# AN ABSTRACT OF THE THESIS OF

Heau San Ma for the M. S.
(Name) (Degree)
in Oceanography presented on 16 June 1969
(Major) (Date)

Title: SEA LEVEL RESPONSE TO LOW-FREQUENCY ATMOSPHERIC PRESSURE FLUCTUATIONS ALONG THE NORTHWESTERN AMERICAN COAST

Abstract approved: Redacted for Privacy
Robert L. Smith

Spectral analysis was used to investigate semidaily mean sea levels and atmospheric pressures at San Francisco, California, Coos Bay, Oregon, and Tofino, British Columbia, in the frequency band 0 to 0.5 cpd. Cross spectral analysis of semidaily mean sea levels and atmospheric pressures at the three stations show that the response of sea level to low-frequency atmospheric pressure fluctuations is nonbarometric in the frequency band studied, and varies with season. Cross spectral analysis of semidaily mean sea levels between adjacent stations shows that there exists significant coherence between the Coos Bay and Tofino sea levels within the frequency band studied and phase difference between the stations is consistent with the hypothesis of continental shelf waves traveling from south to north along the coast.

# Sea Level Response to Low-Frequency Atmospheric Pressure Fluctuations Along the Northwestern American Coast

by

Heau San Ma

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

June 1970

APPROVED:

Redacted for Privacy

Assistant Professor of Oceanography
In Charge of Major

Redacted for Privacy

Chairman of Department of Oceanography

Redacted for Privacy

Dean of Graduate School

Date thesis is presented 16 June 1969

Typed by Marcia Griffin for Heau San Ma

# ACKNOWLEDGEMENT

I wish to acknowledge, with thanks, Dr. Robert Smith for suggesting the topic to me and for guiding me through the research. I also wish to thank Mr. Christopher N. K. Mooers for giving me much useful guidance and encouragement. I am also indebted to Dr. Lawrence A. Mysak for assisting in obtaining the Canadian data and for a critical reading of the manuscripts. Thanks are also given to Drs. George Beardsley, Curtis Collins, and Fred Ramsey for their criticisms of the thesis.

This research is supported by the Office of Naval Research under contract Nonr 1286(10).

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# SEA LEVEL RESPONSE TO LOW-FREQUENCY ATMOSPHERIC PRESSURE FLUCTUATIONS ALONG THE NORTHWESTERN AMERICAN COAST

## INTRODUCTION

This investigation presents a multispectral analysis of the semidaily mean fluctuations of sea level recorded at tide gage stations at San Francisco, California, Coos Bay, Oregon, and Tofino, British Columbia, and the semidaily atmospheric pressure fluctuations recorded at nearby weather stations, during the summer of 1933 and winter of 1933-1934. The standard techniques of time series analysis have been employed to decide whether (1) there is evidence of energy peaks at periods of several days in the spectra, (2) the sea level responds barometrically to low frequency atmospheric pressure fluctuations, and (3) there exists time lags between the sea levels at pairs of adjacent stations in the region studied.

Hamon (1962, 1966) had found that the magnitude of the barometer factor is appreciably less than the expected value of 1.01 cm/mb at four Australian east coast stations and appreciably greater than the expected value at two Australian west coast stations, and that spectral peaks in sea level appeared at about 0.1 and 0.2 cpd. There exist time lags between the sea levels at several pairs of adjacent Australian stations, which suggest the presence of a northward-traveling, low frequency wave on the east coast and a southward-traveling one on the west coast. Mooers and Smith (1968) found spectral peaks at 0.1 and 0.3 cpd and also found that the magnitude of the barometer factor to be greater than the expected value of 1.01 cm/mb at three Oregon coast stations. They also found indications of a northward-traveling wave with a period of about three days. Mysak and Hamon (1969) found evidence of a continental shelf wave traveling from north to south on the United States east coast, and spectral peaks at about 0.3 cpd in the adjusted sea levels. They found that the barometer factor is less than the expected value of 1.01 cm/mb.

Robinson (1964) suggested that small-amplitude, nondispersive waves that travel along a uniformly sloping shelf of finite width, and that are generated by moving low-frequency pressure systems, might explain the observed anomalous sea level behaviour and sea level time lags off the Australian coast. These waves, termed continental shelf waves, are trapped by, and sharply tuned to, the continental shelf. They are characterized by periods of several days, wavelengths of megameters, amplitudes of centimeters, and, for a specified hemisphere, travel parallel to the coast in one direction only, like classical Kelvin waves. Later Mysak (1967) developed a more comprehensive model of shelf waves, taking into account the current, stratification, and a sloping continental slope.

## DATA AND OUTLINE OF COMPUTATION

The locations of the tide gages and the weather stations used in this analysis are shown in Figure 1. Data for San Francisco and Coos Bay stations were obtained by U. S. Coast and Geodetic Survey (ESSA), and the data for the Tofino station was obtained by the Canadian Hydrographic Service. For San Francisco station, hourly data of tides were available from March 26, 1933, to May 6, 1934; for Coos Bay station, from April 2, 1933, to March 31, 1934; and for Tofino station, from May 28, 1933, to August 10, 1933, and from November 29, 1933, to March 14, 1934. The hourly tide heights were read to 0. 1 ft. (3 cm.).

Atmospheric pressure data for the period studied were obtained from meteorological stations near the tide stations. Semidaily barometric pressure data (at 0100 UT and 1300 UT) were available at the San Francisco station and at a station at Estevan Point, about 30 km from the Tofino station. Four-hourly barometric pressure data were available at North Bend, a few kilometers from the Coos Bay tide station. The data for San Francisco and North Bend stations were supplied by the U. S. Weather Bureau (ESSA) and the data for Estevan Point was obtained from the Meteorological Branch of the Department of Transport (Canada). The barometric pressure data were read to 0. 01 inch of mercury (0. 3 mb).

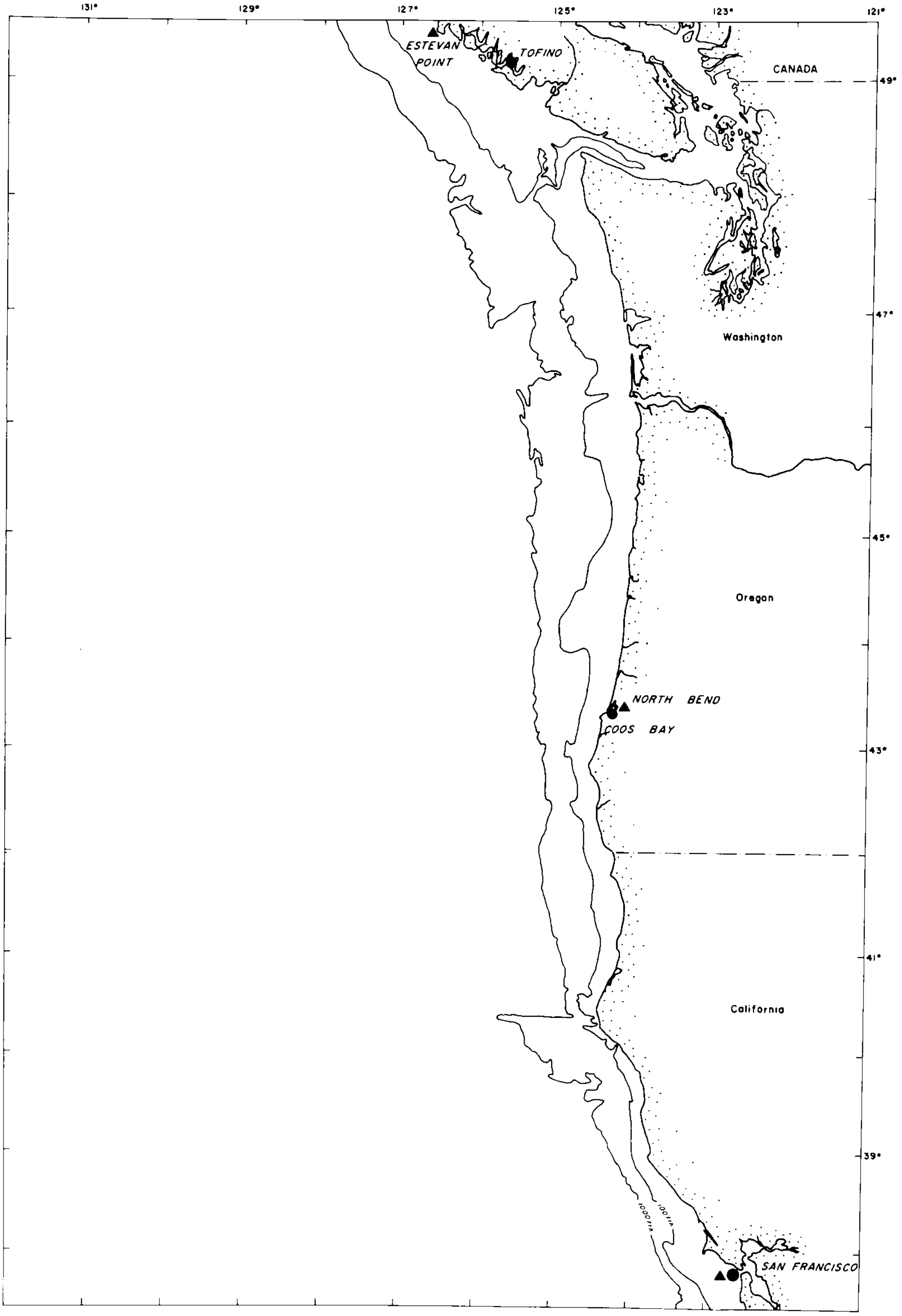

Figure 1. Map showing tide gage stations (circled) and weather stations (triangles) used in this study and the 100- and 1000-fathom contours.

The tide gage and atmospheric pressure data, recorded in feet and inches of mercury, respectively, were first transferred to punched cards and then checked by an error detection formula, which is a low pass numerical filter, as used by Mooers and Smith (1968). The formula has the following form:

$$y_i = 0.75(x_{i-1}+x_{i+1}) - 0.30(x_{i-2}+x_{i+2}) + 0.05(x_{i-3}+x_{i+3})$$

where $x_i$ is the ith original value and $y_i$ is the ith estimated (or predicted) value. The frequency response function is of the form:

$$F(\omega) = 1.5 \cos\omega - 0.6 \cos 2\omega + 0.1 \cos 3\omega$$

where $\omega$ is the frequency in radians per hour if hourly data are used and radians per half day if semidaily data are used. The filter has a half-power point at five hours when used with hourly values and sixty hours when used with semidaily values. Errors in the original data tend to produce a cluster of anomolous estimated values centered about the erroneous original data point and were thus easily identified. Values deviating from the estimate by 9 cm. for sea level and 1.8 mb for atmospheric pressure were rejected, and replaced by the estimates.

In order to remove the tides from the tide gage records and to focus attention on periodicities of two to ten days, the records were numerically filtered. The tides were suppressed by using a

Cosine-Lanczos filter, as recommended by Mooers and Smith (1968), on the hourly tide gage readings. The Cosine-Lanczos filter has the following form:

$$y_i = 1/G \left(x_i + \sum_{m=1}^{60} f(m)(x_{i-m}+x_{i+m})\right)$$

where $x_i$ are the hourly sea level data from the tide gages. The response function is of the form

$$f(\omega) = \left(1 + 2 \sum_{m=1}^{60} f(m) \cos m\omega\right)/G$$

where $f(m) = 1/2\ [(1 + \cos \pi m/60) \sin(0.7\pi m/12)/(0.7\pi m/12)]$ and $G = 1 + 2 \sum_{m=1}^{60} f(m)$. The filter has a half-power point at forty hours. This filtering process was used to obtain an average sea level for every twelve hours (0100 UT and 1300 UT) with the tide removed; this sea level is referred to as the unadjusted semidaily mean sea level.

The atmospheric pressure was recorded only at semidaily intervals at two of the three stations (San Francisco and Estevan Point). No attempt was made to filter the atmospheric pressure data. However, four-hourly pressure data was available from North Bend. In order to clarify whether aliasing occurs in the atmospheric pressure spectra computed from unfiltered, semidaily atmospheric pressure data, the spectrum was computed from the four-hourly as well as from the decimated twelve-hourly atmospheric pressure data for North Bend. The spectra were practically identical in the 0 to 0.5 cpd band and there was no apparent aliasing. The atmospheric tide was negligible at North Bend, the only station where it could be computed.

According to the hydrostatic hypothesis, the sea responds like an inverted barometer: an increase of 1 mb in atmospheric pressure will decrease the sea level by 1 cm, in phase. The sea level was accordingly adjusted by adding the corresponding semidaily atmospheric pressure minus 1000 mb (the approximate average atmospheric pressure) to the corresponding semidaily mean sea level, thus removing the assumed in phase effect of atmospheric pressure variations on sea level. This result will be referred to as the adjusted semidaily mean sea level.

All sets of data had two 100 day record lengths in common: May 31, 1933, to September 7, 1933, and December 2, 1933, to March 11, 1934. These represent the summer and winter seasons, which differ considerably both meteorologically and oceanographically along the northwestern American coast.

# AUTOSPECTRAL ANALYSIS

Figures 2 to 7 show the spectral density for summer and winter unadjusted sea level, adjusted sea level, and atmospheric pressure, at the various stations. The spectra are based on 200 data points (N) from 100 days of record and a maximum lag (M) of 40 data points. The sampling interval is a half day, therefore the Nyquist frequency is 1.0 cpd, and the bandwidth is 0.025 cpd. The degrees of freedom are given by Jenkins and Watts (1968) as 8N/3M which for this analysis is 13. As a measure of statistical significance, the 95% confidence intervals and the bandwidth are shown. The spectra were computed to 1.0 cpd to avoid aliasing but are shown only to 0.5 cpd.

In all spectra, small but significant peaks are present in the frequency band studied. The peaks are particularly significant at 0.3 to 0.325 cpd for the San Francisco summer record, at 0.275 to 0.3 cpd for the Coos Bay summer record, and at 0.30 cpd for the Tofino winter record. The adjusted sea level spectral densities are reduced from the unadjusted sea level but still contain energy peaks common to the unadjusted sea level and atmospheric pressure, indicating that the 1 cm-to-1 mb isostatic adjustment was not effective at all frequencies.

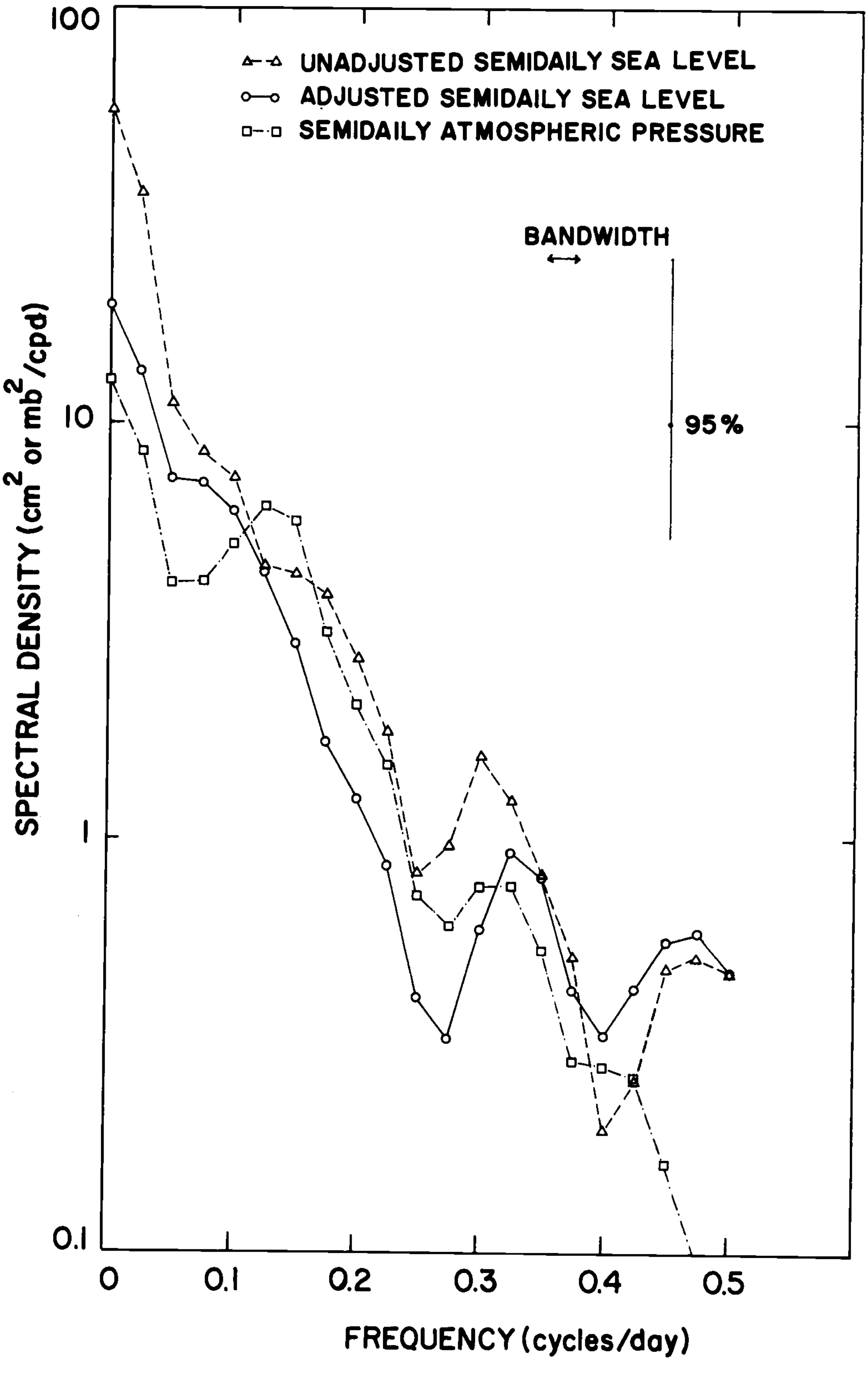

Figure 2. Summer spectral density (cm$^2$ or mb$^2$/cpd) of the San Francisco stations.

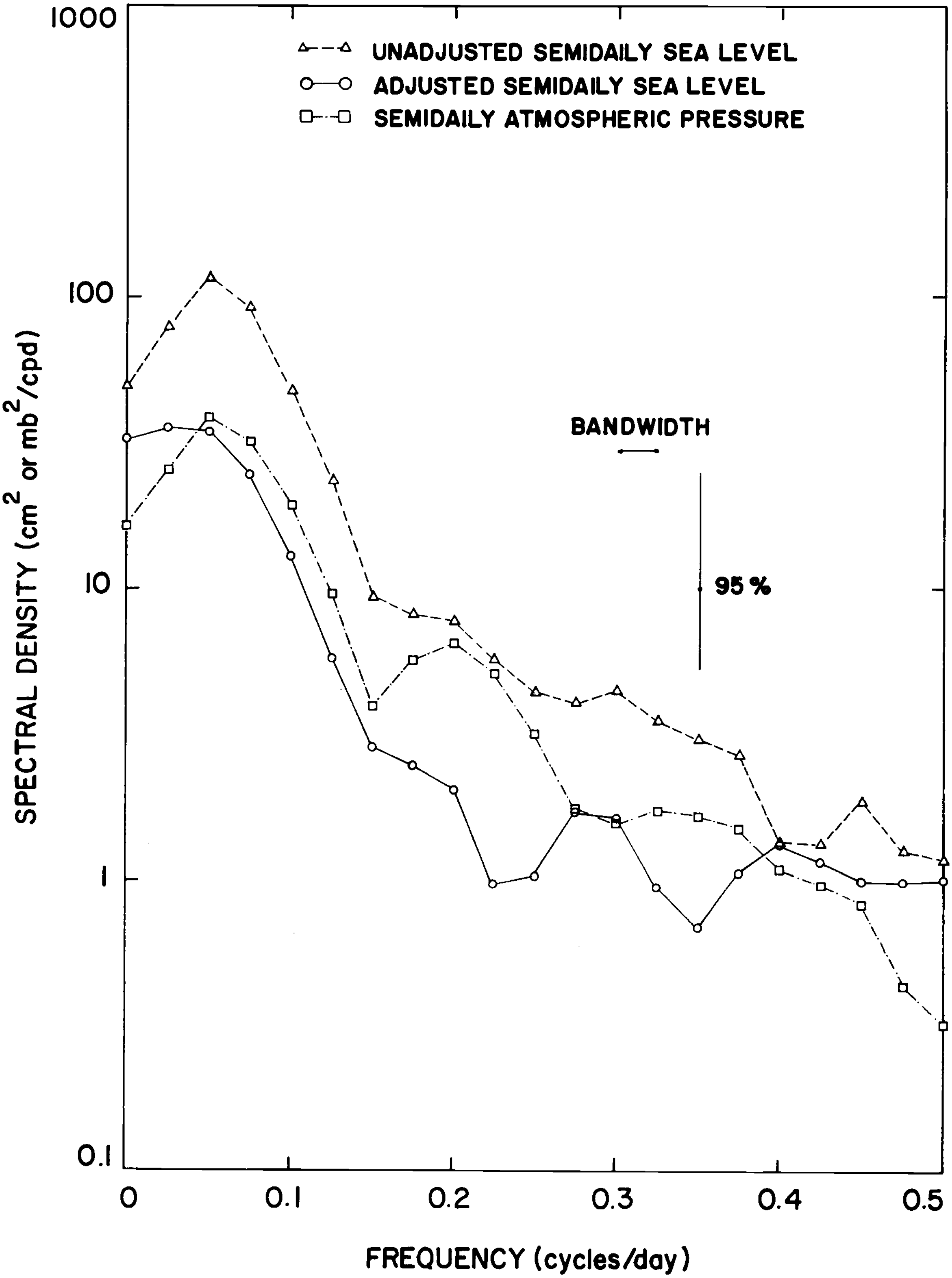

Figure 3. Winter spectral density (cm$^2$ or mb$^2$/cpd) of the San Francisco stations.

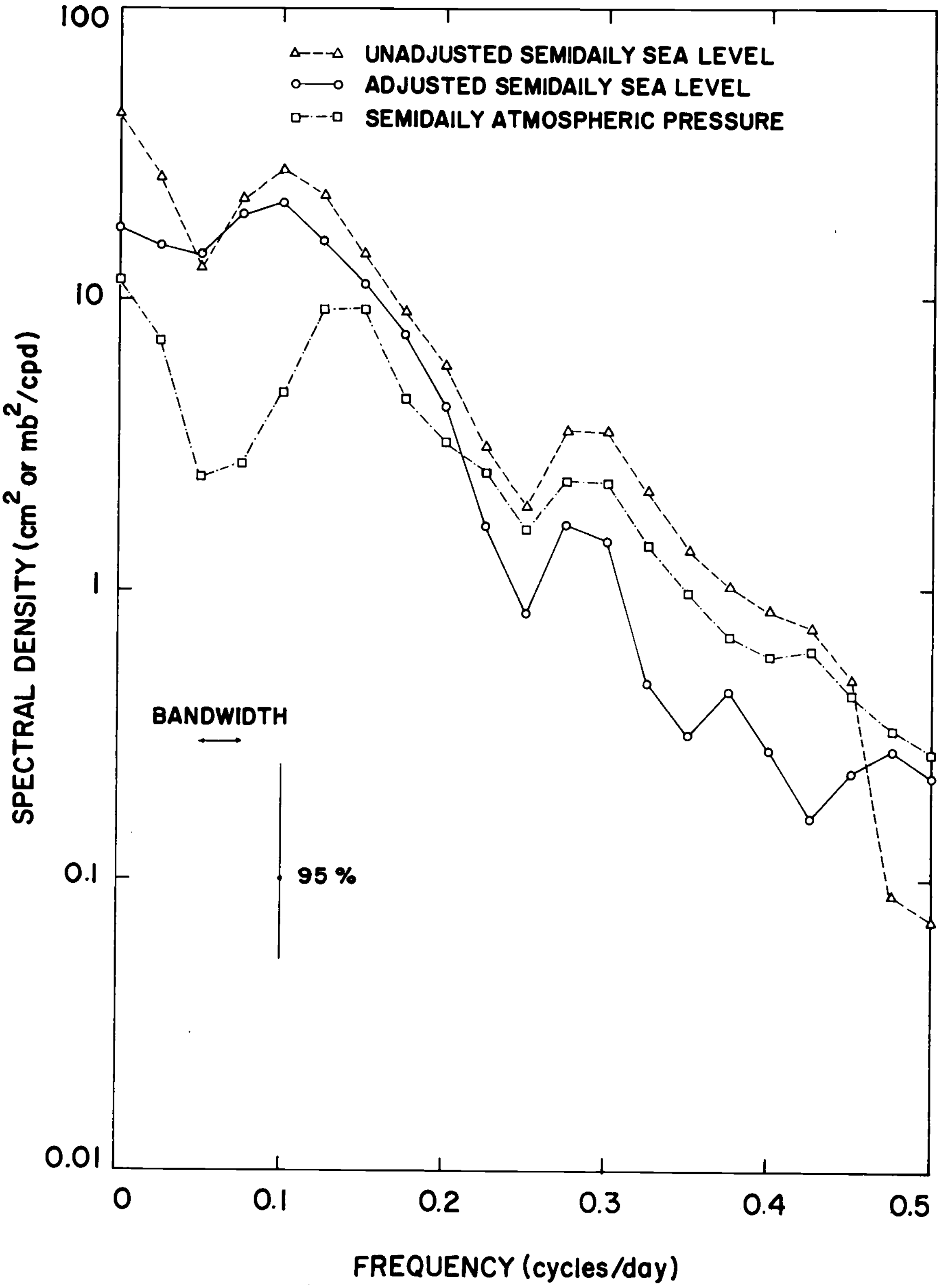

Figure 4. Summer spectral density (cm$^2$ or mb$^2$/cpd) of the Coos Bay-North Bend stations.

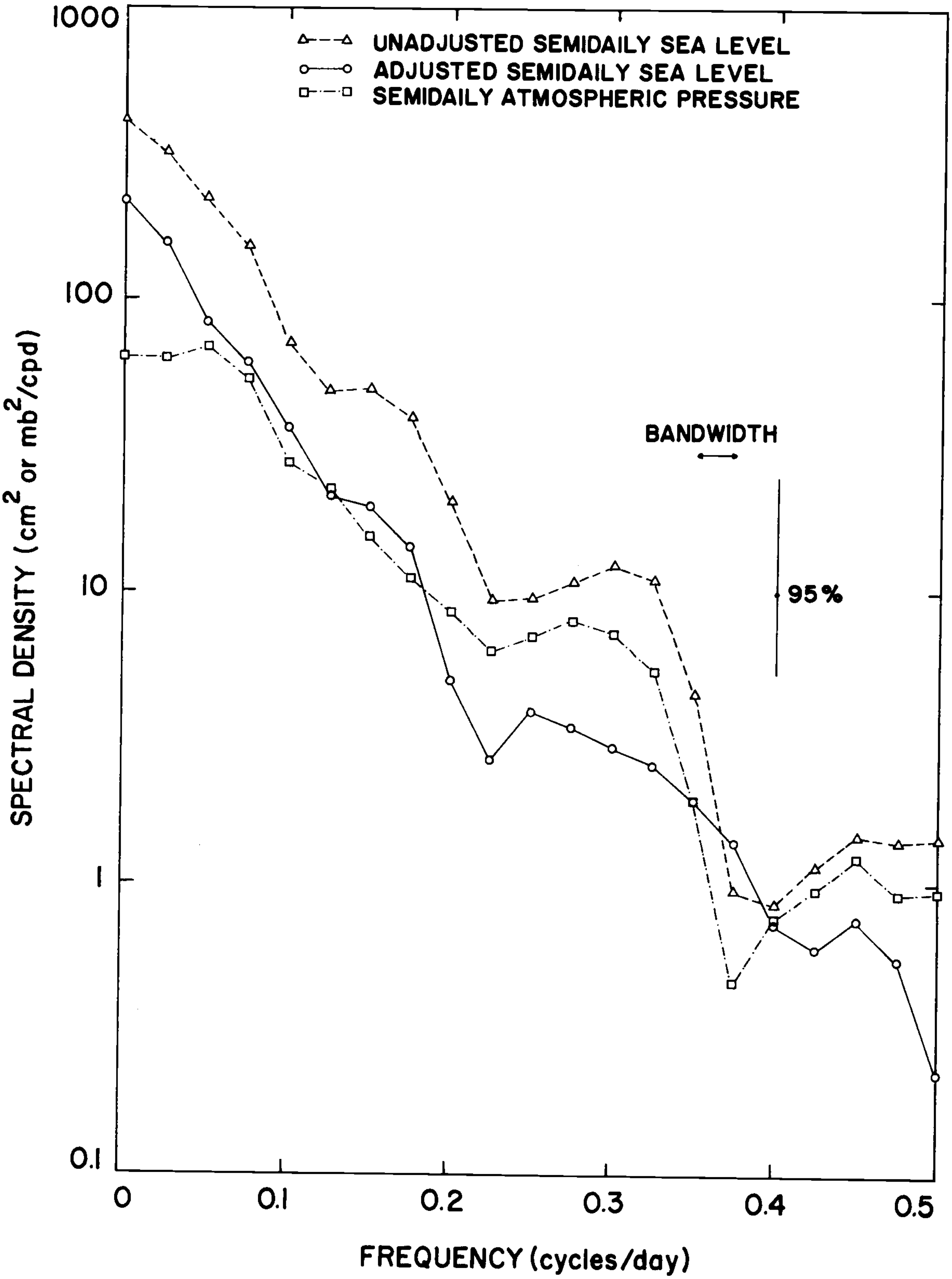

Figure 5. Winter spectral density (cm$^2$ or mb$^2$/cpd) of the Coos Bay-North Bend stations.

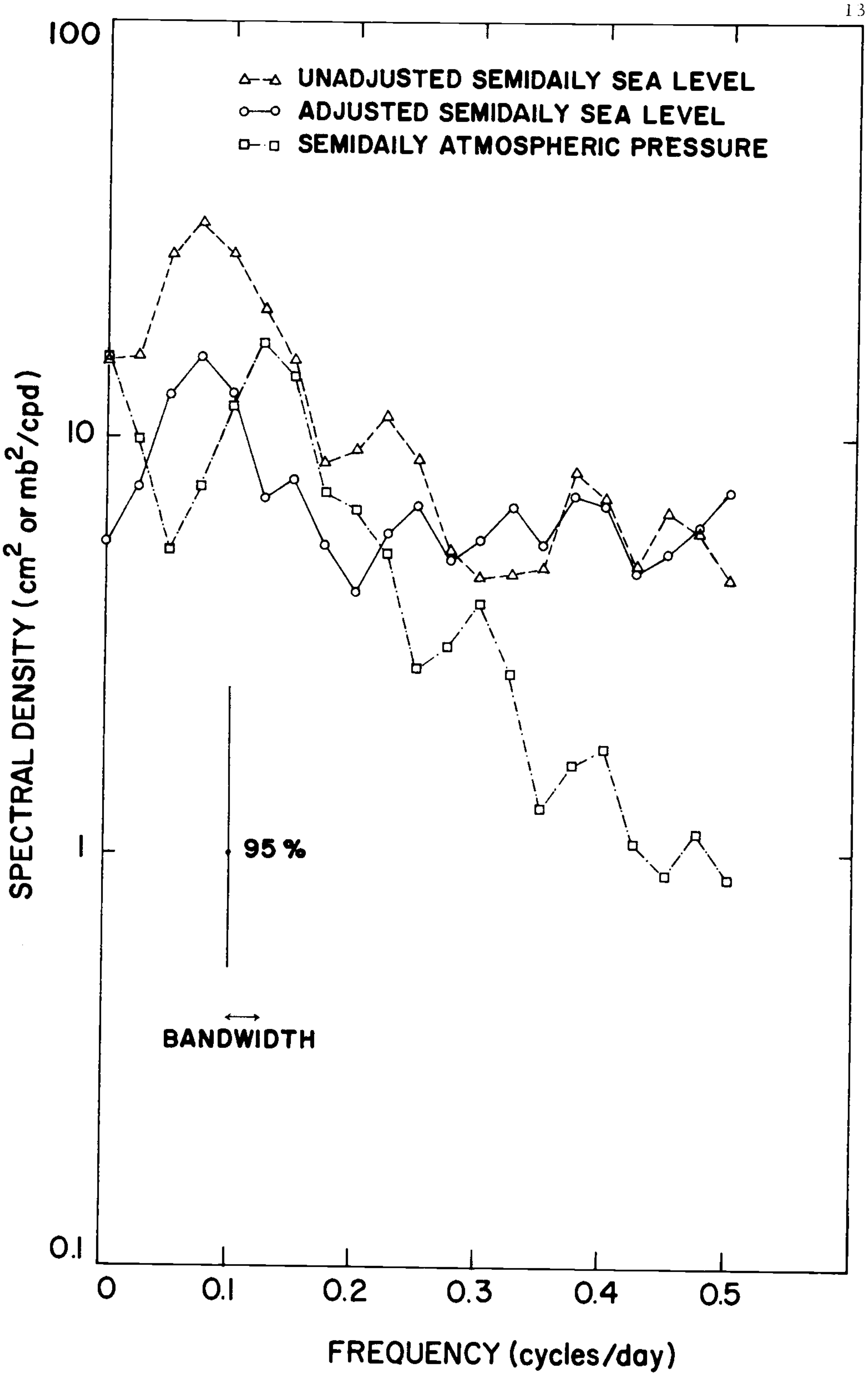

Figure 6. Summer spectral density (cm$^2$ or mb$^2$/cpd) of the Tofino-Estevan Point stations.

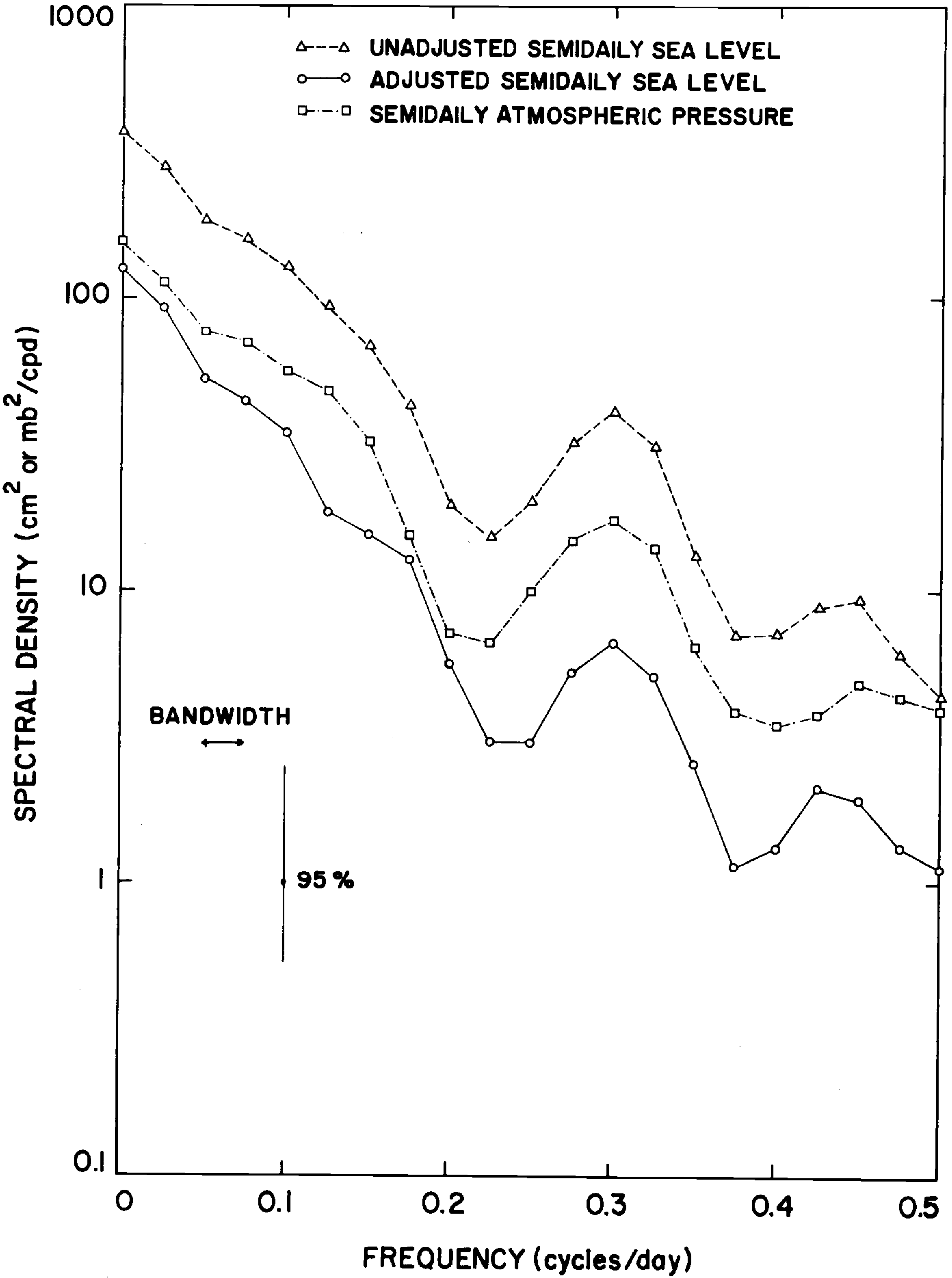

Figure 7. Winter spectral density (cm$^2$ or mb$^2$/cpd) of the Tofino-Estevan Point stations.

## BAROMETER FACTOR

Following Hamon and Hannan (1963), the in-phase barometer factor as a function of frequency, b(f), was computed as the ratio of the sea level-atmospheric pressure co-spectrum to the auto-spectrum of atmospheric pressure for all three stations for both the summer and the winter records. The barometer factors are presented in Figures 8 and 9. In this computation, the sea level spectra were recolored for the effect of the filter used in obtaining the semidaily mean values. Again following Hamon and Hannan (1963), an average barometer factor was obtained by a weighted average of b(f) over frequency; the weighting function is the frequency-dependent signal-to-noise ratio as defined by Hamon and Hannan (1963). The computation again was done for all six records over the frequency range 0-0.4 cpd and the results are shown in Table I. It can be seen from the figures and the table that although the barometer factor is all greater than 1 cm/mb at frequencies 0.3-0.325 cpd, the average barometer factor is less than the expected value of 1 cm/mb in the summer but appreciably greater than the expected value in the winter. In both seasons, the barometer factor is not constant with respect to frequency, and the isostatic hypothesis does not hold for all frequencies. This may indicate resonant response of a sharply tuned coastal regime to atmospheric phenomena, that is, the presence of a continental shelf wave.

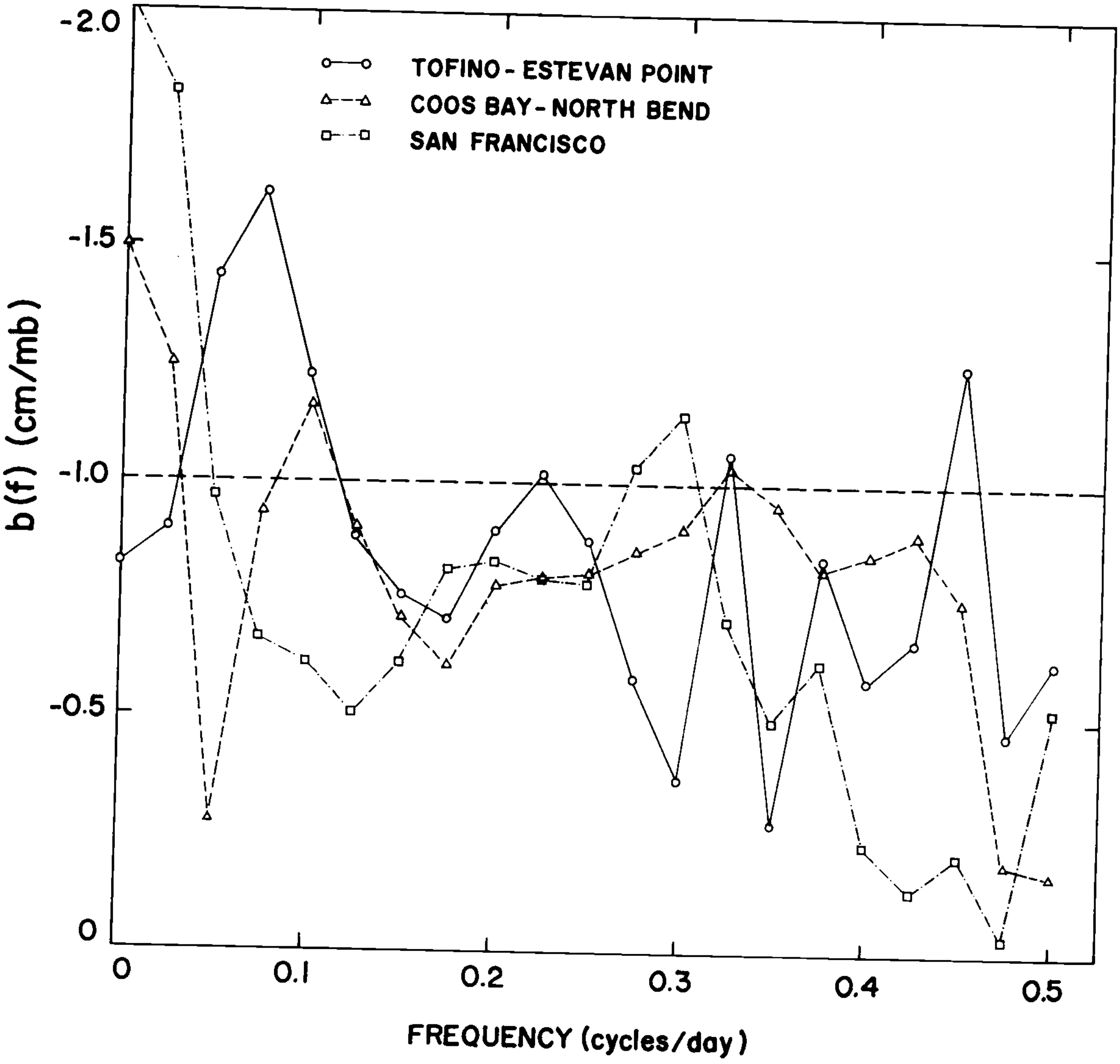

Figure 8. Barometer factor versus frequency for San Francisco, Coos Bay-North Bend, and Tofino-Estevan Point stations for the summer season.

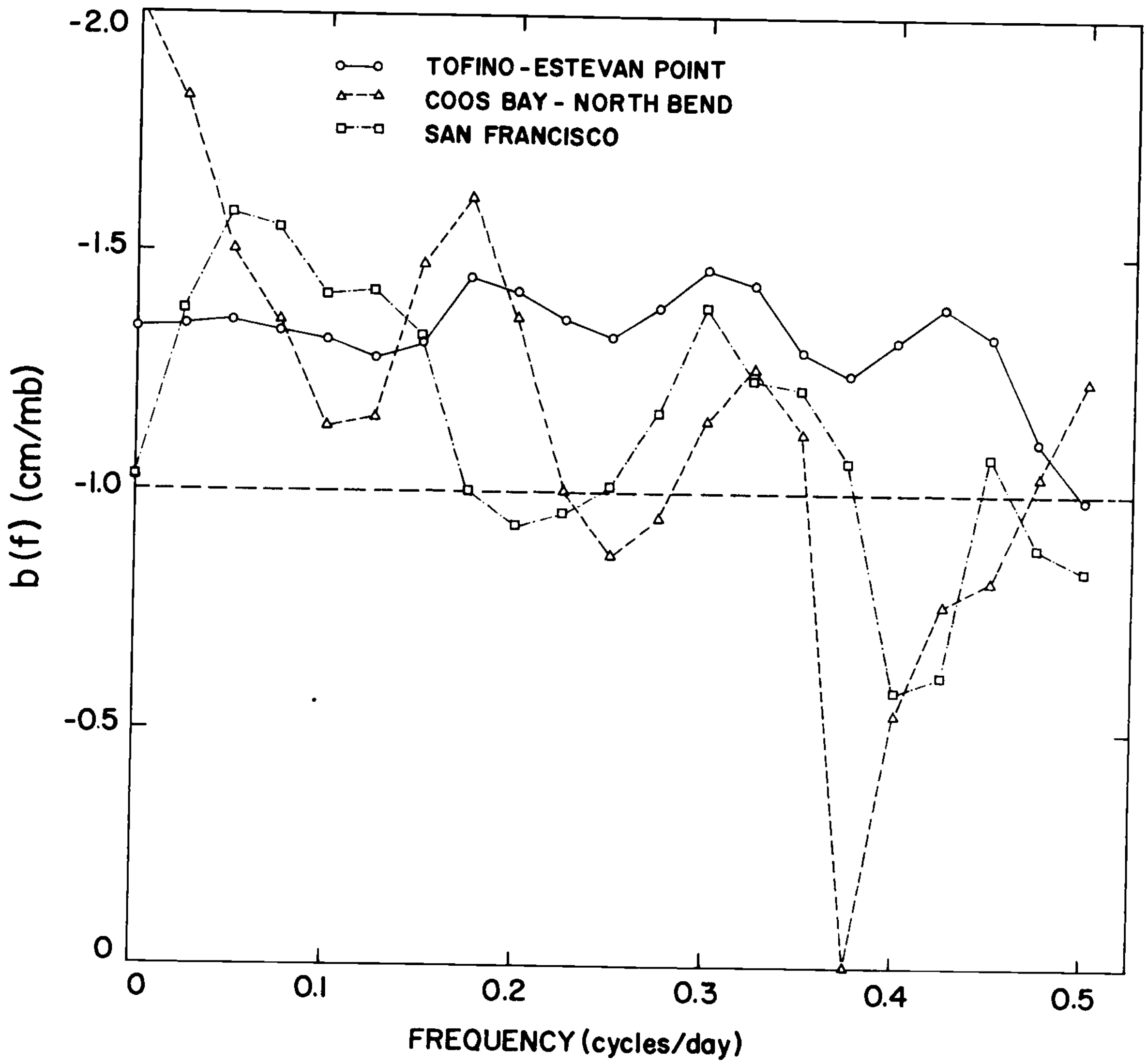

Figure 9. Barometer factor versus frequency for San Francisco, Coos Bay-North Bend, and Tofino-Estevan Point stations for the winter season.

## TABLE I

## THE WEIGHTED BAROMETER FACTORS

| Stations | Summer (cm/mb) | Winter (cm/mb) |
|---|---|---|
| San Francisco | -0.83±0.08 | -1.19±0.07 |
| Coos Bay-North Bend | -0.88±0.09 | -1.18±0.09 |
| Tofino-Estevan Point | -0.92±0.09 | -1.33±0.06 |

# ANALYSIS FOR CONTINENTAL SHELF WAVES

It was suggested by Robinson's model (1964) that nondispersive, traveling waves trapped in a gently sloping shelf of finite width and that are generated by low-frequency moving pressure systems might explain the anomalous sea level behaviour and the existence of sea level time lags between stations off the Australian coast. His model allows the waves to travel in one direction only, the same direction as the classical Kelvin wave. According to his theory, the sea level distortion $\zeta$ is assumed to be of the form

$$\zeta = \eta + \phi$$

where $\phi$ is the negative of the atmospheric pressure fluctuations measured in centimeters of water (1 cm = 1 mb), and $\eta$ the adjusted sea level, or alternatively, continental shelf waves. The amplitude of the shelf wave is observable only as a result of resonance between the shelf wave and the forcing function, e. g., the atmospheric pressure fluctuations. The continental shelf wave could either increase or decrease the apparent barometer factor. According to the model, on the west coast, the barometer factor would be enhanced, which was consistent with the winter results of the present investigation but for the summer results, it is true only within a very narrow frequency range, 0.30 - 0.325 cpd.

In Robinson's model, the frequency of shelf waves is small compared with the Coriolis parameter, and the wavelength is long compared with the shelf width. An infinite number of modes are possible; the first mode has an antinode at the coast, decaying exponentially towards the sea from the shelf edge, and higher modes have nodes and antinodes in between. The phase speed of the waves is assumed to be independent of frequency. For the fundamental mode, the phase speed, c, is given by

$$c = Lf/1.44$$

where L is the shelf width, and f the Coriolis parameter.

To apply Robinson's model to the northwestern American coast, the 100 fathoms contour line was taken to be the edge of the continental shelf. Fifty measurements of the shelf width were taken between Coos Bay and Tofino at regular intervals, and the result averaged. The average shelf width between Coos Bay and Tofino was estimated in this way to be 50 km. A similar procedure gives the average shelf width between San Francisco and Coos Bay to be 24 km. The distance between Coos Bay and Tofino is 720 km., and that between San Francisco and Coos Bay is 660 km., measured along the coast. Using the Coriolis parameter for the mean latitude between the pairs of stations, Robinson's model predicts a continental shelf wave phase speed of 3.6 m/sec. between Coos Bay and Tofino and 1.6 m/sec. between San Francisco and Coos Bay.

Mysak (1967) presented a more comprehensive model which incorporated a linear slope at the edge of the shelf. He also took mean current and deep sea stratification into account, obtaining a model which gave a theoretical phase speed which is about twice that of Robinson's model.

## Cross Spectral Analysis

The squared coherency and phase spectra obtained from the cross spectra of the sea levels give the correlation and the time displacement of one record with respect to the other as a function of frequency. In this computation, adjusted semidaily sea level was used. Computation was made for San Francisco versus Coos Bay, and for Coos Bay versus Tofino, for both the summer and winter records. Figures 10 and 11 show the squared coherency and phase spectra for Coos Bay versus Tofino and for San Francisco versus Coos Bay, respectively. As a test of statistical significance, the 95% significant level test for the squared coherency and the 95% confidence intervals for the phase spectra as given in Jenkins and Watts (1968) are shown in the figures.

It can be seen that the squared coherency for the San Francisco station versus Coos Bay station is not significant at the 95% significant level at frequencies greater than 0. 15 cpd. The adjusted sea levels at Coos Bay station versus Tofino station are not significantly

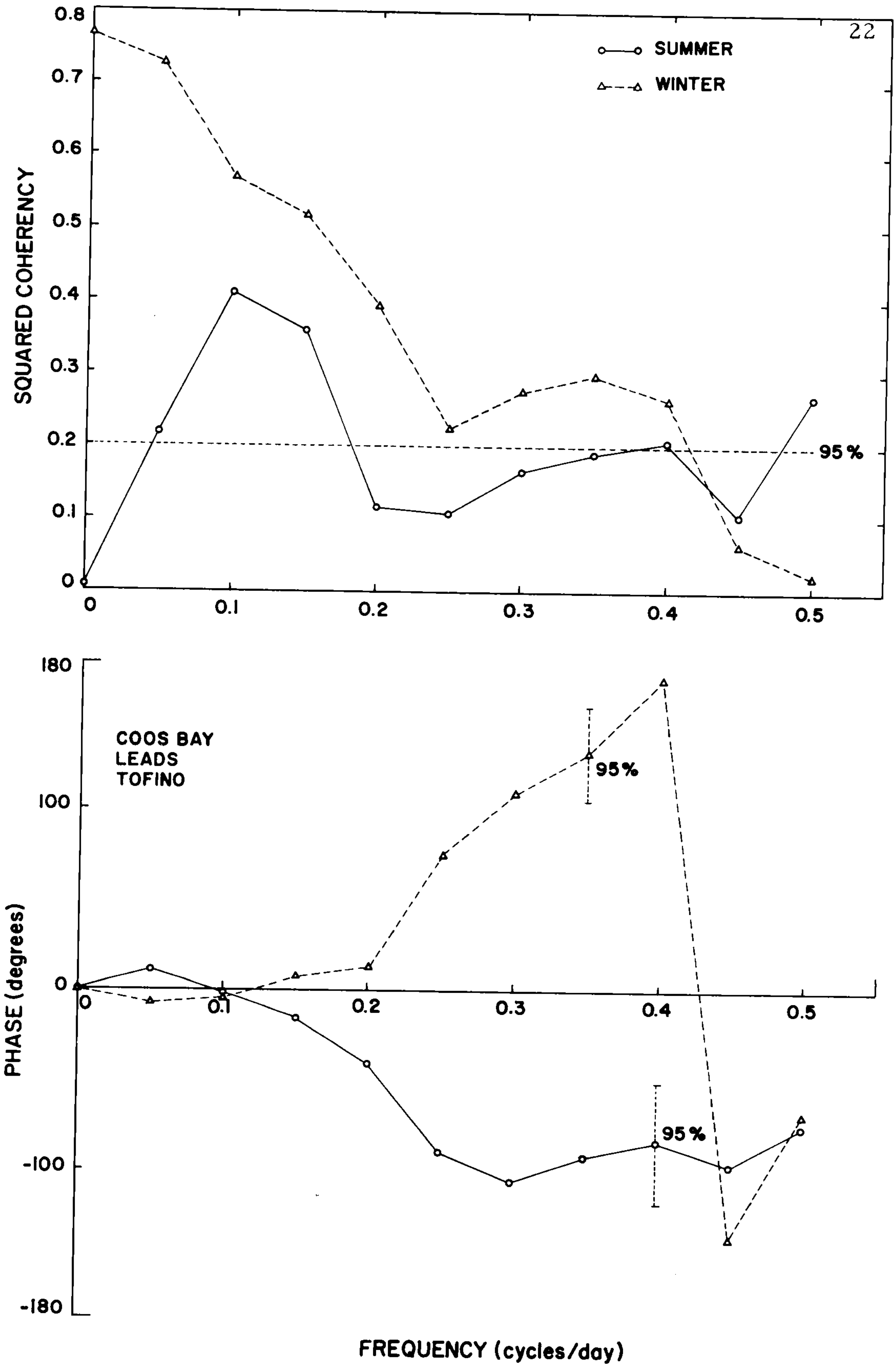

Figure 10. Squared coherency and phase of Coos Bay versus Tofino.

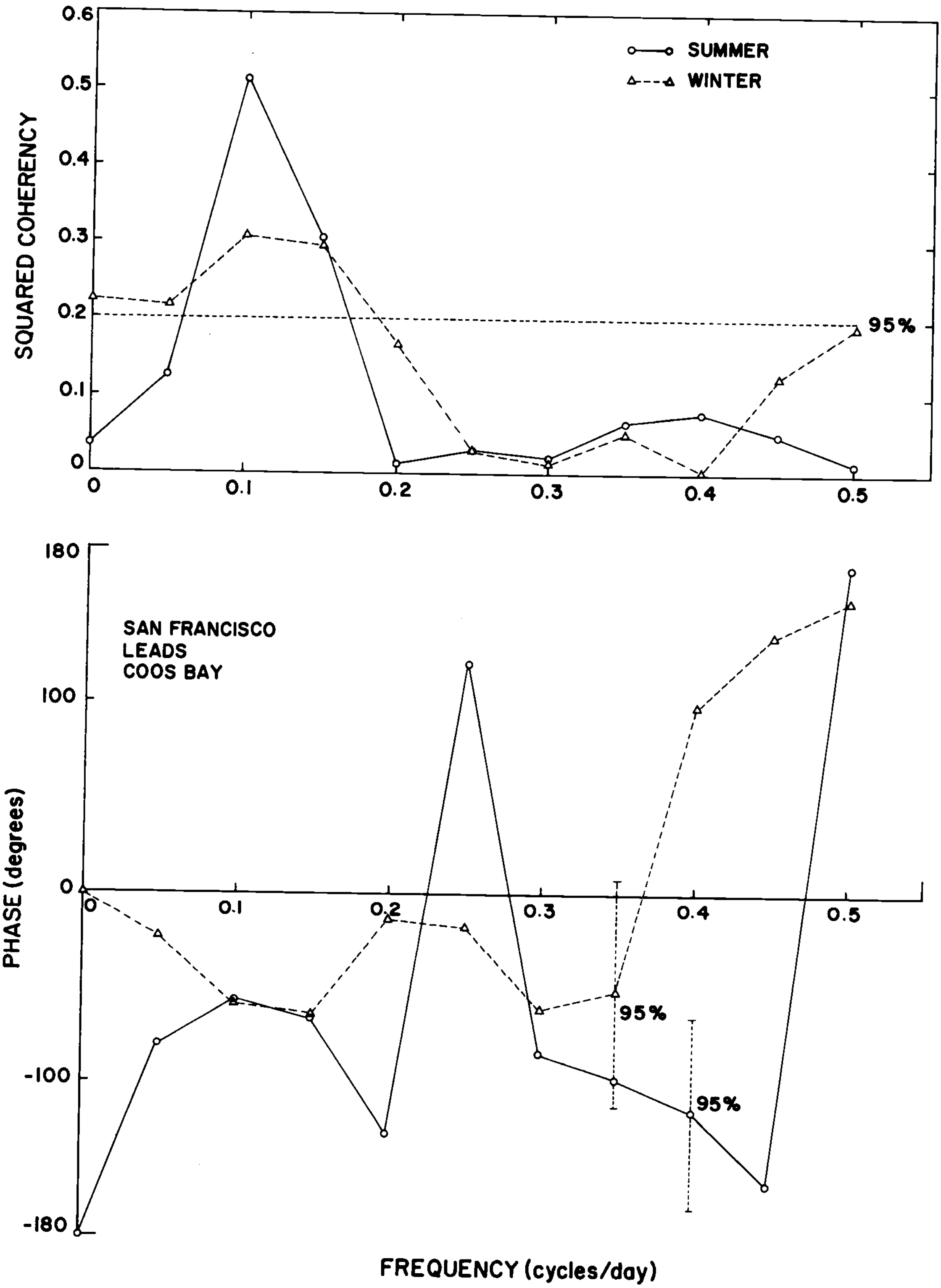

Figure 11. Squared coherency and phase of San Francisco versus Coos Bay.

## TABLE II

## COMPARISON OF THE THEORETICAL AND OBSERVED PHASE RELATIONSHIPS

| Station Pairs | Theoretical phase speed (m/sec.) | (Robinson, 1964) time lag (days) | Observed | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | phase lag | | time lag (days) | | phase speed (m/sec.) | |
| | | | 0.4 cpd | 0.34 cpd | | | | |
| | | | S | W | S | W | S | W |
| Coos Bay - Tofino | 3.6 | 2.4 | 276° | 130° | 1.9 | 1.0 | 4.4 | 8.1 |
| San Francisco-Coos Bay | 1.6 | 4.6 | 244° | 308° | 1.7 | 2.4 | 4.3 | 3.1 |

S = summer

W = winter

coherent at frequencies greater than 0.15 cpd except at 0.40 cpd in the summer, but are coherent at all frequencies less than 0.45 cpd in the winter. The squared coherency maxima above 0.15 cpd occur at 0.35 cpd in the winter and 0.40 cpd in the summer. The phase differences between stations for the frequency of the squared coherency maxima are shown in Table II. The phase differences are interpreted as lag times and the apparent phase speed of a wave.

Phase computations are ambiguous by an integral multiple of ±360°. The interpretation of phase in terms of a wave is thus ambiguous with respect to direction and number of cycles. In the interpretation given in Table II, all phases were taken to be between 0° and 360°. This interpretation leads to values consistent with the continental shelf wave theory and with observations of other investigators. Mooers and Smith (1968) observed significant coherence at 0.35 to 0.40 cpd in adjusted sea levels at Brookings, Coos Bay, and Newport, Oregon, for the same period as in this thesis. The phase differences they found indicated a continental shelf wave traveling northward at about 4 m/sec. Since the distances between the stations were only about 100 km. instead of about 700 km., as in this thesis, the phase difference is more certain. In all cases in the present investigation, the observed phase speed is higher than the theoretical phase speed as predicted by Robinson's model, a fact that was observed elsewhere by Hamon (1966), Mooers and Smith (1968), and

Mysak and Hamon (1969). However, Mysak's model gave a much higher predicted phase speed, which qualitatively agrees with the present result.

# DISCUSSION AND SUMMARY

The analysis of sea level and atmospheric pressure data indicates that the adjusted sea levels have energy peaks in the frequency band studied that are not removed by atmospheric pressure adjustment, indicating that the hydrostatic hypothesis does not account for all sea level variations. The barometer factor function indicates that, in the region of 0. 30 cpd, there is an apparent increase in the direct response of sea level to atmospheric pressure for all summer and winter records. Over the frequency range studied, however, the weighted average barometer factor is less than the expected value of 1. 01 cm/mb in the summer and is more than the expected value in the winter, indicating that factors other than the atmospheric pressure may be involved in the explanation of the generation of the shelf waves. Longshore wind probably is also a driving function for the shelf wave because in the west coast, the wind is intensified in the winter, and shifts from northwesterly in summer to southwesterly in winter. This is an interesting topic for further investigation.

The squared coherency and phase spectra indicates a continental shelf wave traveling from south to north, but with seasonally varying characteristics. (However, the coherence is above the 95% significant level for Coos Bay and Tofino only.) In the summer, the wave is found to travel with a frequency of 0. 4 cpd, and a speed that is greater than that predicted by Robinson (1964). In the winter, the wave has a lower frequency and travels at a higher phase speed, about twice that predicted by Robinson. Mysak's modification of the theory, based on an incorporation of current and deep sea stratifications, increased the theoretical phase speed considerably, which is in close agreement with the observations of the present investigation.

The seasonal variation in the barometer factor and in phase speed of the wave suggests that there may be some other mechanisms generating or affecting the waves. Future investigation should study the wind pattern as well as the atmospheric pressure fluctuations. The low coherency between San Francisco and Coos Bay adjusted sea levels may indicate that the Mendocino Escarpment affects the propagation of the wave. Tide gages should be put on both sides of the escarpment to measure the effect. Three more tide gages should also be put between Coos Bay and Tofino, each about one-quarter wavelength from the other, or about 200 km. apart. Barometer stations should be as close to the tide gage stations as possible.

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