GEOPHYSICAL ESTIMATES OF SEA-SURFACE TEMPERATURES OFF WESTERN NORTH AMERICA SINCE 1671

ARTHUR V. DOUGLAS
Climatology Program
Department of Geography
University of Nebraska
Lincoln, NE 68588

ABSTRACT

Sea-surface temperature (SST) data, which are reflective of air-sea interactions, are only available for the periods 1924 to 1940 and 1949 to 1972. In order to augment this short-term data, reconstruction of SST data are made using climatically sensitive tree-ring data. This involves multiple linear regression analyses between SST for 1° squares off southern California and Baja California (22°N to 33°N) and tree-ring data from seven sites in western North America.

A reconstructed summer SST series is shown to be negatively correlated ($r = -0.49$) with anærobic sediment core estimates of variations in northern anchovy populations off southern Baja California since 1785. Examination of the reconstructed SST reveals that the period 1671 to 1800 was typified by warm winter SST's and cool summer SST's. By the early 1800's, summers became anomalously warm off Baja California, and this summer warming climaxed in the 1840's and 1850's. During this warm summer period, SST anomalies were in excess of +2.0°C, and this is equivalent to a 2° latitudinal shift in SST fields, and a 2° northward shift in the oceanic front off southern Baja California.

RESUMEN

Datos de temperatura de la superficie del mar que reflejan las interacciones aire-mar solamente se han obtenido para los períodos de 1924 a 1940 y de 1949 a 1972. Para aumentar estos datos de corto plazo, se hacen reconstrucciones en los datos de temperatura de la superficie del mar usando los datos climáticamente sensitivos de los anillos anuales arbóreos. Esto implica unos análisis de regresión linear múltiple entre las temperaturas de la superficie del mar para cuadrados de 1° frente al sur de California y Baja California (de 22°N a 33°N), y datos de anillos anuales arbóreos de siete localidades en el oeste de Norteamérica.

Una serie reconstruída de temperaturas de la superficie del mar en el verano muestra tener una correlación negativa (r = -0.49) con cálculos tomados de núcleos de sedimento anaerobio, de las variaciones en las poblaciones de anchoveta del norte frente a Baja California desde 1785. Una examinación de las temperaturas reconstruídas revela que, en el período de 1671 a 1800, las temperaturas de la superficie del mar en el invierno eran típicamente cálidas y en el verano eran frescas. Por la época inicial de los años 1800s los veranos llegaron a presentar una anomalía cálida frente a Baja California, y este proceso de calentamiento en los veranos tuvo su clímax durante el decenio de 1840 y de 1850. Durante este período cálido de verano, las anomalías de temperatura de la superficie del mar eran en exceso de +2.0°C, y ésto equivale a un cambio de 2° latitudinales en los campos de las temperaturas de superficie, y un cambio en el frente oceánico frente al sur de Baja California de 2° hacia el norte.

INTRODUCTION

Objective of the Investigation

Sea-surface temperature anomalies in the eastern North Pacific have been linked to fluctuations in climate across western North America (Allison et al. 1972; Bjerknes 1969; Namias 1969; Pyke 1972). It has been demonstrated that a long-term record of climatic fluctuations in western North America can be obtained from tree-ring data (LaMarche and Fritts 1971; Fritts et al. 1971). One should, therefore, be able to make inferences about past sea-surface temperature (SST) anomalies, as well as climatic anomalies, based upon analyses of tree-ring data.

This study is concerned with the reconstruction of SST data based upon analyses of tree-ring data in southwestern North America. Tree-ring data are useful in paleoclimatic reconstructions due to the availability of a large number of trees, the longevity of trees, and the critical fact that the climatic information they provide is accumulated during a specific year. Douglas (1973) has found that seasonal SST data can be extracted from tree-ring series. By calibrating tree-ring series from western North America against SST data, reconstruction equations can be made for estimating seasonal SST based upon the tree-ring data. In this project, reconstructed SST anomalies are used as indicators of past air-sea interactions off California and Baja California.

Previous Investigations

An apparent relationship between ocean temperatures and precipitation in California was first suggested by McEwen in 1925, who hypothesized that ocean temperatures should influence the atmospheric pressure patterns of the North Pacific region. He suggested that ocean temperatures should also influence the amount of atmospheric moisture available for precipitation. With these ideas, he attempted to forecast cool season precipitation in California based upon previous summer ocean temperatures. These forecasts were reasonably accurate considering his lack of open ocean data. He noted that the predicted departures in precipitation values agreed with the sign of the observed anomaly about 80% of the time.

In 1931, Lynch suggested the possibility of reconstructing past precipitation anomalies in southern California based on annual widths of tree rings. He found that the correlation between tree growth and precipitation was sufficiently high that he could calculate expected rainfall departures back to the 1700's. Using more advanced statistical techniques, LaMarche and Fritts (1971) showed that large-scale tree growth anomalies in the western United States for the past few centuries are a reflection of changes in seasonal precipitation patterns. Variations in precipitation patterns are ultimately linked to changes in large-scale circulation patterns across western North America and the North Pacific. Strong links between anomalies in atmospheric pressure, oceanic and continental precipitation, and SST have been demonstrated by Allison et al. (1972), Bjerknes (1969, 1974), and Namias (1969, 1971, 1972, 1973, 1974). Debate continues as to which variable, pressure or SST, is the most influential in creating climatic fluctuations, but once these variables do become anomalous, they can perpetuate or terminate each other through numerous and complex positive and negative feedback mechanisms.

Success has already been achieved in coastal SST reconstructions (Douglas 1973), and thus, the next step should be the reconstruction of open ocean data. The recent processing of SST data from ship logs dating up to 1972 has allowed this study to concentrate on a larger oceanic area for a longer time period (post-1924) than has previously been possible.

PROCESSING AND SEASONALIZATION OF SST DATA

Prior to forming a set of seasonalized SST data to be calibrated against tree-ring data, the monthly SST data, 1900 to 1972, were examined for possible observational errors and missing data. This involved checking the standard deviation of each average monthly SST value for each 1° square (Figure 1) and comparing all monthly SST values with the data from surrounding 1° squares. Virtually complete records were found to exist from 1924 to 1940 and 1949 to 1972. Only one monthly mean was found to be anomalously low compared to values from nearby squares. This incorrect value plus five missing values had to be estimated. These six monthly values were estimated by calculating the average SST for the two adjacent 1° squares that were north and south of the square with the missing data.

The three seasons examined include winter, spring, and summer, each of which contains four months. These seasons were based on natural criteria in the following ways. From March through June, the cyclonic eddies that

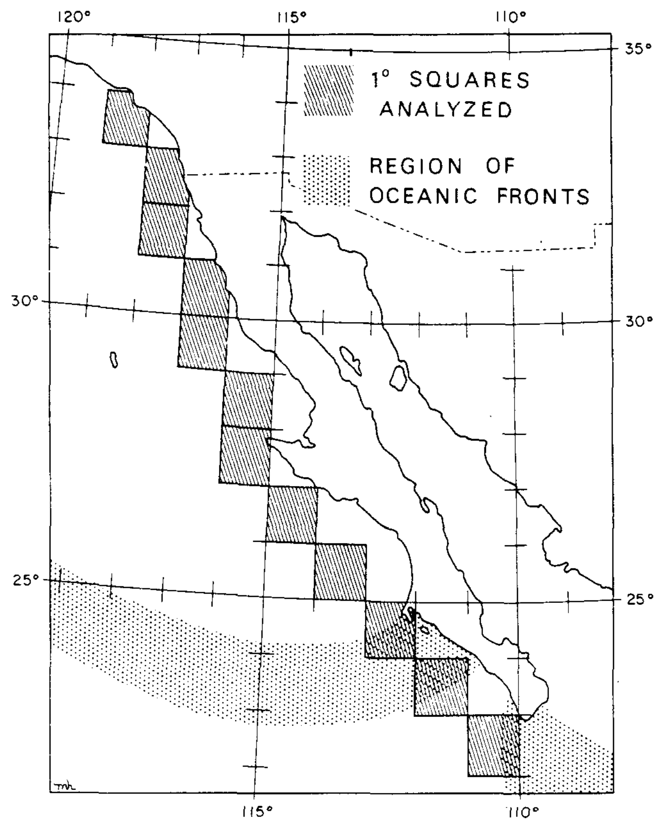


Figure 1. Location of 1° squares for which sea-surface temperature data are analyzed. General areas of oceanic fronts are shaded.

are commonly observed off southern California and Baja California become weak or nonexistent. During this spring period the California Current swings into the inshore waters from California southwards to the southern tip of Baja California. This is a result of an Ekman transport of water towards the south and southwest in association with strong north or northwesterly winds along the entire coast. The thermocline or mean mixed layer depths of spring are of intermediate depth to those of winter and summer.

The cyclonic eddies become established in July as the strongest winds become located farther offshore. During the summer period, July through October, a shallow thermocline is often present in the quieter coastal areas. The summer period is marked by a shallow thermocline and cyclonic eddy development off southern California and Baja California. This period is also characterized by the movement of an oceanic front up the coast of Baja California beginning in July. In June the 25° isotherm which marks this boundary is south of this region of the study, but by July it has advanced to near 23.5°N, 111.5°W and by October it has reached its northernmost position near 25°N.

By November, winter storminess greatly increases along the Pacific coast resulting in the mixing of the shallow thermocline of summer. The deepest thermoclines normally occur by January. Deepening of the thermocline plus decreased incoming solar radiation combine to initiate pronounced surface cooling across the area. At the same time, however, periods of southerly and southwesterly winds become more frequent, and this precludes cooling due to upwelling processes. The southerly winds also promote a strengthening of the cyclonic eddies and a surfacing of the northward flowing Davidson current. The winter season, November through February, is thus characterized by a deep thermocline and northward flowing water in the inshore regions.

DENDROCHRONOLOGY AND DENDROCLIMATOLOGY

Previous Investigations

Relationships between atmospheric circulation anomalies, precipitation anomalies, and tree-ring growth anomalies in North America have been discussed by LaMarche and Fritts (1971). They found that the growth of a tree can be directly or indirectly affected by variations in seasonal temperature and precipitation. These climatic fluctuations influence the energy balance and other physical or physiological conditions in the tree. With respect to trees in the warm parts of southwestern North America, low precipitation and high temperatures during the growing season are linked to the formation of narrow rings in arid site trees (Fritts et al. 1971, Model A). The narrow ring is the result of low soil moisture and increased evaporation which lead to increased water stress in the tree.

In a detailed analysis of the effect of climate on tree growth, Fritts et al. (1971) have obtained growth response fluctuations that indicate the relative effect of monthly temperature and precipitation upon the width of a given year's ring for different tree species on different sites. His analysis has indicated that a given species' response to climate may vary due to differences in location (e.g. differences in elevation, site aspect, substratum, or associated biota). It was also found that climatic conditions during given months may affect one tree species while having no effect on other tree species at the same site. Tree-ring chronologies of a single species at a given site will also contain "hold over" effects of previous climatic anomalies on successive annual rings. The number of years of "hold over" in different species has become a critical part of Fritts' response functions.

The most effective way to reconstruct different year-round conditions of past climate is to obtain a sample from diverse sites and several species within each region. The differences and similarities among sites provide added climatic information. Climatic reconstruction can sometimes be improved by using previous and following years' growth as predictors to handle the effects of food storage or changes in root or shoot area. Thus, the climatically induced growth responses of trees for several sites with different species, and for several years (lagged tree-ring data) may be necessary to accurately predict the climatic conditions during a given season or sets of months.

Chronologies from Southwestern North America

In view of the above findings by Fritts, a number of species from diverse sites throughout southwestern North America have been examined for use in reconstructing seasonal sea-surface temperatures (Figure 2). The need for this diversity was recognized in an earlier analysis of SST reconstructions in which it was found that chronologies from high and low elevation sites contained different climatic information than did chronologies of different species (Douglas 1973). The three most useful chronologies from the earlier study were used in this analysis. They include the *Pseudotsuga macrocarpa* chronology, which is from the steep slopes of the coastal Santa Ana Mountains of California, elevation 1,214 m (Douglas 1973). A *Pinus ponderosa* chronology from California was selected from the gentle slopes of the Baldwin Lake area of California, elevation 2,231 m (Stokes et al. 1973). The high altitude *Pinus flexilis* chronology from Mount San Gorgonio, California, elevation 3,281 m, was also retained for this study (unpublished data on file at the Tree-Ring Laboratory, University of Arizona).

In addition to these chronologies, four more sites (Figure 2) were chosen for their possible usefulness in reconstructing SST's. In northern Baja California two

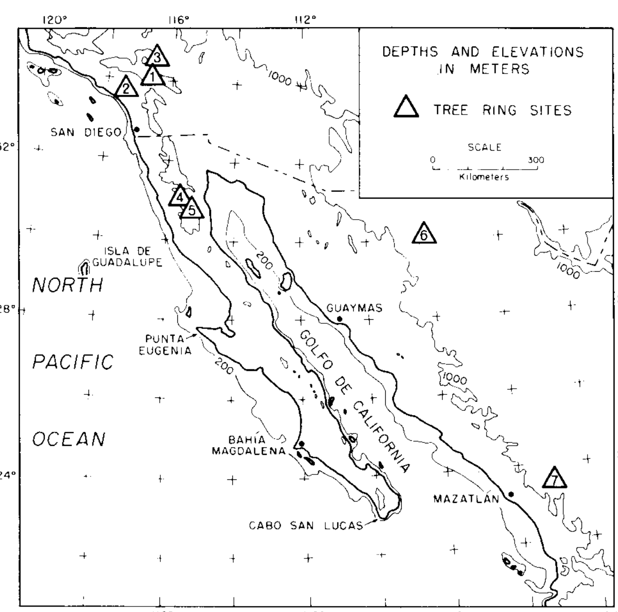


Figure 2. Location map of tree-ring sties and general area from which sea-surface temperature data are available. Sites include: 1) San Gorgonio; 2) Santa Ana Mountains; 3) Baldwin Lake; 4) San Pedro Martir; 5) Tasajera; 6) Rancho Escondido; and 7) El Salto.

chronologies from the San Pedro Martir range were selected: San Pedro Martir (low) and Tasajera. The San Pedro Martir (low) *Pinus jeffreyi* chronology was obtained from a site with a moderately low elevation (1,976 m), as was the Tasajera site chronology (elevation 2,218 m).

Unfortunately, no tree-ring chronologies have been developed for southern Baja California. For this reason two mainland site chronologies east of Baja California were chosen for their known usefulness in reconstructing climate. The northernmost Mexican mainland chronology is from Rancho Escondido, Chihuahua, where the sampled trees, *Pinus ponderosa*, grow at 2,128 m. Farther south in western Durango, Mexico, a *Pseudotsuga menziesii* chronology was selected (elevation 2,432 m).

The latitudinal coverage of the tree-ring chronologies is from 23°N to 34°N, which is about the same latitudinal area for which SST data are available. Most of the chronologies are from the northern sector of the study region because the availability of good long-term tree-ring data precludes any other choice of sites. The greater number of northern tree-ring sites may actually prove useful in reconstructing SST data for waters off western Baja California since the northern region is the source of the southward flowing California Current water.

The chronologies used in this analysis were developed by using the techniques of Fritts et al. (1969). This involves taking the measured raw tree-ring data and fitting the data to a modified exponential curve (growth function), thus producing indices. The indices were obtained by dividing the respective ring widths by the corresponding value from the growth curve, so that the mean of the series is 1.00 or 100% (Figure 3). This conversion is quite useful since the raw ring-width data show a considerable growth trend through time. The trend is induced by increasing age and not climate. Low frequency or long-term variance at frequencies of decades and centuries is preserved in this procedure, but trend is eliminated.

In most cases two cores from each tree are sampled and averaged into a tree chronology. This tree chronology represents an integrated climatological record with reduced nonclimatic noise. A given annual ring around the radius of the tree will minimize these nonclimatic abnormalities. Merging a large number of tree chronologies into a mean site chronology further minimizes the noise caused by growth variations within and between the trees, and the desired climatic information common in all trees is retained.

In developing a chronology from a large sample size (about 12 trees at each of the seven sites), a reliable estimate is obtained of the average limiting effects of climate on the trees. A plot of the final site chronologies for the seven localities is given in Figure 3. Similarities in growth can be noted in the low elevation sites of the north, while the mainland Mexico chronologies do not appear to be highly correlated with the chronologies to the northwest. Less agreement is found between the high and low elevation chronologies.

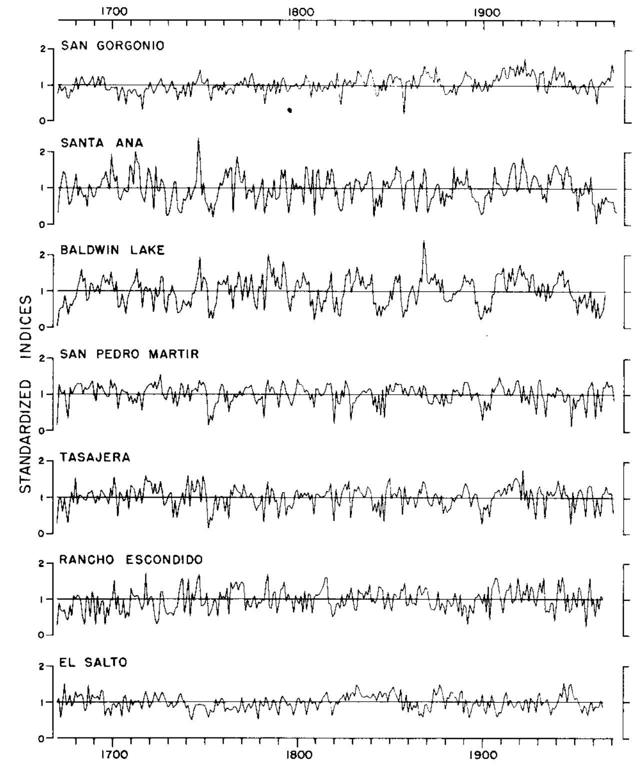


Figure 3. Tree-ring indices for seven sites in the western United States and Mexico. See Figure 2 for the location of sites.

SST RECONSTRUCTIONS

Tree-Ring Reconstructions of Climatic Parameters

Tree-ring data are useful in long-term climatic reconstruction due to the fact that the climatic information in tree rings is accumulated over a specific time period. In addition, one can obtain specific climatic information from tree-ring data that is for a given set of months or natural season. In the southwestern portion of North America, the vast majority of the dendroclimatic work has dealt with trees that are long-lived and sensitive to climatic changes. The following is a brief review of the development of dendroclimatology as it pertains to this study region in western North America.

In 1947, Schulman noted a positive correlation between tree-ring widths and rainfall in southern California. He felt that tree-ring data were reliable indicators of past wet or dry periods in southern California back to 1789. Schulman (1947) calculated a correlation coefficient (r) of 0.86 between tree-ring data from *Pseudotsuga macrocarpa* and rainfall for southern California. Correlation between Los Angeles annual temperature and tree growth was determined to be nonexistent by Schulman ($r = \pm 0.00$). Temperatures in May, June, and July were found, however, to be slightly negatively correlated with tree growth ($r = -0.13$).

Large-scale and prolonged anomalies in precipitation are often linked to detectable changes in the atmospheric circulation. This immediately suggests the possibility of reconstructing past atmospheric pressure anomalies based upon tree-ring data over a large grid such as western North America. Anomalies in the atmospheric circulations of the western portions of North America since 1700 based upon tree-ring data have been calculated by Fritts et al. (1971). Their reconstructions are in the form of surface pressure anomaly maps reconstructed from various tree-ring sites in western North America. Both the surface pressure data (1900-62, excluding 1939-44) and the tree-ring data were subjected to eigenvector analysis before the calibration of the two data sets. The authors noted a good statistical relationship between the reconstructed surface pressure anomaly maps and known sea level pressure anomalies in the North Pacific during the 19th Century.

Growing evidence suggests that surface and upper level pressure anomalies near and over the North Pacific are linked to SST anomalies (Allison et al. 1972; Namias 1969; Bjerknes 1969). This linkage between SST and pressure may involve both positive and negative feedback mechanisms, depending upon the oceanic region and the season. Douglas (1973) took the relationship between climatic anomalies and SST anomalies to be an indication that SST data could also be reconstructed from tree-ring data. The results for southern California were encouraging with about 50% of the variance in SST being explained by the tree-ring data when using a simple multiple linear regression analysis. This type of reconstruction is of interest to both meterologists and oceanographers since SST anomalies have been shown to initiate major pressure, temperature, and precipitation anomalies in North America (Allison et al. 1972; Bjerknes 1969; Namias 1969; Pyke 1972). In addition, the reconstructed SST data could be used to infer changes in ocean currents (Douglas 1973). Reconstructed SST data also serve as an independent check upon other long-term reconstructions of precipitation, air temperature, or sea level pressure.

Multiple Linear Regression Analysis

The reconstruction of a given climate variable from tree-ring data lends itself to multiple linear regression analysis. In this project a stepwise multiple linear regression technique was used for reconstructing seasonal SST records. This is the same procedure used previously by Douglas (1973) in reconstructing coastal SST data for southern California. In the present investigation, however, the desired seasonal reconstructed temperature data are the 5-m depth at La Jolla and SST data at 1° squares (predictands) from southern California southwards to the southern tip of Baja California. The set of seven tree-ring chronologies which were analyzed in the previous section are used as the independent variables (predictors).

The regression equation is an equation for estimating a variable, say Y_1 (seasonal SST), from a number of other variables $X_1, X_2 \ldots$ (the tree-ring data). In the case of the seven tree-ring chronologies the number of independent variables can vary, but the regression equation has the form

$$Y_1 = b_1 + b_2X_2 + b_3X_3 \ldots$$

where b_1, b_2, $b_3 \ldots$ are fitted constants.

As noted earlier, the climatic information for a given year can be "held over" into the rings of the following years. In order to extract this climatic information which is "held over," data from each of the seven chronologies were placed in a matrix of tree-ring data representing the lags over four years. That is, seasonal SST at time "t" could be considered a function of the tree-ring data X at times:

$$X_{t-3}, X_{t-2}, X_{t-1}, X_t$$
$$X_{t-2}, X_{t-1}, X_t, X_{t+1}$$
$$X_{t-1}, X_t, X_{t+1}, X_{t+2}$$
$$X_t, X_{t+1}, X_{t+2}, X_{t+3}$$

The reconstruction equations which on the average account for the greatest percent variance are those with the following lagging: $X_{t-1}, X_t, X_{t+1}, X_{t+2}$ (Douglas 1973). The seasonal SST data were calibrated against the tree-ring data for the following years: 1924 to 1940 and 1949 to 1963 for the 1° squares; and 1927 to 1963 for a 5-m temperature record at La Jolla.

The signficance of the regression equations and their variables can be determined by F-testing (Draper and Smith (1966). In these analyses the cutoff level for including a variable into the equation was an F level of 3.0 or greater. It should be noted, however, that a majority of the equations are totally composed of variables that entered the equations at F levels above 4.0.

Considering the length of record at each 1° square (32 years) and La Jolla (37 years), an F ratio for the reconstruction equation of 4.2 or greater indicates that the equation is significant at the 95% level. An examination of the regression equations reveals that all of the equations are significant at the 95% level, and in fact the majority are significant at the 99% level. Only 1 of the 175 regression coefficients was found not to be significant at the 95% level based upon "Students" t distribution. This one regression constant is used in the summer reconstruction equation for the 1° square at 28.5°N, 115.5°W. Since all regression equations are significant at or above the 95% confidence level, it is probable that 9 or less of the 175 variables used have been chosen by pure chance.

When the coefficient of determination r^2 is multiplied by 100, this gives the percent variance explained by the equation. Values for the variance explained range from a low 30% at 33.5°N, 118.5°W during the summer, to a high 77% at 22.5°N, 110.5°W during the summer. The average percent variance explained at the 1° squares is 53% in winter, 54% in spring, and 55% in summer. Viewed in another way, this indicates a correlation coefficient (r) of about .74 between the tree-ring data and the seasonal SST data. These correlation results are somewhat better than those previously obtained from correlating tree-ring data with shore station SST data from southern California ($r = .67$, N averaging 41 years; Douglas 1973). This difference in r values probably reflects the fact that the oceanic data from south of 30°N are more representative of anomalies across broad areas of the eastern North Pacific. In contrast, shore SST data from California may at times reflect periods of tide-induced upwelling which have little relationship to broad-scale air-sea interactions.

Reconstructed SST and Verifications

Using the equations derived from the multiple linear regression analyses, reconstructions were made of the seasonal SST data and the 5-m temperature data for La Jolla back to 1671 (Figures 4 to 12). In the testing of the reconstructions, the physical reasonableness of the reconstructed data and the relation of the reconstructed data to independent data are important factors to be considered. An examination of the plots of the SST data (Figures 4 to 12) indicates that there is considerable correlation between the reconstructed SST data sets. Occasionally during the winter and summer, however, the reconstructed SST data for the southern California eddy region may show little correlation with the reconstructed SST data for southern Baja California (e.g. winters of 1868 and 1869 and summers of the 1870's). This is not an unusual condition since in the winter above-normal seasonal cooling can take place in the southern California eddy region when strong winter winds enhance oceanic mixing, while to the south lighter winds may allow the warm surface waters of late summer to persist. At times during the summer, anomalously warm waters may be restricted to the coast off southern Baja California. This anomaly pattern develops when the North Pacific Equatorial Current moves northward and influences this region earlier in the season.

A verification of some of the predicted SST data can be made by using SST data that were withheld from the calibration—i.e. the SST data prior to 1924 or from 1941-1948. In Table 1 actual and reconstructed seasonal SST data are presented for four 1° squares. This table shows that many of the reconstructions are within .5°C of the actual observed SST. Since extremes of SST are often emphasized in studying climatic anomalies, it was decided to test the predicted data with the observed data in a method that would stress the accuracy of reconstructing the extremes. A test utilizing specific class limits was developed in the following manner. Three class limits of the seasonal SST data were determined so that, on the average, three-tenths of the observed SST's would fall in each of the above-normal and below-normal classes, and the remaining four-tenths would fall in the normal class. An above-normal class reconstruction was thus considered correct if the actual observed value was above or near normal (100% accuracy), and it was considered incorrect if the actual value was below normal (0% accuracy). A tabulation of the results in Table 1 reveals an 81% accuracy in winter, an 83% accuracy in spring, and an 86% accuracy in summer. This gives an overall accuracy of 83% for the reconstructions.

The poorest reconstructions are for the winters of 1923 and 1945 and for the springs of 1917 and 1922. In these four cases, the actual observed SST anomaly patterns were found to have been undergoing major changes. In 1917 and 1922, rapidly warming conditions characterized the end of the spring, even though the March through June SST averages were below normal. Above-normal seasonal cooling occurred during the winter of 1923, following an anomalously warm summer in 1922. Anomalously cool summer waters in 1944 were followed by relatively warm winter waters in 1945. This analysis suggests that in examining the reconstructed SST data, the major anomalies that lasted for a number of seasons are probably correct, though the exact season in which the given anomaly ended may, at times, be off by one season.

An examination of the predicted summer SST data for all stations suggests an anomalously warm summer period from 1841-59 (Figures 10 to 12). Based on the reconstructions, this mid-1800's summer warmth has never been equalled during the period of actual SST records. The apparent accuracy of this reconstruction is borne out by marine fish collections from off southern California during 1853-60. Hubbs (1948) noted that the fish fauna of San Diego " . . . was definitely more tropical than that of any subsequent decade. Of the 30-odd species reported, six (about 20%) do not now occur so far north or have been so rare recently that one certainly would not expect any to be caught at present by such incomplete and superficial collecting as that of the 1850's and 1860's" (page 464). An examination of the SST plots (Figures 10 to 12) clearly indicated anomalously cold summers from

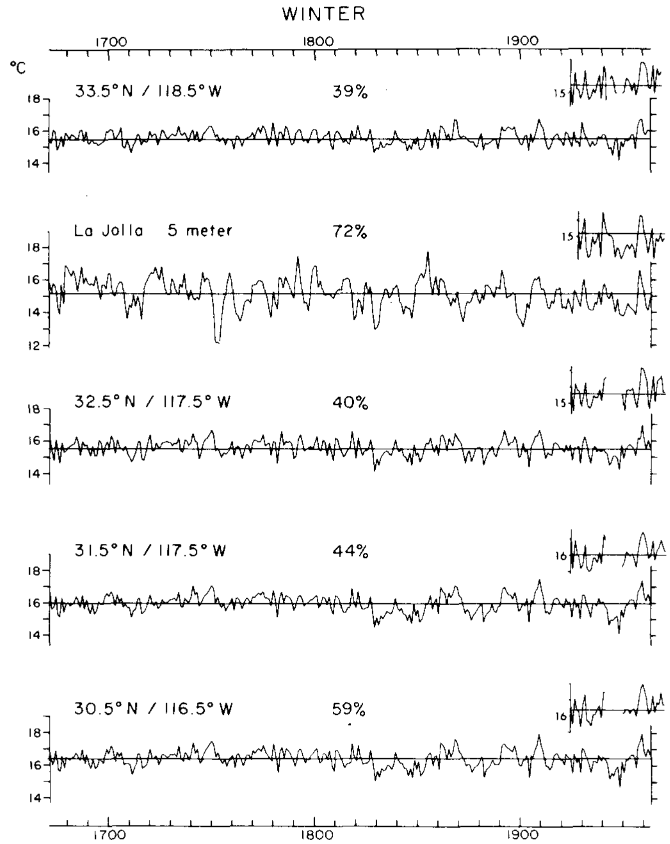


Figure 4. Reconstructed winter sea-surface temperatures for 1° squares from 30°N to 33°N. Winter reconstructed sea-surface temperatures with actual temperature data above each reconstruction. Solid lines through the curves are the means.

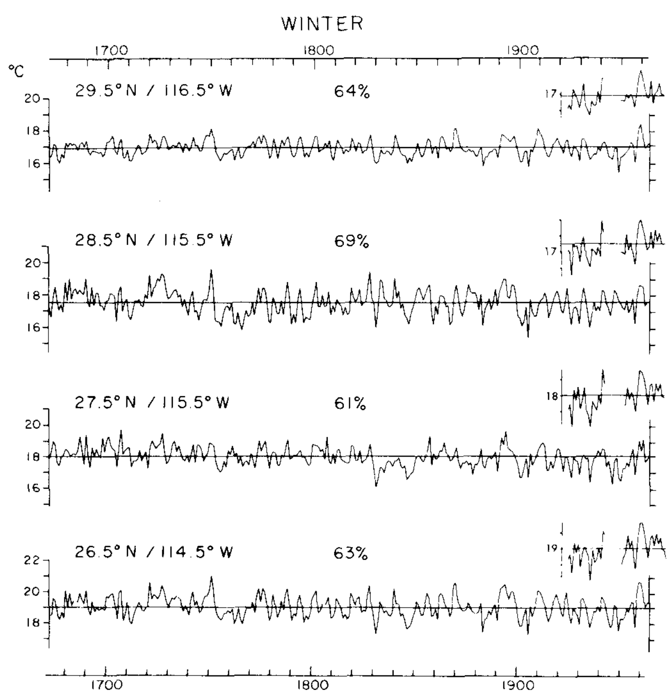
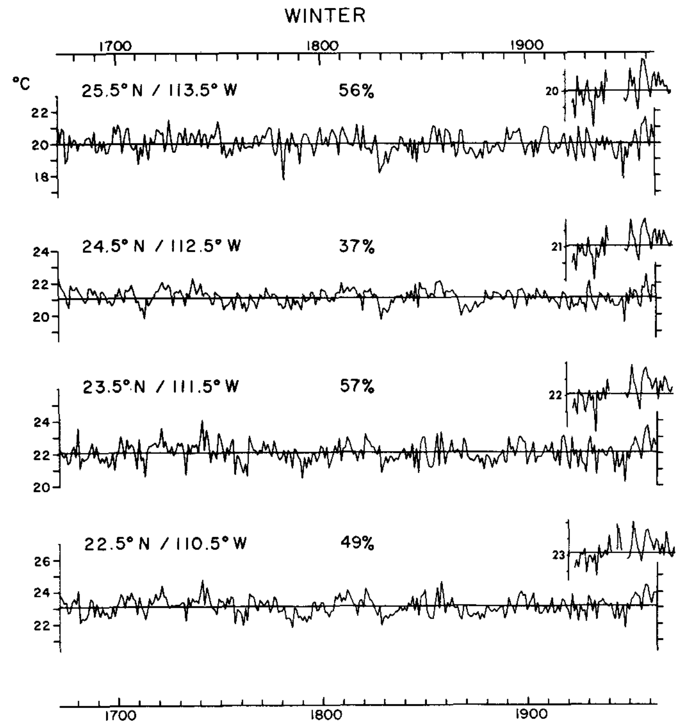


Figure 5. Reconstructed winter sea-surface temperatures for 1° squares from 26°N to 29°N.



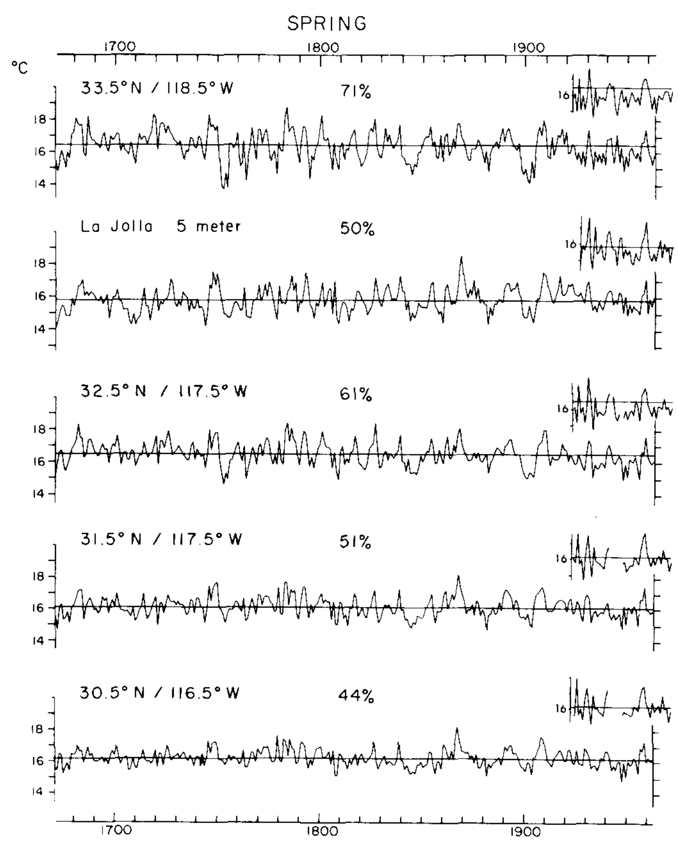


Figure 7. Reconstructed spring sea-surface temperatures for 1° squares from 30°N to 33°N.

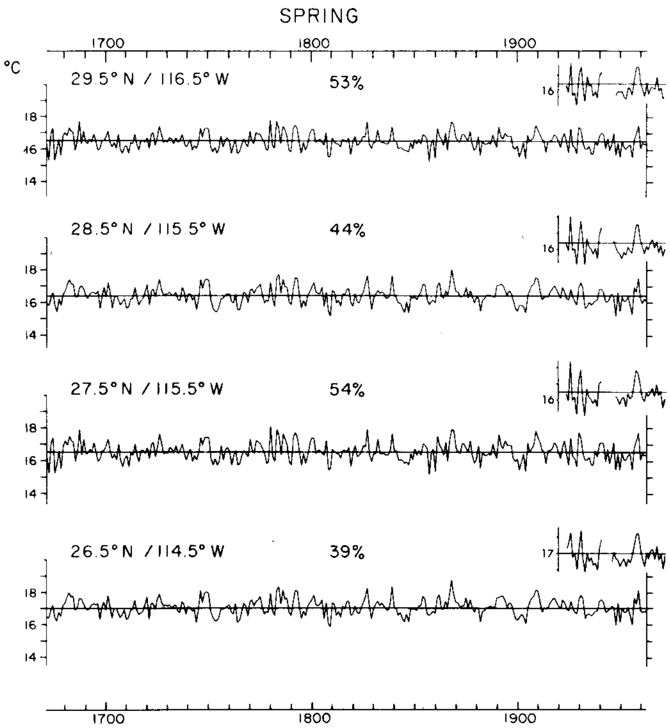


Figure 8. Reconstructed spring sea-surface temperatures for 1° squares from 26°N to 29°N.

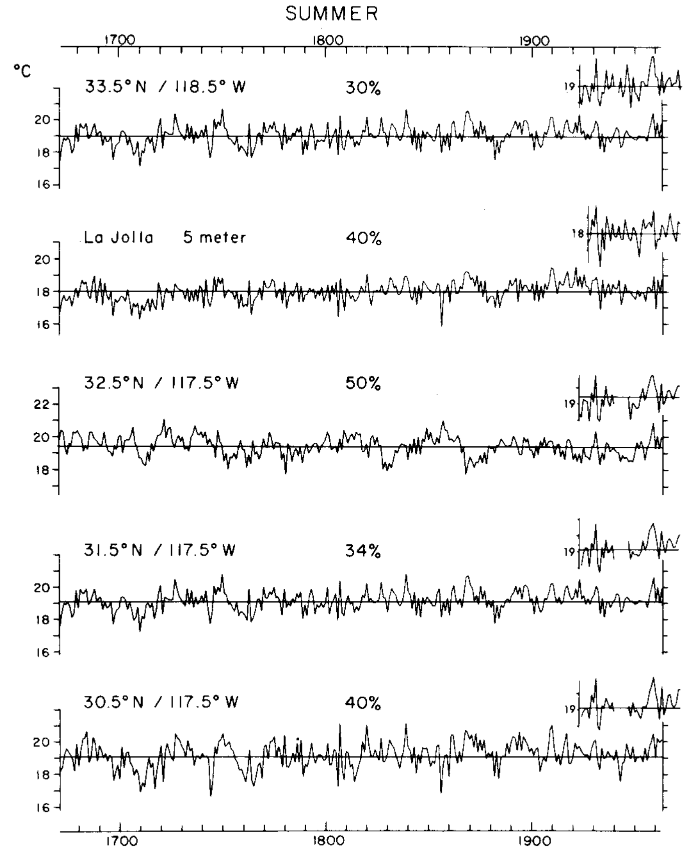


Figure 10. Reconstructed summer sea-surface temperatures for 1° squares from 30°N to 33°N.

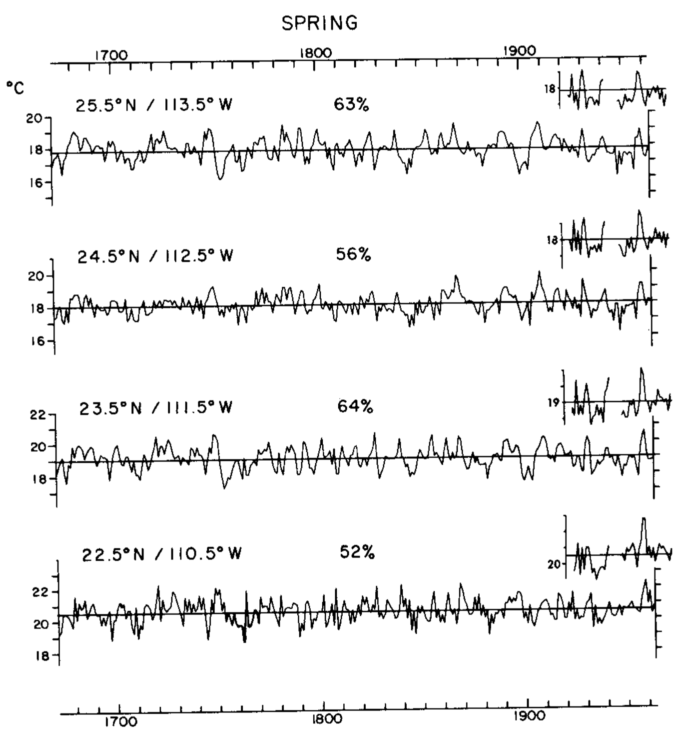


Figure 9. Reconstructed spring sea-surface temperatures for 1° squares from 22°N to 25°N.

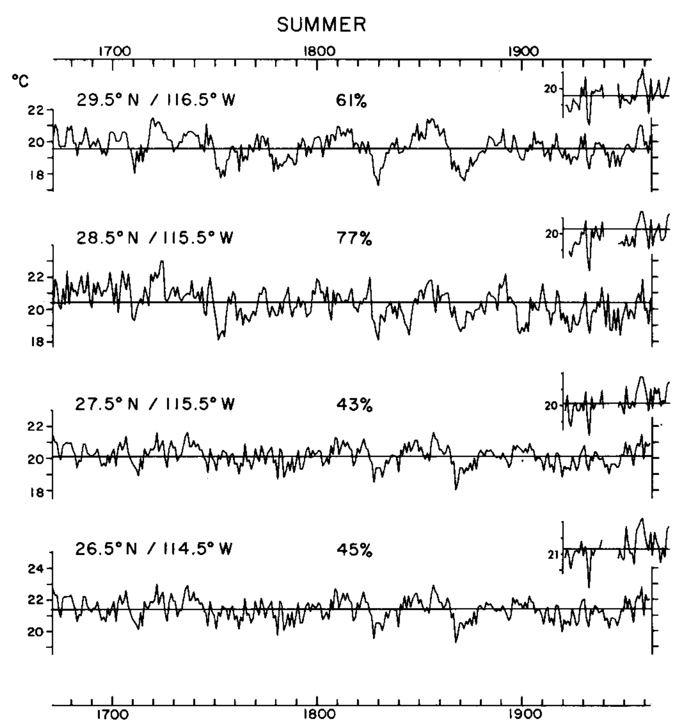


Figure 11. Reconstructed summer sea-surface temperatures for 1° squares from 26°N to 29°N.

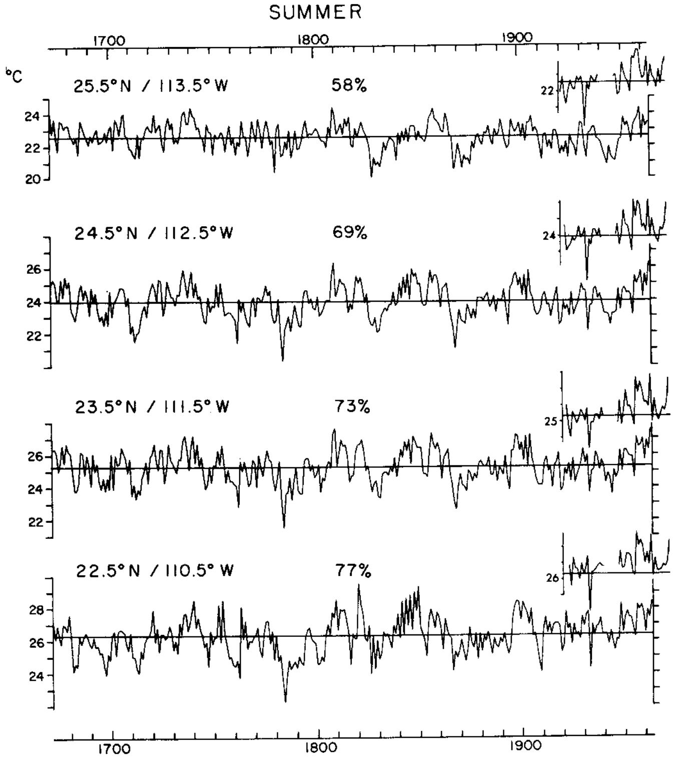


Figure 12. Reconstructed summer sea-surface temperatures for 1° squares from 22°N to 25°N.

1860 to 1880, a condition that undoubtedly resulted in a southward depression of the northern limits of these tropical fish. This reconstructed summer anomaly of the mid-1800's is the most impressive anomaly of any season during the past 200 years (Figures 4 to 12). It is highly encouraging to find that the historical fish-catch records also clearly indicate this to be an unduplicated event.

Hubbs (1948) further noted that long-term SST anomalies along the California coast can affect the distribution and population sizes of numerous marine organisms. An excellent measure of fish population changes can be derived from an examination of anærobic coastal sediments. Such a record exists for the Soledad Basin off Bahia Magdalena (Figure 2, near 25°14'N, 112°41'W). Soutar and Isaacs (1974) found large variations in the population sizes of the northern anchovy (*Engraulis mordax*) as determined from scale counts (Figure 13). These population changes may indicate climatic changes since Baxter (1967) states that "During periods of warmer-than-average water temperatures, adult anchovies became less available in the inshore waters" (page 110). Off central and southern Baja California, 65% of the fish catch is taken in water temperatures ranging between 17.0° and 21.5°C. It would seem, therefore, that anomalously warm periods would favor a paucity of fish, while anomalously cold periods could result in a sizeable increase in the fish population.

TABLE 1

Comparison of the Actual with the Reconstructed Sea-Surface Temperatures at Four Locations.[1]

		Season					
		Winter		Spring		Summer	
1° Square	Year	Actual	Recon.	Actual	Recon.	Actual	Recon.
33.5°N/	1921					18.9	19.9
118.5°W	1923	13.6	15.8	15.7	16.5	18.5	20.4[2]
	1941	16.1	15.7	16.8	16.8		
	1942			16.4	16.9	18.7	19.4
	1943	15.8	14.8	16.6	15.4	19.6	18.3
	1944	16.1	14.9[2]	15.2	16.0	18.3	18.5[2]
	1945	15.7	14.4	14.7	17.1[2]	18.8	19.1
	1946	15.0	15.3	15.9	15.3	20.4	19.4
	1947	15.1	15.5	16.4	16.3	19.5	19.1
	1948			15.5	14.9	17.7	19.0
29.5°N/	1914	16.7	16.3				
110.5°W	1921					19.0	19.5
	1922					19.0	18.8
	1923	16.0	17.5[2]			18.6	19.2
	1941	17.9	17.2	17.2	17.0		
	1945					20.1	19.4
	1947					20.3	19.1[2]
	1948			15.8	15.6	18.8	18.4
26.5°N/	1914	18.7	18.1	17.4	16.9		
114.5°W	1917			16.2	17.5[2]	22.1	21.6
	1919	19.7	19.4				
	1921					20.8	20.7
	1922			15.4	17.5[2]	21.4	20.4
	1923	18.3	20.0[2]			20.0	20.6
	1941	19.9	19.6	17.9	17.5		
	1945					23.6	20.8[2]
	1946	19.1	19.2	16.5	17.1		
	1947			17.1	17.0	20.7	20.4
	1948			16.7	15.9	21.3	20.7
22.5°N/	1914	23.1	22.7				
110.5°W	1917			19.6	21.3[2]	27.2	27.0
	1921					26.1	27.7
	1922			18.4	20.3		
	1923	22.2	22.7			26.9	26.9
	1941	23.2	23.2	21.1	20.9		
	1944	24.9	23.3				
	1945	24.3	22.2[2]	21.6	20.3	26.6	25.3
	1946	23.3	22.7	23.3	20.7		
	1947					26.6	25.9
	1948			20.6	20.6	27.7	28.2
Verification Scores			81%		83%		86%

[1]Data comparison is for the periods not included in the calibrations. Seasonal verification scores are given for each season (see text for details).
[2]Received scores of 0%.

A simple correlation analysis was run between the fish scale count data and the reconstructed summer SST at 25.5°N, 113.5°W (5-year averages for 1785-1919). The results show an r value of -0.49 ($N = 27$), which is significant at the 95% level. This significant negative correlation indicates that from 1785-1923 the northern anchovy was probably common off Bahia Magdelena during cool summer periods (e.g. 1825-34 and 1870-79) and rare

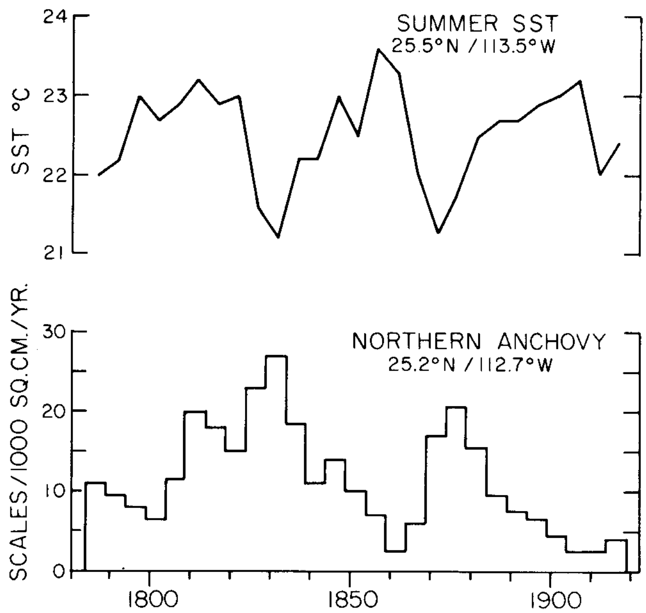


Figure 13. The total number of northern anchovy scales (5-year totals) collected in deep-sea cores from off central Baja California (from Soutar and Isaacs 1974). Plot of reconstructed summer sea-surface temperatures at a nearby location is given for comparison.

during warm-water periods (e.g. 1845-64). The correlation between the northern anchovy and the reconstructed SST might have been higher if it was based on yearly data rather than 5-year means which unfortunately often overlapped apparent warm and cold periods (e.g. late 1830's-early 1840's). This correlation analysis clearly stands out as a verification of these two independent data sets back to 1785.

CONCLUSIONS

Analyses of average monthly SST data for 1° squares off southern California and Baja California indicate that there were two periods of virtually complete records: 1924 to 1940 and 1949 to 1972. Standard ring-width series from western North America were examined for their potential use in reconstructing these SST records back to the 1600's. Climatic information for all months of the year appears to be contained in the tree-ring series. Presumably, tree species were indirectly influenced in their growth by SST changes during the past in a manner similar to that for the period in which the reconstruction equations have been developed (1924 to 1940 and 1949 to 1963).

The average percent variance of the SST data that is explained by the tree-ring series is 53% in winter, 54% in spring, and 55% in summer. This amounts to a correlation of about 0.74 ($N = 32$) between the tree-ring series and the SST series. Tree-ring series are highly correlated with the summer SST off southern Baja California (*r* values of about 0.85). Less correlation is noted between the tree-ring series and the SST data for off southern California (*r* values of about 0.65). Apparently the complex oceanographic conditions of this region are not as well related to widespread changes of climate in the eastern North Pacific.

The reconstructed records of SST indicate a number of changes in seasonal SST patterns since 1671. From 1671 until about 1800 there are suggestions of relatively warm winters and cool summers. This indicates a southward shift in the oceanic regime of the eastern North Pacific, because suppressed seasonal ranges in SST are more typical of central California.

The mid-1800's were characterized by anomalously warm summers and an apparent northward shift in the mean position of the summertime oceanic front off western Baja California. The SST departures from normal during some of these summers exceeded +2.4°C, and this is equivalent to about a 2° latitudinal shift in the SST fields and the oceanic front.

A general upward trend in SST is noted in the 5-m temperature reconstructions for La Jolla, California. This rise in ocean temperatures coincides with the warming at the end of the Little Ice Age, and thus this event may be detectable in SST reconstructions. The rise of about 1°C in the 5-m temperatures is most noticeable during the seasons of upwelling, spring and summer, and may reflect warming of the subsurface water mass off southern California, which originates to the south. It was noted that anomalously warm summer conditions commenced in this southern region about 1800, and this coincides with the beginning of the warming at 5 m.

Verification of the reconstructed SST data was accomplished through a number of methods using different sources of data. The SST data from the periods prior to 1924 or from 1941 to 1948 tended to indicate a fairly high degree of accuracy in reconstructing SST extremes (an 83% accuracy). In most cases the reconstructed anomalies were within 0.5°C of the actual anomalies. Reconstructions were not as accurate during periods of major SST reversals, with the actual season of reversal occasionally being miscalculated by one season.

Verification of the reconstructions for the 1700's and the 1800's involved comparing the reconstructed SST data with deep-sea varve data. The varve data provide estimates of relative variations in northern anchovy populations from 1785 to present. These estimates of fish populations showed a significant negative correlation with summer SST for off southern Baja California (*r* value of −0.49). Plots of the two data sets indicate that the fish species was less common in the warmest summers, and this is in agreement with data that indicate the species is seldom caught when water temperatures rise to about 21.5°C.

ACKNOWLEDGMENTS

This research was made possible through a grant from the Office of Climate Dynamics, National Science Foundation. During the course of the project, M.K. Robinson of Scripps Institution of Oceanography, University of California San Diego, made numerous helpful suggestions concerning the use of SST data. The average monthly SST data were processed and generously provided by Dr. R. T. West, Norpax project, Scripps Institution of Oceanography.

L.M. Drew of the Laboratory of Tree-Ring Research, University of Arizona, was very helpful while I ran the computer analyses. Dr. C.W. Stockton of the laboratory gave me helpful direction and advice throughout this project.

LITERATURE CITED

Allison, L.J., J. Steranka, J.R. Holub, J. Hanse, F.A. Godshall, and C. Prabhakana 1972. Air-sea interaction in the tropical Pacific Ocean. NASA Tech. Note D-6684, National Aeronautics and Space Administration, Washington, D.C. 84 p.

Baxter, J.L. 1967. Summary of biological information on the northern anchovy *Engraulis mordax* Girard. Calif. Coop. Oceanic Fish. Invest. Rep. 11:110-116.

Bjerknes, J.A. 1969. Atmospheric teleconnections from the equatorial Pacific. Mon. Wea. Rev. 97(3):163-172.

__________. 1974. Atmospheric teleconnections from the equatorial Pacific during 1963-67. Final Report, NSF grant GA 27754. Univ. Calif. Los Angeles, 61 p.

Douglas, A.V. 1973. Past air-sea interactions off southern California as revealed by tree-ring chronologies. M.A. thesis, Univ. Arizona Tucson, 98 p.

Draper, N.R., and H. Smith. 1966. Applied regression analysis. John Wiley & Sons, Inc., New York, 407 p.

Fritts, H.C., J.C. Mosimann, and C.P. Bottorff. 1969. A revised computer program for standardizing tree-ring series. Univ. Arizona, Laboratory of Tree-Ring Research, Tree-Ring Bull. 57(1-2):3-18.

Fritts, H.C., T.J. Blasing, B.P. Hayden, and J.E. Kutzbach. 1971. Multivariate techniques for specifying tree-growth and climate relationships and for reconstructing anomalies in paleoclimate. J. Appl. Meteorol. 10(5): 845-864.

Hubbs, C.L. 1948. Changes in the fish fauna of western North America correlated with changes in ocean temperature. Jour. Mar. Res. 7(3): 459-482.

LaMarche, V.C., and H.C. Fritts. 1971. Anomaly patterns of climate over the western United States, 1700-1930, derived from principal component analysis of tree-ring data. Mon. Wea. Rev. 99(2):138-142.

McEwen, G.F. 1925. Ocean temperatures and seasonal rainfall in southern California. Mon. Wea. Rev. 53(11):483-494.

Namias, J. 1969. Seasonal interactions between the North Pacific Ocean and the atmosphere during the 1960's. Mon. Wea. Rev. 97(3):173-192.

__________. 1971. The 1968-69 winter as an outgrowth of air and sea coupling during antecedent seasons. J. Phys. Oceanog. 1(1):65-81.

__________. 1972. Experiments in objectively predicting some atmospheric and oceanic variables for the winter of 1971-72. J. Appl. Meteor. 11(8).

__________. 1973. Thermal communication between the sea surface and the lower troposphere. J. Phys. Oceanog. 3(4):373-378.

__________. 1974. Longevity of a coupled air-sea-continent system. Mon. Wea. Rev. 102(9):638-648.

Pyke, C.B. 1972. Some meteorological aspects of the seasonal distribution of precipitation in the western United States and Baja California. Los Angeles, Univ. Calif. Water Resources Center Contrib. No. 139, 205 p.

Schulman, E. 1947. Tree-ring hydrology in southern California. Univ. Arizona Bull. 28(3) (Lab. of Tree-Ring Res. Bull. 4), 36 p.

Soutar, A., and J.D. Isaacs. 1974. Abundance of pelagic fish during the 19th and 20th Centuries as recorded on anærobic sediment of the Californias. Fish. Bull. U.S. 72(2): 257-273.

Stokes, M.A., L.G. Drew, and C.S. Stockton. 1973. Tree-ring chronologies of western America, I. Selected tree-ring stations. Univ. Ariz., Lab. of Tree-Ring Res., Chron. Series 1:1-87.

Part IV

SCIENTIFIC CONTRIBUTIONS