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## ABSTRACT

Daily sea surface temperature and salinity observations have been made at numerous locations along the B.C. coast for varying lengths of time. This report examines 35 years of data collected from 3 of these light stations at Langara Island, Kains Island and Amphitrite Point. Its primary purpose is to develop techniques which could be applied to the analysis of the data from the other light stations. The interdependencies of temperature, salinity and local rainfall data are examined as well as the relationships between data from separate stations. Techniques applied are simple annual and monthly averaging procedures and the relatively modern technique of spectral analysis.

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# TABLE OF CONTENTS

TABLE OF CONTENTS, CONTINUED

## PREFACE

This report represents the first stage of a critical analysis of the lighthouse salinity and temperature data collection programme. Daily observations of temperature and salinity have been collected at various lighthouse stations along the British Columbia coast for over forty years. The quality of data has changed considerably with perhaps the most significant alteration resulting from the switch to hydrometer determination of salinity in 1969. Nevertheless, the length of the data records permits some interesting analyses using modern spectral techniques and in this first report some of these are developed and applied to three time series obtained at relatively exposed stations on Vancouver Island and the Queen Charlotte Islands.

The intention of this report therefore is to present certain interesting features of the data together with an account of the techniques used in the presentation. This will serve both as a guide to future analysis of lighthouse station data and as an indication of the type of information that may be derived in this way. We hope eventually to be able to extend this form of analysis and presentation to data derived from the remaining stations.

Our final goal will be to carry out a careful analysis of the relative importance of each station in providing new information, not available from data collected at other stations and also to determine the significance to the data quality of changes in observational technique. We shall then be in a position to rationalise the data collection programme and ensure that the particular needs of users are met in the most economical and effective manner.

# I. INTRODUCTION

Daily sea surface temperature and salinity observations have been made at numerous locations along the British Columbia coast for varying lengths of time. Most of the stations are at Ministry of Transport lighthouses where the lightkeepers voluntarily collect the observations. The daily oceanographic data to 1970 have been published in 30 annual record volumes (listed under Data Records) and the results summarized in Pacific Marine Science Report 72-13 (Hollister and Sandnes, 1972).

The purpose of this report is primarily to develop techniques for presentation of certain important features of the data. The report attempts to present an account of long and short term variations, the relationships between their variations and possible relationships between the data of different stations. Initially it was decided to concentrate the analysis on 3 light stations on the outer coast of British Columbia at Langara Island, Kains Island and Amphitrite Point. For Langara Island and Kains Island daily precipitation records exist for most of the period of temperature and salinity observations whereas for Amphitrite Point they exist for 10 years of that period. A detailed analysis of the relationship of daily precipitation to salinities is carried out to determine possible causes of salinity variation.

As each data series consists of approximately 35 years of daily samples it was considered that the analysis should be split into a low frequency section and a high frequency section. The low frequency analysis examines variations of period 1 year or longer such as long term trends. The high frequency analysis is dealt with statistically using the technique of spectral analysis. Using this technique variations of period down to 2 days are examined. Other aspects of the data such as mean seasonal variations are looked at using monthly averaging procedures.

Each of the stations, Langara Island, Kains Island and Amphitrite Point, commenced observations within a year or two of 1935. Observations have been made more or less continuously on a daily basis up to the present. Over the years temperatures have been measured with various types of thermometers with accuracy 0.5°F (0.3°C) or better. Salinities were determined in the laboratory on samples collected in the field by a modified Mohr titration until 1959 then by a conductive salinometer. Towards the end of 1969 collection of salinity samples was replaced by measurement of salinity by hydrometers. The estimated accuracy of the salinity determination fell from better than 0.06 PPT for the titration and salinometer methods to 0.3 PPT for the hydrometer. Because of the reduced accuracy of the salinity data after 1969 the data considered in this report runs to the end of 1969.

NOTE: Throughout this report PPT means Parts Per Thousand.

## II. DATA SOURCES

### A. Stations

The locations of the 3 light stations Langara Island, Kains Island, and Amphitrite Point are shown in Figure 1. Daily precipitations are observed at the Langara Island and Amphitrite Point light stations whereas the closest precipitation measurements to Kains Island are made 20 miles to the east at Quatsino situated on the north side of Quatsino Inlet. The station locations and the data record lengths for precipitation, temperature, and salinity observations are tabulated below:

TABLE I

Summary of Station Locations

| Station | Observed Parameters | Latitude N | Longitude W | Data Duration |
|---|---|---|---|---|
| Langara Is. | T, S | 54° 15' | 133° 03' | Nov. 1936-Aug. 1937<br>March 1940-present |
| " " | R | " | " | July 1936-present |
| Kains Is. | T, S | 50° 27' | 128° 02' | Jan. 1935-present |
| Quatsino | R | 50° 32' | 127° 37' | June 1895-present |
| Amphritrite Pt. | T, S | 48° 55' | 125° 32' | Sept. 1934-present |
| " " | R | " | " | Jan. 1958-present |

T - Temperature
S - Salinity
R - rainfall

### B. Procedures and Equipment

#### 1. Temperature and Salinity Data

The observational procedures are summarized from descriptions given in Pacific Marine Science Report 72-13 (Hollister and Sandnes, 1972). The daily observation is made within 1 hour before the time of high tide, light schedules and other duties permitting. From 1934 the standard procedure included the collection of a sea water sample in a glass bottle and a temperature measurement both taken from a depth of 3 feet below the surface. In 1961 the style of sample bottle changed when a new plastic lined screw cap was introduced to replace the original waxed cork method of sealing. Tests on the new bottles showed salinity increases of up to 0.02 PPT for sea water samples stored over a period of 180 days.

The salinities prior to 1959 were measured using a modified Mohr titration method with an estimated accuracy of 0.06 PPT. Early in 1959 conductive salinometers were used for this purpose, a method which has an estimated accuracy of 0.03 PPT. From late 1969 salinity determinations have been done using a hydrometer in a 25 oz. water sample. An accuracy of 0.3 PPT is estimated for salinities collected by this method.

Temperature has been measured by a thermometer mounted inside a protective case on the end of a sampling rod. During the period since 1935 a number of varieties of thermometer have been used to measure the sea water temperature. Indications are that the earliest thermometers were of the mercury filled type which had an estimated accuracy of something like 0.5°F. (0.3°C). A red liquid filled thermometer reading Fahrenheit degrees with an estimated accuracy of 0.5°F (0.3°C) was in use between 1937 and 1939. This was replaced by a Celsius reading mercury thermometer which in turn was replaced in mid 1949 by a similar type with a Fahrenheit scale. Both thermometers in use after 1939 were compared with a laboratory thermometer and had a maximum allowable scale error of 0.3°F (0.2°C).

The daily temperature and salinity observations used in this study were taken from a magnetic tape supplied by the Marine Environmental Data Service of Environment Canada. Data was available for 17 light stations starting in 1914 and continuing until the end of 1973. Because temperature was written on the tape as degrees Fahrenheit and salinity as parts per thousand (PPT) these will be the units used in this report. The corresponding Celsius temperature is included also in brackets.

2. Rainfall Data

Daily rainfall data was made available for the 3 stations on a magnetic tape supplied by the Climatology Division of the Meteorological Branch of the Department of Transport. This data is the estimated rainfall in inches for consecutive 24 hour climatological days. The commencement time of the climatological day has been changed in the period since 1935. From January 1, 1933 to December 31, 1940 precipitation was measured at 0630 Local Standard Time (LST) on the day following the calendar day to which the precipitation was accredited. In the period January 1, 1941 to December 31, 1954 this measurement time was changed to 0730 Eastern Standard Time, that is to 0430 LST on the B.C. coast. On June 1, 1957 the observation time was advanced 1/2 hour to 0400 LST. From July 1, 1961 to the present the climatological day begins at 0600 GMT or at 2200 LST on the previous evening.

C. Summary of Available Data

The bar graphs shown in Figure 2 illustrate the essential features of data availability for rainfall, temperature and salinity at each station. Also indicated are the periods for which different measurement techniques apply.

Temperature and salinity have been measured continuously at Kains Island and Amphitrite Point at least from January 1, 1935 to the present whereas this continuous data is only available at Langara Island from mid 1940 to the present. It was therefore decided that January 1, 1935 would make a convenient starting point for the analysis. After the introduction of hydrometers for salinity determinations in late 1969 the accuracy of the salinity measurement would be expected to be an order of magnitude less than before so that some time near the end of 1969 would be a desirable termination point for the analysis. For reasons which will be discussed the spectral analysis was carried out on 5 data blocks of 2560 days each which makes the analyzed section of data a total of 12800 days long. Thus the actual date for the termination of analysis is January 16, 1970.

# III. DATA ANALYSIS

## A. Data Preparation

As the temperature and salinity data were available from a source separate from the rainfall data the initial preparation of the 2 types of data was carried out differently. A block diagram of the data analysis scheme is seen in Figure 3.

### 1. Temperature and Salinity Data

Each record on the magnetic tape supplied by the Marine Environmental Data Service contained a daily temperature value and a daily salinity value. Hence, as far as the analysis procedures go temperatures and salinities are considered identically.

For all 3 stations there was a proportion of the data missing for one reason or another. The occurrence of missing data appeared to be random and varied in length from 1 day at a time to almost half a year of consecutive days on one occasion at Amphitrite Point. These missing data were merely filled in by a linear interpolation between the end points of the data gap. Also, the data were checked for any spikes. These were replaced by the arithmetic average of the 2 data points on either side of the spike. A single point was considered a spike if its value was more than 5.0°F (2.8°C) for temperature or 5.0 PPT for salinity different from the data points on either side of it. On examination of the data it was decided that any differences larger than 5.0 were probably due to error. Because of the large amount of missing data up to mid 1940 for Langara Island it was decided to omit analysis on the first block of data and to analyze the last 4 blocks of data only. The amounts of data either missing or occurring as spikes are given in the following table for the sections of data analyzed.

TABLE II

Summary of Data Either Missing or Occurring as Spikes

| Station | Total Points | T missing | S missing | T spike | S spike |
|---|---|---|---|---|---|
| Kains Island | 12800 | 338 | 432 | 6 | 7 |
| Amphitrite Pt. | 12800 | 926 | 1082 | 3 | 89 |
| Langara Is. | 10240 | 1375 | 1478 | 5 | 4 |

Kains Island appears to have the cleanest record with less than 4% of its data having to be filled in. Langara Island is the worst station whereas Amphitrite Point lies between it and Kains Island. The 13% of temperature data and 14% of salinity data missing for Langara Island would be expected to result in similar percentage losses in the variance at high frequencies. As the longest data stretch missing for Langara Island is 105 consecutive days variations of period greater than about 1/3 of a year should be very little affected by missing data. Kains Island and Amphitrite Pointe will suffer smaller percentage losses in high frequency variance than will Langara Island, but the half year missing for Amphitrite Point will affect variances up to about that period to a certain extent.

2. Rainfall Data

The rainfall data supplied from magnetic tape had to be edited before it was analyzed. Each rainfall record was supplied with its date, which was checked to ensure that the records were exactly sequential. The only piece of missing data found in this fashion was an entire September in the data for Langara Island. Since September has a relatively low rainfall anyway it was felt that the replacement of that month's data by zeros should have little effect. Next, all rainfall data which was either trace or unknown was replaced by zero as were any data which had a precipitation magnitude greater than 10 inches for the day. Only over a period of several years in the data series for Langara Island did a few values over 10 inches appear. These values were so high they were obviously incorrect.

## B. Analysis Method

Once the initial data preparation had been accomplished temperature, salinity and rainfall were analyzed in fairly parallel fashion. In order to examine different time scales the data analysis was divided into 3 sections; low frequency analysis, spectral analysis and an analysis of seasonal variations.

### 1. Low Frequency Analysis

The low frequency analysis is concerned with trends and variations of time scales greater than 1 year. To examine these scales the data for a given parameter at a given station have simply been averaged over a year and these yearly averages then plotted.

### 2. Spectral Analysis

The spectral analysis is carried out on a block size of 7 years with a sampling frequency of 1 value per day. Using such a sampling procedure the technique is capable of examining variations of period 7 years down to the Nyquist period of 2 days. Not much reliance can be placed on the lower frequency harmonics so that the results will be interpreted primarily for periods of 1 year and less. The computation of the spectra involves several steps. In order to reduce the leakage of energy from the harmonic of period 1 year into neighbouring harmonics the data are first passed through filters before they are Fourier transformed. The Fourier coefficients are then combined and averaged over bandwidth and over blocks to produce smoothed power spectra, coherences and phases.

#### a) Choice of Block Size

An inevitable consequence of the spectral analysis procedure is that energy present at a frequency not equal to a harmonic frequency will contribute to the computed energy at all the other harmonics. A visual examination of the time series for temperature, salinity and rainfall indicates that most of the energy generally lies in the variation of period 1 year. To minimize the energy leaking from the annual variation into the other harmonics it was necessary to construct the block size such that one of its harmonics would have a period as close as possible to 1 year. This can be accomplished by choosing a block size close to an integral number of years in length. Also, the Fast Fourier Transform used to compute the Fourier coefficients operates much more efficiently if the number of points in the block is factorable into small prime numbers. Based on the preceding considerations a block size of 2560 days was chosen. For the complete 35 years of data it was thus possible to analyze 5 blocks of duration 7 years 3 days each. Furthermore 2560 can be factored into small prime numbers as $2560 = 5 \times 2^9$.

b) Spectral Filters

A preliminary spectral analysis of the temperature and salinity data indicated that the energy density at period 1 year was about 100 times that at higher frequencies. To minimize the effects of energy leakage from this harmonic, the data were run through digital filters in order to reduce the yearly energy before the Fourier transform. The low frequency Fourier coefficients were computed from data which had been passed through a low pass filter whereas those for frequencies above the annual frequency were computed from high pass filtered data.

The low pass digital filter consisted of a moving "box car" average of length 300 days. In constructing the filter a problem arose because the first and last averages ran off the ends of the data block. This problem was circumvented by taking a section from the end of the data block and fastening it to the beginning and vice versa. The transplanted sections were then matched to the ends of the data by adding a DC level to ensure there were no sudden jumps in the augmented record. In general a moving average of length $\Delta$ is easily shown to cause energy density at frequency f to be attenuated by the factor G(f).

$$G(f) = \left[\frac{\sin(\pi f \Delta)}{\pi f \Delta}\right]^2$$

A filter length of 300 days was chosen so that this gain factor would be approximately $10^{-2}$ for the yearly harmonic.

Data with the low frequency components removed can be constructed by subtracting the signal passed by a low pass filter from the original data. The data used in the high frequency analysis was synthesized by first filtering the data by a moving box car average of length 75 days followed by subtraction from the original time series. This filter, which has a gain factor of:

$$G(f) = \left[ 1 - \frac{\sin(\pi f \Delta)}{\pi f \Delta} \right]^2$$

results in an attenuation of $10^{-2}$ at the yearly harmonic. The gain functions of both the high and low pass filters used prior to the Fourier transform are plotted in Figure 4.

c) Fast Fourier Transform

Fourier coefficients were computed from each block for both the high frequency and low frequency data using a Fast Fourier Transform (FFT) subroutine compiled by P. Chang of the Institute of Oceanography at the University of British Columbia. This subroutine is based on an algorithm by R.C. Singleton (1969). The FFT computes coefficients which satisfy the relation:

$$x(t_i) = A_o + \sum_{n=1}^{N/2} A_n \cos 2\pi f_n t_i + \sum_{n=1}^{N/2} B_n \sin 2\pi f_n t_i$$

where:

$x(t_i)$ is the value of the data point at time $t_i$

$A_n$, $B_n$ are the n'th cosine and sine coefficients respectively.

N is the number of points in the data record.

$f_n$ is the positive n'th frequency harmonic.

If T is the time duration of the data record then $f_n = \frac{n}{T}$

The cosine and sine coefficients are computed by the FFT as:

$$A_n = \frac{2}{N} \sum_{i=1}^{N/2} x(t_i) \cos 2\pi f_n t_i$$

and

$$B_n = \frac{2}{N} \sum_{i=1}^{N/2} x(t_i) \sin 2\pi f_n t_i$$

d) Spectra, Coherences and Phases

From the Fourier coefficients power spectra, coherences and phases were computed. One can contruct a power spectrum by considering the energy in the n'th harmonic of a Fourier series which is $\frac{A_n^2 + B_n^2}{2}$ to be made up primarily of energy contributions in the frequency band $f_n - \frac{1}{2T}$ to $f_n + \frac{1}{2T}$. Since each harmonic has a bandwidth $\frac{1}{T}$ the energy per unit bandwidth or equivalently the power at frequency $f_n$ is given by:

$$P(f_n) = \frac{T}{2} (A_n^2 + B_n^2)$$

The cospectrum between 2 data series is a measure of their 'in phase' power. The cospectrum at a particular frequency $f_n$ can be constructed from the Fourier coefficients of the 2 series. Let the coefficients from the first series be unprimed and those of the second be primed then the cospectrum is defined as:

$$C(f_n) = \frac{T}{2} (A_n A_n' + B_n B_n')$$

Likewise a measure of the '90° out of phase' power is the quadrature spectrum given as:

$$Q(f_n) = \frac{T}{2} (A_n' B_n - A_n B_n')$$

In order to obtain reliable spectra it is usually recommended that spectral estimates be averaged in some fashion. In this study the spectra are 'smoothed' in 2 ways. First, the individual spectral estimates were averaged over frequency bands of width $\delta f$ such that $\frac{\delta f}{f_c} = 0.1$, $f_c$ being the center frequency in the band. The band averaged power spectrum is thus:

$$\overline{P(f_c)} = \frac{1}{m} \sum_{n=c-m/2}^{c+m/2} P(f_n)$$

where m is the number of harmonics in the band. The first 6 harmonics (after 0) were too far apart to be averaged with this bandwidth.

The smoothed spectra for each block were then averaged over the number of blocks B to produce a doubly smoothed spectrum.

$$\overline{\overline{P(f_c)}} = \frac{1}{B} \sum_{B} \overline{P(f_c)} \qquad 1)$$

The double smoothing of co- and quad- spectral estimates was carried out in analagous fashion. The smoothed co-, quad- and power spectra can be combined to compute a coherence spectrum. This coherence is just a measure of the proportion of power coherent between 2 data series. At frequency $f_c$ it is defined as:

$$K(f_c) = \left[ \frac{\overline{\overline{C(f_c)}}^{\,2} + \overline{\overline{Q(f_c)}}^{\,2}}{\overline{\overline{P(f_c)}} \cdot \overline{\overline{P'(f_c)}}} \right]^{\frac{1}{2}} \qquad 2)$$

The phase of the coherent power can also be computed:

$$\phi(f_c) = \tan^{-1} \left[ \overline{\overline{Q(f_c)}} / \overline{\overline{C(f_c)}} \right] \qquad 3)$$

A measure of the reliability of a smoothed spectral estimate can be obtained by computing its standard deviation. The standard deviation of the band averaged spectral estimates from their block averaged mean is thus:

$$\sigma(f_c) = \left[ \frac{\sum_{B} \bar{P}^2 - B\bar{\bar{P}}^2}{B - 1} \right]^{\frac{1}{2}} \qquad 4)$$

Each coherence, phase and power spectrum is actually a composite. Those spectral estimates of period 1 year or more were computed from the analysis of low frequency data whereas the higher frequency estimates were computed from data passed through the high pass filter. Before they were plotted all the spectral estimates and standard deviations were corrected for filter attenuation by multiplying them by the inverse of the filter gain functions.

e) Plotting of Spectra

The power spectra are plotted as log (f P(f)) vs. log f. By plotting frequency on a logarithmic scale the lower end of the frequency scale is suitably expanded to permit the observation of details in that part of the spectrum. Let $\delta E$ be the energy contained in the frequency band $\delta f$. The relationship of $\delta E$ and $\delta f$ to the power

P(f) is just:

$$\delta E \simeq P(f)\delta f$$

since: $$\delta(\log f) \simeq \frac{\delta f}{2.3f}$$

$$\delta f = 2.3f\ \delta(\log f)$$

and: $$\delta E \approx 2.3f\ P(f)\ \delta(\log f)$$

Thus f P(f) is proportional to the energy contribution in the logarithmic frequency band $\delta(\log f)$.

The vertical bars on each smoothed spectral estimate define the limits $\overline{\overline{P(f_c)}} \pm \sigma(f_c)$ where $\sigma(f_c)$ is the standard deviation of the block averages computed from 4).

Coherences and phases are both plotted on a linear scale versus log f. A problem arises in determining what are significant coherences. If one were to compute coherences using equation 2) between 2 noise sources the expected coherence will decrease as the amount of smoothing increases. In fact the coherence will be 1.0 if it is computed from unsmoothed co-, quad-, and power spectral values. Jenkins and Watts (1968) derive the expected coherence between 2 noise sources as $h^{-\frac{1}{2}}$ where h is the product of the number of blocks and the number of frequency harmonics averaged in each block for a given coherence calculation. The variance of smoothed coherence for noise is approximated by Jenkins and Watts (1968) as:

$$\sigma^2 = \frac{1}{2h}(1 - K^2)^2$$

from which one can compute the standard deviation of noise coherence as:

$$\sigma = \left(\frac{1}{2h}\right)^{\frac{1}{2}}\left(1 - \frac{1}{h}\right)$$

In Figure 5 are plotted expected noise coherences together with their standard deviations for analysis of 1, 4 and 5 blocks of data. The upper standard deviation will be regarded as a 'level of significance' for the actual coherence spectra. The level appropriate to this number of blocks analyzed is indicated on each plot.

3. Seasonal Variations

Examination of the data records indicated that many important features were dependent on the seasonal cycle. Details of these features were difficult to see using the spectral analysis technique which tends to average them out. In order to look at seasonal variations average monthly salinities, temperatures and rainfall are computed for the section of record for which spectral analysis was done. Two cycles of these monthly averages were plotted.

Also examined was the seasonal variability in the high frequency fluctuations of salinity and temperature. A high frequency temperature fluctuation, $T'$, was obtained by subtracting data passed through a 7 day moving block average filter from the original data. This high pass digital filter has a 50% power attenuation at a period of about 10 days. The attenuation factors of the filter are plotted in Figure 4. The standard deviation of the temperature fluctuations will be defined as:

$$\sigma_{T'} = \frac{1}{Y} \sum_{Y} \left( \frac{1}{D-1} \sum_{D} T'^2 \right)^{\frac{1}{2}}$$

where: Y is the number of years of analysis
D is the number of days in the particular month.

Salinity standard deviations are determined in analagous fashion. Also computed from the high frequency data are the monthly temperature, salinity correlations defined as:

$$\sigma_{TS} = \frac{1}{Y} \sum_{Y} \left( \frac{1}{D-1} \sum_{D} T' \cdot S' \right)$$

where $S'$ is the salinity fluctuation.

# IV. DISCUSSION OF RESULTS

## A. Low Frequency Analysis

Plots of the yearly averages of temperature, salinity, and rainfall are shown in Figure 6.

### 1. Temperature

The yearly temperatures are best correlated between Amphitrite Point and Kains Island. Over the 35 years of analysis Amphitrite Point had an average temperature of 50.48°F (10.27°C) versus an average of 50.25°F (10.14°C) at Kains Island. The shape of the trend and the magnitude of the yearly temperature fluctuations are similar at Langara Island, the most northern station, but its average temperature of 47.59°F (8.66°C) is some 2.5°F (1.4°C) lower. The order of magnitude of the yearly temperature fluctuations at all 3 stations is 1°F (0.6°C).

### 2. Salinity

Salinity variations at Kains Island and Amphitrite Point show a good similarity in shape but Kains Island is somewhat more saline having an average salinity of 30.32 PPT against Amphitrite's 29.72 PPT. The annual salinity variations of these 2 stations which are of order 0.5 PPT contrast with the much smoother salinity curve at Langara Island which has a yearly fluctuation of order 0.1 PPT. Also Langara Island has the highest average salinity of 32.13 PPT. This behaviour likely reflects the greater distance of Langara Island from large fresh water sources. A very striking feature of the salinity at all 3 stations is its downward trend. The reference slope on each graph represents a drop in salinity of 0.4 PPT in 35 years. The rate of decrease of salinity does not seem to be too different at any of the 3 stations so it would appear that it is a phenomenon characteristic of the entire coast. There is no obvious correlation between average salinities and average temperatures. The temperature shows no trend corresponding to the general decrease in salinity nor are temperature fluctuations reflected in salinity fluctuations.

### 3. Rainfall

Average annual precipitations vary wildly from year to year. Only 1 block of data is plotted for Amphitrite Point but presumably its rainfall pattern is similar to that at Kains Island in other years. However, Kains Island seems to have the highest rainfall of all 3. Variations in rainfall correlate to some extent with temperature fluctuations. The rainfall peaks in 1950 and 1955 and falls on the 2 periods of lowest temperature at all 3 stations. Furthermore, the year 1940 and the period 1958 to 1963, years of low rainfall, are also periods of relatively high temperature. Presumably the weather conditions which prevail during years of high rainfall cause a cooling of the sea surface. Rainfall and salinity seem to be little correlated. It is true that the high rainfall of 1950 coincides with the lowest salinities, but on the other hand the rainfall maximum of 1955 appears to be associated with a relatively high salinity. Furthermore, the period of low rainfall from 1958 to 1963 corresponds to a period of relatively low salinity.

B. Spectral Analysis Results

The following table is a summary of the number of blocks of data analyzed for each spectral analysis. A 'P' in brackets indicates a power spectrum was done whereas a 'C' indicates that coherence and phase were computed. The number of blocks analyzed, which was limited by the available data, is also indicated in each square. In the plots of phase to follow a positive angle will mean that the parameter defined along the top of the table below will lead that parameter defined along the side.

TABLE III

Summary of Spectral Analysis Results

| | | Kains Island | | | Amphitrite Point | | | Langara Island | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | T | S | R | T | S | R | T | S | R |
| Kains Island | T | 5(P) | 5(C) | | 5(C) | | | 4(C) | | |
| | S | | 5(P) | | | 5(C) | | | 4(C) | |
| | R | | 5(C) | 5(P) | | | | | | |
| Amphitrite Point | T | | | | 5(P) | 5(C) | | | | |
| | S | | | | | 5(P) | | | | |
| | R | | | | | 1(P) | 1(P) | | | |
| Langara Island | T | | | | | | | 4(P) | 4(C) | |
| | S | | | | | | | | 4(P) | |
| | R | | | | | | | | 4(c) | 4(P) |

1. Temperature

a) Power Spectra

In Figure 7 are shown the temperature power spectra and standard deviations for Kains Island. Also plotted are the temperature power spectra for Amphitrite Point and Langara Island. All 3 spectra appear to be qualitatively and quantitatively similar. The most predominant feature is the annual temperature peak which rises 2 decades above the rest of the spectrum. This peak, representing the seasonal heating and cooling of the sea surface, contains about 90% of the total energy in the spectrum. At periods greater than 1 year frequency•power is roughly proportional to frequency, that is the power is approximately constant. For periods greater than a year the spectral estimates should be less certain. The power is approximately proportional to the inverse of frequency for periods between 1 year and 14 days. However, at the frequencies of the second and third harmonics of the annual frequency the power is somewhat lifted above the general level. Also at a period of 2 weeks the power is higher than in neighbouring estimates. This is likely due to the fact that the sample was collected near high tide every day. As the cycle of the tides progressed so would the time of day at which the observations were made. Thus any diurnal effects such as solar heating or movements of water bodies in response to diurnal winds would appear in the data at tidally related frequencies. At periods shorter than 2 weeks the power begins to fall off at a rate higher than the inverse of frequency. The high frequency 'tail' of the spectrum begins to curl up but this is almost certainly due to the aliasing of energy above the Nyquist frequency of 0.5 $days^{-1}$.

b) Coherences and Phases

Figure 8 shows the coherences and phases between temperatures at Kains Island, the middle light station, and the other 2 stations. Also shown in Figure 8a are 'levels of significance' appropriate to the number of blocks analyzed in each case.

Amphitrite Point and Langara Island are significantly coherent with Kains Island for all frequencies with period down to about 7 days. For periods less than 1 year the coherences lie between 0.8 and 1.0 for both pairs of light stations. That the coherence should be so high is no doubt partly due to the analysis technique but the plots of the annual temperature averages indicate that there are good correlations at low frequencies. Also borne out by the annual averages is the higher low frequency coherence between Amphitrite Point and Kains Island than between the latter and Langara Island. Kains Island is much closer geographically to Amphitrite Point than to Langara Island. At frequencies above the yearly harmonic which has coherences of almost exactly 1.0 the coherences drop sharply yet are still greater than the levels of significance. Generally coherences in this middle frequency range are similar for the 2 pairs of stations if allowance is made for their different levels of significance. The coherences for periods shorter than 7 days drop below the levels of significance. Seven days is approximately the natural period for weather systems which may be the shortest period phenomenon, aside from daily solar heating, capable of affecting all 3 light stations similarly.

The phases for both pairs of stations are all within 45° of 0° for periods longer than about 14 days. The phases of Amphitrite Point with respect to Kains Island for the first, second and third annual harmonics are 1°, -28° and 27° respectively whereas for Langara Island with respect to Kains Island these phases are -8°, -32° and -24°. The different phases reflect the mechanisms by which solar energy is transformed into the heating of the sea surface. At periods shorter than 14 days both Langara Island and Amphitrite Point lag Kains Island. In fact, the ever increasing phase lag between Amphitrite Point and Kains Island is approximately that which would be produced by a constant time lag of 1.5 days between the 2 stations. A constant time lag of 1.5 days is plotted as a dotted line on Figure 8b.

2. Salinity

a) Power Spectra

In contrast to the temperature spectra the salinity spectra which are plotted in Figure 9 are distinct for the 3 stations. At all frequencies the power at Langara Island is of the order of a decade lower than that at Kains Island and Amphitrite Point. This is probably due to the fact that Langara Island is the farthest removed from the salinity-changing effects of river runoff. All 3 light stations have a salinity spectral maximum at the annual frequency although at Langara Island the energy in this harmonic is only 7% of the total energy whereas at Kains Island and Langara Island it is 60% and 44% of the total respectively. At lower frequencies frequency power falls off. However, frequency·power for the 3 stations is approximately constant from the annual period down to periods of about 20 days after which this quantity increases for Langara Island. Thus at higher frequencies Amphitrite Point has somewhat more energy in its salinity spectrum than does Kains Island. There is no tendency for any of the salinity spectra to 'tail off' at their high frequency ends as do the temperature spectra. Local maxima are attained in the salinity spectra for the 1/2 yearly harmonic and the 14 day harmonic for both Kains Island and Langara Island, but curiously these are not evident in the spectrum for Amphitrite Point.

b) Coherences and Phases

Figure 10 shows plots of the salinity coherence and phase between the 2 pairs of light stations Kains Island-Amphitrite Point and Kains Island-Langara Island.

Energy at Kains Island and Amphitrite Point is significantly coherent up to frequencies corresponding to a period of about 14 days. The coherences at frequencies less than the annual frequency are below those for temperature whereas for periods between 1 year and 14 days they are higher. The coherence at the annual frequency is close to 1.0. The coherence at the annual frequency between Kains Island and Langara Island on the other hand is only about 0.8. Coherences with Langara Island are significantly lower than those with Amphitrite Point at most other frequencies, too. Generally, the Kains Island-Langara Island coherences lie below the level of significance for periods less than one year.

For shorter periods than 14 days the phases between the 2 pairs of light stations are relatively scattered reflecting the loss of coherence evident at higher frequencies. At lower frequencies Amphitrite Point tends to lead Kains Island, but the relative phase is less than 30°. The phases between Langara Island and Kains Island on the other hand are more scattered at the same frequencies and in this case Langara Island shows a tendency to lag Kains Island. However, the energy at the annual frequency of Langara Island leads that of Kains Island by 62°.

## 3. Rainfall Power Spectra

Rainfall power spectra for all 3 stations are shown plotted in Figure 11. The rainfall spectrum for Kains Island and that for Langara Island are similar both quantitatively and in shape whereas that for Amphitrite Point is similar in shape to the other 2 but is of lower level. This may be because the analysis for Amphitrite Point was carried out on only 1 block of rainfall data. The years of the Amphitrite Point analysis seem to have had a below average rainfall judging by the more complete record for Kains Island (see Figure 6). At frequencies below the annual frequency the spectrum falls off rapidly. However, the power in the yearly harmonic is of the order of a decade above that in the rest of the spectrum. Frequency·power gradually increases at higher and higher frequencies. Local maxima in the 3 rainfall spectra are pronounced at a period of 1/2 year but not at a period of 1/3 year.

### 4. Kains Island: Temperature-Salinity and Rainfall-Salinity Coherences and Phases

Salinity-temperature (T,S) and salinity-rainfall (R,S) coherences are plotted together in Figure 12a for Kains Island. The T,S coherences behave quite differently from the R,S coherences. Aside from the good coherence at the annual frequency one could not say there was really significant T,S coherence for any frequency lower than that of period 7 days. During a period in which there is vertical mixing in a body of water which is stratified both in salinity and thermally, one might expect temperature and salinity to show a significant correlation. Following such a period of mixing the temperature of the surface water will approach an equilibrium with the atmosphere through the processes of conduction and radiation. That the coherence between temperature and salinity becomes less significant at periods longer than a week indicates that perhaps this is the time required for the temperature readjustment. Conversely rainfall and salinity show significant coherence at most frequencies of period shorter than 1/3 of a year and less significant coherences at longer periods.

The T,S and R,S phase relationships for Kains Island are plotted in Figure 12b. Although the T,S phase varies between 180° and -180° the phases for those periods at which significant coherences were observed, that is for less than 7 days, are clustered near 0°. This indicates that the mixing is predominantly a winter phenomenon which occurs when the higher salinities are associated with warmer temperatures. The phase relationships between rainfall and salinity are peculiar. In keeping with the expectation that high rainfall be associated with low salinity, salinity lags rainfall by 175° at a period of 1 year. At periods about 1/3 of a year, though, the R,S phases are clustered about 0°. Salinity lags rainfall more and more at higher frequencies until at a frequency corresponding to a period of about 4 days the lag is around 120°. It would thus seem that on the shorter term meteorological conditions which move the surface water and which are associated with rainy periods may have as much of an effect on the salinity as does the influence of the rain itself.

### 5. Amphitrite Point: Temperature-Salinity and Rainfall-Salinity Coherences and Phases

T,S and R,S coherences and phases are plotted for Amphitrite Point in Figure 13. T,S coherences are generally not dissimilar from those of Kains Island although coherences are somewhat higher at Amphitrite Point for periods between 40 and 120 days. The coherence between rainfall and salinity at Amphitrite Point could not be said to be significant at any frequency. This R,S analysis, however, is based on only 1 block of data whereas the analysis at Kains Island included the whole 35 years of data.

The phase plot for Amphitrite Point shows that temperature and salinity tend to be 180° out of phase for periods between 250 days and 20 days. At higher frequencies this phase approaches 0° as do the T,S phases for Kains Island. The phases between rainfall and salinity at Amphitrite Point do not show any pattern, which is probably a reflection on the low R,S coherences.

6. Langara Island: Temperature-Salinity and Rainfall-Salinity Coherences and Phases

Figure 14 shows T,S and R,S coherences and phases for Langara Island. For periods less than a year the T,S coherences are significantly higher than they are for either Kains Island or Amphitrite Point. In fact the majority of these higher frequency coherences are above the level of significance. On the other hand the R,S coherence is below the level of significance for most frequencies.

Almost all the phases between temperature and salinity cluster near either 180° or -180°, that is temperature and salinity are of opposite phase. At the annual frequency salinity leads temperature by 97° in contrast to leads of 24° at Kains Island and 22° at Amphitrite Point. Rainfall, although not particularly coherent with salinity, tends to have a phase within 90° of salinity for periods longer than about 10 days.

It seems that the surface water characteristics at Langara Island are governed much more by the periodic vertical mixing of cooler, more saline, deeper water into the surface than by the direct or indirect effects of rainfall. In contrast the R,S relationship is stronger than the T,S relationship at the other 2 stations for periods longer than a week or so. This suggests that for lower frequencies at least the surface water characteristics at Amphitrite Point and at Kains Island are affected appreciably by the local movements of horizontally stratified water bodies of varying salinities.

C. Monthly Means

1. Temperature, Salinity and Rainfall

Shown plotted in Figure 15 are 2 cycles of the monthly means for temperature, salinity and rainfall. The salinity cycles for Amphitrite Point and Kains Island are similar in shape and range but vary in average level. These 2 stations both reach their maxima in August and their minima in December. Langara Island being situated further from any major fresh water sources exhibits a much smaller annual salinity range of the order of 0.5 PPT versus 4 PPT for the other 2 stations. This station has a salinity maximum in June and a minimum in November but a secondary maximum also appears in August.

Rainfall is small at all 3 stations during the summer months June to August. It begins a sharp increase in November to reach a maximum in January. The average salinities begin to drop before the rainfall starts to rise appreciably so it would appear that it is more than precipitation which causes the annual salinity variations. Pickard and McLeod (1953) have suggested that changes in the seasonal evaporation rates and in upwelling caused by the long shore seasonal winds are partly responsible.

The mean annual range in temperature is approximately 10°F (6°C) at all 3 stations. Monthly temperatures at Kains Island and Amphitrite Point are virtually identical but those at Langara Island are 2.5°F (1.4°C) lower. Also, the temperature cycles of the 2 southerly stations precede that of Langara Island. From results computed using spectral analysis the phase lag of the annual frequency harmonic is 8° which represents a time lag of 8 days.

## 2. Standard Deviations of Salinity and Temperature; T,S Correlation

Standard deviations of salinity and temperature and the T,S correlation are shown plotted in Figure 16. The standard deviation of temperature is a maximum for Kains Island and Amphitrite in July and for Langara Island a month later whereas the minima occur for the 3 stations in March or April. That this seasonal variation occurs is not surprising since the surface water is more strongly thermally stratified during the summer months. Any disturbance causing vertical mixing will thus cause larger temperature variations at that time.

The standard deviations of salinity display an inverse cycle to that of temperature for Kains Island and Amphitrite Point. They are minima in late summer and maxima around November or so. This is not surprising as the salinity stratification is expected to be a minimum during the period of minimum rainfall. For these 2 southern stations the peak in the salinity standard deviations occurs a couple of months ahead of the peak in precipitation. It would seem that later on in the winter, storms could markedly erode the high salinity stratification. One also notes that the standard deviations of salinity are everywhere higher for Amphitrite Point than they are for Kains Island. On the other hand the temperature standard deviations are higher at their peaks for Kains Island than for Amphitrite Point. It would seem that Amphitrite Point achieves the greater salinity stratification whereas Kains Island achieves the greater temperature stratification. The standard deviations of salinity at Langara Island show a smaller average and much less variation than at the other 2 stations.

The T,S correlation curves are much as expected. At Kains Island and Amphitrite Point during the months May to September, the T,S correlation is negative as the fresher surface layer is heated by the summer sun and negative for the months October to March. Langara Island shows different behaviour. Its T,S correlation is negative from June to November and is near zero for the rest of the year.

## V. SUMMARY AND CONCLUSIONS

It is evident that each of the analysis techniques used in this study point up different features of the data. The relatively modern technique of spectral analysis is useful in examining the time scales at which variations and co-variations in parameters such as salinity, temperature and rainfall occur. However, yearly and seasonal variations are better examined using simple averaging procedures.

Despite the geographical separations of the 3 light stations examined in this report their temperature records show a good statistical similarity. Although average temperatures at Langara Island are 2.5°F (1.6°C) lower than they are at the 2 southern stations the magnitudes and shapes of the yearly fluctuations correspond to one another. Also, these variations in yearly averaged temperatures seem to be related to changes in the annual precipitations. Presumably the meteorological conditions associated with higher rainfall such as greater cloud cover and particular atmospheric circulation patterns are the cause.

All 3 stations exhibit a seasonal maximum in surface temperature in late summer and a minimum in February. The average seasonal range in temperature is in each case near 10°F (6°C). Indications are that the water columns are most thermally stratified in summer and least stratified in early spring.

The temperature power spectra at Kains Island, Langara Island and Amphitrite Point are quite similar to one another. In each case approximately 90% of the energy is represented at the annual frequency. At higher frequencies the energy per unit bandwidth decreases. For periods longer than about a week the temperature energy at Amphitrite Point and at Langara Island is significantly coherent with that at Kains Island.

In contrast to temperatures the salinity records at the 3 stations differ considerably. The variation of the yearly salinity averages at Kains Island and Amphitrite Point show a correspondence which is not as good as that of temperature. The fluctuations of the yearly averages at these stations are of order 0.5 PPT. The pronounced seasonal variation in salinity has an average range of 4.0 PPT on the other hand. At all times of the year Kains Island is 0.5 PPT salinity higher than Amphitrite Point.

Compared to the 2 Vancouver Island stations, Langara Island shows much less yearly and seasonal salinity variation. The magnitudes of the fluctuations are approximately 0.1 PPT and 0.5 PPT for the yearly and seasonal variations respectively. This behaviour and the fact that Langara Island has the highest average salinity are likely due to the absence of any large sources of fresh water in the vicinity of the station.

Salinities from all 3 stations show a decrease over the 35 years of the study of about 0.4 PPT. The fluctuations of the annual averages bear little obvious relationship to either changes in precipitation or in temperature.

Salinities at the 2 southern stations are highest in August, a month of low precipitation. They have fallen appreciably by October yet the rainfall does not begin to rise until November. Lowest salinities occur in December although the highest rainfalls occur in January. Both the standard deviations of the salinity and the temperature-salinity correlation are high in November to December indicating a high salinity stratification, the more saline water being associated with warmer temperatures. The standard deviations of salinity are small for all times of the year at Langara Island, however.

The salinity spectra indicate that something like 50% of the energy is concentrated in the annual frequency for Kains Island and Amphitrite Point against less than 10% for Langara Island. The coherence of salinity energy is naturally best between the 2 southern stations and is only marginal with Langara Island. For periods less than 14 days this coherence becomes insignificant. The coherences of temperature with salinity at Kains Island and at Amphitrite Point are most significant for periods less than 7 days, but are more coherent at Langara Island to longer periods. On the other hand, rainfall and salinity at Langara Island are less coherent than they are at the other 2 stations.

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LIST OF FIGURES

List of Figures continued

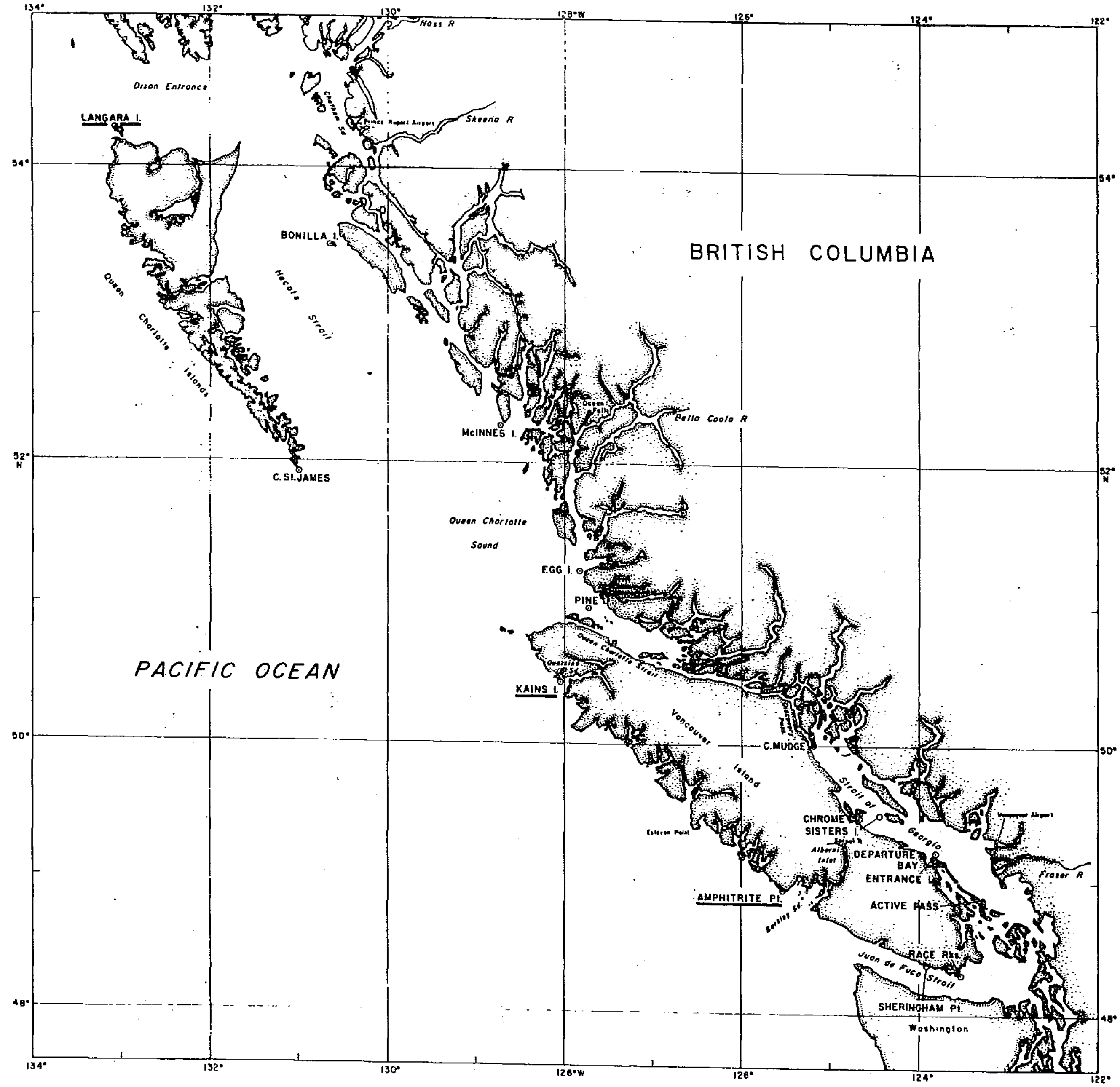



Figure 1. Map of British Columbia's coast showing locations of sampling stations Langara Island, Kains Island and Amphitrite Point. (all underlined)

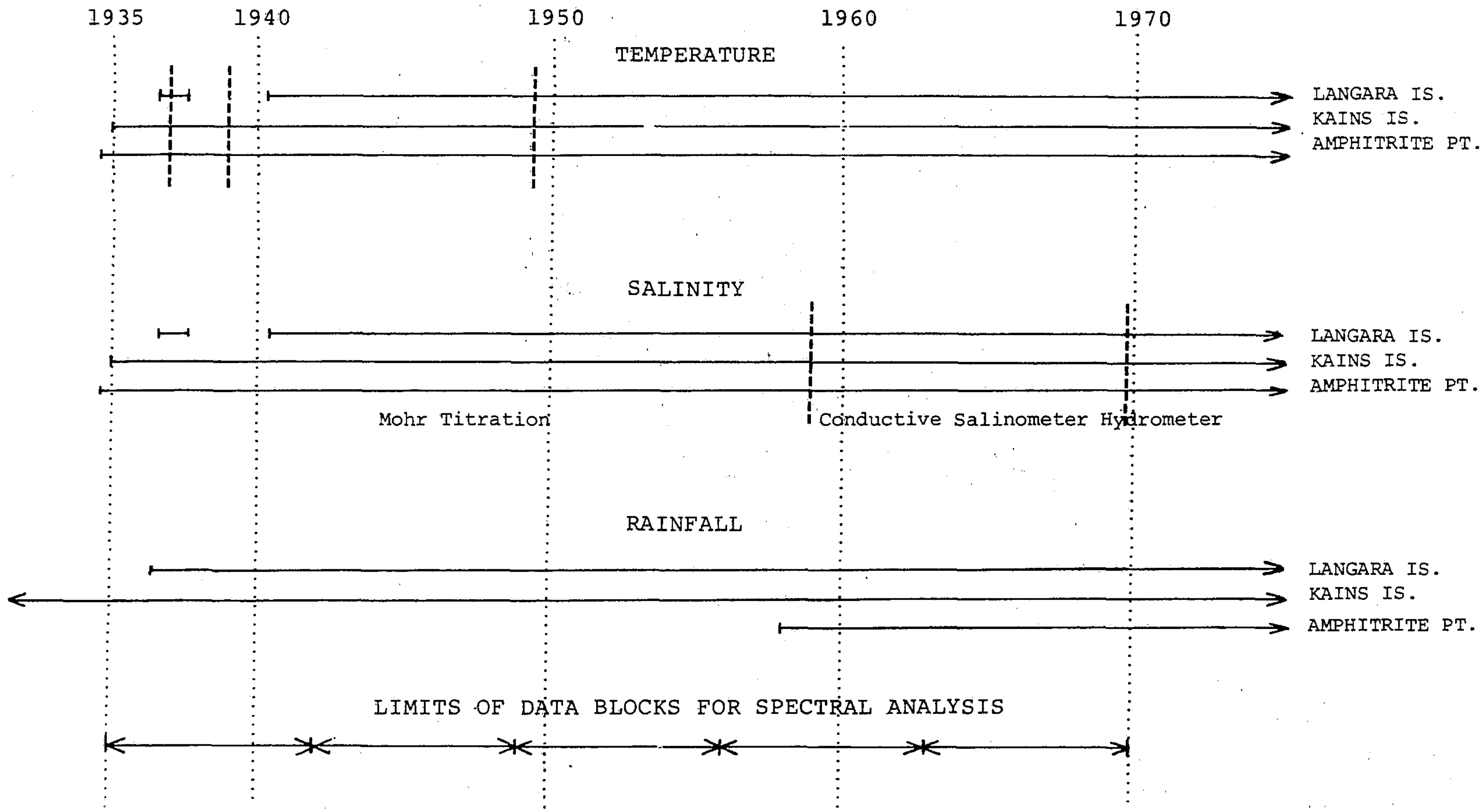



Figure 2. Schematic diagram of data availability for Langara Island, Kains Island and Amphitrite Point. Vertical dashed lines mark changes in the analysis procedure. The extents of the blocks used in the spectral analysis are indicated at bottom.

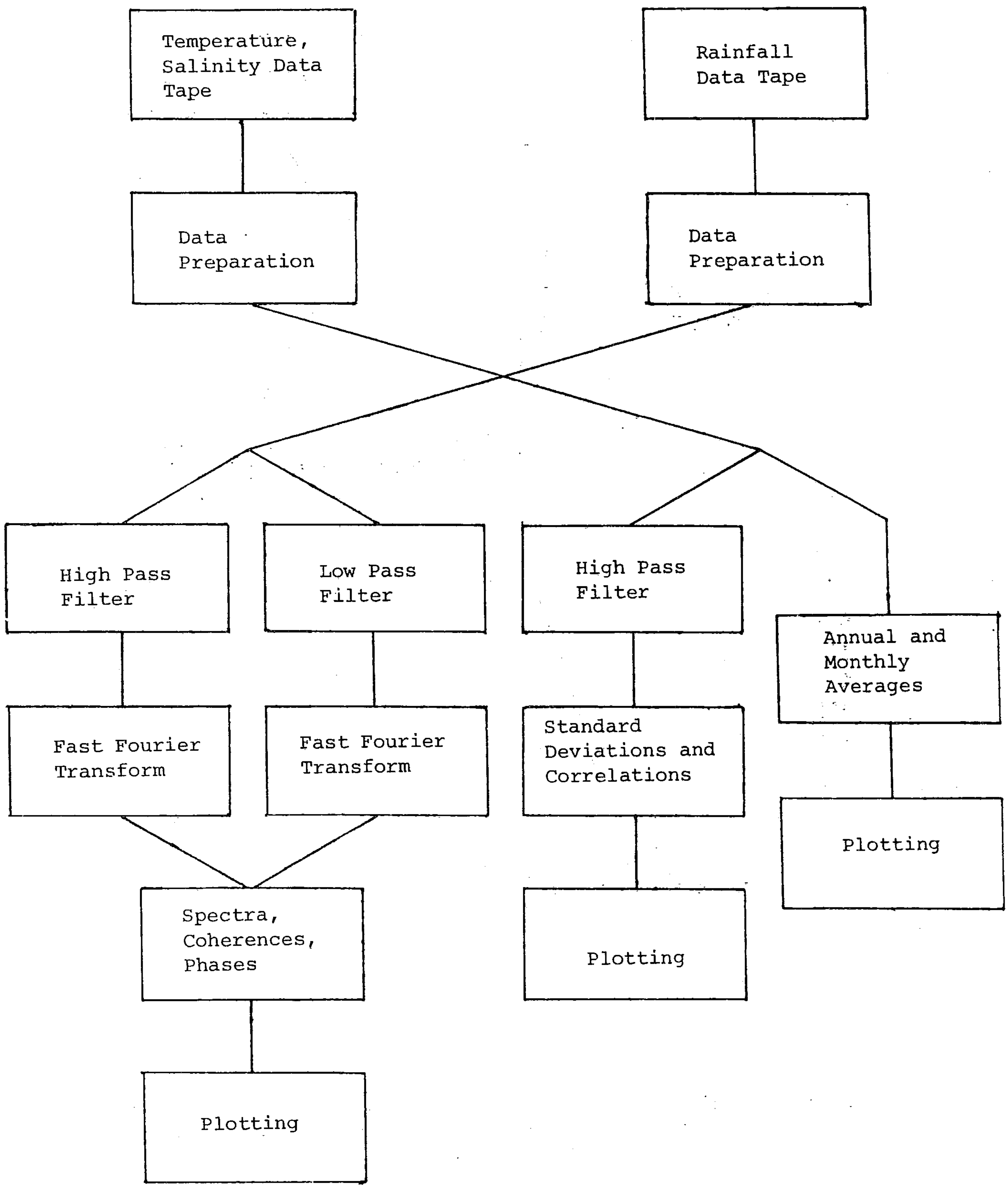



Figure 3. Schematic diagram of the analysis procedure.

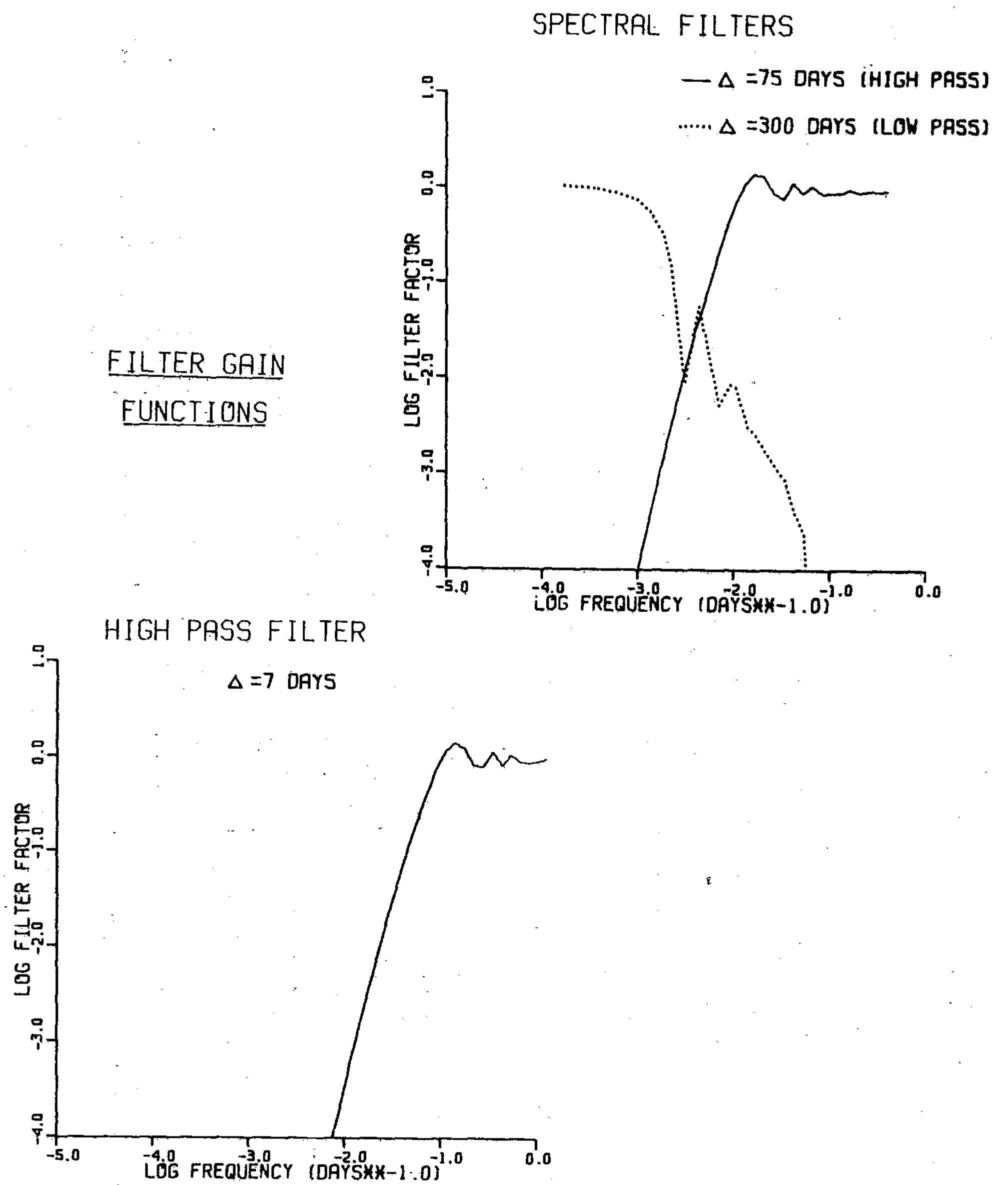



Figure 4. Gain functions for filters used in spectral analysis and in computation of temperature, salinity standard deviations and correlations.

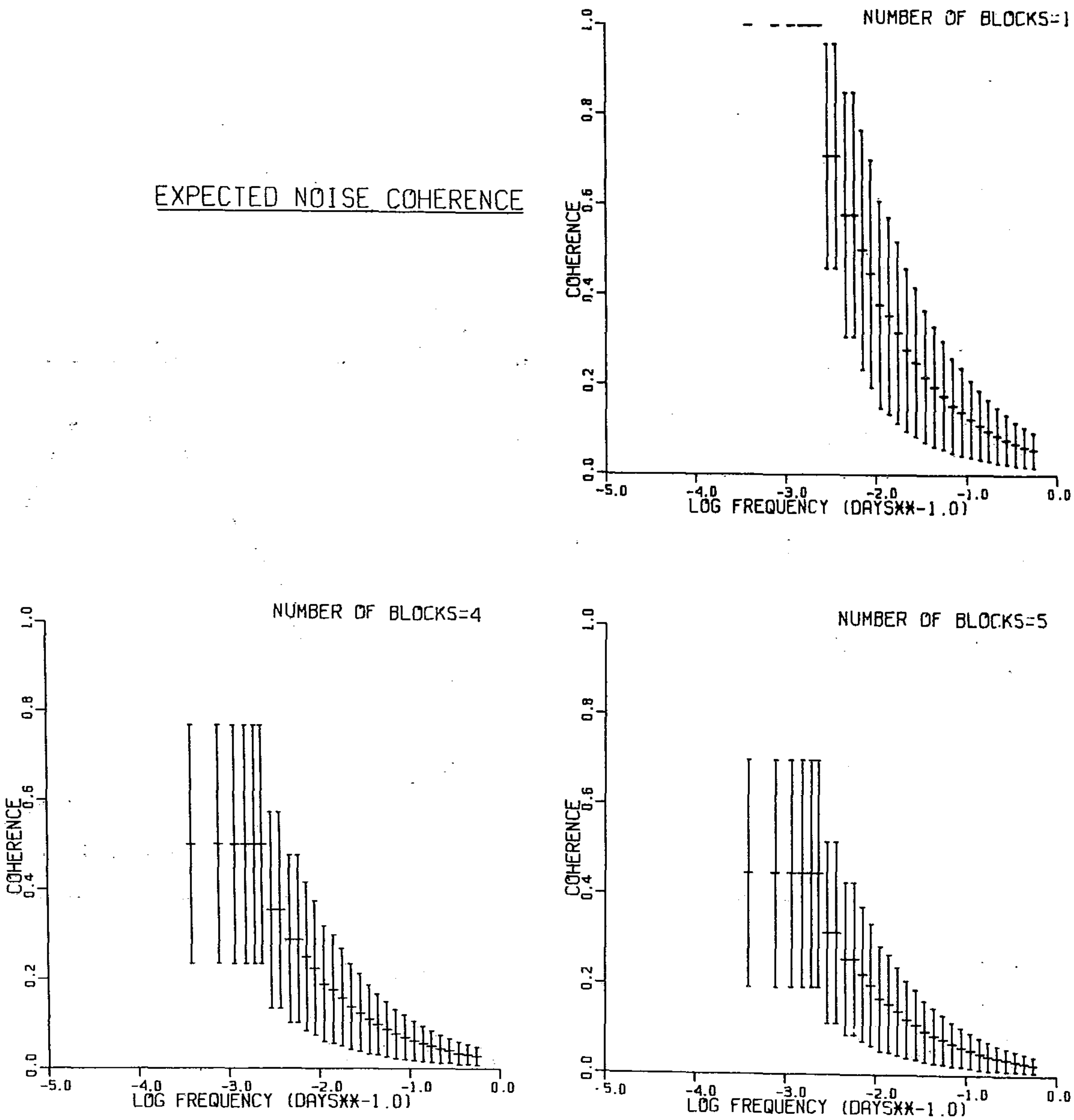



Figure 5. Expected noise coherences for 1, 4 and 5 blocks of analysis. The vertical bars represent the + and - standard deviations of the expected noise coherence.

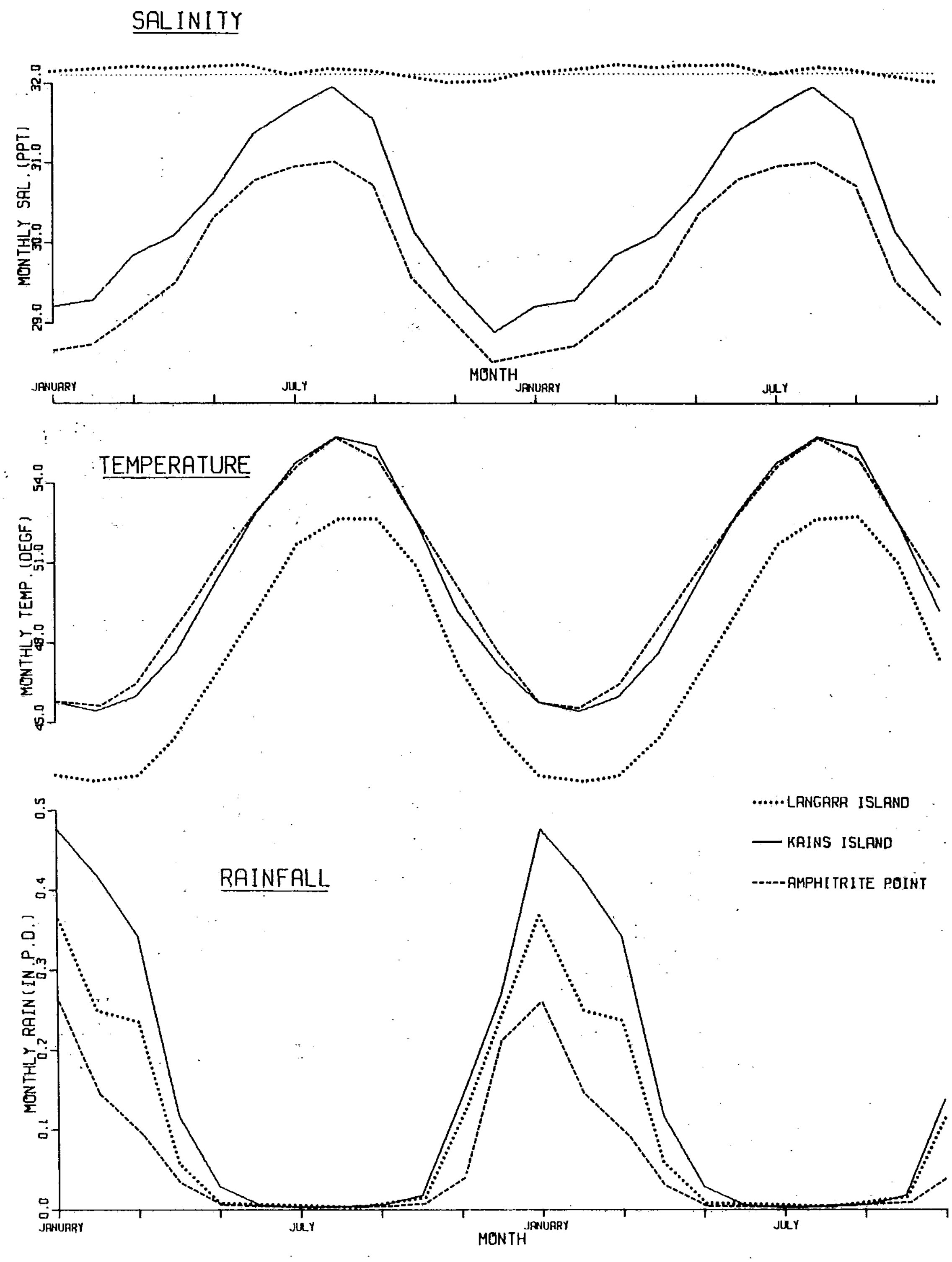



Figure 6. Annual averages of salinity, temperature and rainfall for Langara Island, Kains Island and Amphitrite Point.

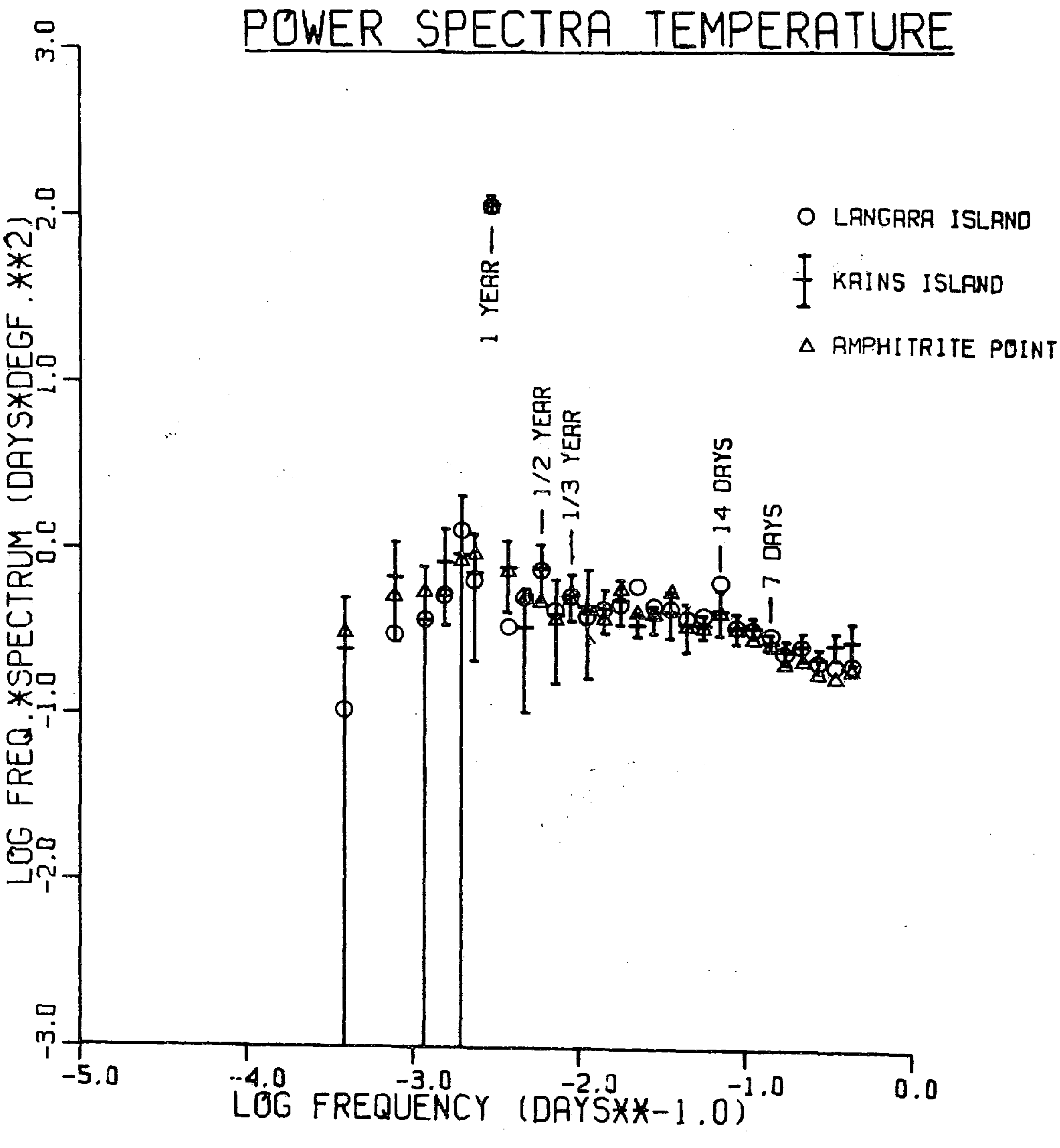



Figure 7. Power spectra of temperatures for Langara Island, Kains Island and Amphitrite Point. Vertical bars indicate the standard deviations between blocks for Kains Island.

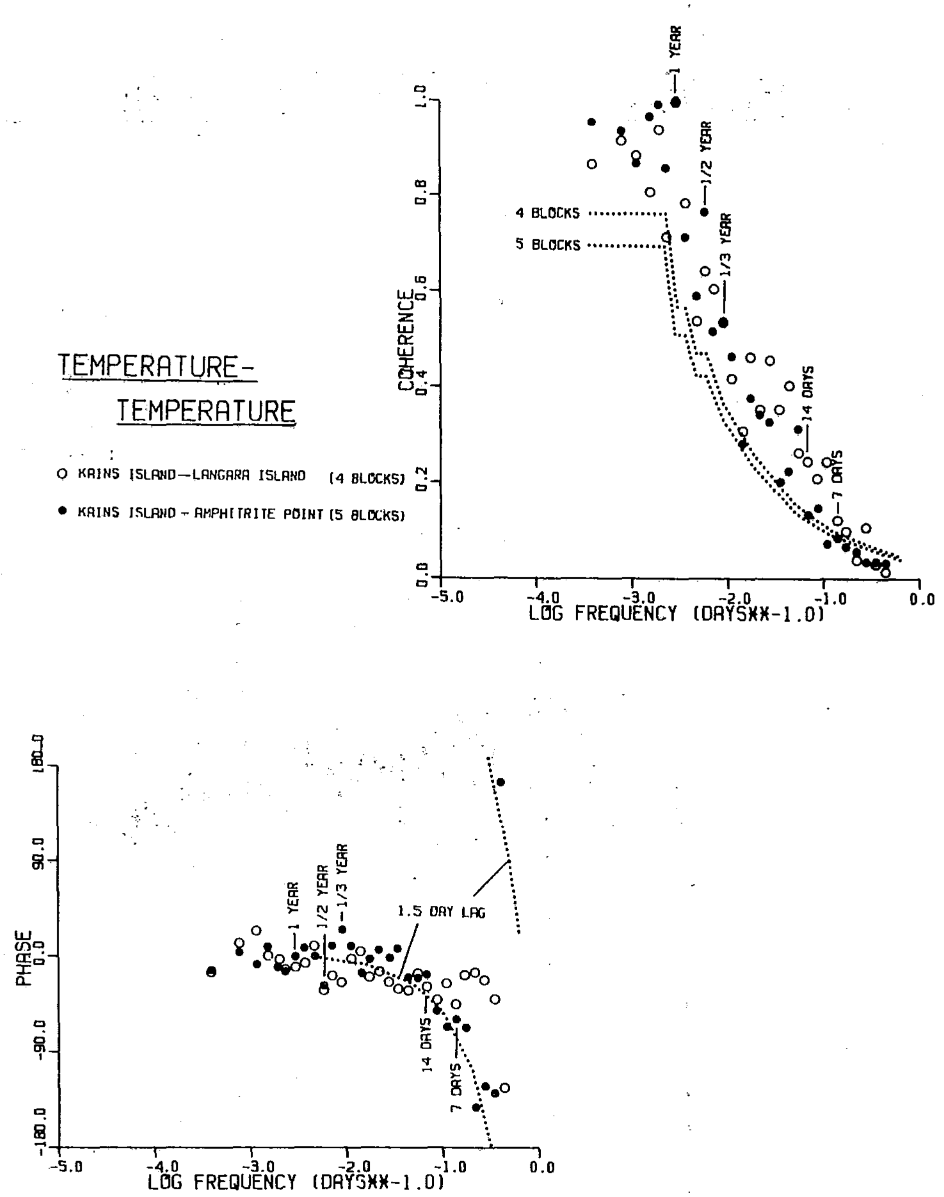



Figure 8. Coherences (Figure 8a) and Phases (Figure 8b) of temperatures between the two pairs of stations Kains Island, Langara Island and Kains Island, Amphitrite Point. The dotted line in Figure 7a is the 'level of significance' for coherences appropriate to the number of blocks analyzed.

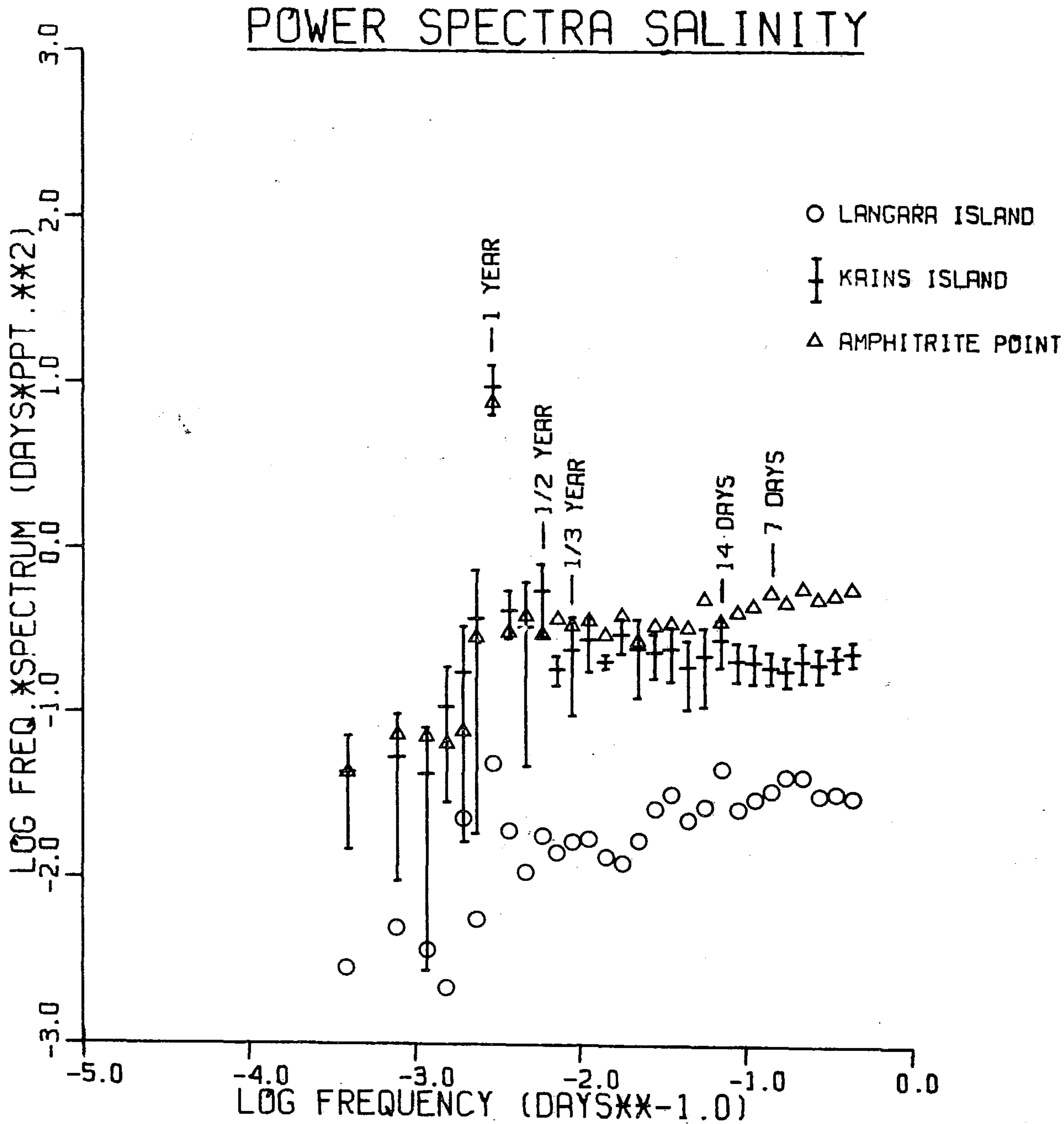
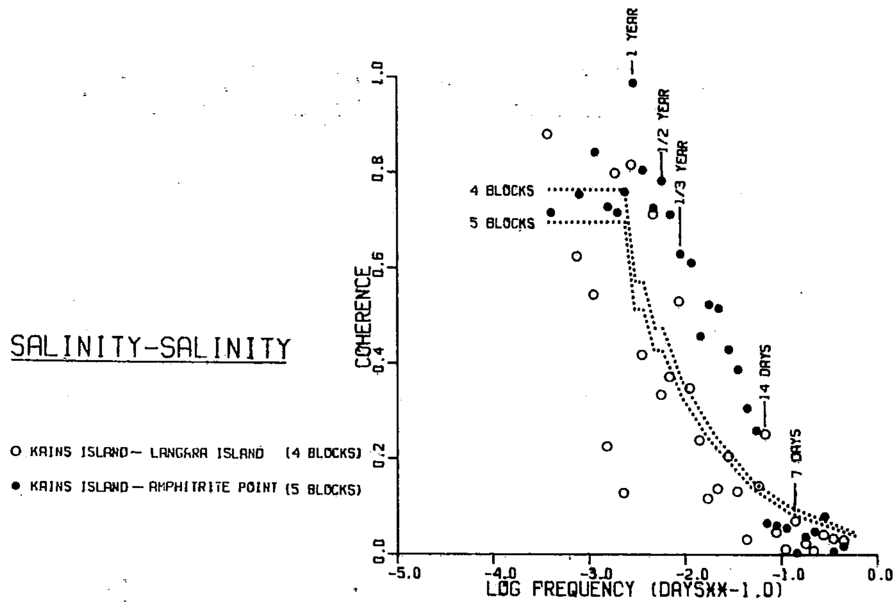



Figure 9. Power spectra of salinities for Langara Island, Kains Island and Amphitrite Point.



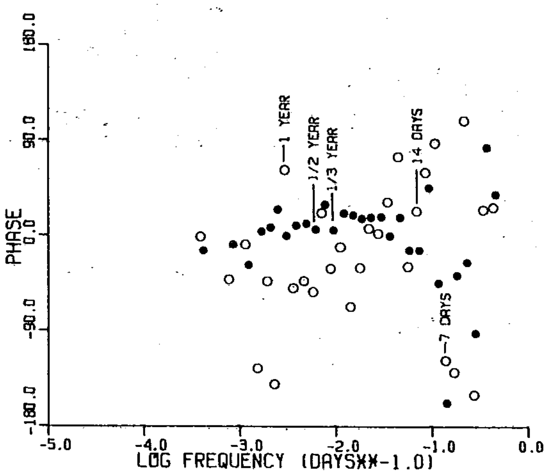




Figure 10. Coherences (Figure 10a) and Phases (Figure 10b) of salinities between the two pairs of stations Kains Island, Langara Island and Kains Island, Amphitrite Point.

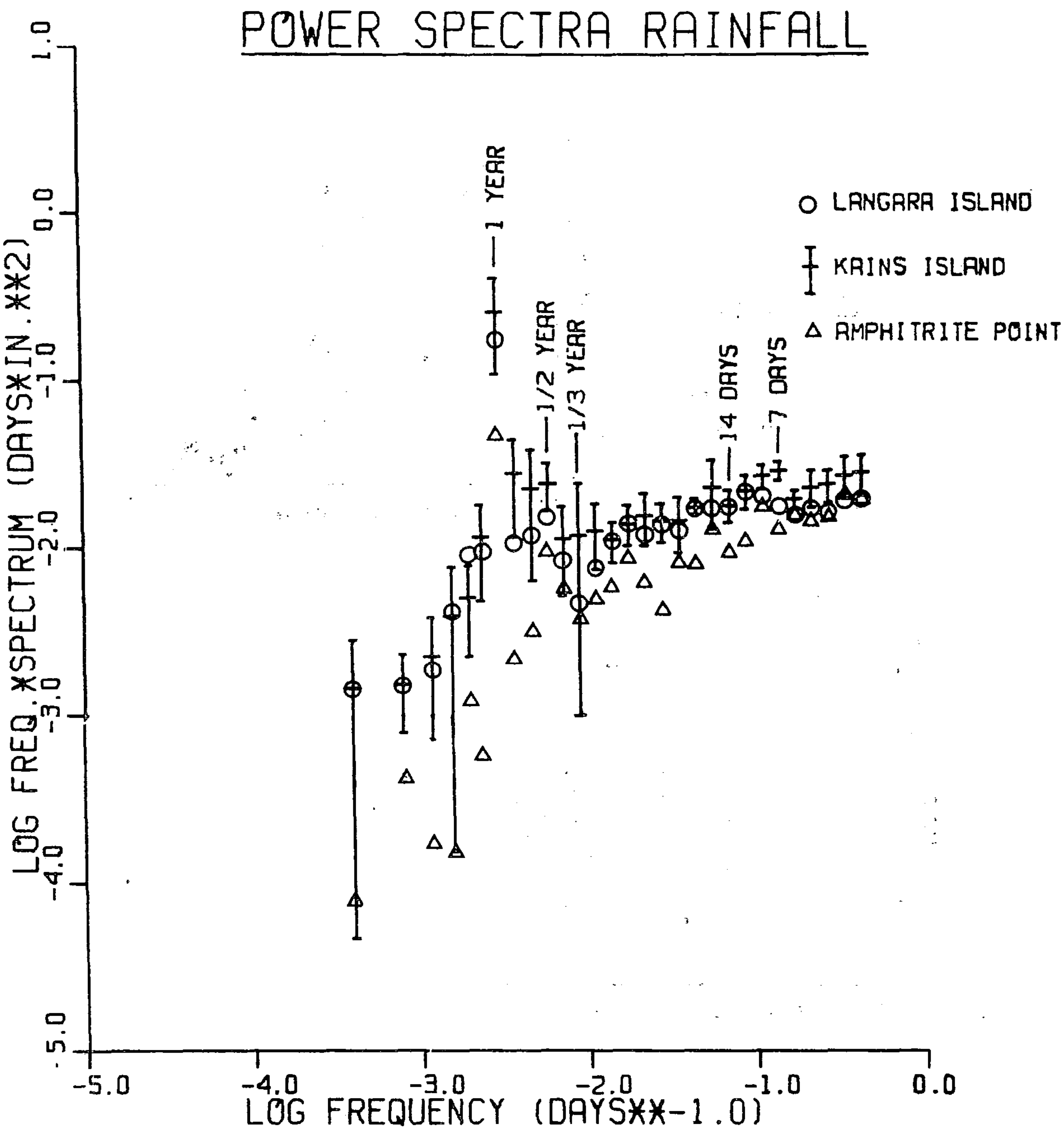



Figure 11. Power spectra of rainfall for Langara Island, Kains Island and Amphitrite Point.

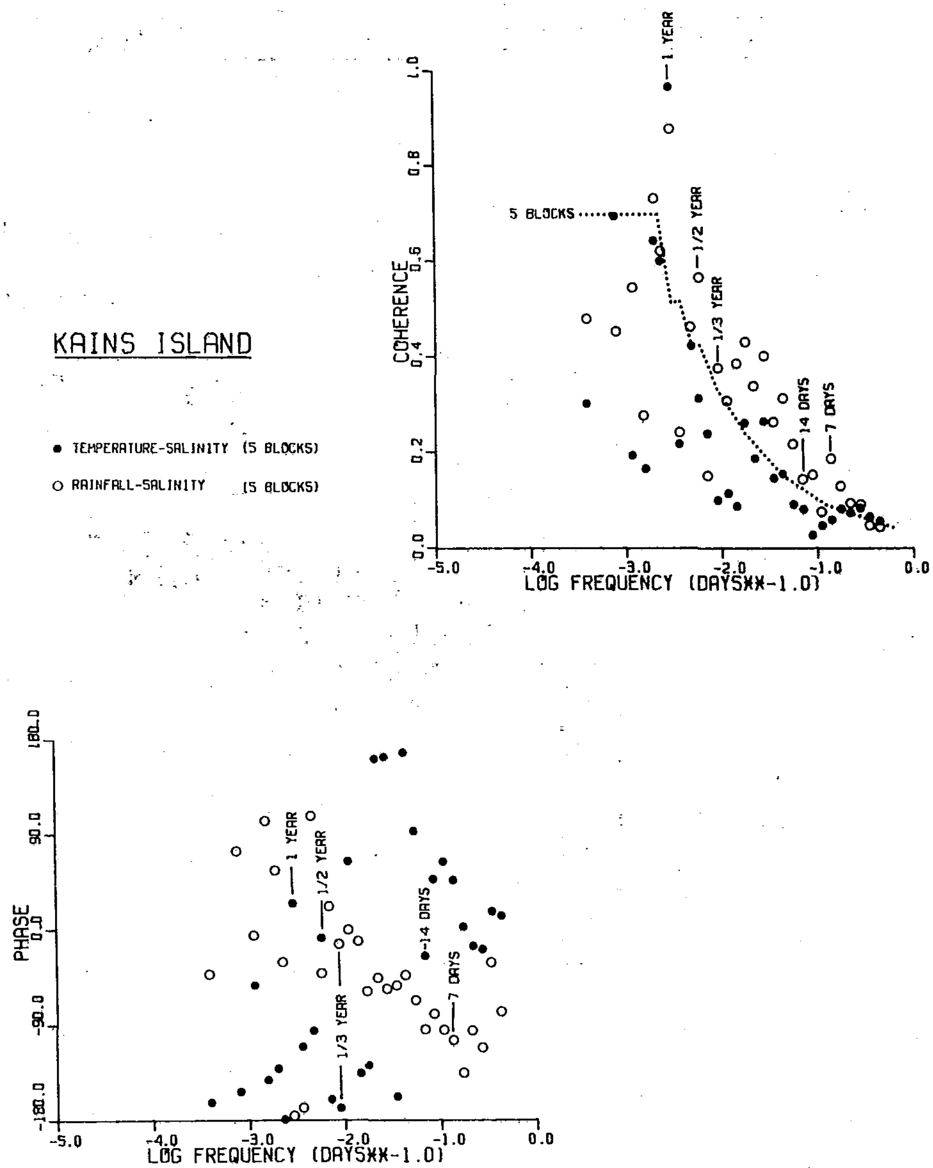



Figure 12. Coherences (Figure 12a) and Phases (Figure 12b) of temperature and rainfall with salinity for Kains Island.

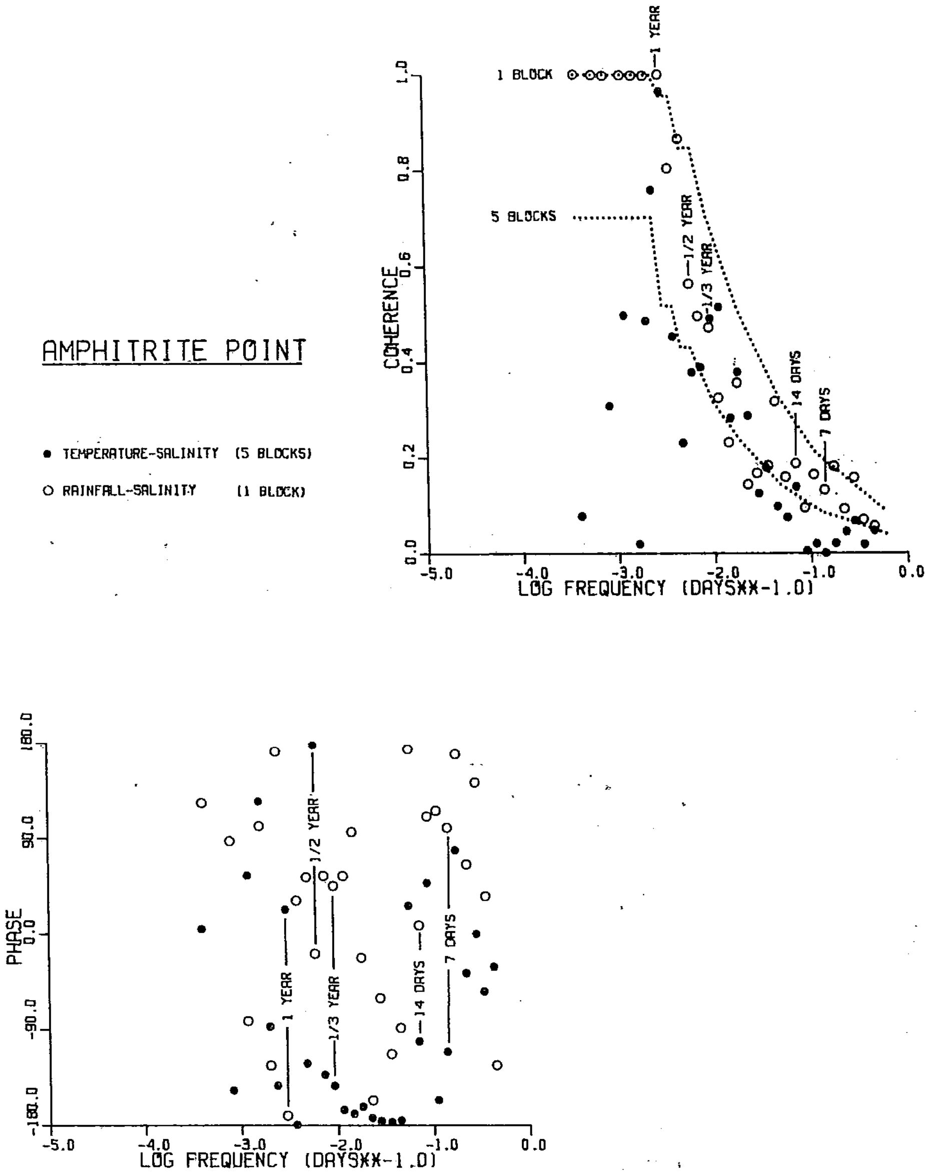



Figure 13. Coherences (Figure 13a) and Phases (Figure 13b) of temperature and rainfall with salinity for Amphitrite Point.

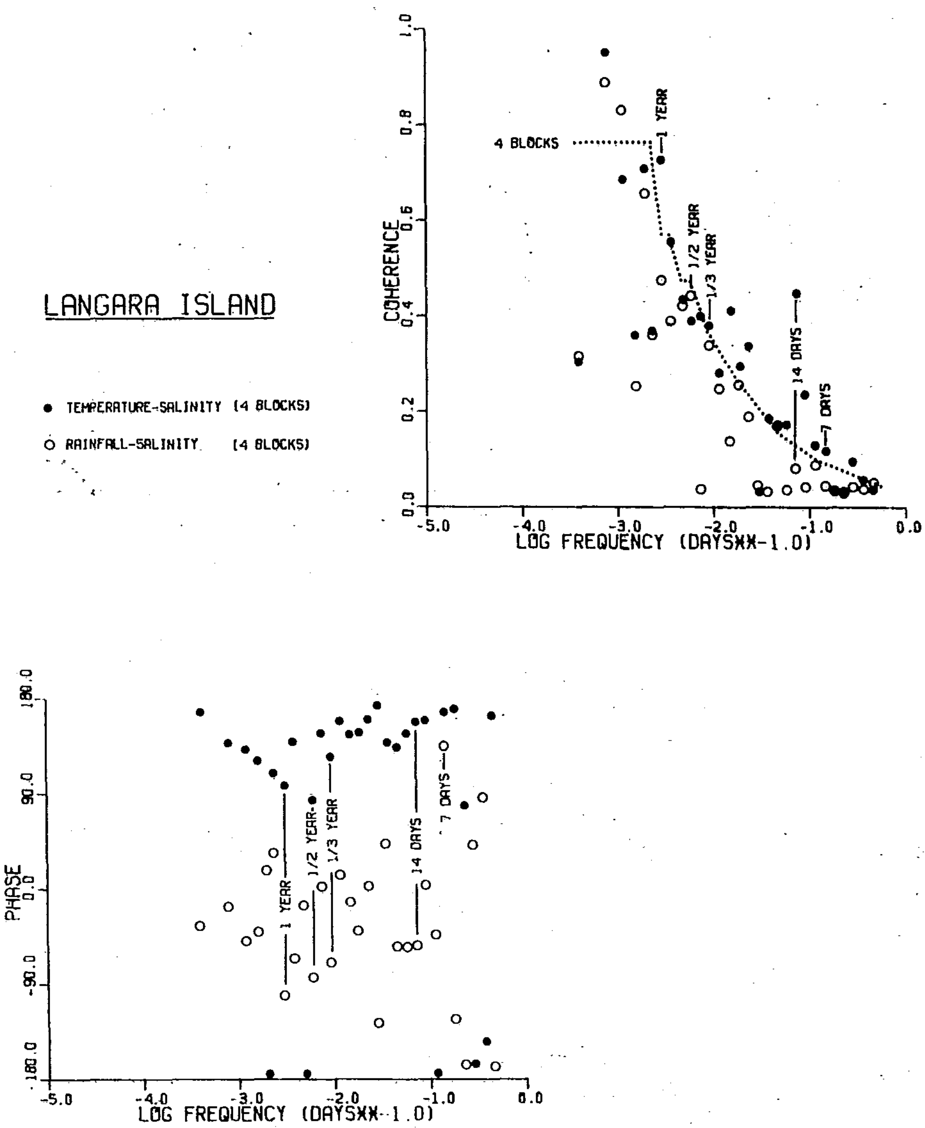



Figure 14. Coherences (Figure 14a) and Phases (Figure 14b) of temperature and rainfall with salinity for Langara Island.

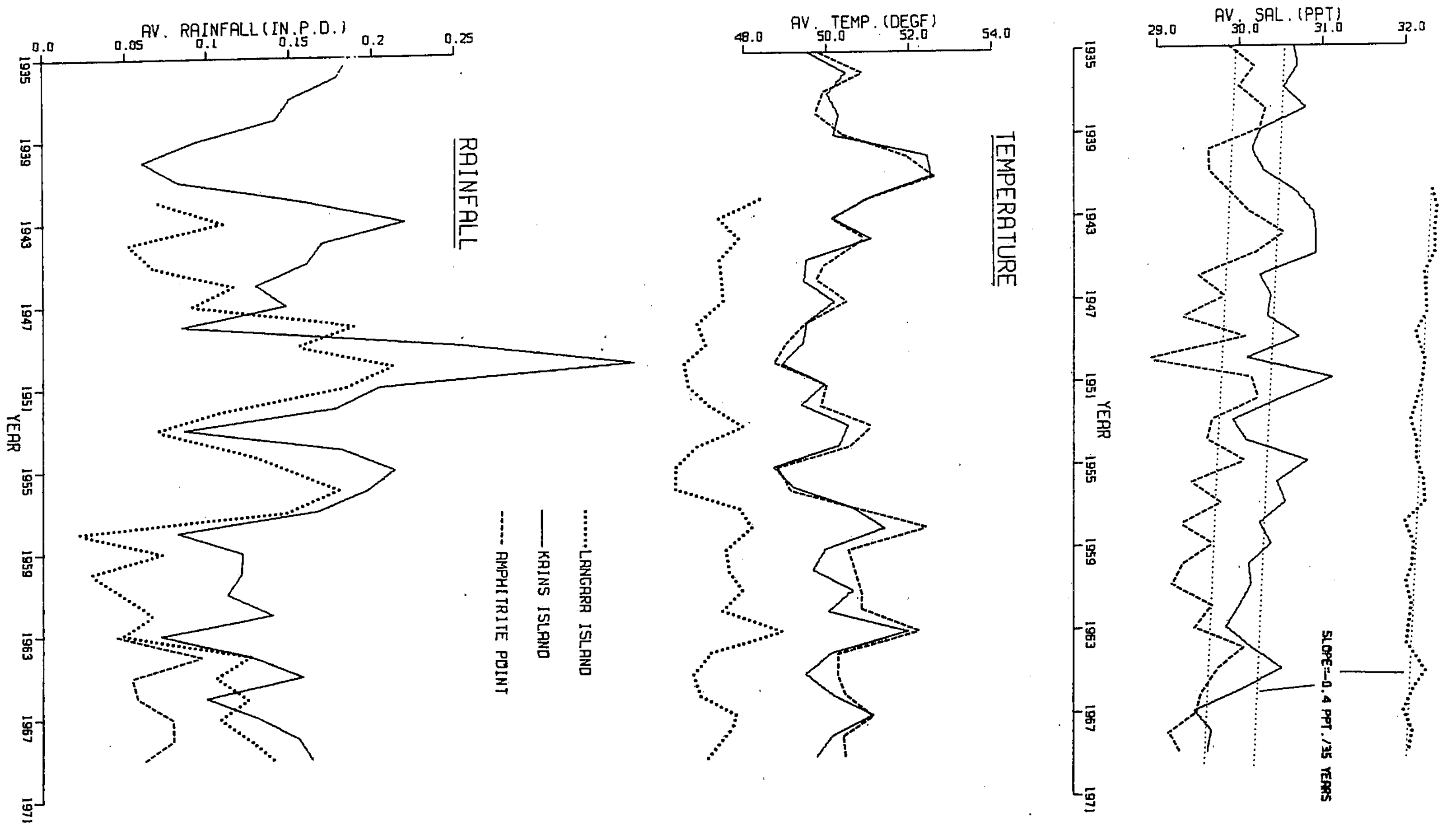



Figure 15. Average monthly salinities, temperatures and rainfall at Langara Island, Kains Island and Amphitrite Point.

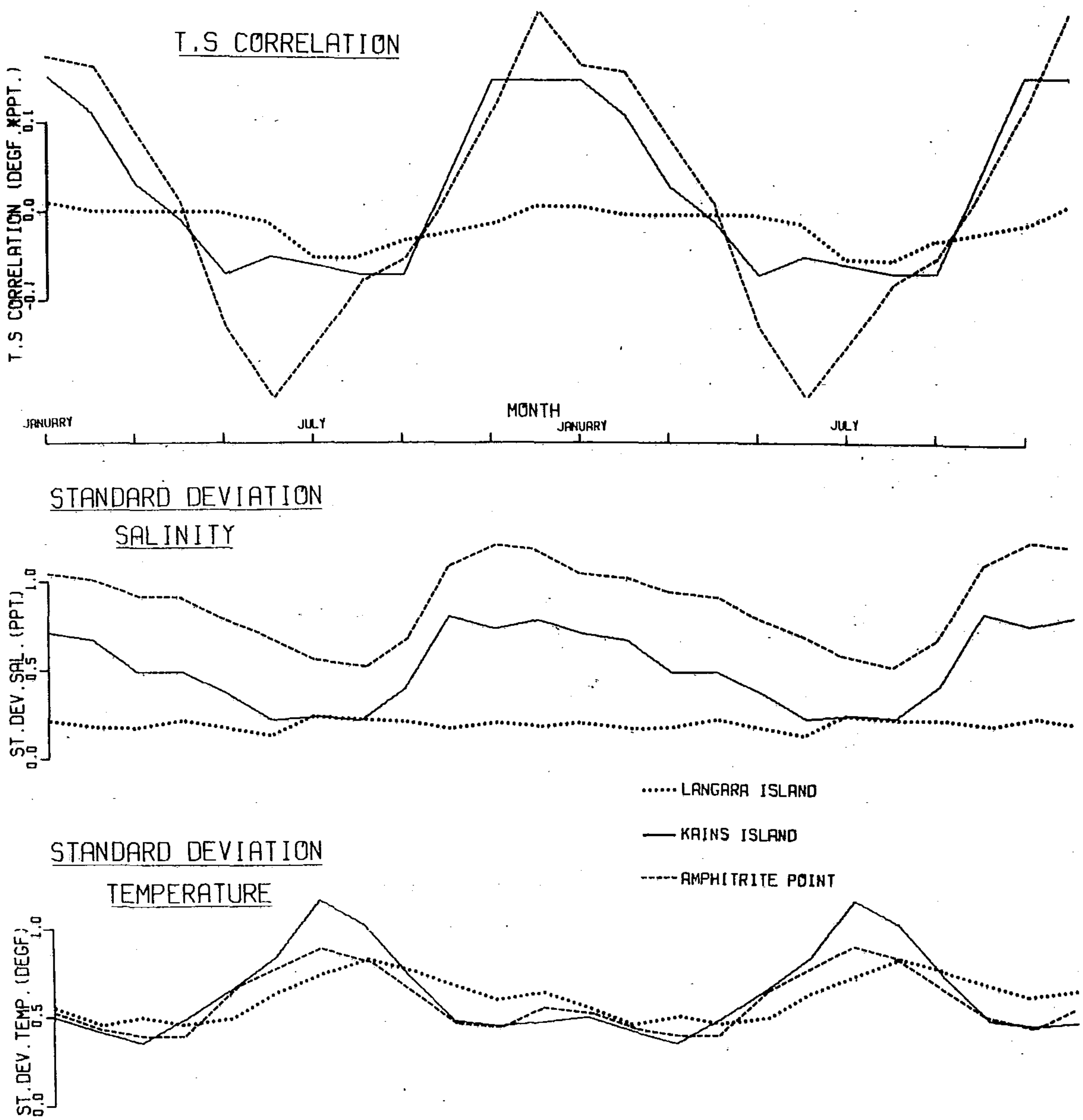



Figure 16. Average monthly temperature, salinity correlations and standard deviations of salinity and temperature for Langara Island, Kains Island and Amphitrite Point.