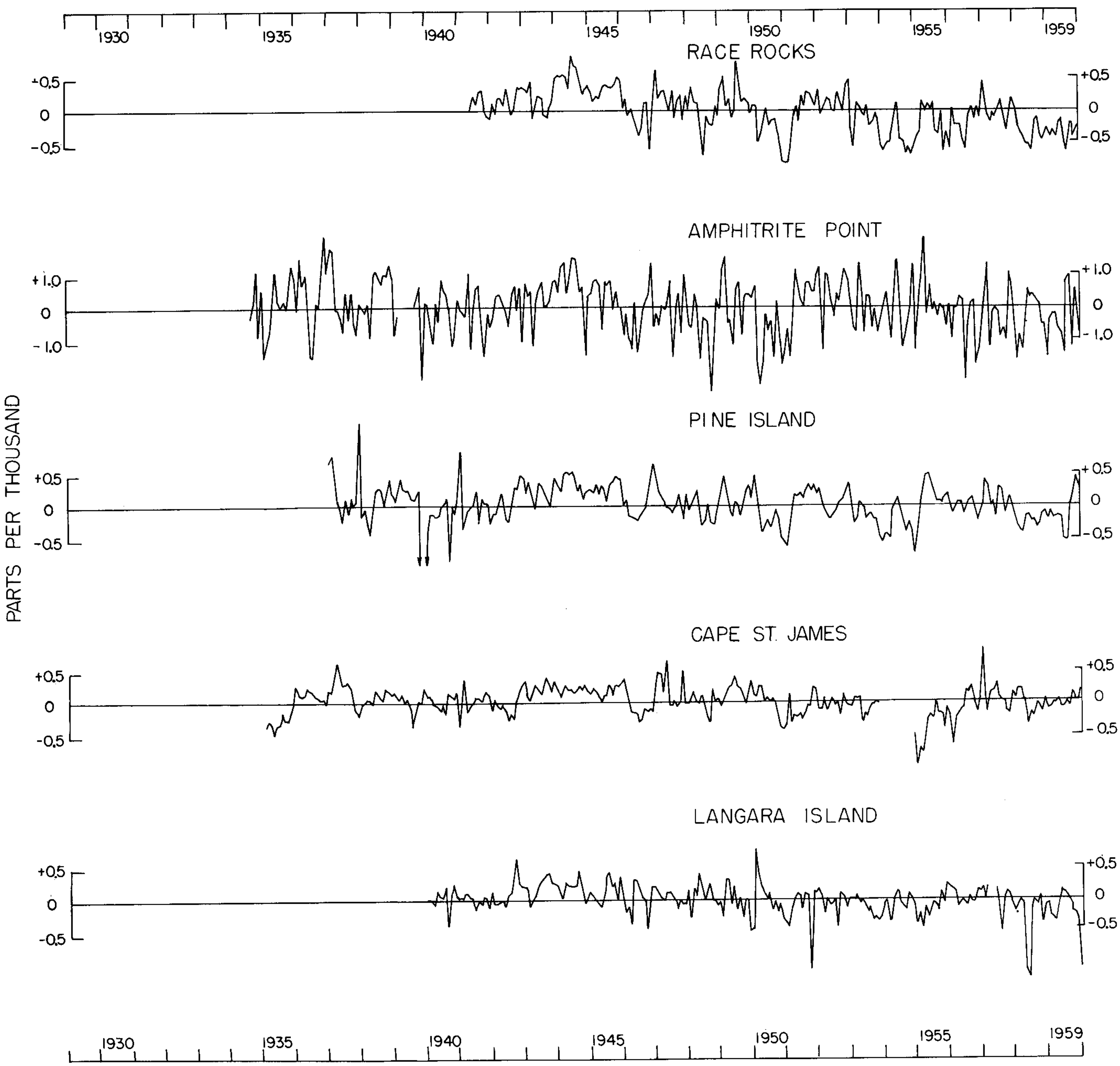

FIGURE 8. Salinity anomalies at British Columbia stations.

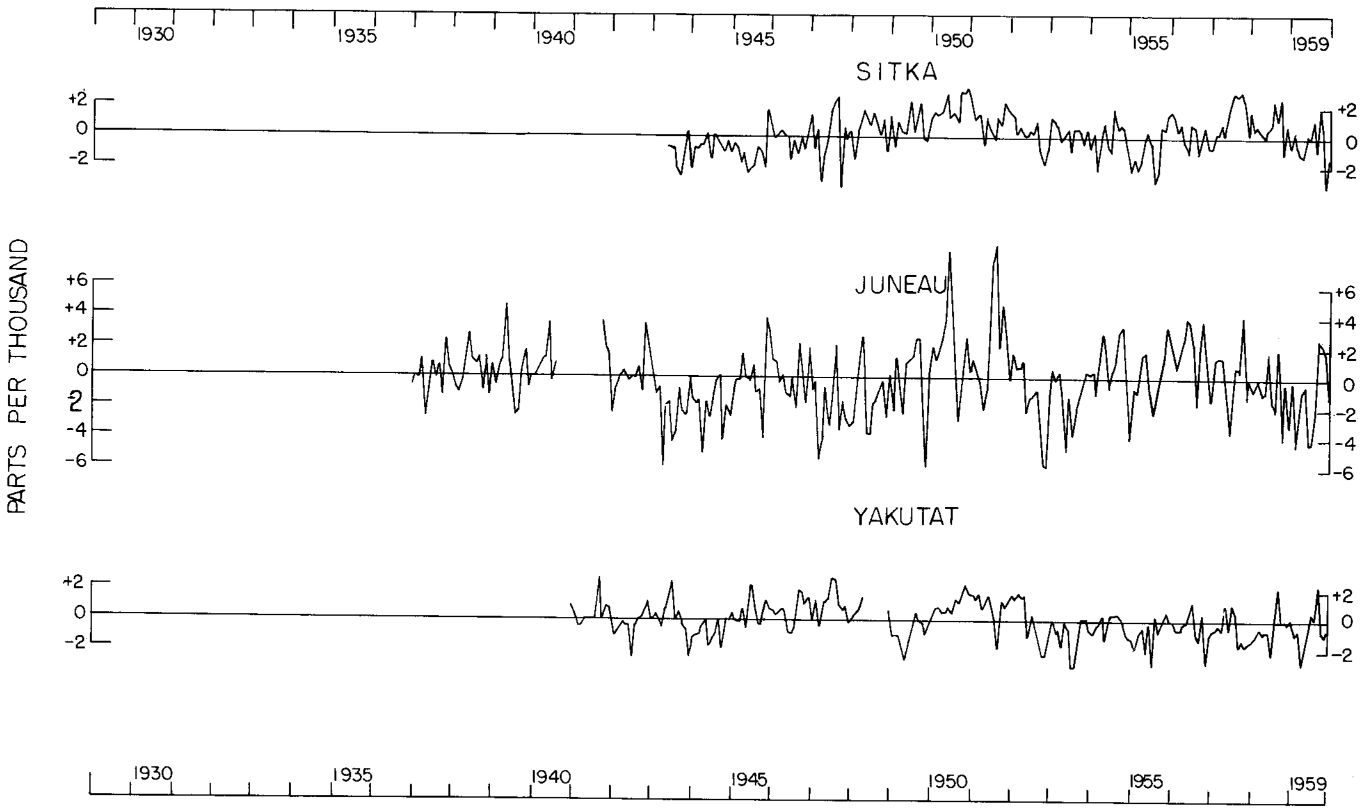

FIGURE 9. Salinity anomalies at Alaskan stations.

Runoff records were obtained from the U.S. Geological Survey (1958) and the Surface Water Branches in Menlo Park, California, and Sacramento, California. They are considered to be accurate within 5% of the individual flow.

The sea surface temperature records are shown in figures 2 to 5. Although the details of the records vary, a few preliminary results can be obtained from a visual inspection of them; (a) the magnitude of the anomalies is about the same for all stations, (b) the maximum amplitude of the anomalies appears to be 4C, (3) there are no obvious periodicities discernible, (d) the anomalies are similar over distances of several hundred kilometers and (e) for the majority of stations the mean of the record does not change appreciably, indicating stationary conditions.

The surface salinity records are shown in figures 6 to 9. A visual examination of them leads to the following preliminary conclusions: (a) the magnitude of the salinity anomalies varies greatly from one station to another, (b) the smallest anomalies are found at stations in Southern California where rainfall is scarce and at stations in straits where tidal mixing is considerable, (c) the largest anomalies occur at stations where there is considerable influence by both runoff and oceanic water, (d) there are no obvious periodicities. The salinity anomalies at La Jolla, Balboa, Hueneme and Pacific Grove show a sharp discontinuity in magnitude and general character about 1944. Although there was some reduction of the magnitude of other anomalies at this time (Isaacs 1960), no sharp discontinuities of the type shown here were observed.

The salinity determinations of the above mentioned stations were all done by the same observer, and it is possible that the discontinuity is due to a change in instrument, or to some other reason. Since the cause is not known, the records between 1944 and 1955 should be regarded with suspicion. Similarly the Seattle record suggests some radical change, and should be questioned.

The probability distribution of sea surface temperature and salinity anomalies is shown in figure 10. It is seen that the temperature anomalies are normally distributed, and that their probabilities vary very little from one station to another. The salinity anomalies are generally not normally distributed, and tend to be negatively skew. This is particularly the case where there is considerable influence of runoff (San Francisco).

The standard deviations and extreme ranges for each of the stations are given in Table 1. For sea surface temperature anomalies there is no dependence upon latitude; the anomalies appear, however, to be larger for stations situated in shallow bays and harbors than for those situated in straits and sounds, suggesting that tidal mixing may be important in reducing the amplitude of the temperature variation. For air temperature anomalies there is a slight dependence upon latitude, the anomalies being somewhat larger at high than at low latitudes. The salinity and precipitation anomalies are dependent upon the particular environment of the station and do not suggest a relation to latitude.

TABLE 1

Standard Deviations (σ) and Extreme Ranges (r) of Monthly Sea Surface Temperature (θ), Salinity (S), Air Temperature (A) and Precipitation (p) Anomalies

STATION*	σ_θ °C	σ_s °/oo	σ_A °C	σ_p cm	r_θ °C	r_s °/oo	r_A °C	r_p cm
La Jolla-San Diego	0.9	0.1	1.1	2.8	6	1	7	24
Balboa-Los Angeles	1.0	0.1	1.3	4.1	7	1	7	24
Hueneme-Sta. Barbara	1.1	0.2	1.2	4.4	7	3	7	34
Pacific Grove-Sta. Cruz	0.9	0.2	1.2	6.0	6	2	7	36
SE. Farallon Isl.-Pt. Reyes	0.9	0.3	..	2.9	5	4	..	24
San Francisco	0.8	2.3	1.0	3.9	5	13	7	33
Blunts Reef-Eureka	0.9	0.3	1.2	5.6	4	3	8	41
Crescent City	1.1	1.7	1.2	11.5	6	10	8	61
Astoria-North Head	1.0	1.1	1.2	..	7	8	9	..
Neah Bay-Tatoosh Isl.	1.0	1.0	1.2	7.3	5	7	10	43
Seattle	0.8	1.9	1.4	4.0	5	11	10	26
Race Rocks-Victoria**	0.5	0.3	1.2	3.4	3	2	10	21
Amphitrite Point**	0.9	0.8	..		4	4		..
Pine Island-Port Hardy**	0.5	0.2	1.3	5.8	4	4	8	37
Cape St. James**	0.8	0.2	..	..	7	2	.	
Langara Island-Masset**	0.8	0.2	1.5	4.2	4	2	11	24
Ketchikan	0.8	1.8	.	13.5	4	14		65
Sitka	0.8	1.3	1.6	9.0	4	6	11	58
Juneau	0.8	2.3	2.0	8.4	4	11	10	42
Yakutat	1.0	1.1	1.9	13.1	5	5	11	107

* Where two names occur, the first refers to the oceanographic, the second to the meteorological station.
** Salinity determined by titration.

COMPUTATIONAL PROCEDURES

Let $\theta\ (t)$ and $A\ (t)$ denote anomalies of sea surface temperature and air temperature, respectively. Then the autocorrelations and crosscorrelations are defined by

$$(1) \qquad \begin{aligned} \phi_{\theta\theta}(\tau) &= \langle\theta(t)\theta(t+\tau)\rangle; \\ \phi_{AA}(\tau) &= \langle A(\mathrm{t})A(t+\tau)\rangle; \\ \phi_{\theta A}(\tau) &= \langle\theta(t)A(t+\tau)\rangle \end{aligned}$$

provided the records are stationary. Here $\langle\ \rangle$ denotes the time average over the entire record length, and τ is the time lag in months.

The power spectral densities and cross power spectral densities are obtained from a Fourier transform of the correlation functions

$$(2) \qquad E_{\theta\theta}(\omega) = \frac{2}{\pi}\int_0^\infty \phi_{\theta\theta}(\tau)\cos\omega\tau d\tau;$$

$$E_{AA}(\omega) = \frac{2}{\pi}\int_0^\infty \phi_{AA}(\tau)\cos\omega\tau d\tau;$$

$$E_{\theta A}(\omega) = \frac{1}{\pi}\int_{-\infty}^\infty \phi_{\theta A}(\tau)e^{-i\omega\tau}d\tau$$

Practical methods for evaluating the power spectra are given by Munk, Snodgrass and Tucker (1959).

The coherence between $\theta\ (t)$ and $A\ (t)$ is defined by

$$(3) \qquad \mathrm{R}_{\theta A}(\omega) = \frac{E_{\theta A}(\omega)}{[E_{\theta\theta}(\omega)\ E_{AA}(\omega)]^{1/2}}$$

and must lie between the values zero and one. If $R = 1$ the coherence is perfect, if $R = 0$ there is no coherence between the two variables. The phase lag of θ (t) over A (t) is defined by

$$(4)\quad \Pi_{\theta A}(\omega) = \text{arc tan}\,\frac{E_{\theta A}(\omega) - E_{A\theta}(\omega)}{E_{\theta A}(\omega) + E_{A\theta}(\omega)}$$

provided that for a positive numerator $0 \leqq \pi \leqq 180$ and for a negative numerator $180 \leqq \pi \leqq 360$. If $\pi = 0$ degrees, the two variables are related directly to each other, if $\pi = 180$ degrees there exists an inverse relationship between them.

Similar relations can be established for any other pair of variables. The length of the records used varies from 163 months at Crescent City to 444 months at Ketchikan. The length of the record at each station, n, the number of lags used, m, and the resulting *degrees of freedon*, ν, defined by

$$(5)\quad \nu = \frac{2n}{m}$$

are given in Table 2. Also shown in this table are the 95% confidence limits for the power spectra, provided the variables are normally distributed.

TABLE 2

Total Length of Record (n), Number of Spectral Estimates Used (m), and Resulting Degrees of Freedom (ν). Also Given Are the 95 Percent Confidence Limits for the Power Spectra (P)

STATION	n month	m month	ν	P (unit)^2/c.p.y.
La Jolla-San Diego	504	24	42	0.67–1.62
Balboa-Los Angeles	348	24	29	0.63–1.81
Hueneme-Sta. Barbara	420	24	35	0.66–1.69
Pacific Grove-Sta. Cruz	480	24	40	0.67–1.64
SE. Farallon Isl.-Point Reyes	204	24	17	0.56–2.25
San Francisco	336	24	28	0.63–1.83
Blunts Reef-Eureka	228	24	19	0.58–2.13
Crescent City	163	24	14	0.53–2.54
Astoria-North Head	372	24	31	0.64–1.78
Neah Bay-Tatoosh Isl.	276	84	23	0.60–1.97
Seattle	408	24	34	0.65–1.71
Race Rocks-Victoria	192	24	16	0.56–2.73
Amphitrite Point	276	24	23	0.60–1.19
Pine Island-Port Hardy	174	24	15	0.55–2.40
Cape St. James	192	24	16	0.56–2.31
Langara Island-Masset	228	24	19	0.58–2.13
Ketchikan	444	24	37	0.66–1.67
Sitka	192	24	16	0.56–2.31
Juneau	204	24	17	0.56–2.25
Yakutat	216	24	18	0.57–2.19

It should be pointed out that the power spectral densities depend upon the amount of averaging done upon the original data (Munk 1960); if the monthly means were obtained from hourly readings, the power spectrum will be different from one where the monthly means were obtained from daily readings. In case of a simple Markov process the power is decreased by an increased amount of averaging.

The computations of the power spectra, coherence and phase were performed on a IBM 709 electronic calculator at the Western Data Processing Center in Los Angeles.

POWER SPECTRA OF TEMPERATURE AND SALINITY ANOMALIES

The power spectra of sea surface temperature anomalies are shown in figure 11 for the frequency range between zero and 6 cycles per year (c.p.y.). It is seen that most of the power is concentrated at low frequencies, mainly between 0 and 1.5 c.p.y. and that the high frequency end of the spectrum contains relatively little power. This suggests that there is very little contamination from frequencies beyond 6. c.p.y. in the spectra shown here. Most of the spectra indicate an exponential decrease of the power with frequency, suggesting a Markov type process, for which prediction is not very effective (Roden and Groves 1960). The spectra for Neah Bay, Washington, and Seattle, Washington, show peaks near 1 c.p.y., which, when real, would indicate an annual periodicity. The peaks are, however, barely significant (upon applying the confidence limits shown in Table 2), and the periodicity is therefore not well established.

The power spectra of surface salinity anomalies are shown in figures 12 and 13. Most of the power is concentrated between 0 and 2 c.p.y., and for the majority of stations the spectra do not contain any power for frequencies higher than about 4 c.p.y. There is a large variation from station to station of the power contained in each spectrum; the Canadian stations located on small islands and the Californian island stations contain a hundred times less power than those along the mainland coast, excepting the Southern California stations. There are no significant peaks, or periodicities, contained in spectra of the salinity anomalies.

COHERENCE AND PHASE BETWEEN SEA SURFACE AND AIR TEMPERATURE ANOMALIES

The coherence (Fig 14) between sea and air temperature anomalies is moderate to good for stations along the open coast and for island stations, and is relatively poor for stations located considerable distances from the open coast along inland sounds. Thus for Blunts Reef, Neah Bay and Yakutat the coherence varies around 0.7 whereas for Seattle and Juneau it is only 0.4 or less. The maximum values of coherence vary around 0.9, indicating that in the most favorable cases about 80% of the anomalies can be related to each other. The phase (Fig. 15) between sea and air temperature anomalies varies around zero degrees and is at most stations independent of frequency, which suggests a direct relation between sea and air temperature anomalies, for all frequencies between 0 and 6 c.p.y. The considerable scatter at Juneau together with the low coherence indicates the absence of any significant relationship there.

The ratio of the power of sea surface to air temperature anomalies is shown in Table 3. For the Californian stations and Yakutat the ratio is somewhat larger at low than at high frequencies suggesting that a certain time is required for the anomalies to respond to each other. For Neah Bay and Langara Island there is no simple dependence upon frequency.

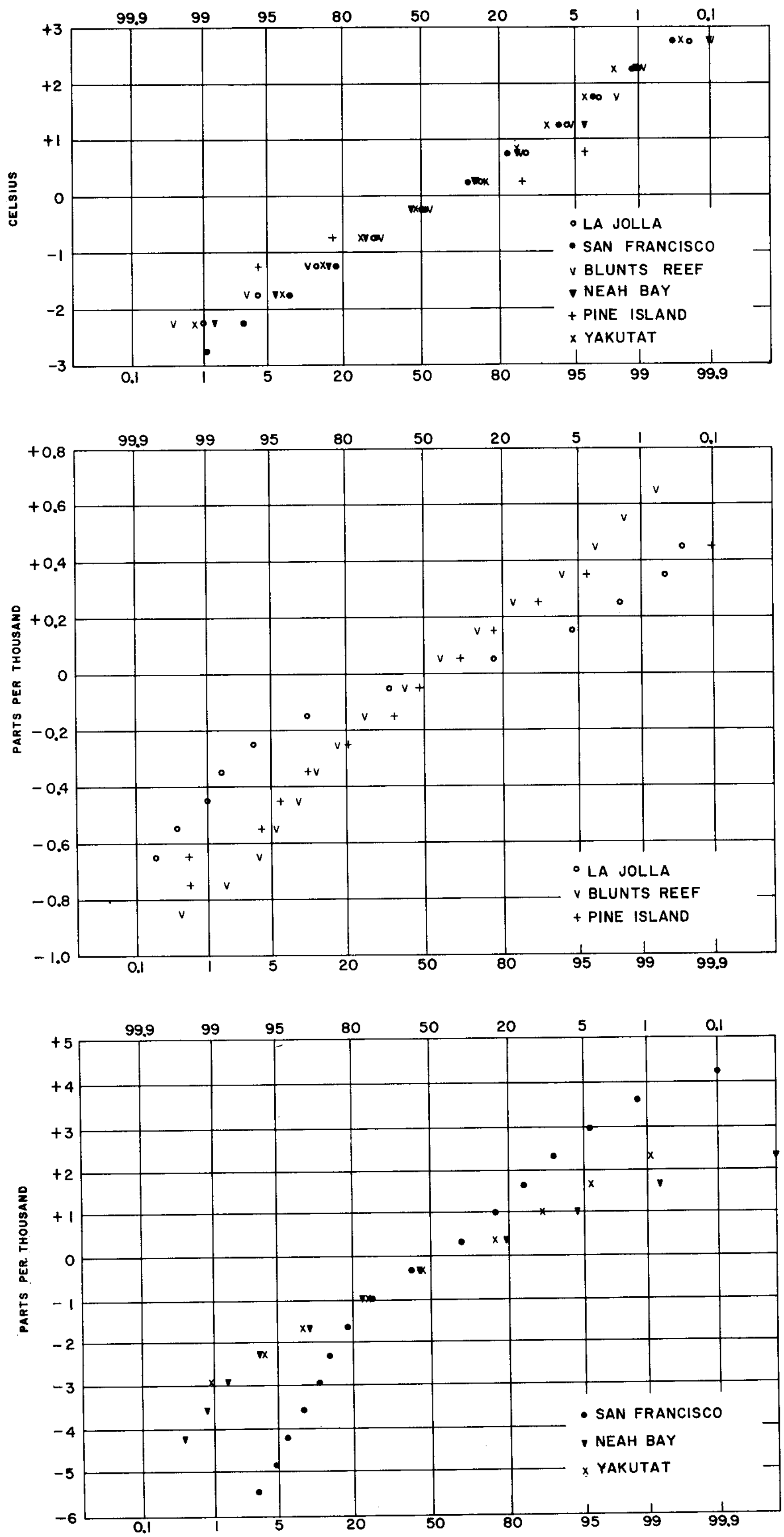

FIGURE 10. Probability distribution of sea surface temperature and salinity anomalies.

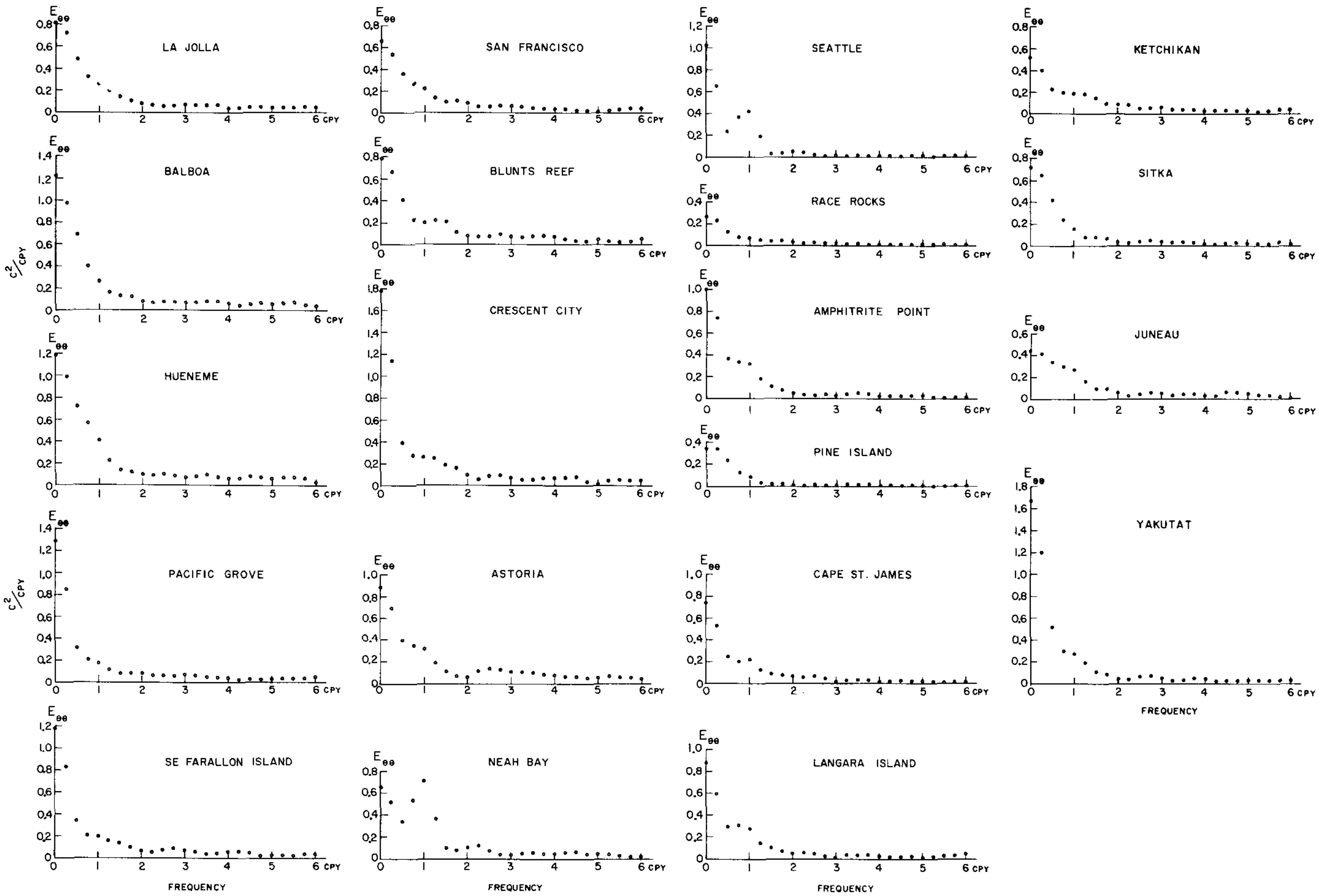

FIGURE 11. Power spectra of sea surface temperature anomalies.

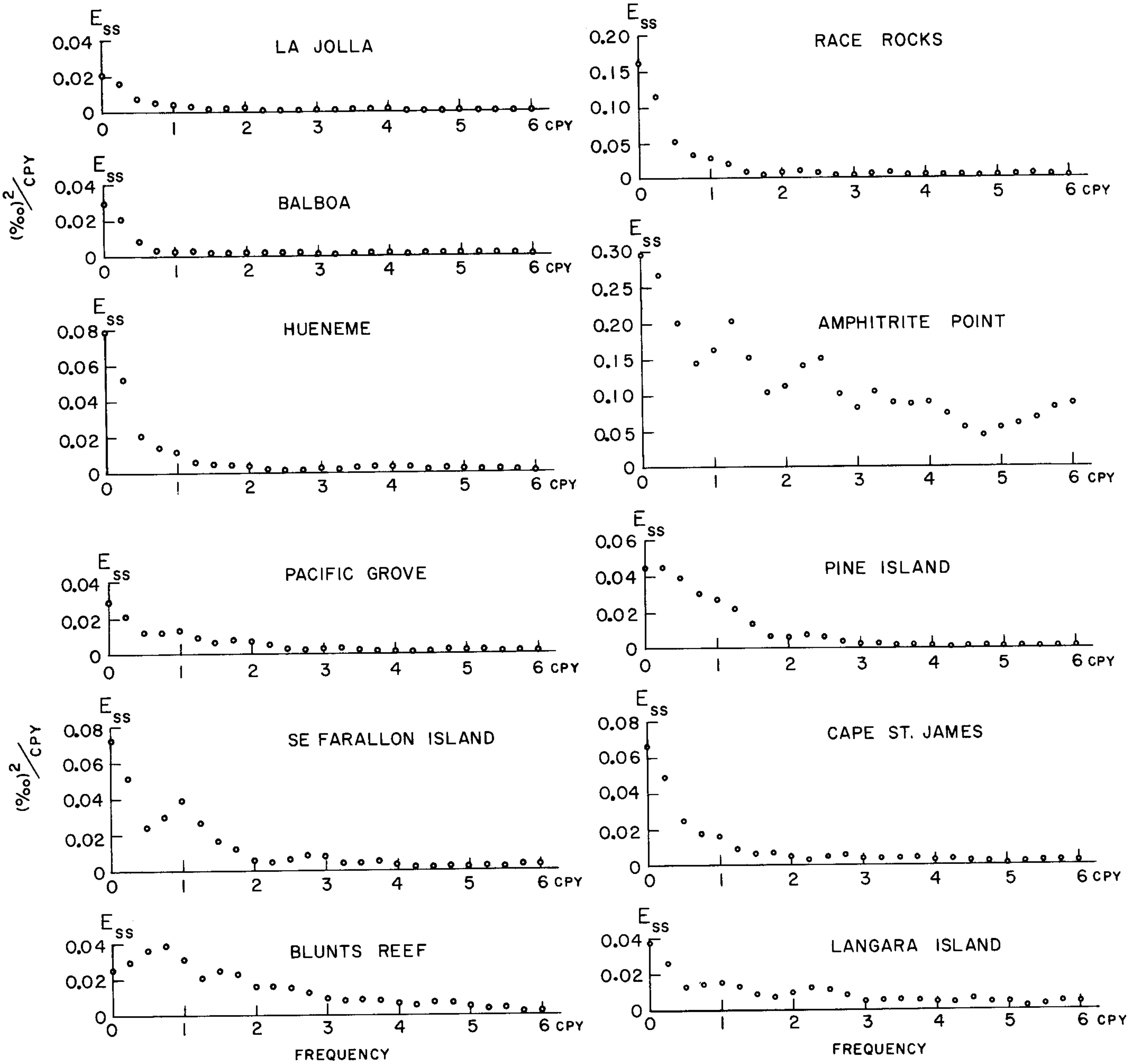

FIGURE 12. Power spectra of salinity anomalies.

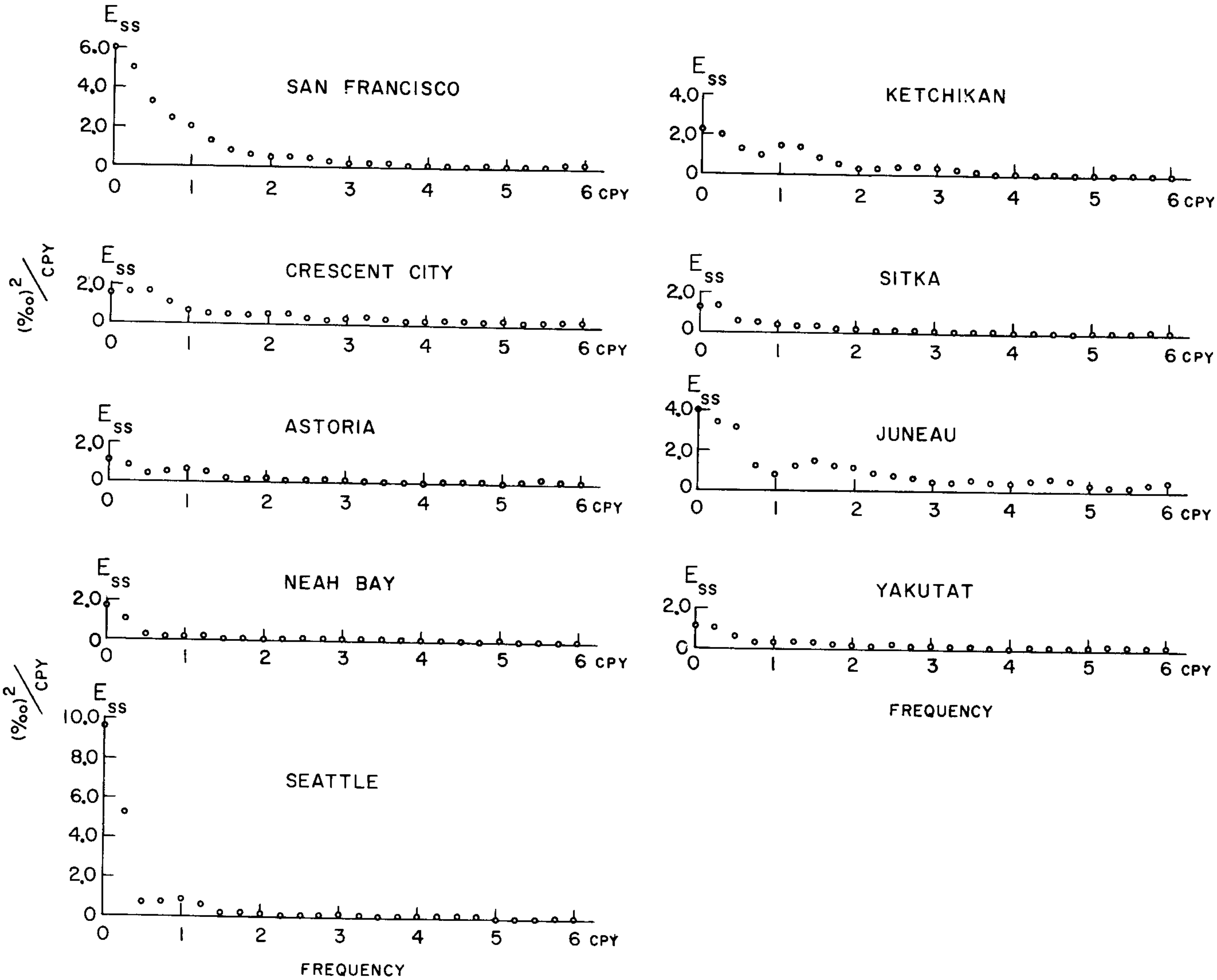

FIGURE 13. Power spectra of salinity anomalies.

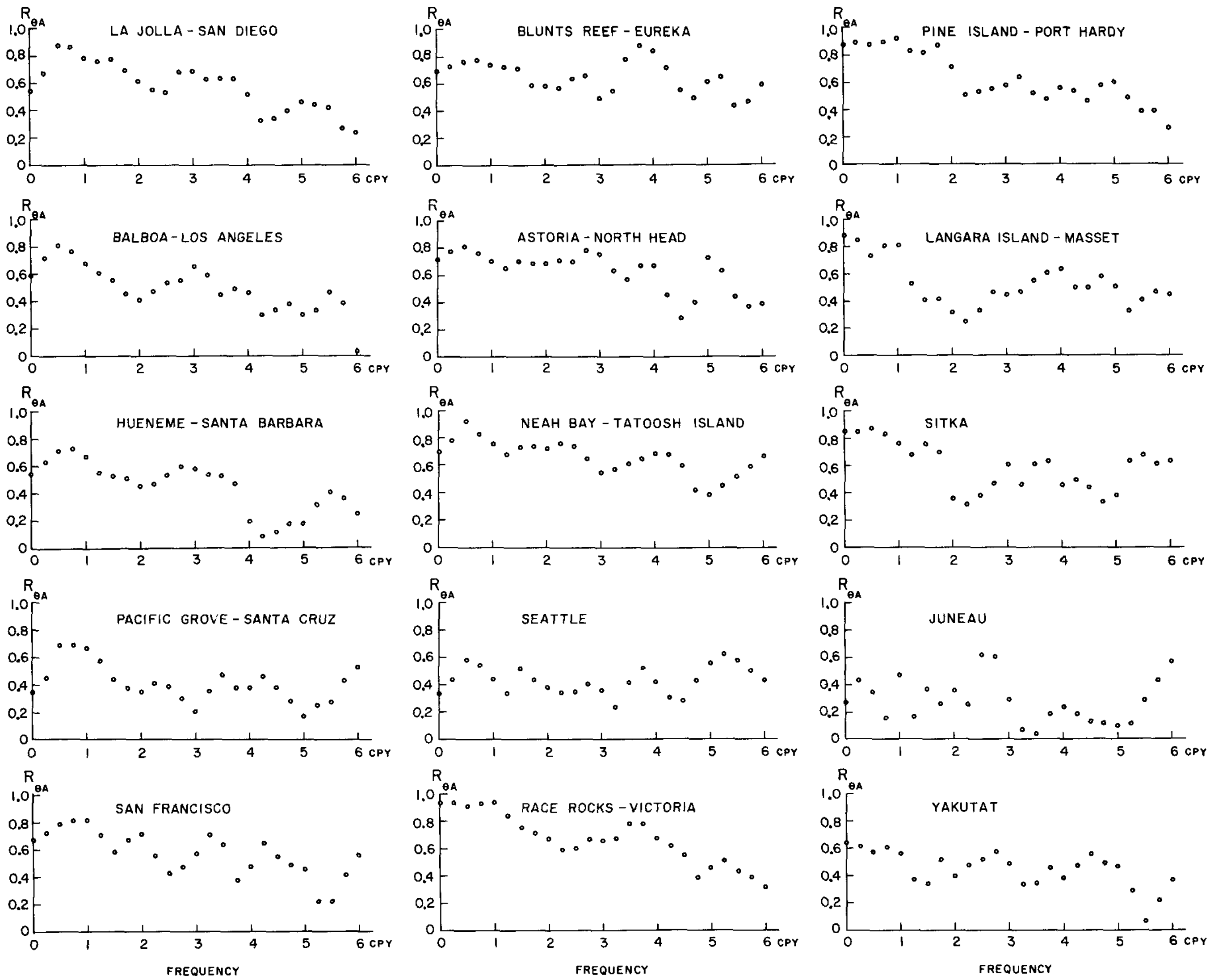

FIGURE 14. Coherence between sea surface temperature and air temperature anomalies.

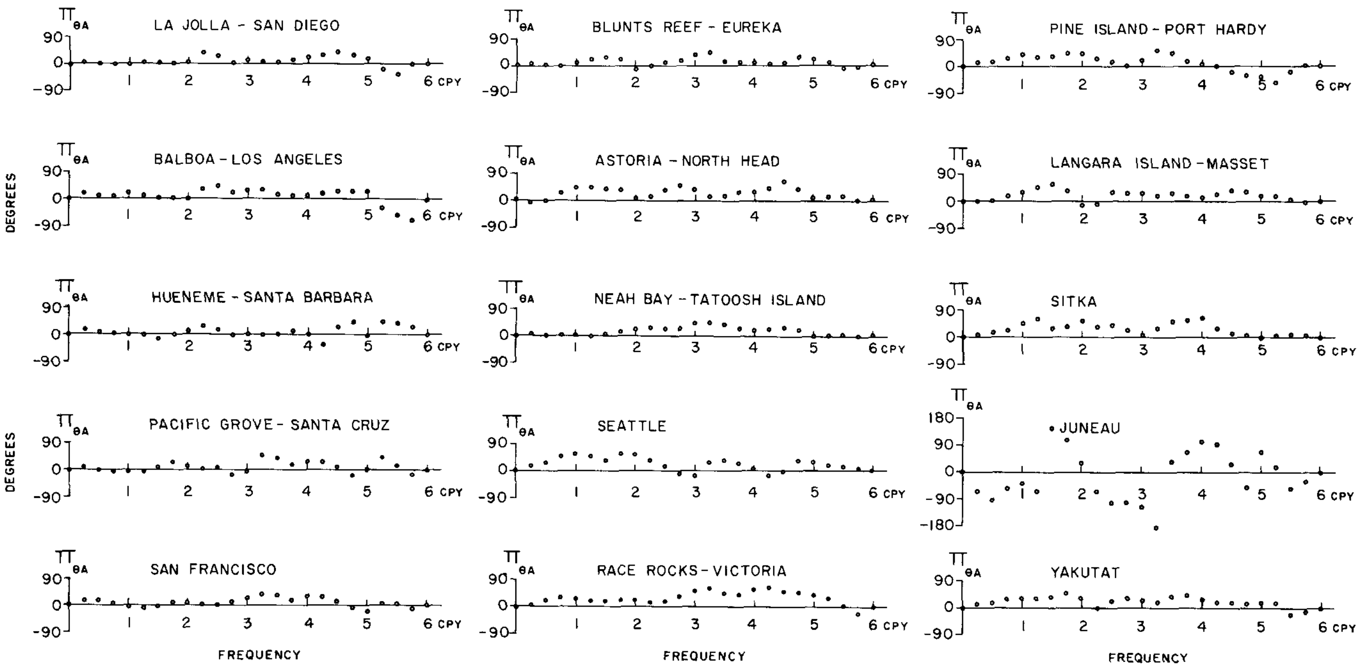

FIGURE 15. Phase between sea surface temperature and air temperature anomalies.

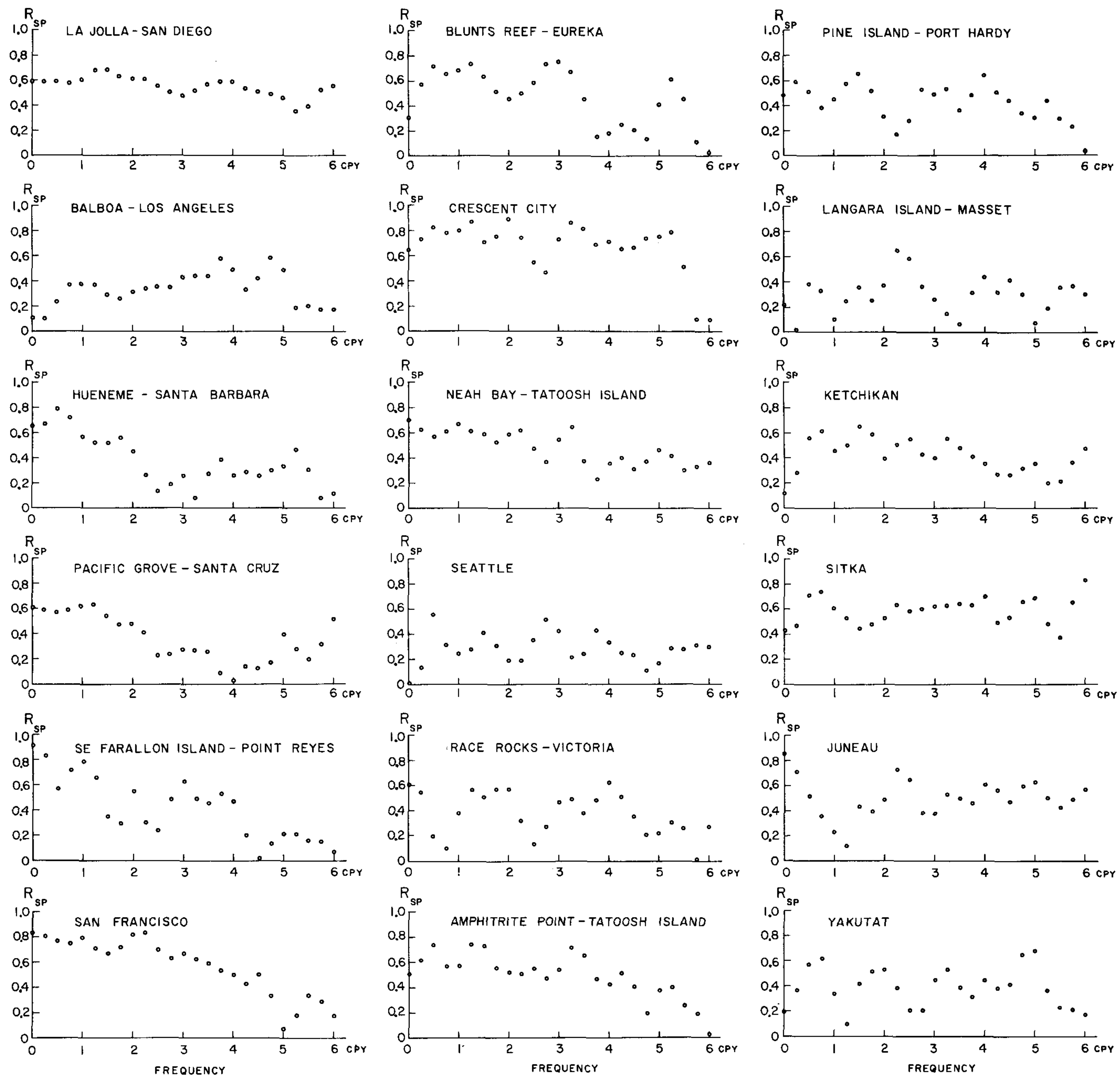

FIGURE 16. Coherence between salinity and precipitation anomalies.

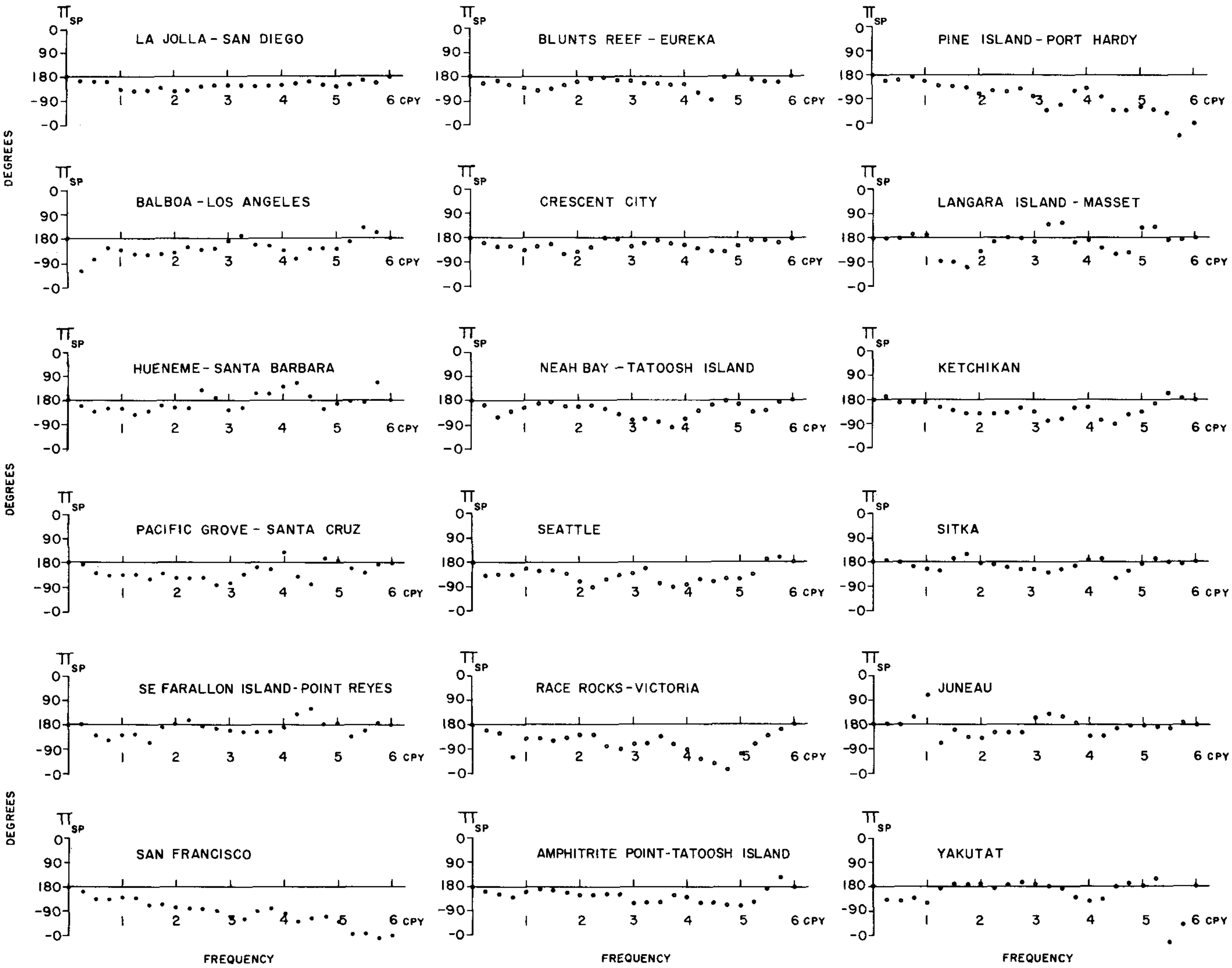

FIGURE 17. Phase between salinity and precipitation anomalies.

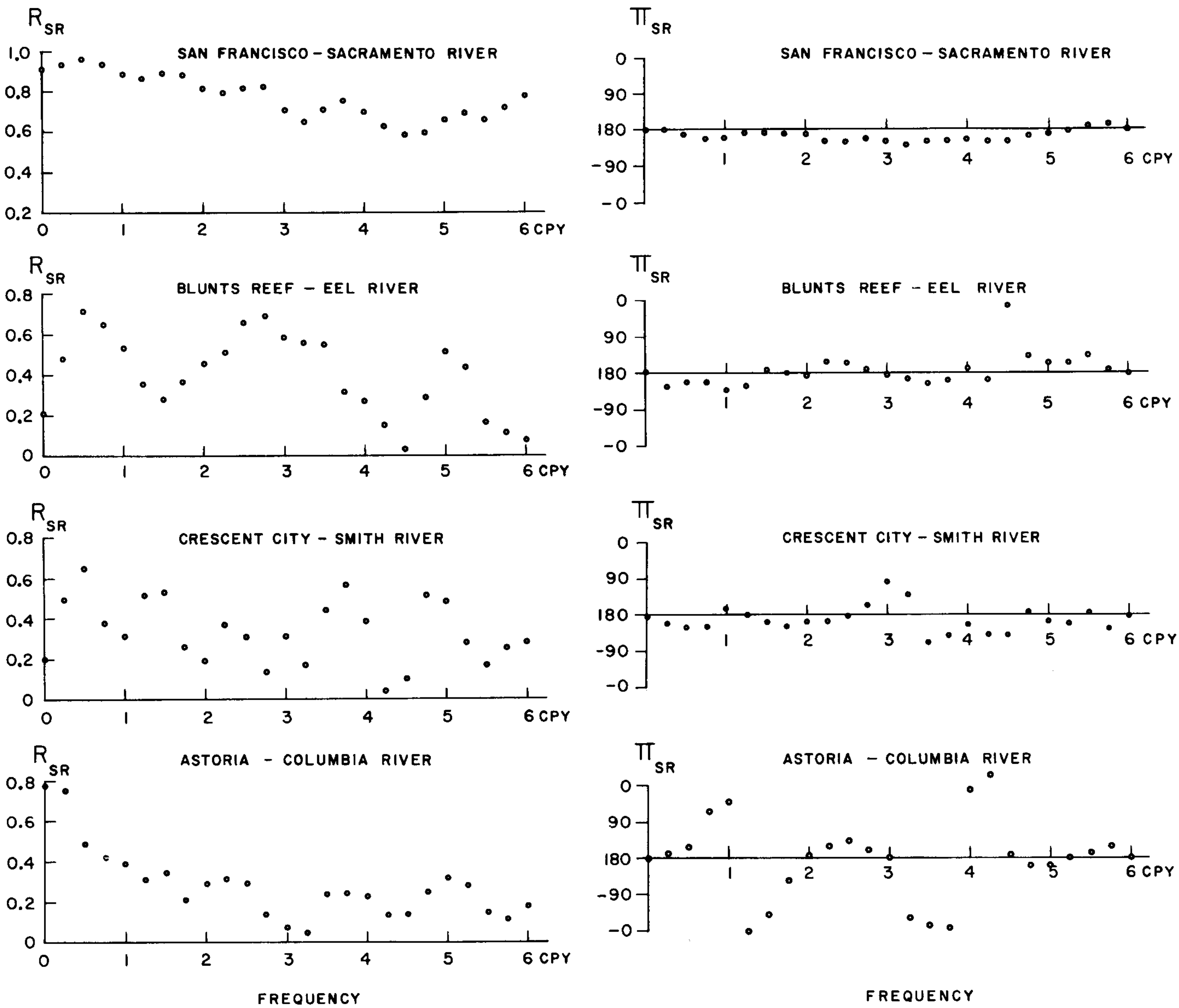

FIGURE 18. Coherence and phase between salinity and river discharge anomalies.

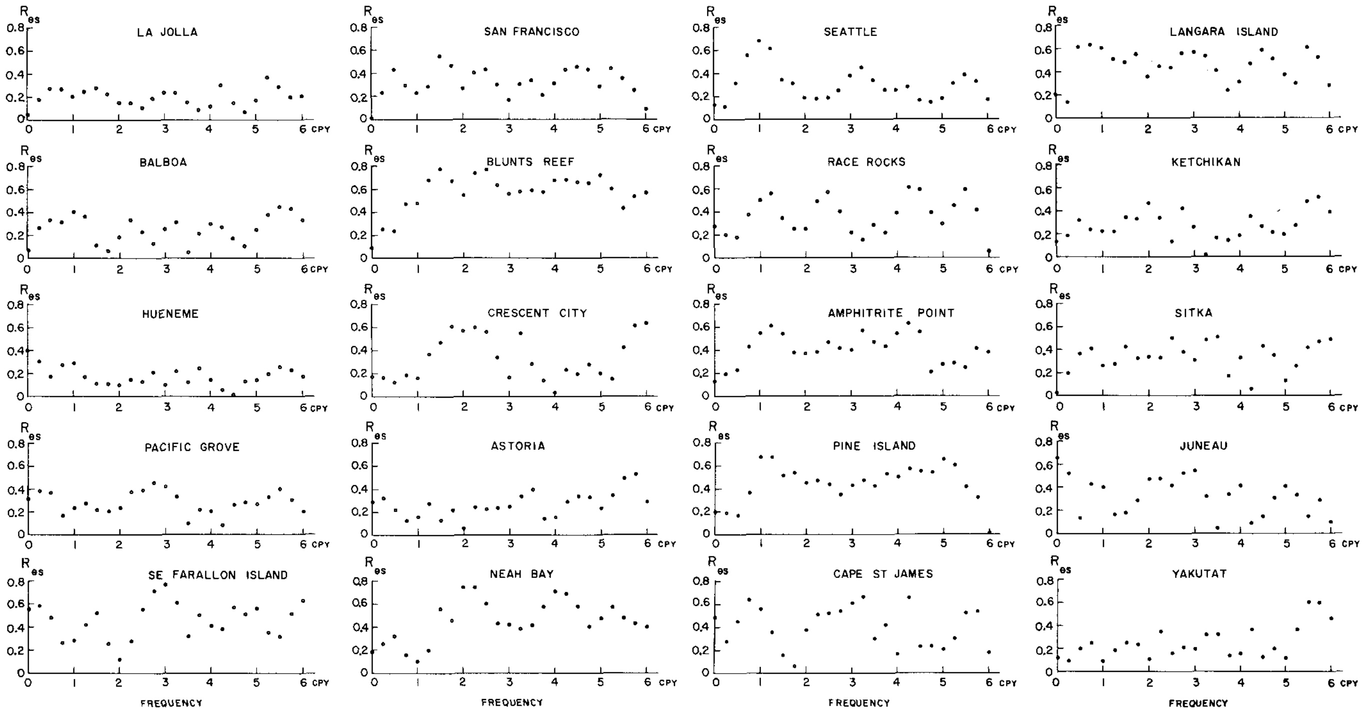

FIGURE 19. Coherence between sea surface temperature and salinity anomalies.

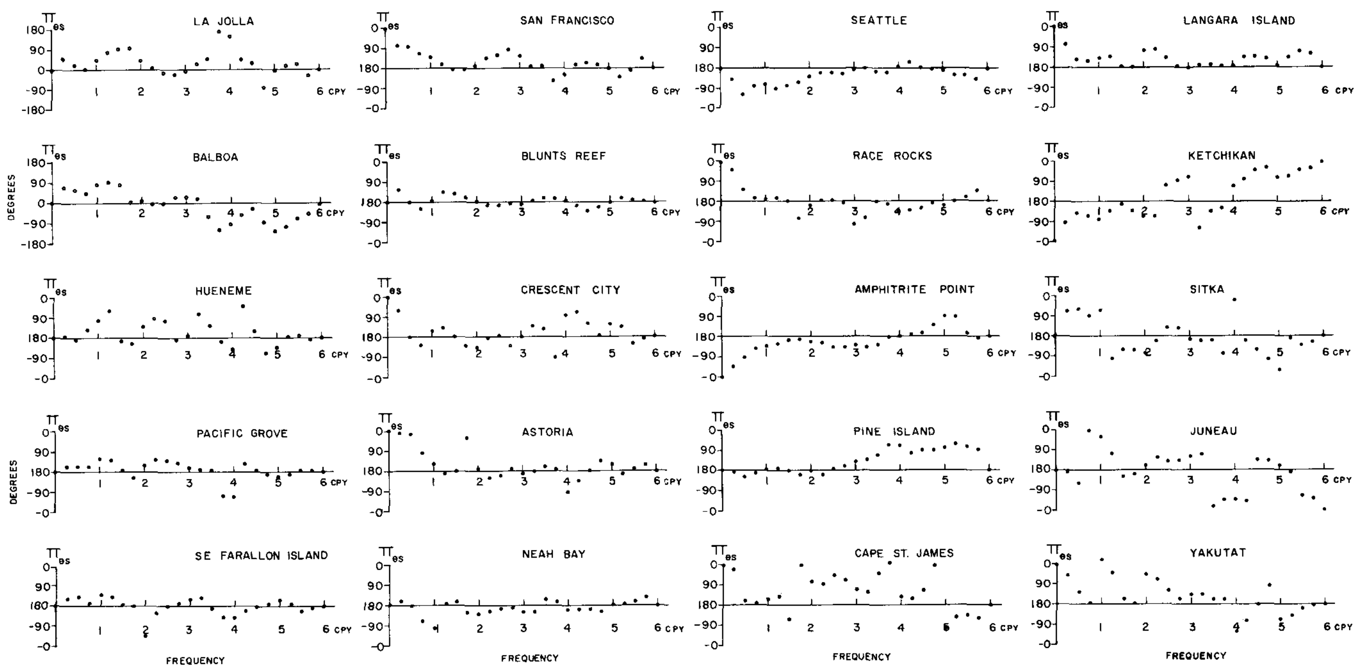

FIGURE 20. Phase between sea surface temperature and salinity anomalies.

TABLE 3

The Ratio E_{00}/E_{AA} As a Function of Frequency

f c.p.y.	La Jolla	San Francisco	Blunts Reef	Neah Bay	Langara Isl.	Yakutat
0	0.70	0.73	1.01	0.45	0.36	0.65
1	0.84	0.69	0.67	1.39	0.68	0.30
2	0.67	0.64	0.57	0.54	0.25	0.10
3	0.44	0.70	0.42	0.28	0.11	0.14
4	0.40	0.50	0.47	0.39	0.15	0.16
5	0.50	0.50	0.31	0.83	0.13	0.10
6	0.56	0.50	0.37	0.50	0.45	0.06

COHERENCE AND PHASE BETWEEN SALINITY AND PRECIPITATION ANOMALIES

The coherence (Fig. 16) between salinity and precipitation anomalies varies widely from station to station, because of the very local character of rainfall. For La Jolla, Crescent City, Neah Bay, Amphitrite Point and Sitka the coherence is relatively high and does not vary much with frequency. About 40% to 60% of the salinity anomalies at these stations can be related to anomalies in precipitation. At San Francisco and SE Farallon Island the coherence is high at low frequencies (0 to 3 c.p.y.) and low at high frequencies, which suggests that short period salinity variations are related to some other factor than rainfall. At Blunts Reef the coherence scatters widely, which is probably due to the influence of upwelling, in addition to precipitation, upon the surface salinity. The phase (Fig. 17) between the anomalies is generally 180 degrees, which shows that salinity and precipitation anomalies are related inversely to each other. At San Francisco and a few other places there is a phase drift from 180 degrees at low frequencies to 0 degrees at high frequencies; this is, however, not significant in view of the low values of coherence at higher frequencies.

COHERENCE AND PHASE BETWEEN SALINITY AND RUNOFF ANOMALIES

At stations located near rivers, the variation in the discharge of the river can be expected to have considerable influence upon the surface salinity. This is particularly true of stations located near the boundary of oceanic and river water. In figure 18 are shown the coherence and phase between the salinity anomalies at Fort Point, San Francisco and the discharge of the Sacramento River at Verona, and other cases. It is seen that about 70% of the San Francisco salinity anomalies can be accounted for in terms of anomalies of river discharge. The relatively low coherence between the salinity anomalies at Astoria and the discharge of the Columbia River at The Dalles is not surprising in view of the fact that Astoria is located right at the river and is seldom influenced by oceanic water. The coherence between the Blunts Reef salinity and the Eel River discharge at Scotia is moderate, and is better at certain frequencies than at others, which is probably due to the additional influence of upwelling upon the salinity. In the best cases about 50% of the salinity anomaly can be related to discharge anomalies. The coherence between the Crescent City salinity anomalies and the discharge of the Smith River near Crescent City is not particularly good. The phase between salinity and runoff anomalies is 180 degrees where the coherence is high.

COHERENCE AND PHASE BETWEEN SEA SURFACE TEMPERATURE AND SALINITY ANOMALIES

The coherence between surface temperature and salinity anomalies (Fig. 19) is moderate for stations on islands and on well exposed capes and points, and relatively poor elsewhere. The best coherence is found for Blunts Reef Lightship, where for frequencies between 1.5 and 6 c.p.y. about 50% of the variations can be related to each other. The phase (Fig. 20) is 180 degrees indicating that an inverse relation exists between the anomalies. This is not surprising, since in summer low temperatures are associated with high salinities, owing to upwelling, and in winter relatively high temperatures are connected with low salinities due to abundant precipitation. A similar but poorer relation is also found at SE Farallon Island. Several northern stations, particularly Race Rocks, B.C., and Seattle, Washington, show an oscillation of the coherence with frequency; the cause for this remarkable feature is not known. The phase between temperature and salinity anomalies scatters about 180 degrees at many stations which suggests that high temperatures are associated with low salinities and vice versa; this is not an unexpected result in view of the extensive upwelling occuring during summer months.

CONCLUSION

The following results were obtained from a statistical analysis of the various oceanographic and meteorological records:

(1) At most well exposed stations air temperature anomalies can be used as an indicator of sea surface temperature anomalies. The relation between these anomalies is direct and instantaneous.

(2) At most stations not affected by river discharge local precipitation anomalies can be used as an indicator of salinity anomalies. The relation between these anomalies is an inverse one.

(3) The relation between river discharge and salinity anomalies is good at stations located at the boundary between oceanic and river water. It is not good upstream. The anomalies are related inversely to each other.

(4) Temperatures and salinity anomalies at most coastal stations are not related to each other. At island stations and on lightships there is a moderate and inverse relation between these anomalies. The inverse relation between temperature and salinity anomalies is characteristic of upwelling regions off the west coast of the United States.

(5) Sea surface and air temperature anomalies occur more or less simultaneously over very large areas. Salinity and precipitation anomalies are very local phenomena.

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