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INVESTIGATION OF THE INFLUENCES ON THE MIXED-LAYER DEPTH DURING THE COOLING SEASON

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Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
METEOROLOGY

United States Naval Postgraduate School
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ABSTRACT

An analysis of bathythermograph data recorded at Ocean Station Papa (latitude 50N, longitude 145W) during the cooling season (October through December) indicates that the annual deepening and subsequent decay of the seasonal thermocline is accompanied by many random fluctuations. The physical processes causing the decay and the fluctuations in the mixed-layer depth are examined and qualitatively evaluated.

The Tukey spectrum analysis programmed for the CDC 1604 electronic digital computer was used in analysis of oscillations at the bottom of the mixed layer to determine the distribution of wave energy for series of data taken at hourly intervals. An energy peak centered near 12 hours was observed to predominate, and this energy is equivalent to that of a 12-hour internal wave with height of 27.0 feet. The computer was also used to select the significant meteorological and oceanographic parameters which could be used to predict a change in the mixed-layer depth by use of the BIMD 07 multiple regression program. The most significant parameter was sea surface temperature. The best correlation coefficient for this parameter occurred for lags of zero to 12 hours.

The results of the analysis support the theory that convection is the physical process which causes the seasonal decay of the thermocline during the cooling season and that short-term fluctuations of the mixed-layer depth are due primarily to internal waves.

The authors wish to express their appreciation for the assistance and encouragement given them by Associate Professors G. H. Jung and J. B. Wickham, and by Professor D. A. Williams and the staff of the computer center at the U. S. Naval Postgraduate School in this investigation. The authors also wish to thank the Pacific Oceanographic Group of Canada for making the oceanographic data available.

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TABLE OF SYMBOLS AND ABBREVIATIONS

$[A(h)]^2$	energy density (spectrum analysis)
BT	bathythermograph
$[C(h)]^2$	energy density (cross-spectrum analysis)
f	frequency
F	low cloud cover (eights)
FF	wind speed
FF_{-5}	wind speed with 5-hour lag
GPM_5	500-mb height in geopotential meters
$H_{1/3}$	significant-wave height
h	$2\pi f\Delta t$ ($H = 0, 1, 2.....m$)
$(H_{1/3})_{-5}$	significant-wave height with 5-hour lag
k	number of lags ($k = 0, 1, 2.....m$)
m	maximum lags and number of spectral values
MLD	mixed-layer depth
$\overline{MLD}$	mean mixed-layer depth
N	number of observations
P	pressure change
P_{-5}	pressure change with 5-hour lag
R'	multiple-correlation coefficient
RH	relative humidity
RH_{-11}	relative humidity with 11-hour lag
RH_5	500-mb relative humidity
RR	range of residuals
S	standard deviation
SE	standard error of the estimate
T	period (hours)

T_a	air temperature
T_{a-2}	air temperature with 2-hour lag
T_a-T_w	air-sea temperature difference
$(T_a-T_w)_{-2}$	air-sea temperature difference with 2-hour lag
T_{dp}	dew-point temperature
T_w	sea-surface temperature
T_{w-2}	sea-surface temperature with 2-hour lag
T_{wb}	wet-bulb temperature
T_5	500-mb temperature
Δt	sampling interval

1. Introduction

The vertical temperature structure of the near-surface layer in the open ocean is a complicated phenomenon which varies in space and time. Certain aspects of the temperature structure are of great significance in determining sonar effectiveness. Thus, both the military and the commercial fishing industries are interested in prediction of the thermal structure.

Various processes continually modify the thermal structure to produce an essentially homogeneous (mixed) surface layer, underlain by a thin layer of rapidly increasing density, which varies in thickness throughout the year. The mixed-layer depth (referred to as the MLD) is the depth below the water surface to which mixing has established isothermal conditions. The lower boundary of the MLD is the top of the thermocline, a thin layer of large, negative vertical temperature gradient, usually associated with the layer of increasing density. A complex interaction of meteorological, oceanographic, and (indirectly) astronomical factors provide the driving forces for changes in the ocean thermal structure.

Random and periodic fluctuations of the MLD have been examined by many investigators. It is known, as a result, that the MLD may vary from a few inches in the heating season to several hundred feet in the cooling season. At times it may fluctuate tens of feet in a matter of minutes.

The objective of this research is to identify more clearly significant processes which affect the MLD during the cooling season and to relate the MLD to meteorological and oceanographic parameters. The processes capable of affecting the vertical temperature distribution are discussed in the appendix. Certain of these processes will be considered in this paper: (1) thermohaline convection, (2) dynamic convection due to wind and wave action, and (3) unidentified processes which generate internal waves.

Up to now, only qualitative descriptions of the mixed-layer behavior during the cooling season are found in the literature. These usually state that increased wind stirring and surface cooling act together during the cooling season to drive the seasonal thermocline down to its maximum annual depth. Our findings will show that, at Station Papa, thermohaline convection is the most important factor and that wind mixing (dynamic convection) is actually insignificant during the cooling season.

Meteorological and oceanographic parameters contributing significantly to the change in the MLD during the cooling season are determined, and from these the physical processes of importance are inferred. The investigation was carried out with the aid of statistical correlation and wave-analysis programs, the BIMD 07 [16] and the Tukey spectrum analysis [15], utilizing the CDC 1604 digital computer. Regression equations and correlation coefficients are obtained by the BIMD 07 program. One part of the Tukey spectrum analysis was used to determine cross spectra of the MLD fluctuations and the sea-surface temperatures. This program was also used in the analysis of internal waves.

The investigation is based on oceanographic and weather data obtained by the Fisheries Research Board of Canada, Pacific Oceanographic Group, for the months of October, November, and December during the years 1956, 1957 and 1958 [6, 7].

2. Background

The attempt to identify the factors which bring about the hourly fluctuations in the MLD was based on the authors' earlier endeavor to derive an empirical method to predict the average MLD on a daily basis during the cooling season. It became apparent then that the hourly fluctuations of the MLD could be of equal or larger magnitude than the average deepening of the MLD during one or more days; thus, to use one or an average of two or more observed MLD values per day as representative of the depth for any particular hour of that day is misleading [5]. The probable cause of these fluctuations is internal waves.

Students at the U. S. Naval Postgraduate School during 1961 and 1962 derived empirical methods to predict the MLD at Ocean Station Papa during each of the 12 months of the year. In addition, the onset of the seasonal thermocline at Ocean Station Papa, which takes place in April or May, was studied by Clark in 1961 [2]. Clark successfully related the thermocline onset to upper-air parameters. During the heating season, when the seasonal thermocline gradually increases in magnitude, wind mixing processes have been clearly established as the dominant factor in determining the MLD, by Tabata [22] and Geary [10] in 1961. The cooling season remains to be studied. We have made this attempt.

3. Description of Ocean Station Papa

The geographic location of Ocean Station Papa is 50N, 145W (figure 1). It is approximately 400 miles north of the boundary between the eastern subarctic water mass and the subtropic water mass [8]. The water depth at Papa's location is 2000 fathoms; therefore, the thermal structure is in no way influenced by bottom topography. Also, its location is approximately in the center of the Alaskan Current Gyral [8, 9] (figure 1). Because of this location, the effects of advection are minimized and will not be considered.

The weather ship normally maintains an on-station position within a ten-mile square centered on 50N, 145W. In order to avoid rough weather, the ship may steam anywhere within the 210-mile square grid (figure 2). Each bathythermograph (BT) sounding is identified by a two-letter code. If the ship is on-station, the letter group OS indicates the position. The ship position for the greater part of the period of our concern was within a 30-mile square centered at OS. Any data outside of this 30-mile square were not considered in this study.

4. Review of Temperature and Salinity Structure during the Cooling Season

Figure 3 represents the decay of the thermocline during the year 1956. In August, the surface layers have been heated to a maximum, approximately 57F. Due primarily to wind mixing, there is a shallow mixed layer approximately 100 feet in depth with a sharp underlying thermocline. Within the thermocline, the water temperature drops to 40F at a depth of 200 feet. Progressing into the fall and winter, the MLD continually increases and the magnitude of the thermocline decreases. By the end of December, the MLD is nearly 330 feet in depth; and the sea-surface temperature has decreased to approximately 42F. Due to the presence of an intense halocline, the MLD reaches a limiting depth of 330 feet in January; and isothermal conditions prevail down to this depth for the remainder of the winter.

The basic salinity structure for the eastern subarctic Pacific water mass is shown in figure 4. Three zones are indicated. The upper zone extends from the sea surface to a depth of 330 feet, and is characterized by relatively low-salinity water (32.7‰) [21]. In the fall, the upper zone is isohaline and is marked by the presence of the seasonal thermocline. Because of the isohaline conditions in the upper 330 feet, we assume that significant variation in density is governed by changes in temperature only.

The halocline represents a transition zone between the upper and lower zones. Here, the salinity increases markedly with depth (as much as one part per thousand within an interval of 330 feet). The halocline represents a limiting depth for the seasonal thermocline. It is similar to having an ocean bottom at this depth as far as convective mixing is concerned. The density increase is so great through this layer that mixing cannot take place through it [20]. Within the lower zone (> 650 feet) the salinity gradually increases with depth to the ocean bottom.

5.a. Object

The purpose of this statistical study of the MLD is three-fold. An attempt is made: (1) to determine the relative importance of thermohaline convective mixing and wind-induced mixing on the deepening of the thermocline during the cooling season; (2) to determine the lag between a significant meteorological or oceanographic event and a subsequent change in the MLD; and (3) to examine the importance of the seemingly random short-term fluctuations of the MLD and to provide a description of those internal waves present.

First, the parameter or parameters are identified which have the largest linear correlation with the deepening of the MLD. Next, a further investigation has been undertaken of these significant parameters to determine the lag in the mixing process, that is, the time between the onset of a change in the parameter and a subsequent deepening of the MLD. Finally, the observed variations in the MLD which cannot be accounted for by either mixing process are investigated.

5.b. Method of Investigation

The parameters to be investigated are sub-divided into three groups. Those related to convective stirring are: (1) temperature of the sea, at the time of the sounding and with a 2-hour lag; (2) air temperature, at the time of the sounding and with a 2-hour lag; (3) dew-point temperature and wet-bulb temperature, at the time of the sounding; (4) relative humidity, at 2-hour and 5-hour lags; and (5) low-cloud cover, with a 2-hour lag.

Parameters chosen to represent wind and wave mixing are: (1) wind speed, at 2-hour and 5-hour lags; and (2) height of significant waves, at 2-hour and 5-hour lags.

Parameters chosen which were shown to have a correlation with the thermal structure by others in previous studies, but did not conveniently fall into the above categories, are: (1) 500-mb height, in geopotential meters; (2) 500-mb temperature and 500-mb relative humidity, at a 2-hour lag; and (3) surface-pressure change, with a 2-hour and 5-hour lag.

These data were obtained from synoptic 3-hourly reports, twice-daily constant-pressure records, and the BT traces. The available BT's for the period of investigation were tabulated in two groups, 0200Z and 1700Z, for each year to eliminate any possible yearly anomalies or diurnal trends. An investigation by Scripps Institution of Oceanography of the annual MLD fluctuation in the northeastern Pacific Ocean shows that the MLD most frequently observed in a given month often varies considerably from year to year [18]. The available literature on diurnal trends during the cooling season is not so clear. A preliminary investigation of the data showed no marked diurnal trend. This indication was supported by Dr. Tully of the Pacific Oceanographic Group, in a conversation with the authors, in which he stated that during the cooling season the MLD is too deep to have a clearly defined diurnal fluctuation.

With the aid of a multiple-regression and correlation analysis, the BIMD 07 programmed for the CDC 1604 high-speed computer, the linear-correlation coefficients were obtained for the pre-selected group of meteorological and oceanographic parameters with the MLD. The BIMD 07 program was used because it can select different sub-samples of data that are obtained from the same population. Thus, the program would perform linear-correlation analysis and linear multiple regression on the data for 0200Z and 1700Z, separately and in combination. In this way, a close examination of possible diurnal trends could be made for each of the three years studied, 1956 through 1958. The analysis provided regression equations for nine different data groups for the periods shown in Table I.

The BIMD 07 program yields best results when the number of independent variables is not greater than one-half the number of values of the dependent variable. Since the smallest number of values for the dependent variable is 36 (at 0200Z, 1958)[1], only 18 independent variables were investigated. A set of 18 secondary parameters was tabulated in the event that the analysis of the 18 primary parameters proved inconclusive.

There was no attempt by the authors to eliminate possible duplication of parameters that are indicative of the same process. For example, dew-point temperature, wet-bulb temperature, relative humidity, and low-cloud cover are all related to evaporation; but it was left to the BIMD 07 program to discern which ones, if any, were significant in contributing to the prediction of the deepening of the MLD.

The BIMD 07 is unable to produce a multiple linear-regression equation if any independent variable is a linear combination of two or more independent variables. Therefore, temperature of the air minus temperature of the sea, which is often used as an indicator of thermohaline convection, could not be investigated in conjunction with the air temperature and sea temperature. Consequently, three additional problems were computed using the air-minus-sea temperature parameter in place of sea-temperature parameters. See Table II for the tabulated results of the 12 problems.

In analysis of all the data, certain facts and tendencies are evident; these are discussed in the following two paragraphs.

The only parameters that show a consistently high linear correlation with the MLD in every sample or sub-sample are the sea-surface temperatures, at the time of the sounding and with a 2-hour lag. They also accounted

[1] (This small number results because BT data for October, 1958 are missing; only a small number of observations was available in 1957 as well, since December, 1957 observations were not taken.)

for almost all of the variance explained by the regression equation using all 18 parameters. Figure 4 shows the close relationship between the sea-surface temperature and the MLD from October through December, 1958. Likewise, Zettel [25] suggested that sea-surface temperature might be a good "indicator" for the MLD.

Wind speed and height of the significant waves, the parameters chosen as indicators of wind stirring, have either very low negative or low positive correlation coefficients.

In order to determine the time required for an increase in convective activity due to a reduction of sea-surface temperature to effect a subsequent deepening of the MLD, the MLD's for 1700Z, 1956, were tabulated with the sea temperature at lags of zero, two, five, eight, eleven, fourteen, seventeen, twenty-one, and twenty-three hours as the independent variables. A simple linear-correlation program was used to determine that the lag yielding the best correlation was two hours (Table III).

Also, two one-hourly series of MLD for 79 hours in October, 1957, and for 51 hours in November, 1958, were tabulated with their corresponding sea-surface temperatures. The energy-density spectrum and the cross-spectrum of both the MLD and the sea-surface-temperature time series was obtained from the Tukey analysis. Maximum lags of 39 hours and 24 hours were used for the 79-hour and 51-hour series respectively. The two co-spectra for the 79-hour and the 51-hour series show large values for h's around 8 hours and 4 hours respectively (figure 5).

From the results of the simple linear correlation and the Tukey analysis,[1] it is seen that all lags from two to six hours show high correlation. Beyond 12 hours the correlation rapidly decreases.

A linear-regression equation was derived for 1700Z, 1956, using sea temperature with a 2-hour lag as the single independent variable (Table IV).

[1] on cross-correlation, not shown

The fact that the results of this equation as measured by the standard error compare favorably with the multiple-regression equation derived from 18 independent variables for the same year supports the initial analysis of the problem. If a regression equation were to be used to forecast MLD, one using only the sea-surface temperature taken with a lag of up to 12 hours would be much more reliable than an equation with more parameters. This is true simply because it would have a larger number of degrees of freedom. Note that all of the regression equations have a standard error of from 15 to 30 feet, with an average for all problems of 22.15 feet (Table V, Table VI).

There are several possible explanations for this standard error of more than 20 feet: (1) it is possible that not enough parameters were used, and that by substituting for primary parameters which showed a very poor correlation, some of the secondary parameters or primary parameters with different lags, the standard error of the new regression equation would be reduced; or (2) there is a strong possibility that a non-linear relationship between a parameter and the MLD could account for a large part of the standard error (however, the BIMD 07 program cannot detect this); or (3) the error may be due to internal waves. Of these possibilities, (3) seems the most likely reason to explain the observed standard error.

6. Analysis of Internal Waves

The base of the mixed layer in the ocean is subject to many vertical oscillations. Figure 7 shows a series of daily MLD's for the period October through December, 1956. Each plotted point on the curve is an average daily value of the MLD. Two individual soundings are normally used; however, up to 24 soundings were available on several days. It is observed that the MLD undergoes a seasonal downward trend. During the October through December period, the seasonal trend of the MLD finds it increasing from approximately 130 feet to 330 feet. This is an average deepening of 2.17 feet per day. Also, large vertical fluctuations are superimposed on this downward trend, which become larger in magnitude as the mixed-layer thickness increases. Note in figure 7 that the vertical fluctuations of the MLD can be ten times greater than the average daily deepening. In addition, it is seen (figure 8) that hourly fluctuations can be of equal or greater magnitude than the average daily deepening during the fall.

Figure 8 represents a one-hourly time series for 51 consecutive hours during November, 1958 (series 1). A second one-hourly time series represents 79 consecutive observations taken during October, 1957 (series 2). The magnitude of the MLD fluctuations is about the same, whether it is computed from hourly, twice-daily, or daily observations. The average fluctuation per hour of the MLD for series 1 is 18 feet. The average fluctuation between the consecutive 0200Z and 1700Z soundings for the month of November, 1958, is 21 feet. Also, the averaged daily fluctuations during November is 25 feet. The numbers for series 2 are similar. A December, 1956, one-hourly time series (figure 9) was available but was too short for detailed analysis. However, it illustrates the extreme fluctuation of the MLD which takes place over a short time interval. Over a 3-hour period, the MLD increased from 270 feet to 370 feet, and then decreased again to 235 feet.

Since mixing processes can account for only an increase in the MLD, and since observed fluctuations are in both directions (up and down), and are a consistent feature of the data, these observed fluctuations are considered to be due to internal waves.

Internal waves may occur within stratified water and in water in which the density increases with depth. The largest vertical displacements of the water particles are to be found within the boundary between layers of different density. The displacement amplitude diminishes above and below this boundary, approaching zero at the sea surface and the ocean bottom. The density difference between the waters above and below the seasonal thermocline is, of course, much less than the density difference between the air and the water at the sea surface. Therefore, a boundary within the ocean can be much more easily displaced than the surface of the sea [17] Ufford [24] states that surface waves require 30,000 times more energy to start and maintain than is required for internal waves of the same amplitude. Energy for internal waves could come from surface disturbances or from currents within the ocean.

Besides rapid vertical oscillations in the MLD, it was observed that the thickness (or vertical extent) of the thermocline layer below the MLD may vary markedly with time. Figure 10 shows the thermocline thickness for series 1. Variations in the thermocline thickness indicate that internal-wave characteristics of phase and amplitude vary with depth. Also, the temperature gradient in the thermocline varies markedly because of changes in its thickness. The actual temperature difference through the thermocline is a relatively stable feature and is therefore predictable [11] .

Tabata [22] has estimated from theory that internal waves with as low a period as five minutes could form and propagate during the summer at the level of the seasonal thermocline at Ocean Station Papa. With one-hourly observations available for analysis, the minimum period that could be investigated is two hours.

The Tukey spectrum analysis, programmed for the CDC 1604 computer, was used to analyze each time series. The main object was to find any predominant periods and associated amplitudes present in the MLD oscillations. The Tukey analysis estimates the energy-density as a function of period in a given series. This is done by computing the auto-correlation function for a number of given lags in the series; then a smoothed spectral estimate is obtained from the Fourier cosine transform of the auto-correlation function.

Initially, a correlogram was plotted for both time series (figure 11). The correlogram is a plot of the non-normalized auto-correlation coefficients as a function of the lag (k). Inspection of this correlogram appears to indicate that the spectrum of series 1 has a relatively large energy-density maximum near the 12-hour period and a secondary maximum with a peak near six hours; and that the spectrum of series 2 has only one maximum near 12 hours.

Next, the energy-density spectrum of both time series was obtained from the Tukey analysis. Figure 12 is a plot of the energy-density spectrum for series 1. A maximum lag (m) of 24 hours was used, which allowed the spectrum to include a range of periods from two hours through 48 hours. The spectrum helps confirm the indications of the correlogram. A maximum of energy of the variance of the MLD is shown to be produced by fluctuations with periods on the order of 12 hours. Also, a large energy-density is indicated for periods around six hours. There is an energy gap for the periods around eight hours, and the energy for periods less than five hours drops off rapidly to an insignificant amount.

The total energy is a known quantity, equal to twice the variance. By measuring total area under the spectrum curve and the area under each frequency peak between half-energy points, equivalent amplitudes for waves with periods near 12 hours and six hours were computed. These computed amplitudes are 18 feet and 12 feet for the 12-hour and the 6-hour periods, respectively.

The energy-density spectrum for series 2 is shown in figure 13. A maximum lag (m) of 30 hours was used, which allowed inspection of periods ranging from two hours through 60 hours. A relatively large energy maximum is again indicated for periods around 12 hours. The curve then falls off rapidly, but shows a slight maximum near the 6-hour range of periods. A single sine wave with energy equivalent to that under the 12-hour peak would have an amplitude of nine feet.

This analysis reveals three features of the thermal structure at Ocean Station Papa during the time interval investigated.

(1) Vertical oscillations of the MLD are present at the thermocline during the cooling season. The magnitudes of these oscillations are similar in all data, whether they be from hourly, twice-daily, or daily observations.

(2) Although the time series available was much too short on which to base strong conclusions, the analysis did reveal that the major energy peaks occurred with a period of approximately 12 hours with an average amplitude of 13.5 feet.

(3) The value of the standard error of estimate resulting from the BILD 07 regression equations is very close to the height of the postulated 12-hour wave (that is, 27 feet). Therefore, it is concluded that there

is a direct relation between this error and the presence of internal waves during the period of investigation.

7. Conclusions and Recommendations

As a result of this study of the influences on the MLD during the cooling season, the following conclusions can be reached.

(1) Thermohaline convection is the important process for the deepening of the MLD in the autumn season.

(2) During the period of study, the MLD is too deep to be affected by wave stirring or diurnal trends.

(3) The time lag between surface cooling and deepening of the MLD by the convective process is small; this suggests that once the cooling season begins, convective circulation is essentially continuous. This circulation may be maintained during periods of near-zero heat flux across the air-sea interface by wind energy, as suggested by LaFond [13]; however, until an injection of potential energy in the form of rapid surface cooling, the MLD will remain relatively static. If the increased surface density caused by surface cooling is sufficient, the convective circulation intensifies and drives the MLD deeper.

(4) A major portion of the MLD variability appears to be associated with internal waves. The analysis of internal waves revealed that the major energy peaks occurred with a period of approximately 12 hours with an average amplitude of 13.5 feet.

Early in 1953, at a Navy-sponsored thermocline conference attended by 20 of this country's most prominent oceanographers and meteorologists, the following question was asked his colleagues by Dr. T. F. Malone: "How accurate a prediction of the MLD and its hourly fluctuations is required by the military?" [19] This remains a vital question.

If the military is willing to accept forecasts of the MLD within ranges of 20 or 30 feet, then existing methods of prediction will suffice. Any increase in accuracy over existing schemes for predicting the MLD at a particular hour on a particular day can be accomplished in areas where internal waves are important only after prediction of the internal wave pattern is possible. This is a complicated problem.

If a sufficiently long, detailed time series of BT's could be made available, internal waves could be filtered out by use of a technique such as proposed by Linnette [14]. This would leave a time series of the MLD that is due entirely to convective mixing or other causes, thus enabling a much better quantitative analysis of the convective process. This is suggested as the next logical extension of the research reported in this paper.

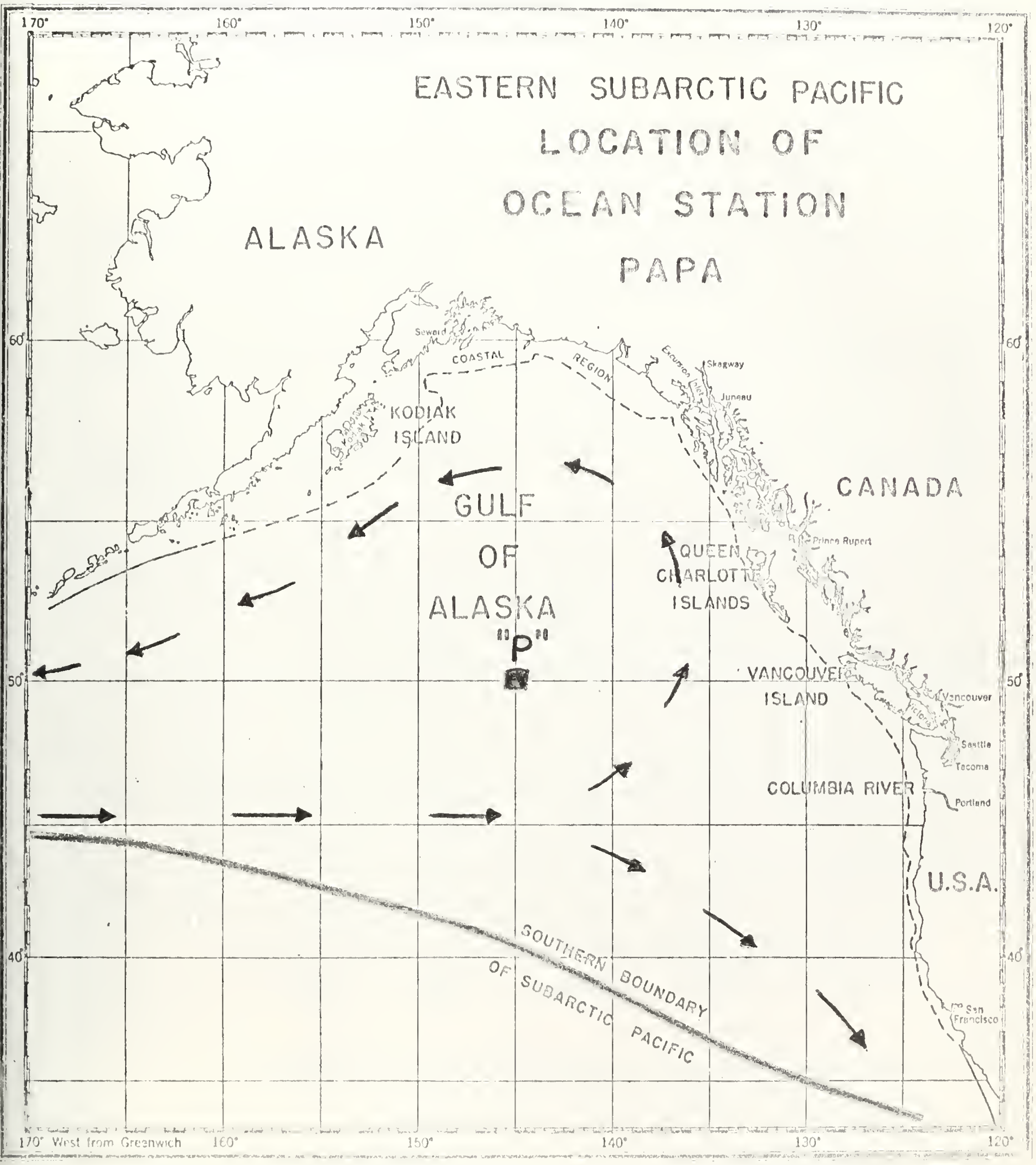

EASTERN SUBARCTIC PACIFIC
LOCATION OF OCEAN STATION PAPA
ALASKA
CANADA
U.S.A.
GULF OF ALASKA
"P"
KODIAK ISLAND
QUEEN CHARLOTTE ISLANDS
VANCOUVER ISLAND
COLUMBIA RIVER
COASTAL REGION
SOUTHERN BOUNDARY OF SUBARCTIC PACIFIC
Seward
Skagway
Juneau
Prince Rupert
Vancouver
Seattle
Tacoma
Portland
San Francisco
170° West from Greenwich
160°
150°
140°
130°
120°
60°
50°
40°

FIGURE I

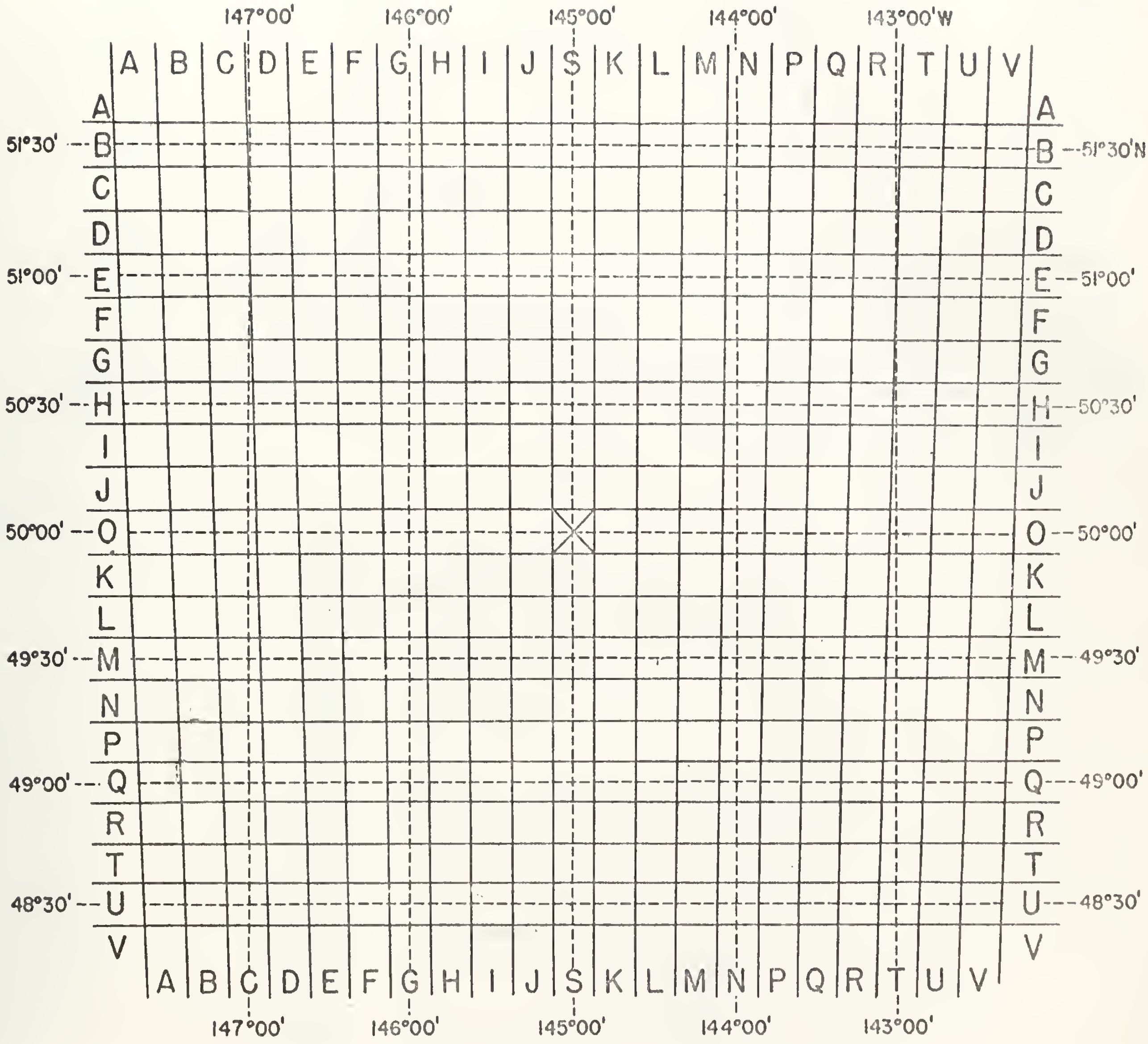


Figure 2. Position-Indicating Grid for Ocean Weather Station Papa, with a Mercator Projection of a Latitude and Longitude Grid Superimposed

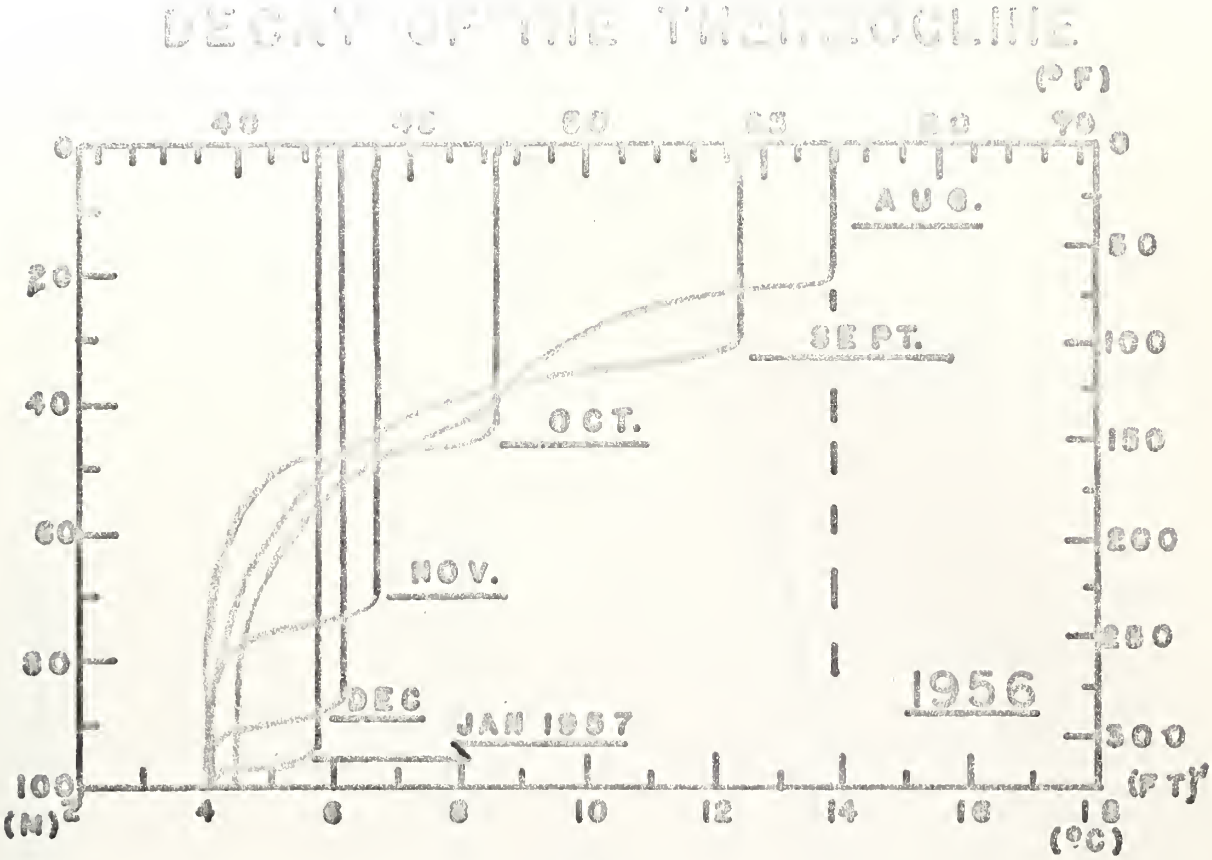


Figure 3.

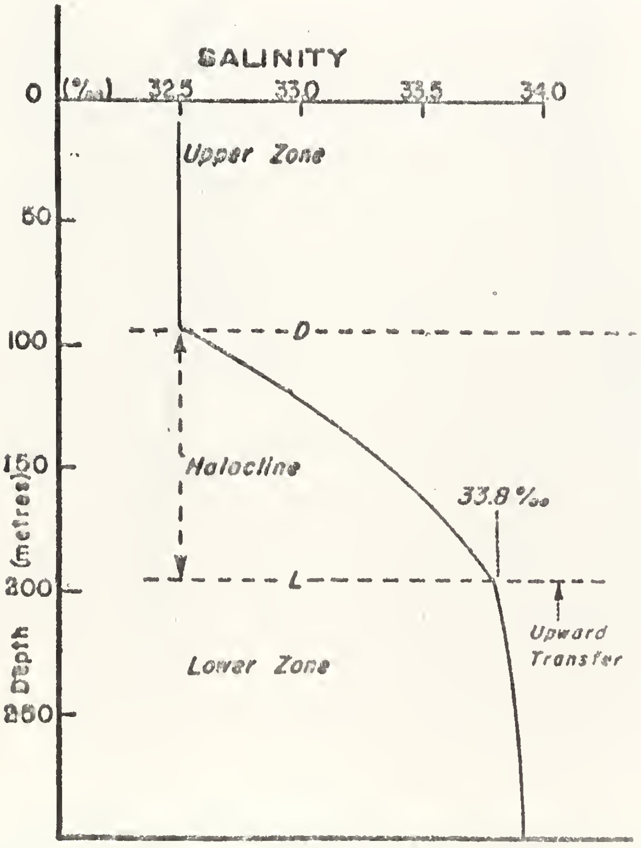
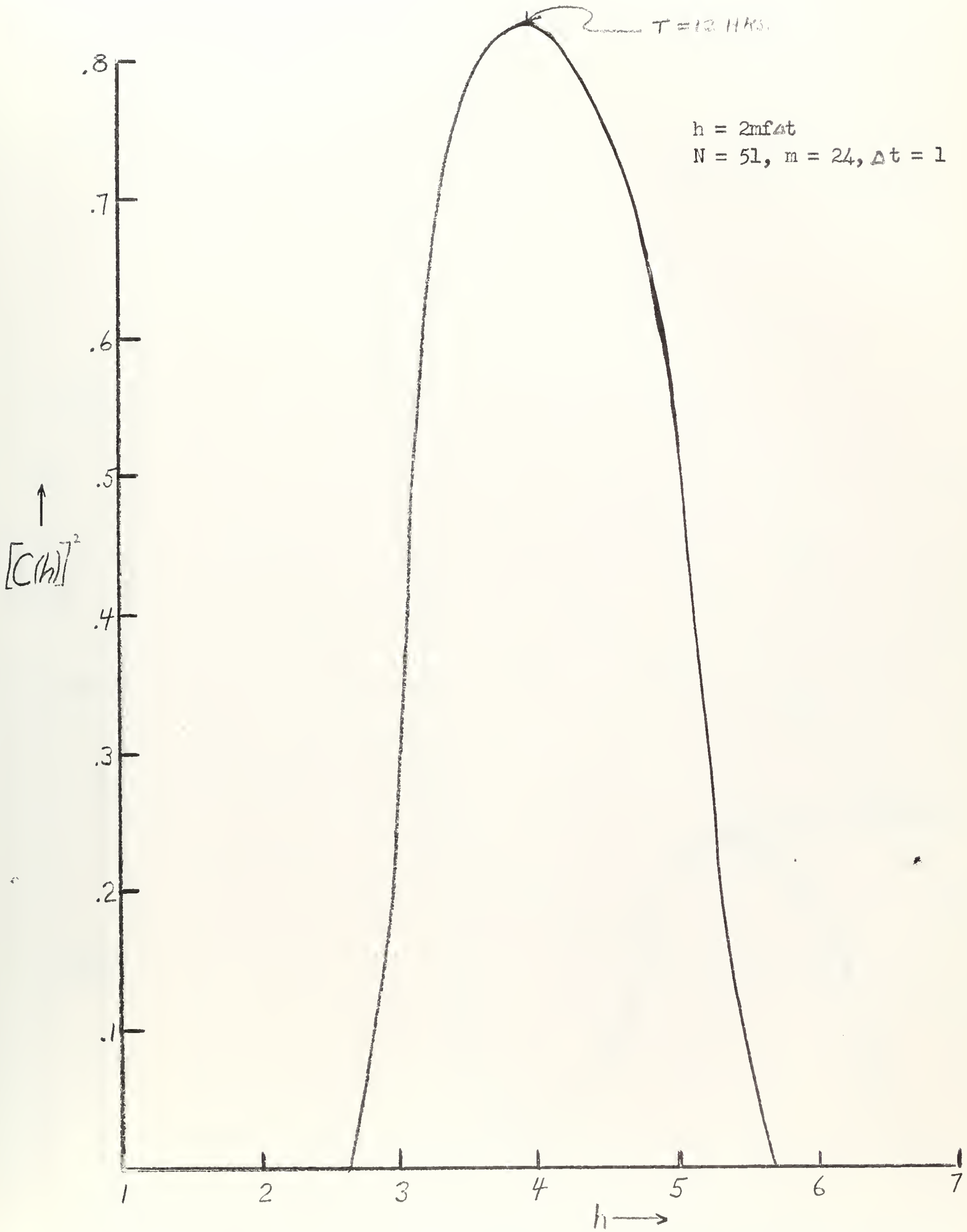


Figure 4. Salinity Structure in Eastern Subarctic Pacific Ocean

Figure 5.2. Cross-Spectrum - MLD and Sea-Surface-Temperature Time Series (November. 1958)



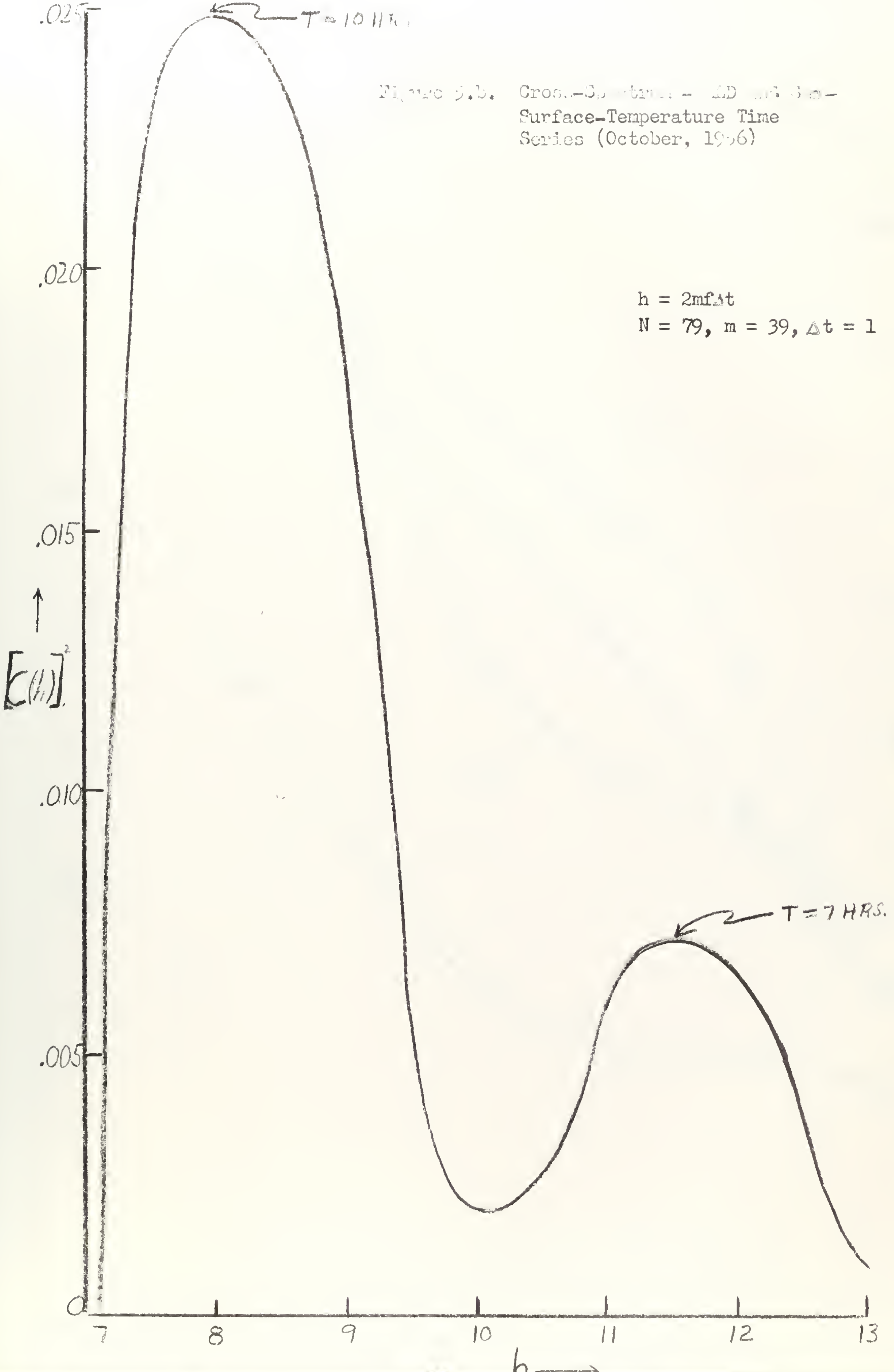


Figure 5.b. Cross-Spectrum – ILD and Sea-Surface-Temperature Time Series (October, 1956)

$h = 2mf\Delta t$
$N = 79,\ m = 39,\ \Delta t = 1$

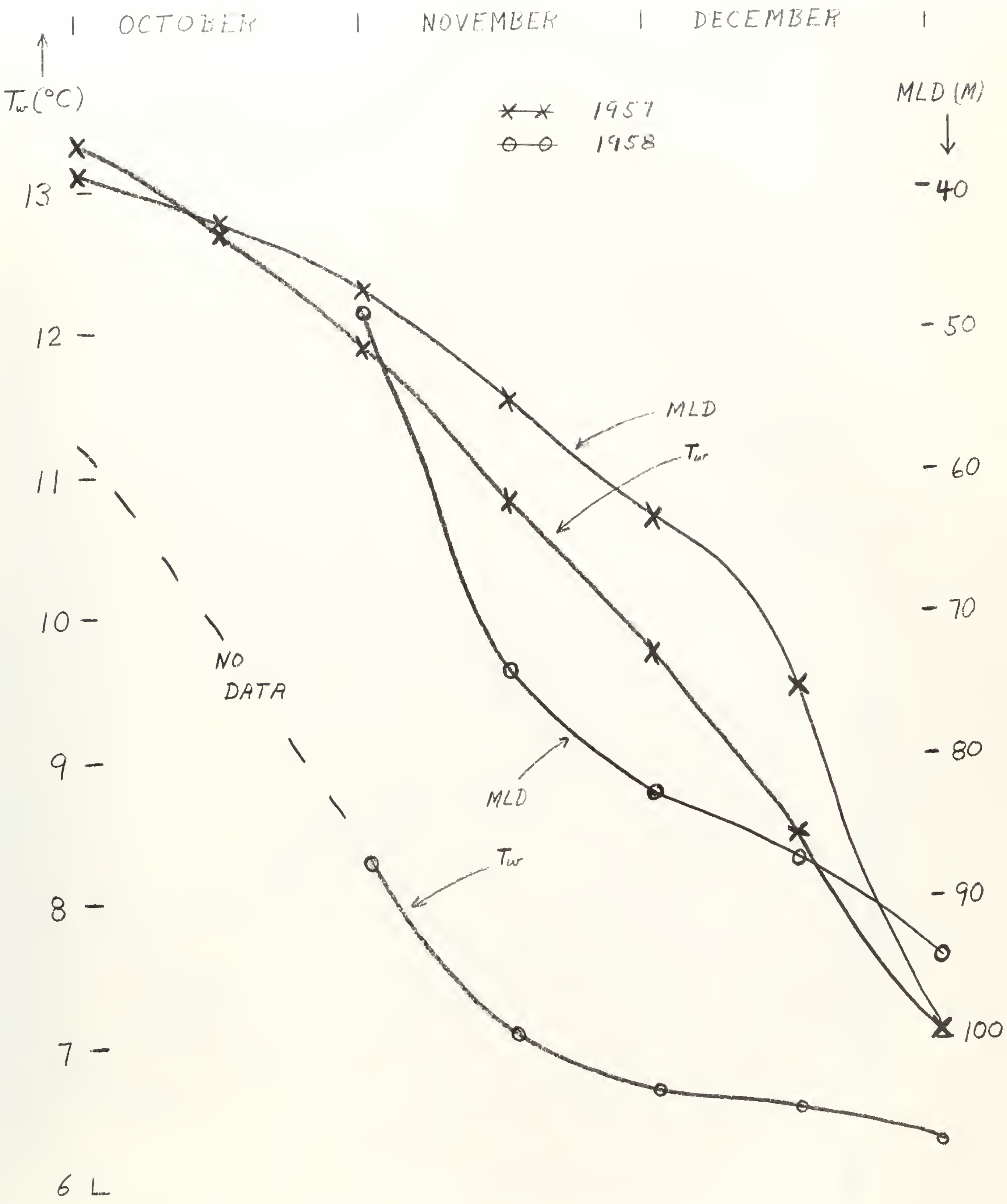


Figure 6. Mean MLD and Sea-Surface Temperature
(October through December, 1957 and 1958)

Figure 7. Average Daily MLD
(October through December, 1956)

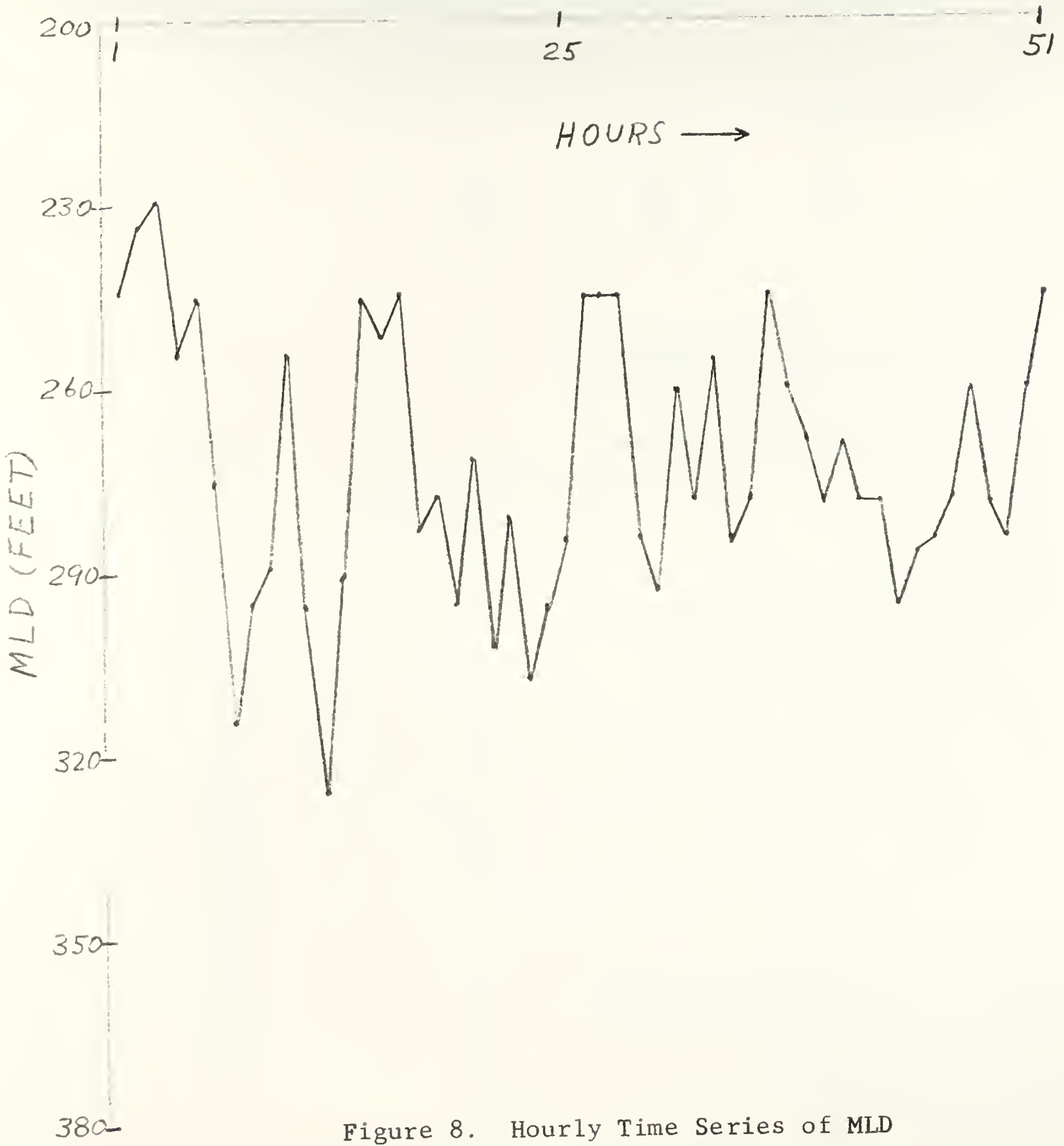


Figure 8. Hourly Time Series of MLD (November, 1958)

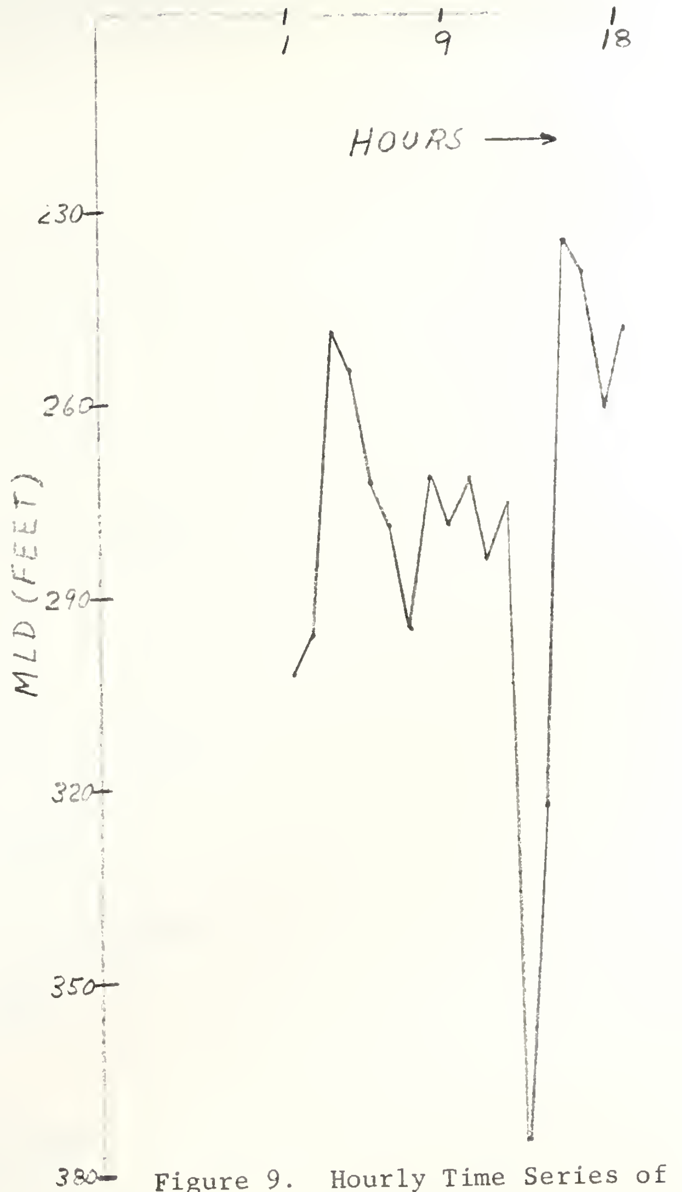


Figure 9. Hourly Time Series of MLD (December, 1956)

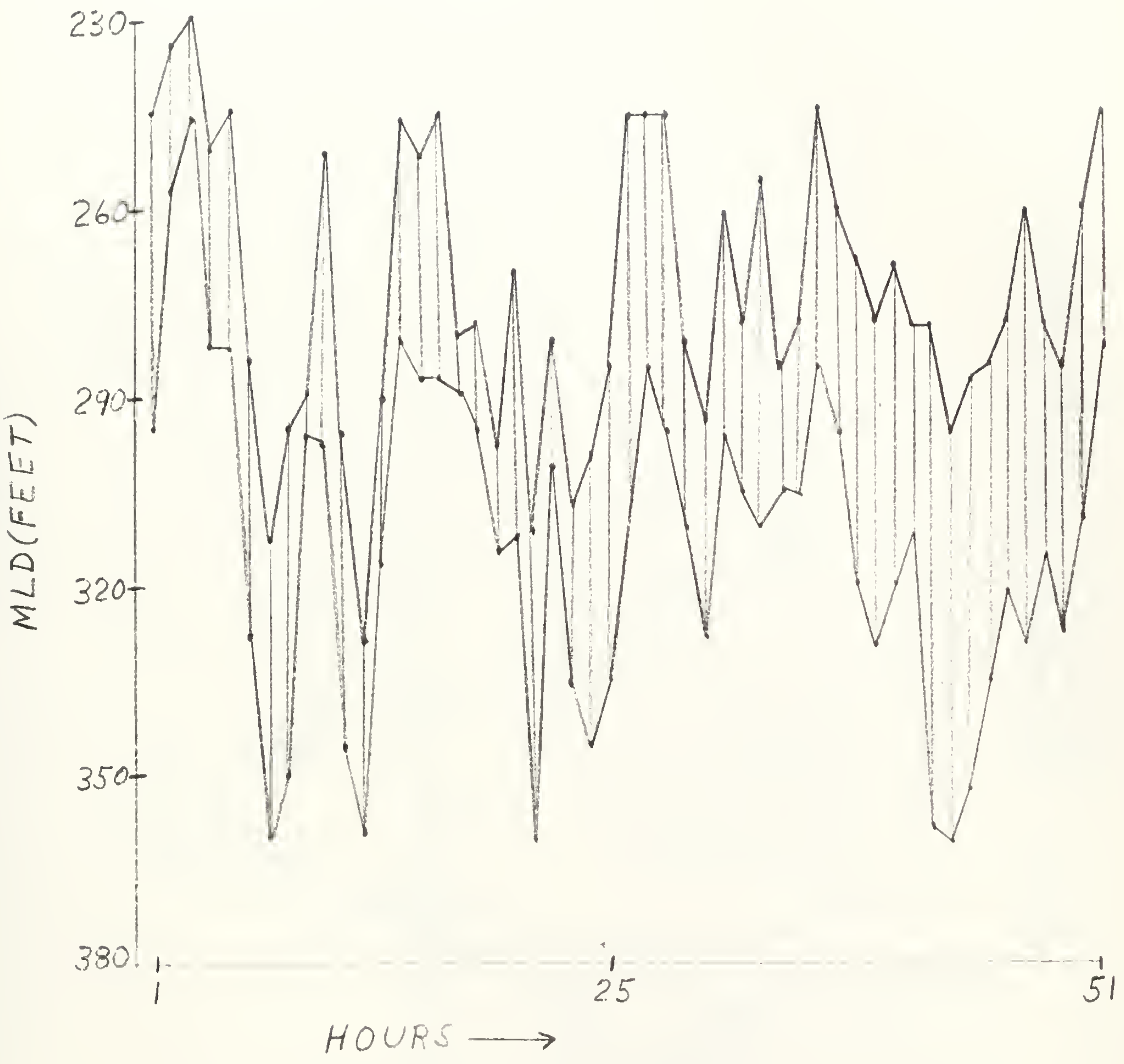


Figure 10. Hourly Time Series of Thermocline Thickness
(November, 1958)

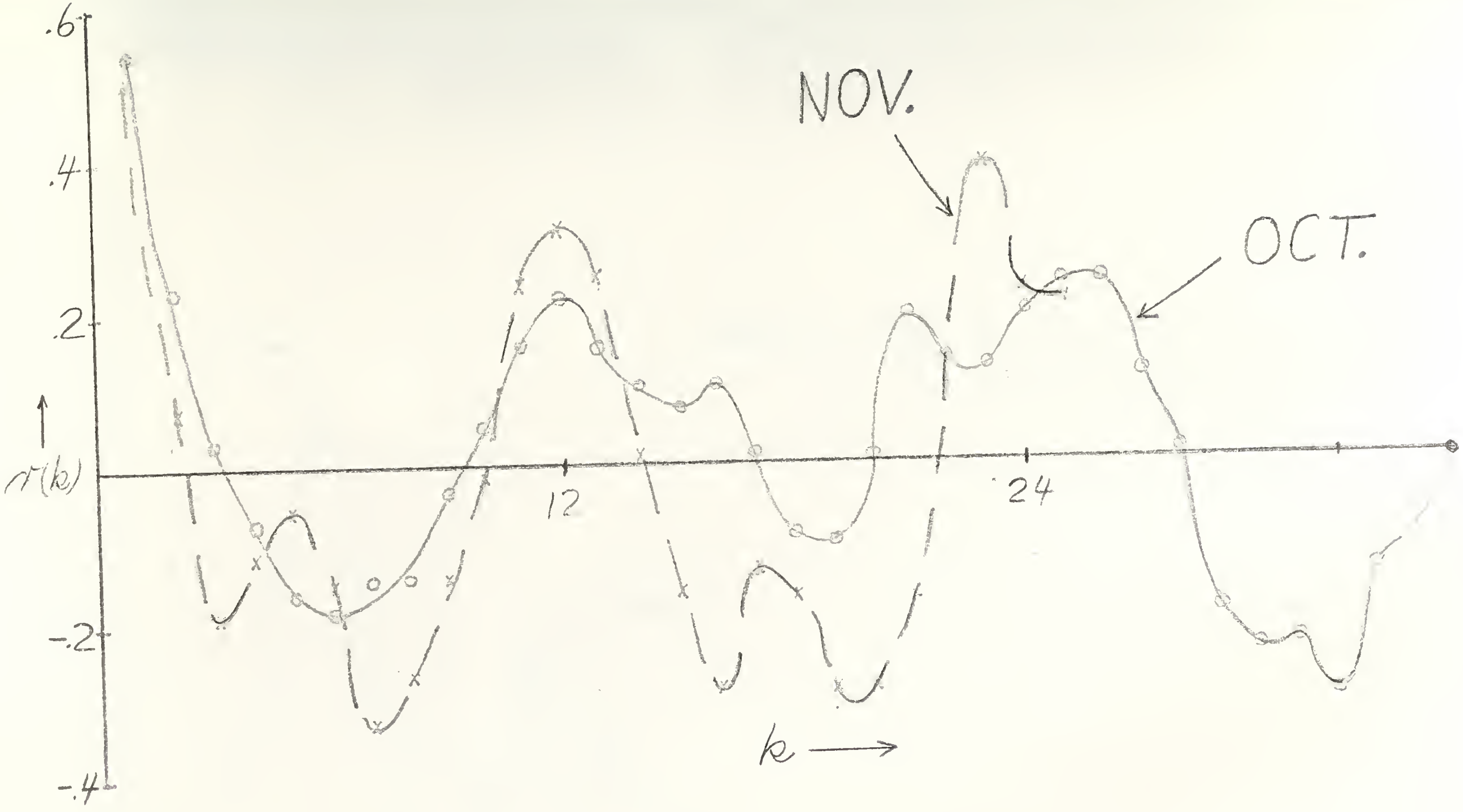


Figure 11. Correlogram for One-Hourly Time Series (October, 1957, and November, 1958)

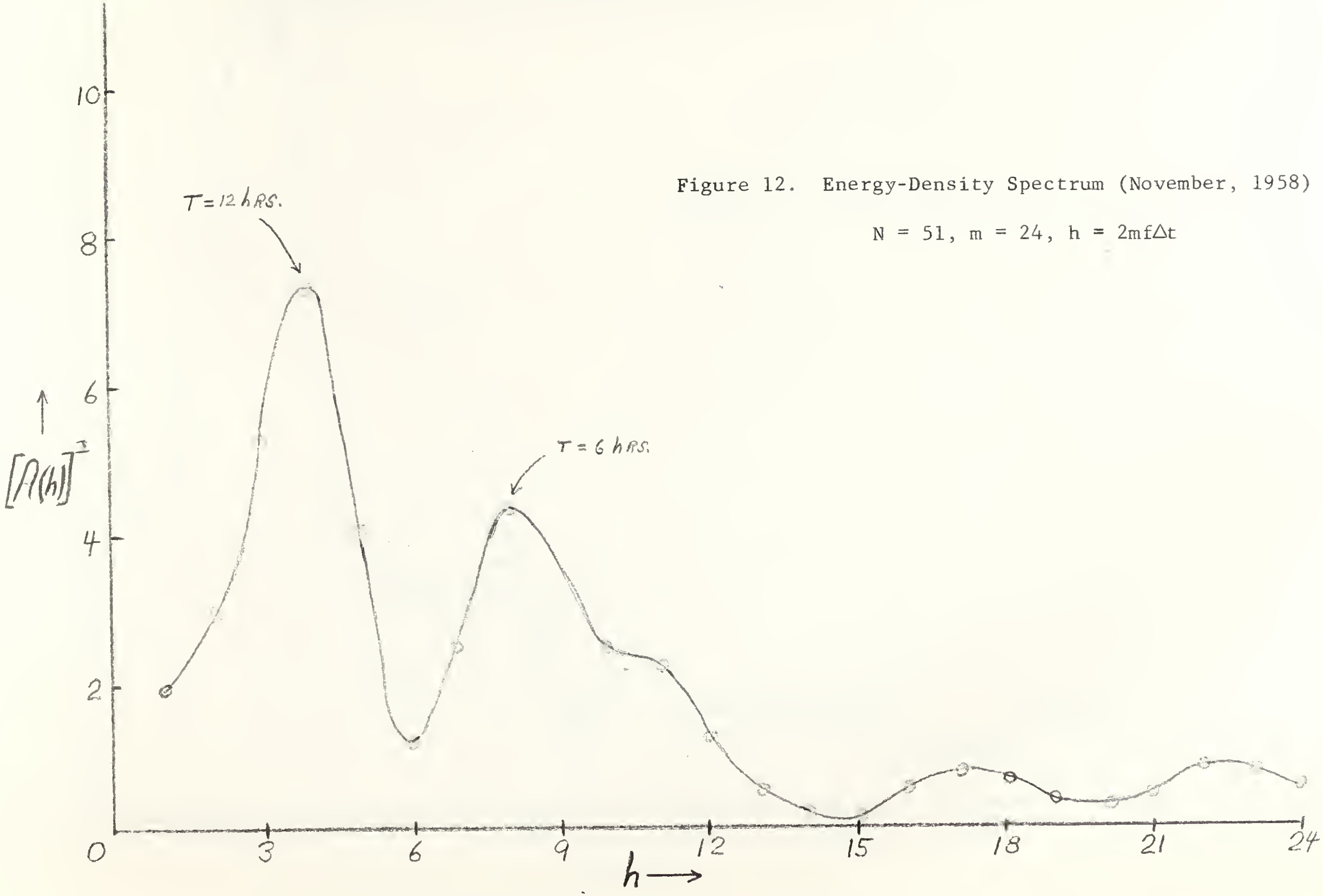


Figure 12. Energy-Density Spectrum (November, 1958)

N = 51, m = 24, h = 2mfΔt

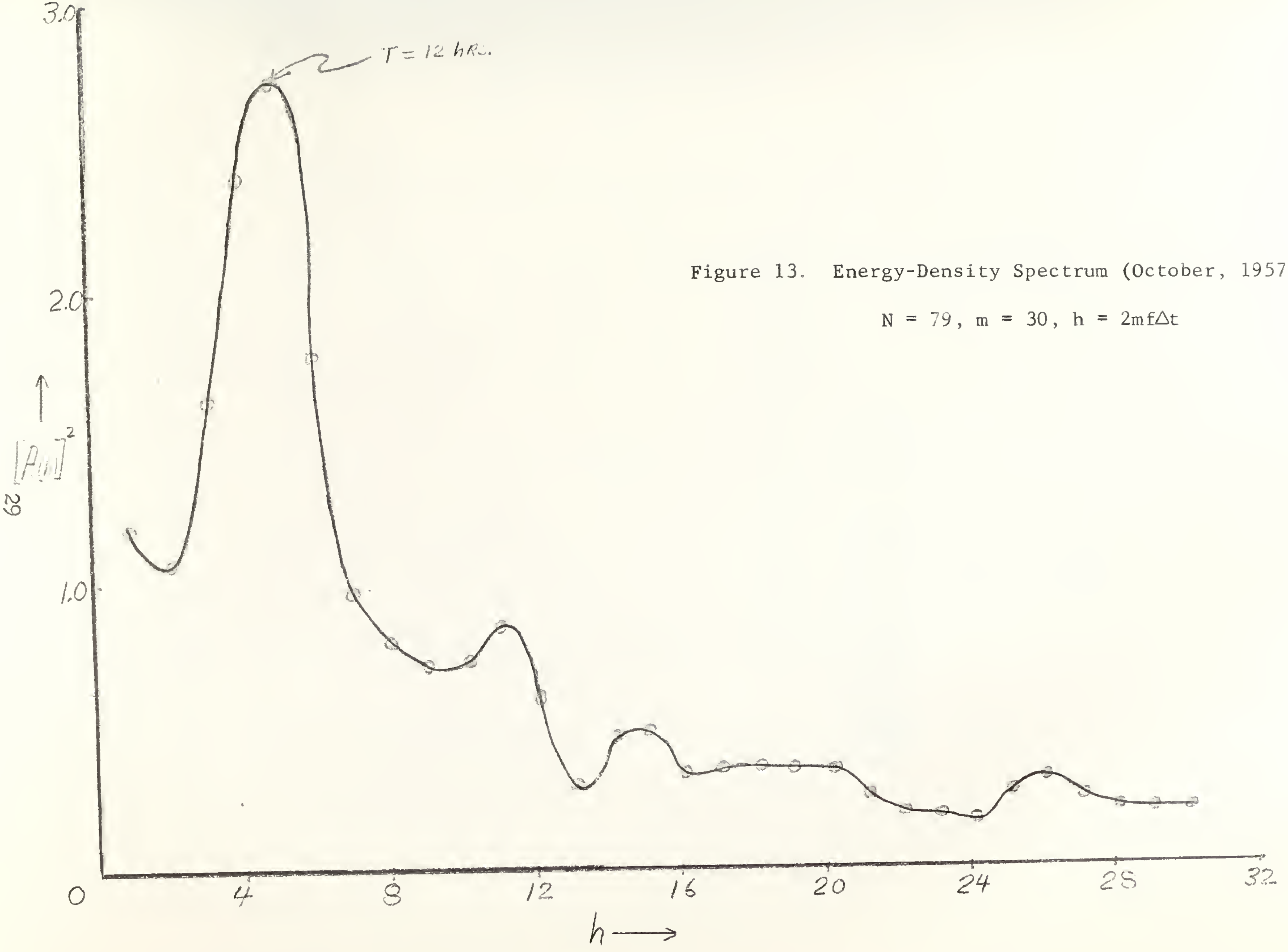


Figure 13. Energy-Density Spectrum (October, 1957)

N = 79, m = 30, h = 2mfΔt

Table I

	1956	1957	1958
0200Z	48	44	36
1700Z	61	46	43
	109	90	79

(0200Z is 1600 local mean time)
(1700Z is 0700 local mean time)

Bathythermograph Soundings Available

Table II

	0200Z			1700Z			0200Z and 1700Z		
Parameter	1956	1957	1958	1956	1957	1958	1956	1957	1958
T_w	-.905	-.903	-.649	-.850	-.767	-.814	-.871	-.829	-.734
T_a	-.635	-.583	-.354	-.410	-.386	-.331	-.502	-.489	-.333
T_a-T_w	.369			.372			.369		
T_{dp}	-.344	-.146	.104	-.162	-.020	.017	-.242	-.050	.062
T_{wb}	-.519	-.284	-.008	.153	-.189	-.115	.092	-.211	.063
RH	.167	.266	.272	.121	.290	.202	.141	.263	.238
$(RH)_{-11}$	.028	.266	.333	.069	.400	-.015	.049	.327	.148
F	.180	.107	.212	.351	-.093	.249	.276	.004	.231
FF	-.046	.389	.012	.110	.307	-.131	.047	.360	-.062
$H_{1/3}$	-.200	.686	-.089	-.077	.487	-.058	-.127	.581	-.060
$(T_w)_{-2}$	-.925	-.879	-.793	-.884	-.649	-.843	-.899	-.726	-.819
$(T_a)_{-2}$	-.684	-.646	-.228	-.382	-.440	-.314	-.505	-.502	-.277
$(T_a-T_w)_{-2}$	.314			.448			.383		
$(FF)_{-5}$	.019	.302	-.073	-.262	.352	0.172	-.143	.311	-.115
$(H_{1/3})_{-5}$	-.200	.683	-.037	-.223	.525	-.389	-.192	.583	-.245
P	-.311	-.134	.125	.039	.170	-.342	-.107	-.027	-.090
$(P)_{-5}$	-.060	-.004	-.101	.041	.327	-.215	.047	.125	-.158
GPM_5	.118	-.463	-.043	.215	-.419	.143	.169	-.437	-.050
T_5	.113	-.439	.091	.166	.623	.080	.145	.181	.080
RH_5	-.136	.285	.150	.137	.045	.186	.028	.166	.154

Simple Linear-Correlation Coefficients
between the 18 Primary Parameters and the MLD

Table III

Sea-Surface-Temperature Lag in Hours	Correlation Coefficients with the MLD
0	-.84975
2	-.88409
5	-.87828
8	-.87576
11	-.87173
14	-.86479
17	-.86829
20	-.86125
23	-.85189

Simple Linear-Correlation Coefficients

for Sea-Surface Temperatures and the MLD

Table IV

Linear-correlation coefficient (for T_{s-2})	-.884
Standard error of the estimate	30.33
Range of residuals	121.2

Regression equation: $MLD_{est.} = 1152.94 - 20.24\ (T_{s-2})$

Regression Results for One Independent Variable
(1700Z, 1956)

Table V

	0200Z			1700Z			0200Z and 1700Z		
	1956	1957	1958	1956	1957	1958	1956	1957	1958
(T_W and T_{W-2} included, T_a-T_W and $(T_a-T_W)_{-2}$ omitted)									
R'	.950	.941	.864	.915	.831	.915	.909	.874	.863
SE	26.5	14.4	26.7	31.4	18.0	19.4	29.9	15.8	21.0
RR	80.4	45.4	29.9	104.8	49.6	59.8	118.8	57.1	102.5
$\overline{MLD}$	210.1	179.4	273.3	212.7	170.5	279.6	211.6	174.8	276.8
S	67.3	32.4	37.0	64.9	25.0	36.27	65.7	29.0	36.5
(T_a-T_W and $(T_a-T_W)_{-2}$ included, T_W and T_{W-2} omitted)									
R'	.950			.917			.910		
SE	26.5			30.9			29.8		
RR	80.4			104.4			121.8		
$\overline{MLD}$	210.1			212.7			211.6		
S	67.3			64.9			65.7		

Multiple-Regression Results for 18 Independent Variables

Table VI

Multiple-correlation coefficient (for 18 independent variables)	.896
Linear-correlation coefficient (for T_s and T_{s-2})	-.814
Standard error of the estimate	22.15
Range of residuals	72.0
Standard deviation	43.8

Three-Year Averages for Regression Results

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APPENDIX

Heat Transport in the Sea and Exchange across the Air-Sea Interface

A. Thermohaline convection. The vertical displacement of small parcels of water occurs when a small part of a water mass is heavier than the water underneath it. To restore this unstable condition to equilibrium, the heavier water tends to sink while the lighter water rises. Associated with these forced vertical movements of small parcels there is also a transport of the characteristic properties of sea water in a vertical direction which leads to an equalization of any vertical differences in these properties which may be present. It is believed that convective mixing is as important an agent of heat transfer in the ocean as wind stirring during the cooling season [2, 12, 20].

An initial increase in the density of small particles at the surface accompanies an increase in salinity (due to evaporation, or to the formation of ice) or a decrease in temperature. One or more of these in combination may be involved in thermohaline convection. In lower latitudes, where there are only small variations in the temperature, the heat loss is outweighed by the effect of evaporation; in polar regions, in addition to radiation and evaporation the increase in salinity due to formation of ice is also effective. In temperate latitudes the heat loss by radiation is the decisive factor.

Convective sensible heat exchange (conduction) between air and sea surface has been studied by Kuhbrodt [4] for the North Atlantic. He has shown the convectional heat flux to be approximately 20 gm cal/cm^2 per day during the period of the year when the air is cooler than the sea surface. This value, even as a rough estimate, is too large to be neglected in the heat budget of the ocean. If the surface of the sea is warmer than the atmosphere, the air is heated at the interface and the vertical stratification of the air becomes unstable; the air becomes turbulent with a constant replacement by cool air at the sea surface and the vertical heat transport becomes large.

Values given by Defant [4] for the heat loss in units of gm cal/cm^2 per day for 50N latitude are 116 units due to effective back radiation, 78 units due to evaporation, and 20 units due to convection of sensible heat (conduction) as a yearly average. Certainly, during the cooling season heat loss due to conduction would be even more significant. These values are derived, assuming that the heat exchange through the ocean surface occurs independently for each separate latitude belt. Therefore, no meridional heat exchange (by ocean currents and by horizontal mixing) was considered.

B. *Dynamic convection (forced vertical mixing due to wind and wave action)*. This process has been well studied and considered to be the dominant process of vertical mixing in the heating season. Laevastu [12] has proposed an empirical formula for determining the MLD by significant wave height alone.

C. *Dynamic convection due to forced vertical mixing of ocean currents* can result in convective mixing, and influences the MLD. This process was not considered because of the difficulty of measurement; however, since the Station is located in the center of the Alaskan Gyral, ocean-current effects are probably small.

D. *Thermal conductivity* can take place when a vertical temperature gradient exists in the ocean. Heat is transferred by molecular heat conduction processes. Defant [4] concludes that this process is insignificant in oceanographic investigations due to the extremely long period involved in the conduction process. Therefore, this process will not be considered in this study.

E. *Entrainment due to turbulence at the pycnocline*. During the cooling season in the open ocean, a well-defined isothermal surface layer exists which extends downward to an interface of rapidly decreasing temperature. Investigations of the subarctic water indicate an isohaline condition to a depth of 330 feet, so the effect of salinity on density can be ignored [23], and thus we may consider the thermocline as a pycnocline. Because less dense warmer water overlies dense cold water, we have a stable condition much like a surface inversion in the atmosphere. When surface cooling takes place, thereby creating an unstable condition, free convection can occur. Cromwell [3] has demonstrated that this free convection in a model causes a turbulent exchange across the thermocline which is one-way. The fluid particles which move upward from the region below the thermocline are rapidly deformed and mixed throughout the upper layers; fluid particles which move downward toward the quiet layer below the MLD are buoyed upward intact. Thus, the upper layer increases in thickness, but decreases in temperature, at the expense of the lower layer. This same phenomenon is observed when the turbulence is induced by wave action or internal wave action [1].