SEA-SURFACE TEMPERATURE ESTIMATION

Time-series length necessary for long-term estimation of sea-surface temperature

E. R. Anderson and C. J. Van Vliet • Research Report • 17 January 1967

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PROBLEM

Develop statistical, physical, and computer techniques for interpreting, summarizing, and extrapolating oceanic and meteorologic data for reliable estimation of the sound velocity distribution in the ocean. Specifically, determine the length of time-series necessary to produce reliable long-time estimates of sea-surface temperatures; and, as a corollary, find whether or not systematic variations of sea-surface temperatures, over periods of several years, are to be expected.

RESULTS

1. Using autocorrelation and regression techniques, six time-series of sea-surface temperature measurements were examined.

2. Plots of the $100R^2$ statistic (percent variance explained by regression) as a function of time-series record length for the six time-series records considered lead to the conclusion that record lengths of 8 to 10 years are necessary to obtain reliable long-time estimates of sea-surface temperature. This conclusion is supported by the behavior of the autocorrelation coefficients for the 40-year Scripps Pier record.

3. An examination of the annual average temperatures confirmed previously published conclusions regarding the systematic year-to-year variability in sea-surface temperatures. In addition it showed that such long-term variability is not unusual or unexpected.

ADMINISTRATIVE INFORMATION

Work was performed under SR 104 03 01, Task 0586 (NEL L40571). The report covers work from July 1961 to August 1964 and was approved for publication 17 January 1967.

The assistance of Dr. George W. Snedecor, in providing motivation, encouragement, and advice; of Mrs. J. M. Baker, J. S. Buehler, and H. W. Frye, for numerical analysis assistance; and of Mrs. G. L. Jones, for handling the many details essential to the success of such a study, is gratefully acknowledged.

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INTRODUCTION

This study is the fourth in a series of studies concerned with the analysis of sea-surface temperature observations. The first study dealt with the effect of missing data in long time-series of sea-surface temperature measurements on certain regression and autocorrelation analyses.[1] The second examined the use of regression models for time-space interpolation of sea-surface temperature observations.[2] The third presented the results of an autocorrelation, regression, and trend analysis of time-series of sea-surface temperature measurements made at six locations representing different oceanographic conditions and considered the difficulties encountered in applying these techniques to oceanographic data samples.[3]

This study considers the oceanographic aspects of the last of the above studies.[3] In particular, it examines the length of time-series necessary to produce reliable long-time estimates of sea-surface temperature. In addition, it considers the corollary question of whether or not systematic variations of sea-surface temperatures, over periods of several years, are to be expected.

TIME-SERIES LENGTH

The length of time-series necessary to produce reliable long-term estimates of sea-surface temperatures interests oceanographers concerned with observational programs for obtaining information necessary for establishing average sea-surface temperatures.

The time-series of data used to obtain insight into this question are listed in table 1. Van Vliet and Anderson[3] concluded from their autocorrelation, regression, and trend analyses of these time-series that the following regression model, with $k = 2$, provided a good statistical fit to the observed daily sea-surface temperatures:

$$T' = \beta_0 + \sum_{i=1}^{k} \alpha_i \sin\left[2\pi i\left(D - \theta_i\right)/365\right] + \epsilon \qquad \text{(1A)}$$

or expanding,

$$T' = \beta_0 + \sum_{i=1}^{k} \left[\beta_{2i-1} \sin(2\pi i D/365) + \beta_{2i} \cos(2\pi i D/365)\right] + \epsilon \qquad \text{(1B)}$$

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[1]Superscript numbers denote references in the list at the end of this report.

where D is time measured in days from some arbitrary origin, and T' is the fitted value of the surface temperature. Fitting equation (1B) to the observed surface temperature, T, using the method of least squares yields estimates of the regression coefficients, β, and an estimate of the variance of ϵ. The amplitude α and phase θ can be obtained from the β's. The quantity ϵ is the random error of residual term.

TABLE 1. LOCATION OF SEA-SURFACE TEMPERATURE TIME-SERIES

Location	Time Period
Weather Ship PAPA 50°N 145°W North Pacific	1/56-8/62 6 yr 7 mo
Weather Ship ECHO 35°N 48°W North Atlantic	9/49-9/56 7 yr
Cape St. James 52°N 131°W North Pacific	1/35-1/61 21 yr (5 yr missing)
Triple Island 54°N 131°W North Pacific	1/40-1/61 21 yr
Langara Island 54°N 133°W North Pacific	1/41-1/61 20 yr
Scripps Pier 33°N 117°W North Pacific	1/21-1/61 40 yr

An integral part of any estimation problem is the determination of the reliability of the estimate as measured by the variability of observed data about the estimated values. As a measure of this variability consider the statistic R^2, the fraction of variability explained by a statistical fit. Equation (1B) was fitted to the Scripps Pier data using samples within the 40 years of lengths 1, 5, 8, 10, 20, and 40 years. This resulted in the following samples: forty 1-year, eight 5-year, five 8-year, four 10-year, two 20-year, and one 40-year.

Figure 1 summarizes the R^2 statistic for records of various lengths for the Scripps Pier data. In general, a single year's data are expected to yield a higher R^2 than would several years of data, where year-to-year variations would give a poorer fit, although in the forty single-year fits there are some years with poorer fits than those for longer periods. To compensate for the few years of poor fits there are many years of excellent fits. The fact that for 33 years R^2 was greater than 0.81 and for 23 years was greater than 0.86 substantiates this conclusion.

To compare R^2's for the various record lengths, L, the mean R^2's for the available runs of each length have been computed and $100R^2$'s have been plotted on figure 2. As expected the mean R^2 is a decreasing function of the length of record, L. More unexpected is the actual shape of the curve. From $L = 1$ the curve drops off sharply to somewhere between $L = 5$ and $L = 10$, from which point on there is a negligible decrease in R^2.

The mean R^2 is plotted in preference to the mean R or to the mean of Fisher's $Z = \frac{1}{2} \log \frac{1+R}{1-R}$, since R^2 is easiest to interpret. In addition, the relationship of R to R^2 in the range of consideration of R^2 is so nearly linear that a plot of mean R with appropriate scale changes cannot be distinguished from that of mean R^2. The relationship of Z to R^2 is such that the curvature of figure 2 would be even more emphasized if Fisher's statistic were plotted. The distribution of R^2 is asymptotically normal for $R \neq 0$.[4]

Because of the dependence of the average R^2 among the samples from which they were computed, and because of the autocorrelated residuals, the development of confidence limits for these average R^2's seems intractable. However, as a rough estimate of their variability, one standard deviation of the mean R^2 is plotted as a vertical bar in figure 2. These standard deviations are given by the formula:[4]

$$\sigma(\overline{R}^2) = \frac{2R(1-R^2)}{N^{1/2}(365)^{1/2}} \qquad (2)$$

They are computed under the assumption that repeated sampling over the same $N = 40$ year period at Scripps Pier is possible. In this conceptually possible but practically impossible situation, the deviations about the same mathematical model of regression are assumed to be independent among the repeated samples.

Under these assumptions the confidence limits for the plotted points are narrow, and it is concluded that the sharp change in slope of the curve in the region $5 < L < 10$ is real.

Attention is called to the systematic change in the absolute magnitude of the average R^2's, for the data for PAPA, ECHO, Langara Island, Cape St. James, and Triple Island. This change appears to be associated with the exposure, or "continentality," of the station – thus, PAPA and ECHO are typical of open-ocean locations; Triple Island is much like an open-ocean location, being a very small coastal island; and Scripps Pier is least like an open-ocean location with the observations being made at the end of a 1000-foot pier. Cape St. James and Langara Island have a "continentality" between Scripps Pier and Triple Island.

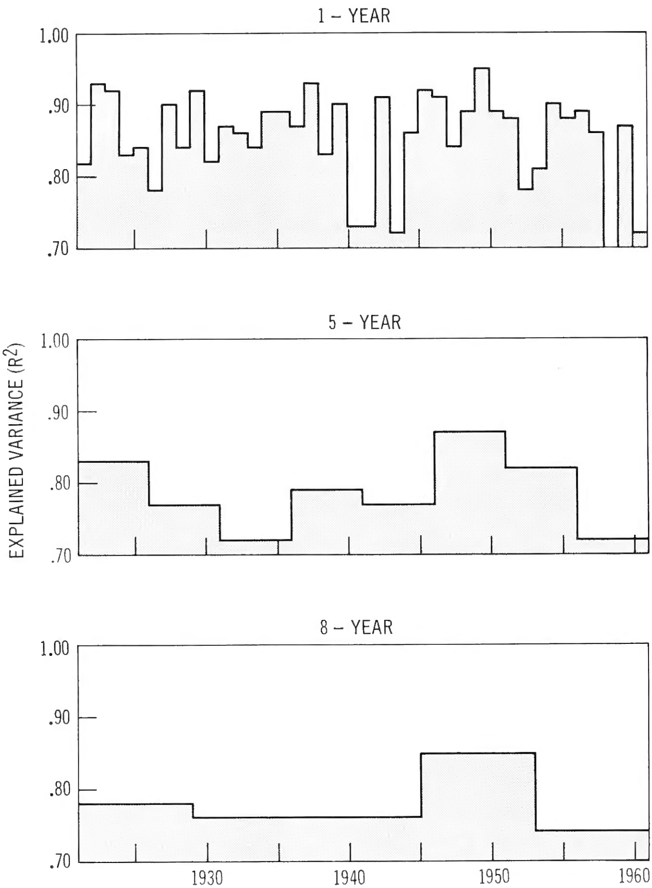

Figure 1. R^2 statistic for Scripps Pier data for records of varying length.

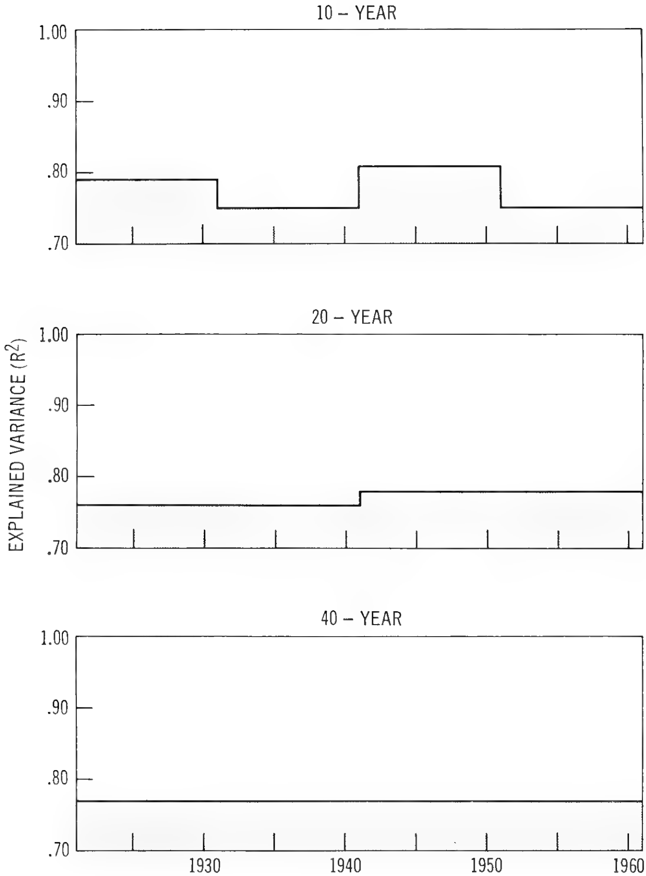

Figure 1. (Continued)

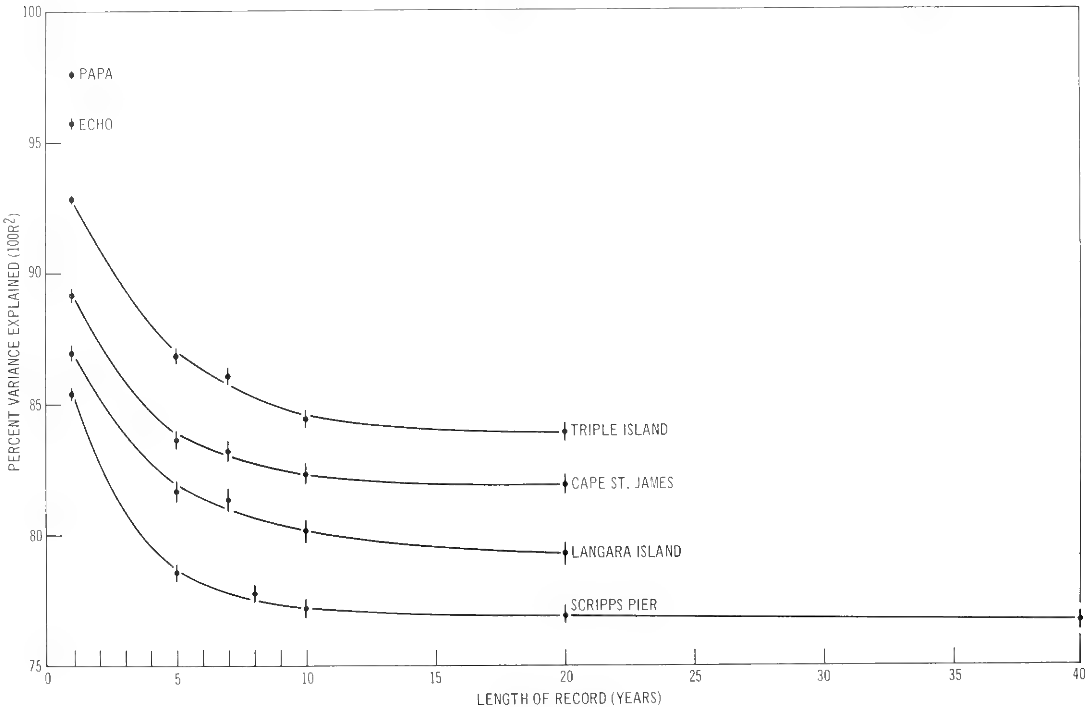

Figure 2. Percent variance explained by equation (1B) as a function of record length for six long-time-series of sea-surface temperature measurements.

The implications of figure 2 are:

1. A record of daily surface temperatures of 10-year length is adequate for fitting a regression curve to estimate long-term variability.

2. The unexplained long-term variability, that is, variability unexplained by the regression model, varies from about 23 percent at Scripps Pier, for a sample longer than 10 years; to less than 5 percent at PAPA and ECHO, both one-year samples taken at exposed open-ocean locations. Since R^2 is not degraded by extending a record beyond 10 years, the estimates of regression coefficients based on 10 years are as adequate as those that might be obtained from a longer record. In the same light, records of 5 years or less reflect shorter-term variability in temperature and thus give an improved fit as record length decreases.

Additional information on the length of time-series necessary for obtaining long-term estimates of sea-surface temperature may be obtained from an examination of the autocorrelation function available from the 40 years of Scripps Pier record.

For the various samples of Scripps Pier data, the autocorrelation functions were determined for the time-series consisting of the differences of the observed surface temperatures and the temperatures estimated by the fit of combined annual and semiannual terms, equation (1B) ($k=2$). The functions were computed for lags at intervals of 5 days up to 900 days in most cases. Consider first the autocorrelation functions for the eight different 5-year samples of data plotted in figure 3. There is considerable variability among the functions. It would be desirable to compute some measure of this variability, and compare it with the corresponding variability of the autocorrelation functions for the 8-, 10-, and 20-year records of figure 4.

Before computing any such measure, we have to make a decision as to the range of lags to use in the comparison. The value of the standard deviation of the nonsignificant autocorrelations, σ_c for the 40 years of Scripps Pier data is 0.0293.[3] For a 10-year record $\sigma_c = 0.0586$, and the 95 percent significance values are ± 0.115. For reasons previously discussed, a 10-year record of sea-surface temperature is needed in order to obtain reliable estimates of the long-term variability. Thus it is not necessary to consider 5- or 8-year records in selecting the range of lags to use. If we assume the 40-year autocorrelation function is close to the true function, lags out to 145 days yield autocorrelations greater than 0.115 and can be used to compare the sets of functions.

For the set of autocorrelation functions based on samples of length L years and for each lag $\tau = 5(5)145$ days, we determine the following sum of squares:

$$Q(\tau,L) = \sum_{j=1}^{40/L} \left[C_j(\tau) - \bar{C}(\tau)\right]^2 \qquad (3)$$

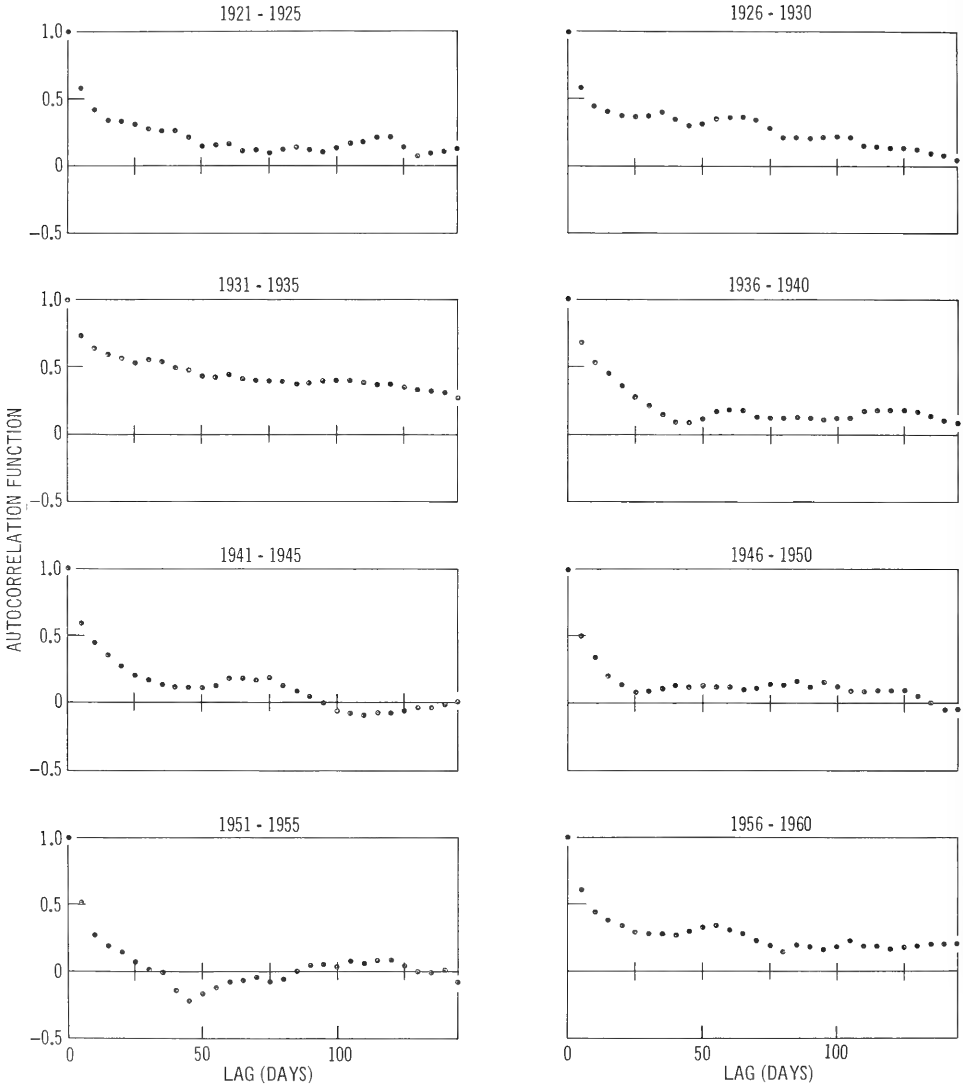

Figure 3. Autocorrelation functions for 5-year records of Scripps Pier data.

where $C_j(\tau)$ is the autocorrelation coefficient for lag τ of the j-th of $40/L$ sets, and $\bar{C}(\tau)$ is the mean of $40/L$ coefficients with the same lag τ. By analogy with normal distribution theory, the quantity $Q(\tau,L)/\sigma^2(\tau,L)$ is like a chi-square variable with $(40/L)-1$ degrees of freedom, where $\sigma^2(\tau,L)$ is the variance of $C(\tau)$ for a sample of length L. Assume the $Q(\tau,L)$'s are independent, and that $\sigma^2(\tau,L)$ is inversely proportional to sample length and the same for all τ. That is, $\sigma^2(\tau,L) = k\sigma^2/L$ where k is any proportionality constant. Then $kL \sum_{\tau} Q(\tau,L)/\sigma^2$ is like a chi-square variable with $\nu = 29\,[(40/L) - 1]$ degrees of freedom. For two different values of L, L_1 and L_2, the ratio

$$F = \frac{L_1 \sum_{\tau} Q(\tau,L_1)/\nu_1}{L_2 \sum_{\tau} Q(\tau,L_2)/\nu_2} \qquad (4)$$

is like an F-variable with ν_1,ν_2 degrees of freedom.

The "mean square," $L \sum_{\tau} Q(\tau,L)/\nu$, and the F-ratios using the mean square for 20 years as the denominator, are shown in table 2. Assuming a robust F-test, none of these ratios is significant (though less than 1) and it is concluded that the variability in the autocorrelation functions is about as expected.

TABLE 2. VARIABILITY IN AUTOCORRELATION FUNCTIONS

L	Mean Square	F-ratio
5	0.0994	0.83
8	0.1182	0.99
10	0.0889	0.74
20	0.1195	----

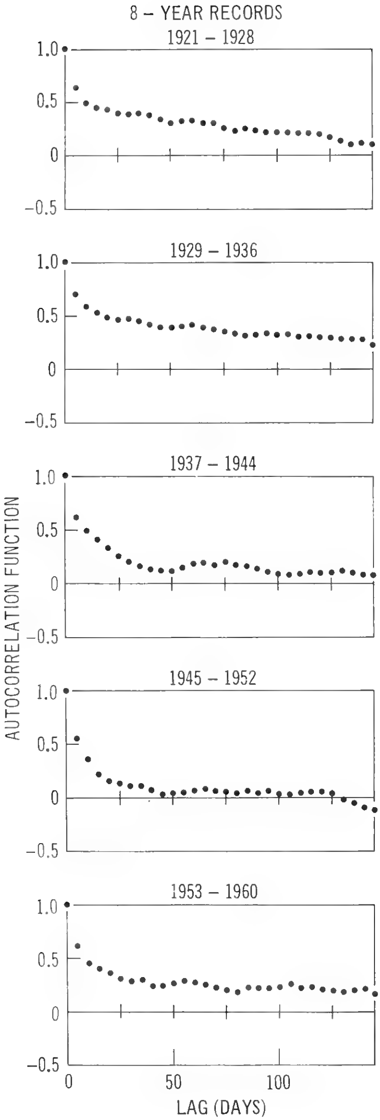

Figure 4. Autocorrelation functions for 8-, 10-, 20-, and 40-year records of Scripps Pier data.

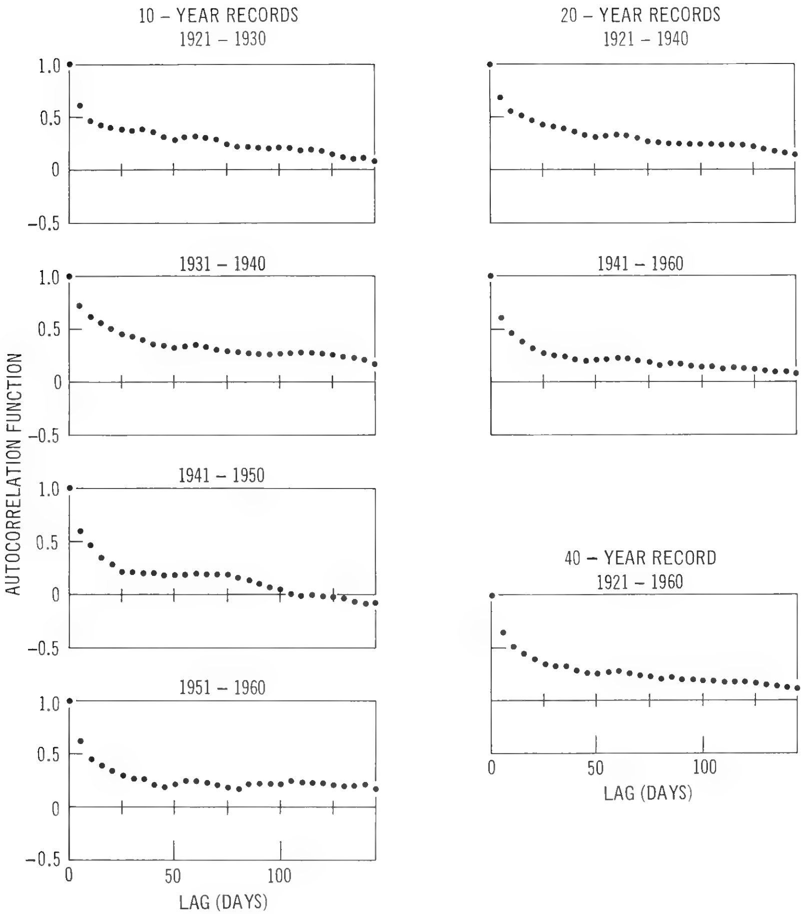

Figure 4. (Continued)

The investigation of the square of the multiple correlation coefficient suggested that about 10 years of record are sufficient for certain curve-fitting and estimation problems. It has just been concluded that there is no such break in the variability of the autocorrelation coefficient as a function of record length. Thus a decision as to the sample length necessary to obtain useful estimates of the autocorrelation function must be made on some absolute basis, or a cost function must be introduced such that a combination of increasing cost and decreasing variability with sample size results in an optimization problem.

Two additional comments are pertinent. First, figure 4 shows the autocorrelation functions for samples of 8, 10, and 20 years, respectively. Attention is called to the 10-year records. It appears that the autocorrelation functions agree well out to a lag of about 80 days. Second, autocorrelation functions for the same record lengths have been averaged by lags, and are shown in figure 5. There is a strong indication that autocorrelation functions from finite samples are biassed. Restricting the discussion to lags out to 80 days, and assuming the autocorrelation function for the 40-year sample is close to the true function, the mean functions for 5- and 8-year samples are badly biassed with little bias indicated in the 10- and 20-year mean functions. It is concluded that 10-year samples provide consistent and usable autocorrelation functions out to a lag of 80 days.

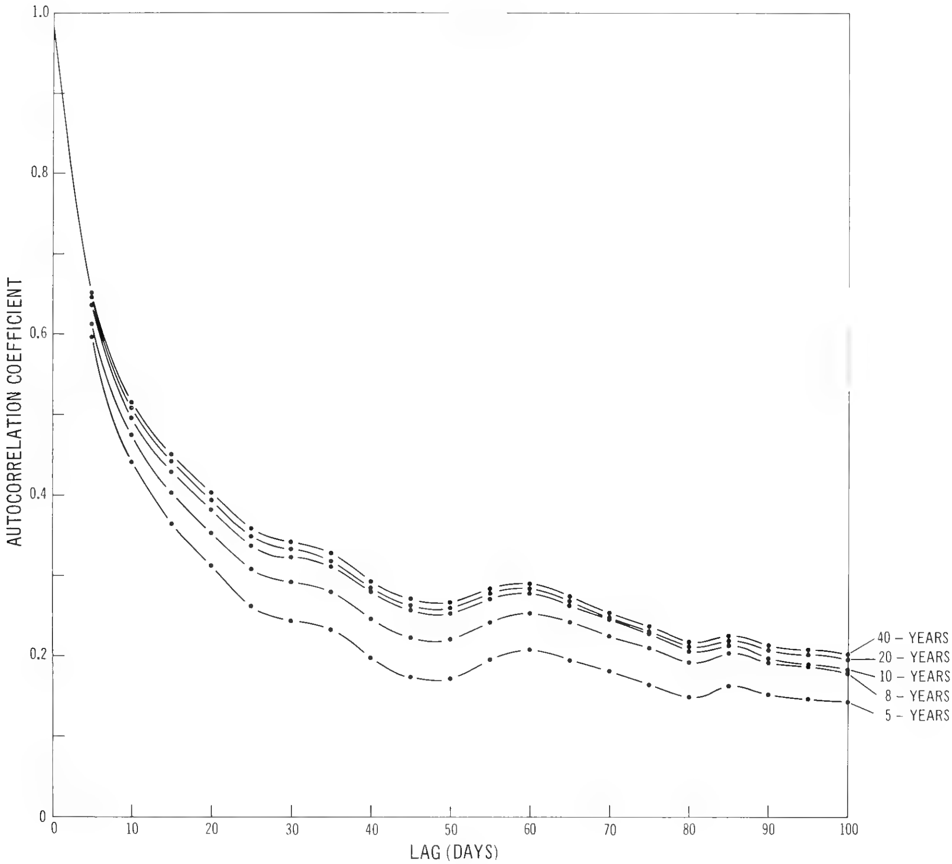

Figure 5. Average autocorrelation functions for various record lengths for Scripps Pier data.

SYSTEMATIC VARIATION OF SEA-SURFACE TEMPERATURE OVER PERIODS OF SEVERAL YEARS

In connection with the question of whether or not sea-surface temperatures vary significantly over periods of several years, four specific time periods are examined here in some detail:

1. 1947 to 1956 which has been referred to as displaying "A uniform monotony of conditions in at least the eastern North Pacific that is scarcely suggested by any similar series of years in this century."[5]

2. 1936 to 1956 where there are indications of a cooling trend.

3. 1957 and 1958 recognized as "the changing years."[5]

4. 1930 to 1935, another period, unique to this century, which appears to contain long-term oscillations.

In the previous discussion on trends by Van Vliet and Anderson,[3] a variety of statistical considerations led to the general conclusion that no trend existed in the records for any of the locations examined and that quantities such as the annual average temperature (β_0), annual amplitude (α_1), annual phase (θ_1), and percent variance explained by regression ($100R^2$) all behaved as independent random variables are expected to behave. In addition it was pointed out that this conclusion does not deny the existence of real year-to-year differences in the ocean, but rather emphasizes that these differences are not unexpected from the viewpoint of statistics and thus are not considered unusual or improbable events.

First the period 1947 to 1956 is examined in the light of the statistical parameters developed in this analysis. Figure 6 contains a plot of the average annual temperatures (β_0) for four eastern North Pacific locations. During this decade, for 8 of the 10 years at all four stations, the β_0's were below the median value and for 2 years were at the median or slightly above suggesting that on the average the decade was cooler than normal. Figure 7 contains parameters that determine the shape of the seasonal variation (α_1, α_2, θ_1, θ_2). A study of these four parameters does not suggest anything unusual about the shape of the seasonal surface temperature variation during this decade. Figure 8 contains the percent variance explained by regression and the standard deviation, both parameters concerned with the variability. Again a study of these factors does no suggest anything unusual in the amount or degree of variability. Thus, this analysis suggests that the surface temperature variation during this decade was unusual as compared with other decades observed in this century in that the average temperature was slightly below the median value.

Although too much after-the-fact analysis of data is contrary to statistical philosophy, sometimes it is of interest to do such analysis. Specifically, for the Scripps Pier data shown on figure 6 there is a suggestion of a cooling trend for the years 1939 through 1956. Applying the theory of runs to this period[3] the following sequence is obtained:

AAAAA BB AA BBB A BB A BB

This sequence has eight runs. The critical number of runs at the 5 percent probability level for 18 observations is six, and it is concluded that no trend exists even in this selected period of time. The applicable median β_0 is 16.60° C.

The years 1957 and 1958 have been recognized from a consideration of several natural science parameters as the changing years.[5] These years appeared to conclude the 1947-to-1957 decade -- a decade of below-median sea-surface temperatures. On figure 6, the β_0's for the succeeding years, 1959 to 1962 inclusive, have been included for Scripps Pier. In 1959 the annual average temperature continued to increase for the third successive year followed by an abrupt decrease in 1960 and lesser decreases in 1961 and 1962. This same pattern, though less marked, occurred for the three island locations. Thus, it appears that in 1956 a long-term oscillatory variation, of period at least 6 years, began and that it was still in progress in 1962.

In examining the Scripps Pier β's in figure 6, we find that the period 1930 to 1935 also appears to contain an oscillatory term with a period of several years. In figure 3 are plotted the eight correlograms, obtained after removing the annual and semiannual oscillatory terms, for 5-year periods at Scripps Pier. Although these correlograms are plotted out to lags of only 150 days, they were computed out to lags of 900 days. A study of the eight 900-day lag correlograms shows one to be somewhat different from the remaining seven – the correlogram for the 1931-to-1935 period. The correlogram for this period for lags out to 1400 days (fig. 9) shows a peak in the autocorrelation coefficient of 0.46 at a lag of about 1170 days, or a period of about 3.2 years. Since the points are scattered in the neighborhood of this peak as well as in the neighborhood of the minimum at lag about 750 days, another estimate of period length is given by twice the difference in lags between the up-crossing at lag 960 days and the down-crossing at lag 265 days, or about 3.8 years. Either period confirms the intuitive conclusion reached from an examination of figure 6.

It thus appears reasonable to conclude that sea-surface temperatures will vary significantly over periods of several years and that these occurrences are not unexpected or improbable.

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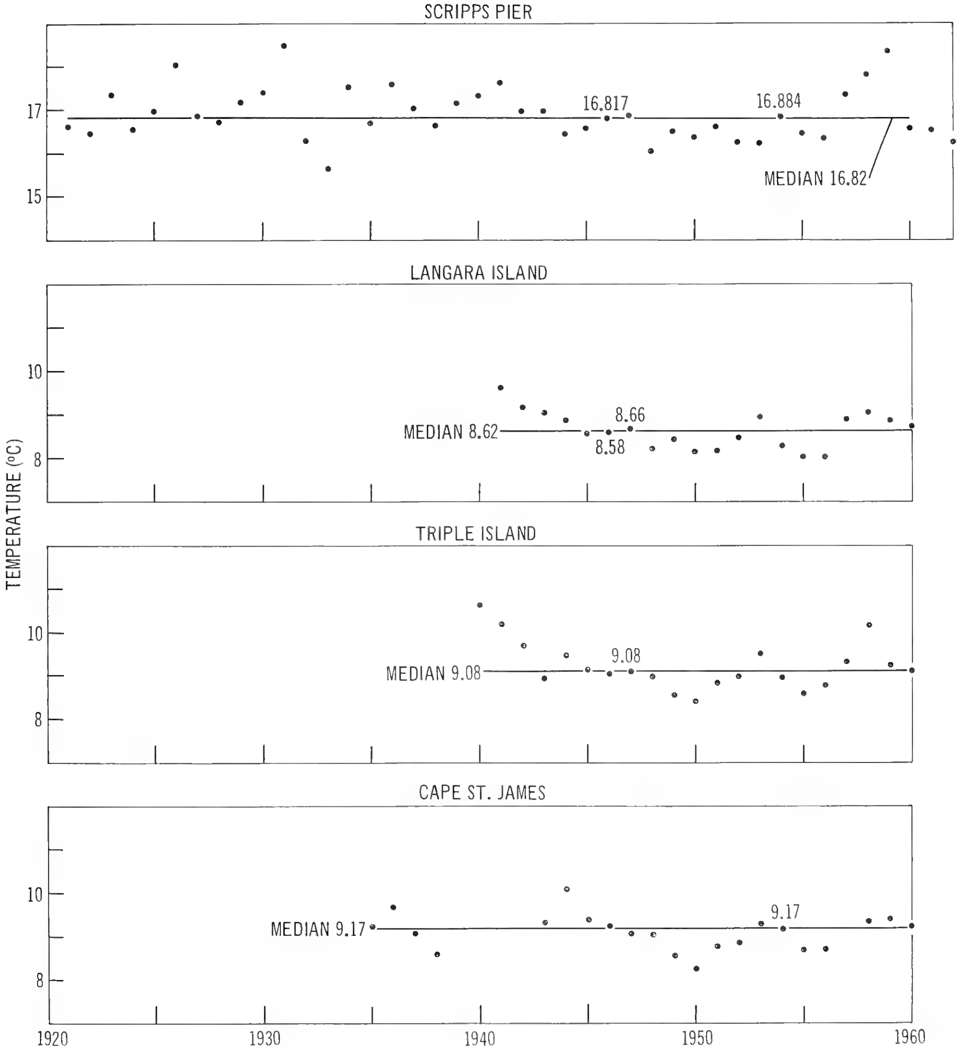


Figure 6. Annual averages of sea-surface temperature for coastal and island locations.

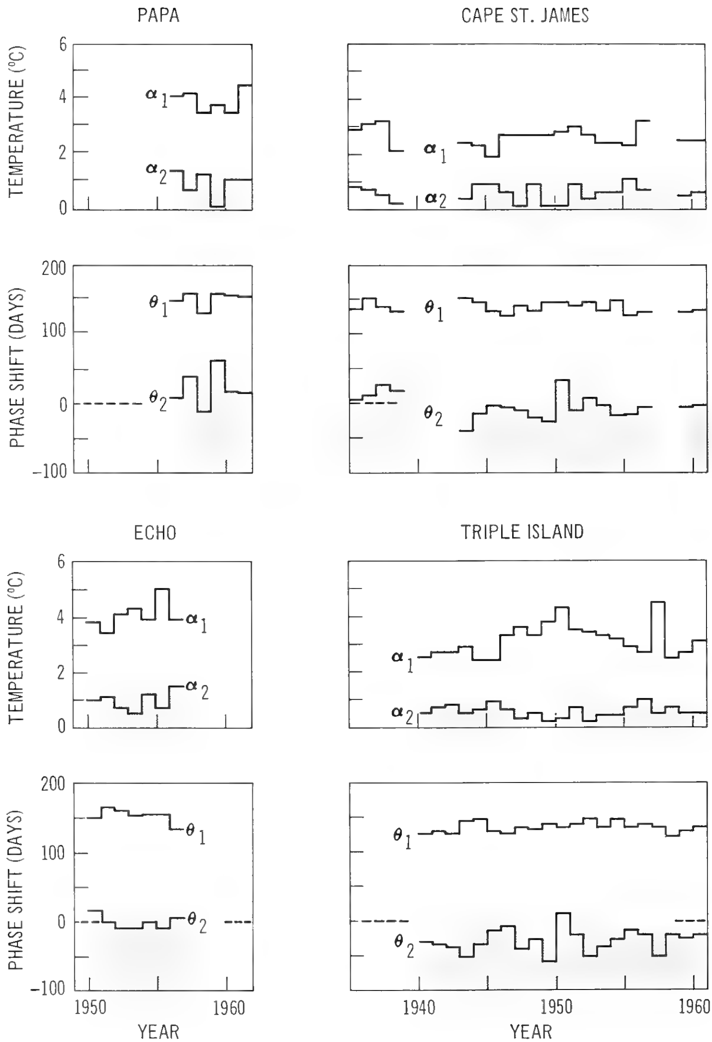
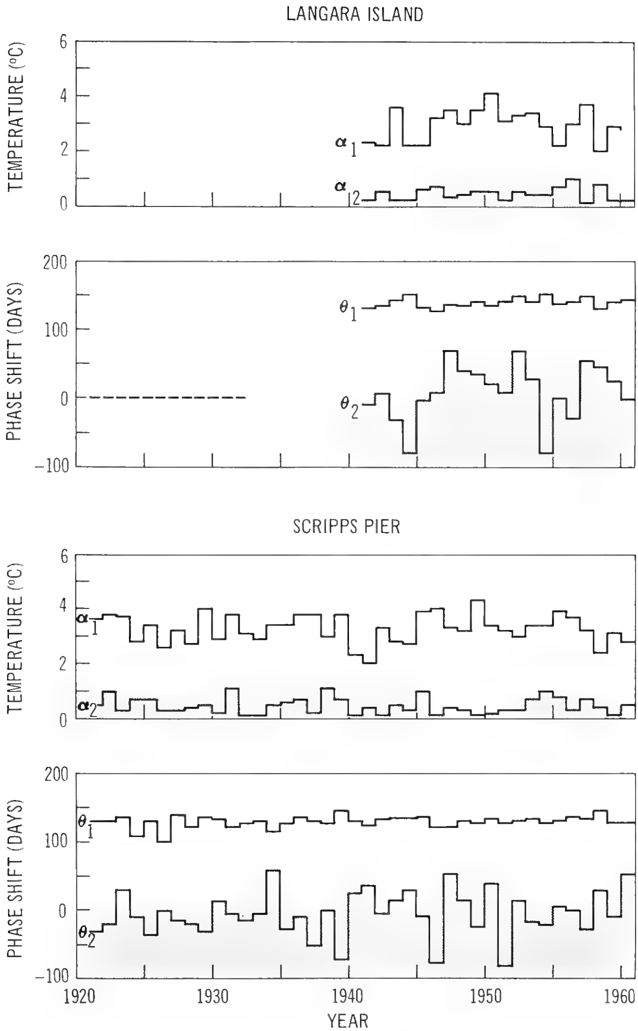


Figure 7. Annual and semiannual amplitudes and phases for all stations as a function of time.



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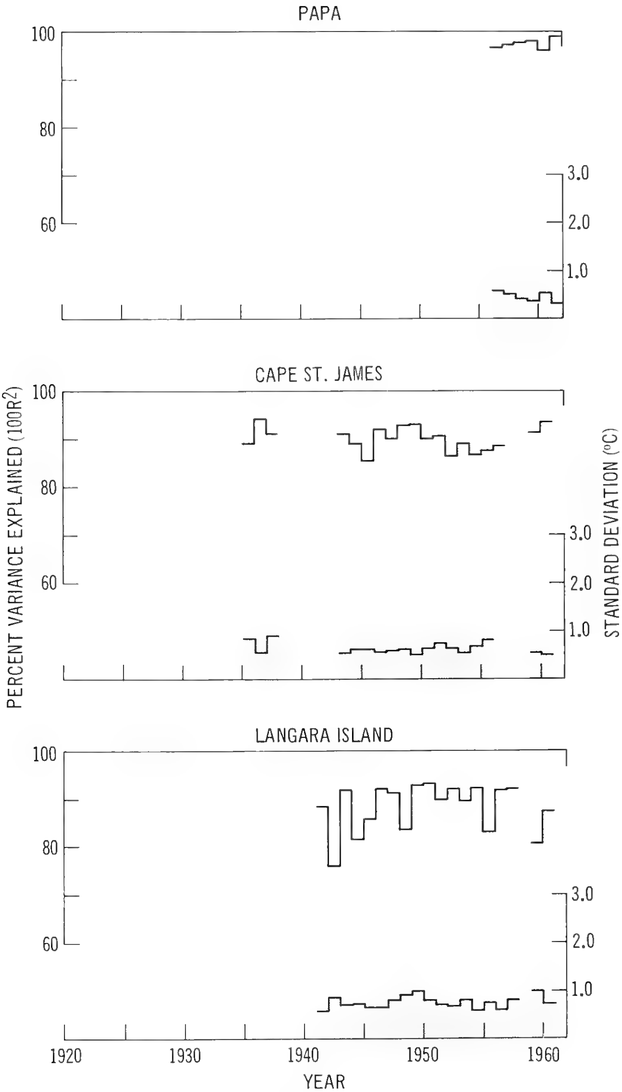

Figure 8. Percent variance explained and standard deviation of residuals for annual records for all stations.

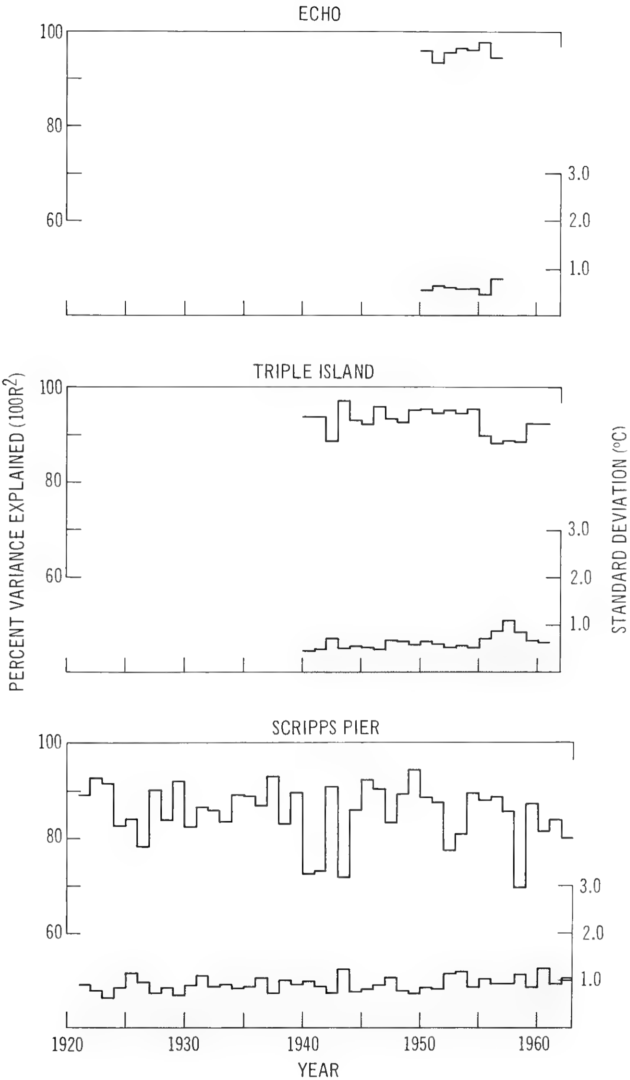

Figure 8. (Continued)

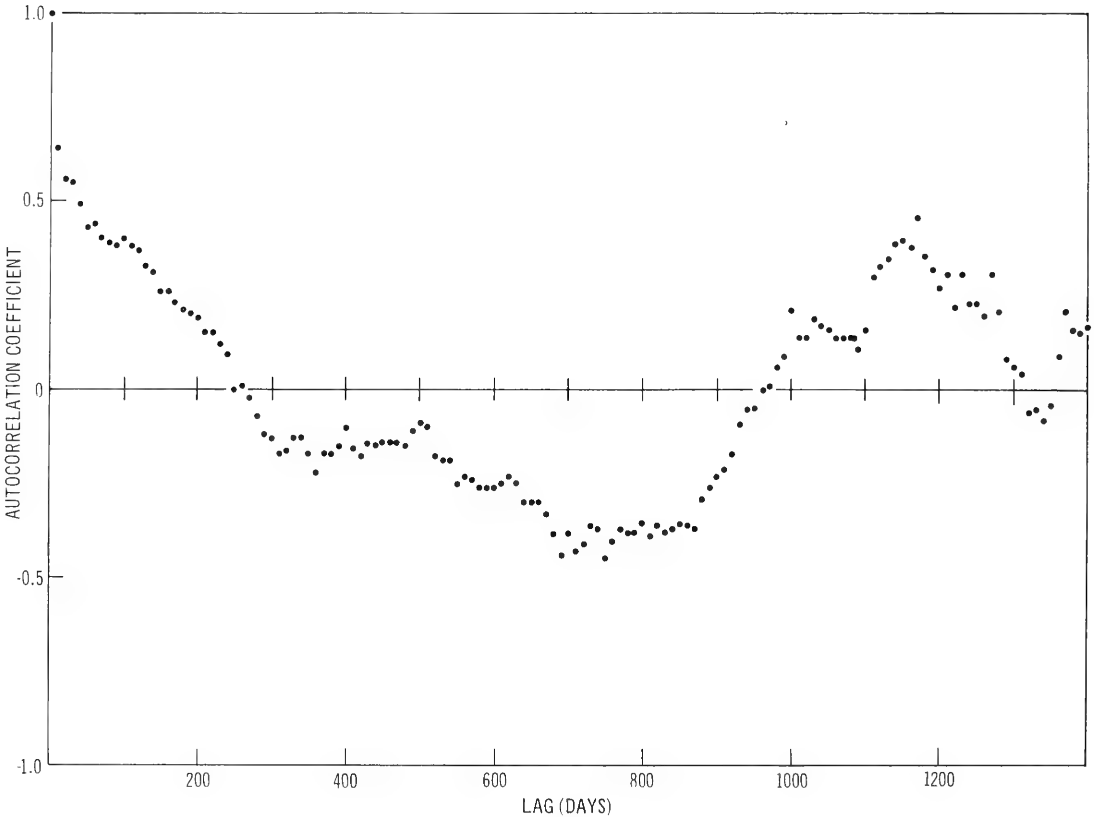

Figure 9. Autocorrelation coefficients for 1931 to 1935 Scripps Pier data with lags extended to 1400 days.

SUMMARY AND CONCLUSIONS

Using autocorrelation and regression techniques, six time-series of sea-surface temperature measurements were examined to determine the length of time-series necessary for obtaining reliable estimates of sea-surface temperature and to determine whether or not systematic variations of annual average sea-surface temperatures over periods of several years is to be expected.

Plots of the $100R^2$ statistic (percent variance explained by regression) as a function of time-series record length for the six time-series records considered lead to the conclusion that record lengths of 8 to 10 years are necessary to obtain reliable long-time estimates of sea-surface temperature. Additional support for this conclusion was obtained from an examination of the behavior of the auto-correlation coefficients for the 40-year Scripps Pier record.

An examination of the annual average temperatures confirmed previously published conclusions regarding the systematic year-to-year variability in sea-surface temperatures. In addition it showed that such long-term variability is not unusual or unexpected.

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13. ABSTRACT

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Ocean Surface - Temperature - North Pacific Ocean						
Ocean Surface - Temperature - Statistical Analysis						

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