TIME AND SPACE SCALES OF SOME OCEANIC AND ATMOSPHERIC PARAMETERS IN THE GULF OF ALASKA

A

THESIS

Presented to the Faculty of the University of Alaska

in Partial Fulfillment of the Requirements

for the Degree of

MASTER OF SCIENCE

By

Cynthia Juyne Beegle, B.S.

Fairbanks, Alaska

May 1986

ABSTRACT

Time series of monthly means up to 65 years long were examined to determine the time and spatial scales of variablity in the Gulf of Alaska. Sea level, sea level pressure (SLP), air temperature, fresh water discharge, sea surface temperature (SST) and the Southern Oscillation Index (SOI) are the variables chosen to gain insight into local and global responses in the gulf. This study reports four major results. 1) Sea level anomalies (variations from the annual cycle) are driven by wind and fresh water; temperature effects in sea level are not seen. 2) SST anomalies cannot be predicted from sea level data, but SLP in southeastern Alaska and air temperature in Seward may be useful indicators on a two to three month time scale. 3) On the whole, anomalies in coastal and interior Alaska weather occur together, with SLP 180° out of phase with air temperature and precipitation. Using empirical orthogonal functions, the Southeast and Southcoast district can be separated. 4) A statistically significant SOI signal is seen is both SLP ($p>0.995$, Seward) and sea level ($p>0.995$) records.

TABLE OF CONTENTS

List of Figures

List of Tables

ACKNOWLEDGEMENTS

Some people deserve thanks for supplying data which are often obscure: Jerome Namias and Dan Cayan of the Scripps Institution of Oceanography for the sea level pressure data; Ted Fathauer of the National Weather Service Forecast Station in Fairbanks for historical barometric pressure data; James R. Hubbard of the National Oceanic and Atmospheric Administration Tides and Water Levels Branch for recent sea level data and an explanation of Seward's ups-and-downs; Joe Neibauer of the Institute of Marine Science for Southern Oscillation Index Data; and Tom Royer of the Institute of Marine Science for sea surface temperature, Seward subsurface temperature and fresh water discharge data.

Without financial assistance this study would not have been possible. My advisor, Tom Royer, did what every graduate student wishes there advisor to do - he removed the burden of funding from my shoulders onto his. Initially this work was supported by the Alaskan Coastal Jet project funded by the National Science Foundation (OCE8308232), and, later, by the Alaska Sea Grant Program.

My committee deserves special thanks for enduring the fast pace of the work at the end of this study. Each endured my countless questions most admirably. Tom Royer and Ted Cooney are to be additionally commended for their patience in dealing with a neurobiologist-turned-physical oceanographer. Walt Johnson was especially helpful when Tom was away and in pointing out better alternatives for material presentation. Tsuneo Nishiyama taught me just how important physical oceanography is to the fisheries industry. For helping me to understand myself, life and the university system, John Turner deserves a great deal of thanks.

Everything that we endeavor in has a human part, whether active participant, or outside observer. The human part of me wishes to thank (in order of appearance) Allen L. S. Evans, Beth A. Hayward and Bill D. Murphree for their support, love and understanding during an "interesting time" (in the Chinese sense).

1. INTRODUCTION

Today's oceanography often involves analysis of long time series. Physical scientists now have access to data that were unavailable in the last decade. Thus, one can step back and place single events, long term trends and variability of natural systems, into a much larger scale of perspective. Within this study, historical data sets of oceanographic and atmospheric parameters dating as far back as 1919 are examined in an attempt to build a foundation to relate the physical setting in the Gulf of Alaska into a global perspective. With this information, a later study can relate phenomena occurring in the gulf with the local fishery conditions.

A. Gulf of Alaska; A Synopsis of the Physical Setting

At 40°N, the North Pacific Current flows east toward the British Columbia coast. This current bifurcates in the vicinity of 140° to 120°W, forming the California and the Alaska Currents. The Alaska Current flows counter clockwise along the shelf break around the Gulf of Alaska as it forms the Alaska Gyre (Pickard and Emery, 1982).

Rapid, large-scale atmospheric activity in the Gulf of Alaska is generated by the advection of Arctic air masses into the region. The large horizontal thermal and humidity gradients common to the gulf are created by the exchange of heat and moisture from the warmer sea surface to the cold, dry overlying air (Winston, 1955). Two pressure systems, the "Aleutian Low" and the "North Pacific High", alternate domination of the subarctic North Pacific with the seasons (Thompson and Van Cleve, 1936). In winter, the Aleutian Low predominates with easterly winds in the northern Gulf of Alaska. During the summer, the North Pacific High moves into the area between 30°N and 40°N as the Aleutian Low weakens. This leads to light, variable winds over the Gulf of Alaska (Dodimead, et al, 1963). One should note that the Aleutian Low is not a specific low pressure system, but the statistical presense of low pressure systems off the Aleutian islands (Overland, 1981).

Fresh water is an important factor in the circulation of the Gulf of Alaska (Roden, 1967 and Royer, 1982). Elevations in the Alaska Coastal Range of over 4 km exist within a coastal drainage area which is often less than 150 km wide. Adiabatic movement of moisture laden air masses over this mountain range causes high precipitation rates (>240 cm year^{-1}). Depending upon the seasonal temperature cycle, this precipitation is either stored as snow in the numerous glaciers along the Alaska coast for later release or enters the hydrological cycle directly as rain. The mean value of fresh water discharge into the Gulf of Alaska is 23,000 m^{3} s^{-1}, with the total discharge varying from almost 0 in midwinter to more than 60,000 m^{3} s^{-1} at the October maximum (Royer, 1982). Fresh water input and wind stress maintain a narrow baroclinic jet which flows counterclockwise around the perimeter of the Gulf of Alaska (Royer, 1981).

Precipitation exceeds evaporation in the gulf by 50 cm year^{-1} (Jacobs, 1951). Because of the low surface salinity, the cold, dry Arctic air does not extract enough heat from the water for deep or bottom water formation as in the North Atlantic (Fleming, 1958). However, I believe that if the large amount of fresh water did not empty into the Gulf of Alaska, such as during an ice age, deep water formation would be likely to occur.

B. Objectives

The main objective of this study is to describe long time series data of some physical parameters in the Gulf of Alaska. From these time series, individual and long term cyclic phenomena can be examined and used to produce a time scale of phenomena in the Gulf of Alaska.

The propagation of global phenomena, such as the El Nino - Southern Oscillation (ENSO), to high latitudes can also be determined from extensive time series data. Enfield (1984) lists three reasons why sea level is the best variable for characterizing ENSO events. First, sea level is directly related to the ENSO dynamics. Second, sea level integrates the surface flow over the baroclinic deformation radii. Third, sea level is generally a long, continuous time series.

Another objective is to determine whether the Seward subsurface temperature record can be extrapolated back in time using sea level data. Royer (personal communication) suggested that the latest increase in subsurface temperature at the Seward hydrological station could be due to the most recent ENSO event, but the time series is not extensive enough to determine whether or not such events always propagate to high latitudes. Increased temperature in the water column should show up as increased sea level, hence the long time series of sea level can be used to recreate missing temperature data.

Due to the nonlinearity of the equation of state of sea water, at high latitudes the temperature effect is not observed in sea level because it is masked by the magnitude of the local salinity effects. Thus for reasons that are explained more fully later, this objective was not accomplished.

2. TIME SERIES DATA

A. Station Locations

A total of six meteorological stations were included in this study: five coastal and one interior (Figure 2-1). Seward, Alaska is the most important station location because of the long time series of temperature profiles that exist for a nearby hydrological station. The other coastal stations, Yakutat, Juneau, Sitka and Ketchikan, were chosen because each is upstream of Seward, hence phenomena seen at one of these stations should propagate downstream toward Seward. Fairbanks was included as an interior Alaskan meterological station for comparative purposes and as a point of provincial interest to the author.

B. Sea Level

Sea level data were supplied by the National Oceanic and Atmospheric Administration (NOAA), National Ocean Service Tides and Water Levels Branch in Rockville, Maryland as monthly means from the Anonymous (1983) publication <u>Sea Level Variations for the United States 1855-1980</u>, augmented by more recent NOAA data for individual stations. The sea level measurements used in this study, with the associated years in parentheses, are for Juneau (1936 to 1980), Ketchikan (1919 to 1980), Seward (1925 to 1938 and 1944 to 1983), Sitka (1938 to 1980) and Yakutat Bay (1940 to 1982) with some short lapses in the records (Figure A2-1).

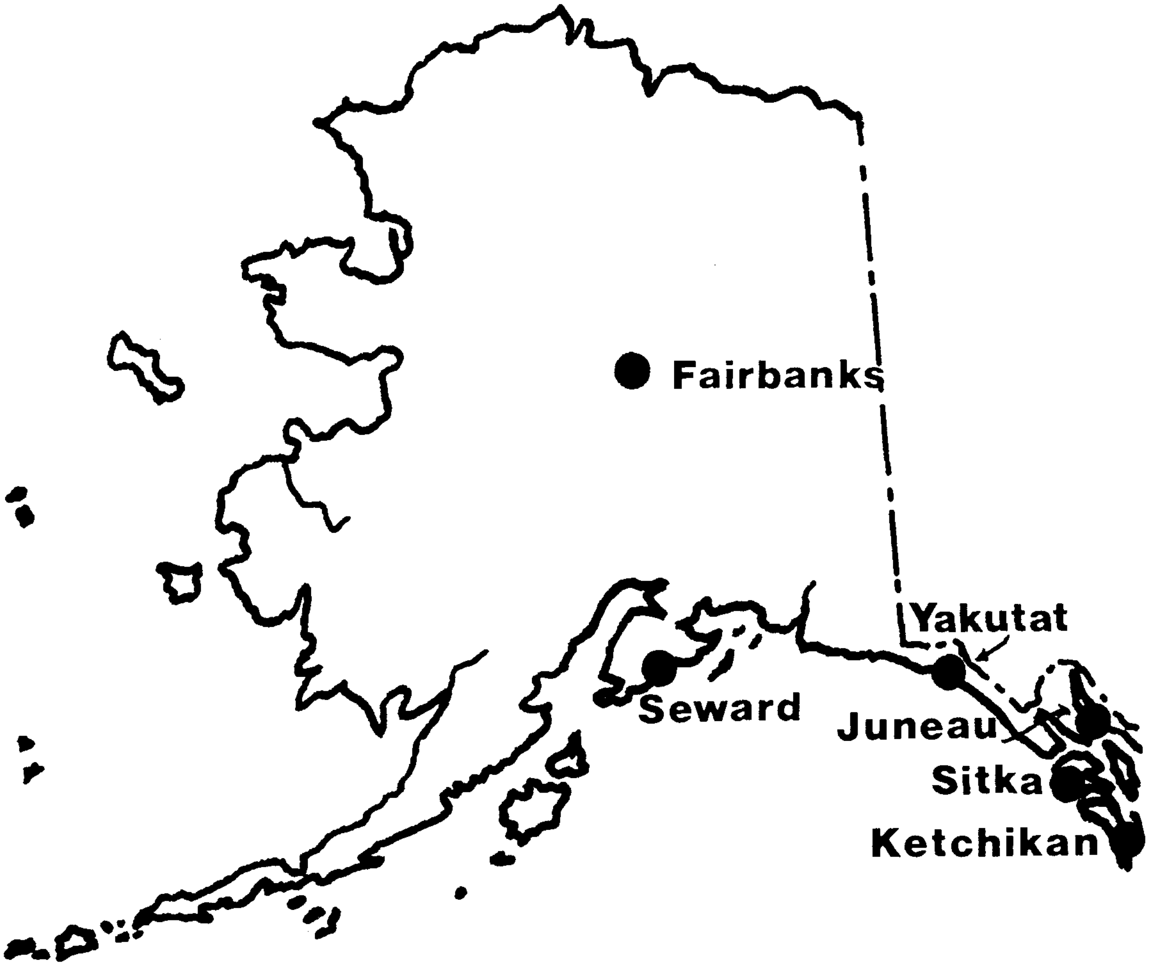

Figure 2-1. The locations of the six meteorological stations used in this study.

Table 2-1. Sea level stations and locations, Anonymous (1983).

Station	Location
Juneau	58° 17.9'N, 134° 24.7'W
Ketchikan	55° 20.0'N, 131° 37.5'W
Seward	60° 0.58'N, 149° 26.8'W
Sitka	57° 0.31'N, 135° 20.5'W
Yakutat Bay	59° 32.8'N, 139° 44.1'W

C. Barometric Pressure

Monthly mean barometric pressure data are taken from three sources. The majority of these data were sea level pressure (SLP) from the Climate Research Group (CRG) at Scripps Institute of Oceanography (Namais, personal communication) reported either as a 3^{o} latitude by 3^{o} longitude grid (April 1954 to July 1982) or as a 5^{o} latitude by 5^{o} longitude grid (January 1919 to March 1954) of the North Pacific. Barometric pressures for Seward, Yakutat, Juneau, Sitka and Ketchikan were chosen from the grid point closest to each station. Some SLP data are available from meteorological stations near the individual station locations through the U.S. Department of Agriculture, Weather Bureau (WB) (1919 to 1940) and the U.S. Department of Commerce, WB (1941 to 1947). Some further SLP data are available from the National Weather Service (NWS) (Fathauer, personal communication). To correct sea level data for the inverse barometer effect (Gissler, 1747), SLP is required. Thus, station pressures were reduced to SLP when necessary using the pressure reduction ratio, R(T), which is a function of temperature, T, for a given station location. If P_{STN} is the station pressure, then SLP can be approximated by using the formula:

$$SLP = R(T) \cdot P_{STN}.$$

Where available, the WB data were used in the barometric pressure records. The NWS data were then used to fill in as many missing data points as possible, and the CRG data were used to complete the entire record. There were two places where the NWS data were not used: 1943 and 1944 at Juneau and at Ketchikan because the resulting anomalies with the NWS data were on the order of 10 mbar greater than those for the rest of the record. The problem was corrected by using the CRG data for these two years. Since the correlation coefficient between the WB and CRG data, where the two overlapped, was 0.92 ($p>0.995$) for Juneau and 0.81 ($p>0.995$) for Ketchikan, I have confidence that the substitution is in order. A pictorial overview of this process is given an Appendix 1.

D. Air Temperature

Monthly mean air temperatures are available from the U.S. Department of Agriculture, WB (1919 to 1940), the U.S. Department of Commerce, WB (1941 to 1965), the U.S. Department of Commerce, Environmental Sciences Services Administration (1966 to 1970) and the U.S. Department of Commerce, NOAA, Environmental Data Service (1971 to 1984). These means were converted from degrees Fahrenheit to degrees Celcius.

E. Fresh Water Discharge

Fresh water discharge estimates are those used in Royer (1982). These data are totals for two U.S. Weather Service divisions: Southeast Alaska (approximately 130°W to 140°W) and Southcoast Alaska (approximately 140°W to 155°W). The divisional monthly averages are used in analyses as Southeast fresh water discharge (SEFD) and Southcoast fresh water discharge (SCFD).

F. Sea Surface Temperature

The sea surface temperature (SST) data are from Dr. T.C. Royer (personal communication). These data are a regional mean average of SST values from a 5° latitude by 5° longitude grid of the North Pacific (Namais, personal communication). The mean is taken over the region from 45°N to 55°N and from 170°W to the North American coast, after Chelton (1984).

G. Southern Oscillation Index

The SOI is a time series depicting more global phenomena than the aforementioned data. Dr. H.J. Neibauer provided the values as the difference in barometric pressure between Tahiti and Darwin, Australia, that is,

$$SOI = P_{Tahiti} - P_{Darwin}.$$

Normally the pressure at Darwin is lower than at Tahiti, hence the circulation patterns which maintain the northern Australian rain forests. During an ENSO, SOI changes sign, Australia suffers severe droughts (Ralph, 1983), and precipitation is greater then normal east of the International Dateline to South America.

3. METHODS

A. Sea Level Adjustments

The inverse barometer effect (Gissler, 1747) was removed from the sea level records (see Appendix 2), using the conversions:

$$1 \text{ mbar} = 0.75 \text{ mm Hg}$$

and

$$h_{SL} = -P_A$$

where h_{SL} is the change is height of sea level in cm and P_A is the atmospheric pressure in mbar (Neumann and Pierson, 1966). For ease in further computations, each station's sea level record was offset by a constant height to yield the complete record with minimum values, which are positive. No corrections were made for the possible influence of wind stress even though changes in wind occur with changes in pressure. The wind stress effect can possibly be larger and opposite in sign to the pressure effect (Patullo, et al, 1955). This explains why sea level variation may be greater after the record is corrected for the inverse barometer effect (Patullo, et al, 1955).

The rate of isostatic rebound was calculated at each station by fitting a least squares line of regression to the data and then removing the trend from the time series (see Appendix 2). Values of land emergence, derived from these data, were in good agreement with the published values of Hicks and Shofnos (1965) for Yakutat, Juneau, Sitka and Ketchikan (Table 3-1). No published values exist for Seward.

Table 3-1. Rates of isostatic rebound (cm $year^{-1}$).

Station	These data	Hicks and Shofnos (1965)		
		Total Series	1949-1962	1944-1962
Seward	-0.11 ± 0.10	---	---	---
Yakutat	-0.52 ± 0.12	-0.73 ± 0.12[1]	-0.73 ± 0.12	-0.55 ± 0.15
Juneau	-1.25 ± 0.10	-1.46 ± 0.09[2]	-0.52 ± 0.12	-1.25 ± 0.12
Sitka	-0.34 ± 0.11	-0.34 ± 0.09[3]	-0.37 ± 0.09	-0.15 ± 0.09
Ketchkan	-0.04 ± 0.06	-0.03 ± 0.03[4]	-0.15 ± 0.09	-0.03 ± 0.12

[1] (1940-1962).

[2] (1936-1962).

[3] (1939-1962).

[4] (1919-1962).

Besides the lack of previously reported values for Seward's rate of land emergence, this station posed an additional difficulty to the removal of the isostatic trend. During the 1964 earthquake, the Seward Tidal Bench Mark was displaced vertically by 109.42 cm (Hubbard, personal communication). This offset had to be removed from the post 1964 sea level record. The complete resultant time series yields an isostatic trend of -0.11 cm year^{-1}, but even after this slope and offset are removed, the record still appears to retain a long term linear trend in certain sections, and a discontinuity still exists at the time of the 1964 earthquake. This break is probably due either to an error in the reporting of the Bench Mark height change due to the earthquake, a vibration induced error in the sea level gauge, or the replacement of the gauge. The Seward sea level record may be divided into three sections by two major discontinuities. The first section consists of the record from 1925 to 1939; after 1939, the record contains a 5 year gap. The second section is from the 1964 earthquake to the present. If these three sections of the Seward record are fitted with a regression line, then the slopes from the three segments are -0.196, +0.213 and -0.189 cm year^{-1} ($\pm$0.035 cm year^{-1}). The oldest and youngest sections contain trends which could be considered to be the same within the error limits. Extending these two regression lines to overlap yields an 11.17 cm vertical separation, with the youngest section less than the oldest. Discounting the positive trend in the middle section, an argument could be made that there was an error in the measurement of the Seward

Tidal Bench Mark after the 1964 earthquake. Since the trend in the middle section cannot be explained geologically, no further alterations were made in this time series. Thus the overall trend of -0.11 cm year^{-1} was used for removal of isostatic rebound at Seward.

B. Generation of the Total Fresh Water Discharge

The coastal current which flows adjacent to the Southcoast district stations (Seward and Yakutat) has had fresh water input from both districts. The parameters at these stations should be better correlated with a total fresh water discharge (TFD) that is the sum of SEFD and SCFD lagged by some amount of time. Time lags betweem TFD and other parameters of up to 3 months lead and lag were used. For all but the Seward sea level record, the correlation coefficients for each station were highest with SEFD lagging SCFD by 1 month, in agreement with Royer (1982). Thus, TFD represents

$$TFD(t) = SEFD(t-1) + SCFD(t).$$

C. Generation of the Anomalies

The annual cycle was removed from the sea level, SLP, fresh water discharge and air temperature data by obtaining the mean value for each calendar month and then subtracting this overall mean from all the data values from that particular month (see Appendix 4). The SST and SOI data had already been adjusted for their annual cycles when received. The resulting anomalies formed the data for the subsequent analyses. Patullo, et al, (1955) note that for sea level records of monthly means longer than 10 years, solar induced tides are predominant and nearly independent of the number of degrees of freedom, N. Because all anomaly values are small in comparison to the standard deviation, this method of using the mean calender month value for removing the annual signal is adequate for sea level data. For atmospheric data, Trenberth (1984) recommends the method proposed by Straus (1983) of determining the 12 and 6 monthly cycles augmented by the 4 and 3 monthly cycles. However, Trenberth's discussion pertains to daily records. Monthly mean data preclude this type of analysis.

D. Event Analysis

In order to place the 23 time series in a single perspective, a method of simplifying the data was necessary. All anomalies greater than 2 standard deviations from the mean were classified as "events". This selects the greater anomalies from each time series, and allows examination of the strongest events. Because the complete set of data is included in both the standard deviation and the event analysis, approximately 33% or 14 anomalies in each series were classified as events by this method.

E. Auto- and Crosscorrelations

Auto- and crosscorrelations were determined using the University of Alaska VAX computer with the "Minitab" statistics software. All correlations were carried out to a maximum lag of $\tau = \pm X\, 5^{-1}$ or 20% of the record where τ is the time lag in months, and X is the total number of monthly data points in the record. This was done because conclusions drawn from a more extensive range of offsets might not be meaningful. Correlation coefficients and significance levels cannot be used to establish a cause and effect relationship.

Crosscorrelations can only yield evidence that such a relationship might exist. No significant correlations were found with lags greater than 24 months.

Since the parameters were not necessarily independent, that is, autocorrelations were significant at lags other than 0, N was reduced to the effective number, N_{EFF}, for significance considerations using the formula:

$$N_{EFF} = \frac{N}{1 + 2\sum_{i=1}^{N} (1 - i/N) r_{1i} r_{2i}}$$

where r_{1i} and r_{2i} are the respective autocorrelation coefficients at $\tau = i$ for the data sets 1 and 2 being crosscorrelated (Trenberth, 1984). All correlation coefficients will be accompanied by the Students'-t statistical probability that the hypothesis is true, that is, a relationship exists between the two parameters which are being compared. Because of the large numbers of measurements, $p>0.995$ and $p>0.9995$ were considered the significant and highly significant levels, respectively. If an initial signal was apparent at $p>0.995$, the $p>0.95$ significance level was sometimes considered for further insight into driving mechanisms.

F. Empirical Orthogonal Functions

Empirical orthogonal function (EOF) analysis decomposes a Z dimensional symmetrical matrix into a set of Z eigenvectors with Z associated eigenvalues. The first eigenvector defines an axis in covariance or correlation space (depending upon the type of analysis) which accounts for the maximum amount of variance in the data. The Z-1 remaining eigenvectors successively explain the remaining amounts of variance such that the sum of the percentage of variances explained for the Z eigenvectors is, by definition, equal to 100%.

Empirical Orthogonal Function analyses were performed on the covariance and correlation matrices to determine the matrices' characteristic vectors. Covariance is the joint variation of two variables about their common mean. The formula for computing the covariance between variables j and k (cov_{jk}) is

$$cov_{jk} = \frac{n \sum_{i=1}^{n} X_{ij} X_{ik} - \sum_{i=1}^{n} X_{ij} \sum_{i=1}^{n} X_{ik}}{n(n-1)} .$$

The correlation may then be thought of as the ratio of the covariance of the two variables to the product of their standard deviations

$$r_{jk} = \frac{cov_{jk}}{s_j \, s_k}$$

where s_j and s_k are the standard deviations of j and k, respectively. The software was developed by Dr. W.R. Johnson utilizing the University of Alaska Computer Network International Mathematical and Statistical Libraries statistical software. The EOFs for sea level, SLP and air temperature at the various stations were calculated, as well as the EOFs of sea level, SLP, air temperature and fresh water discharge at each coastal station.

4. RESULTS

A. Event Analysis

Anomaly time series (Appendix 3) were examined for events more than 2 standard deviations from the mean. Figure 4-1 shows the events for all variables. Only those points in time with 4 or more events within the sea level, SLP or air temperature records are noted as synchronous events. This assures that most of the study area is involved in a synchronous event. Other stations not meeting the 2 standard deviation criterion may have experienced similar forcing, but not enough for significance at the proposed level. For fresh water discharge, both districts and the resultant total must evidence events. In the SST and SOI records, events which repeat over 2 months are noted. All of these events occur between October and March, when weather is most variable in the Gulf of Alaska.

To examine pervasive events, time periods are selected when events occur in 3 different variables over 2 months, and when at least 60% of the coastal stations show an event in one or more of the variables. This information cannot be used for determination of phase relations between variables because too few data are presented for a statistical sample and, by the nature of the selection criteria, only peaks rather than trends are present. Crosscorrelations were calculated to resolve the time scales of interactions between variables.

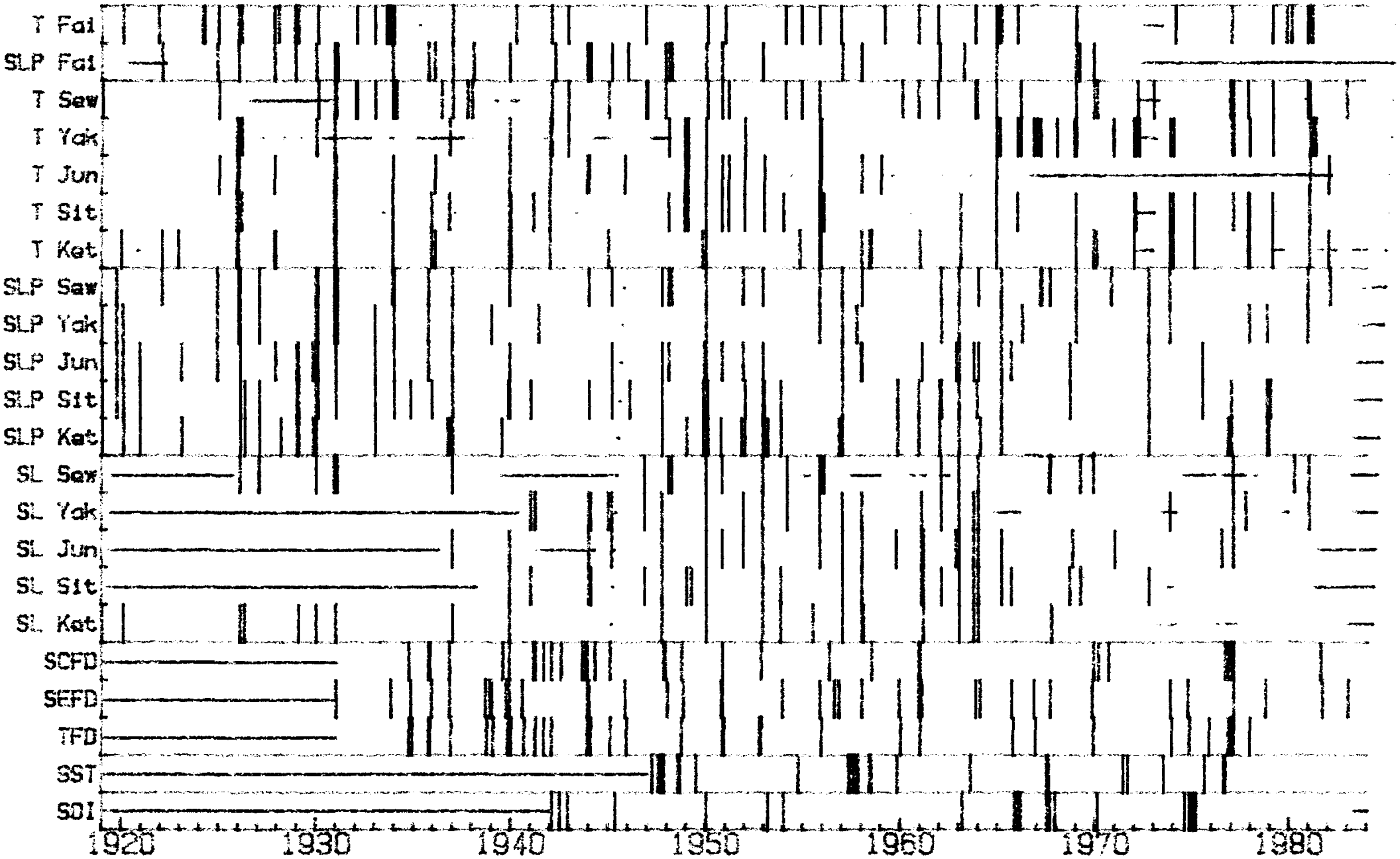

Figure 4-1. The events in each time series that are more than 2 standard deviations from the mean. Black indicates a positive deviation; red - a negative deviantion. Missing data are indicated with a horizontal line.

Examination of the overall anomaly records (Figure 4-1) yields three main observations. First, for a given variable there are no occasions where an event occurs at one station with an opposite event at another station in the same month. Second, different stations generally experience an event at the same time for a given variable. And, third, events occur simultaneously in different parameters, though not necessarily in the same direction (positive or negative). These observations indicate that coastal stations can experience the same or similar forcing, and this forcing can extend into the Alaskan interior. Events generally occur in winter, which may not be obvious from examination of Figure 4-1, 94% of the sea level events, 96% of the SLP events, 79% of the fresh water discharge events and 30% of the SST events occur between October and March. Also, in the southern equatorial region, 80% of the SOI events occur during the austral winter.

1. Sea Level

Because of gaps in the early record (1919 to 1936), synchronous events occurring in the sea level record at more than two stations cannot be determined until after 1937. There are events in February 1926, January 1930 and January 1931 which occur in both the Ketchikan and Seward time histories, but these are omitted from this discussion because the sea level selection criterion is 4 or more synchronous events. Because these two stations are the farthest apart of the coastal stations, the signal would be likely to be seen in one or more of the intervening stations if data did exist from 1919 to 1936.

Using the criterion mentioned above, the sea level record has eight instances of synchronous events, all between 1947 and 1964, The absence of simultaneous events in the 1970s and 1980s is striking. The positive events occur in October 1947, December 1952, January 1958, October 1963 and January 1964. From January to February 1961 there is a positive simultaneous event with a broad signal. Yakutat, Juneau and Sitka each experience a positive event, then Juneau and Sitka remain high for 2 months with Ketchikan also experiencing a positive event in this second month. Over this 2 month period, positive events do occur at 4 coastal stations. Negative simultaneous events occur in January of 1950, 1957 and 1963. With all but the last positive synchronous event, the sign of each simultaneous event alternates.

2. Sea Level Pressure

Over the 65 years of SLP records, most of the 14 synchronous events are positive. These positive synchronous events occur in January 1920, February 1920, January 1930, January 1937, January 1950, February 1957, January 1963, March 1965 and October 1972 (Figure 4-1). The five negative synchronous events occur in February 1926, February 1930, January 1931, January 1933 and January 1934. In five cases the synchronous events are associated with other events within a month. The January 1930 simultaneous high at each of the meteorological stations is preceeded by highs in Juneau and Ketchikan, and followed by a low at every station except Ketchikan. The January 1931 synchronous negative is led by a high in Seward, and the January 1937 positive event is led by 2 months of highs in Ketchikan. What appears to be a broad event in 1950 is actually a low in Sitka and Ketchikan, followed by a high in Juneau, the positive synchronous event, and then another negative event in both Ketchikan and Sitka.

3. Air Temperature

Of the 12 synchronous events selected in the air temperature record, 5 are positive and 7 are negative. Positive synchronous events occur in the January of 1926, 1931, 1940, 1942 and 1981. Negative synchronous events occur in December 1933, January 1950, December 1955, December 1964, January 1974, November 1978 and February 1979. Only events in the 1940s and 1950s are associated with other highs and lows. The positive synchronous event in January 1940 is led by a positive event in December, and the negative synchronous event in December 1955 is led by another negative event in November. The positive event in January 1942 is bracketed by two other positive ones. The apparent correlation between immediate events says more about the severity of the winter than about the possible forcing mechanisms.

4. Fresh Water Discharge

There are eight time periods in the fresh water records which show synchronous events in each of the different records. Since the total fresh water discharge is extimatedd by summing the Southcoast and Southeast districts records lagged by 1 month, events are expected to occur in one of the individual records as well as the total record. The six synchronous positive events occur from November to December

1936, October 1939 to January 1940, November 1943 to January 1944, November to December 1969 and January to December 1977. The simultaneous negative events occur from October to December 1934 and October to November 1950. All of the events occur between October and February, with most of them occuring in December. During the change from summer to winter as the fresh water input is rapidly changing from the seasonal peak (October) to the seasonal minimum (January or February), abnormal precipitation or temperature would have the greatest effect on the discharge values.

5. Sea Surface Temperature

The SST record has one negative and five positive groups of events. In August and September 1976 there are two negative events. Double positive events occur in August and September 1948, June and July 1958 and July and August 1967. Longer series of positive events occur in 1947 (April, August, September, October and November) and in 1957 (May, June, August, October and November). Unlike the other variables discussed, SST events usually occur in summer. The amount of insolation has the largest effect on this variable. Summer stratification would keep temperature effects near the surface, whereas in winter, mixing would mask them. Also, during the high latitude winters, changing cloud cover would not have as great an effect on insolation as similar changes during the summer. Hence SST is more responsive during the summer.

An interesting note in the SST record is the change of sign of events. From the late 1940s through the 1960s all of the events are positive. From the 1970s until the end of the record in the early 1980s all of the events are negative. Whether this is a statistical abberation due to a slightly skewed distribution or a long term climatological effect cannot be determined from this information alone. The surface temperature anomalies at the Seward hydrological station presented by Xiong and Royer (1984) show a warming trend throughout their data (1971 to early 1983). This warming trend is also evident in their subsurface data. Thus the cause of the change to positive events is probably unrelated to the mechanism for the warming trend of Xiong and Royer (1984).

6. Southern Oscillation Index

Only three groups of events occur in the SOI time series. During the winter of 1965-1966 positive events occur in November, January and March. In 1967, positive events occur in July, September and December. The longest series occurs during the winter of 1974-1975 when negative events occur during August, and then monthly from October through March. Series of events do not occur during the SOI time history earlier than the late 1960s.

7. Pervasive Phenomena

Using the criteria explained above to select the most pervasive series of events, 16 can be chosen (Table 4-1). The 1950-1951 series is particularly noteworthy because it is the only one that persists at the 3 standard deviation level. Rather than discussing the individual series, the major trends among these data are discussed.

Table 4-1. Pervasive events in the anomaly records.

January to February 1926
January to February 1930
December 1930 to February 1931
October to December 1935
October 1936 to January 1937
October 1939 to January 1940
February to March 1942
August 1947 to March 1948
January to February 1950
October 1950 to January 1951
October 1952 to January 1953
November 1955 to January 1956
October 1957 to February 1958
December 1961 to February 1962
January to February 1963
November 1976 to February 1977

Sea level and SLP always experience opposite events during a given month. This suggests that low pressure systems (storms) generate high alongshore (cyclonic) winds which advect water onshore in the Gulf of Alaska. Generally, sea level and air temperature are in phase, while SLP is opposite in phase. Storms not only alter the sea level, but can advect warmer air from the central gulf onshore.

Fresh water discharge and SLP are inversely related. Unusually low pressure systems or an unusually high number of low pressure systems in the gulf should increase the amount of precipitation significantly. Fresh water discharge is hypothesized to be more related to precipitation than melting because there is no clear pattern between temperature, the major influence on melting, and fresh water discharge.

B. Crosscorrelation Analysis

Crosscorrelations were performed on the variables in the local, regional and global scales. For example, sea level, air temperature and SLP are local variables measured at specific station. SEFD, SCFD, TFD and SST are regional variables combining data from more than one station and can be considered mesoscale. SOI is a global variable even though only data from two stations are used. The distance between Tahiti and Darwin, Australia, and the length scale of ENSO events make this a global variable. Crosscorrelating the above parameters is like looking for a single variation in a Bach Fugue; possible, but not simple without looking at the score.

1. Southern Oscillation Index

SOI does not correlate significantly ($p>0.995$) with either air temperature (Figure 4-2), SCFD, SEFD or TFD at any station in this study. SOI does have a detectable corresponding atmospheric pressure (Figure 4-3) and sea level (Figure 4-4) signal in the Gulf of Alaska. The SLP at Seward and SOI have a significant correlation ($p>0.995$) when SOI leads by 8 months, but no other SLP station in the gulf shows significant correlation coefficients at this level. When the significance level is lowered to $p>0.95$, then significant correlations occur with all of the coastal stations except Sitka. The relationship shows SOI leading SLP by 8 to 11 months, and SLP leading SOI by 10 to 11 months.

SOI and sea level have a significant ($p>0.9995$) correlation only at Ketchikan. Changes in SOI are led by sea level changes in Ketchikan by 10 months. Because no other station shows this relationship, either the signal is undetectable at latitudes higher than Ketchikan, or the other sea level records are not long enough to show the trend. If the significance level is decreased to $p>0.95$, then the relationship between sea level and SOI takes on a slightly different character. At Ketchikan, the signal broadens from sea level leading by 10 months to sea level leading by 9 to 13 months, and at Yakutat, sea level leads SOI by 11 months. In Sitka, there are still no significant correlation coefficients. The most striking change occurs at Seward and Juneau. There, sea level leads SOI by 10 to 11

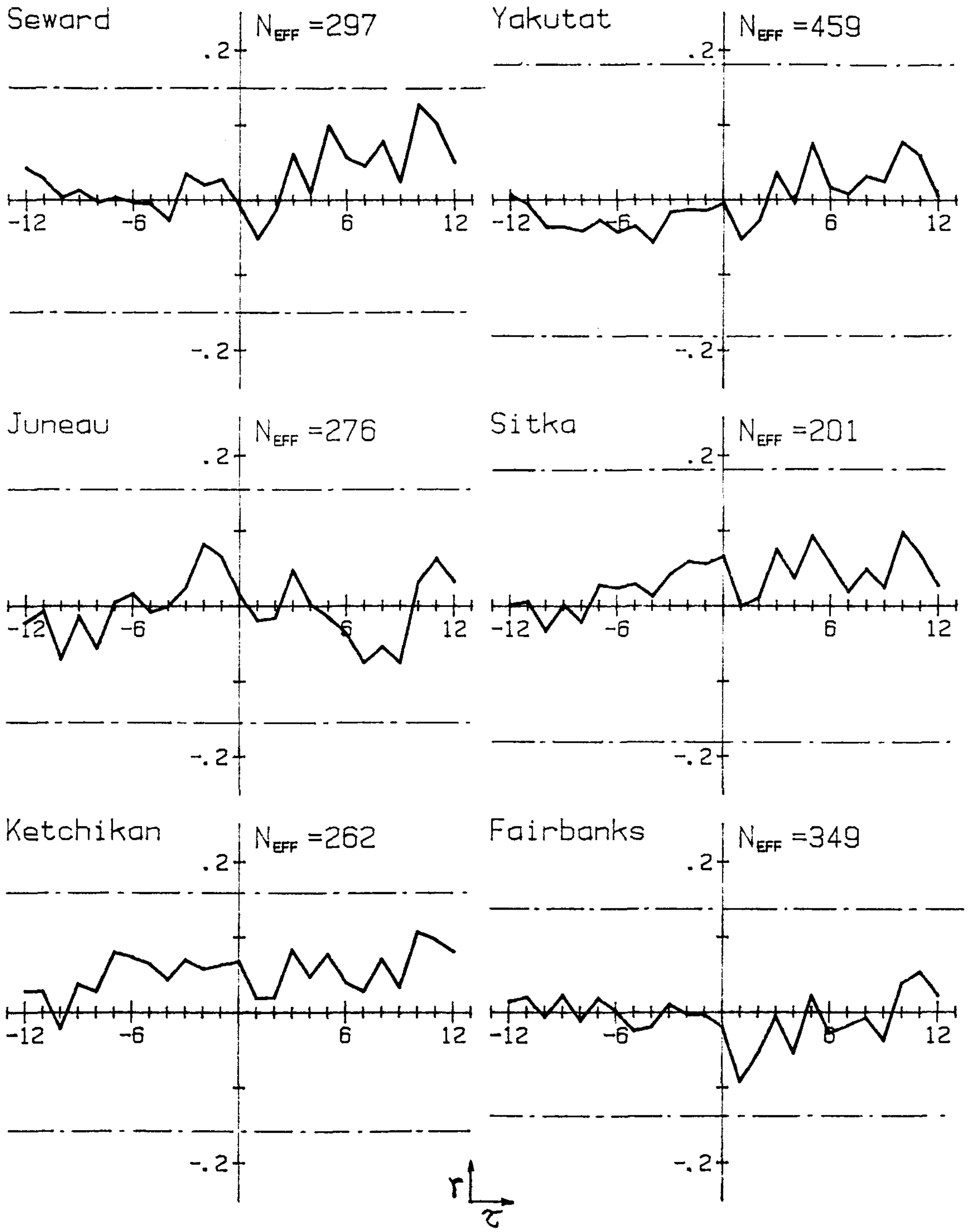

Figure 4-2. Crosscorrelation coefficients of the Southern Oscillation Index and air temperature. If $\tau<0$, then the Southern Oscillation Index leads. If $\tau>0$, then air temperature leads. $p>0.995$ — · — · — · — · —

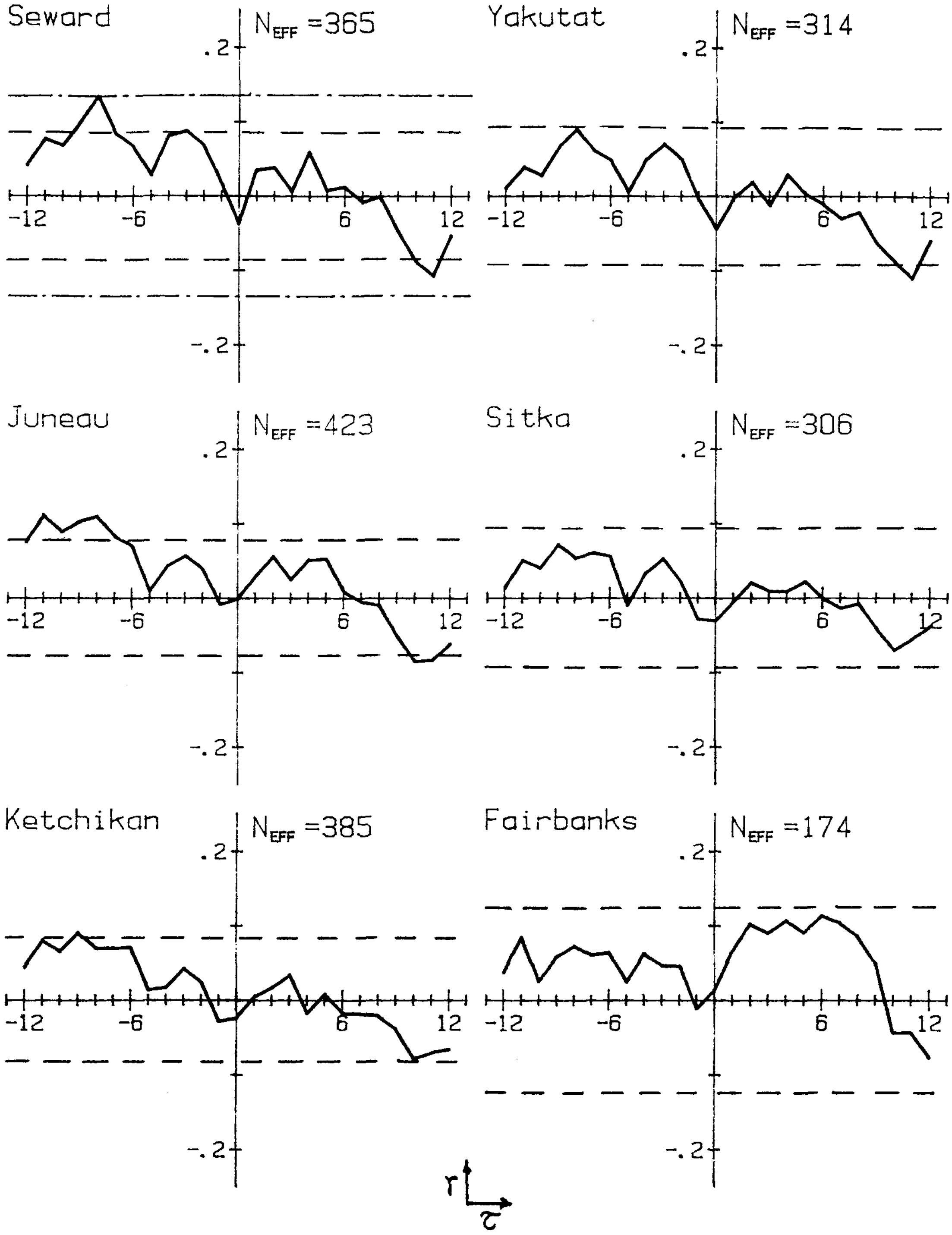

Figure 4-3. Crosscorrelation coefficients of the Southern Oscillation Index and sea level pressure. If $\tau<0$, then the Southern Oscillation leads. If $\tau>0$, then sea level pressure leads.
p>0.995 —·—·—·— p>0.95 — — — — —

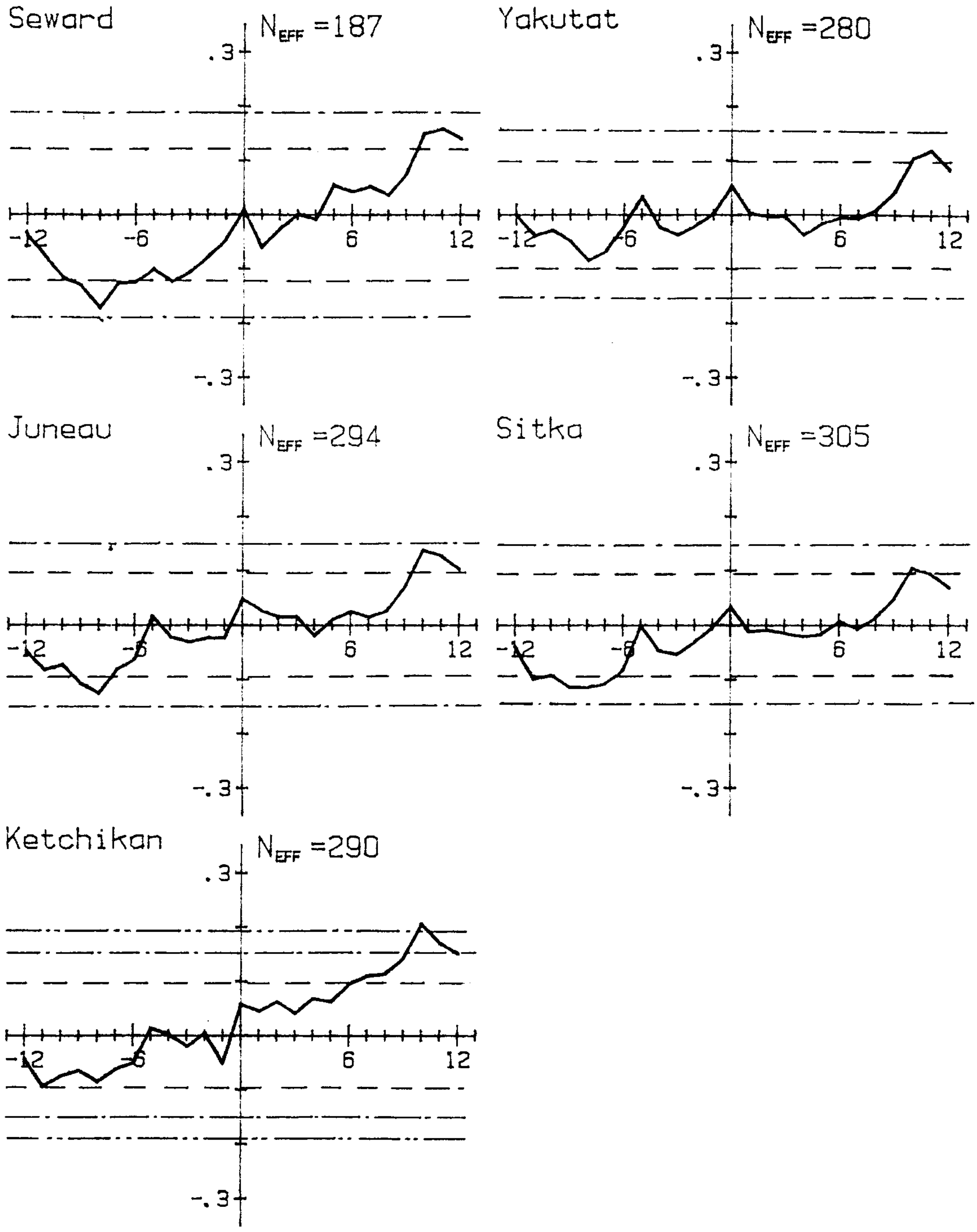

Figure 4-4. Crosscorrelation coefficients of the Southern Oscillation Index and sea level. If τ<0, then the Southern Oscillation Index leads. If τ>0, then sea level leads.
p>0.9995 —··—··— p>0.995 —·—·—·— p>0.95 — — — — — —

at Juneau and by 10 to 13 months at Seward. SOI also leads sea level at Seward by 6 to 9 months.

The crosscorrelations of SOI and SLP (Figure 4-3) and sea level (Figure 4-4) at the coastal stations show a definite trend from correlation coefficients of one sign to the other. The transition from positive to negative in the SOI and SLP values is not as smooth as the transition from negative to positive in the SOI and sea level values. Transitions such as these suggest cycles between these variables.

2. Sea Surface Temperature

SST and air temperature at each station show a positive maximum in correlation when the two are in phase (Figure 4-5). At Seward and Ketchikan, the SST leads air temperature significantly ($p>0.9995$) by up to 2 months. At each of the coastal stations, SST is significantly correlated with air temperature for up to 4 months. At Seward, the SST leads air temperature ($p>0.995$) by up to 2 months, with the maximum when the two variables are in phase.

For all meteorological stations, SST and SLP are positively correlated at the $p>0.95$ confidence level when SST leads SLP by 1 month (Figure 4-6). In fact, these results are evidenced at the $p>0.9995$ confidence level at Seward, Juneau and Ketchikan. All but Juneau show a negative correlation when SLP leads SST by 2 to 3 months at $p>0.95$. At Ketchikan, the significance level for SLP leading SST by 3 months is at the $p>0.995$ confidence level. The overall change

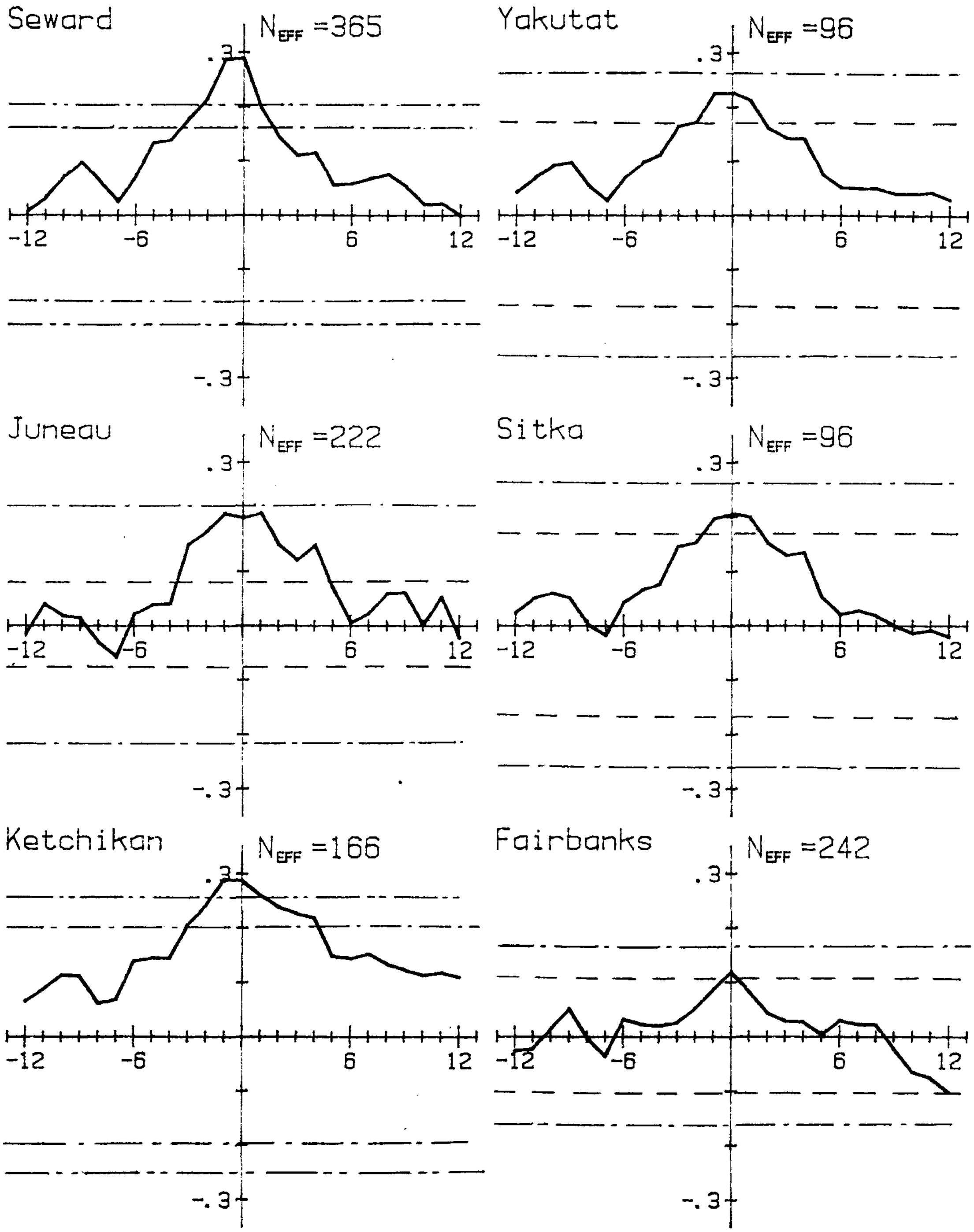

Figure 4-5. Crosscorrelation coefficients of sea surface temperature and air temperature. If $\tau<0$, then sea surface temperature leads. If $\tau>0$, then air temperature leads.
p>0.9995 ——-·——·-—p>0.995—·—·——p>0.95— — — —

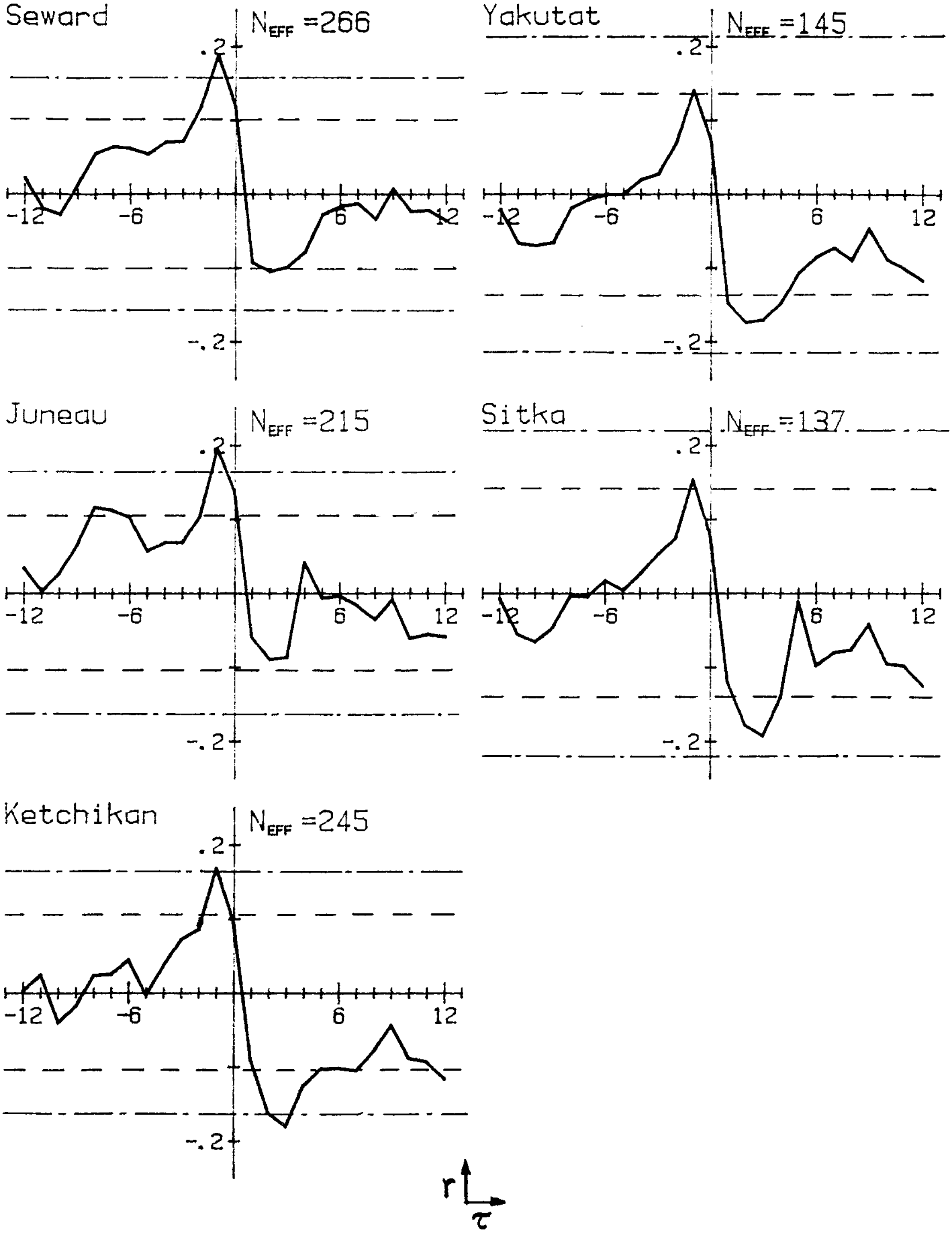

Figure 4-6. Crosscorrelation coefficients of sea surface temperature and sea level pressure. If $\tau<0$, then sea surface temper- leads. If $\tau>0$, then sea level pressure leads.
p>0.995 —·—·—·—   p>0.95 — — — — — — —

from positive correlations when SST leads to negative correlations when SLP leads suggest that SST and SLP mutually influence each other.

For sea level and SST (Figure 4-7), changes in SST occur 1 month before opposite changes in sea level, that is, higher SST leads to reduced sea level. In Ketchikan, Sitka and Juneau, this correlation is significant at the $p>0.9995$ level, while in Yakutat and Seward, this correlation is at the $p>0.995$ confidence level. In Ketchikan, sea level is significantly ($p>0.9995$) positively correlated with SST when sea level leads by 3 months. This could be a thermal influence on sea level which disappears at higher latitudes with colder ambient temperatures. As with SST and SLP, there is an overall change from positive to negative correlations; SST and SLP change from positive to negative while SST and sea level change from negative to positive correlation coefficients.

Relating fresh water discharge to SST, SCFD leads SST by one month at the $p>0.995$ significance level, but SEFD and SST are not significantly correlated. TFD is significantly correlated ($p>0.995$) with SST when TFD leads by 2 months, a result that was not anticipated because $TFD(\tau)$ is the sum of $SCFD(\tau)$ and $SEFD(\tau-1)$, where τ is time in months.

3. Sea Level Pressure, Air Temperature and Fresh Water Discharge

Changes in SLP occur with opposite changes in air temperature (Figure 4-8), that is low pressures accompany increases in air temperature. For Fairbanks, Seward and Juneau, the correlation coefficients for SLP and air temperature when the two are in phase and

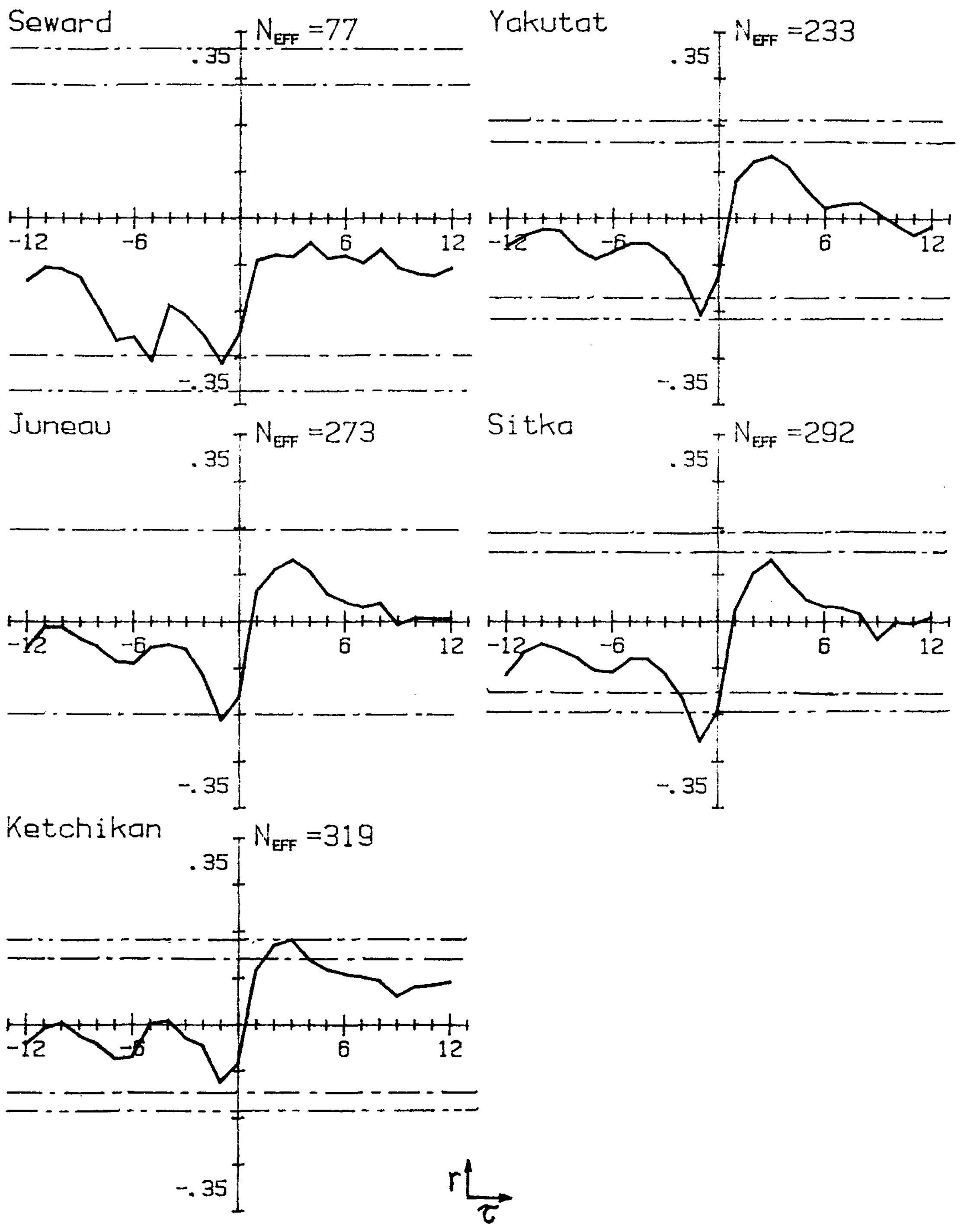

Figure 4-7. Crosscorrelation coefficients of sea surface temperature and sea level. If τ<0, then sea surface temperature leads. If τ>0, then sea level leads.
p>0.9995 —··——··——··—— p>0.995 —·—·—·—

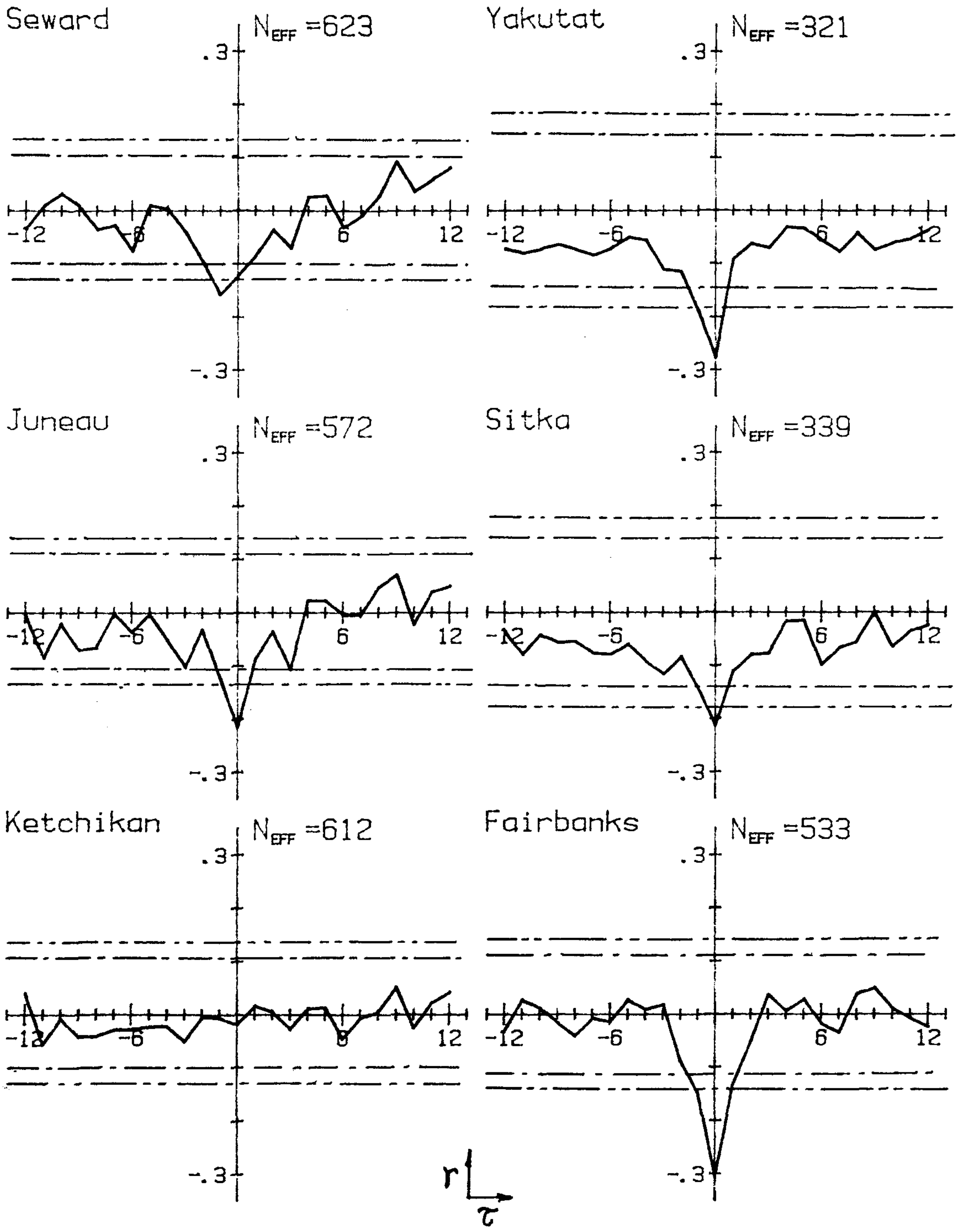

Figure 4-8. Correlation coefficients of sea level pressure and air temperature. If $\tau<0$, then sea level pressure leads. If $\tau>0$, then air temperature leads.
$p>0.9995$ —‐‐‐——‐‐——‐‐—— $p>0.995$ —‐——‐——‐————‐——

when SLP leads by 1 month are significant at the $p>0.9995$ significance level. For Yakutat and Sitka, the correlation coefficients are significant at the $p>0.9995$ level when SLP and air temperature are in phase, and at the $p>0.995$ level when SLP leads by 1 month. At Ketchikan there are no significant correlations between SLP and air temperature.

SEFD and SLP correlations become increasingly significant in a counterclockwise sense around the Gulf of Alaska: from Ketchikan ($r=-0.010$, not significant) to Sitka ($r=-0.226$, $p>0.9995$), Juneau ($r=-0.236$, $p>0.9995$), Yakutat ($r=-0.408$, $p>0.995$) and Seward ($r=-0.546$, $p>0.9995$). SCFD and SLP are increasingly correlated from Yakutat ($r=-0.191$, not significant) to Seward ($r=-0.306$, $p>0.9995$). All of the above correlation coefficients are when the two variables are in phase. A similar relation, though with opposite signs, occurs between SEFD and sea level (Figure 4-9).

Air temperature and fresh water discharge (Figure 4-10) are significantly ($p>0.9995$) positively correlated when the two are in phase except at Seward where SEFD leads air temperature by 1 month. When air temperature is crosscorrelated with SCFD, all of the meterological stations show a positive maximum when the two are in phase. This is reasonable since the hydrology model depends on air temperature to determine snow melting and storage.

4. Sea Level

Sea level and SLP are strongly correlated ($r\sim-0.7$, $p>0.9995$) only

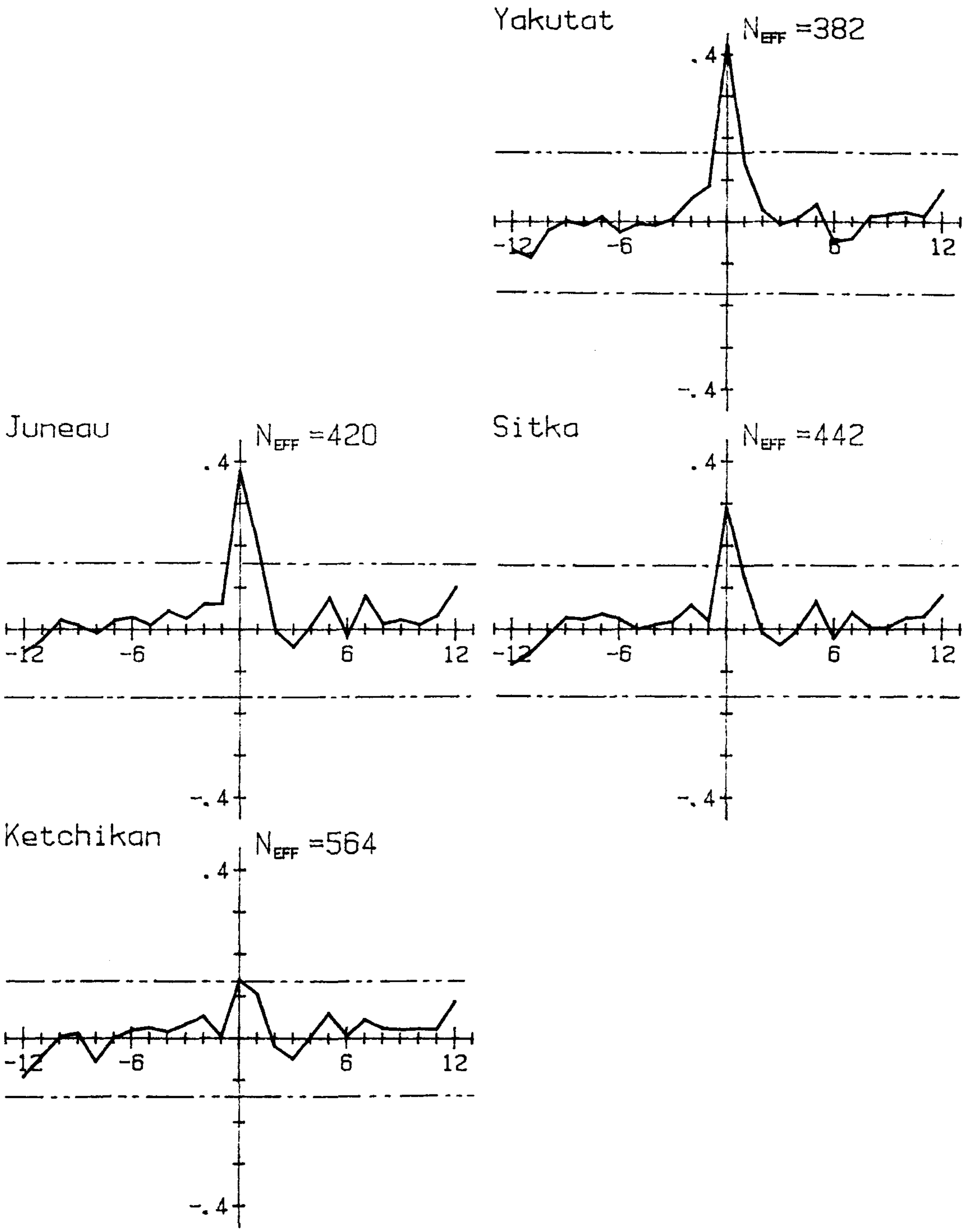

Figure 4-9. Correlation coefficients of Southeast fresh water discharge and sea level. If $\tau<0$, then the fresh water discharge leads. If $\tau>0$, then sea level leads.
$p>0.9995$ —·—·—·—

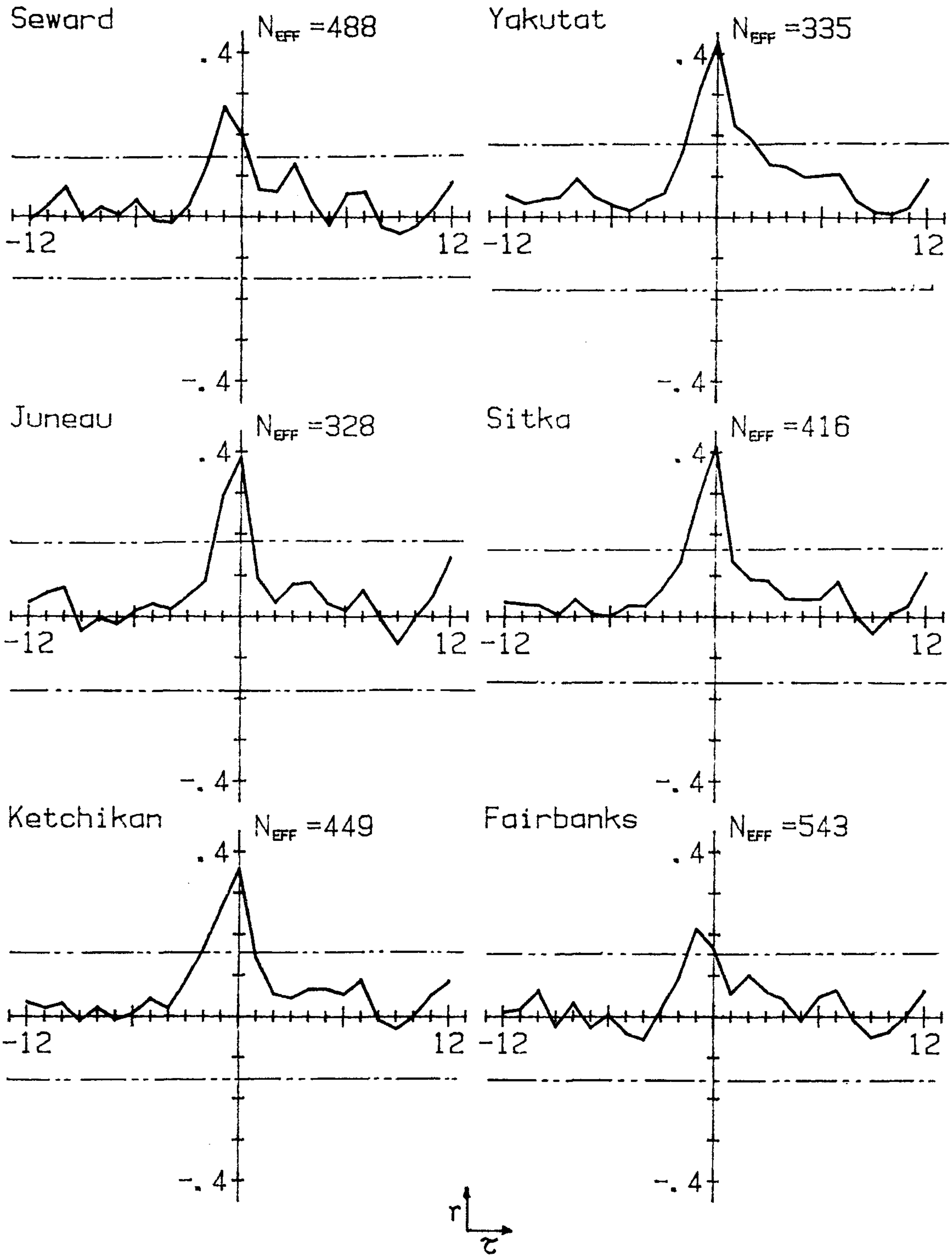

Figure 4-10. Correlation coefficients of Southeast fresh water discharge and air temperature. If $\tau<0$, then the fresh water discharge leads. If $\tau>0$, then the air temperature leads.
$p>0.9995$ —— - - ——— - - ———

when the two variables are in phase (Figure 4-11). The peak for each station is sharp, with the correlation coefficients dropping below significance within 1 month. To a lesser extent, sea level and air temperature are significantly correlated ($p>0.9995$), with the correlation coefficients increasing from Ketchikan to Seward (Figure 4-12).

The correlation coefficients of SCFD and sea level increase along the coastal current's flow from $r=-0.033$ (not significant) in Ketchikan to $r=0.093$ (not significant) in Sitka, $r=0.114$ ($p>0.995$) in Juneau and $r=0.255$ ($p>0.9995$) in Yakutat. The result for Seward is $r=0.181$, which does not fit with the above trend. The correlation coefficients can be increased to the $p>0.995$ significance level in Ketchikan, Sitka and Juneau by lagging the fresh water discharge by 1 month. For the Southeast district, the correlation coefficients also increase from Ketchikan ($r=0.140$, $p>0.995$) to Yakutat ($r=0.452$, $p>0.9995$) (Figure 4-9), but decrease again at Seward ($r=0.322$, $p>0.9995$). This value is still reasonably close to the overall trend, and the discrepency is probably due to the difficulties with the Seward sea level record which are discussed in the methods chapter.

C. Empirical Orthogonal Function Analysis

The results of the station by station covariance matrices are not reported because their covariances are so widely distributed among the variables. This means that at each station, each variable separated distinctly from the others into a solitary mode. Computing the EOFs

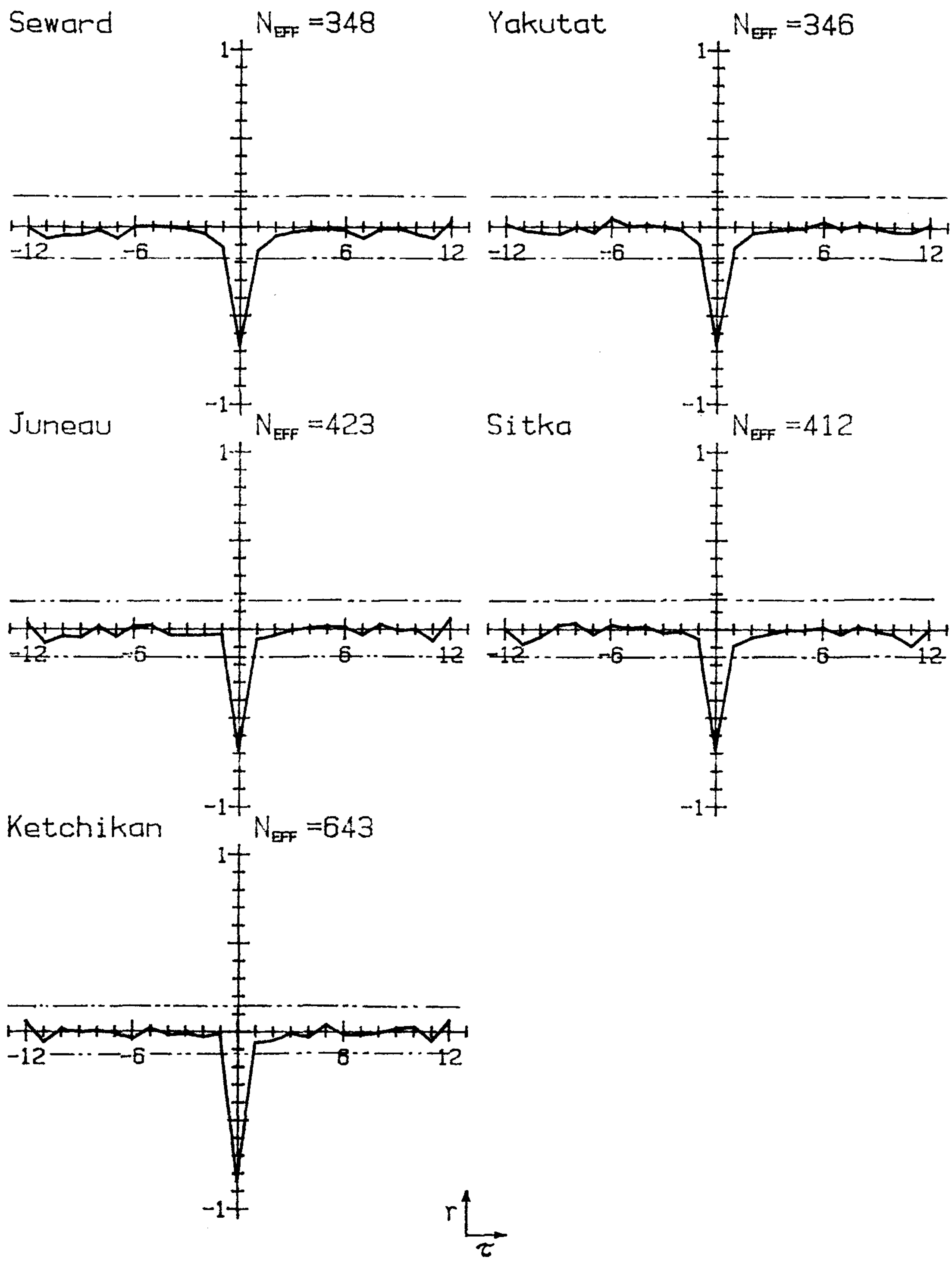

Figure 4-11. Correlation coefficients of sea level pressure and sea level. If $\tau<0$, then sea level pressure leads. If $\tau>0$, then sea level leads.
$p>0.9995$ — - - — - - — - - — - -

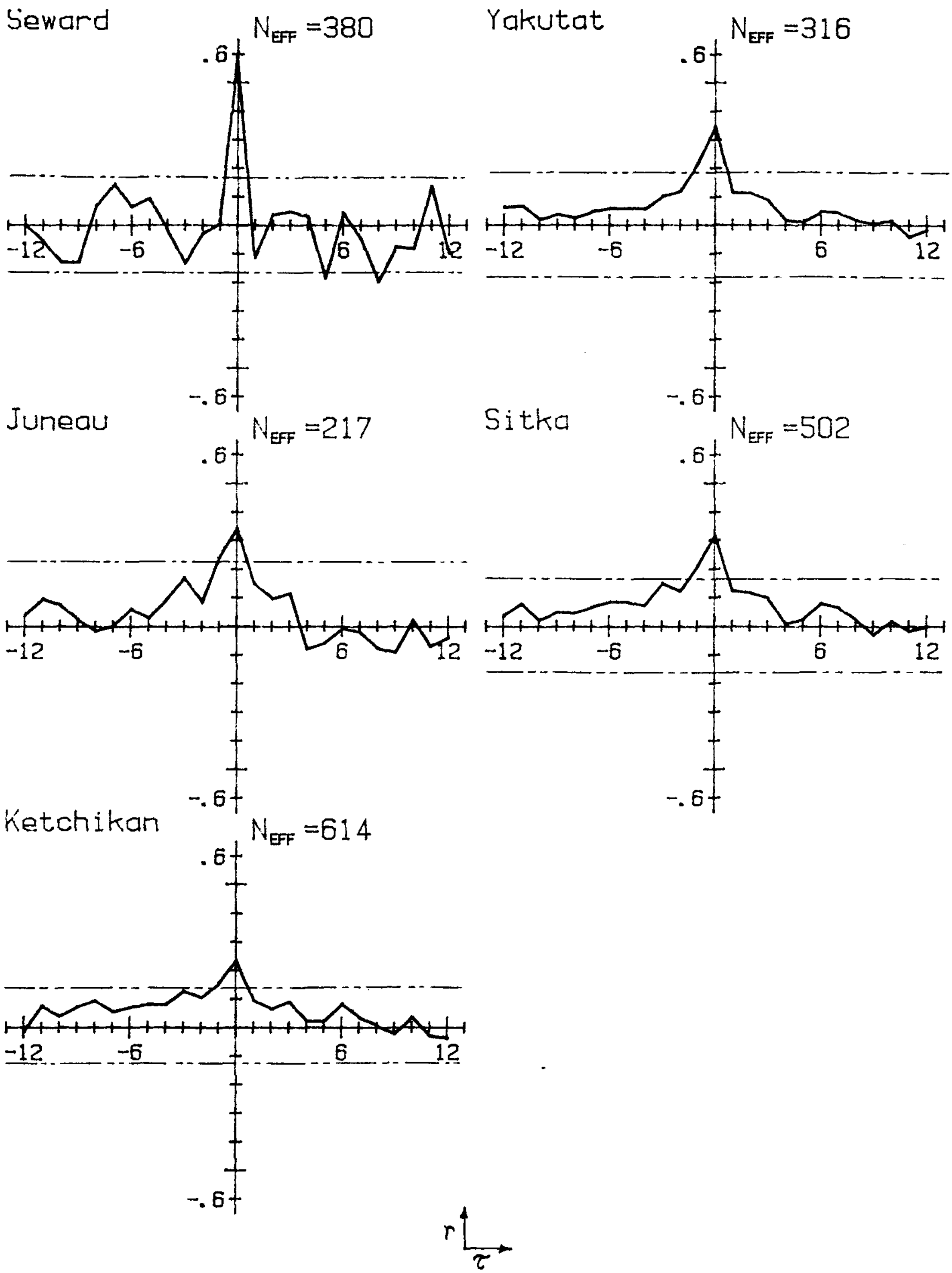

Figure 4-12. Correlation coefficients of sea level and air temperature. If $\tau<0$, then sea level leads. If $\tau>0$, then air temperature leads.
$p>0.9995$ —·—·—·—

for time series measured in different units requires that the correlation matrix be used.

1. **Sea Level Pressure**

The first mode of both the covariance and correlation (Table 4-2) matrices' EOFs indicates that all 6 stations to have anomalies of the same sign. This mode accounts for about 78% of the variance in the covariance matrix, and an average of 76% in the correlation matrix. Fairbanks has the lowest magnitude in the first mode eigenvector, and thus the lowest percentage of variance explained (<50%). The second mode for both these EOFs separates most of the remaining Fairbanks SLP variance, and also separates the more northern (Fairbanks and Seward) from the more southern (Juneau, Sitka and Ketchikan) stations with Yakutat as the nodal point. This mode removes approximately 23% of the remaining variance in the Ketchikan record. The third through fifth modes are difficult to interpret physically. The third mode separated Sitka from the other stations and the remaining modes each account for less than 12% of the variance in any one records. The possibility exists that the third mode is simply a higher harmonic of the second mode.

To clarify the Fairbanks effect in the previous analyses, both were repeated on matrices that did not contain Fairbanks data. The first mode for the covariance matrix (Table 4-3) remained unchanged. The average percentage of variance explained is 84% and all the stations fluctuate in unison. The second mode separates northern from southern stations, separating Seward and Yakutat as definitely

Table 4-2. Results of EOF analysis of the sea level pressure data at the six stations. Results are reported as the percentage of variance explained by the mode and by the individual stations. The algebraic sign is from the eigenvector.

Covariance Matrix

Station	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Total for mode	78	13	4.4	2.8	1.3
Seward	-88	-4.8	4	-0.9	0.9
Yakutat	-93	-0.1	5	0.1	-0.0
Juneau	-79	3.6	-4.1	-12	-1.4
Sitka	-84	9.2	0.0	4.2	-1.7
Ketchikan	-65	23	-6.5	0.4	4.6
Fairbanks	-47	-44	-7.7	1.0	-0.0

Correlation Matrix

Station	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Total for mode	76	14	4.4	3.2	1.4
Seward	-85	-6.6	4.4	-0.9	-1.5
Yakutat	-90	-0.6	6.8	0.0	-0.0
Juneau	-82	2.7	-4	-11	0.6
Sitka	-85	6.5	0.8	3.5	3.3
Ketchikan	-70	21	-3.9	2.2	-2.6
Fairbanks	-45	-47	-6.7	1.6	0.1

Table 4-3. Results of EOF analysis of sea level pressure data at the five coastal stations. The format is as in Table 4-2.

Covariance Matrix

Station	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Total for mode	85	9.2	3.6	1.5	1
Seward	-84	14	-0.3	0.9	1
Yakutat	-92	4.4	1	-0.1	-2.4
Juneau	-81	-2.6	-15	-1.6	-0.0
Sitka	-89	-4.5	4.4	-1.5	0.8
Ketchikan	-72	-23	-0.0	4.8	-0.1

Correlation Matrix

Station	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Total for mode	84	9.5	4.1	1.7	0.8
Seward	-80	17	-0.1	-1.4	-1.2
Yakutat	-89	7.3	1.2	0.0	2.4
Juneau	-84	-1.3	-14	0.74	0.0
Sitka	-90	-1.8	4.9	3.1	-0.1
Ketchikan	-76	-20	0.5	-3.1	0.0

northern stations this time. The most percentage of variance was explained by SLP in the second mode at Ketchikan (23%) and at Seward (14%). The third mode again explained the most variance in Juneau (15%).

2. Sea Level

The results using sea level at the five coastal stations are similar to the results for SLP. The first mode shows all the stations experiencing anomalies of the same sign and explains 69% of the variance in the covariance matrix and 72% in the correlation matrix (Table 4-4). The second mode in the covariance matrix separates Seward and possibly Sitka, while this mode in the correlation matrix definitely isolates Seward. Whether it is a real phenomenon or an aspect of the aberrations in the Seward sea level record is difficult to ascertain. Both second mode eigenvectors show that Yakutat, Juneau and Sitka fluctuate in unison. The third mode in the covariance matrix isolates Yakutat, while the same mode in the correlation matrix separates Ketchikan.

3. Air Temperature

The air temperature EOFs using data from all six stations (Table 4-5) are also similar to the SLP EOFs. The first mode has all six stations fluctuating in concert and explains 71% of the variance in the covariance matrix and 68% in the correlation matrix. The second modes of the two techniques diverge from each other. In the covariance matrix, Seward is excluded and does not contribute more than 1% of its variance until mode 4, where it is isolated. The

Table 4-4. Results of EOF analysis of sea level data at the five coastal stations. Results are formatted as in Table 4-2.

Covariance Matrix

Station	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Total for mode	69	18	9.1	3.0	1.5
Seward	-64	36	-0.0	-0.0	0.0
Yakutat	-73	-4.1	-12	8.2	-1.3
Juneau	-75	-8.3	-4.5	-11	-1.3
Sitka	-75	-16	-2.2	-0.0	7.5
Ketchikan	-66	-5.8	2.8	0.2	-0.1

Correlation Matrix

Station	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Total for mode	72	13	9.0	3.8	2.0
Seward	-47	-52	-0.9	0.1	-0.2
Yakutat	-81	1.4	-8.3	-7.8	1.7
Juneau	-84	2.7	-1.4	11	1.3
Sitka	-86	7.0	-0.2	-0.0	-0.7
Ketchikan	-65	-0.0	34	-0.5	0.4

Table 4-5. Results of EOF analysis of air temperature data at the six stations. Results are formatted as in Table 4-2.

Covariance Matrix

Station	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Total for mode	71	16	5.0	4.3	2.5
Seward	68	-0.1	0.7	-32	-0.0
Yakutat	62	-15	18	1.4	-1.8
Juneau	49	-21	-21	0.0	-9.2
Sitka	59	-30	1.3	0.9	0.2
Ketchikan	38	-42	-4.1	0.1	14
Fairbanks	87	12	-0.1	0.5	0.1

Correlation Matrix

Station	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Total for mode	68	14	7.3	5.0	3.8
Seward	-64	-18	-0.9	-16	-1.8
Yakutat	-75	-0.0	19	1.2	-1.6
Juneau	-68	5.5	-18	3.8	-4.9
Sitka	-83	5.0	4.1	0.0	-0.0
Ketchikan	-65	21	-0.7	-3.2	8.7
Fairbanks	-55	-33	-0.9	5.7	5.7

second mode in the correlation matrix separates the more northern from the more southern stations, with Yakutat as the node. The most variance explained in this mode are for Fairbanks (33%), Ketchikan (21%) and Seward (18%). The third mode of both EOFs has Yakutat and Juneau fluctuating oppositely, with minor contributions from the other stations.

To understand how the air temperature at the five coastal stations interact, EOF analysis was performed on the matrices without the Fairbanks data. The different analyses yield strikingly similar results. For both the covariance matrix and the correlation matrix (Table 4-6), the first mode has all of the stations fluctuating in unison and explains an average of 72% of the variance. The second mode separates the Southcoast from the Southeast districts with the most contribution from Seward (32%) and Ketchikan (14%). The third mode shows Yakutat and Juneau fluctuating in opposition with minor contributions from the other stations.

The relationship of SST to air temperature was examined by EOF analysis on matrices developed from the coastal air temperature data and the SST data. The first mode in the covariance matrix and in the correlation matrix (Table 4-7) both show the six stations fluctuating in unison. The covariance mode explains an average of 71% of the variance and the correlation matrix explains an average of 68%. The second modes diverge sharply, but still explain about the same percentage of variance. The correlation matrix groups Seward air temperature and SST moving in opposition to Juneau, Sitka and

Table 4-6. Results of EOF analysis of coastal air temperature data. Results are formatted as in Table 4-2.

Covariance Matrix

Station	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Total for mode	72	12	9.0	4.9	2.5
Seward	-60	-32	-6.6	0.8	0.4
Yakutat	-78	-1.2	18	-1.7	-1.9
Juneau	-68	7.7	-14	-10	-0.1
Sitka	-86	1.9	2.9	0.2	8.9
Ketchikan	-69	14	-1	14	-2.0

Correlation Matrix

Station	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Total for mode	72	11	8.5	5.3	2.5
Seward	-57	32	-8.4	2.0	-0.0
Yakutat	-75	3.8	16	-2.6	3.3
Juneau	-70	-6.8	-14	-9.4	0.1
Sitka	-87	-0.5	4.6	-0.0	-8.1
Ketchikan	-73	-13	-0.0	13	1.1

Table 4-7. Results of EOF analysis of coastal air temperature and sea surface temperature data. Results are formatted as in Table 4-2.

Covariance Matrix

Station	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Total for mode	71	16	5.0	4.3	2.5
Seward	68	-0.1	0.6	-32	-0.0
Yakutat	62	-15	18	1.4	-1.8
Juneau	49	-21	-21	0.9	-0.2
Sitka	59	-30	1.3	0.9	0.2
Ketchikan	38	-42	-4.1	0.1	14
SST	87	12	-0.1	0.5	0.1

Correlation Matrix

Station	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Total for mode	68	14	7.3	5.0	3.8
Seward	-64	-18	-0.87	-16	-1.8
Yakutat	-75	0.0	19	1.2	-1.6
Juneau	-68	5.5	-18	3.8	-4.9
Sitka	-83	5.0	4.1	0.1	-0.0
Ketchikan	-65	21	-0.7	-3.2	8.7
SST	-55	-33	-0.9	5.7	5.7

Ketchikan, with Yakutat as the node. The covariance matrix groups Yakutat, Juneau, Sitka and Ketchikan fluctuating in opposition to SST with Seward as the node. The third mode in both analyses primarily shows Yakutat and Juneau moving in opposition. Also in both analyses, the fourth mode is primarily Seward, with each of the other stations near 0.

4. Station by Station

EOF analyses on the station correlation matrices (Table 4-8) separates the stations into two groups on the basis of the first mode response of sea level and SLP: 1) Seward, Yakutat and Juneau, and 2) Sitka and Ketchikan. The first mode in Seward, Yakutat and Juneau is dominated by SLP and sea level fluctuating in opposition. Air temperature and fresh water discharge contribute the most to the percentage of variance explained, fluctuating in phase with sea level, while SST contributes only slightly at these locations. The first mode in Sitka and Ketchikan has sea level, air temperature and fresh water discharge all oscillating in phase. At Sitka, SLP and SST contribute the most to the percentage of variance explained. Unlike the other 4 stations, however, SLP and sea level at Sitka are in phase with SST in opposition. At Ketchikan, SLP and SST contribute a minor amount. In the second mode of both groups, SST is the dominant parameter. At Sitka, SLP and SST move in opposition, with the second mode explaining 61% of the variance of both variables. At Ketchikan, the second mode also groups SST and SLP moving inversely. This mode explains 52% of the variance in SLP and 54% in SST. The algebraic

Table 4-8. EOF results for variables at each of the five coastal stations.

Station / Parameter	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Seward					
Mode Average	37	26	16	15	6
SLP	-75	3	0	7	14
Sea Level	72	-7	-7	-0	14
Air Temperature	13	43	-13	31	-1
TFD	25	19	55	0	1
SST	-1	59	-4	-35	0
Yakutat					
Mode Average	41	24	16	12	7
SLP	-63	11	-9	3	14
Sea Level	67	-12	3	-0	17
Air Temperature	41	20	-1	37	-0
TFD	33	15	-36	-16	-0
SST	0	64	30	-5	0
Juneau					
Mode Average	41	23	16	14	6
SLP	65	-8	-11	5	-12
Sea Level	-76	5	4	-0	-16
Air Temperature	-25	-25	-30	-20	-0
SEFD	-39	-15	-2	42	1
SST	1	-64	33	-1	-0
Sitka					
Mode Average	33	31	16	13	8
SLP	19	-61	1	-2	-17
Sea Level	32	15	-48	-6	-1
Air Temperature	52	6	22	-17	4
SEFD	46	14	2	37	-1
SST	-15	61	6	-3	-15
Ketchikan					
Mode Average	27	22	19	17	15
SLP	-2	52	-23	-23	-0
Sea Level	30	1	37	-32	0
Air Temperature	49	0	-13	3	36
SEFD	50	3	-1	7	-38
SST	2	-54	-20	-21	-3

signs are reversed between Ketchikan and Sitka, but since only the relative sign within the matrix is important, the difference in sign between SST and SLP is important, but not the difference in sign from Sitka SST to Ketchikan SST.

The third mode at each of the stations are different. In Seward, this mode has primarily fresh water discharge (55% of the variance explained) with air temperature (13%) fluctuating in opposition. At Yakutat, the third mode groups fresh water (36%) and SST (30%) in opposition. At Juneau, this mode groups air temperature (30%) and SST (33%) in opposition. At Sitka, the third mode is primarily sea level (48%) grouped inversely with air temperature (22%). At Ketchikan, the third mode shows sea level (37%) moving inversely with SLP (23%) and SST (20%). Thus, given time series from an unknown station, after defining it as northern or southern by the first or second mode, the third mode would be the next most important in defining the actual location.

5. DISCUSSION AND CONCLUSIONS

A. Discussion

1. Weather in the Gulf of Alaska

The results of event analysis, crosscorrelations and EOF analyses verify that the gulf oceanic and atmospheric anomalies fluctuate in unison. In the EOF analysis, the second mode separates the northern from the southern stations. This should not be interpreted as Southcoast getting warmer while Southeast is getting colder, but as a second harmonic with Southcoast getting warmer faster than Southeast. The second mode EOF results reinforce the validity of the Southeast/Southcoast district distinctions within the Gulf of Alaska.

The methods employed in analyzing the air temperature, fresh water discharge and SLP data suggest possible relationships between these parameters in geographical extent and in time. The results of crosscorrelating the above three parameters show that air temperature and fresh water discharge are in phase, with SLP 180° out of phase. This agrees with the results of the event analysis, which showed SLP always experiencing events opposite in sign to those in the air temperature and fresh water discharge records. EOF analyses showed that, in general, anomalies in the Gulf of Alaska occur similarly at each of the stations. Not until the second mode do the Southeast and Southcoast districts separate. The first mode shows the overall weather patterns on a large scale, while the second mode shows smaller scale weather anomalies.

The relationships of fresh water discharge with SLP and with air temperature are due to the overall weather patterns. Atmospheric lows cause increased precipitation, while atmospheric highs during above freezing weather would cause increased snow melt. This may also be because the hydrology model treats precipitation as a larger factor than snow melt (Royer, 1982). Air temperature probably controls the melt component of the fresh water discharge, while barometric pressure controls the precipitation component.

2. Interaction of Sea Surface Temperature and Weather

The results of the various crosscorrelations with SST show three phenomena: that SST and air temperature are positively correlated and in phase (Figure 4-5), and that a 7 to 8 month feedback cycle exists between SST and SLP (Figure 4-6) and between SST and sea level (Figure 4-7). To visualize this air temperature relation, one should think of how the ocean and the atmosphere drive each other. High air temperatures should warm the surface water, and <u>vice versa</u>. Also, the sea surface and the air are both heated by insolation. The lower correlation coefficient between SST and air temperature at Fairbanks than between SST and air temperature at the coastal stations is due to geographical considerations. Overall, the Gulf of Alaska and interior Alaska experience the same weather, but the relationship between the gulf and the interior stations in not as close as between the gulf and the coastal stations.

A 7 to 8 month feedback cycle is apparent between SST and SLP (Figure 4-6) and, to a lesser degree, between SST and sea level

(Figure 4-7). From examining the two peaks in the figures, one can deduce that the half cycle is 3 to 4 months (1 month lead + 2 or 3 months lag for SST). The semiannual cycle is discounted because it would have been removed when the annual cycle was removed. By assuming similar 7 to 8 month cycles for SLP and SST phase shifted so that SST leads SLP by 1 month, the positive correlation where SST leads SLP by 1 month and the negative correlation where SLP leads by 2 months can be reconstructed. The reason that the correlation coefficient values do not repeat the cycles at larger time offsets is probably because the relationship is more stochastic than truly cyclic. This means that an anomaly is required to initiate this feedback cycle, but the anomalies will not necessarily remain as a periodic function for more than one cycle. The 7 to 8 month cycle is weaker between SST and sea level because the sea level record contains the SLP 7 to 8 month cycle superimposed by wind stress forcing, not because of SST changing the sea level.

This 7 to 8 month feedback cycle can be reduced to two components. The first is SST leading SLP and sea level by one month. SST is positively correlated with SLP because the SLP change is due to warming. SST and sea level are negatively correlated because higher pressures cause lower sea level and lower pressures cause higher sea level due to geostrophic wind stress. The second component has SLP and sea level leading SST by 2 to 4 months. The mechanism behind this component is the advection of water from the south. SLP leads SST with a negative correlation coefficient because lower pressures are associated with increased cyclonic winds which would advect more warmer water from the south into the area, while higher pressures indicate lighter winds and, thus, less northward advection.

EOF analysis indicates that SLP anomaly data at Sitka or Ketchikan is the best indicator of the mean SST anomalies in the Gulf of Alaska (inversely and in the second mode). The phase difference determined by the crosscorrelation analysis is most easily expressed as SST leading SLP by one month, but for practical purposes, SLP anomalies may be used to predict opposite anomalies in SST two or three months later. Air temperature anomalies at Seward might also be used to predict SST anomalies. These two variables are related in the second mode with the same algebraic sign. Because SLP and air temperature explain little variance in the SST records, the use of these predictors is somewhat questionable but not unreasonable for a gross estimate.

3. Sea Level at High Latitudes

The conclusion of Pattulo _et al_ (1955) is that high latitude sea level does not respond to tha annual temperauture cycle as does lower latitude sea level. They propose working more closely at high latitude regions where changes in temperature are large but sea level variations due to the temperature changes are not. Patullo _et al_ (1955) do not mention the salinity fluctuations found in high latitude sea level which are the cause of the sea level fluctuations (Royer, 1979). The results of this study indicate that sea level in the Gulf of Alaska is primarily controlled by two factors: wind and fresh water.

SLP controls sea level through geostrophic winds (Miller, 1957) and wind stress (Hellstrom, 1941, and Nomitsu, 1935). Hellstrom (1941) and Nomitsu (1935) independently develop the theory of changes in sea level due to wind and pressure driven "piling-up effects". Miller (1957) introduces the concept of "set-up" of water driven by the wind. These two phenomena are both important in the Gulf of Alaska. Increases in the coastal pressure should cause a decrease in the usual positive onshore pressure gradient, which would decrease the geostrophic winds. Decreases in SLP cause increases in this positive pressure gradient thus increasing the alongshore, cyclonic winds. The Gulf of Alaska's cyclonic circulation leads to winds that produce net onshore Ekman transport and changes in sea level. This relationship is demonstrated in the crosscorrelations. Generally the sea level crosscorrelation with a given variable is of the same shape as the SLP correlation with that variable except that the sea level crosscorrelation coefficients are opposite in sign and somewhat lower in magnitude (Figures 4-3 and 4-4, 4-6 and 4-7, and 4-11). This agrees with Lisitzin's (1974) results for the Gulf of Bothnia that the most important factor in sea surface fluctuations is wind driven transport.

Enfield and Allen (1979) determined that San Francisco is the dividing point between sea level stations influenced more by equatorial forcing and those more influenced by wind stress. Stations north of San Francisco were determined more influenced by local wind stress than temperature. However, their two farthest north stations, Yakutat and Sitka, did not show correlation with wind stress at even the 95% confidence interval. Enfield and Allen's (1979) results seem to indicate that geostrophic winds might not be responsible for the set-up of sea level in the Gulf of Alaska, but no alternative mechanism is proposed. Why Enfield and Allen's results do not support those of this study is unknown.

Sea level is influenced by fresh water as demonstrated by the increasing confidence level of the correlation of parameters from Ketchikan to Yakutat, as one moves downstream with the coastal current and with the Alaska gyre. Also downstream with the coastal current, the total amount of fresh water in the system increases as more sources contribute. Since high latitude sea water density is controlled more by changes in salinity than changes in temperature, the increasing dilution of the surface water should increase the sea level. The results of this study reiterate that high latitude sea level cannot be used to predict temperature anomalies and _vice versa_.

Considering the many coastal streams and rivers as a line source (Royer, 1982), the total amount of fresh water at a given position along the coastline should increase downstream with the coastal current (east to west). This result has implications for a seasonal longshore pressure gradient due to fresh water that increases from Ketchikan to Seward along the coast. This pressure gradient should influence the coastal circulation on the scale of the baroclinic radius of deformation (25 km).

A zonal model of this effect is easy to construct, and is more illustrative of the physics involved than a 2-dimensional model. Using the standard geophysical definitions of coordinate axes, which has the x direction positive toward the east, the momentum equation without rotation effects can be written as

$$\frac{DU}{Dt} = -\frac{1}{\rho}\frac{\partial P}{\partial x}$$

where U is the velocity in the x-direction and P is the pressure gradient. If the pressure gradient increases to the west, then $\frac{\partial P}{\partial x} < 0$ and the above equation can be rewritten as

$$\frac{DU}{Dt} > 0.$$

The coastal jet current has a velocity $U = f(x,t)$ where $f(x,y,t)$ is an unknown function with $U_x < 0$. Using this current for expansion of the total derivative yields

$$\frac{\partial U_x}{\partial t} + U_x \frac{\partial U_x}{\partial x} > 0.$$

Without further knowledge of the function $f(x,y,t)$, which term might dominate in the above equation at a given time and place cannot be predicted. Each term may be examined as if it were dominating the other term. Assuming steady-state, substituting the known signs of U_x and separating the terms yields the following relation:

$$\frac{\partial U_x}{\partial x} < 0.$$

This equations indicates that the coastal current increases in speed from east to west. Hence the result of this exercise is a seasonal surface flow driven by fresh water.

There are two forces which must be considered in the analysis: wind stress and friction. The predominant cyclonic wind stress pattern in the Gulf of Alaska would counteract offshore flow, forcing the fresh water to remain near to shore. Frictional effects would slow the current and cause cross isobaric flow toward lower geopotential. In the Gulf of Alaska, this would be toward the left or offshore. Because SLP and sea level are strongly negatively correlated, wind stress is the most likely choice for maintaining sea level and the nearshore coastal flow. This agrees with the observed current structure and the wind stress variability (Royer, 1982).

4. El Nino - Southern Oscillation Signal at High Latitudes

The sea level and SLP records show that a faint ENSO signal is detectable at high latitudes. This agrees with Royer's (personal communication) results from relating subsurface temperatures near Seward that indicate an ENSO signal is seen as a temperature increase 9 months after the onset of an ENSO. This would explain the evidence for the ENSO leading changes in sea level or SLP. Why sea level changes would precede the SOI is unknown. SOI does not correlate significantly with air temperature or fresh water discharge (precipitation). The results that SOI does correlate with higher values and at a higher significance level with sea level than with SLP combined with Royer's results above indicate that if an ENSO signal does propagate to high latitudes, then it's signal is better seen in the ocean than in the atmosphere.

Enfield and Allen (1979) found that sea level is significantly ($p>0.95$) correlated with SOI along the Pacific Coast of the Americas. The only stations along the Gulf of Alaska used in their study were Sitka and Yakutat. As found in this study, these two stations did not show significant ($p>0.95$) crosscorrelations. It is important to note that in this study, other stations along the Gulf of Alaska were found to be highly significantly ($p>0.995$) correlated with SOI. The difference is time scale between the Enfield and Allen (1979) results (2-5 years) and the results of this study (9 to 12 months) is probably due to the different confidence levels chosen in the two studies. Enfield and Allen (1979) propose "poleward propagation by low-frequency, wave dynamical means" as the mechanism behind the correlation. Though this mechanism is possible, more evidence would be required for its proof.

5. Limitations of the Analyses

Because the majority of the observations in this study are historical data recorded without confidence levels or error bars, it is impossible to know how accurate these data are. The analysis techniques used in this study do not require a high degree of accuracy in the data; precision is more important than accuracy, since fluctuations are discussed. One must assume that the error is small and without longterm trends, so that the error is somewhat negligable within analyses of the monthly means. For example, the 1985 report by the IAPSO Advisory Committee on Tides and Mean Sea Level indicates that "good" sea level records have accuracy to 1mm, which is certainly reasonable for use in the types of analyses performed in this study. From the results of this study, all of the sea level data except for that at Seward could be considered "good." The confidence interval for the other data is unknown.

The results promulgated in this study do not lead to concrete cause and effect relationships, but merely suggest what relationships might exist. The physical interpretation of these results gives them meaning, but not proof.

6. Importance of This Study to Fisheries

An important aspect of fisheries oceanography is the prediction of the occurrence and abundance of fish. Fisheries managers determine the fishing season duration and catch allotments for each species from various models. In turn, enterpreneurs attempt to predict the location of the best fishing grounds. The success of these predictions is directly related to the accuracy in fishery population models. Within these models, physical oceanographic data are important because fish survival, migration, aggregation and distribution are related to oceanographic conditions (Gallucci, 1983 and Wooster, Banse and Gunderson, 1983). Both the quality and the history of these data influence how useful a particular model will be.

Although depth and salinity are important oceanographic parameters in migratory choices made by fish (Scott, 1982), temperature is the most important parameter because fish are poikilotherms. Temperature affects schooling and dispersal, vertical, spawning and feeding migrations, swimming speed and overall degree of activity, initiation and duration of spawning, growth, mortality and interspecies relations in fish (Brett, 1970 and Laevastu and Hayes, 1981). Turbulence and volume transport are also key abiotic factors in the survival of fish (Bakun et al, 1982). Climatic fluctuations have also been recognized to affect fish population dynamics (Cushing, 1982 and Dow, 1977) by altering the above conditions along with light and other nutrient levels which affect food availability.

7. Suggestions for Further Research

This research could be profitably expanded by adding several more parameters to those already used in this study. SST data taken near each of the coastal stations would be useful to gain more insight into local air-sea interactions. The regional SST used yields evidence of large scale interaction, but nothing on the local scale. Because sea level proved to be highly related to SLP, the addition of wind stress curl to the parameters used is the logical next step. These additional statistics determine whether or not sea level is truly set up by geostrophic winds as suggested here, or something else as the Enfield and Allen (1979) results might suggest. Finally, fishery statistics could be added to begin development of a prediction model based on the available parameters.

Spectral analysis of the individual time series would be useful for identification of long term cycles within any of the parameters. This information would also be useful in relation to the other analyses performed in this study as additional evidence in favor of or opposed to the mechanisms suggested.

The result that an ENSO signal is seen at high latitude suggests that the ENSO is only a part of a larger scale phenomenon. Investigation into this larger mechanism should proceed first by looking for a phenomenon that could be termed either the Pacific Oscillation or a Global Oscillation because of its large extent. This new parameter could be added into the analyses already performed and perhaps explain a larger amount of the variance than the SOI.

B. Conclusions

1) Overall, sea level, SLP, air temperature, fresh water discharge and SST in the Gulf of Alaska tend to fluctuate together. This is interpreted as meaning they respond to the same large scale atmospherid forcing. Air temperature and fresh water discharge vary in phase, with SLP 180^{o} out of phase.

2) SST and air temperature are positively correlated and vary in phase. The atmosphere and the ocean drive each other with thermal transport across the interface, and both are heated by insolation. SST and SLP and, to a lesser degree, SST and sea level show a 7 to 8 month feedback cycle. SST is positively correlated with SLP because the SLP change is due to warming. SST and sea level are negatively correlated because of geostrophic wind stress.

3) Sea level is inversely related to SLP due to the geostrophic wind transport of water. Sea level in the Northeast Pacific is not related to SST. The nonlinearitites in the equation of state of sea

water cause sea level to be driven more by fresh water input than temperature. This conclusion can be extended, with caution, to other high latitude regions.

4) A faint ENSO signal is detectable ($p>0.95$) in high latitude sea level and SLP records. Changes in SOI are led by sea level changes at 9 to 13 months months at Ketchikan and Yakutat, while sea level leads changes in SOI by 10 to 13 months at Juneau and Seward. SOI also leads SLP by 8 to 11 months at each of the meteorological stations except Sitka, and SLP leads SOI by 10 to 11 months at the same stations. This result indicates that the signal which is correlated with ENSO is propably a local manifestation of a more global phenomena.

The historical data gathered for this study are available from both the author and the Institute of Marine Science at the University of Alaska in Fairbanks. Now that the historical compilation is complete, analyses of this nature can be easily extended forward in time as new data is added. The data are available in both electronic (University of Alaska VAX computer) and printed format.

Literature Cited

Anonymous (1983). Sea Level Variations for the United States 1855-1980. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service, Tides and Water Levels Branch, Rockville, Maryland. 170 pp.

Anonymous (1985). The Oceanography Report:Changes in Relative Mean Sea Level. EOS 66(45):754-756.

Bakun, A., J. Beyer, D. Pauly, J.G. Pope and D.D. Sharp (1982). Ocean sciences in relation to living resources. Canadian Journal of Fisheries and Aquatic Sciences 39:1059-1070.

Brett, J.R. (1970). Temperature: Fishes-Functional Responses. pp. 515-560. In Kinne, O. (ed.), Marine Ecology. Vol. I, Part 1. Wiley-Interscience, London. 618 pp.

Chelton, D. (1984). Commentary: short-term climatic variability in the northeast Pacific Ocean, pp. 87-99, in Pearcy, W.G. (ed.) The Influence of Ocean Conditions on the Production of Salmonids in the North Pacific: A Workshop, November 8-10, 1983, Newport, Oregon. Oregon State University Press, Corvallis. 327 pp.

Cushing, D.H. (1982). Climate and Fisheries. Academic Press, N.Y. 373 pp.

Dodimead, A.J., F. Favorite and T. Hirano (1963). Review of oceanography in the subarctic Pacific Region: Salmon of the North Pacific. Bullettin of the International North Pacific Fisheries Commission 13. 195 pp.

Dow, R.L. (1977). Effects of climatic cycles on the relative abundance and availability of commercial marine and estuarine species. J. cons. Perm. int. Explor. Mer 37(3):274-280.

Enfield, D. (1984). Workshop on Climate Variability of the Eastern North Pacific and Western North America. March 4-8 1984, Asilomar Conference Center, Pacific Grove, California. 103 pp.

Enfield, D. and J.S. Allen (1980). On the structure and dynamics of monthly mean sea level anomalies along the Pacific Coast of North and South America. Journal of Physical Oceanography 10:557-578.

Fleming, R.H. (1958). Notes concerning the halocline in the Northeastern Pacific Ocean. Journal of Marine Research 17:158-173.

Gallucci, V.F. (1983). Numerical simulation in fisheries oceanography, pp. 196-198, in Wooster, W.S. (ed.) From Year to Year: Interannual Variability of the Environment and Fisheries of the Gulf of Alaska and the Eastern Bering Sea. Washington Sea Grant, Seattle. 208 pp.

Gissler, N. (1747). Anladning at finna hafvets affal for vissa 'ar. (Reason for finding a decreased sea levl in certain years.) Kgl. Svenska Vetenskapsakad, Hardl., Stockholm. 142 pp.

Hellstrom, B. (1941). Wind effect in lakes and rivers. Handl: Ing. Vetensk. Akad. 158. 191 pp.

Hicks, S.D., and W. Sofnos (1965). The determination of land emergence form sea level observations in Southeast Alaska. Journal of Geophysical Research 70:3314-3320.

Hubbard, J.R. Tidal Datums Section, National Ocean Service, NOAA, 6001 Executive Blvd., Rockville, MD 20852

Jacobs, W.C. (1951). The energy exchange between the sea and atmosphere and some of its consequences. Bulletin of the Scripps Institution of Oceanography 6:27-122.

Laevastu, T., and Hayes, M.L. (1981). Fisheries Oceanography and Ecology. Page Bros. (Norwich) Ltd., Norwich. 201 pp.

Lisitzin, E. (1974) Sea Level Changes. Elsevier Oceanography Series 8, New York. 286 pp.

Miller, A.R. (1957). The effect of steady winds on sea level at Atlantic City. Woods Hole Oceanographic Institution Contribution 829:24-31.

Namias, J. Climate Research Group, Scripps Institution of Oceanography, La Jolla, CA 92093.

Neibauer, H.J., Institute of Marine Science, University of Alaska, Fairbanks, Alaska 99701.

Neumann, G. and W.J. Pierson (1966). Principles of Physical Oceanography. Prentice-Hall Inc., New Jersey. 456 pp.

Nomitsu (1935). A theory of tsumanis and seiches produced by wind and braometric gradient. Mem. Coll. Sci. Kyoto Univ. 18:201-214.

Overland, J.E. (1981). Marine climatology of the Bering Sea, pp. 15-22, in Hood, D.W. and J.A. Calder (eds.), The Eastern Bering Sea Shelf: Oceanography and Resources Vol II. O.M.P.A., 625 pp.

Patullo, J., W.H. Munk, R. Revelle, and E. Strong (1955). The seasonal oscillation of sea level. Journal of Marine Research 14(1):88-155.

Picard, G.L., and W.J. Emery (1982). Descriptive Physical Oceanography: An Introduction. Pergamon Press, New York. 249 pp.

Ralph, W. (1983). Drought and the El Nino phenomenon. Ecos 38:13-15.

Robuck, A. (1984). An updated climate feedback diagram. Bulletin of the American Meteorological Sociey 66(7):786-787.

Roden, G.I. (1967). On river discharge into the northeastern Pacific and the Bering Sea. Journal of Geophysical Research 81:3100-3110.

Royer, T.C. (1979). On the effect of precipitation and runoff on the coastal circulation in the Gulf of Alaska. Journal of Geophysical Research 9(3):555-563.

Royer, T.C. (1981). Baroclinic transport in the Gulf of Alaska, Part II, fresh water driven coastal current. Journal of Marine Research 19:251-266.

Royer, T.C. (1982). Coastal fresh water discharge in the northeast Pacific. Journal of Geophysical Research 87(c3):2017-2021.

Straus, D.M. (1983). On the role of the seasonal cycle. Journal of Atmospheric Science 40:303-313.

Thompson, W.F., and R. Van Cleve (1936). Seasonality in the Southern Hemisphere eddy statistics at 500 mb. Journal of Atmospheric Science 39:2507-2520.

Trenberth, K.E. (1984). Some effets of finite sample size and persistence on meterological statistics. Monthly Weather Review 112:2369-2368.

U.S. Department of Agriculture, Weather Bureau (1919-1940). Climatological Data, Alaska Section. 5 (1919), 108 pp.; 6 (1920), 108 pp.; 7 (1921), 108 pp.; 8 (1922), 108 pp.; 9 (1923), 108 pp.; 10 (1924), 108 pp.; 11 (1925), 108pp.; 12 (1926), 108 pp.; 13 (1927), 108 pp.; 14 (1928), 108pp.; 15 (1929), 18pp.; 16 (1930), 108 pp.; 17 (1931).; 62 pp.; 18 (1932). 62 pp.; 19 (1933), 57 pp.; 20 (1934). 56 pp.; 21 (1935), 61 pp.; 22 (1936), 79 pp.; 23 (1937), 84 pp.; 24 (1938), 84 pp.; 25 (1939), 85 pp.; 26 (1940), 87 pp.

U.S. Department of Commerce, Weather Bureau (1941-1965). Climatological Data, Alaska. 27 (1941), 86 pp.; 28 (1942), 85 pp.; 29 (1943), 84 pp.; 30 (1944), 79 pp.; 31 (1945), 78 pp.; 32 (1946), 79 pp.; 33 (1947), 132 pp.; 34 (1948), 185 pp.; 35 (1949), 161 pp.; 36 (1950), 168 pp.; 37 (1951). 184 pp.; 38 (1952), 181 pp.; 39 (1953), 183 pp.; 40 (1954), 90 pp.; 41 (1955), 197 pp.; 42 (1956), 215 pp.; 43 (1957), 215 pp.: 44 (1958), 203 pp.; 45 (1959), 217 pp.; 46 (1960), 213 pp.; 47 (1961), 226 pp.; 48 (1962), 219 pp.; 49 (1963), 229 pp.; 50 (1964), 244pp.; 51 (1965). 254 pp.

U.S. Department of Commerce, Environmental Sciences Services Administration (1966-1970). Climatological Data, Alaska. **52** (1966), 238 pp.; **53** (1967), 246 pp.; **54** (1968), 253 pp.; **55** (1969), 252 pp.; **56** (1970), 264 pp.

U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service (1971-1984). Climatological Data, Alaska. **57** (1971), 260 pp.; **58** (1972), 268 pp.; **59**(13) (1973), 15 pp.; **60**(13) (1974), 15 pp.; **61**(13) (1975), 16 pp.; **62**(13) (1976), 17 pp.; **63**(13), (1977), 16 pp.; **64**(13) (1978), 16 pp.; **65**(13) (1979), 16 pp.; **66**(13) (1980), 15 pp.; **67**(13) (1981), 28 pp.; **68**(13) (1982), 28 pp.; **69**(13) (1983), 29 pp.; **70**(2) (1984), 31 pp., (3), 31 pp., (4), 31 pp., (5), 30 pp., (6), 27 pp., (7), 34 pp., (8), 28 pp., (9), 27 pp., and (10), 30 pp.

Winston, J.S. (1955). Physical aspets of rapid cyclo-genesis in the Gulf of Alaska. Tellus 5:481-500.

Wooster, W.S., K. Banse and D.R. Gunderson (1983). On the development of strategies for the study of ocean fish interactions, pp. 199-206 in Wooster, W.S., (ed.) From Year to Year: Interannual Variability of the Environment and fisheries of the Gulf of Alaska and the Eastern Bering Sea. Washington Sea Grant, Seattle. 280 pp.

Xiong, Q., and T.C. Royer (1984). Coastal temperature and salinity in the northern Gulf of Alaska, 1970-1983. Journal of Geophysical Research **89**(c5):8061-8068.

Appendix 1

Generation of the Final Barometric Pressure Data

As described in the section on barometric pressure in Chapter 2, the sea level pressure data are from 3 different sources: the National Weather Service (NWS) (Fathauer, personal communication), the National Weather Bureau (NWB) (U.S. Department of Agriculture, Weather Bureau, 1919 to 1940, and the U.S. Department of Commerce, Weather Bureau, 1941 to 1947) and the Climate Research Group (CRG) at Scripps Institute of Oceanography (Namias, personal communication). Figures A1-1 through A1-6 show the different time series of sea level pressure available for each station. One should note the anomalous nature of the data during World War II for Juneau (Figure A1-3) and Ketchikan (Figure A1-5). Though the NWS data was generally preferred over the CRG data in constructing the final sea level pressure time series, these 2 sections were omitted in preference for the CRG data. Figure A1-7 shows the completed time series for all 6 stations.

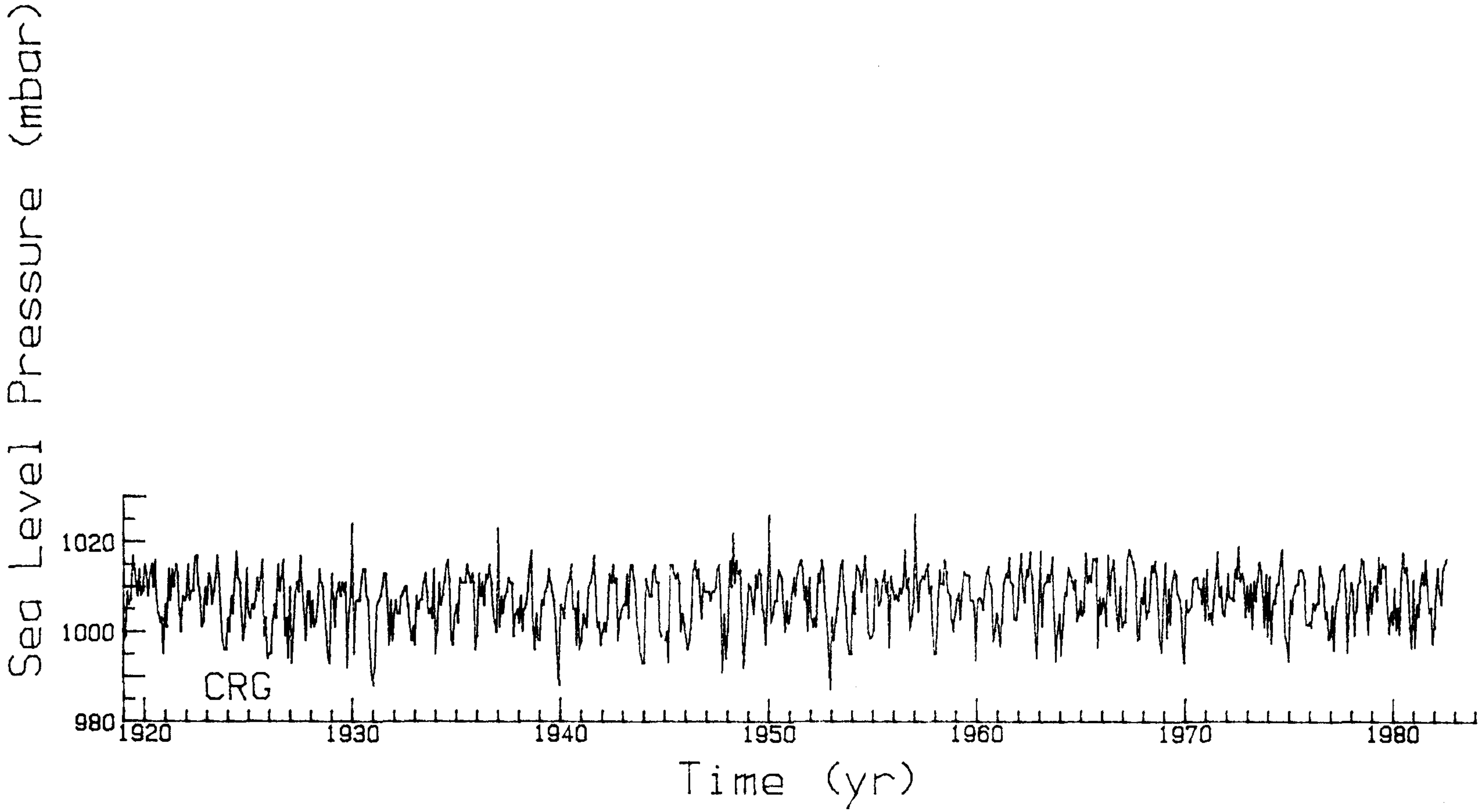

Figure A1-1. Sources of sea level pressure data for Seward.

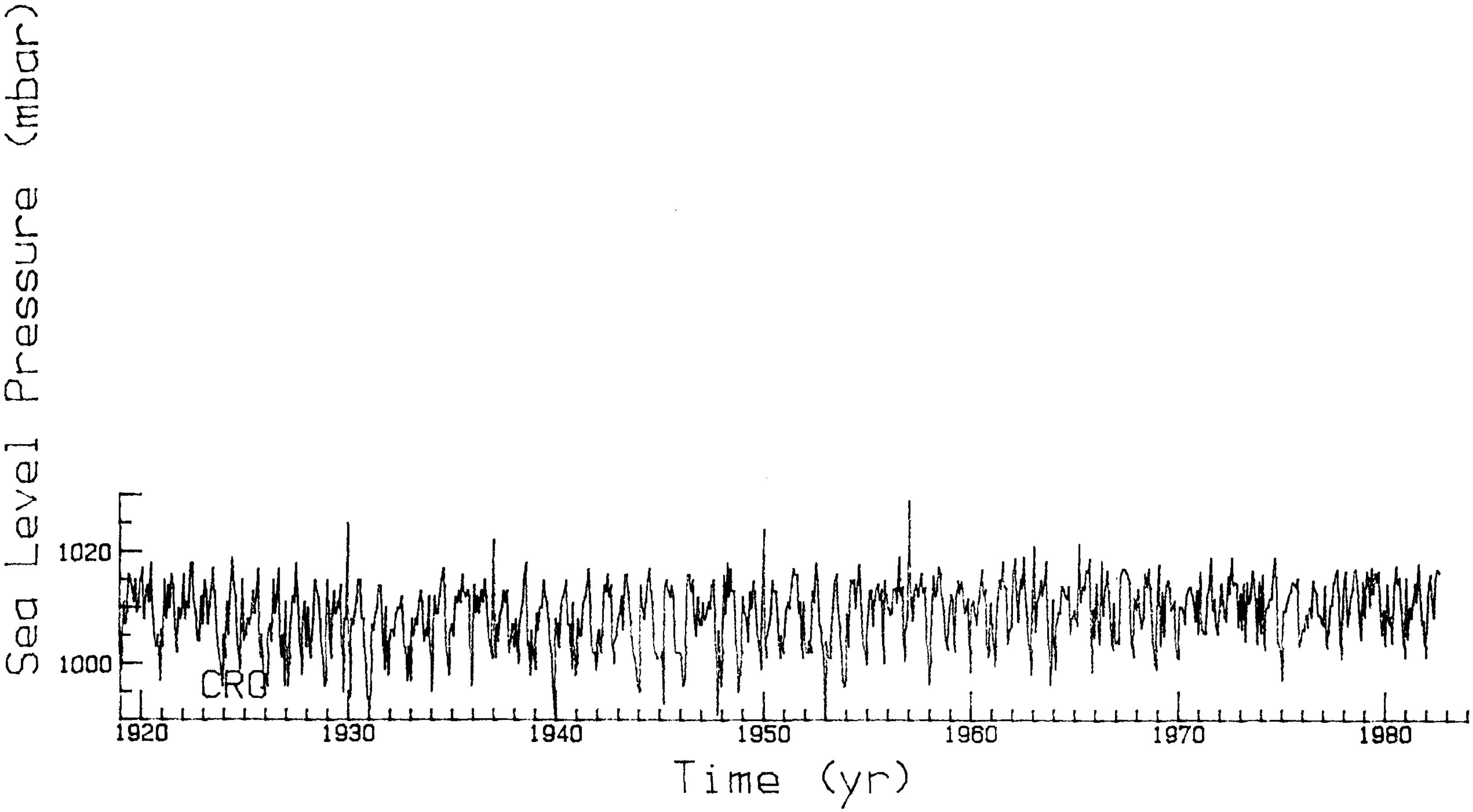

Figure A1-2. Sources of sea level pressure data for Yakutat.

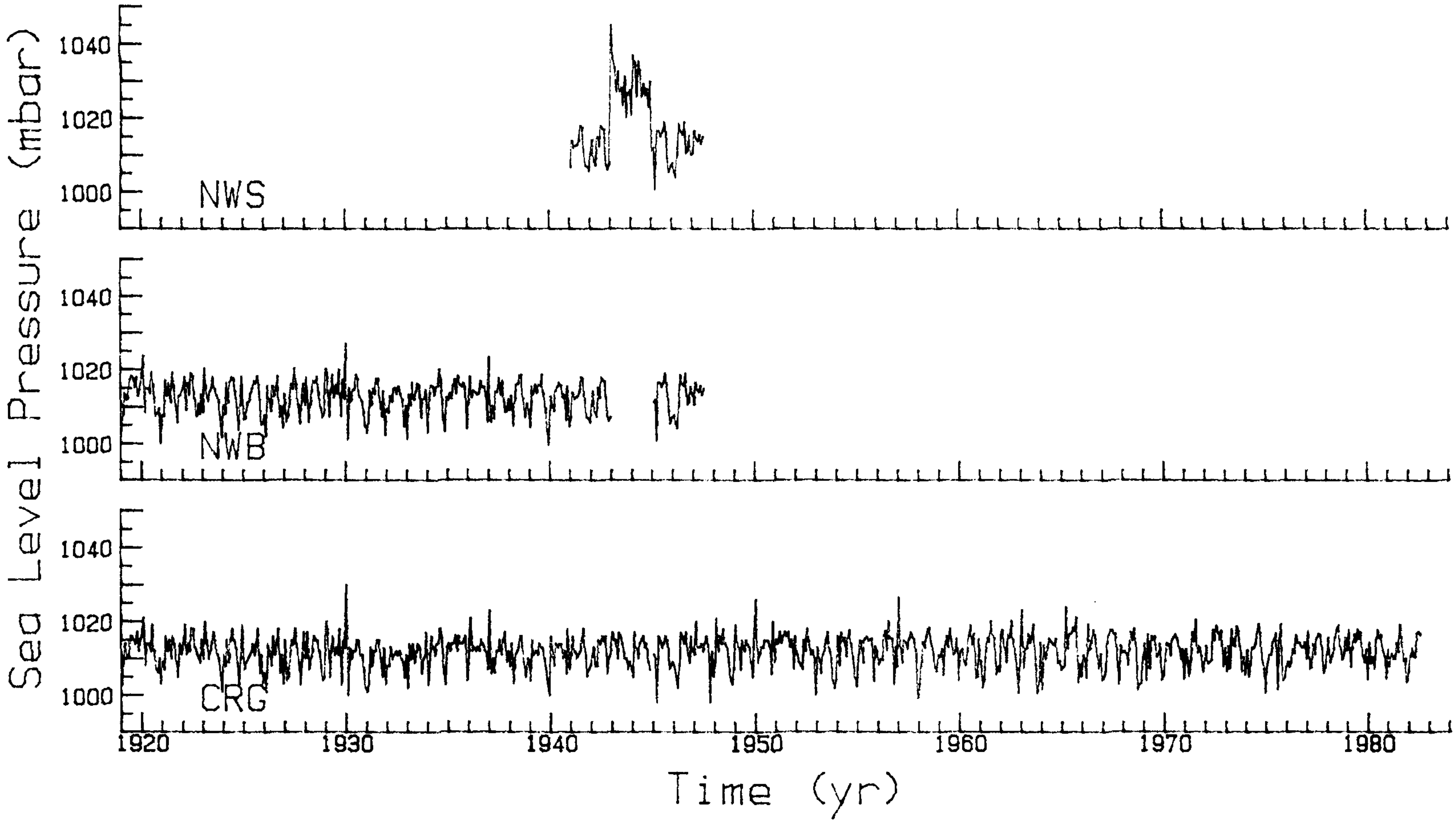

Figure A1-3. Sources of sea level pressure data for Juneau.

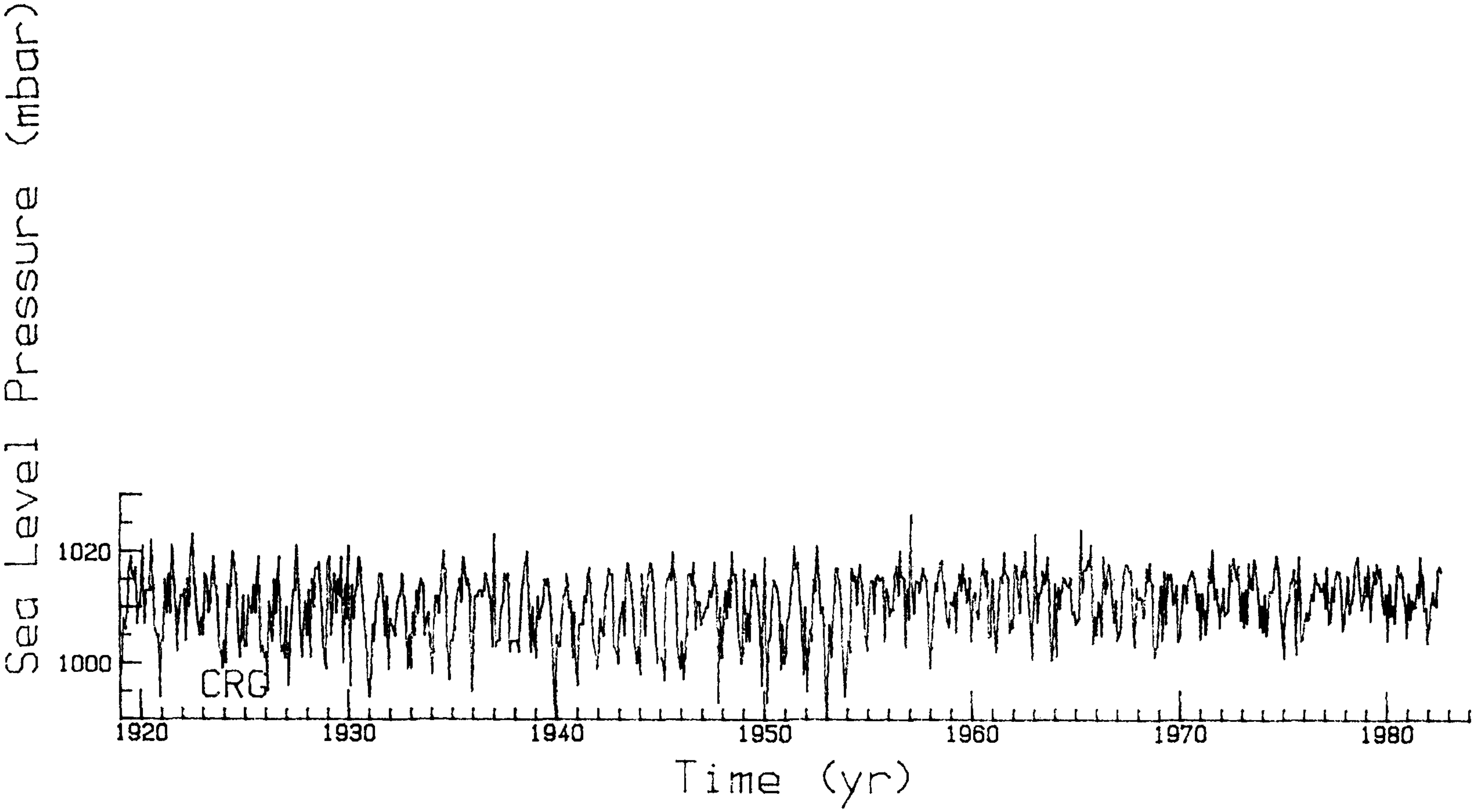

Figure A1-4. Sources of sea level pressure data for Sitka.

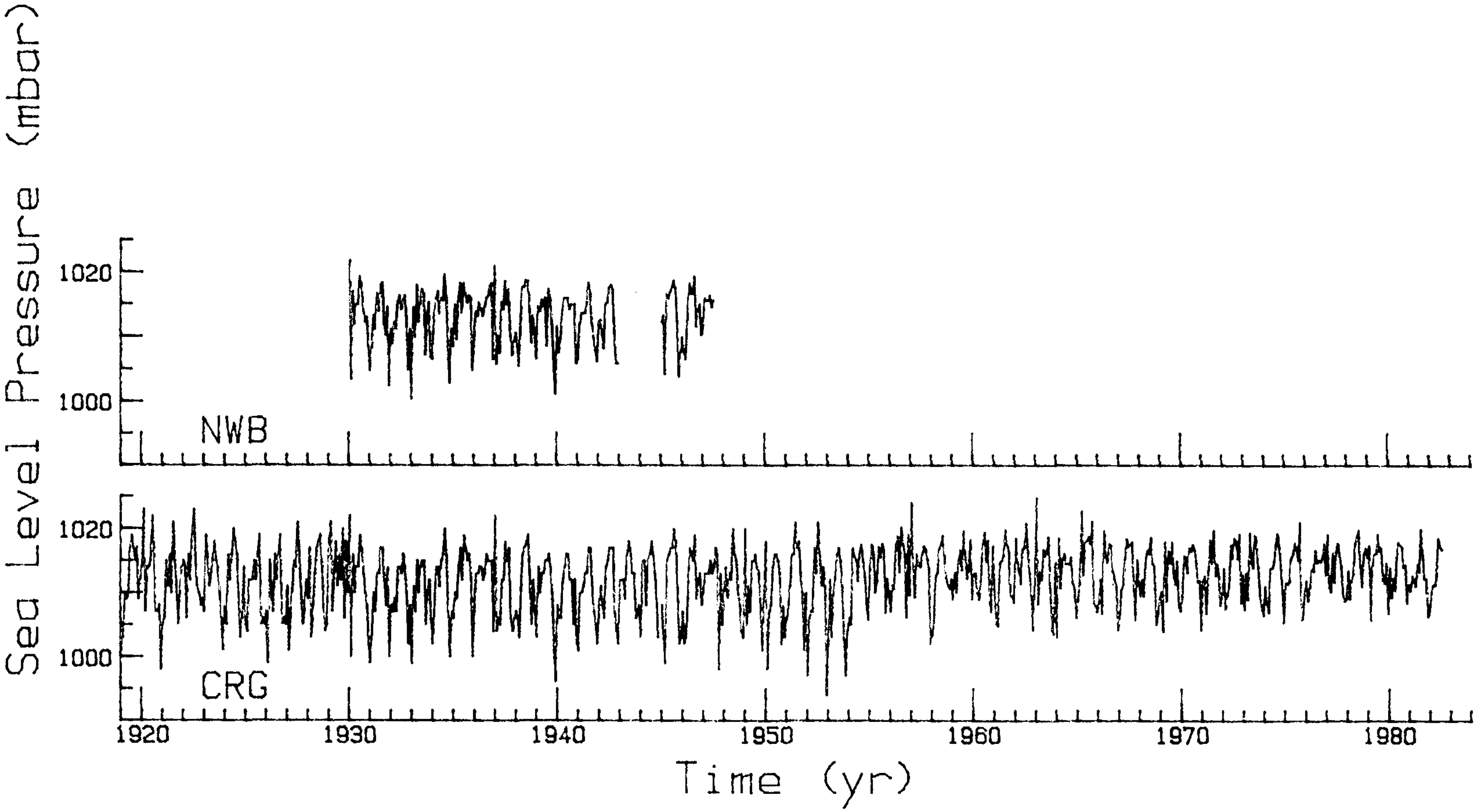

Figure A1-5. Sources of sea level pressure data for Ketchikan.

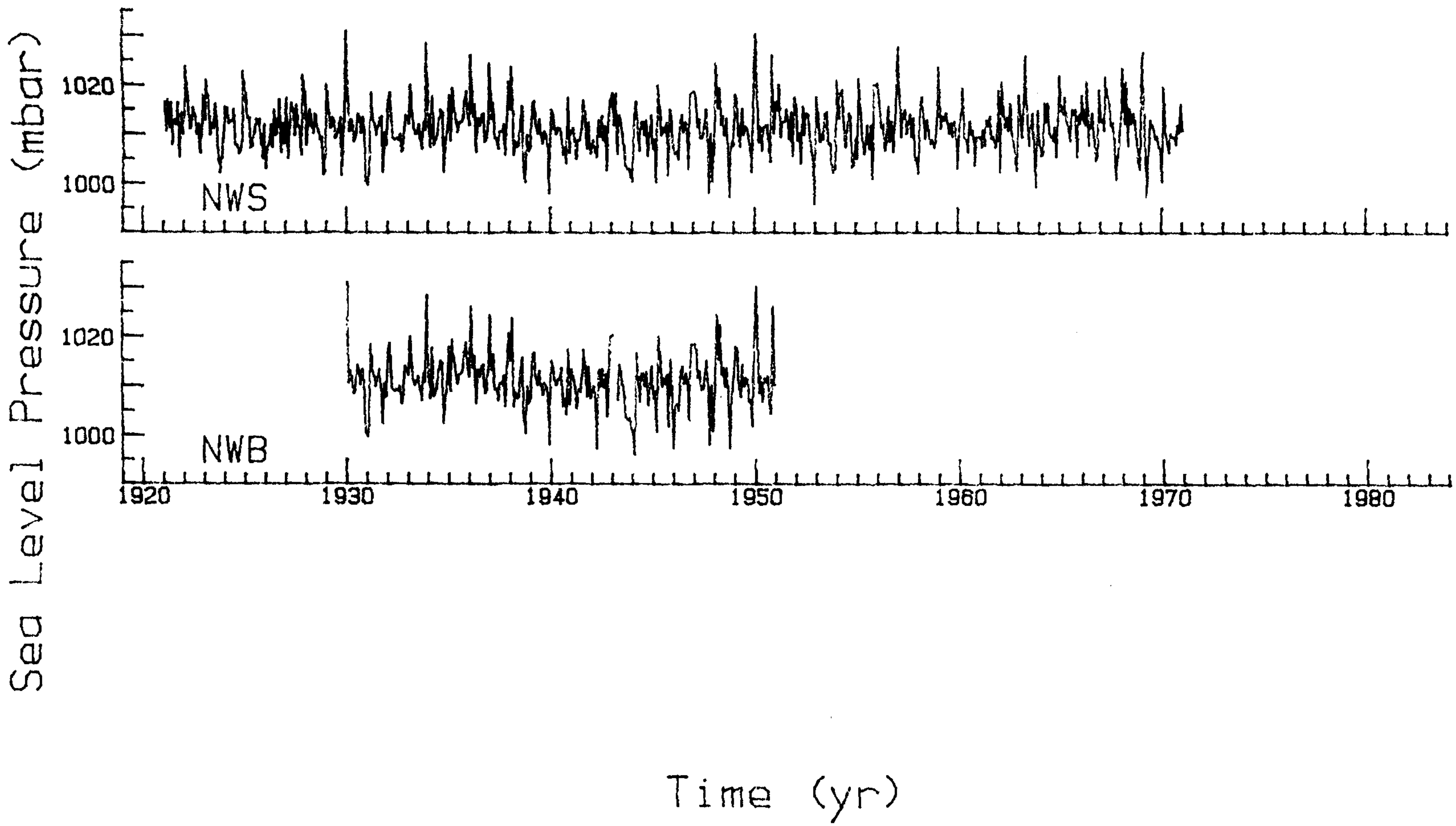

Figure A1-6. Sources of sea level pressure data for Fairbanks.

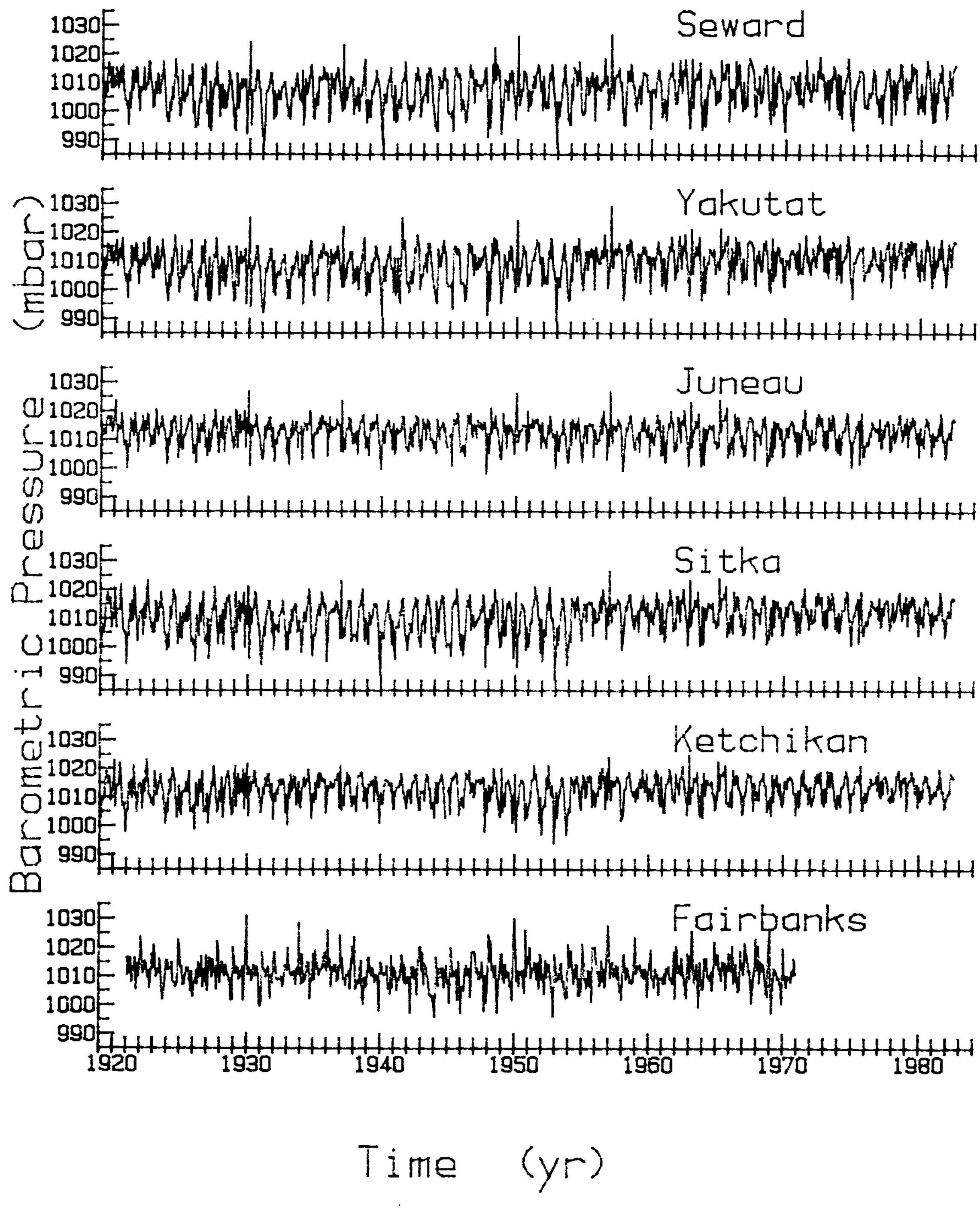

Figure A1-7. The final sea level pressure data used.

Appendix 2

Reduction cf the Raw Sea Level Data

Raw sea level data is characterized by apparent secular trends resulting from two basic causes: vertical changes in the land or in the water column. A summary is given below of the effects different types of vertical land movements and changes in the water column have on sea level. Not all of these effects are easy to remove from a sea level record: often data are not available to correct an entire time series.

Vertical land movements occur both on a long and short time scale. Glacial-eustacy concerns the weight dependent equilibrium of the lithoshpere's geopotential height. Changes of this nature occur on the order of cm year^{-1}. In the Gulf of Alaska, sea level data evidence isostatic rebound, a long term linear depression in sea level caused by the rising of previously glacier-depressed land. This type of long term trend is best seen in the sea level record for Juneau (Figure A2-1). Earthquakes can cause rapid vertical land movements in the order of cm to m. The 1964 Anchorage earthquake (Hicks, 1972) is well documented in the raw sea level data for Seward (Figure A2-1).

Changes in the water column are caused by different climatological and oceanographic phenomena. The density of sea water is dependent upon both salinity and temperature. At high latitudes, the low ambient water temperatures make sea water density more dependent upon salinity than temperature. Thus, changes in the amount of evaporation *versus* precipitation affect the water column in the Gulf of Alaska. Local atmospheric pressure also affects sea level through the inverse barometer effect (Gissler, 1747). Increases in atmospheric pressure will depress sea level and *vice versa*. The above local effects are on a shorter time scale than global phenomena. Changes in sea level due to global warming or cooling do occur, from changes in the overall temperature of the water column and in the amount of ice stored in the polar ice caps.

Sea level data obtained from tide station measurements are relative. Because sea level movement is the resultant vector from adding the individual vectors for each water column and land effect, one cannot *a priori* determine the direction of these different effects. Supplementary data, such as glacial history, water column temperature, sea level pressure, and global sea level trend, are important in sea level analysis.

The sea level data obtained from the National Oceanic and Atmospherical Administration, National Ocean Service Tides and Water Levels Branch (1983), as described in the sea level section of Chapter 2, could not be used directly in the computations involved in this thesis. The time series were adjusted only to take the effects of atmospheric pressure and isostatic rebound into account. Other effects still reside in these time series because insufficient data are available to remove them. The changes that occurred in the time series are shown in Figures A2-1 through A2-5.

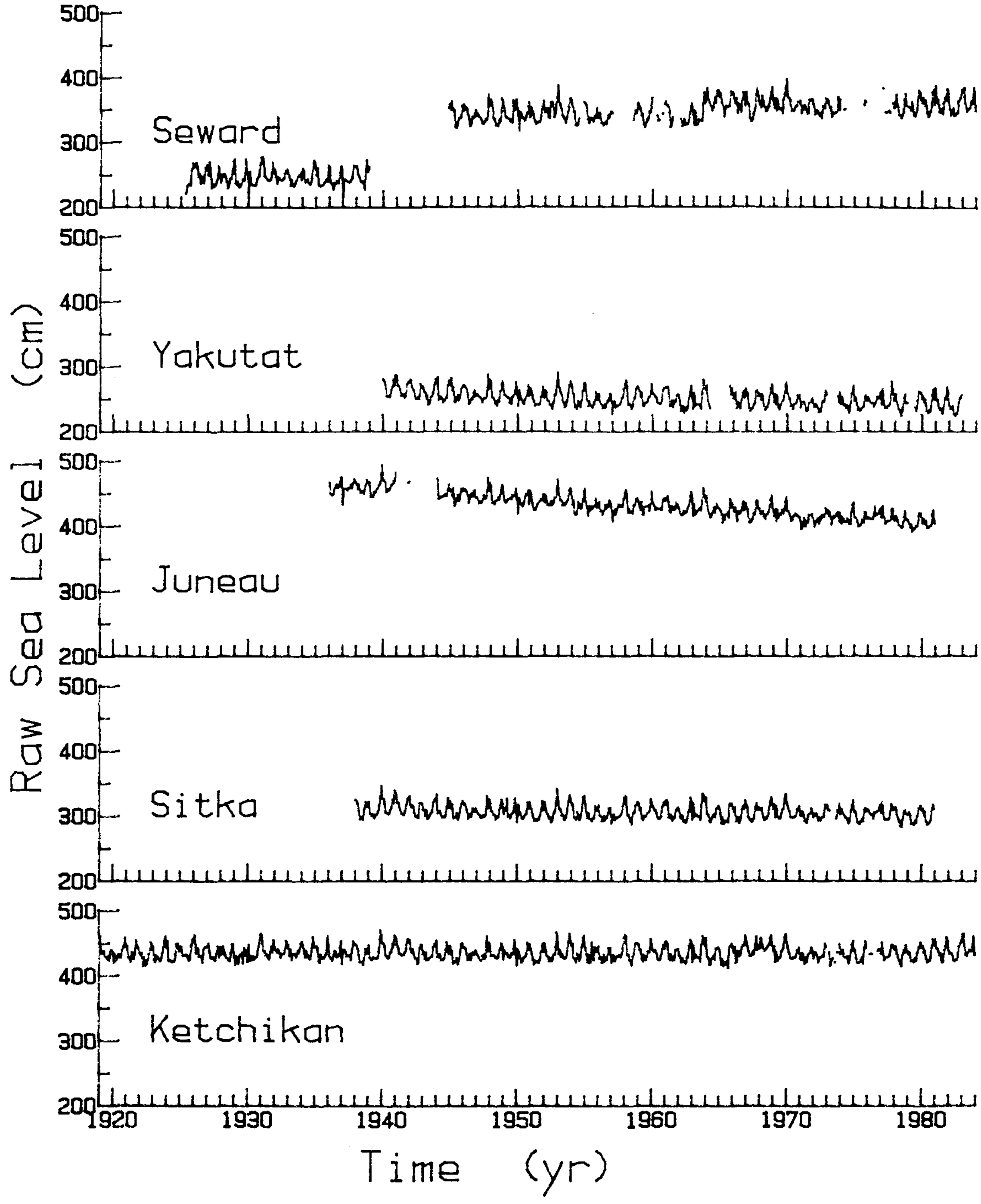

Figure A2-1. Raw sea level data for the 5 coastal stations.

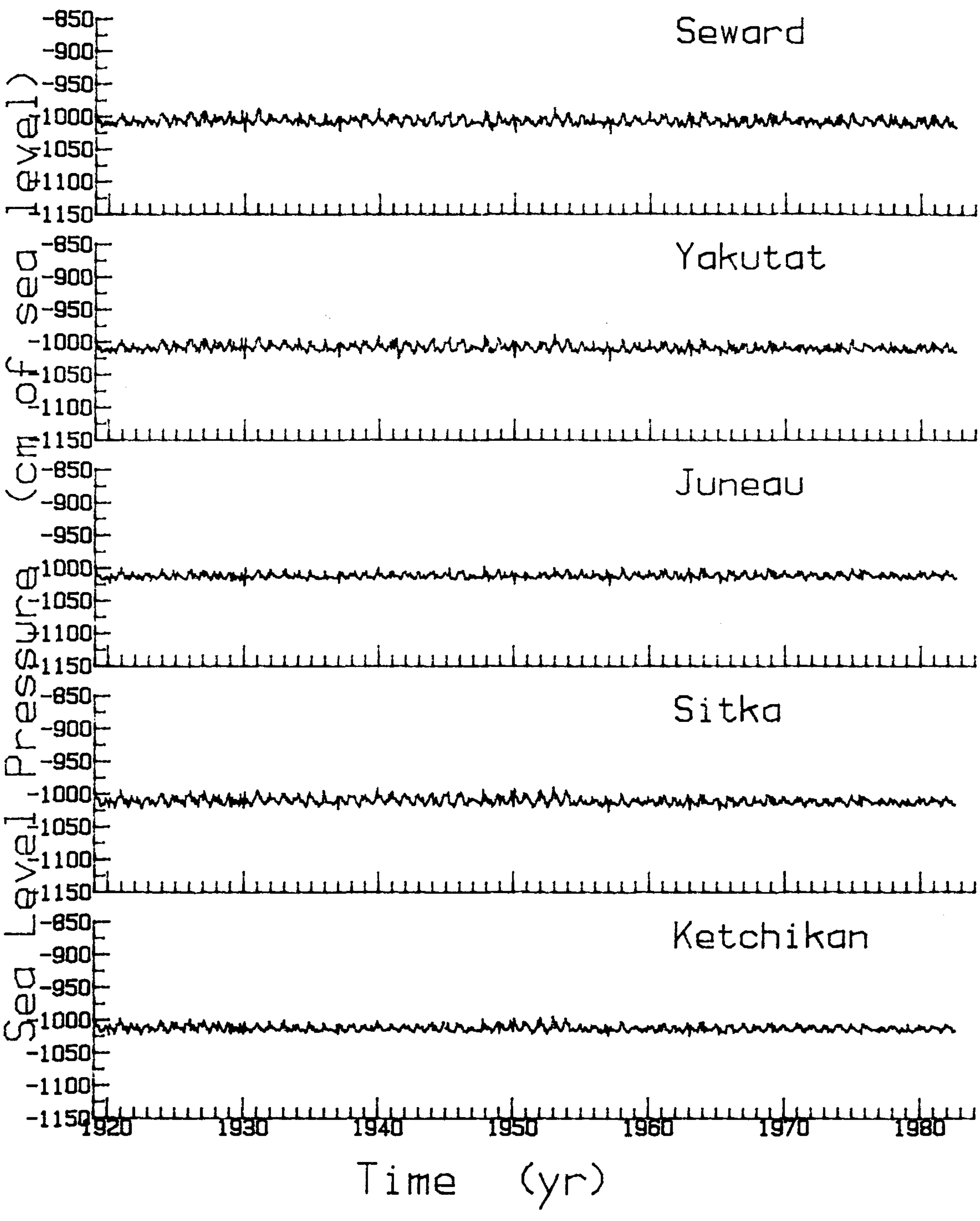

Figure A2-2. The sea level pressure data used to correct sea level data for the inverse barometer effect. The vertical scale is in cm of sea level equivalent to that used in Figure A2-1 for comparison purposes.

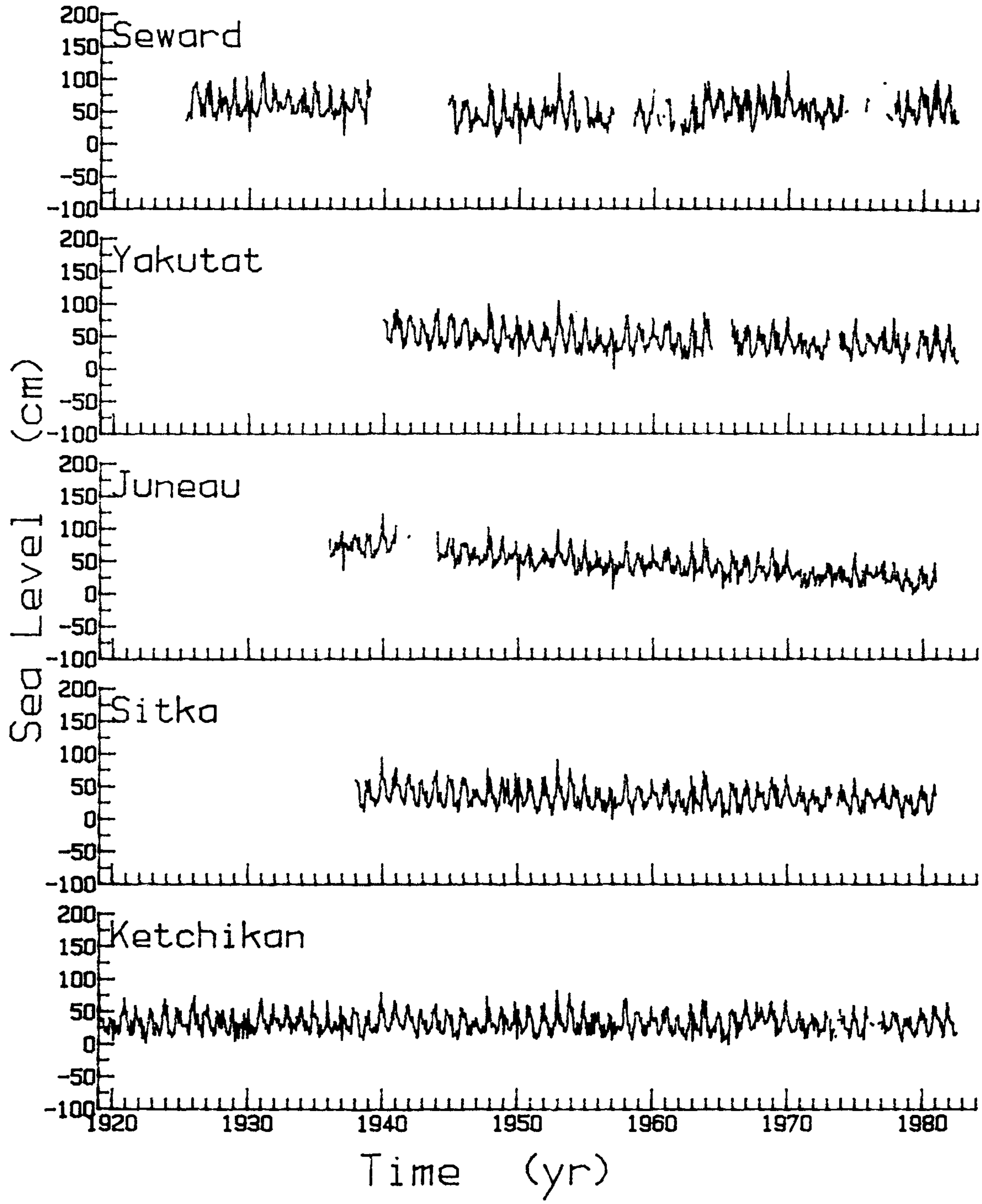

Figure A2-3. Sea level data corrected for the inverse barometer effect.

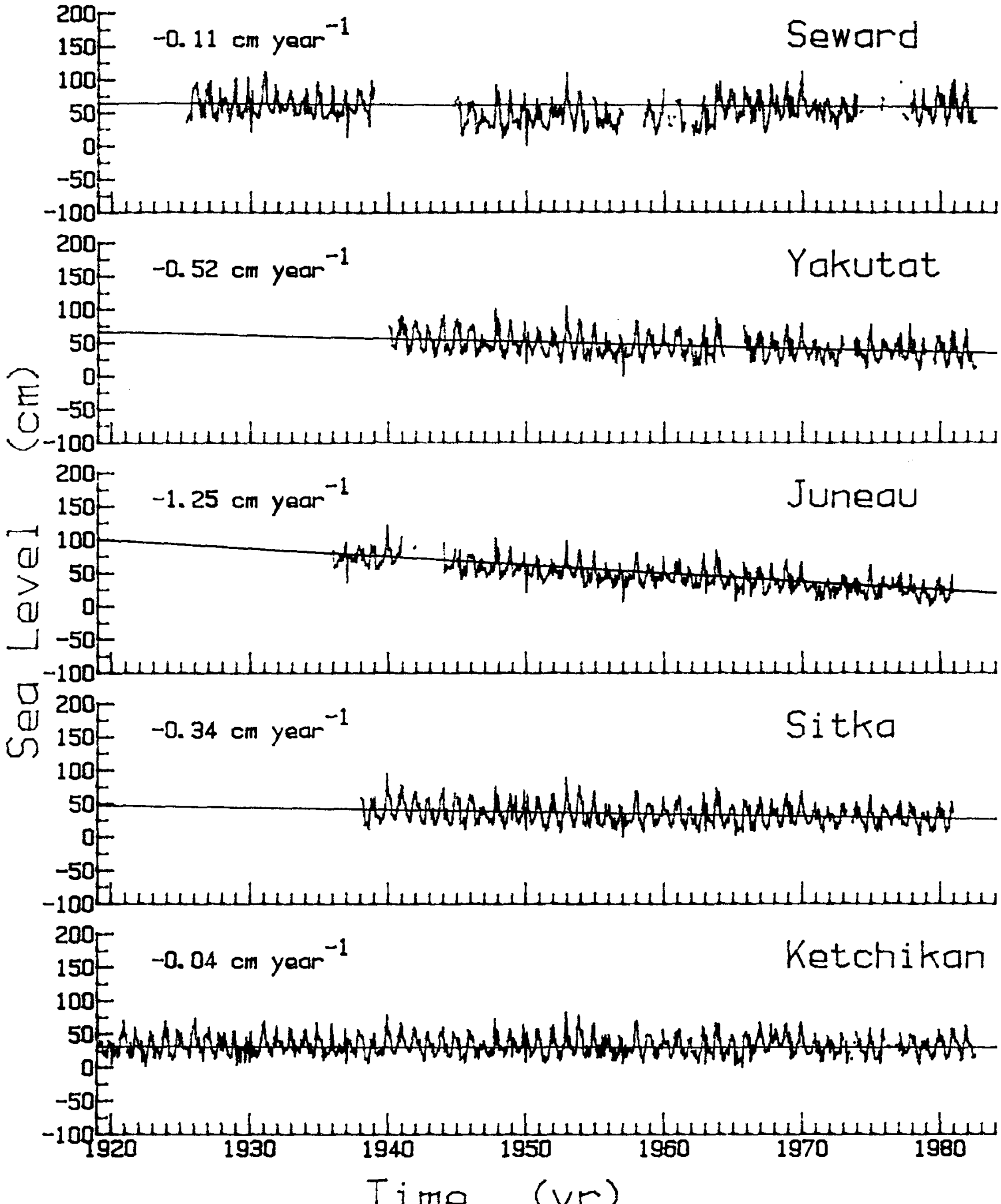

Figure A2-4. Sea level data corrected for the inverse barometer effect, with the trend for isostatic rebound drawn in red.

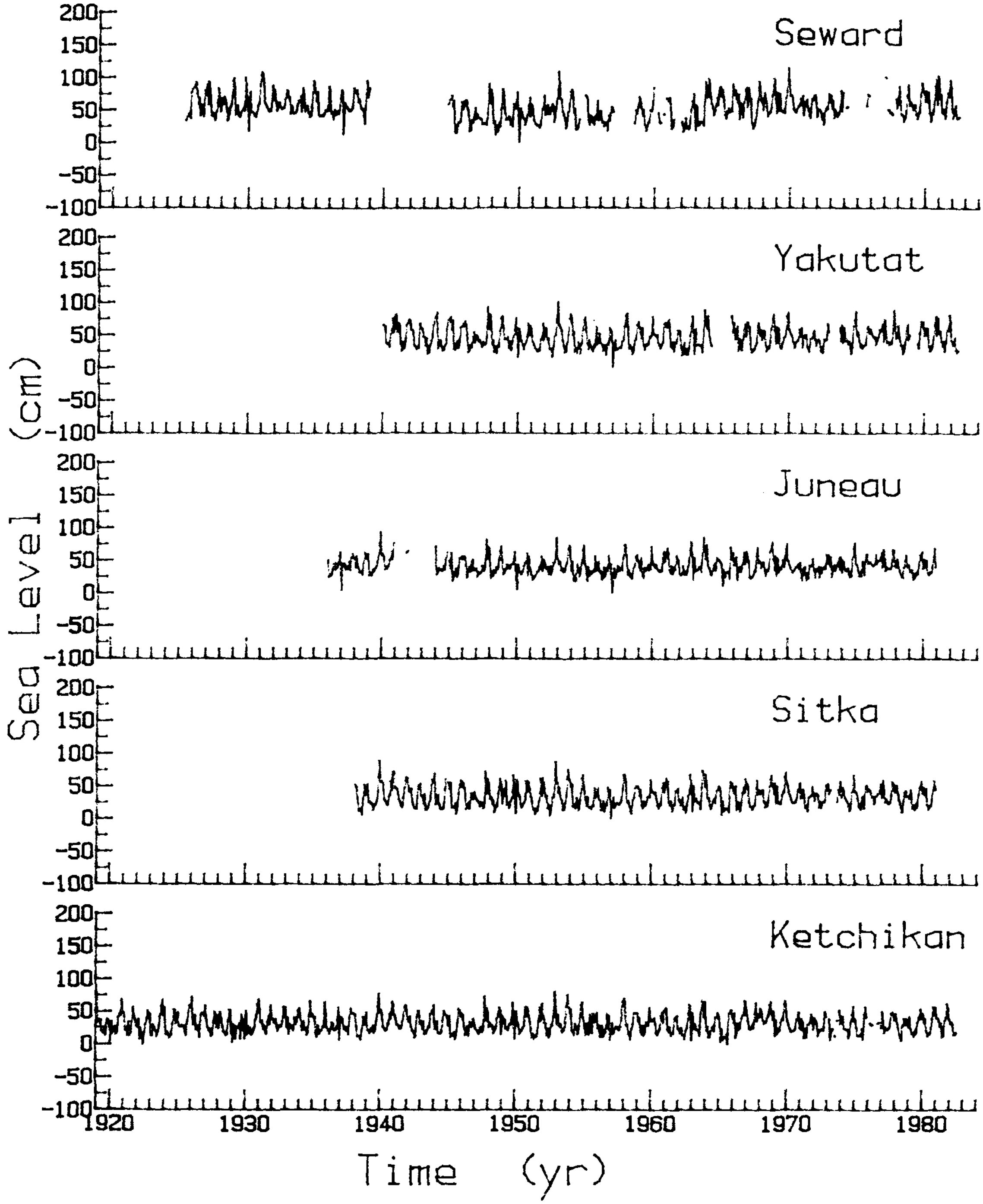

Figure A2-5. Sea level data corrected for isostatic rebound.

Appendix 3

Time Series of Data Anomalies

Figures A3-1 through A3-5 show the time series for each variable at each station (where applicable) used in this study. Figure A3-1 shows SLP anomalies. Figure A3-2 shows sea level anomalies. Figure A3-4 shows fresh water discharge anomalies. Figure A3-5 shows SST and SOI anomalies.

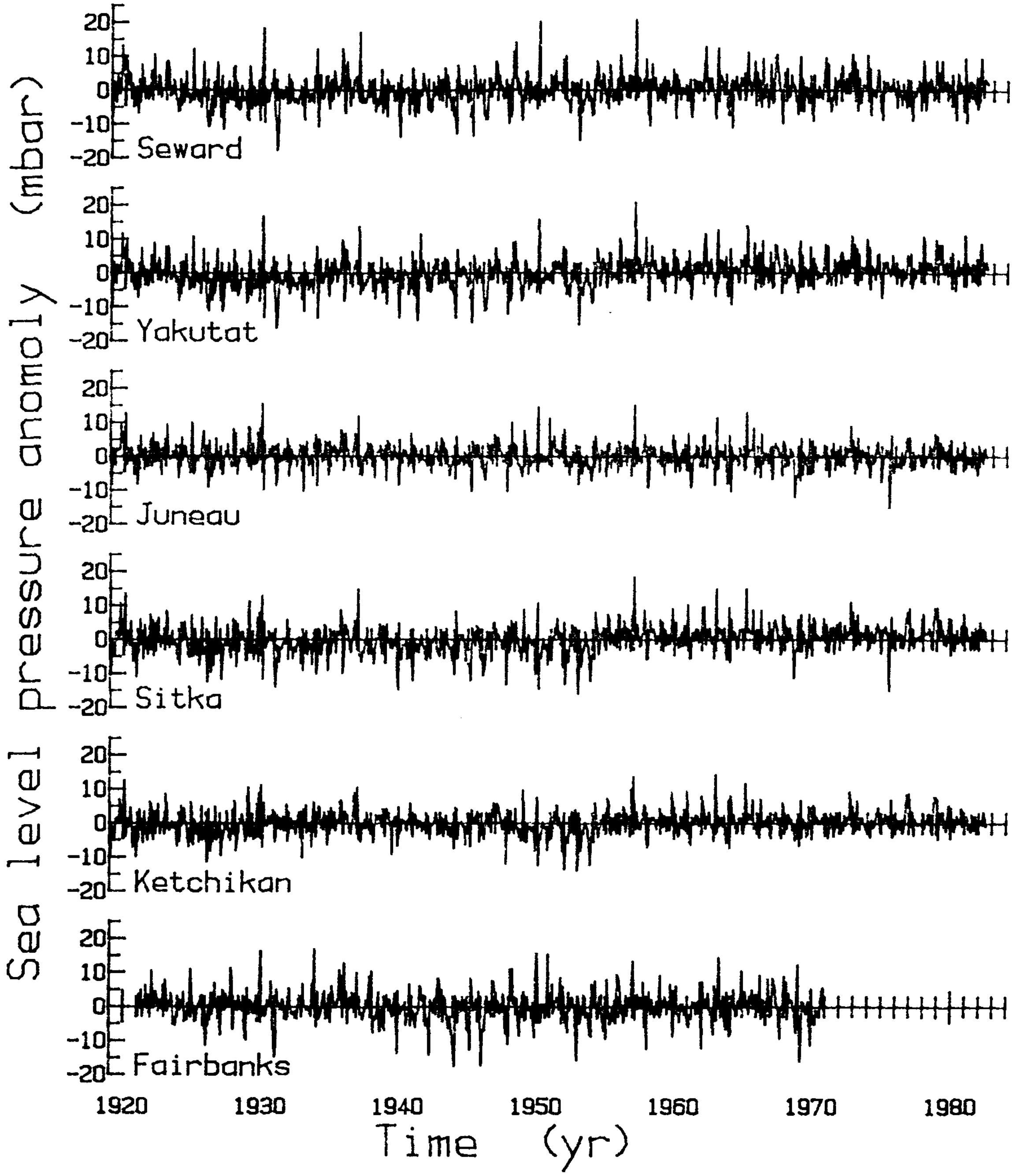

Figure A3-1. Sea level pressure anomalies for the 6 stations.

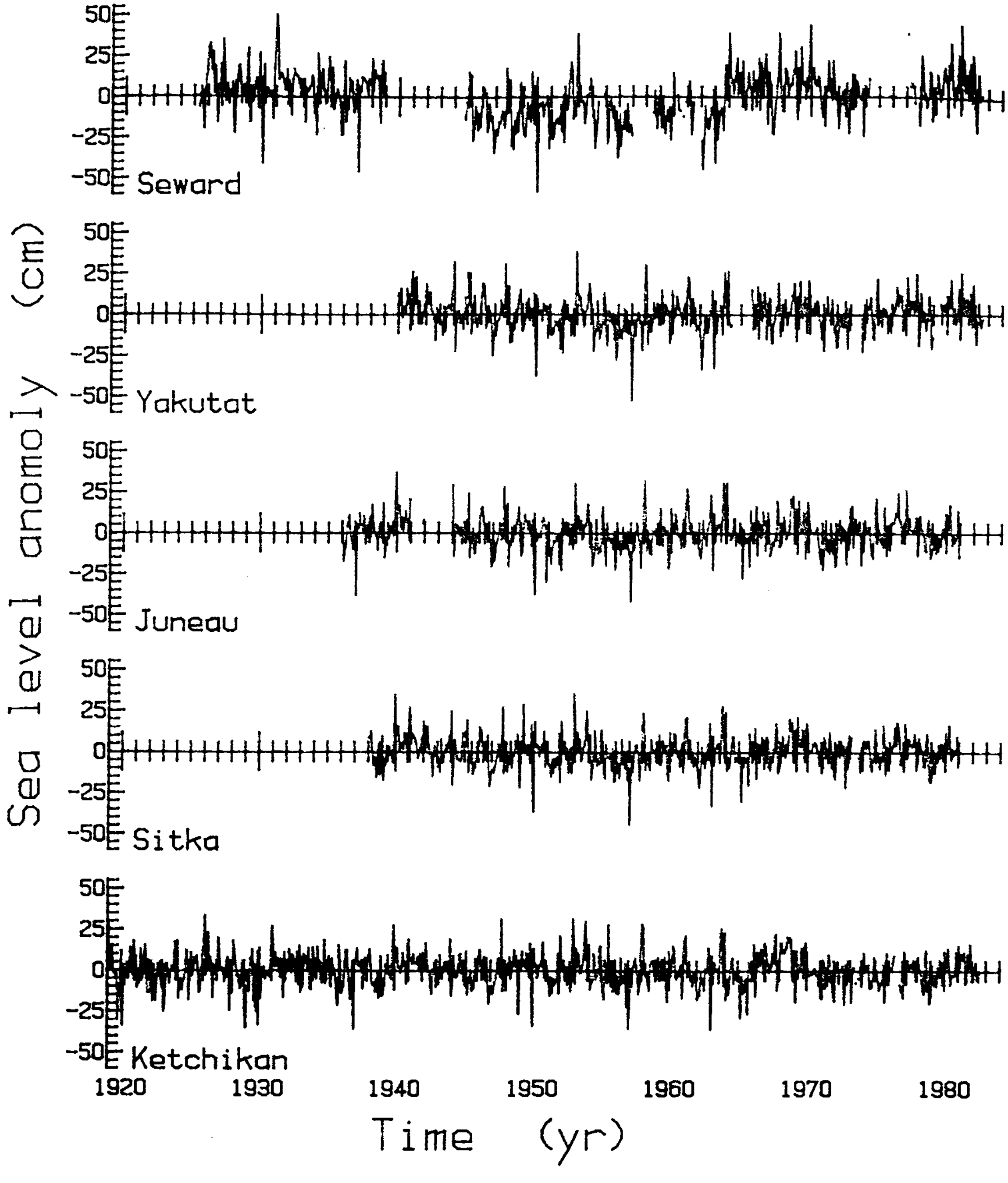

Figure A3-2. Sea level anomalies for the 5 coastal stations.

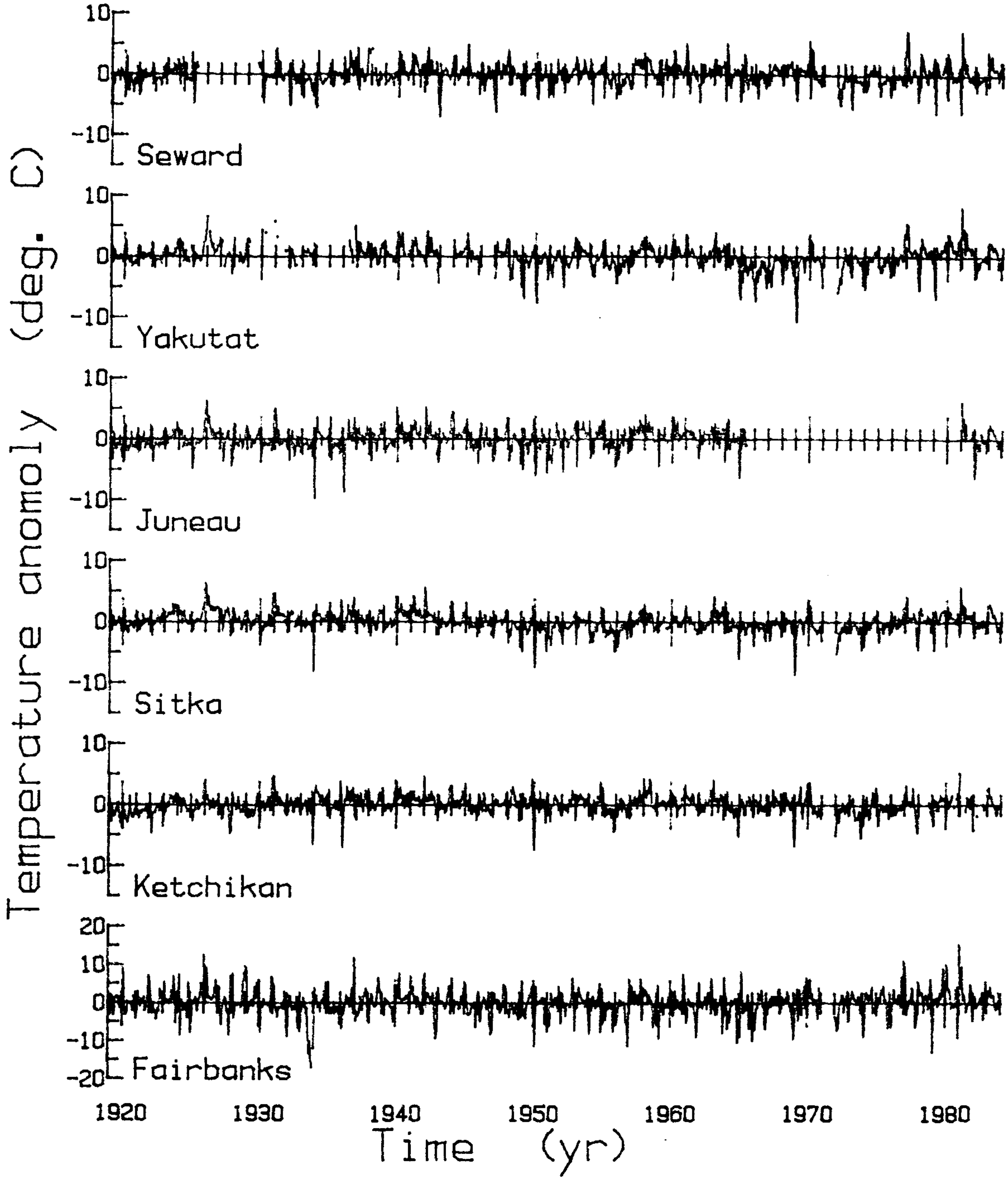

Figure A3-3. Temperature anomolies for the 6 stations in this study.

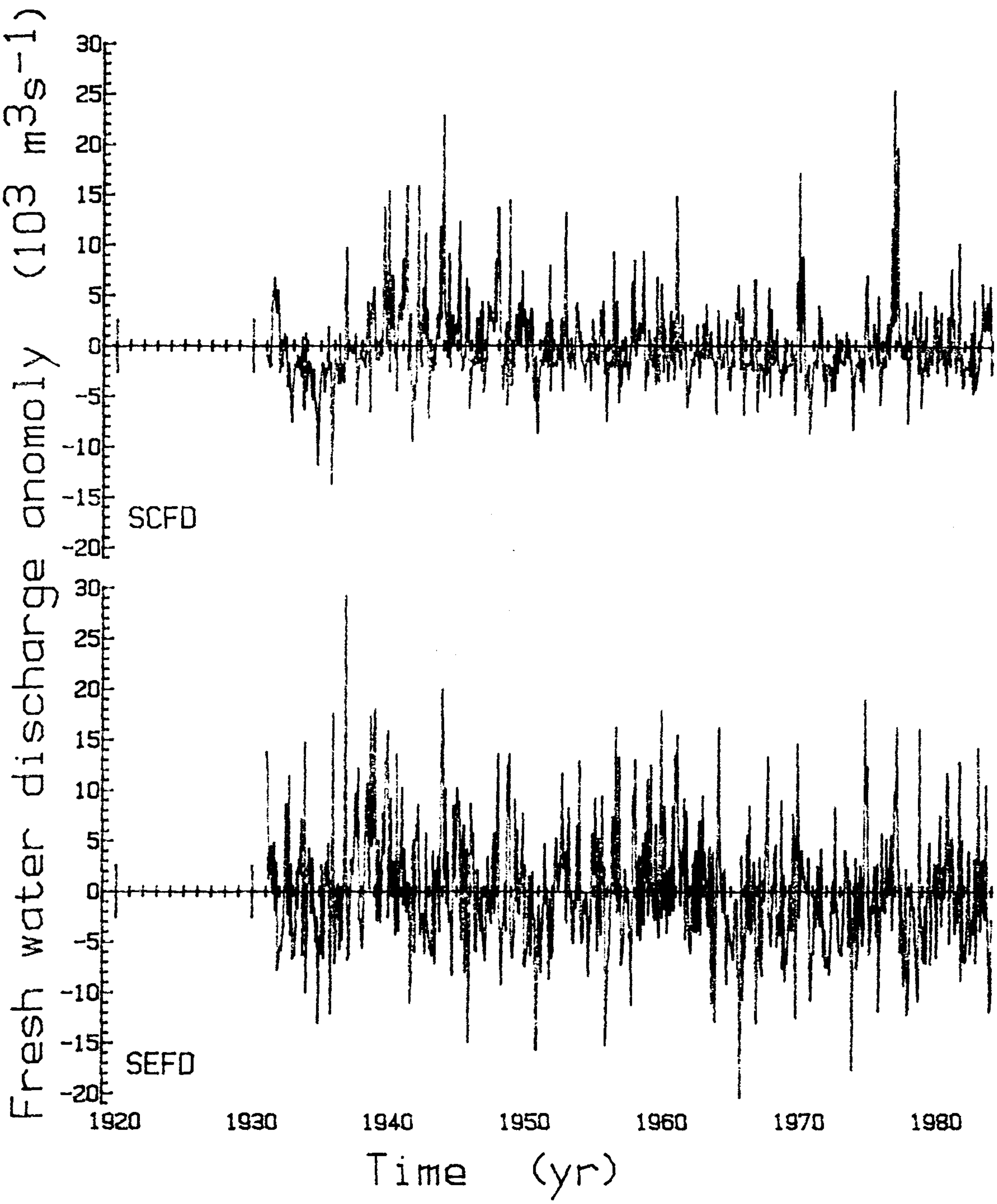

Figure A3-4. Fresh water discharge anomalies for the Southeast (SEFD) and Southcoast (SCFD) districts of Alaska.

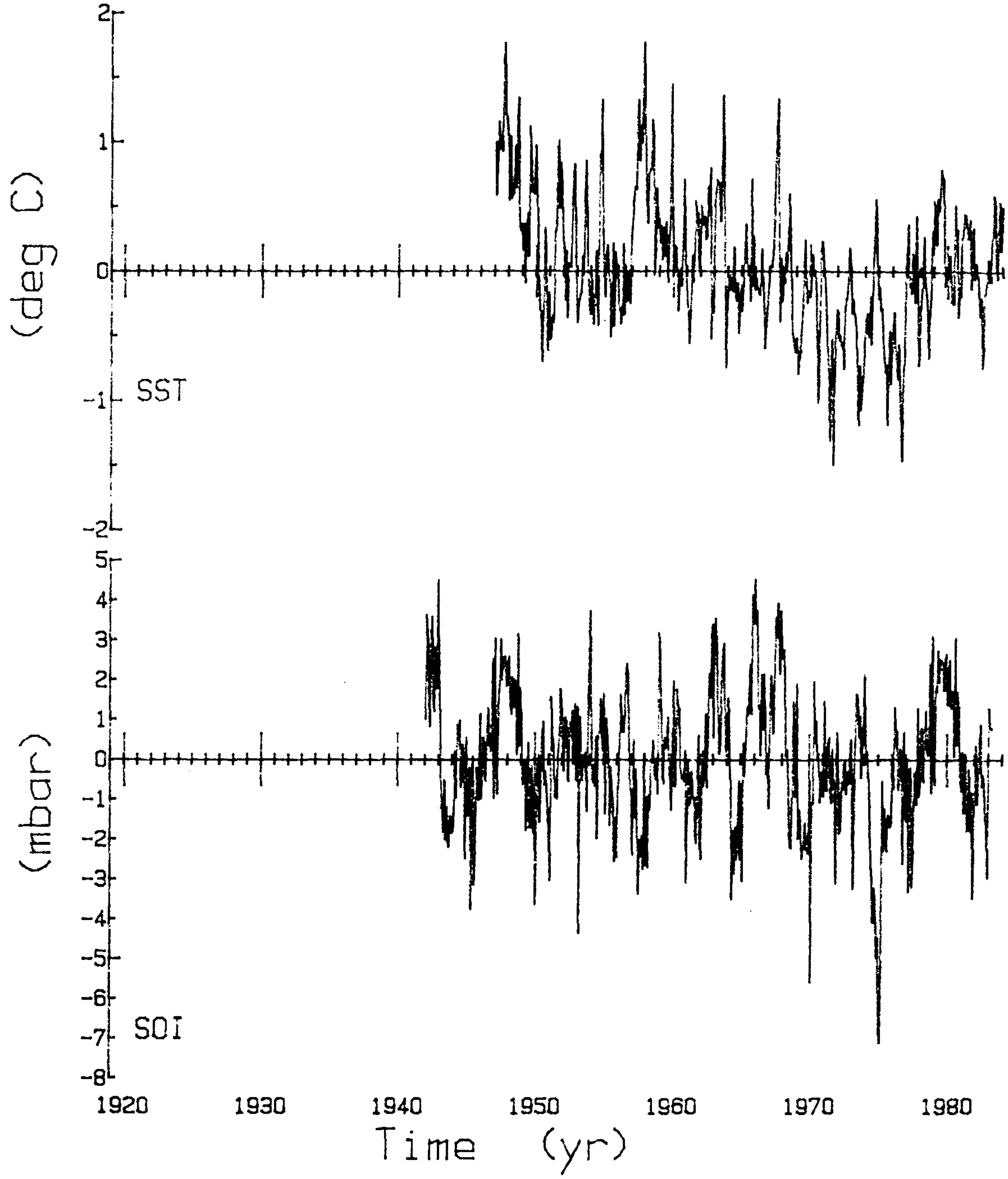

Figure A3-5. Anomolies of sea surface temperature (SST) for the northeast Pacific and the Southern Oscillation Index(SOI).

Appendix 4

Annual Cycles

Of the annual signals for SLP, sea level, air temperature and fresh water discharge, only the air temperature data show a smooth sinusoidal trend. The other variables show maxima and minima related to the statistical character of the variables. These cycles are depicted in Figures A4-1 through A4-2 at the end of this appendix.

A. Sea Level Pressure

The annual signal for SLP is higher in summer than in winter (Figure A4-1). The winter to summer increase, from February to July, is more gradual than the drop to winter conditions from July to October. The minimum in SLP occurs in October or November and is the result of a greater number of low pressure systems (storms) in the gulf.

As one might expect, the annual signal of SLP for Fairbanks is different from that of the coastal stations. The maximum in SLP occurs in January for Fairbanks as compared to July for the coastal stations, and the range of SLP is smaller in Fairbanks than at the coastal stations. This latter difference was expected because Fairbanks is located in the interior of Alaska, away from the storms in the gulf.

B. Sea Level

Sea level has an annual signal that is approximately inverse to that of SLP in the Gulf of Alaska (Figure A4-2). The minimum of sea level occurs in July, and the maxima occur from October through December. High rates of precipitation and low pressure systems also occur in October, thus I would expect the sea level to be higher during this month due to the increased wind stress and fresh water input. The increase in the October "peak" in sea level from Ketchikan around the Gulf of Alaska to Seward is probably due in part to the increasing fresh water effect downstream.

C. Air Temperature

For each station, the annual signal of air temperature is a smooth sinusoid with mean temperature inversely related to latitude (Figure A4-3). At the coastal stations, the annual cycle is out of phase with the annual insolation cycle by approximately one month. However, at Fairbanks the annual signal is in phase with insolation. The phase difference between the coastal and inland stations is probably due to the influence of oceanic heat storage. The oceans have larger heat capacities and greater thermal inertia than the continents. Even after the annual insolation minimum, the ocean continues to radiate heat gained during the summer to the atmosphere, so the coastal air temperature minimum occurs after the continental minimum. Likewise, the heat gained during the insolation maximum is not radiated to the atmosphere until after the summer solistice has passed. On a smaller scale (days rather than months), the phase relation is probably influenced by the moisture content of the air. Because Fairbanks is normally an arid locale, the near-surface air gains and looses heat readily. With more humid air masses, such as at the coastal stations, the moisture content of the air results in cloudiness which increases the albedo and decreases the amount of absorbed solar radiation, which causes the phase lag (Robuck, 1984).

D. Fresh Water Discharge

The annual signal of fresh water discharge for both the Southeast and Southcoast districts of Alaska peaks in September or October and has a minimum between January and March (Royer, 1982) (Figure A4-4). The minimum occurs at the same time of year as oceanographic winter. An April-May submaximum is caused by the onset of spring runoff. The increasing amounts of meltwater and precipitation through the summer months causes the discharge to increase to the October maximum. The spring submaximum in Southeast precedes that along the Southcoast by approximately 1 month while the maximum lags by 1 month. Also, the mean monthly discharge values for Southeast are greater than those for Southcoast. This is due to the greater amount of precipitation and larger drainage area in Southeast Alaska.

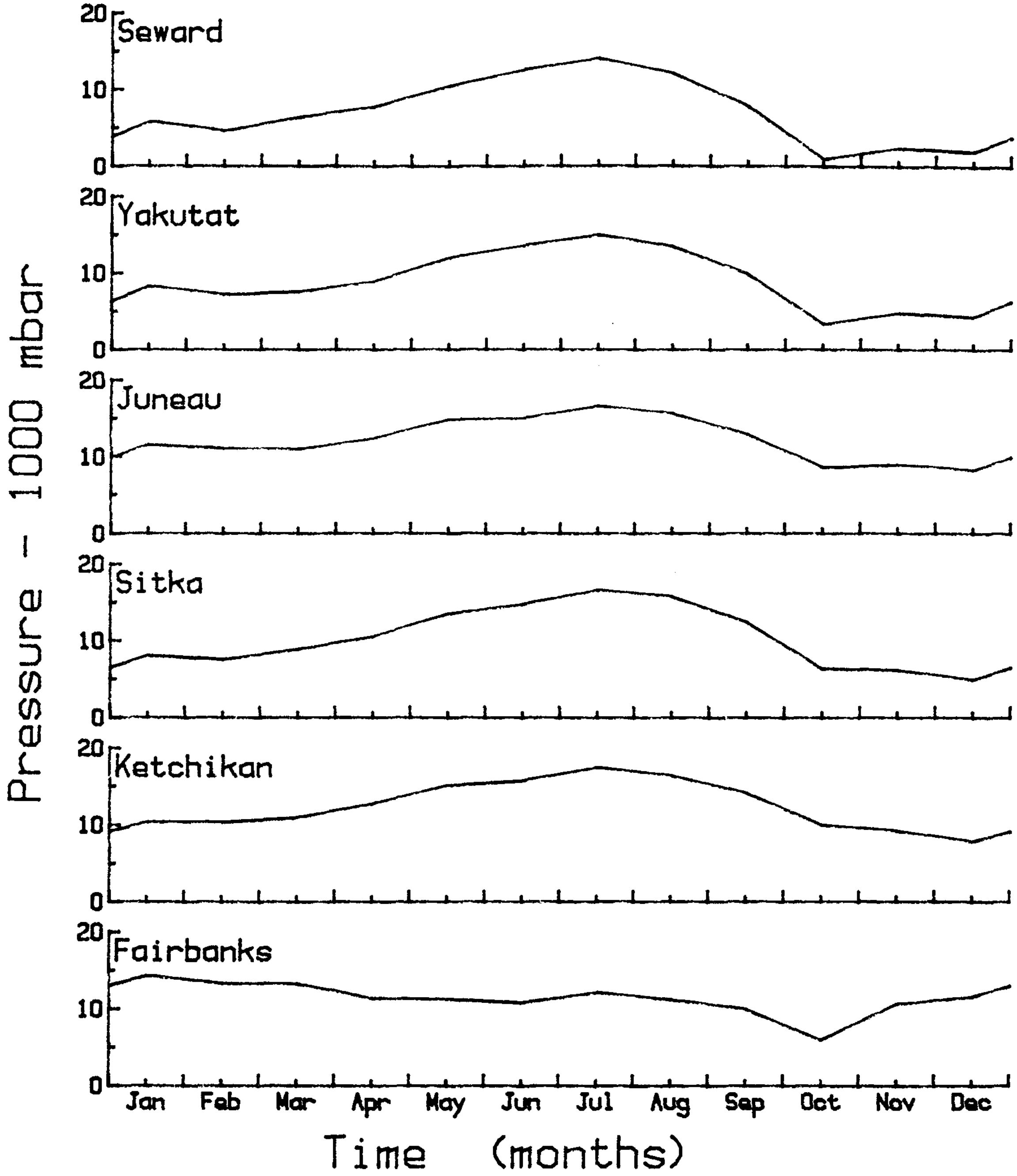

Figure A4-1. The annual cycle of sea level pressure for the 6 stations.

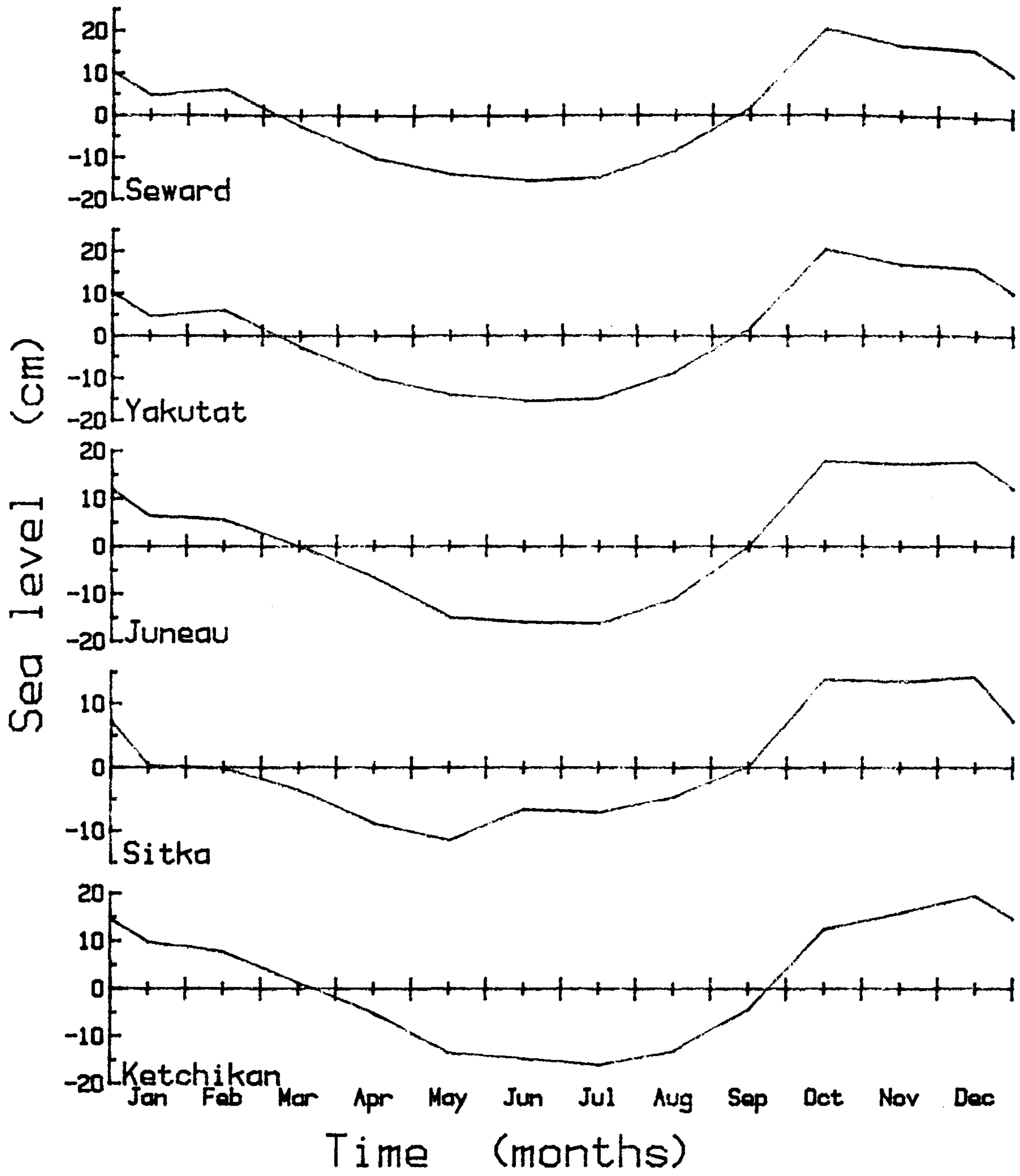

Figure A4-2. The annual cycle of sea level for the 5 coastal stations.

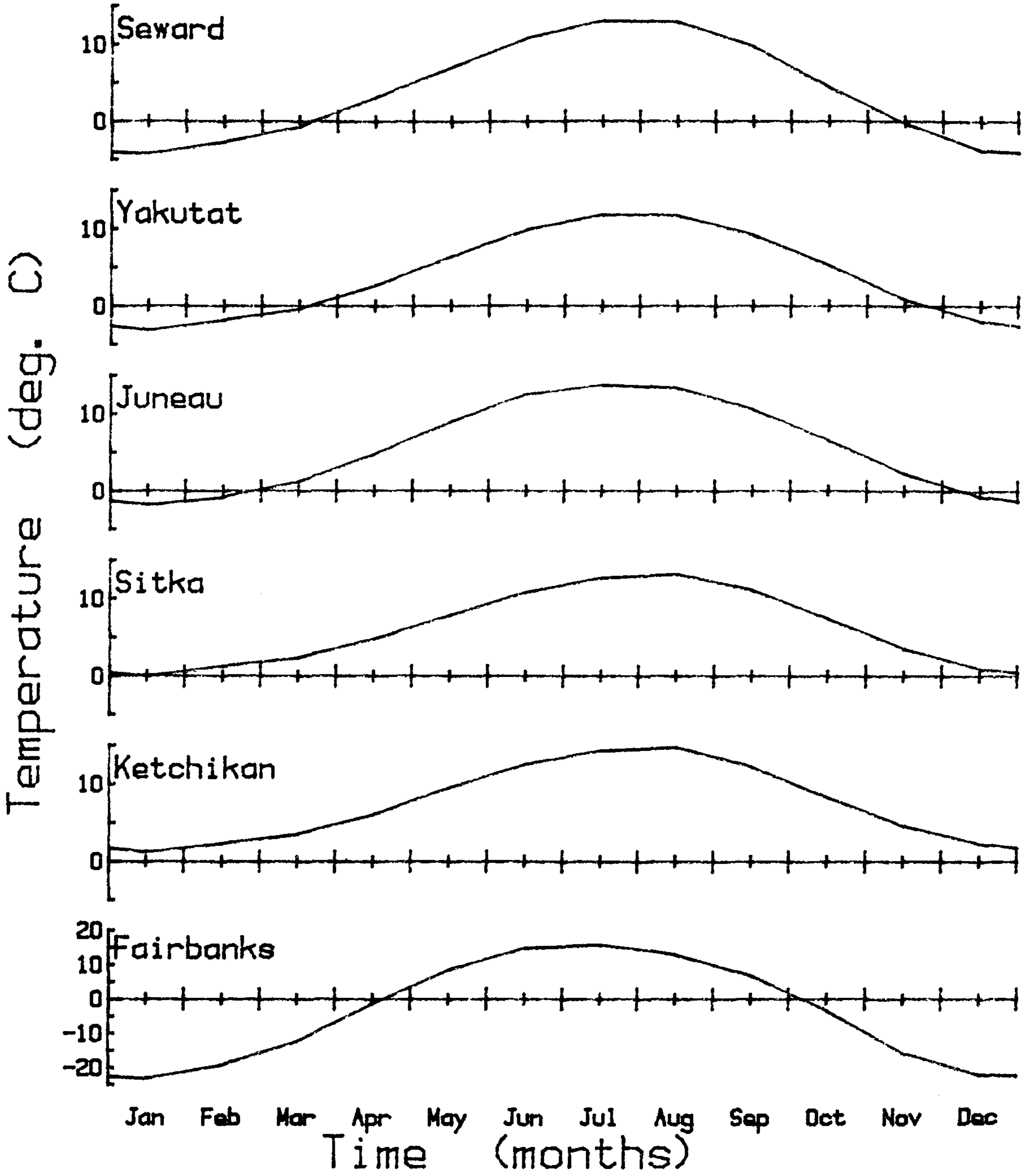

Figure A4-3. The annual cycle of temperature for the 6 stations.

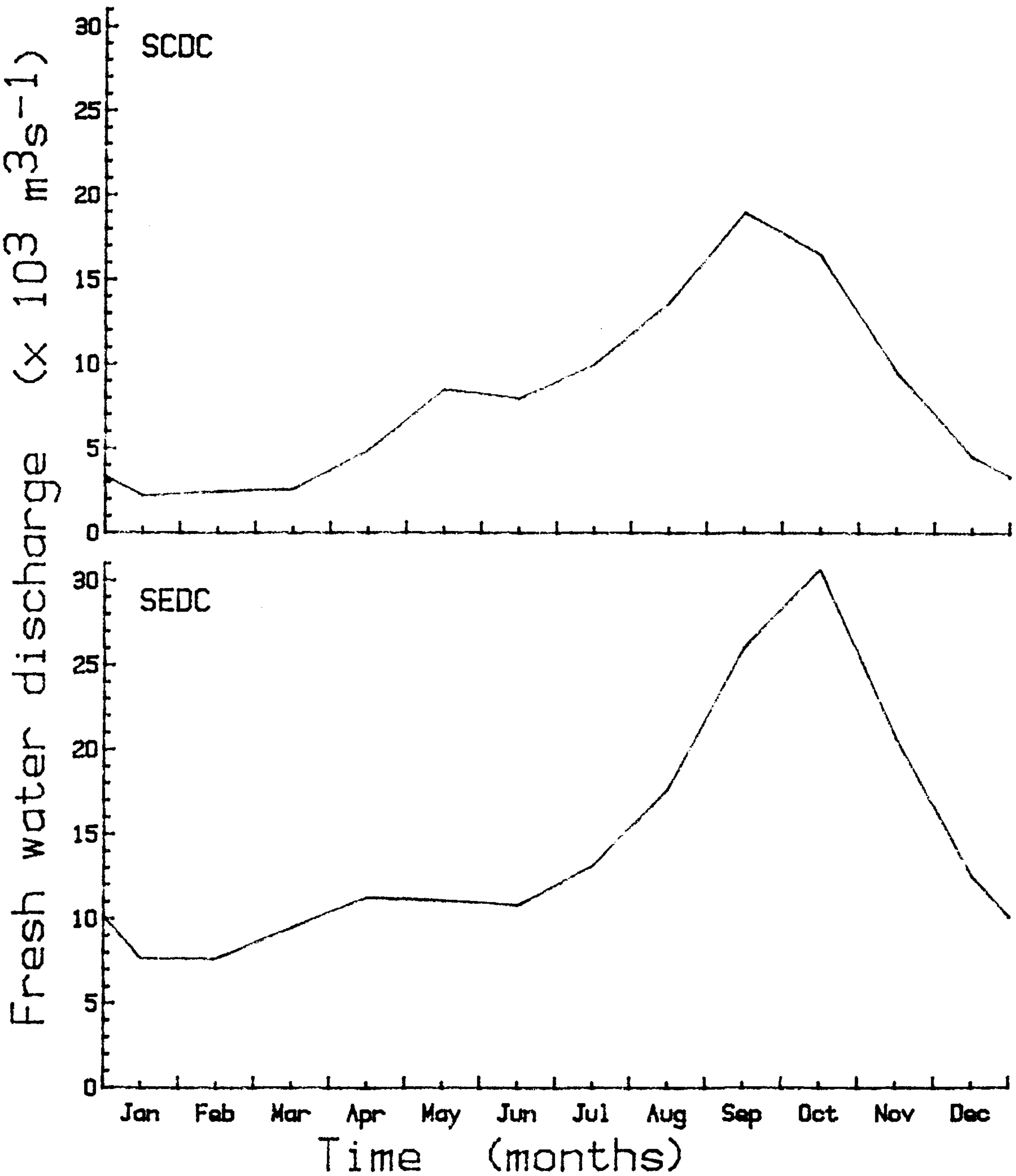

Figure A4-4. The annual cycles of fresh water input for Southeast (SEFD) and Southcoast (SCFD) Alaska.