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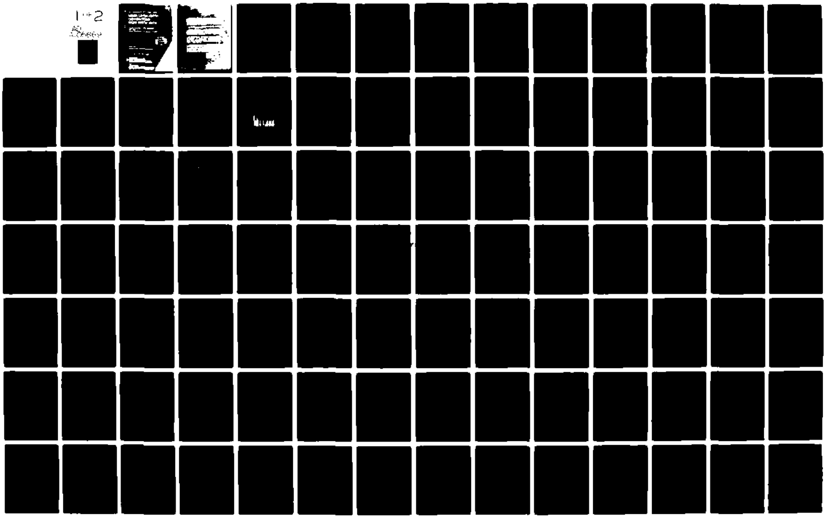

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Mixed layer depths defined in terms of each of four parameters (temperature, sound speed, density and stability) are determined for an area in the northern North Atlantic. The distributions of the mixed layer depth are broken down by season (spring, summer and fall) and by area (Rockall Trough, Iceland Flank, Iceland-Faeroe Front). It is found that seasonal fluctuations in values of mixed layer depth are in excess of 40 meters (fall deeper than

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) summer). Variation in the values of mixed layer depth by area are only about 10 m but are also significant. The Iceland Flank mixed layers are deeper than the Rockall Trough or the Iceland-Faeroe Frontal Zone mixed layers. The stability definition is found to be faulty in its present form and an increase in the significant peak criteria from 2 to 3 cycles per hour is suggested. The Iceland-Faeroe Frontal Zone has greater deviation in MLDs which affect the different definitions of MLD in a complex manner.

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Section 1
INTRODUCTION

Measurements from continuously recording, in situ, sound velocity, salinity, temperature, depth probes (SVSTDs) at 262 stations are used to describe the distribution of mixed layer depths (MLDs) in the northern North Atlantic. Because the term mixed layer refers to a sea surface layer with nearly, but not completely, homogeneous temperature and salinity properties, several definitions of MLD are possible. Four definitions based on four parameters are used here. The four parameters are temperature, sound speed, density and stability.

The purpose of this work is twofold. The first purpose is to determine if there are any significant differences in the distribution of MLDs among various seasonal and spatial subsets of stations in the area of interest. Eleven such subsets (called "classes") have been identified. The second purpose is to determine if there are any significant differences in the distribution of MLDs due to the four different definitions of MLD.

The vertical profiles from the SVSTD measurements are smoothed to reduce the effect of noise and the effect of finestructure with vertical wave lengths smaller than five meters (5m). The details of this smoothing process are presented in section 2.1. The four parameters used in the definitions of MLD are calculated for each vertical level using the algorithms detailed in section 2.2. In that section, also, the distinction between depth and pressure, which is maintained throughout the report, is elucidated.

In section 3, the definitions of MLD based on each of the four parameters are stated and reference is made to the computer routines written to implement the definitions. Listings of the computer routines are provided in Appendix A. The eleven classes are then defined. Finally presented in section 3 are the results: the distributions of MLD in the form of histograms for all eleven classes for each of the four definitions.

Each distribution is characterized in section 4 by its mean and its variance. Confidence intervals for these parameters are presented based on the assumption that the MLDs represent samples from a Gaussian distribution. The degree to which the assumption of normality is justified is tested with a chi-square goodness-of-fit test. Section 4 also identifies the significant variations of the MLD distribution characteristics with class and definition through the use of non-parametric statistical methods.

The major results of this investigation are summarized in section 5. Items requiring further investigation are identified in section 6.

Section 2
PROFILE PREPARATIONS

The SVSTD stations are preconditioned by smoothing vertical profiles of temperature and salinity and then calculating values of sound speed, density (specific gravity anomaly) and stability (Brunt-Väisälä frequency).

2.1 FILTER

The data are supplied with a resolution of 1.0047 dbar, but noise in the data, including quantizing noise introduced by rounding both temperature and salinity values to the nearest hundredth, has a large effect on the vertical gradients calculated by taking differences over such small scales. Consequently, filtering was performed to reduce the contribution to the stratification by components with vertical scales less than 5 dbar. Because many of the mixed layer depth definitions require a comparison to a value at 5m and because the shallowest values at many stations is 5m, the filtering scheme must retain end values.

In an ideal situation, the first observation is at 0 dbar so an eleven weight filter would return a value at nominally 5 dbar. For this reason only filters with eleven weights or less were considered. Using a computer program that will design finite impulse response, linear phase, digital filters using the Remez Exhange Algorithm (McClellan, 1973), an eleven point filter was designed that would pass components with scales larger than 10 dbar and would strongly attenuate (i.e., stop) components with scales less than 5 dbar. In the filter design there is an inverse relationship between the degree of attenuation in the stop band and the degree of uniformity of gain in the pass band. After trying several cases with a nine weight filter it was determined that nonuniformity in the gain of the pass band did not affect the large scale features of the stratification noticeably. That is, the location and size of large scale variations did not show shifts of a decibar or more. The degree of attenuation in the stop band did have a noticeable effect on the gradient dependent parameters such as Brunt-Väisälä frequency. Therefore, in the filter design, emphasis was placed on attenuating the short wave lengths.

The smoothed profiles produced by the nine weight filters were compared to those of an eleven weight filter. Use of the eleven weight filters did not result in a noticeably smoother Brunt-Väisälä profile; therefore, the extra calculations necessary for the eleven weight filter were deemed unwarranted. The nine weight filter was selected for smoothing the profiles of temperature and salinity. The weights of the chosen nine point filter are given in table 2.1, the impulse response is given in figure 2.1a and the wave number response is given in figure 2.1b.

In order that the filter may be applied, the input data must consist of a uniform pressure series. Consequently linear interpolation was performed to generate values of temperature and salinity every 1.0047 dbar.

In order to retain the end values of the pressure series, filters with odd numbers of weights less than nine must be applied. The nine point filter gives a value appropriate at the fifth pressure in the series, a seven point filter provides a value appropriate at the fourth, a five point filter at the third, and a three point filter at the second. The value at the first pressure is retained at its original magnitude. This scheme is applied to the beginning of the pressure series and the weights for these filters are given in table 2.2.

Profiles of temperature, sound speed, density and Brunt-Väisälä frequency (stability) at a sample station are shown for both original data (figures 2.2 and 2.3) and for smoothed data (figures 2.4 and 2.5).

2.2 ALGORITHMS

Mixed layer depths are to be defined in terms of several parameters. All these parameters can be calculated from pressure series of temperature and salinity. This section presents the formulas for the calculation of the parameters of interest: depth (D), sound velocity (C), sigma-T (σ_T) and Brunt-Väisälä frequency (N).

2.2.1 Pressure-Depth

Pressure (P) measured by the STD was converted to depth (Z) by NOO personnel (R. Rushton, personal communication) using the relation

$$Z = \frac{P}{1.0047} \qquad (2\text{-}1)$$

TABLE 2.1

NINE POINT FILTER WEIGHTS

POSITION	WEIGHT
1	.00954717
2	.06623742
3	.12782102
4	.18947470
5	.21383940
6	.18947470
7	.12782102
8	.06623742
9	.00954717

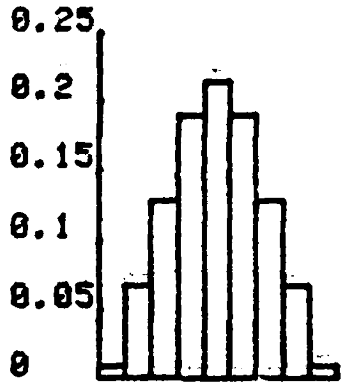

Figure 2.1a   Impulse response of nine point filter.

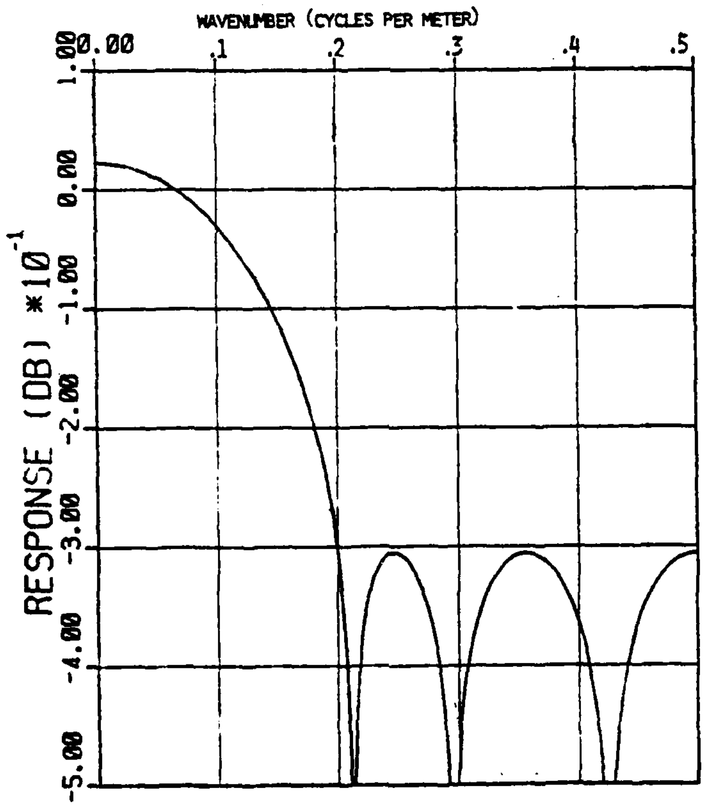

Figure 2.1b   Wavenumber response of nine point filter.

TABLE 2.2

WEIGHTS FOR THE SEVEN, FIVE, THREE AND ONE POINT FILTERS

POSITION	SEVEN	FIVE	THREE	ONE
1	.0624060	.1566329	.3716116	1.0000000
2	.1293414	.2164613	.2567772	
3	.1963272	.2538113	.3716116	
4	.2238503	.2164613		
5	.1963272	.1566329		
6	.1293414			
7	.0624060			

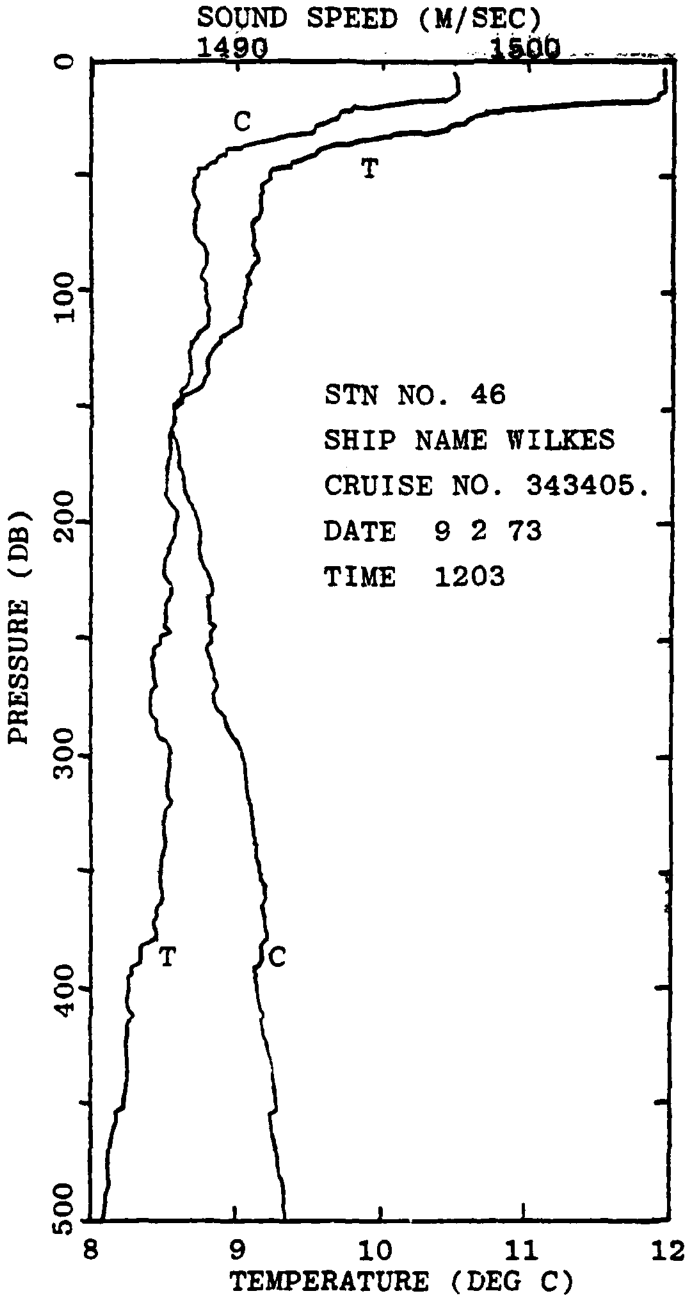

Figure 2.2 Sound speed (C) and temperature (T) profiles at a sample SVSTD station before smoothing.

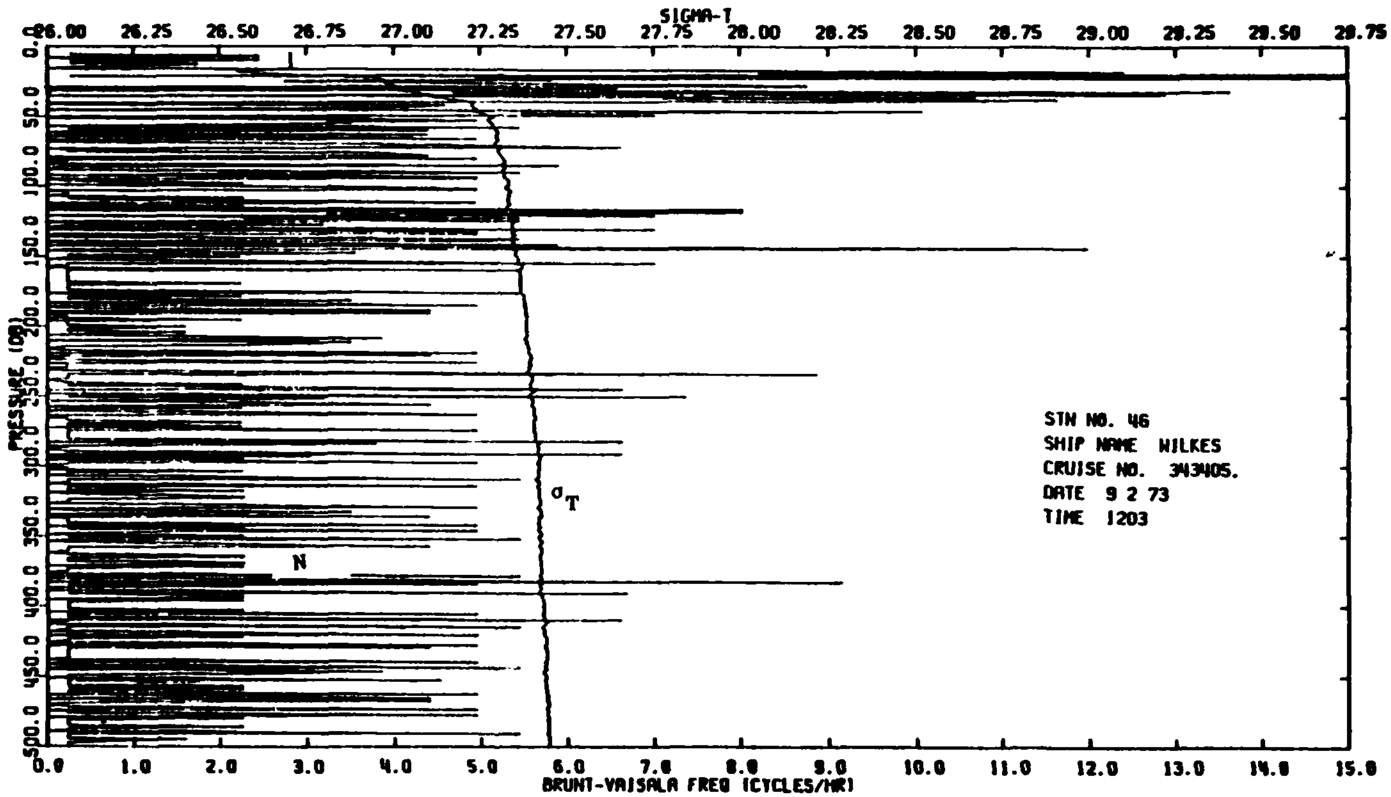

Figure 2.3 Brunt-Väisälä frequency (N) and density (specific gravity anomaly, σ_T) profiles at a sample SVSTD station before smoothing.

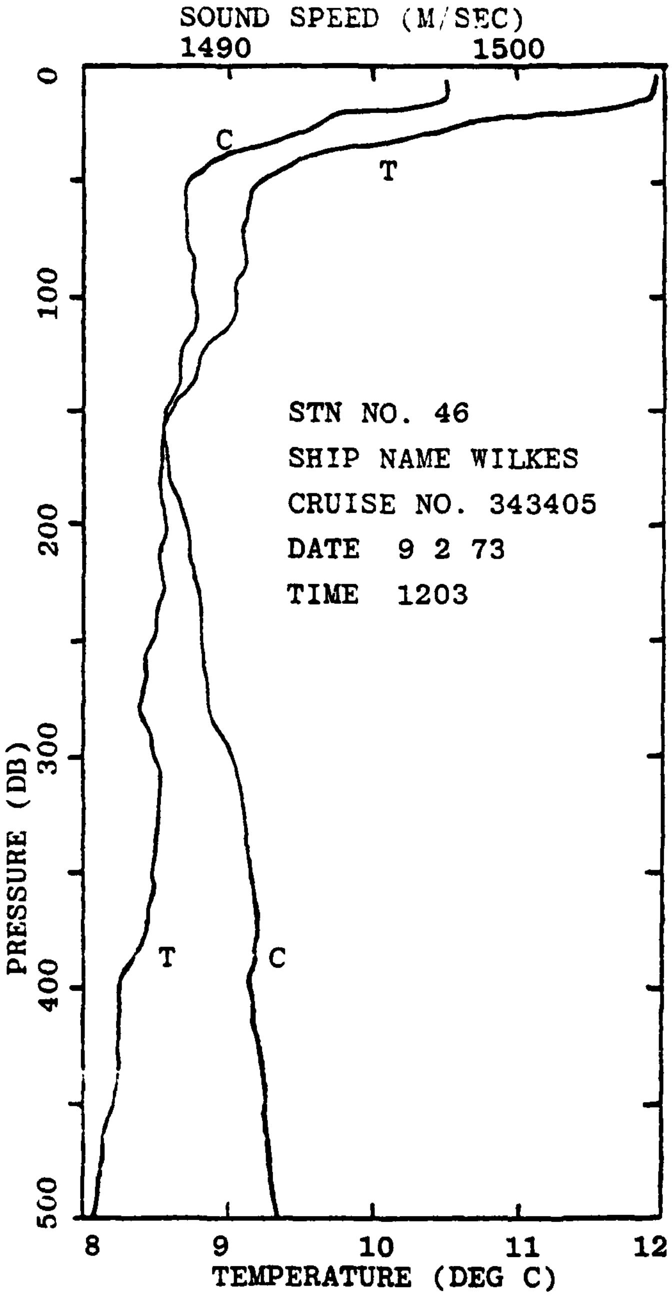

Figure 2.4 Sound speed (C) and temperature (T) profiles at a sample SVSTD station after smoothing.

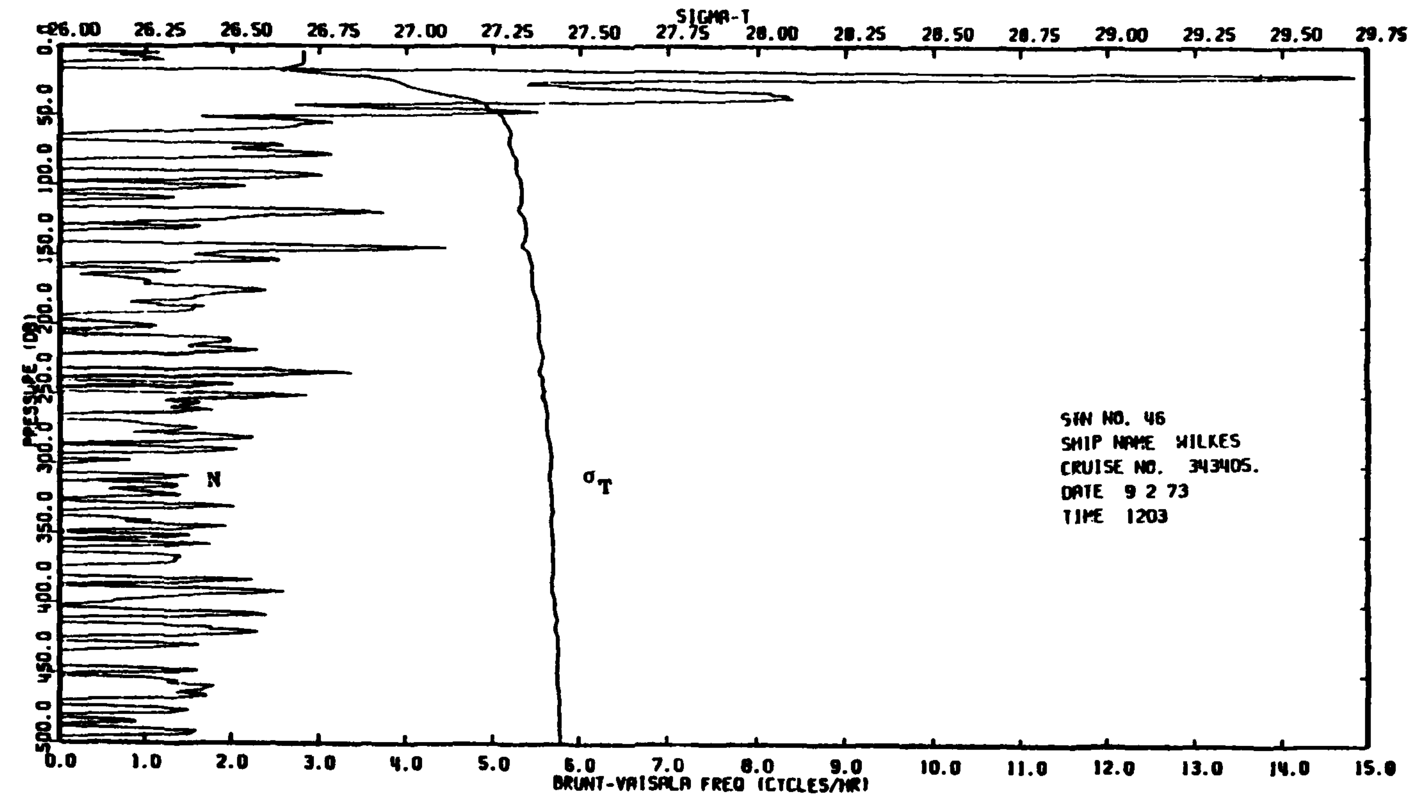

Figure 2.5 Brunt-Väisälä frequency (N) and density (specific gravity anomaly, σ_T) profiles at a sample SVSTD station after smoothing.

where Z is depth (m) and P is pressure (dbar). Pressure is desirable for many calculations (sound velocity and in situ specific volume) so the vertical coordinate was transformed back to pressure using the inverse of equation (2-1) before filtering. Depth at the nth observation can then be calculated from pressure and in situ specific volume by performing the summation based upon the hydrostatic relation

$$Z = 10^4 \sum_{i=1}^{n} g_i \left(P_i - P_{i-1}\right) \frac{1}{2}\left(\alpha_i + \alpha_{i-1}\right) \tag{2-2}$$

where

P_i = pressure at level i (dbar), $P_0 = 0$

α_i = in situ specific volume at level i, $\alpha_0 = \alpha_1$

$_i$ = gravitational acceleration at level i (m sec^{-2})

The value of g_i can be calculated as by Saunders and Fofonoff (1976)

$$g_i = 9.780318\left(1+5.3024\text{x}10^{-3}\sin^2\phi - 5.9\text{x}10^{-6}\sin^2 2\phi\right) + 1.113 \text{ x } 10^{-6} * \left(P_i + P_{i-1}\right) \tag{2-3}$$

where ϕ is latitude.

The value of α_i is determined from T_i and S_i using equation (2-15).

2.2.2 Sound Speed

Sound speed depends upon pressure, temperature and salinity. To be most consistent with NAVOCEANO calculations of sound speed the Wilson (1960) formula is used in this study. Wilson uses a pressure unit of kg/cm^2. Pressure in the ocean is expressed in terms of decibars above atmospheric pressure. The two units must be related to use the formulas.

If PO is the oceanographic pressure in dbar, and P the total pressure in kg/cm^2, then

$$P = \frac{PO + 10.1}{9.8} \tag{2-4}$$

This pressure, plus temperature (already in ^{o}C) and salinity (already in $^{o}/oo$), are used in the formula of Wilson

$$C = SV(T,S,P) = 1449.14 + V_T + V_P + V_S + V_{STP} \quad (2\text{-}5)$$

where

$$V_T = 4.5721\, T - 4.4532\times10^{-2}\, T^2 - 2.6045\times10^{-4}\, T^3 + 7.9851\times10^{-6}\, T^4$$

$$V_P = 1.60272\times10^{-1}\, P + 1.0268\times10^{-5}\, P^2 + 3.521\times10^{-9}\, P^3 - 3.3603\times10^{-12}\, P^4$$

$$V_S = 1.39799(S-35) + 1.69202\times10^{-3}(S-35)^2$$

and

$$\begin{aligned} V_{STP} = {} & (S-35)\,(-1.1244\times10^{-2}\, T + 7.7711\times10^{-7}\, T^2 + 7.7016\times10^{-5}\, P \\ & -1.2943\times10^{-7}\, P^2 + 3.158\times10^{-8}\, PT + 1.5790\times10^{-9}\, PT^2) \\ & +P(-1.8607\times10^{-4}\, T + 7.4812\times10^{-6}\, T^2 + 4.5283\times10^{-8}\, T^3) \\ & +P(-2.5294\times10^{-7}\, T + 1.8563\times10^{-9}\, T^2) \\ & +P^3(-1.9646\times10^{-10}\, T) \end{aligned}$$

2.2.3 Sigma-T

The specific gravity anomaly, σ_t, is calculated using the formula of Knudsen (1901) with a slight modification in the salinity (S) - chlorinity (Cl) relationship. Whereas Knudson defined $S = 0.03 + 1.805\, Cl$, in this work the following definition is used:

$$S = 1.80655\, Cl. \quad (2\text{-}6)$$

This ensures that both salinity and chlorinity are conservative properties. Equation (2-6) is then used to define a chlorinity value to insert in the Knudson formula

$$\sigma_T(T,S) = \Sigma_T + (\sigma_o + .1324)\Big(1 - A_T + B_T(\sigma_o - .1324)\Big) \quad (2\text{-}7a)$$

where

$$\sigma_o = -.069 + 1.4708 \times Cl - .001570 \times Cl^2 + .398 \times 10^{-4} \times Cl^3 \quad (2\text{-}7b)$$

$$\Sigma_T = -(T-3.98)^2(T+2.83)/\big[(503.57)(T+67.26)\big]$$

$$A_T = T\big(4.7867 - .098185T + .10843\times10^{-2}T^2\big) \times 10^{-3}$$

$$B_T = T\big(18.03 - .8164T + .01667T^2\big) \times 10^{-6}$$

2.2.4 Brunt-Väisälä Frequency

The calculation of Brunt-Väisälä Frequency (N) follows closely a routine developed by N. Fofonoff (1971), with some modifications. By definition N, in cycles per hour (cph) is given by

$$N = \frac{3600}{2\pi} \sqrt{\frac{g}{\rho} \frac{\partial \rho}{\partial Z}\bigg|_p} \qquad (2\text{-}8)$$

where

g = acceleration of gravity

ρ = density

Z = depth

$\frac{\partial \rho}{\partial Z}\big|_p$ = vertical density gradient at constant pressure

For two observations of temperature (T), salinity (S) and pressure (P, in dbar)

$$N = \frac{3600}{2\pi} \sqrt{\frac{g}{\frac{1}{2}(\rho_1+\rho_2)} \frac{(\rho_2-\rho_1)}{(Z_2-Z_1)}} \qquad (2\text{-}9)$$

where

Z_2 = depth of deeper observation

Z_1 = depth of shallower observation

ρ_2 = density of deeper observation at a reference pressure

ρ_1 = density of the shallower observation at the same reference pressure.

The density in equations (2-8) and (2-9) is computed from an equation by Ekman (1908) for in situ specific volume where a reference pressure, PR, midway between the two observations is used. The density equation depends upon the reference pressure, the salinity of the observation and the potential temperature (θ_{PR}) of the observation at the reference pressure. θ_{PR} can be computed from T, the pressure difference (PR-P) and the adiabatic lapse rate (γ). The value of γ can be computed from a formula by Bryden (1973) which depends on temperature, salinity and pressure. The pressure used for the calculation of θ_{PR} is a pressure midway between the observed pressure and the reference pressure.

The algorithm for the computation of N from observations of P_1, T_1, S_1, and P_2, T_2, S_2 therefore consists of the following steps.

$$PR = (P_1 + P_2) \tag{2-10}$$

$$PP_i = (P_i + PR) \quad \text{for } i = 1,2 \tag{2-11}$$

From Bryden (1973),

$$\gamma^i = 10^{-3} \sum_j \sum_k \sum_\ell A_{jk\ell} PP_i{}^j (S_i - 35)^k \, T_i{}^\ell \tag{2-12}$$

for $i = 1,2$

where

$A_{000} = .35803 \times 10^{-1}$ $\quad$ $A_{102} = .87330 \times 10^{-8}$

$A_{001} = .85258 \times 10^{-2}$ $\quad$ $A_{103} = -.54481 \times 10^{-10}$

$A_{002} = -.68360 \times 10^{-4}$ $\quad$ $A_{110} = -.11351 \times 10^{-6}$

$A_{003} = .66228 \times 10^{-6}$ $\quad$ $A_{111} = .27759 \times 10^{-8}$

$A_{010} = .18932 \times 10^{-2}$ $\quad$ $A_{200} = -.46206 \times 10^{-9}$

$A_{011} = -.42393 \times 10^{-4}$ $\quad$ $A_{201} = .18676 \times 10^{-10}$

$A_{100} = .18741 \times 10^{-4}$ $\quad$ $A_{202} = -.21687 \times 10^{-12}$

Then,

$$\Theta_{PRi} = T_i + \left(PR - P_i\right) \gamma_i \qquad \text{for } i = 1,2 \tag{2-13}$$

and

$$\rho_i = \frac{1}{\alpha\left(\theta_{PRi}, S_i, PR\right)} \qquad \text{for } i = 1,2 \tag{2-14}$$

From Ekman (1908),

$$\alpha(\theta_{PRi}, S_i, PR) = \alpha_{0i} - [PR(\alpha_{0i} \times 10^{-9})(A - B_i + C_i - D_i - F_i + G_i)] \tag{2-15}$$

where

$$A = \frac{4886}{\left(1+.183\times10^{-4}PR\right)}$$

$$B_i = 227 + 28.33\theta_{PRi} - .551\ \theta^2_{PRi} + .004\ \theta^3_{PRi}$$

$$C_i = PR\ 10^{-4}\left(105.5+9.50\ \theta_{PRi}-.158\ \theta^2_{PRi}\right)$$

$$D_i = 1.5\ PR^2\ \theta_{PRi}\ 10^{-8}$$

$$F_i = \left(\frac{\sigma_{oi}-28}{10}\right)\Big(147.3-2.72\ \theta_{PRi}+0.04\ \theta^2_{PRi}$$

$$-PR\ 10^{-4}\left(32.4-87\ \theta_{PRi} + .02\ \theta^2_{PRi}\right)\Big)$$

$$G_i = \left(\frac{\sigma_{oi}-28}{10}\right)\left(4.5-0.1\ \theta_{PRi}-PR\ 10^{-4}\left(1.8-0.6\ \theta_{PR}\right)\right)$$

and

$$\alpha_{oi} = \frac{1}{\left(1+\sigma_T\left(\theta_{PRi},S_i\right)\ 10^{-3}\right)}$$

Both σ_0 and $\sigma_T(\theta_{PRi},S_i)$, are defined according to the relations of Knudsen (1901) given in equations (2-7a) and (2-7b).

Finally, the depth difference is approximated by the pressure difference

$$(Z_2 - Z_1) \approx (P_2 - P_1) \qquad (2\text{-}16)$$

The values of ρ_1, ρ_2 and $(Z_2 - Z_1)$ are then substituted into equation (2-9) to produce a value of N.

2.3 ERROR ESTIMATES

Estimates of errors in the four parameters used to define mixed layer depths are necessary if the values are to be used properly. The uncertainty in all parameters depends upon the uncertainties in the basic parameters pressure, temperature and salinity. The original data are reported every 1.0047 dbar, to a resolution of .01°C and .01 °/oo. These values can be taken as the precision of the temperature and salinity, respectively. The smoothed profiles consist of values still every 1.0047 dbar but averaged (with uneven weights) over nine points. The major contribution to the average comes from the central three weights so that for the purpose of approximating the precision error in the smoothed temperature and salinity an average over 3 points can be assumed. Then the uncertainty in temperature is $.01^{o}C/\ \ 3 = .006^{o}C$ and the uncertainty in salinity is $.01\ ^{o}/oo/\ \ 3 = .006\ ^{o}/oo$. Such uncertainties in temperature and salinity affect the calculation of sound speed by less than .05m sec^{-1} over the range of temperatures, salinities and pressures encountered in this work. The effect of errors in temperature and salinity on σ_T is .01 σ_T units. Therefore, changes in σ_T can be estimated with an error of under .015 σ_T units. The effect on Brunt-Väisälä frequency (N) requires a more complicated calculation and is found to be a function of the value of N. At values of 1 cycle per hour (cph), the error is about 1cph. At 2cph the error is .5cph and at 4cph the error is .25cph.

Section 3
DISTRIBUTIONS OF MLD

The smoothed profiles of temperature (T), sound speed (C), specific volume anomaly (σ_T), and Brunt-Väisälä frequency (N) are used with four definitions of mixed layer depths to produce MLD_T, MLD_C, MLD_D, and MLD_N, respectively. Each of the 262 stations in the northern North Atlantic is assigned to several of eleven total classes based on season (winter, spring, summer and fall) and subregions (termed areas I, II and III). The distribution of each of the four kinds of MLD for each of the eleven classes are presented in this section.

3.1 FOUR DEFINITIONS OF MIXED LAYER DEPTH

In all these definitions the first 5m (5.0235 dbar) of data are excluded.

3.1.1 Temperature Mixed Layer Depth (MLD_T)

According to the temperature criterion the mixed layer is defined as the near surface depth at which the absolute value of the temperature gradient exceeds .005^{o}C m^{-1} and at which the temperature itself differs by at least 0.2^{o}C from that at 5m. Applying this criterion to the pressure series .005^{o}C m^{-1} was taken to be equivalent to .005^{o}C per 1.0047 dbar. The computer subroutine that implements this criterion is provided in appendix A, section 1.

3.1.2 Sound Speed Mixed Layer Depth (MLD_C)

According to the sound speed criterion the mixed layer is defined as the near surface depth at which the first maximum in sound velocity occurs. During the implementation of this criterion a maximum was not considered unless it was greater than deeper values of sound speed by .5m sec^{-1} which is more than the expected error. Before this test the sound speeds are rounded to the nearest .1m sec^{-1}. The computer subroutine that implements this criterion is provided in appendix A, section 2.

According to the density criterion the mixed layer is defined as the near surface depth at which the first maximum positive density gradient occurs and at which the density itself exceeds that at 5m by at least .02 sigma-T units. During implementation, density data within .02 sigma-T units are skipped first. Once large enough density values are found a maximum difference is considered if it is greater than deeper differences by .01 sigma-T units or more. Though the expected noise in the difference is .015 sigma-T units, the described implementation gives results that compare favorably to choices made by visually inspecting the density profile. The computer subroutine that implements the criterion is provided in appendix A, section 3.

3.1.4 Stability Mixed Layer Depth (MLD_N)

According to the stability criterion the mixed layer is defined as the near surface depth at which the first maximum exceeding 2 cycles per hour (cph) in the Brunt-Väisälä frequency (N) occurs. During implementation N values less than 2cph are not considered until a value greater than 2cph is found. The maximum is then defined if a deeper value of N is less than the maximum by more than .5cph which is the expected error at 2 cph. The computer subroutine that implements this criterion is provided in appendix A, section 4.

3.2 ELEVEN CLASSES OF STATIONS

Data provided for this study consist of stations that span several seasons in three subregions termed I (Rockall Trough), II (Iceland Flank) and III (Iceland-Faeroe Frontal Zone). Figure 3.1 shows a map locating these three areas. In area I data is available in summer and fall, in area II data is available in summer and fall, and in area III there is data in spring, summer and fall. Each season for each area constitute each of the first seven classes. The cruises and stations making up these basic classes are summarized in table 3.1. The remaining classes consist of all seasons for each area (three classes) and all seasons for all areas (one class).

TABLE 3.1

STATIONS PROVIDED FOR STUDY

AREA	SEASON	CRUISE	STATION NUMBERS
I	Summer	932014 343406 343405	1-3, 20-29 20-44, 46, 47 39-44
I	Fall	933005	57-66
II	Summer	932014 343406 343405	4-19 1-19, 49-55 1-24, 26-38, 55-58
II	Fall	933005	41-43, 48-54
III	Spring	343525	1-2, 17-20, 22, 24-36, 38-47, 50-54
III	Summer	343405 343622	45-54 1-56
III	Fall	343606	2-4, 6, 17-19, 22, 24, 29, 31, 36, 37

The computer tapes provided by NAVOCEANO also contained additional stations, duplicate stations and several additional casts of each of two yo-yoed stations. All these data were ignored in compiling the statistics presented here.

3.3 HISTOGRAMS OF MLDs

The four mixed layer depths found for each station were assembled in the eleven classes just described to give 44 distributions of MLD. These distributions are presented here as histograms of percent frequency of occurrence per 5 meter bin for the upper two hundred meters in figures 3.1 to 3.44. The first bin, including occurrences in the depth interval 0 to 4.9999m, can have no members because all four definitions of MLD excluded the first 5m of data. For these histograms depth was not determined from pressure by the numerical integration of equation 2-2. Instead depth values in meters were considered identical to pressure values in decibars rounded to the greatest integer. This simplification saves many computations and is only likely to be in error by a fraction of a meter. All mixed layer depths greater than 200m are assigned to the last bin in the histograms. MLD_T is presented in figures 3.2 to 3.12, MLD_C in figures 3.13 to 3.23, MLD_D in 3.24 to 3.34 and MLD_N in figures 3.35 to 3.45.

The salient feature of the cumulative histograms (figures 3.12, 3.23, 3.34 and 3.45) are that sound speed and stability criteria give distributions of MLD that peak in the shallowest allowable bin while both temperature and density criteria give distributions that peak at depth (20-25m MLD_T and 30-35m for MLD_N). The cause for this may be that the latter two have a stipulation in their definitions that the value at the base of the mixed layer differ from the 5m value by a minimal amount. The first two definitions do not specify a minimum difference.

The summer histograms (figures 3.2, 3.3, 3.4, 3.13, 3.14, 3.15, 3.24, 3.25, 3.26, 3.35, 3.36, 3.37) show that area II has the deepest MLDs and the greatest variance for all criteria. While both area I and area III have shallower MLDs, area III shows the smallest variance for MLD_T and MLD_D. For MLD_C and MLD_N area I is more strongly peaked in the shallowest bin (5-10m). Fall distributions are deeper than summer for all criteria but the deepest MLDs are found for a small percentage of the spring observations.

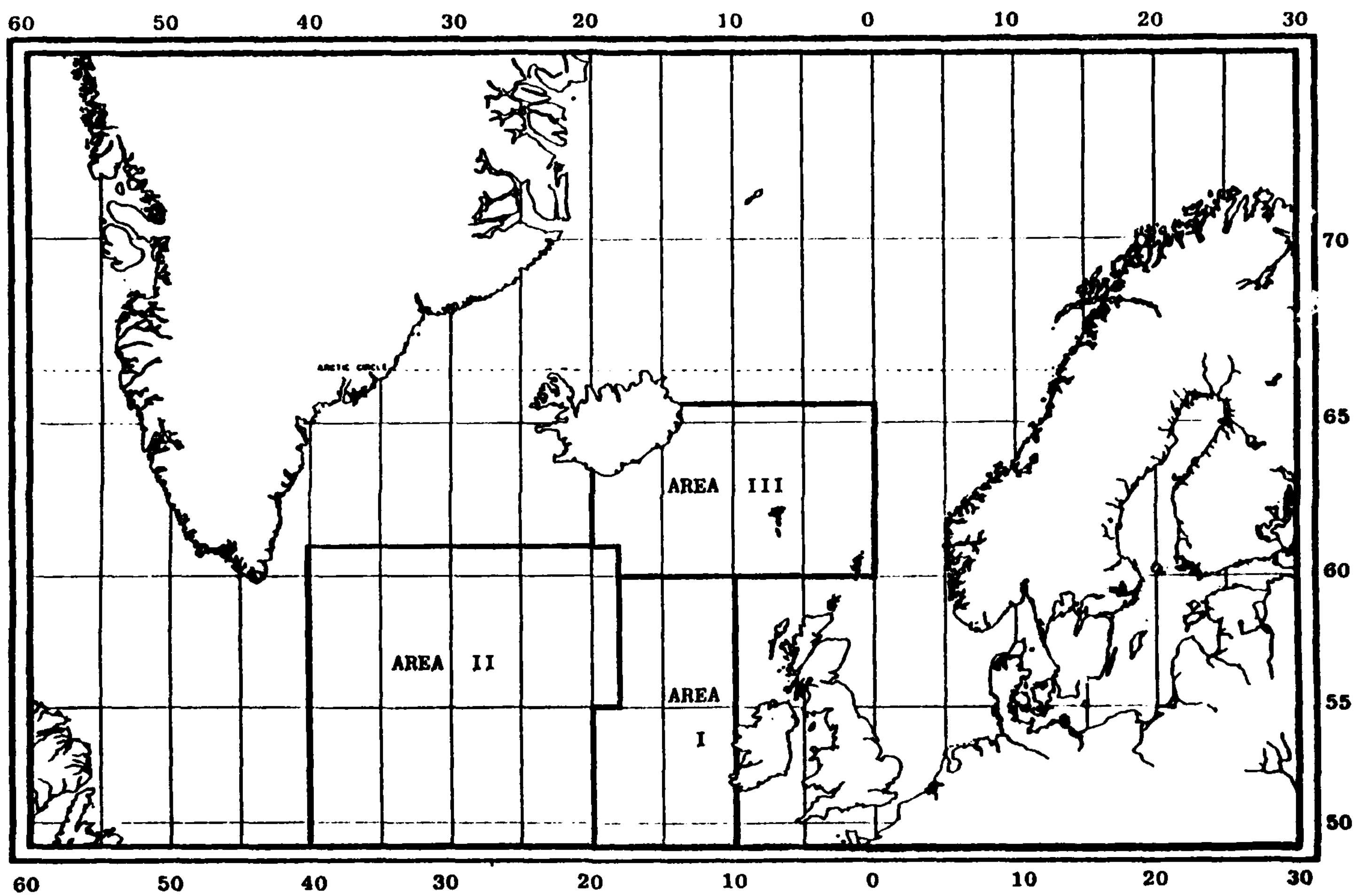

Figure 3.1 Map showing the locations of the three areas in which the SVSTD stations are grouped.

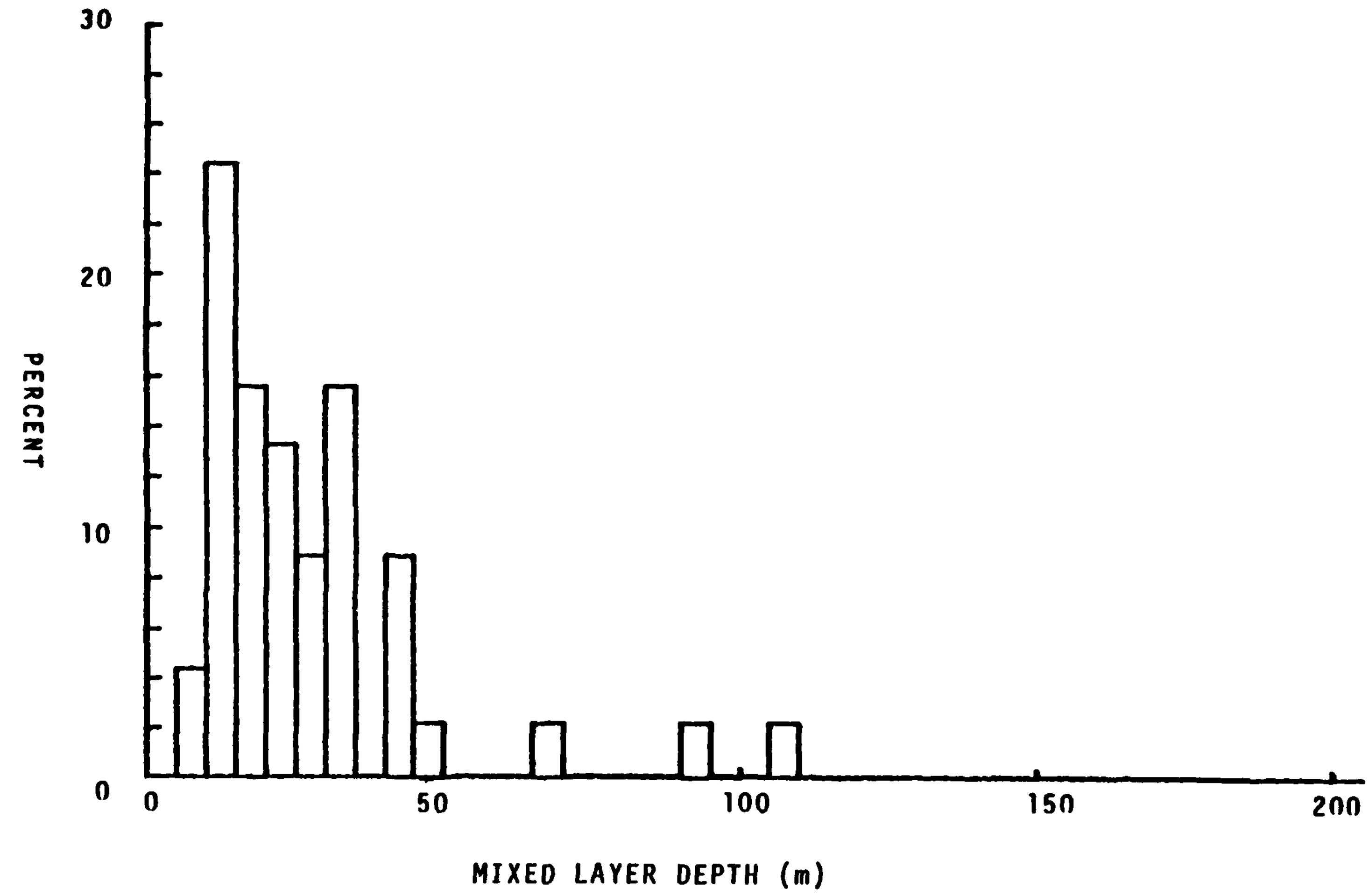

Figure 3.2 Histogram of MLD_T for Summer, Area I (45 Stations)

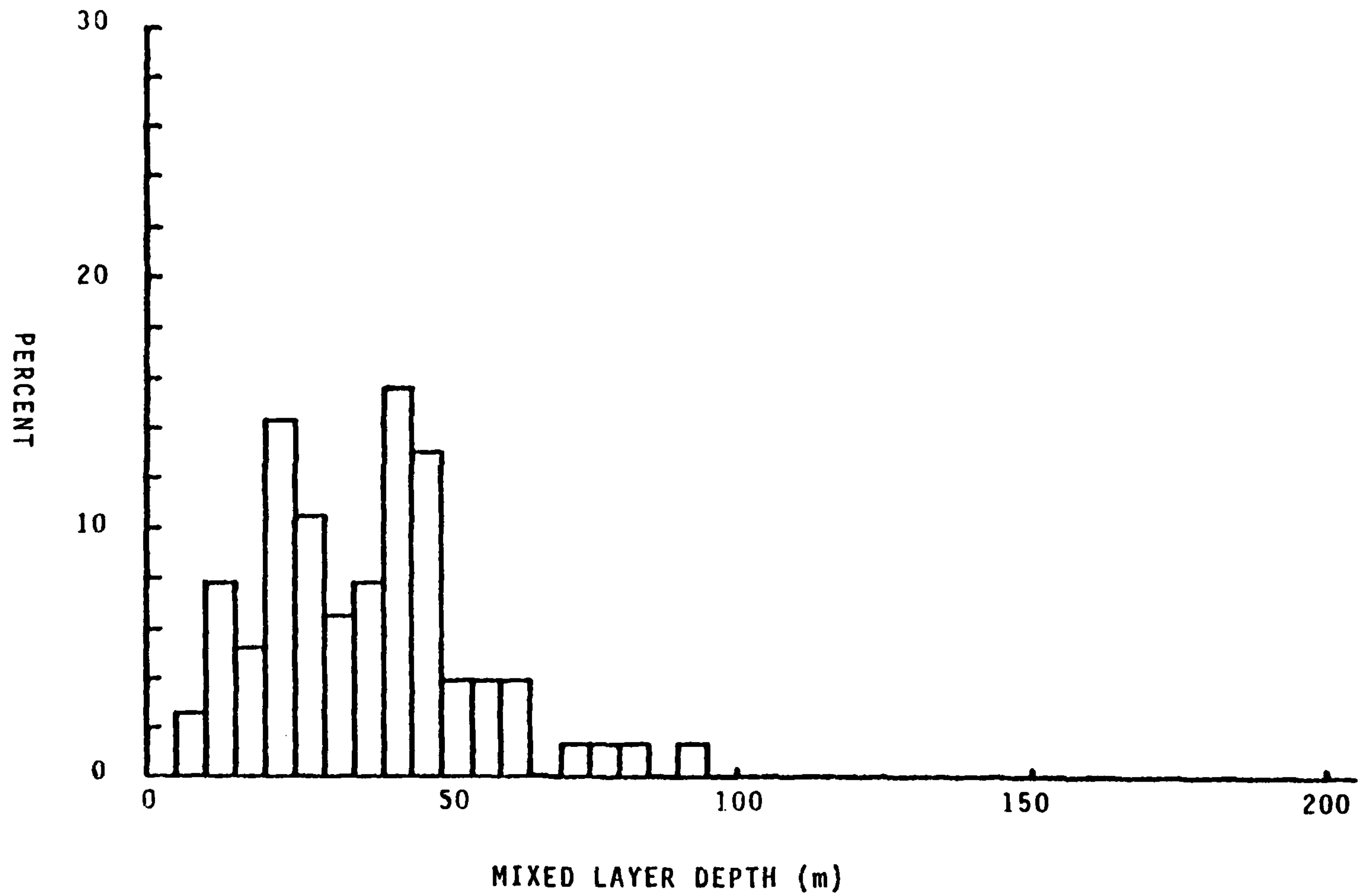

Figure 3.3 Histogram of MLD_T for Summer, Area II (77 Stations)

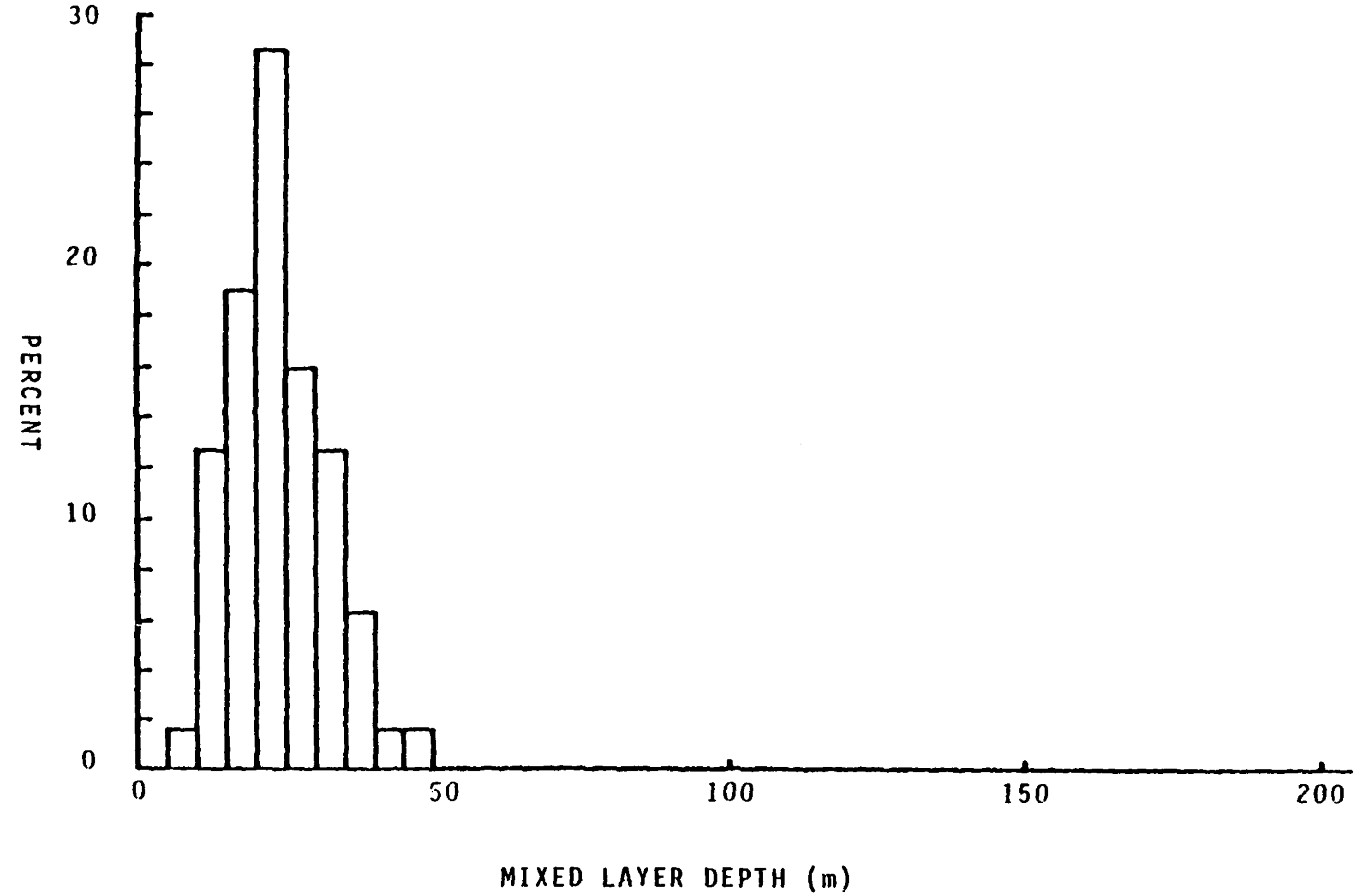

Figure 3.4 Histogram of MLD_T for Summer, Area III (63 Stations)

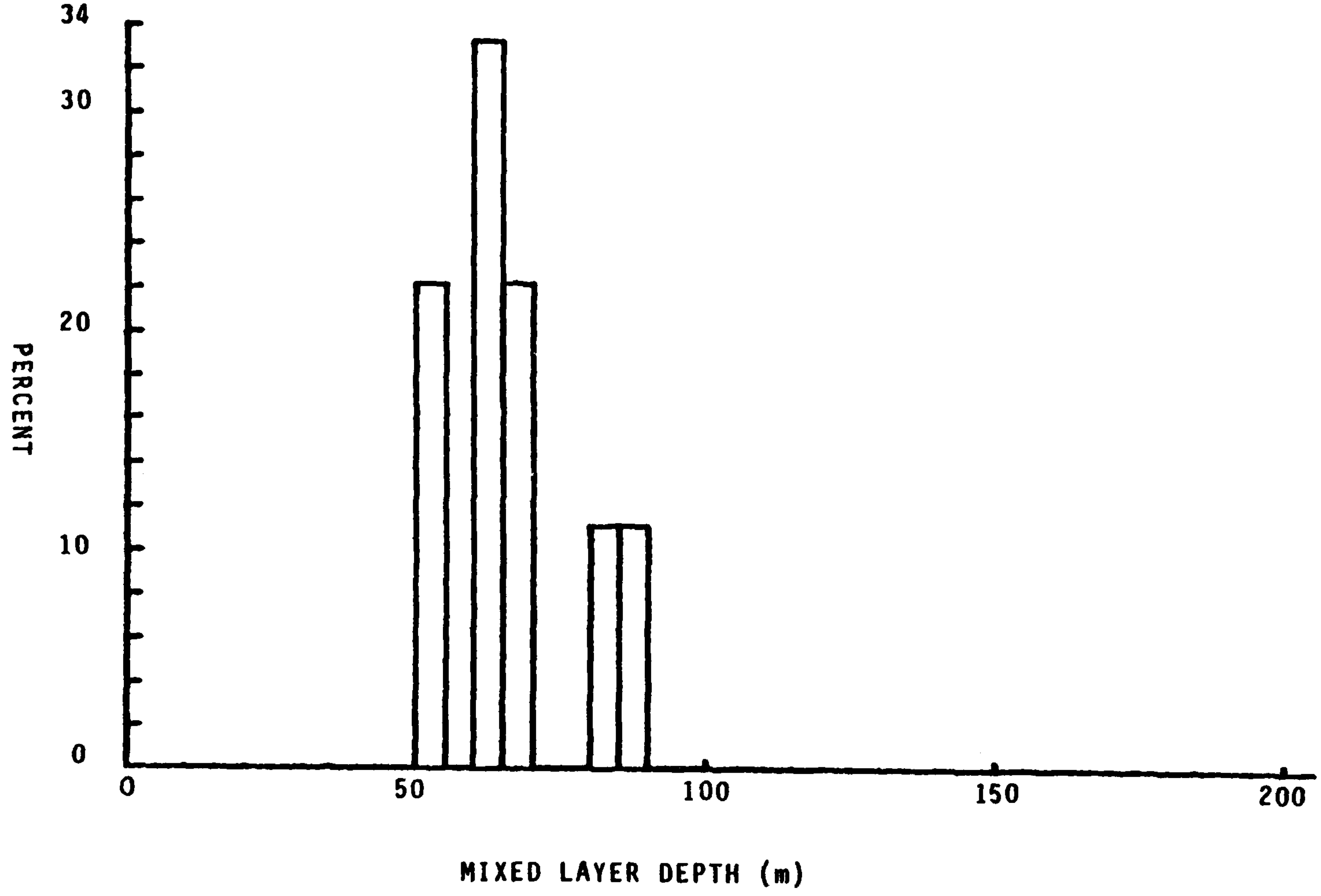

Figure 3.5 Histogram of MLD_T for Fall, Area I (9 Stations)

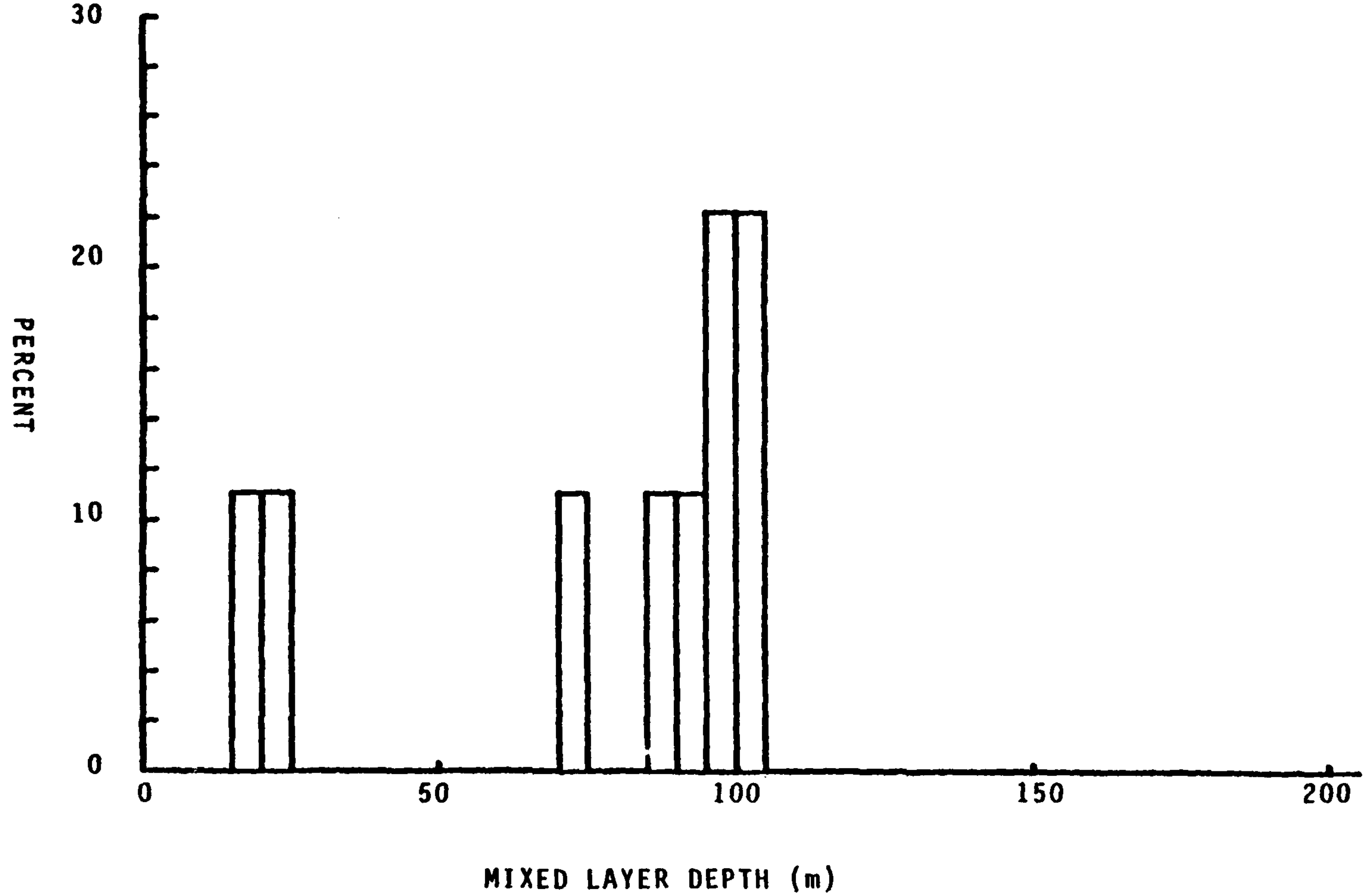

Figure 3.6 Histogram of MLD_T for Fall, Area II (9 Stations)

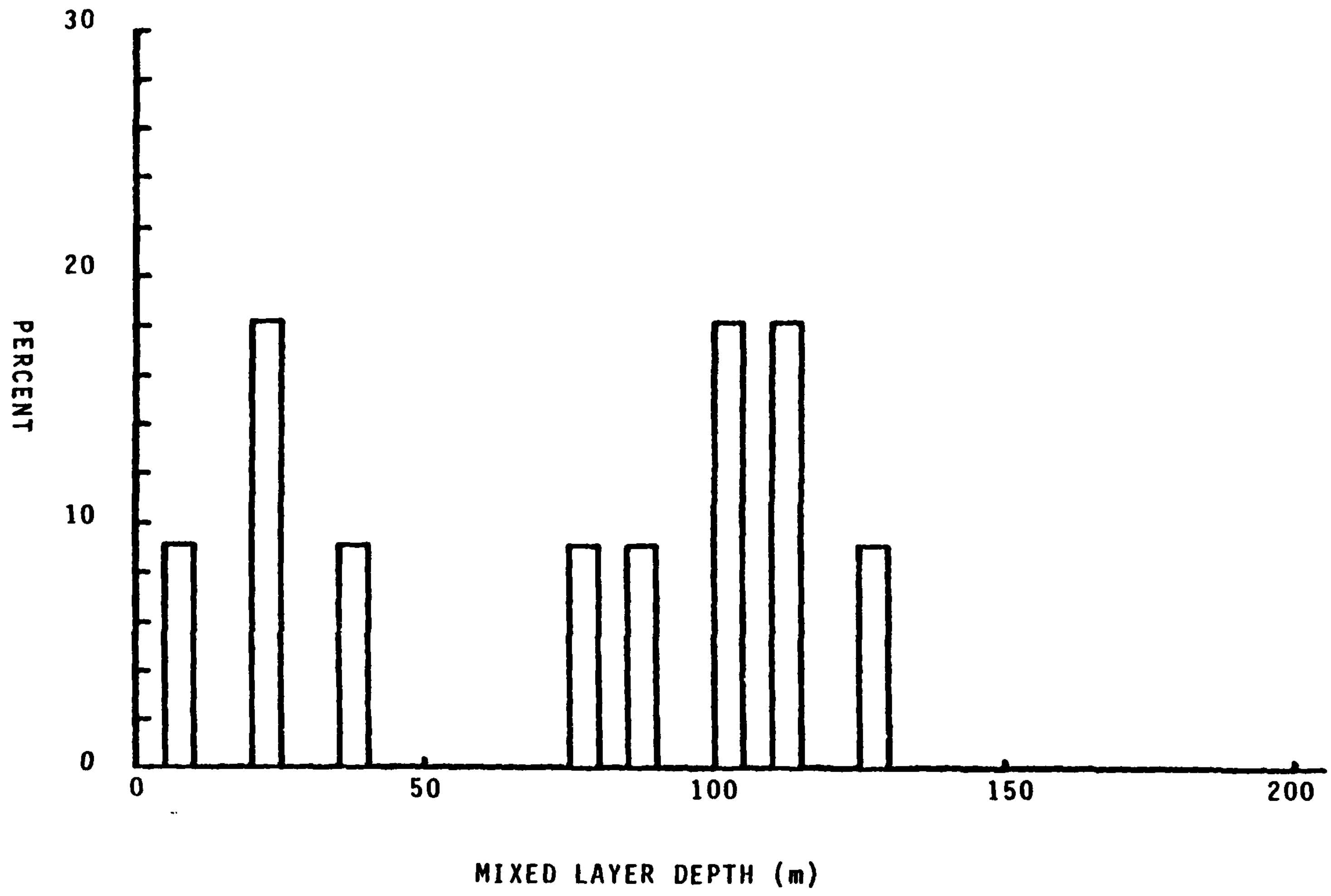

Figure 3.7 Histogram of MLD_T for Fall, Area III (11 Stations)

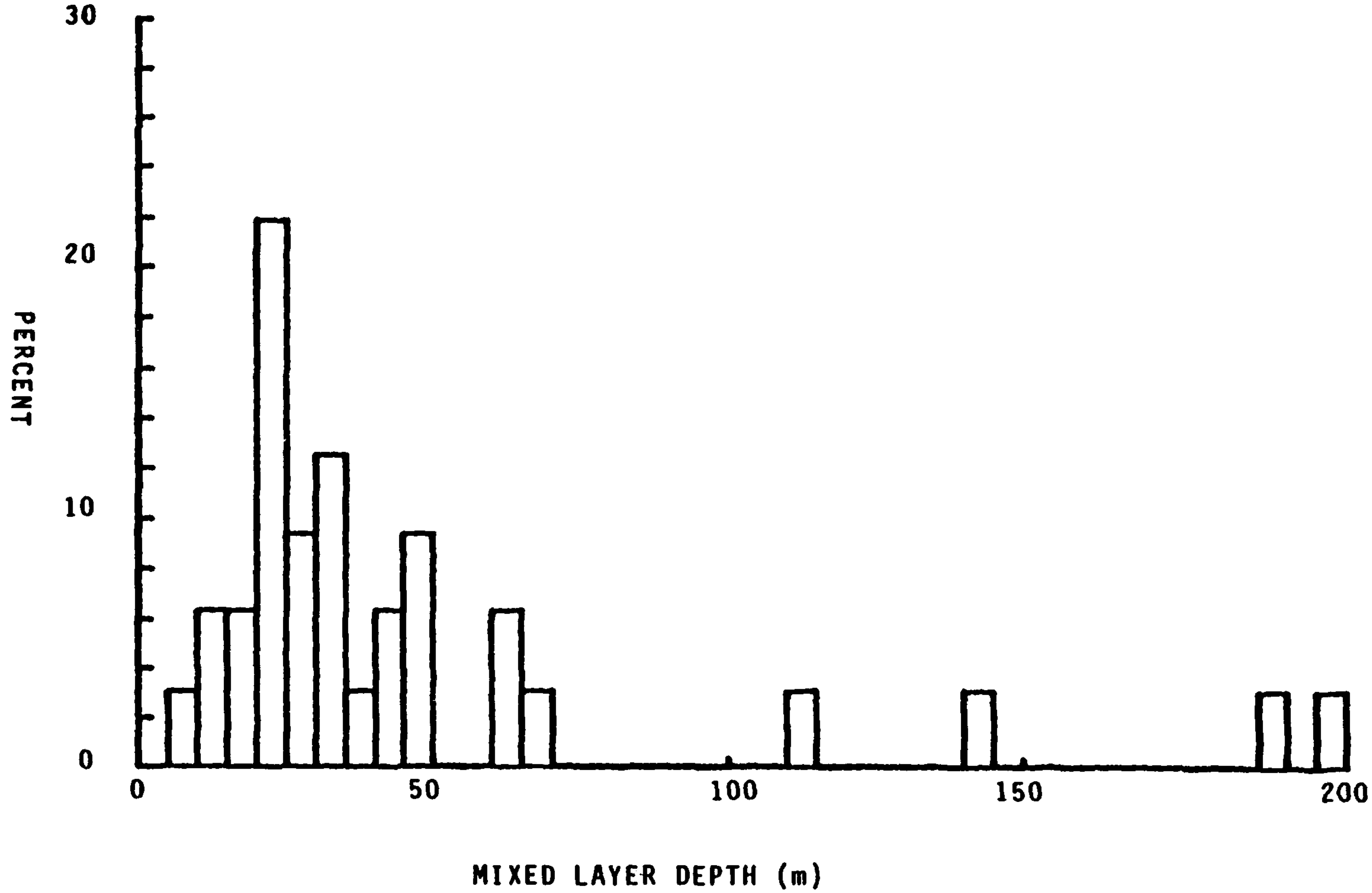

Figure 3.8 Histogram of MLD_T for Spring, Area III (32 Stations)

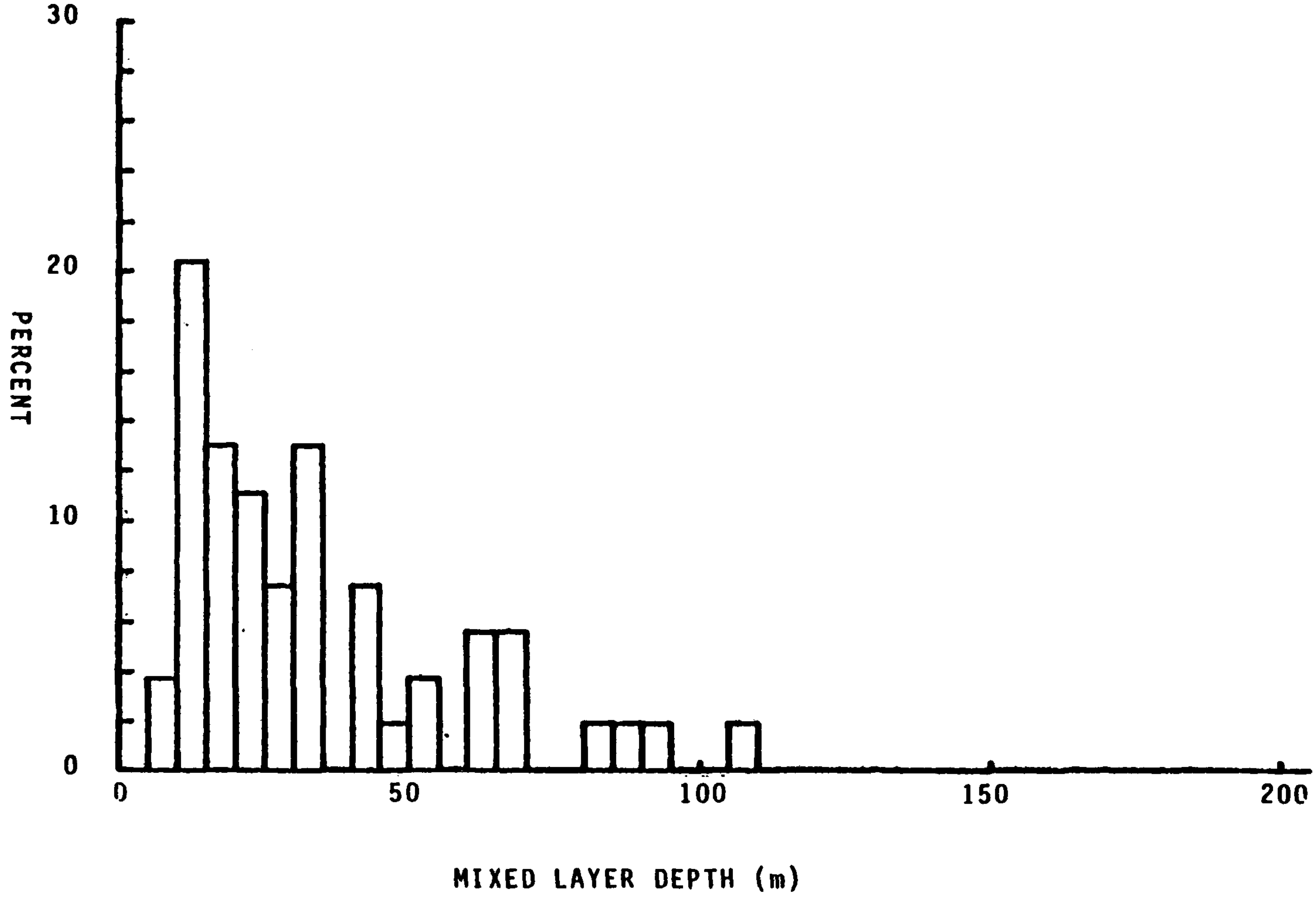

Figure 3.9 Histogram of MLD_T for All Seasons, Area I (54 Stations)

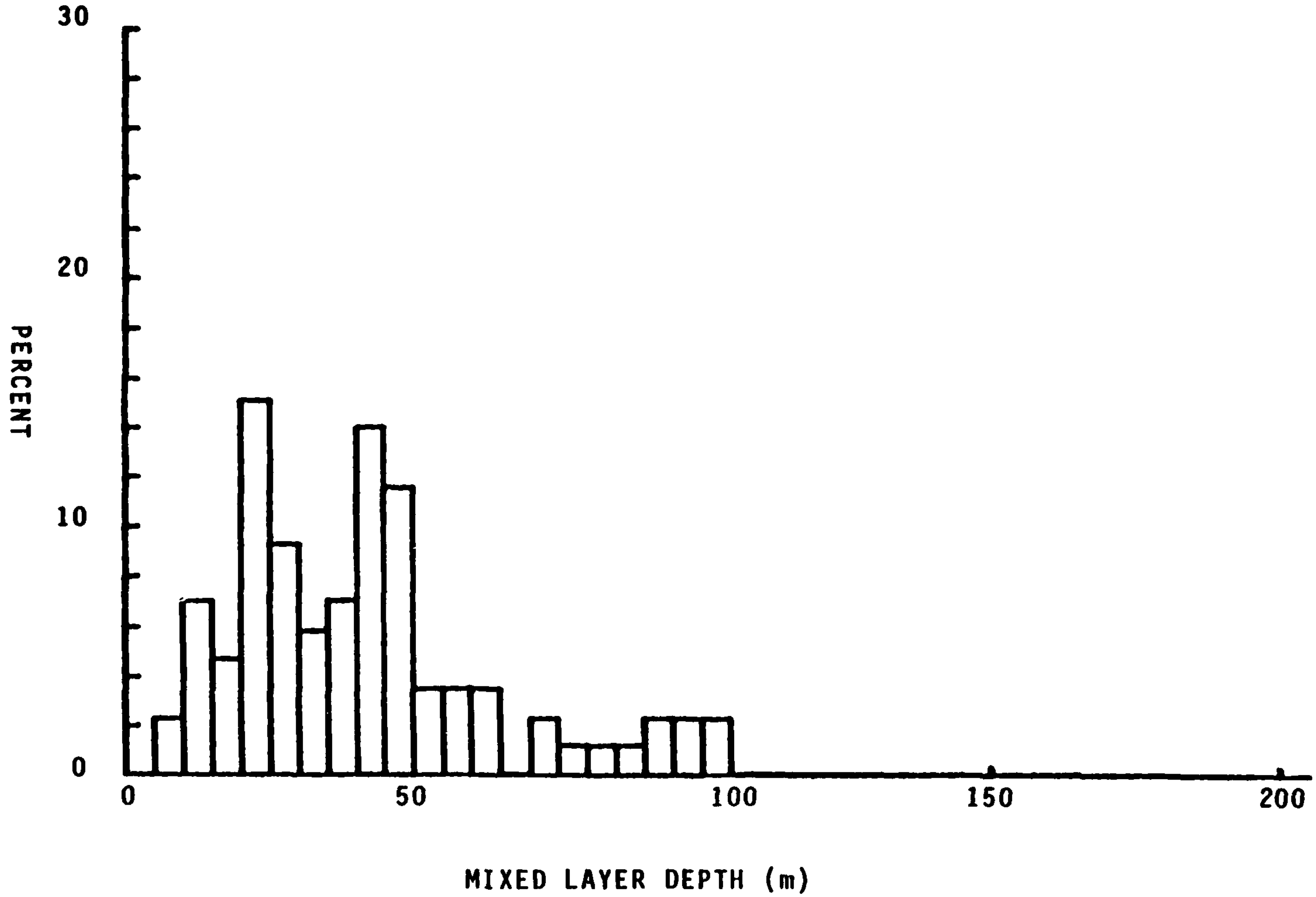

Figure 3.10 Histogram of MLD_T for All Seasons, Area II (86 Stations)

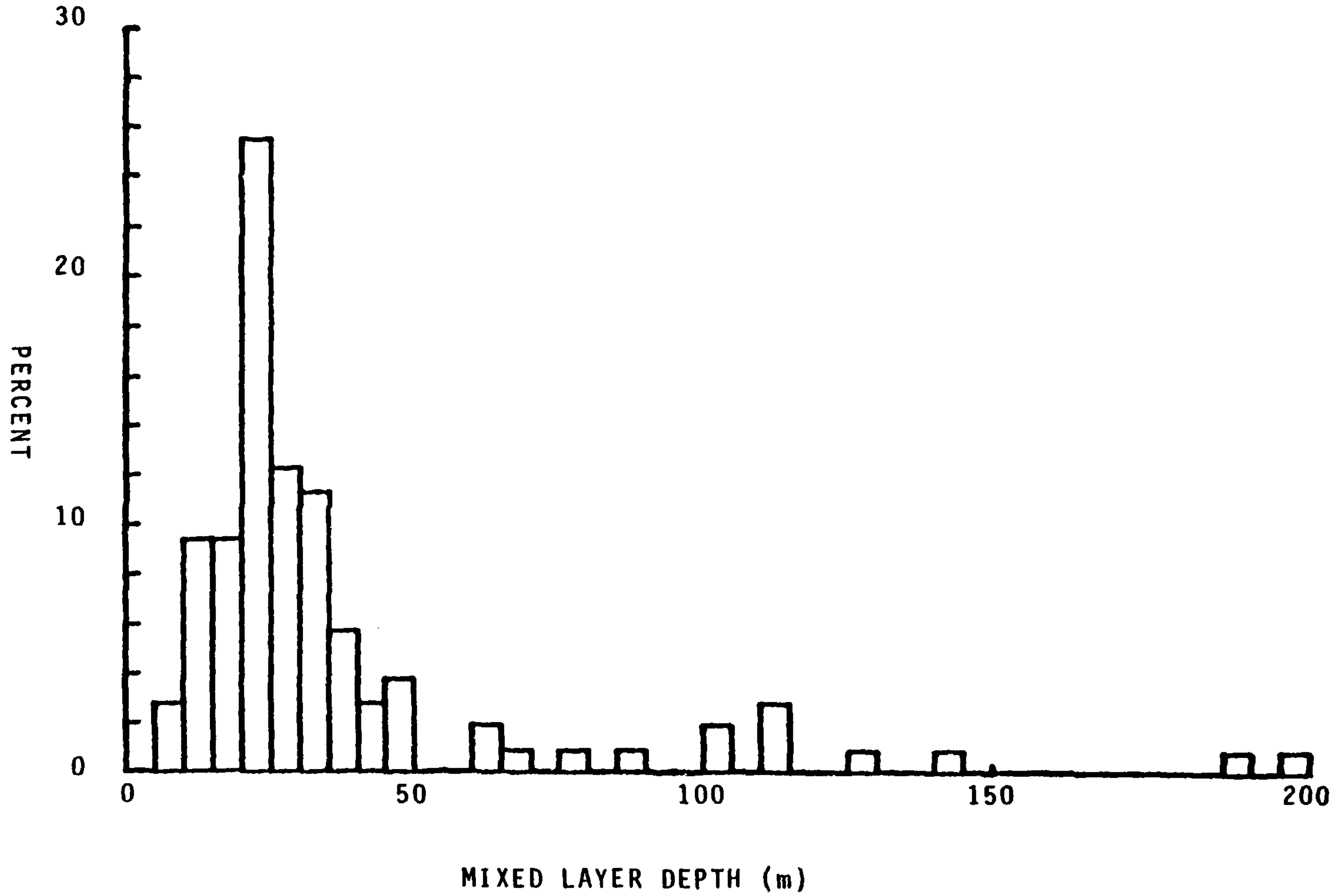

Figure 3.11 Histogram of MLD_T for All Seasons, Area III (106 Stations)

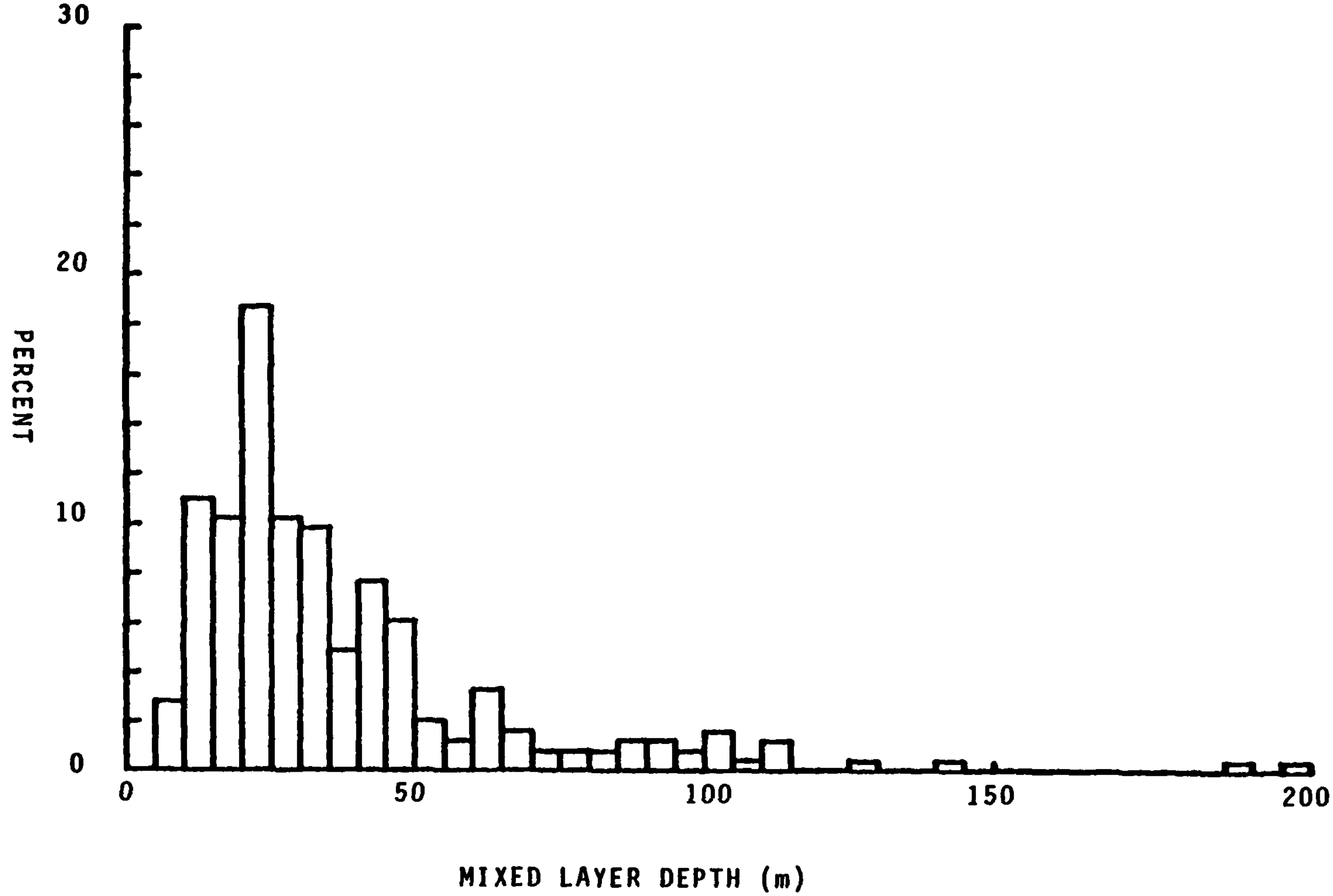

Figure 3.12 Histogram of MLD_T for All Seasons, All Areas (246 Stations)

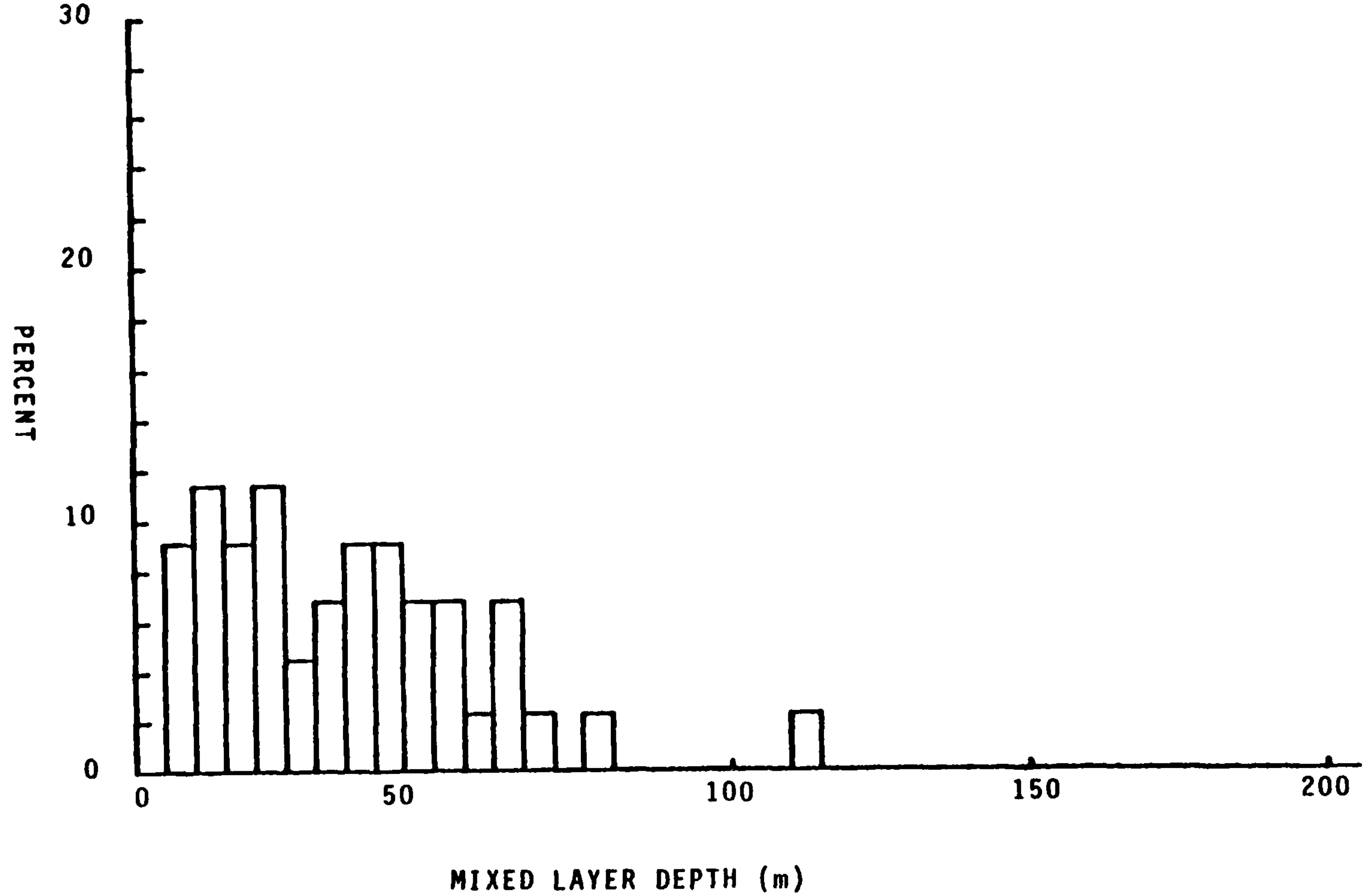

Figure 3.13 Histogram of MLD_C for Summer, Area I (44 Stations)

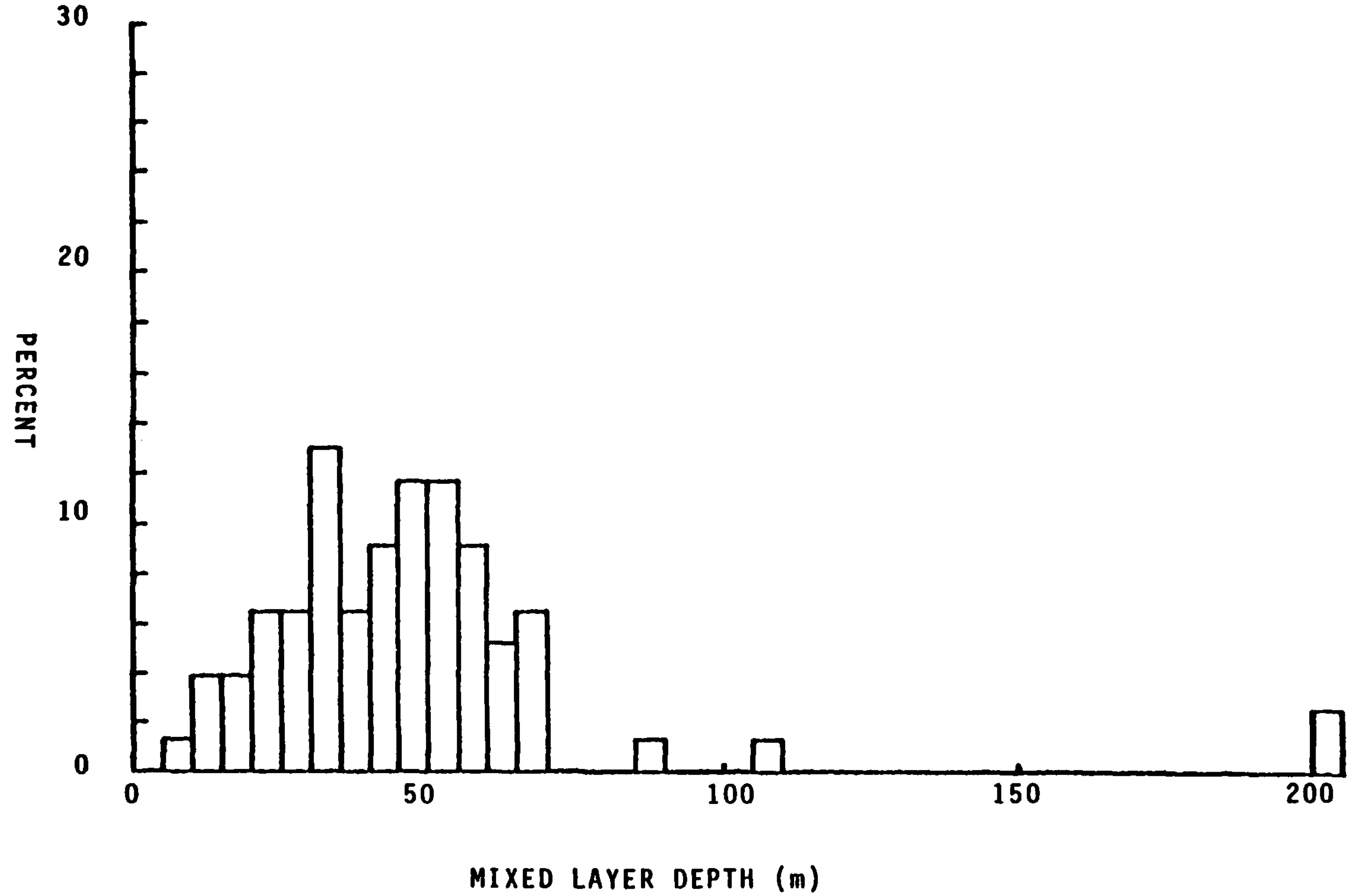

Figure 3.14 Histogram of MLD_C for Summer, Area II (77 Stations)

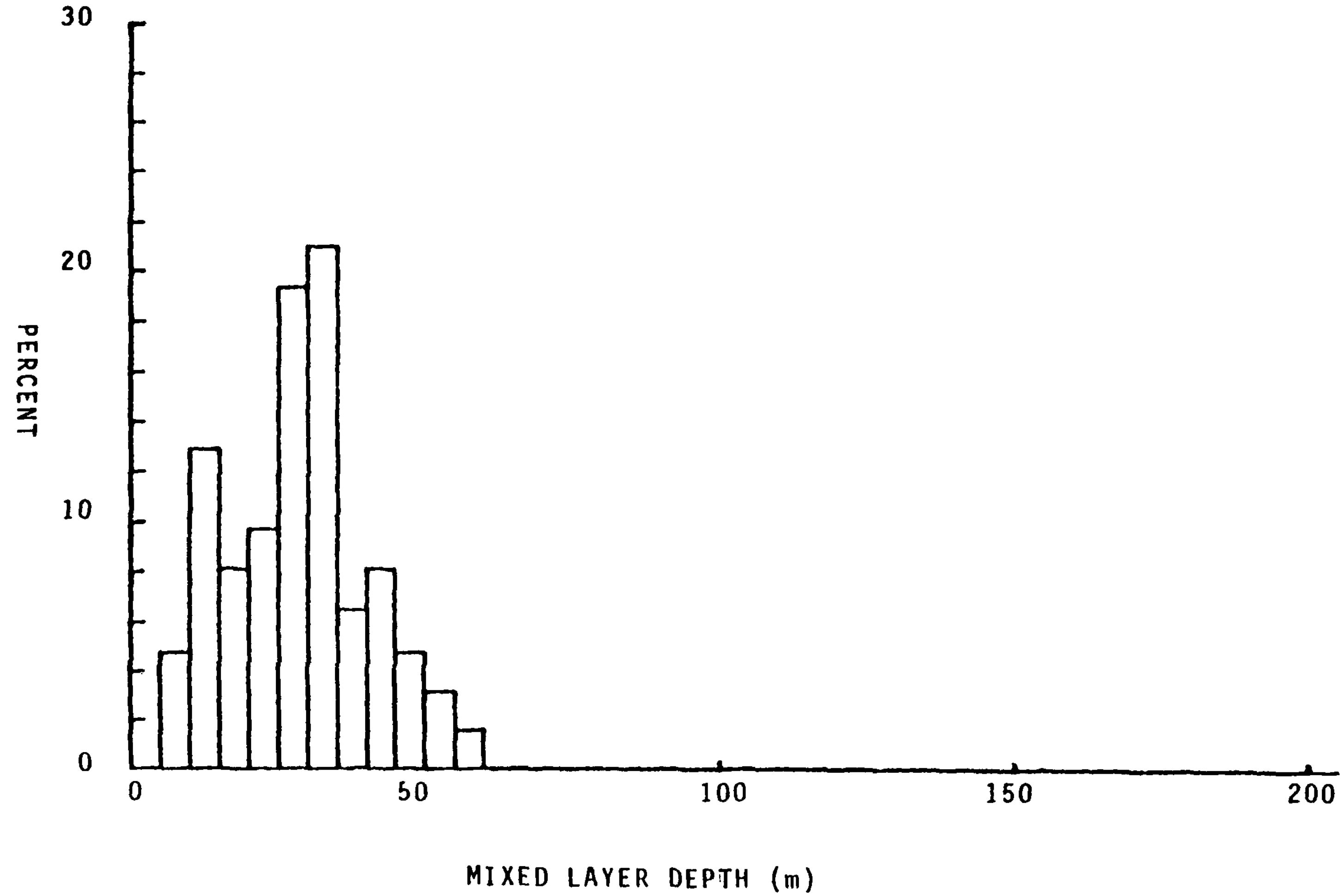

Figure 3.15 Histogram of MLD_C for Summer, Area III (62 Stations)

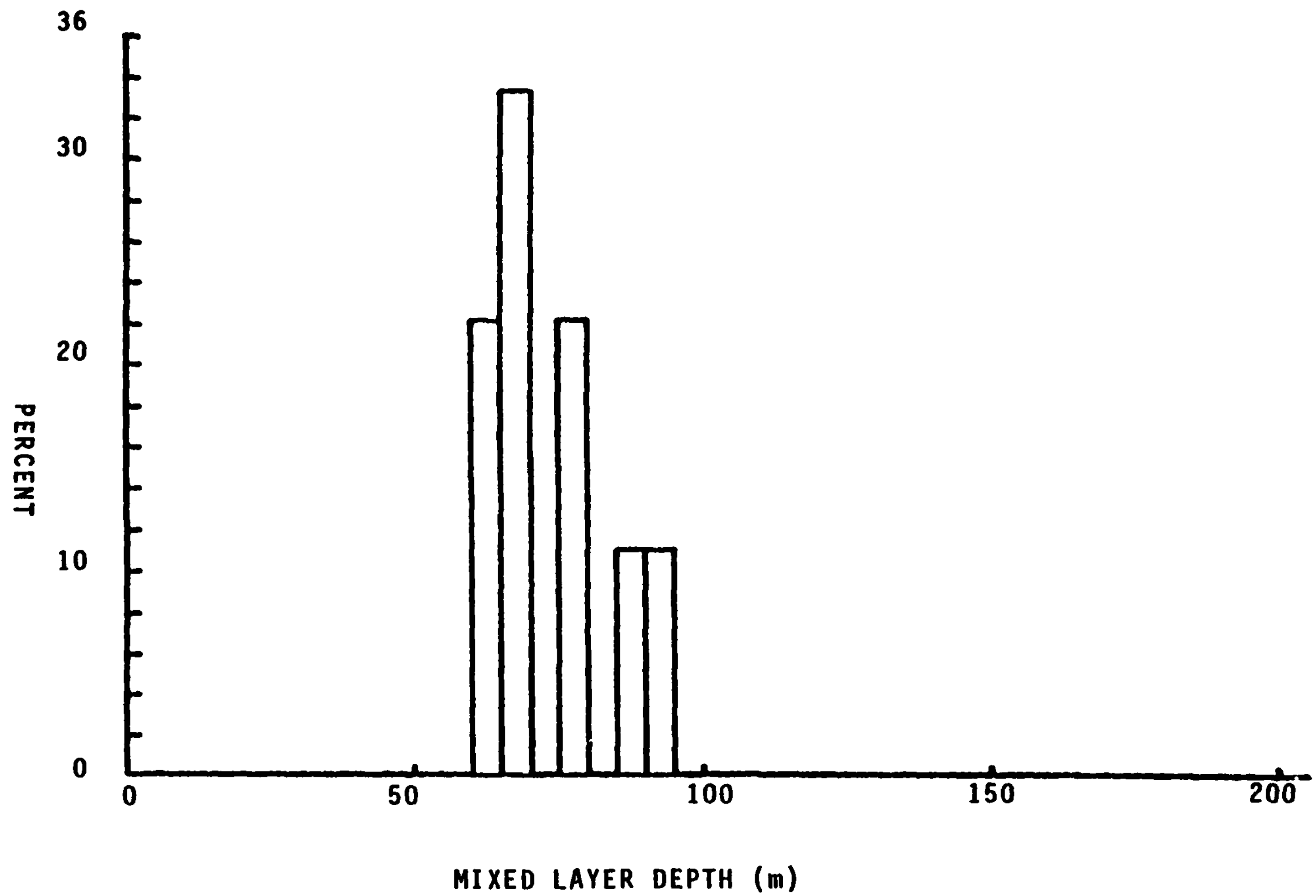

Figure 3.16 Histogram of MLD_C for Fall, Area I (9 Stations)

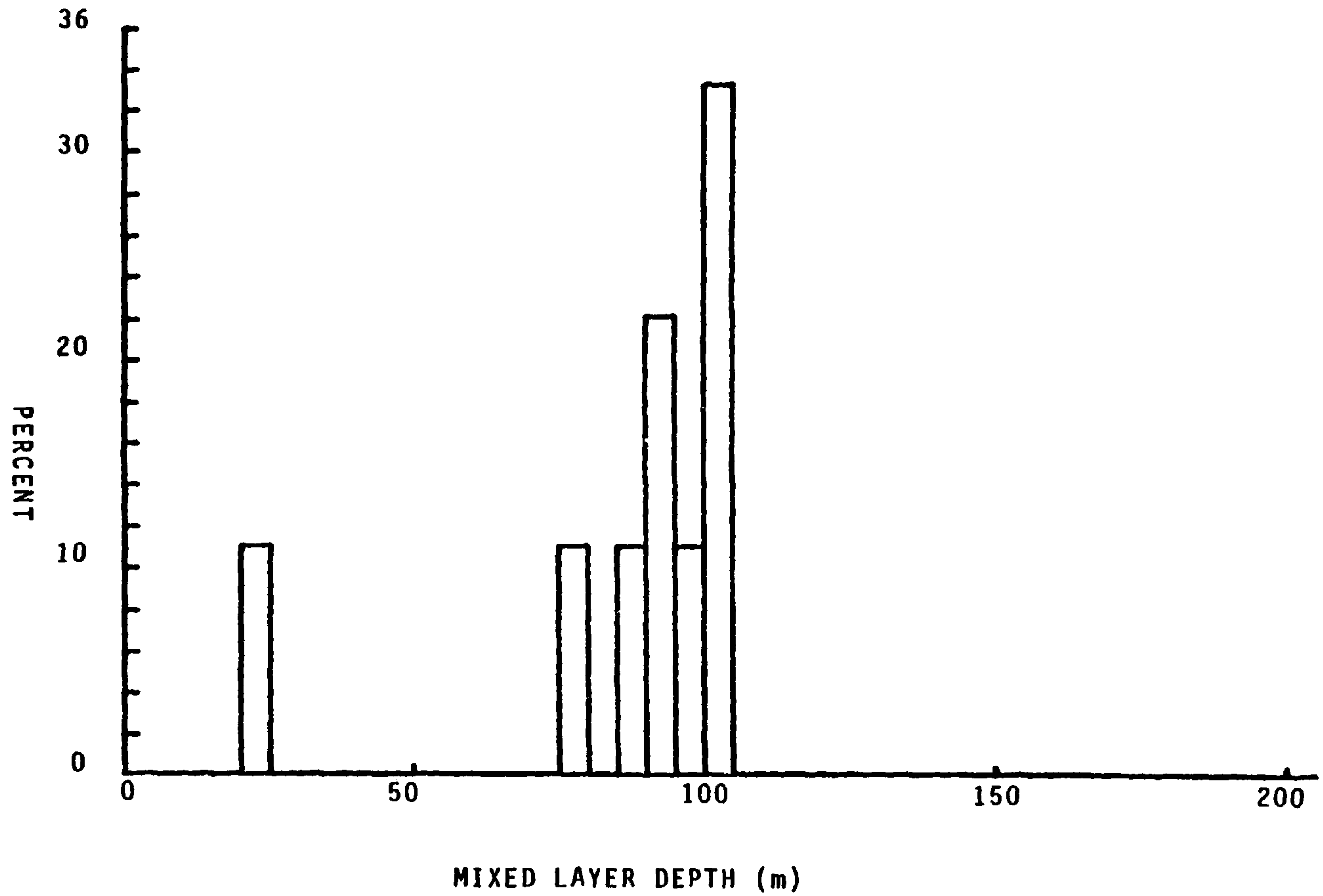

Figure 3.17 Histogram of MLD_C for Fall, Area II (9 Stations)

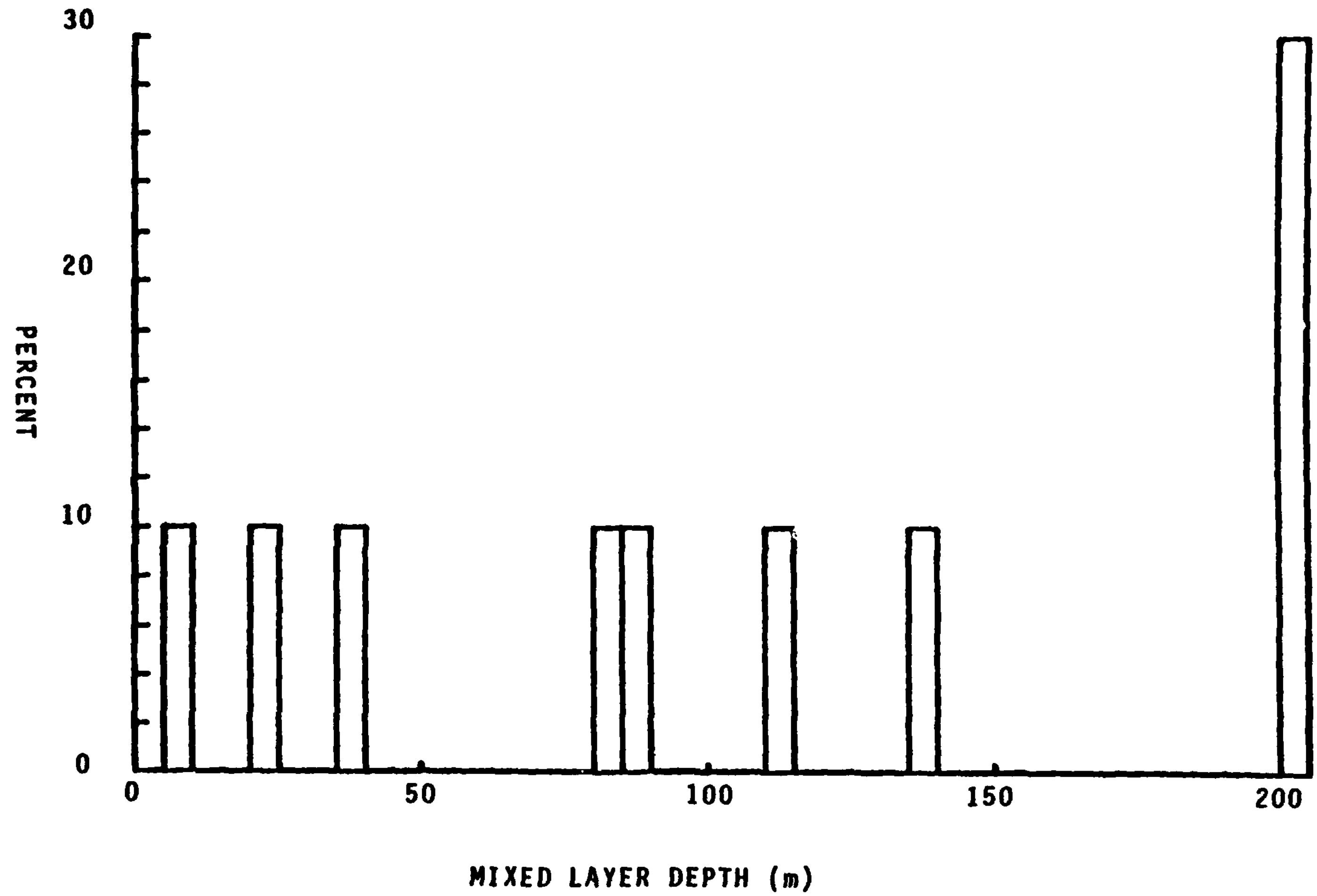

Figure 3.18 Histogram of MLD_C for Fall, Area III (10 Stations)

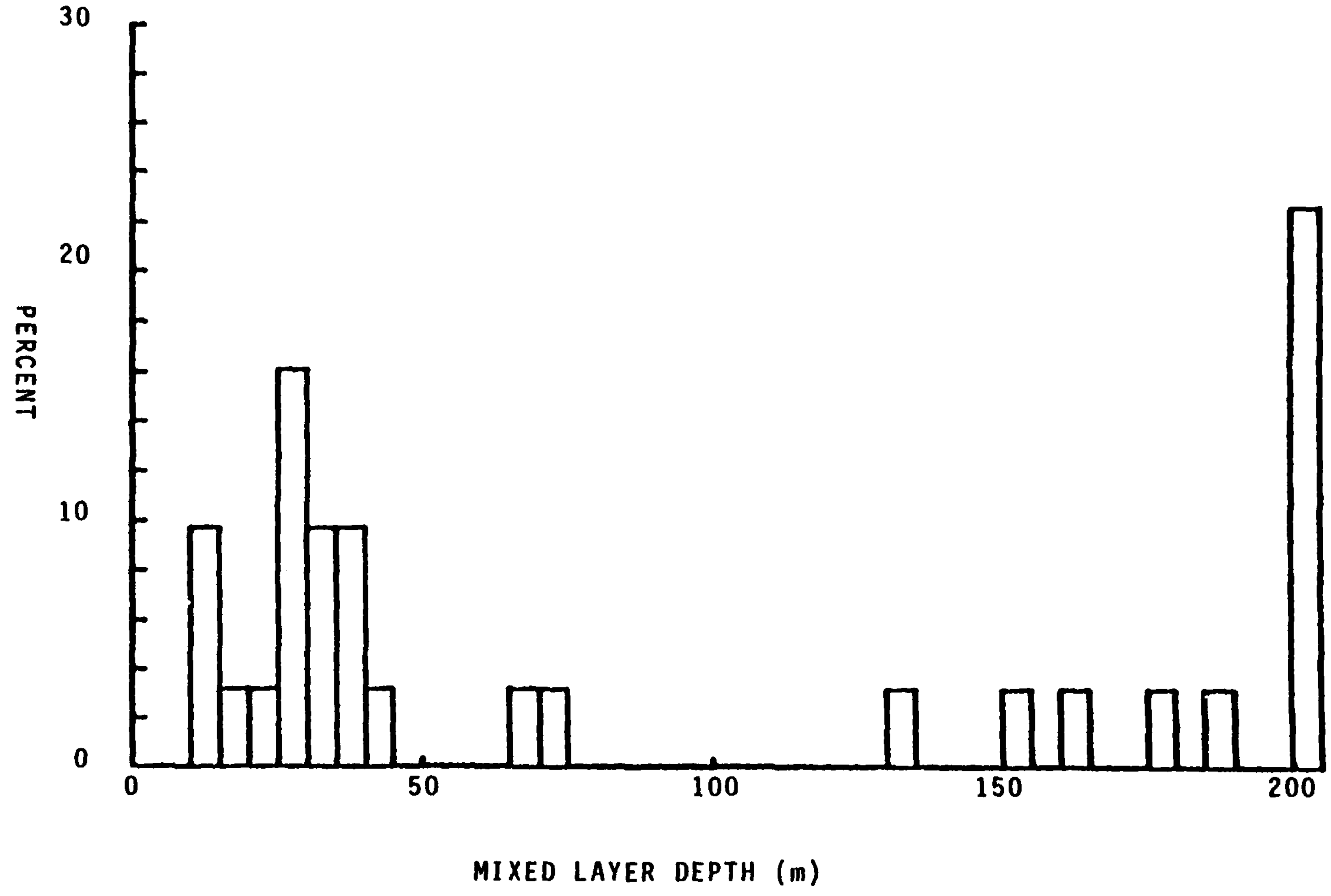

Figure 3.19 Histogram of MLD_C for Spring, Area III (31 Stations)

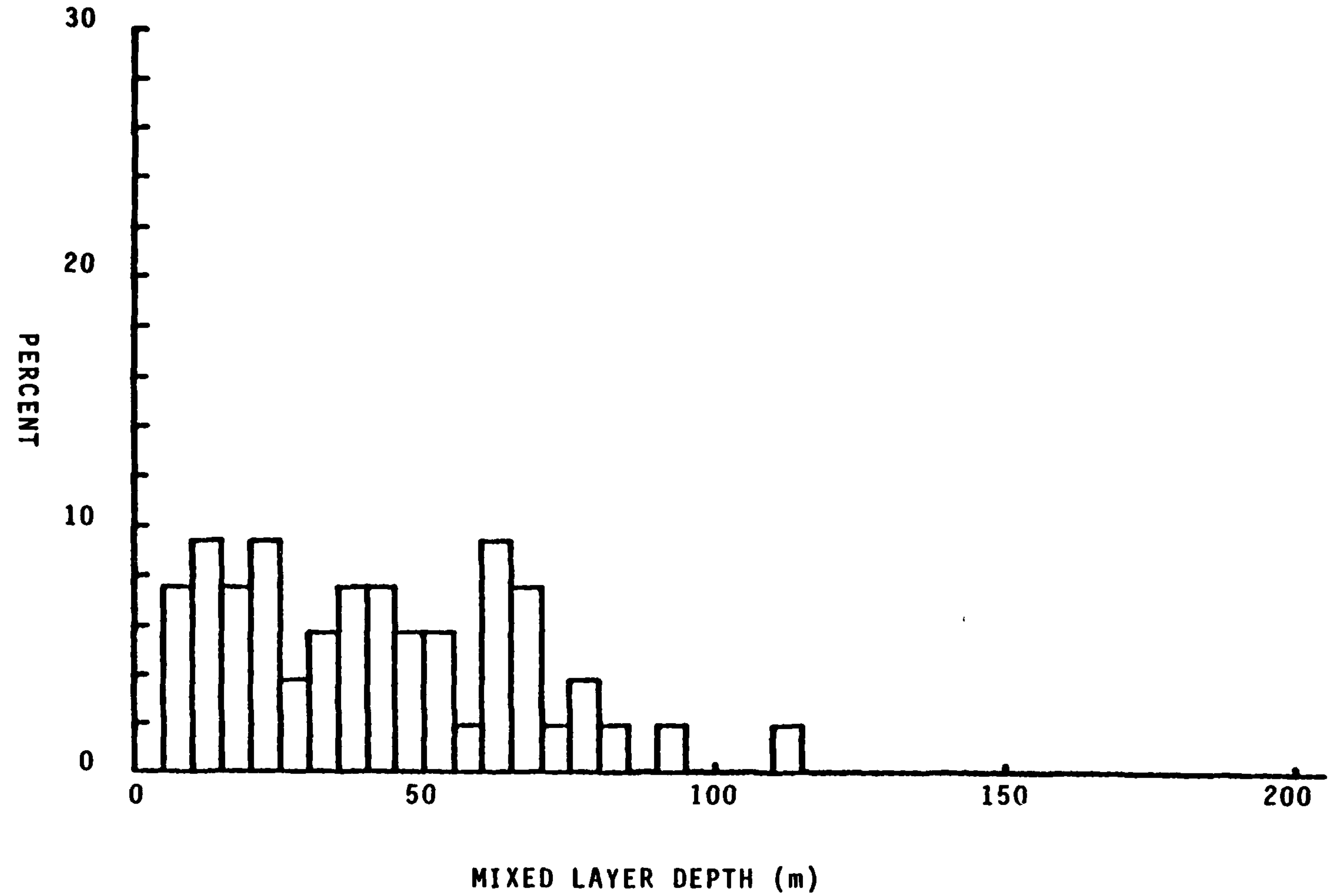

Figure 3.20 Histogram of MLD_C for All Seasons, Area I (53 Stations)

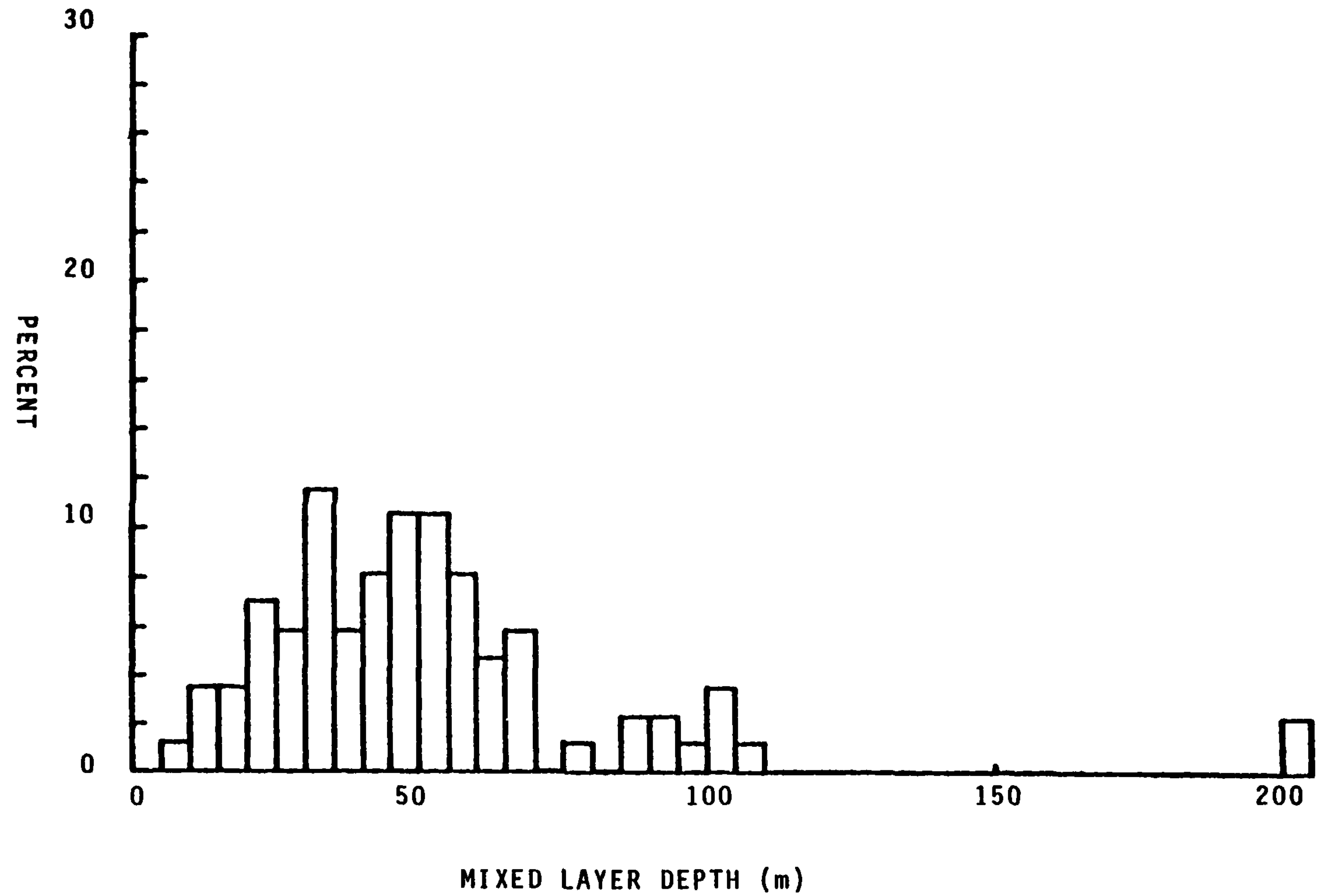

Figure 3.21 Histogram of MLD_C for All Seasons, Area II (86 Stations)

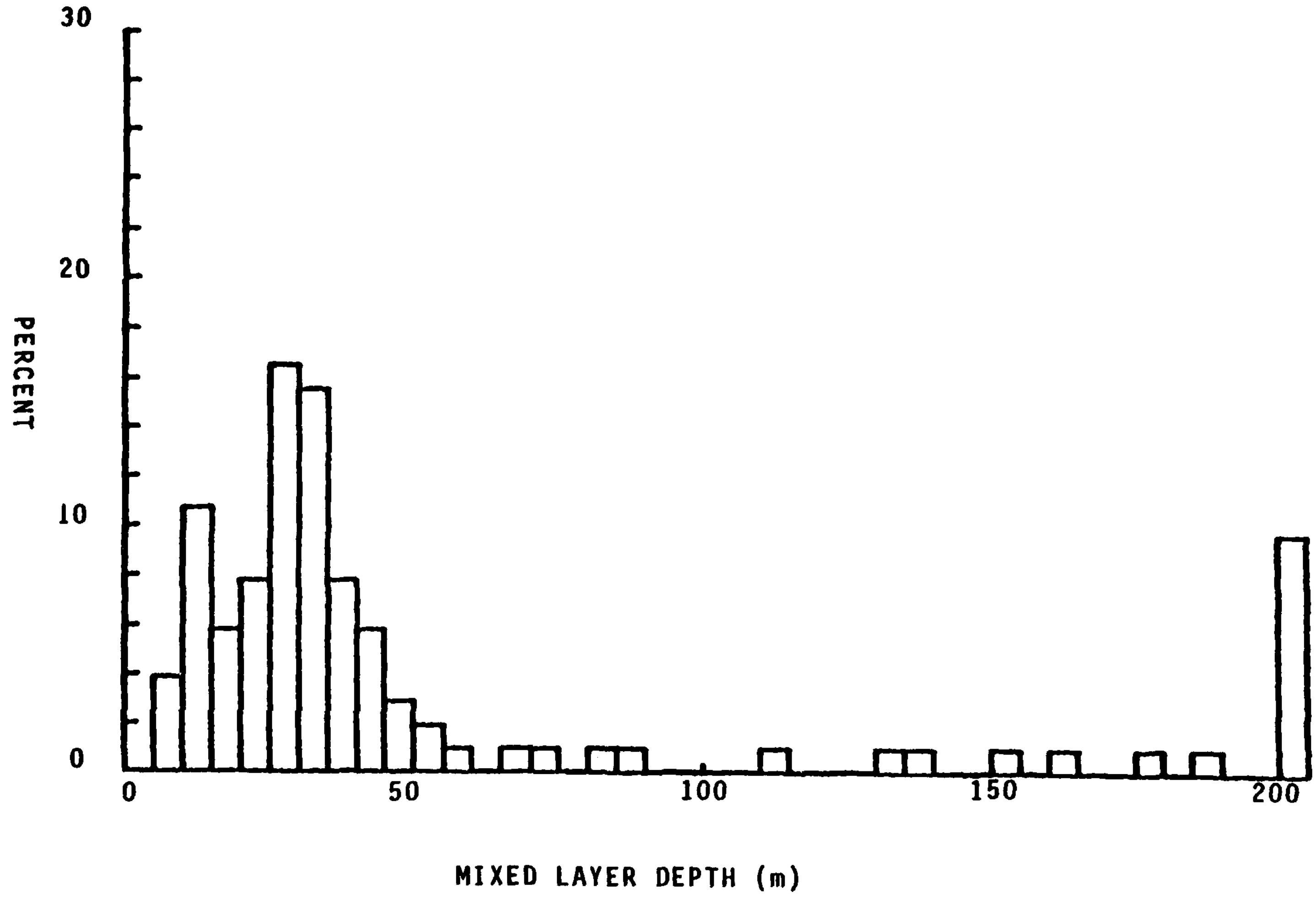

Figure 3.22 Histogram of MLD_C for All Seasons, Area III (103 Stations)

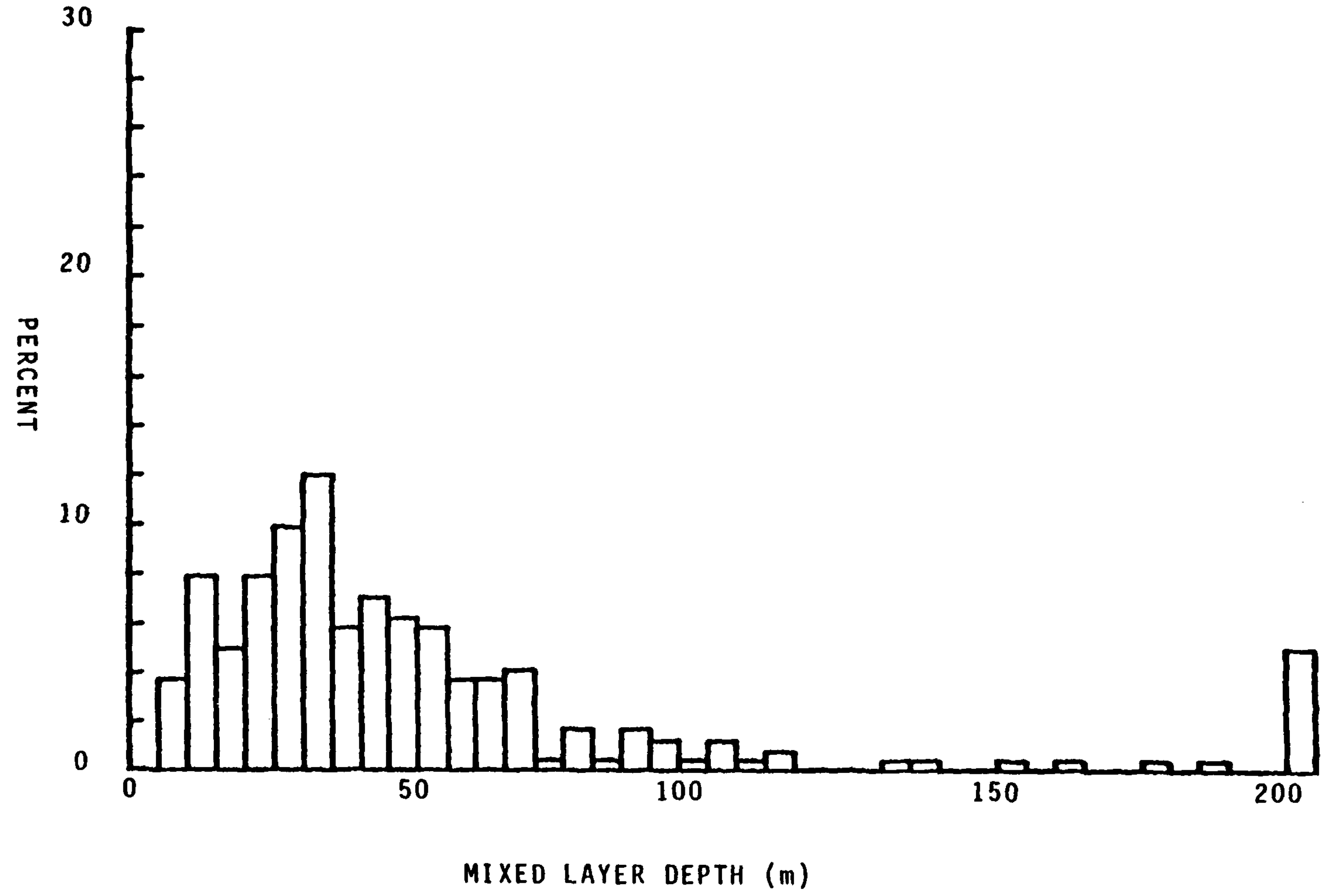

Figure 3.23 Histogram of MLD_C for All Seasons, All Areas (242 Stations)

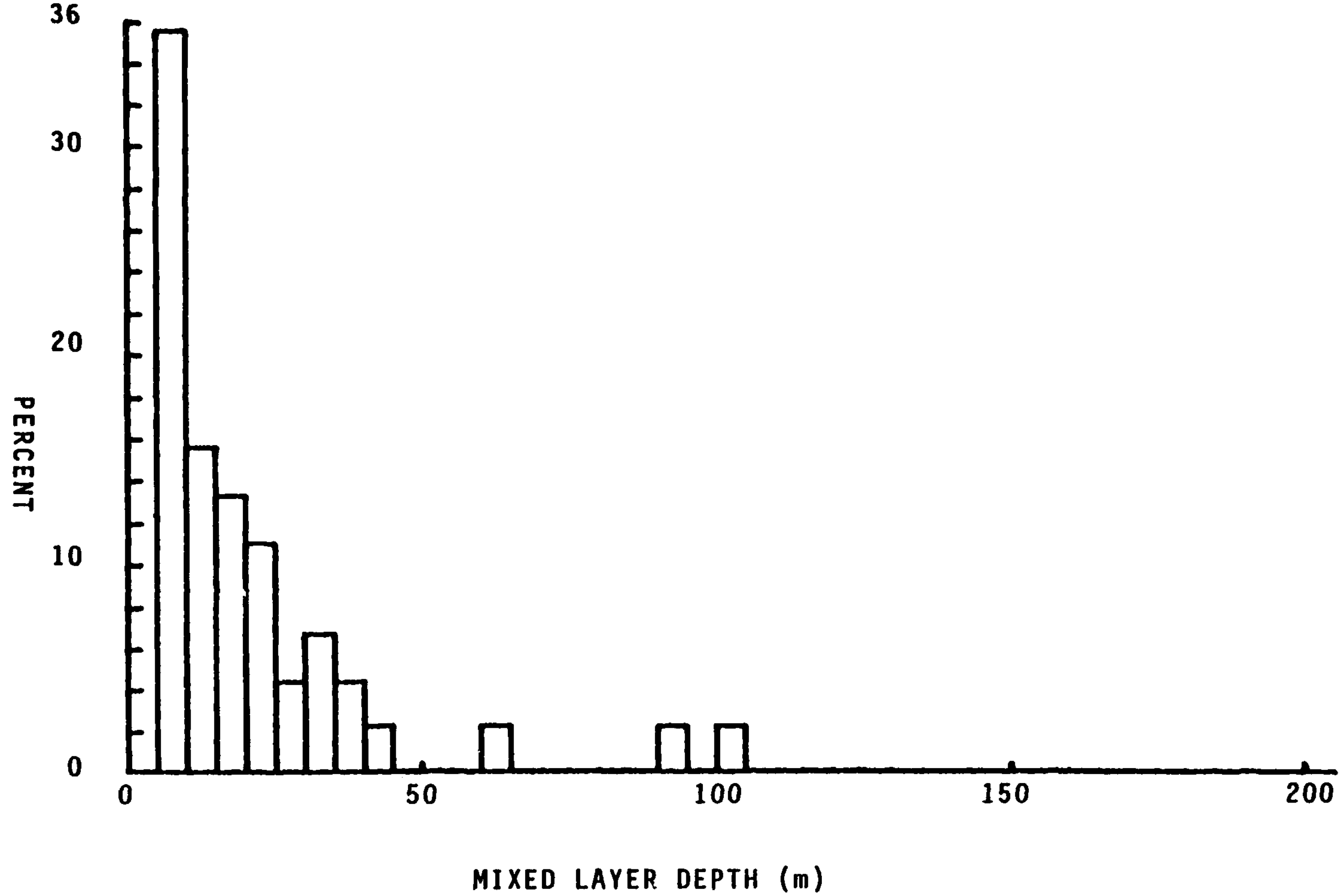

Figure 3.24 Histogram of MLD_D for Summer, Area I (45 Stations)

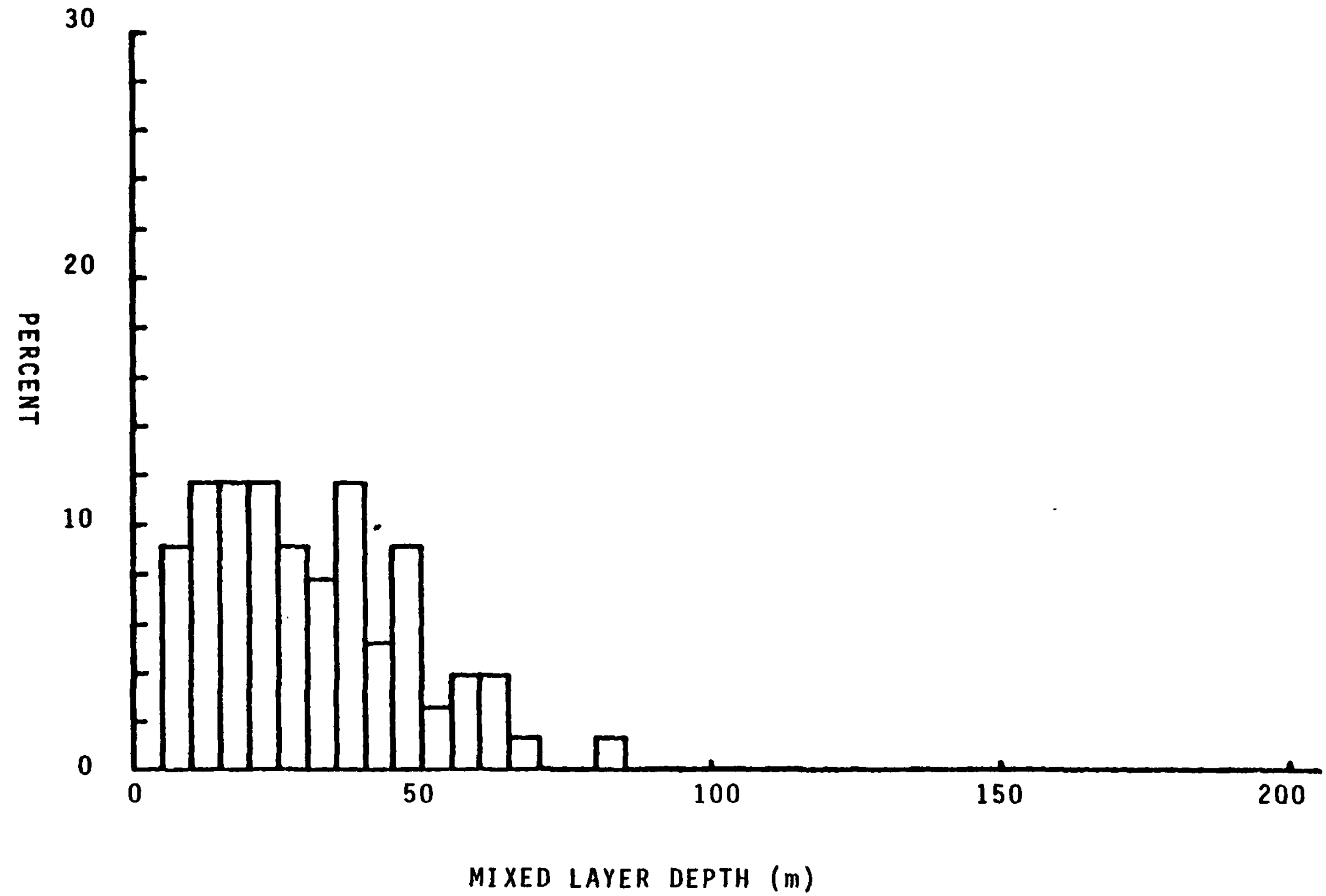

Figure 3.25 Histogram of MLD_D for Summer, Area II (77 Stations)

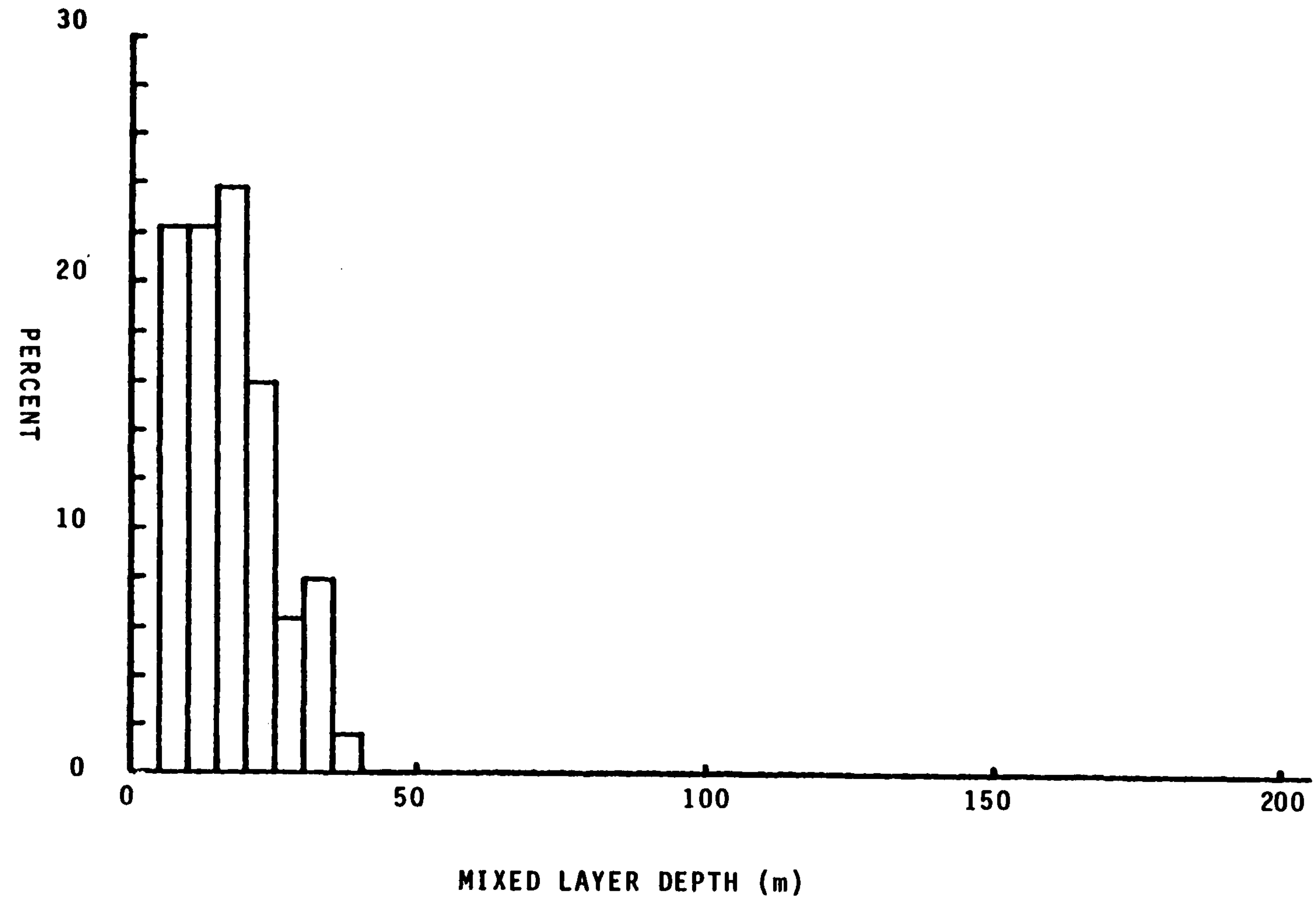

Figure 3.26 Histogram of MLD_D for Summer, Area III (63 Stations)

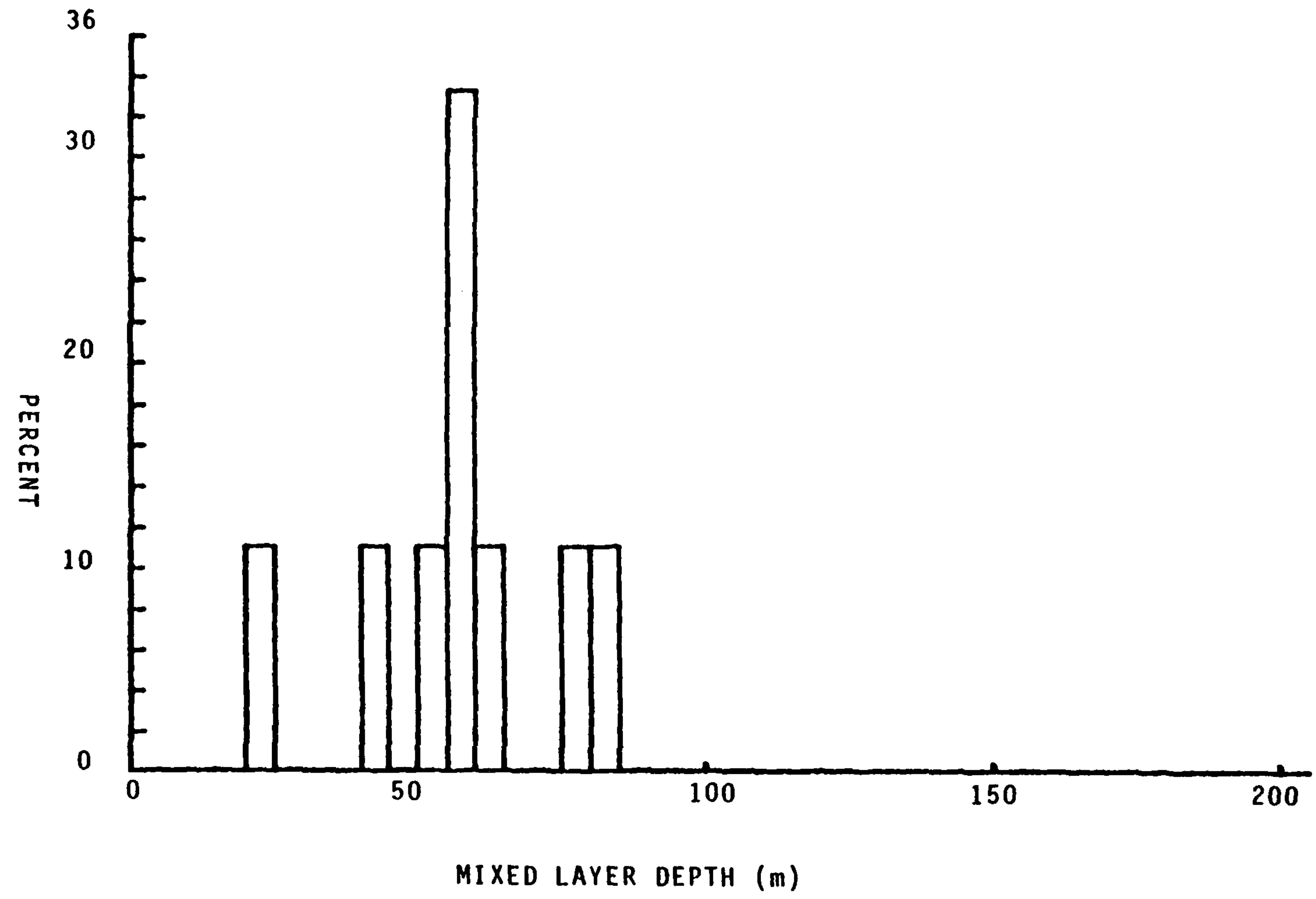

Figure 3.27 Histogram of MLD_D for Fall, Area I (9 Stations)

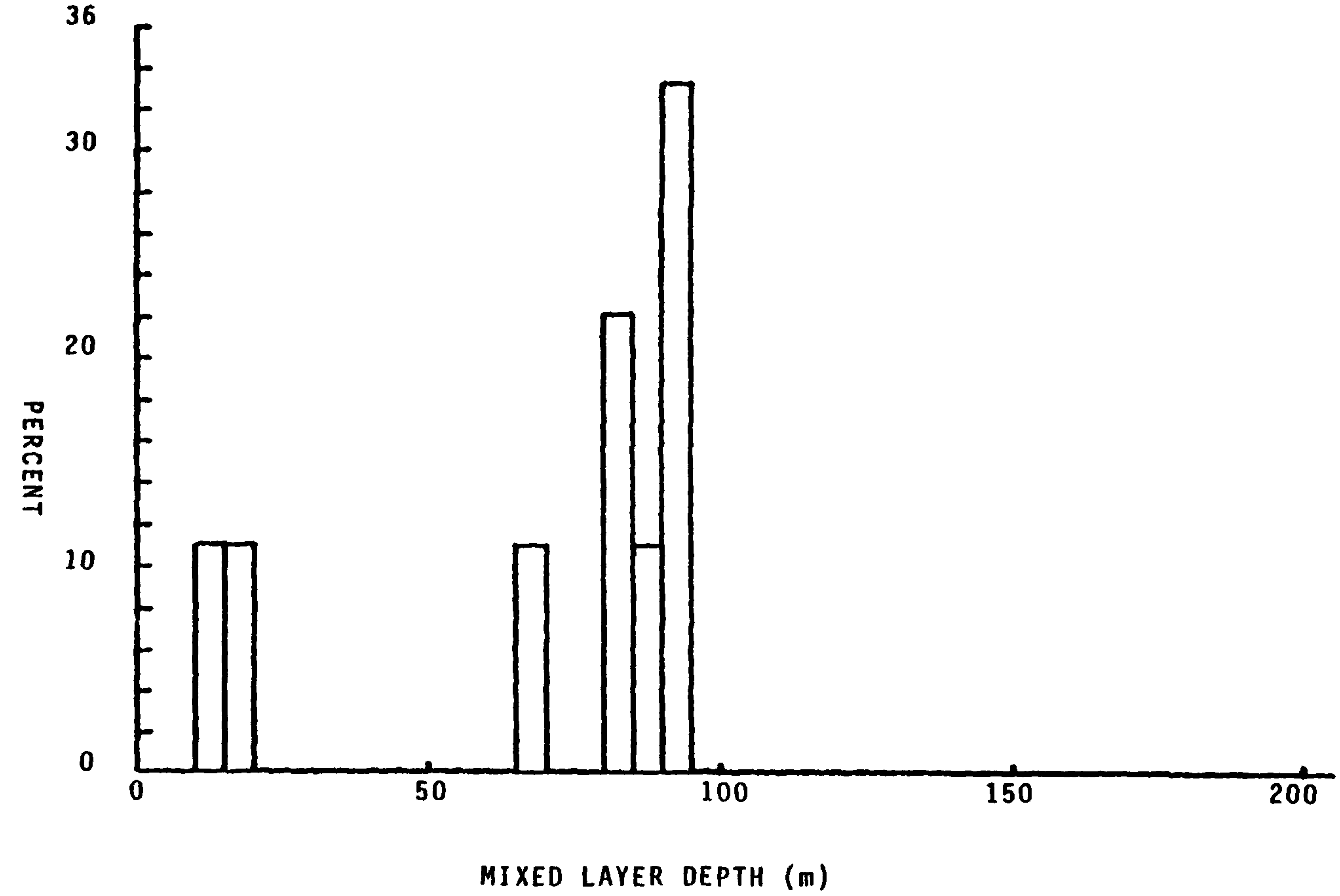

Figure 3.28 Histogram of MLD_D for Fall, Area II (9 Stations)

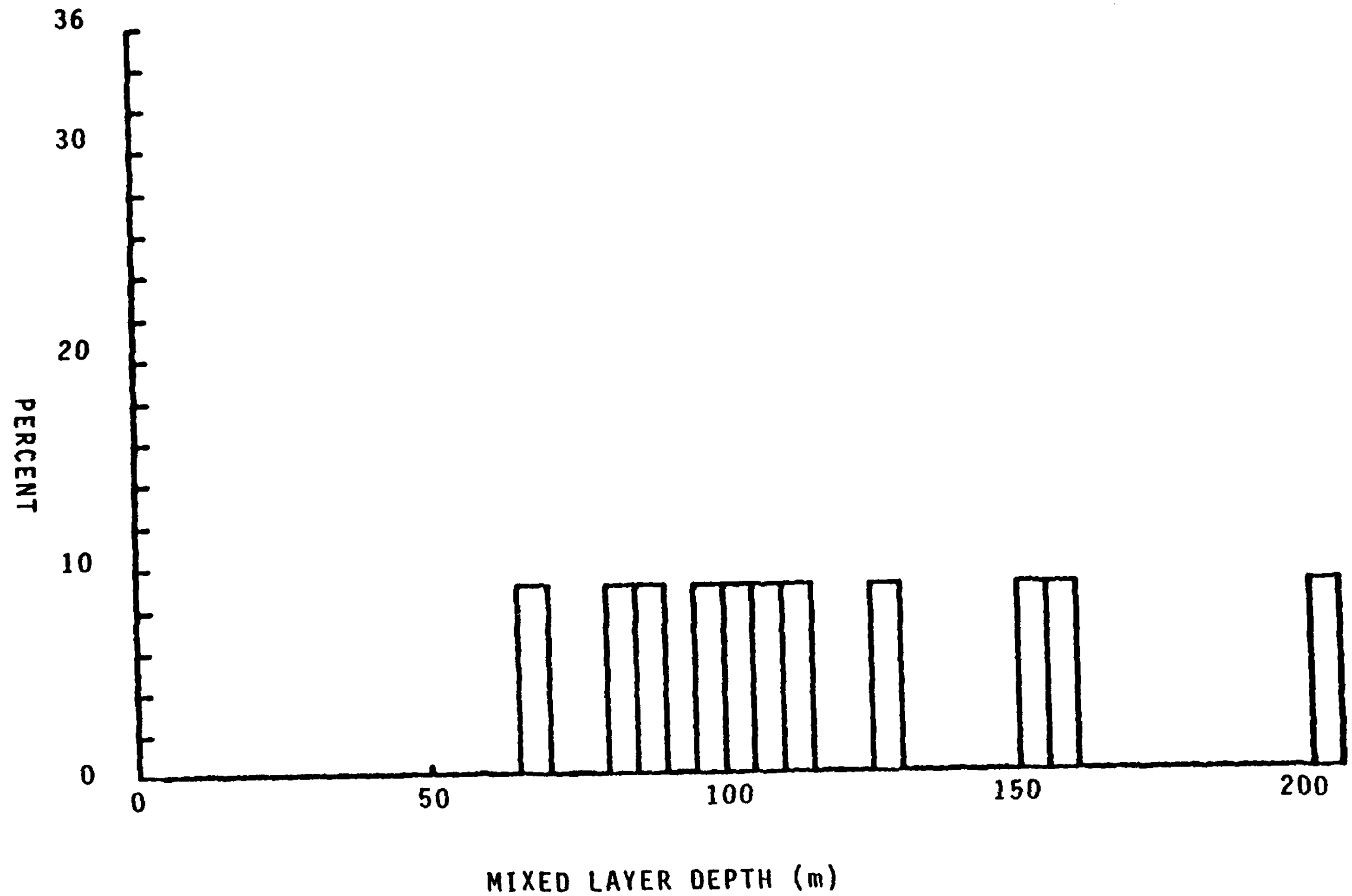

Figure 3.29 Histogram of MLD_D for Fall, Area III (11 Stations)

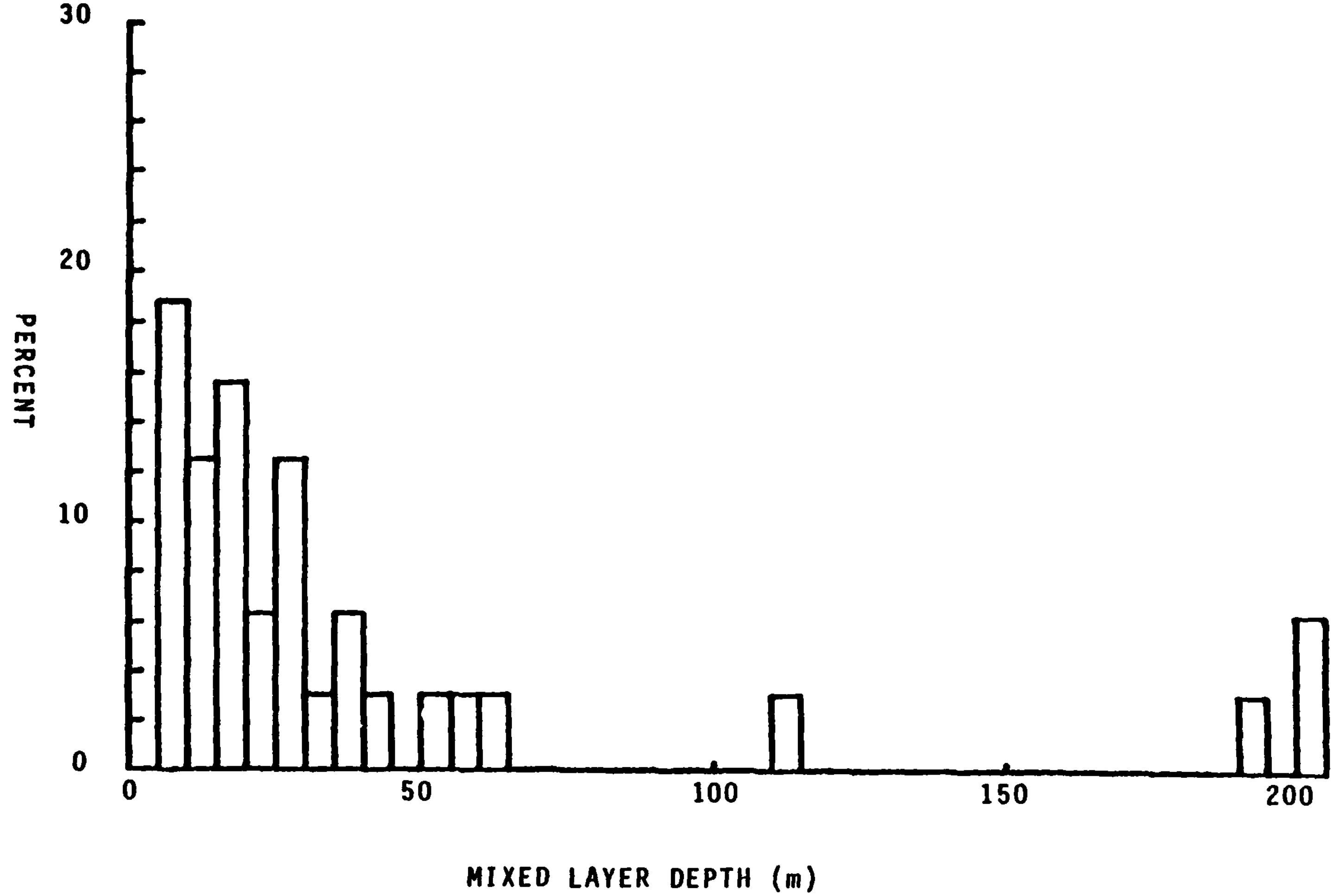

Figure 3.30 Histogram of MLD_D for Spring, Area III (32 Stations)

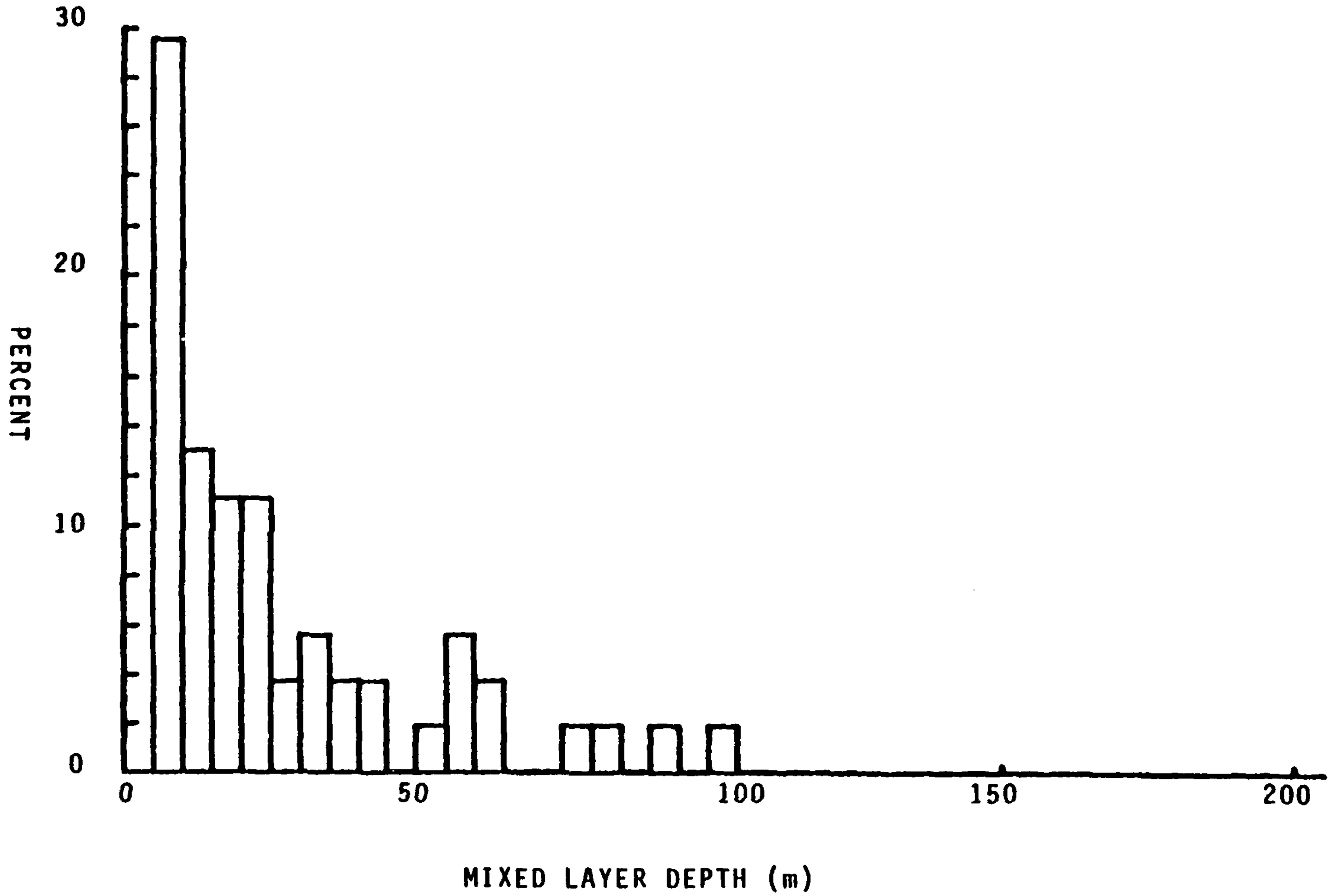

Figure 3.31 Histogram of MLD_D for All Seasons, Area I (54 Stations)

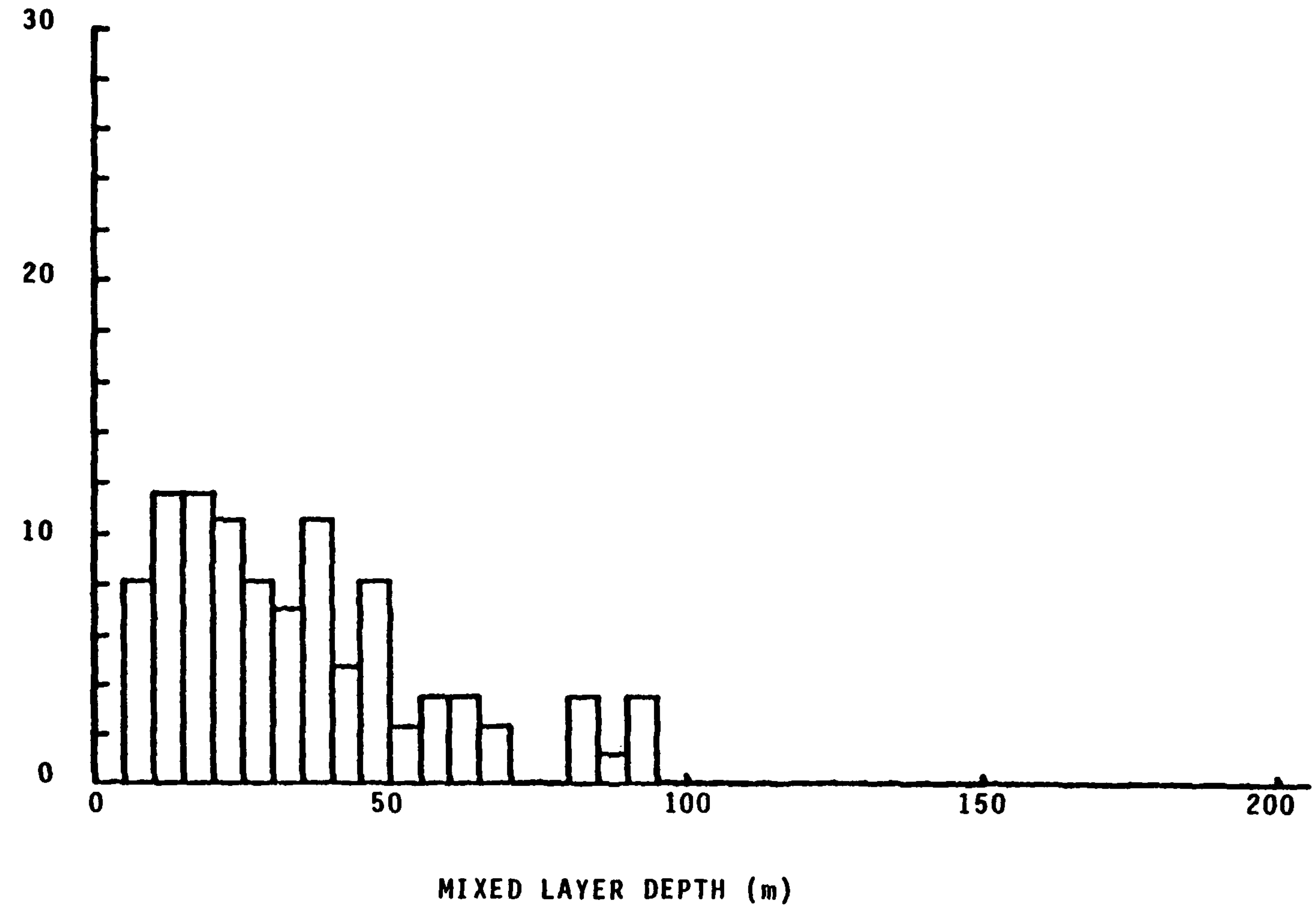

Figure 3.32 Histogram of MLD_D for All Seasons, Area II (86 Stations)

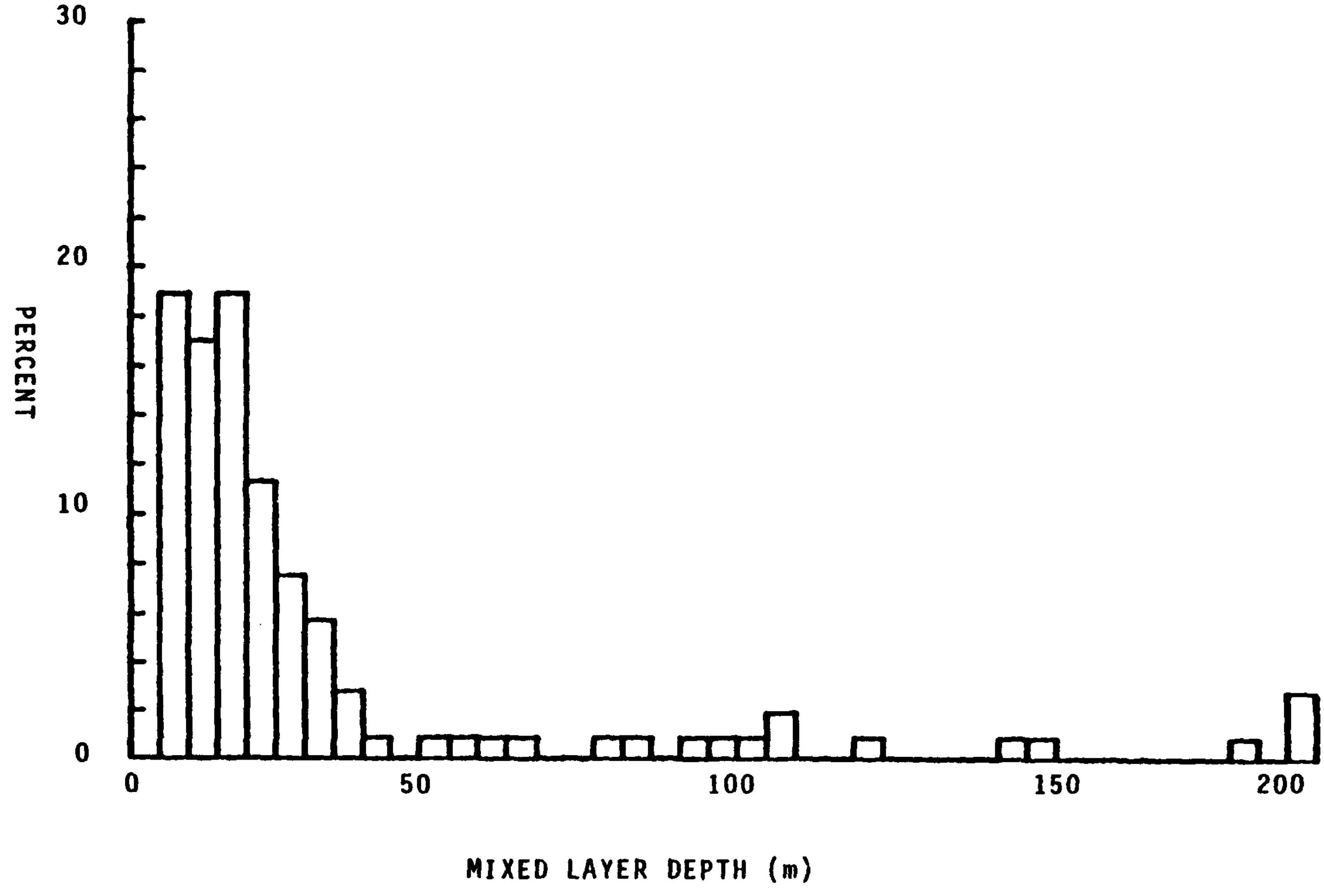

Figure 3.33 Histogram of MLD_D for All Seasons, Area III (106 Stations)

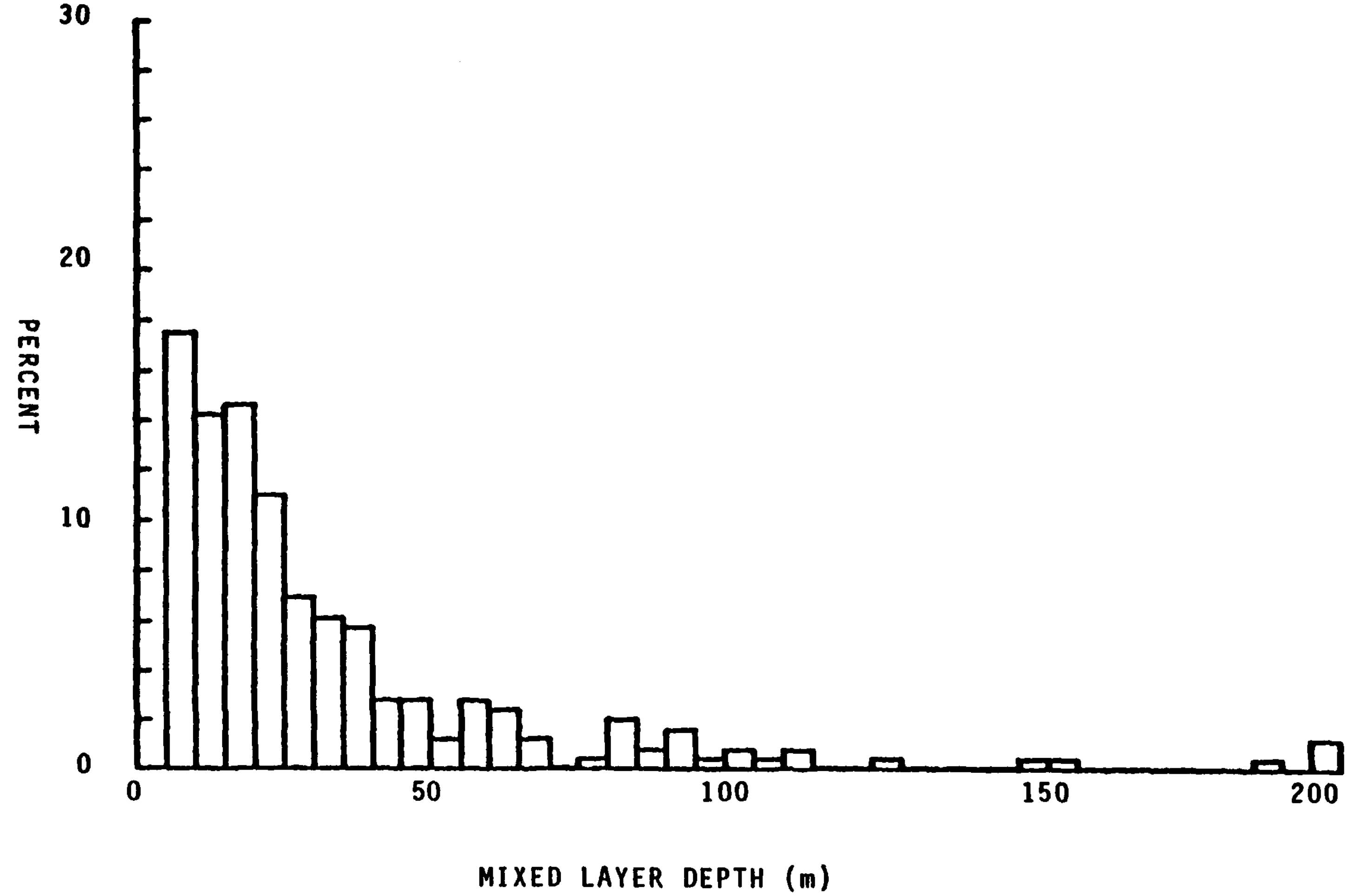

Figure 3.34 Histogram of MLD_D for All Seasons, All Areas (246 Stations)

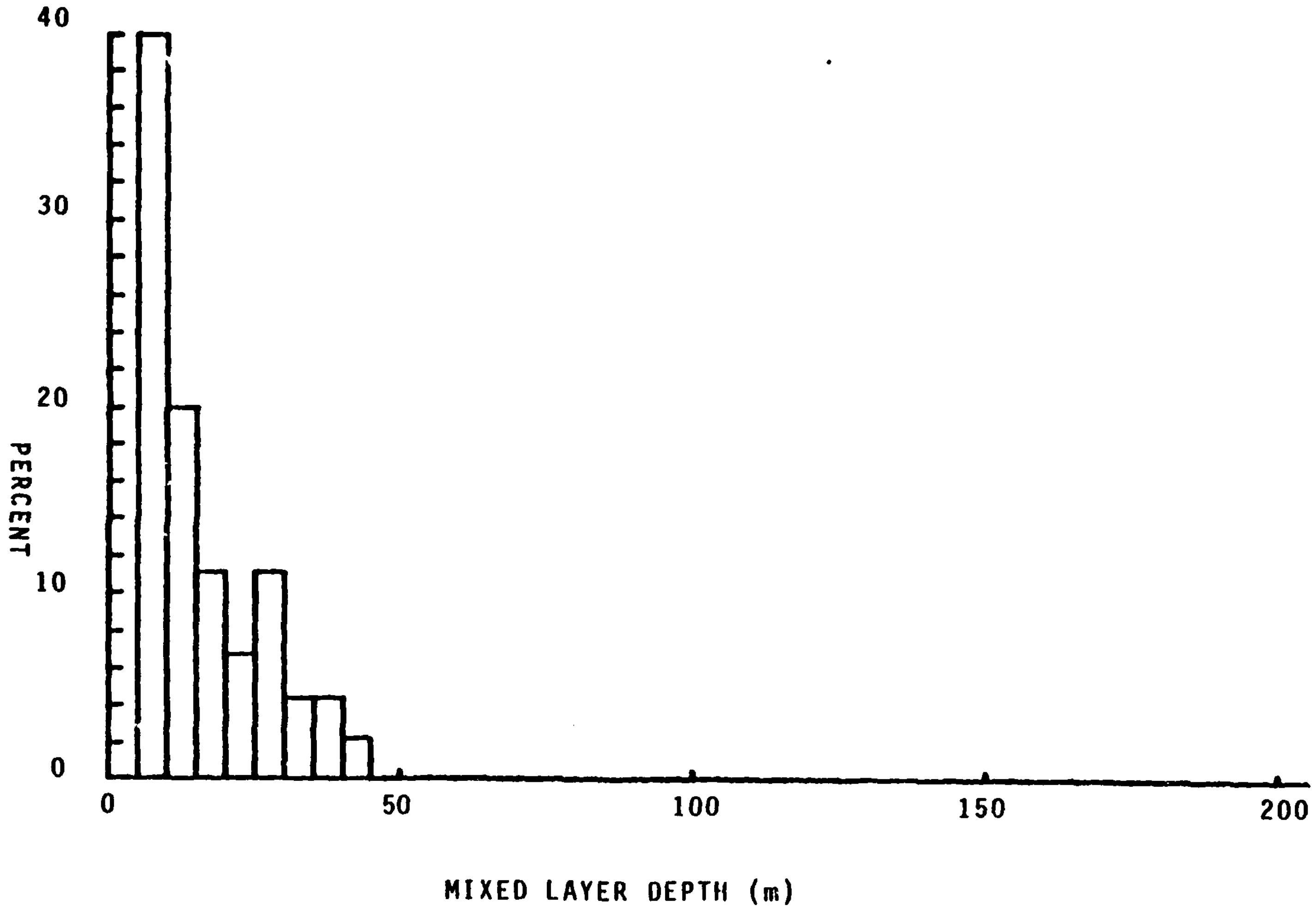

Figure 3.35 Histogram of MLD_N for Summer, Area I (45 Stations)

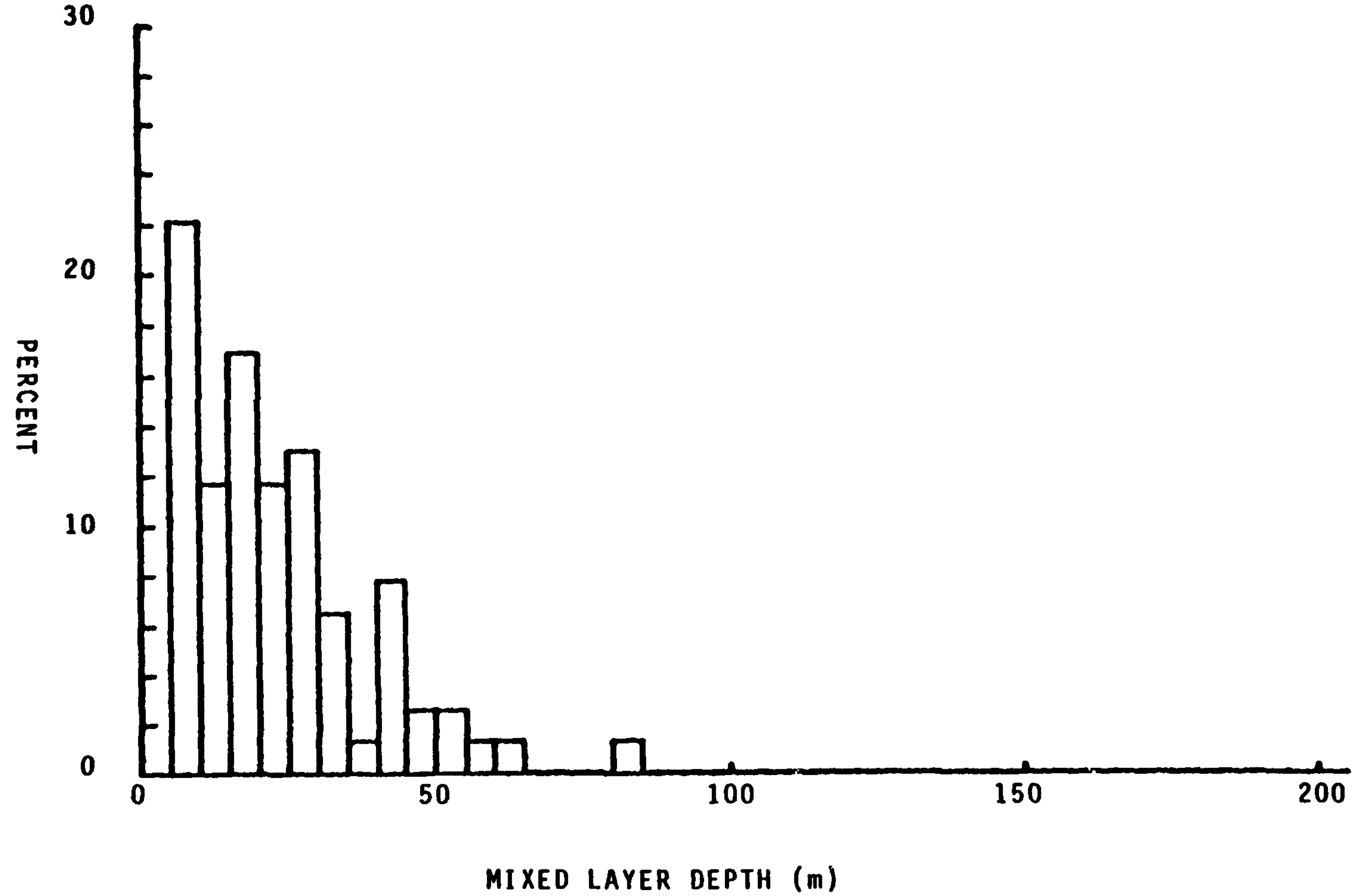

Figure 3.36 Histogram of MLD_N for Summer, Area II (77 Stations)

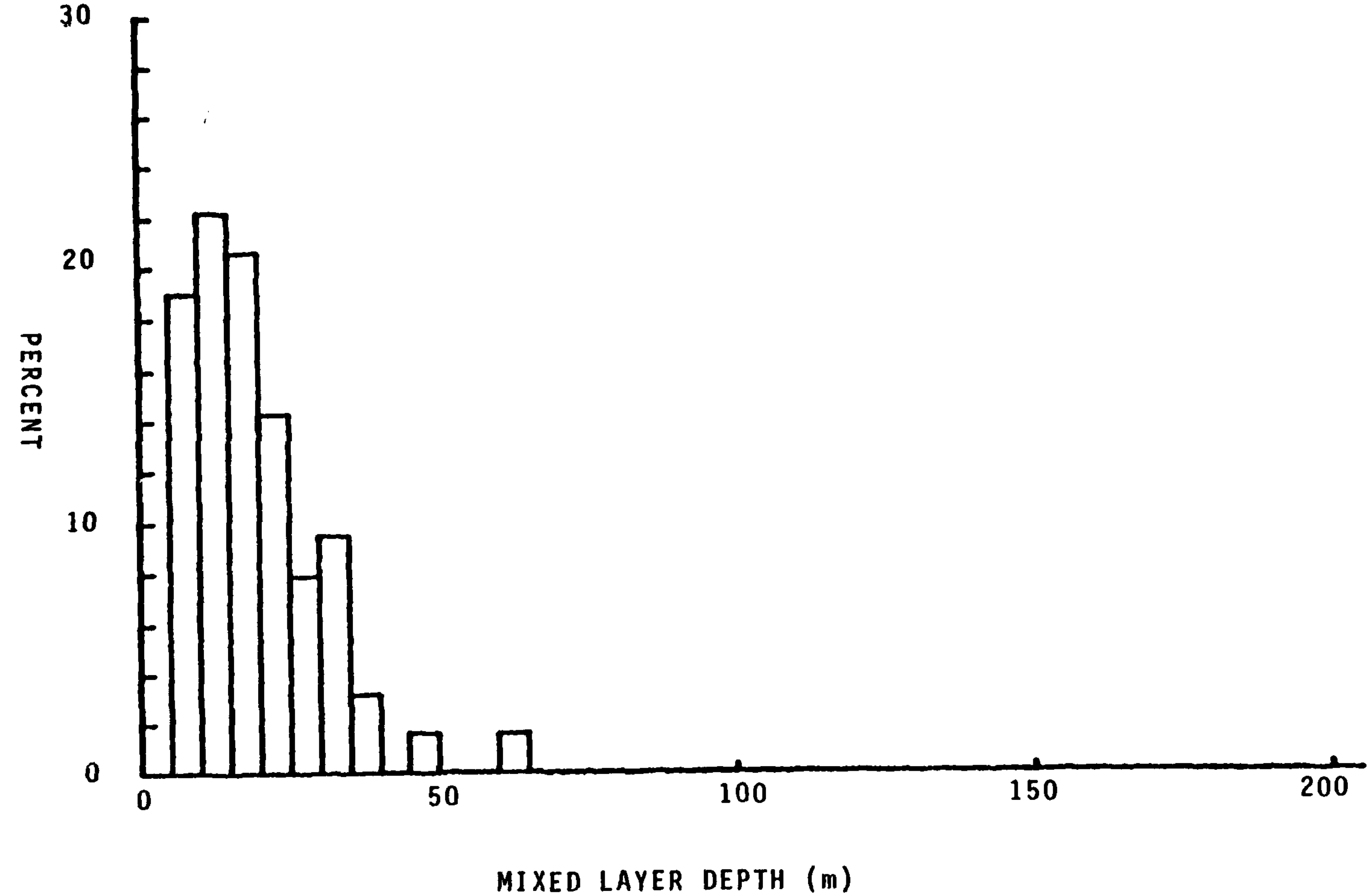

Figure 3.37 Histogram of MLD_N for Summer, Area III (63 Stations)

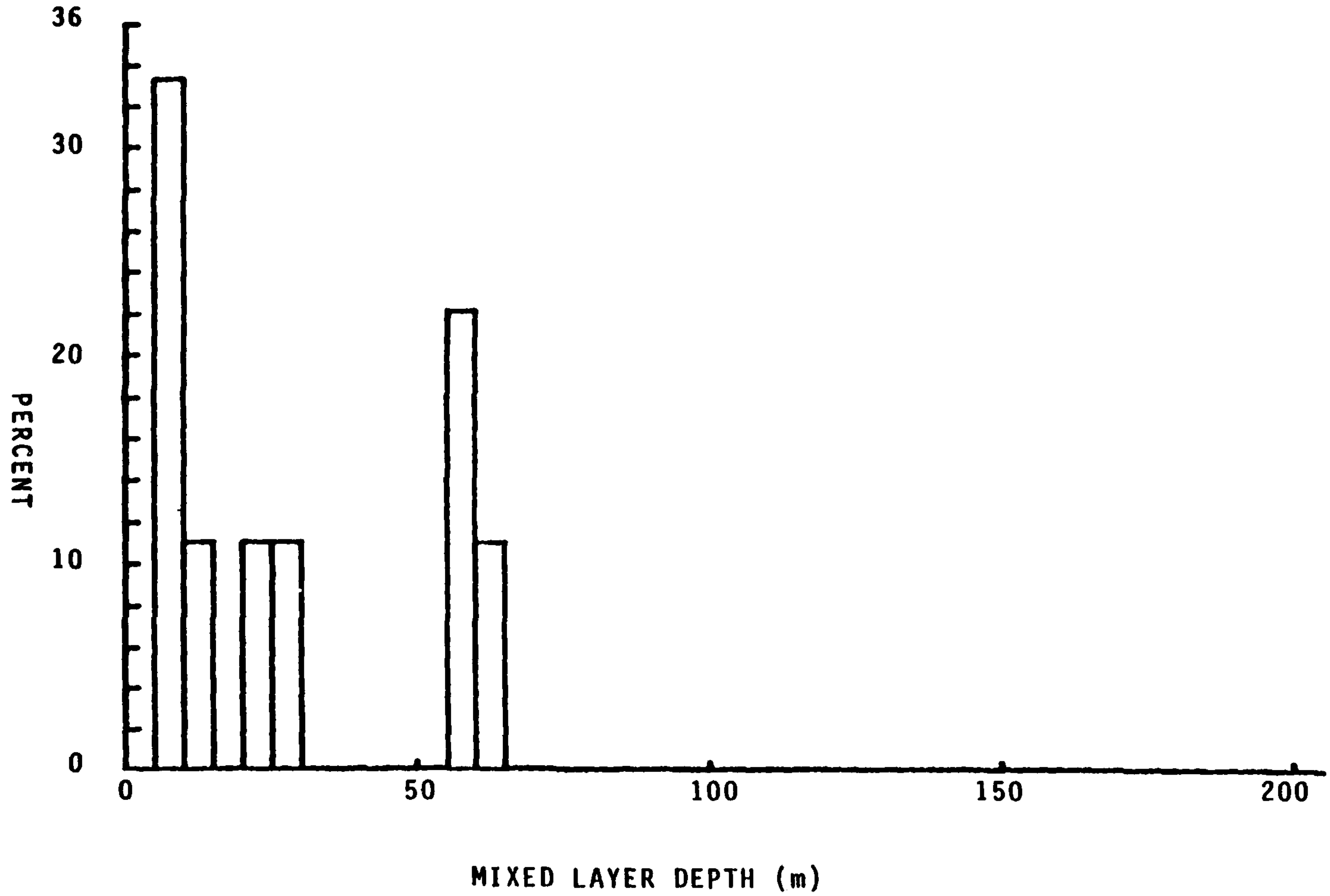

Figure 3.38 Histogram of MLD_N for Fall, Area I (9 Stations)

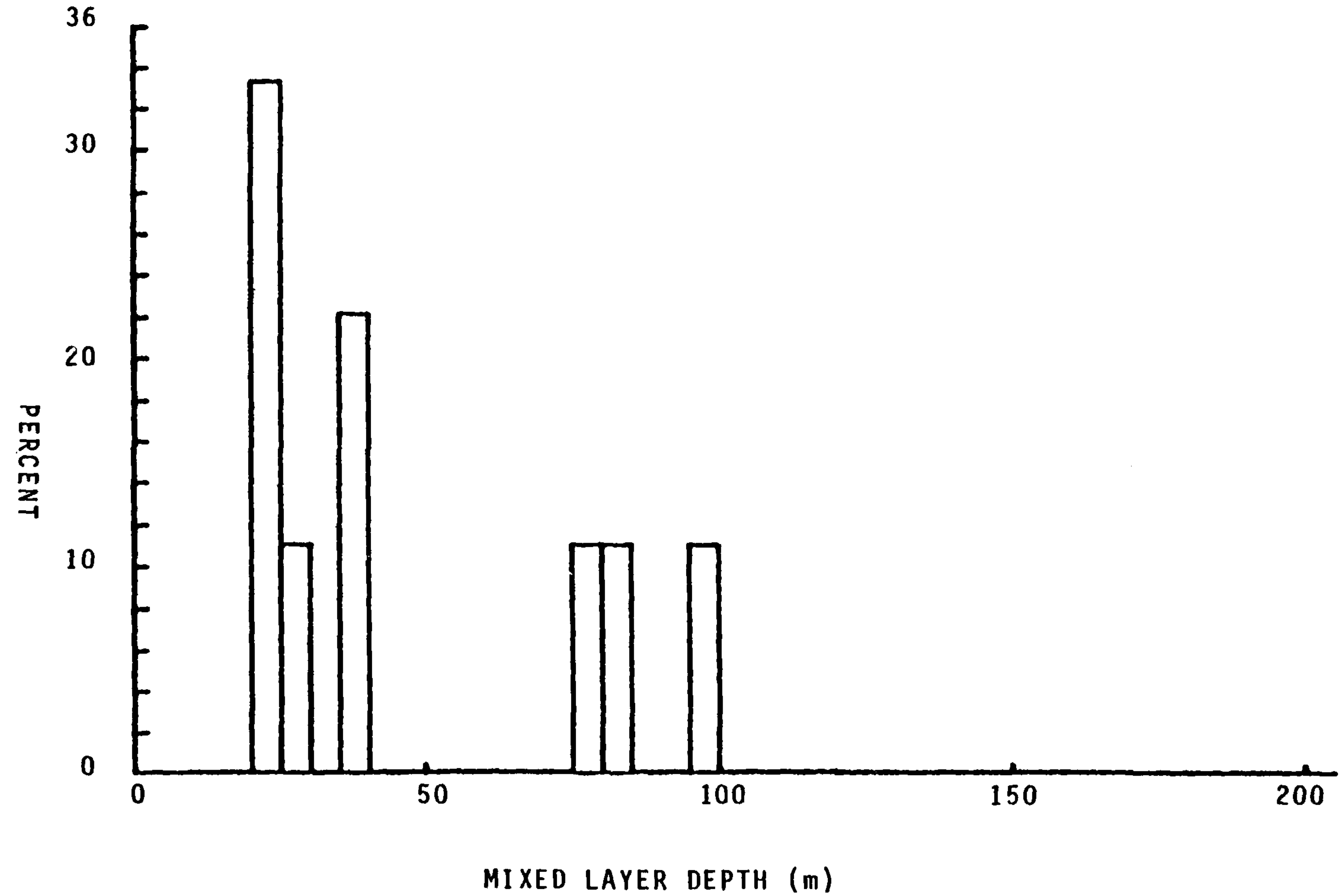

Figure 3.39 Histogram of MLD_N for Fall, Area II (9 Stations)

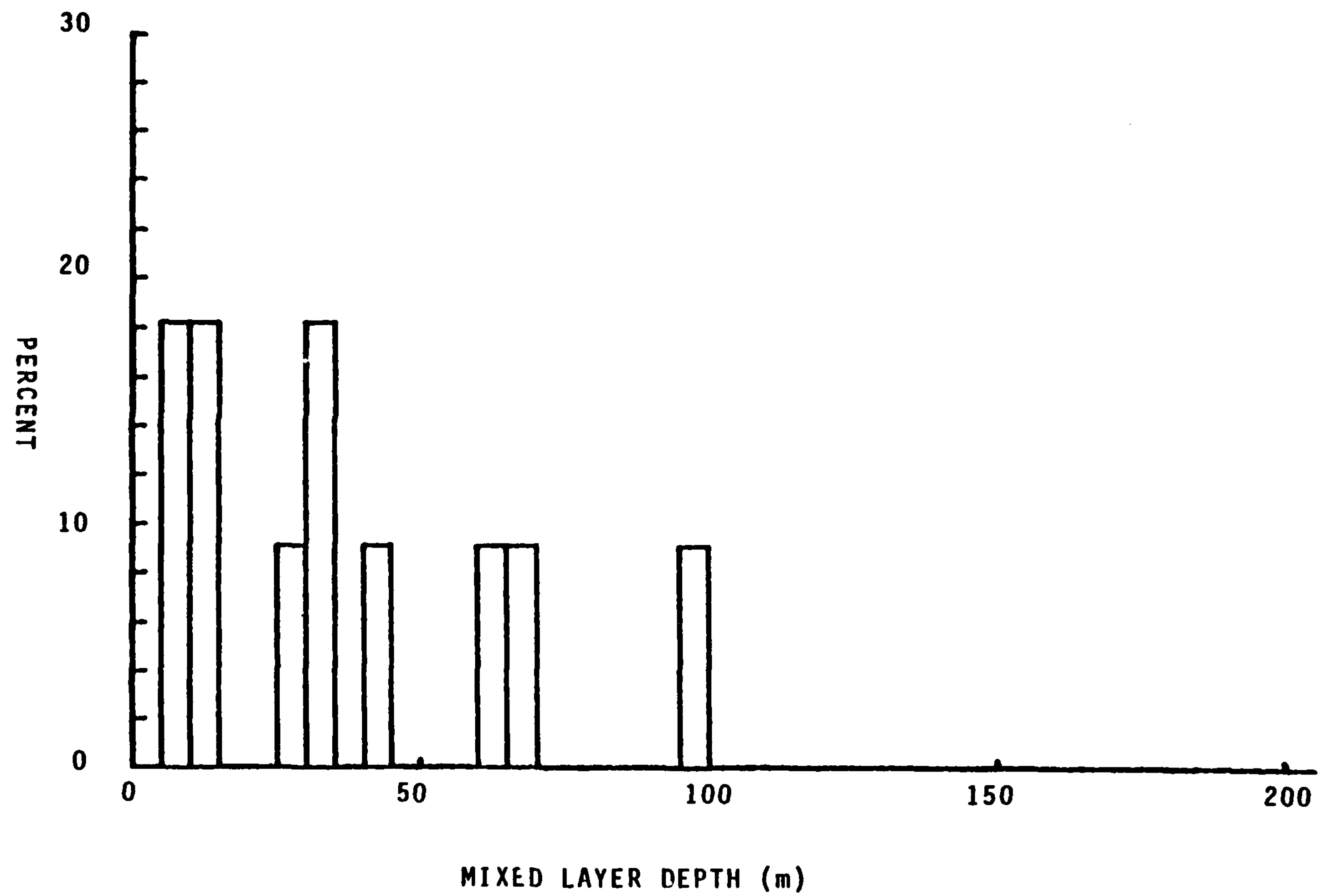

Figure 3.40 Histogram of MLD_N for Fall, Area III (11 Stations)

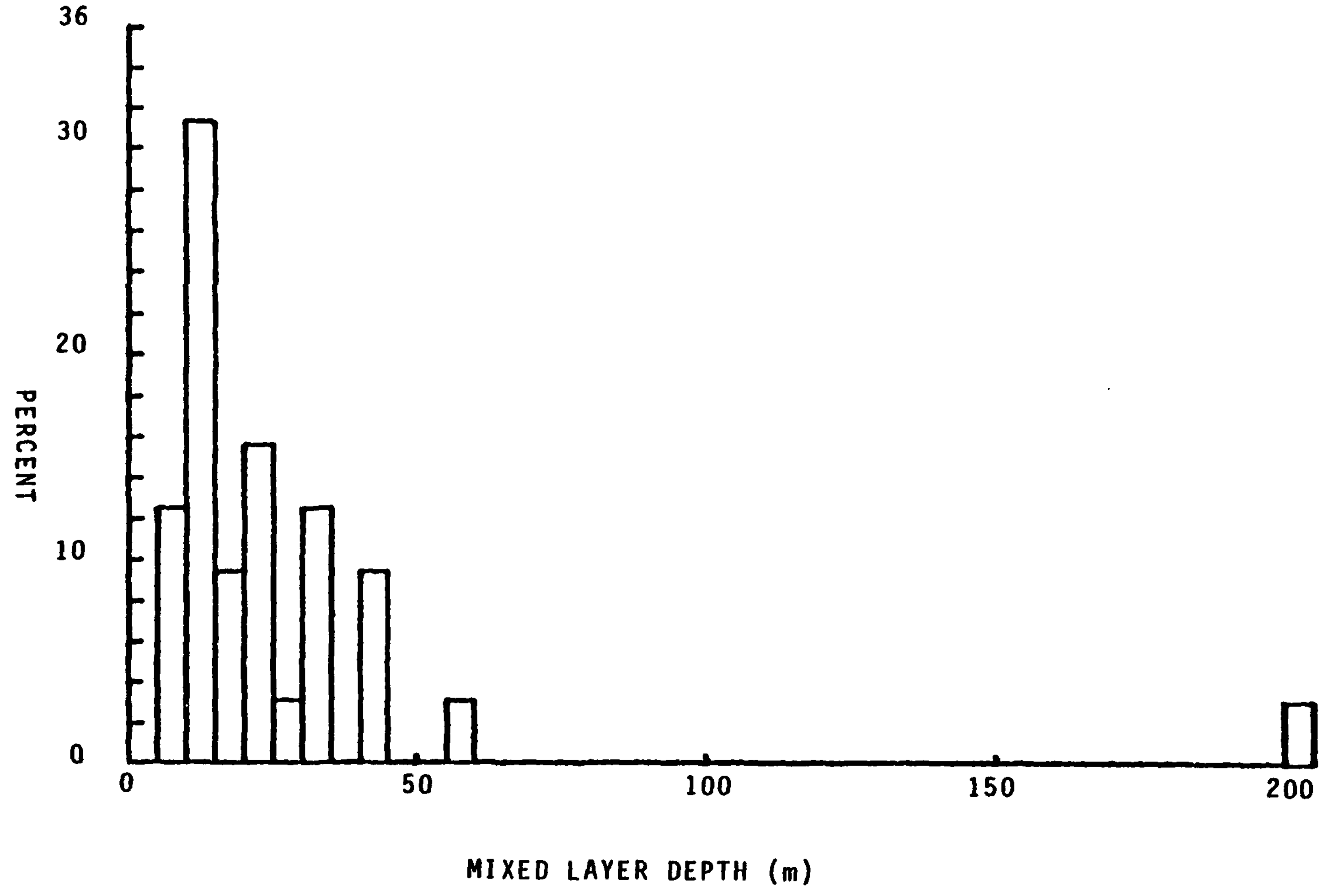

Figure 3.41   Histogram of MLD_N for Spring, Area III (32 Stations)

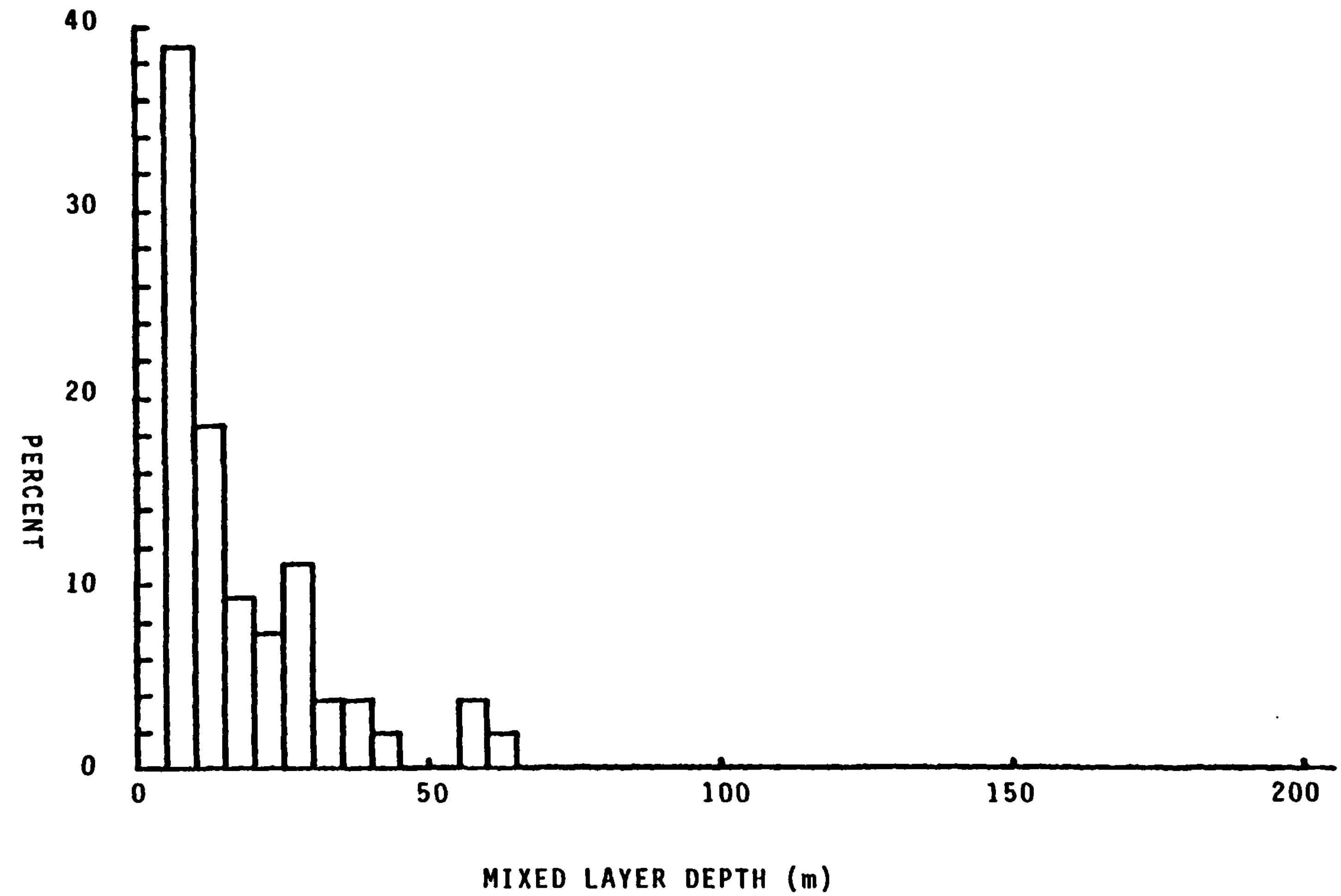

Figure 3.42 Histogram of MLD_N for All Seasons, Area I (54 Stations)

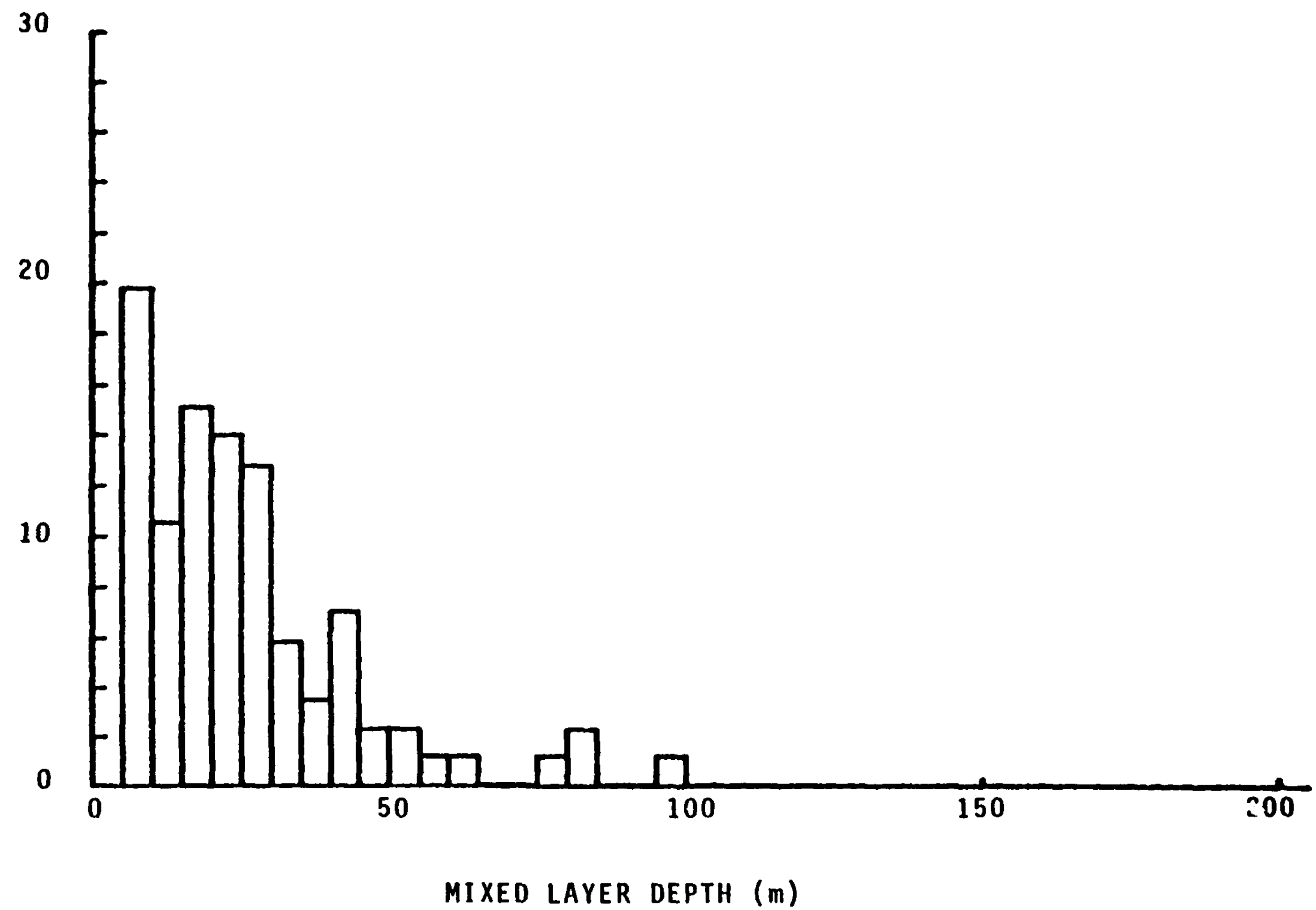

Figure 3.43 Histogram of MLD_N for All Seasons, Area II (86 Stations)

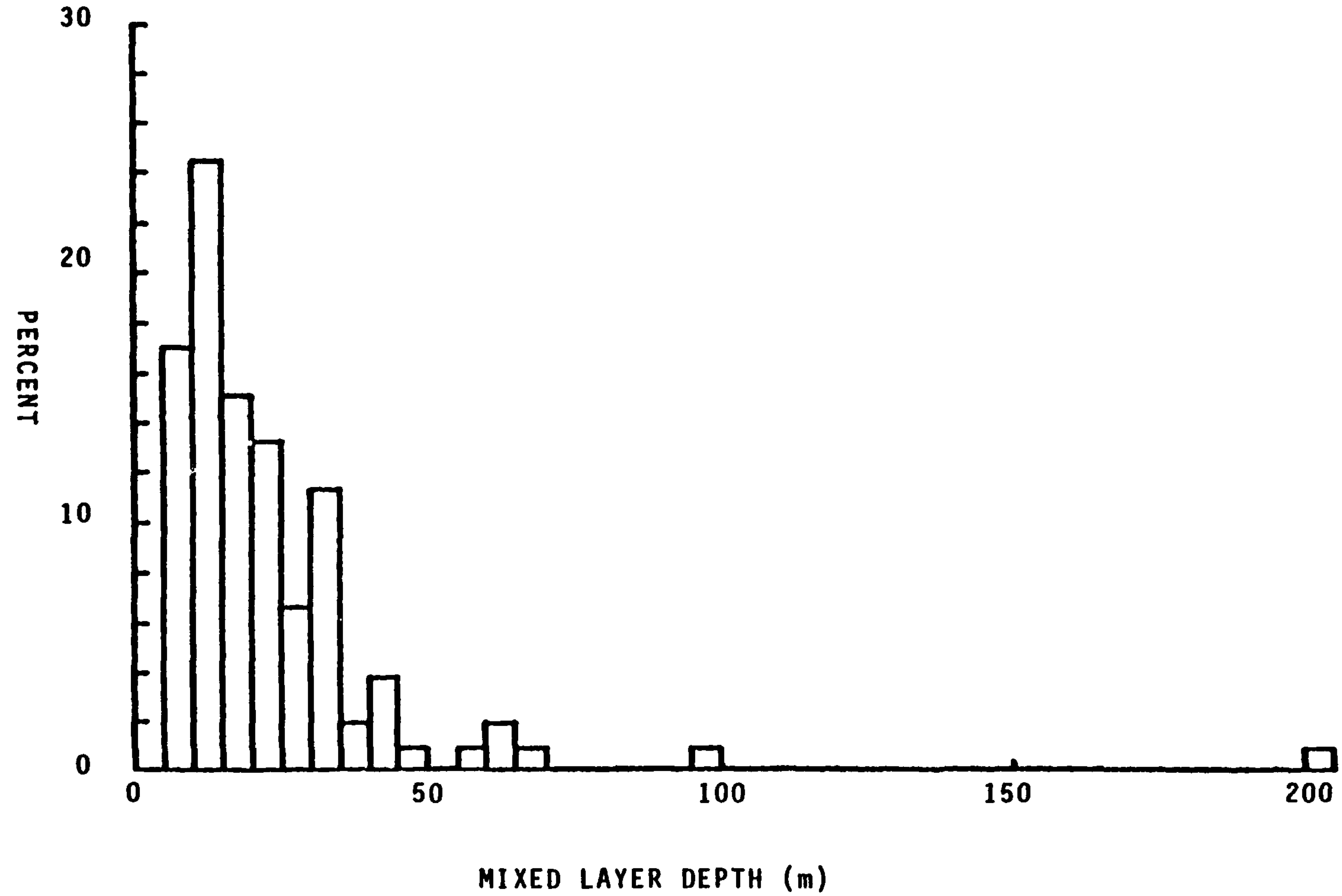

Figure 3.44 Histogram of MLD_N for All Seasons, Area III (106 Stations)

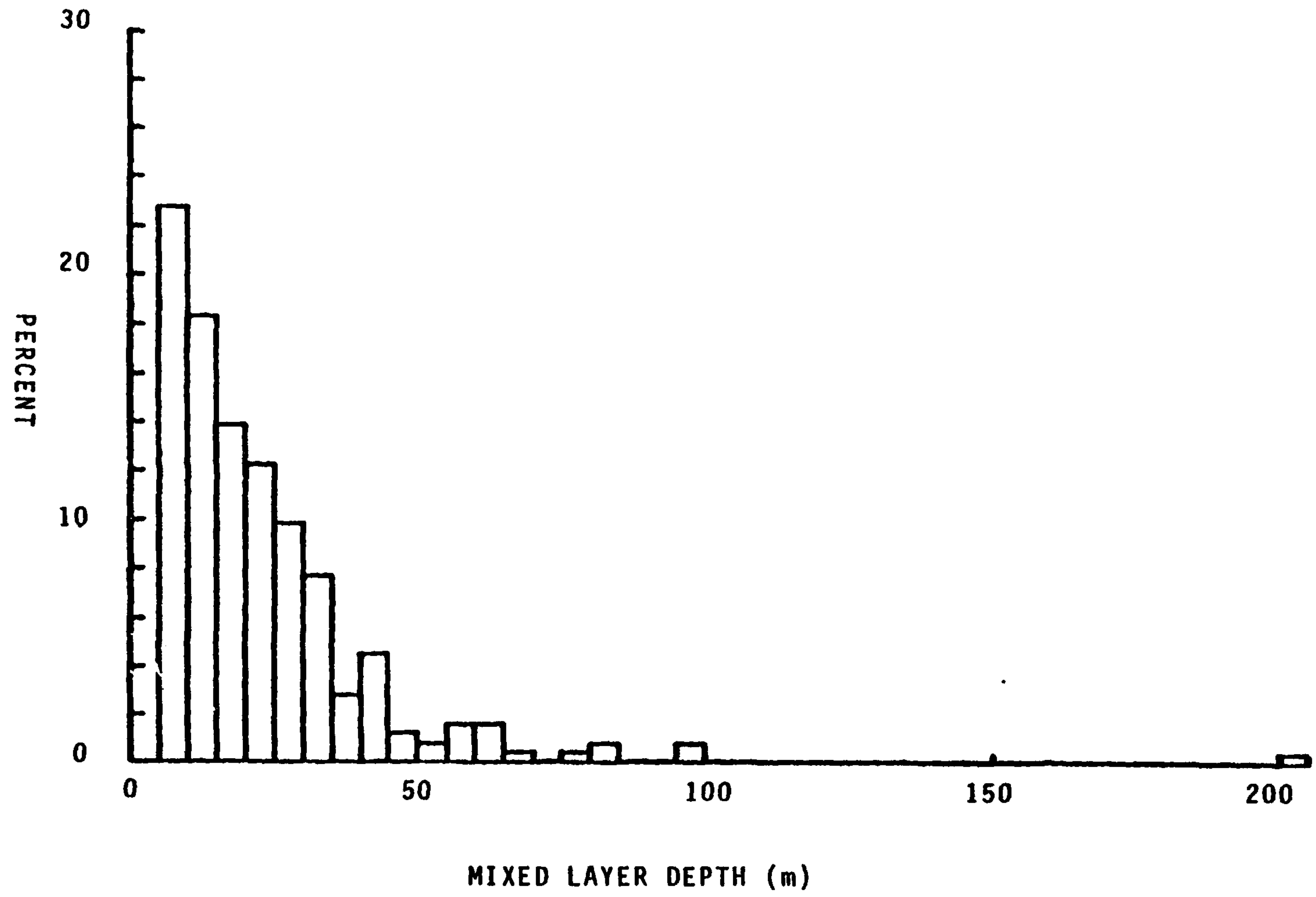

Figure 3.45 Histogram of MLD_N for All Seasons, All Areas (246 Stations)

Section 4
SIGNIFICANT VARIATIONS

The information in the large number of histograms presented in section 3 is summarized here and analyzed by means of both parametric and non-parametric statistical methods to indicate the most significant relationships.

4.1 MEANS AND STANDARD DEVIATIONS OF MLDS

The histograms presented in the previous section can be characterized by their means and standard deviations. These values are presented in table 4.1 along with estimates of their confidence intervals based upon Student-t and chi-square distributions. Both these computations assume that the underlying distributions are Gaussian, an assumption that is not ideal, as will be shown. However, the intervals are useful as first order estimates of statistical significance.

The entries in table 4.1 are summarized in figures 4.1 to 4.4 which, for each definition show how the mean MLD varies with season and area. Similar plots are shown for MLD standard deviations in figures 4.5 to 4.8.

These plots show that most of the variability, for all definitions, is associated with the change of season and relatively little is associated with a change of area. Only for MLD_N do these statistics show that the mean of area II is deeper than the mean of area I. The other definitions show only that the mean of area II is deeper than the mean of area III. That is, the 95% confidence intervals for these cases do not overlap.

Only for the density and stability criteria is the deviation in area II significantly higher than the deviation in area I. These plots do show that in fall the deviations in Area III are larger than the deviations in Area I for all criteria except stability. In general, more appropriate statistical tests are required to demonstrate an area dependence in MLD distributions. Non-parametric statistics will provide the necessary tests in the following section.

The rather high uncertainty in spring and fall for all definitions is caused by the large standard deviations of those distributions which themselves are caused by

TABLE 4.1
MEANS AND STANDARD DEVIATIONS OF MLD DISTRIBUTIONS
(in meters)

CLASS--CRITERION	MEAN MLD	95% LOWER BOUND	95% UPPER BOUND	STANDARD DEVIATION	95% LOWER BOUND	95% UPPER BOUND
Summer, Area I						
T	28.5	21.9	35.1	22.2	18.4	28.0
C	21.8	14.9	28.7	23.2	19.3	29.2
D	35.0	28.0	42.1	22.3	18.5	28.3
N	15.5	12.6	18.4	9.8	8.1	12.3
Fall, Area I						
T	65.1	55.5	74.8	12.6	8.5	24.0
C	57.1	43.4	70.9	17.9	12.1	34.3
D	73.3	65.6	81.0	10.0	6.8	19.2
N	28.7	10.5	46.8	23.6	15.9	45.2
Summer, Area II						
T	36.6	32.7	40.5	17.3	14.9	20.5
C	30.3	26.5	34.1	16.9	14.6	20.0
D	63.7	32.7	94.7	136.4	117.8	162 1
N	22.9	19.4	26.5	15.7	13.6	18.7
Fall, Area II						
T	76.2	51.7	100.8	32.0	21.6	61.2
C	69.4	44.9	94.0	31.9	21.6	61.2
D	85.9	66.4	105.3	25.3	17.1	48.5
N	47.2	24.4	70.1	29.7	20.1	56.9
Spring, Area III						
T	53.6	26.9	80.3	74.0	59.4	98.4
C	65.9	15.3	116.6	140.5	112.6	186.7
D	138.5	72.7	204.4	179.5	141.6	234.7
N	27.6	13.2	42.0	39.9	32.0	53.1
Summer, Area III						
T	23.0	20.9	25.0	8.3	7.1	10.0
C	16.5	14.5	18.6	8.2	7.0	9.9
D	27.6	24.7	30.6	11.7	9.9	14.2
N	18.6	15.9	21.4	10.9	9.3	13.2

TABLE 4.1 (continued)
MEANS AND STANDARD DEVIATIONS OF MLD DISTRIBUTIONS
(in meters)

CLASS--CRITERION	MEAN MLD	95% LOWER BOUND	95% UPPER BOUND	STANDARD DEVIATION	95% LOWER BOUND	95% UPPER BOUND
Fall, Area III						
T	75.8	45.1	106.6	45.8	32.0	80.3
C	132.2	79.5	184.9	78.5	54.8	137.7
D	162.7	48.2	277.2	160.1	110.1	292.3
N	33.6	12.4	54.9	31.6	22.1	55.4
All Area I						
T	34.5	27.8	41.3	24.9	21.0	30.7
C	27.6	20.6	34.6	25.9	21.8	31.9
D	41.5	34.6	48.5	25.3	21.2	31.3
N	17.6	14.0	21.3	13.7	11.5	16.8
All Area II						
T	40.8	36.0	45.5	22.6	19.7	26.6
C	34.4	29.7	39.1	22.3	19.4	26.19
D	66.1	38.7	93.4	129.4	112.5	152.24
N	25.5	21.4	29.5	19.0	16.5	22.3
All Area III						
T	37.7	28.7	46.7	47.1	41.5	54.3
C	43.4	26.6	60.3	88.7	78.2	102.3
D	74.1	50.3	97.9	123.1	108.3	142.7
N	22.9	18.0	27.8	25.8	22.8	29.7
All Stations						
T	38.1	33.6	42.5	35.6	32.8	39.2
C	36.8	29.2	44.4	61.0	56.2	67.2
D	64.1	50.0	78.3	112.3	103.5	123.9
N	22.6	20.0	25.3	21.4	19.8	23.6

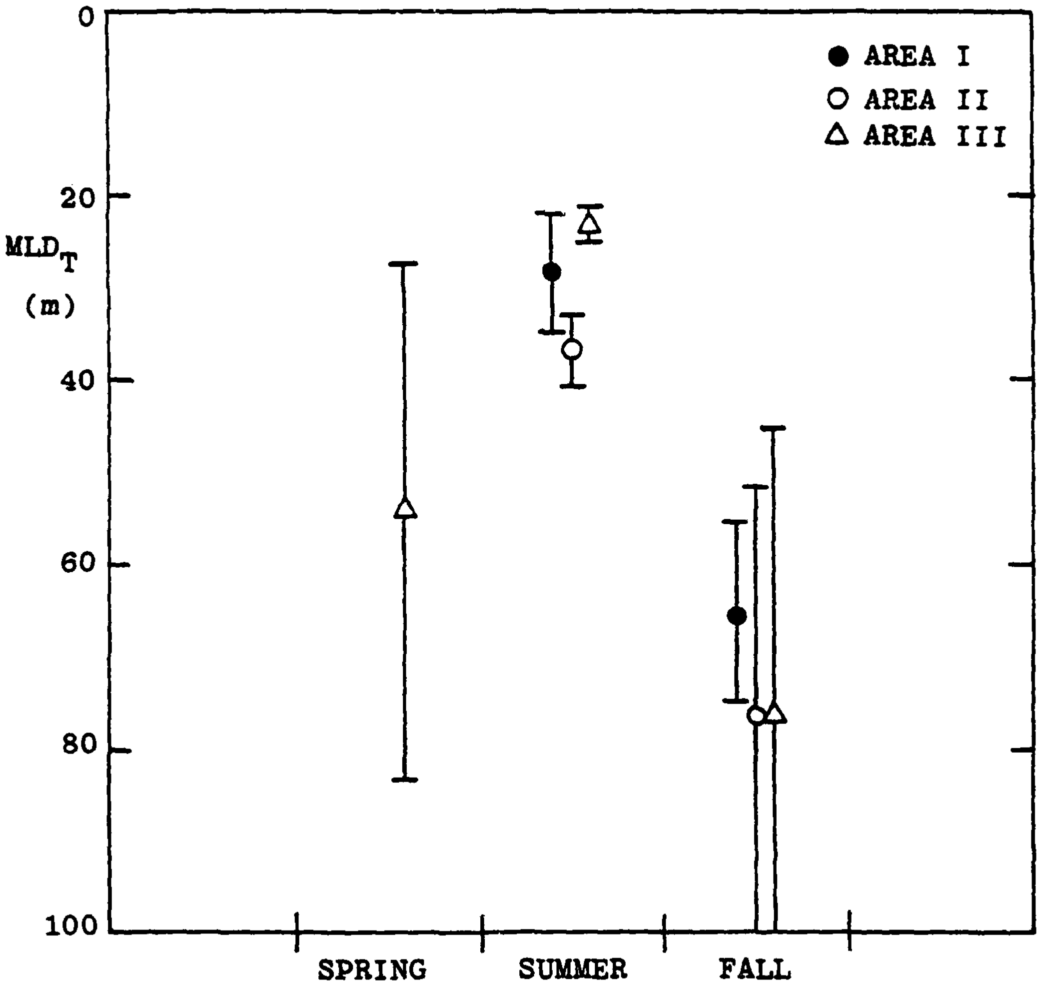

Figure 4.1 Dependence of MLD on area and season for temperature criterion. Mean MLD_T and 95% confidence interval about mean. Areas are denoted by symbols and seasons arranged along horizontal axis. Areas within a season are offset for clarity.

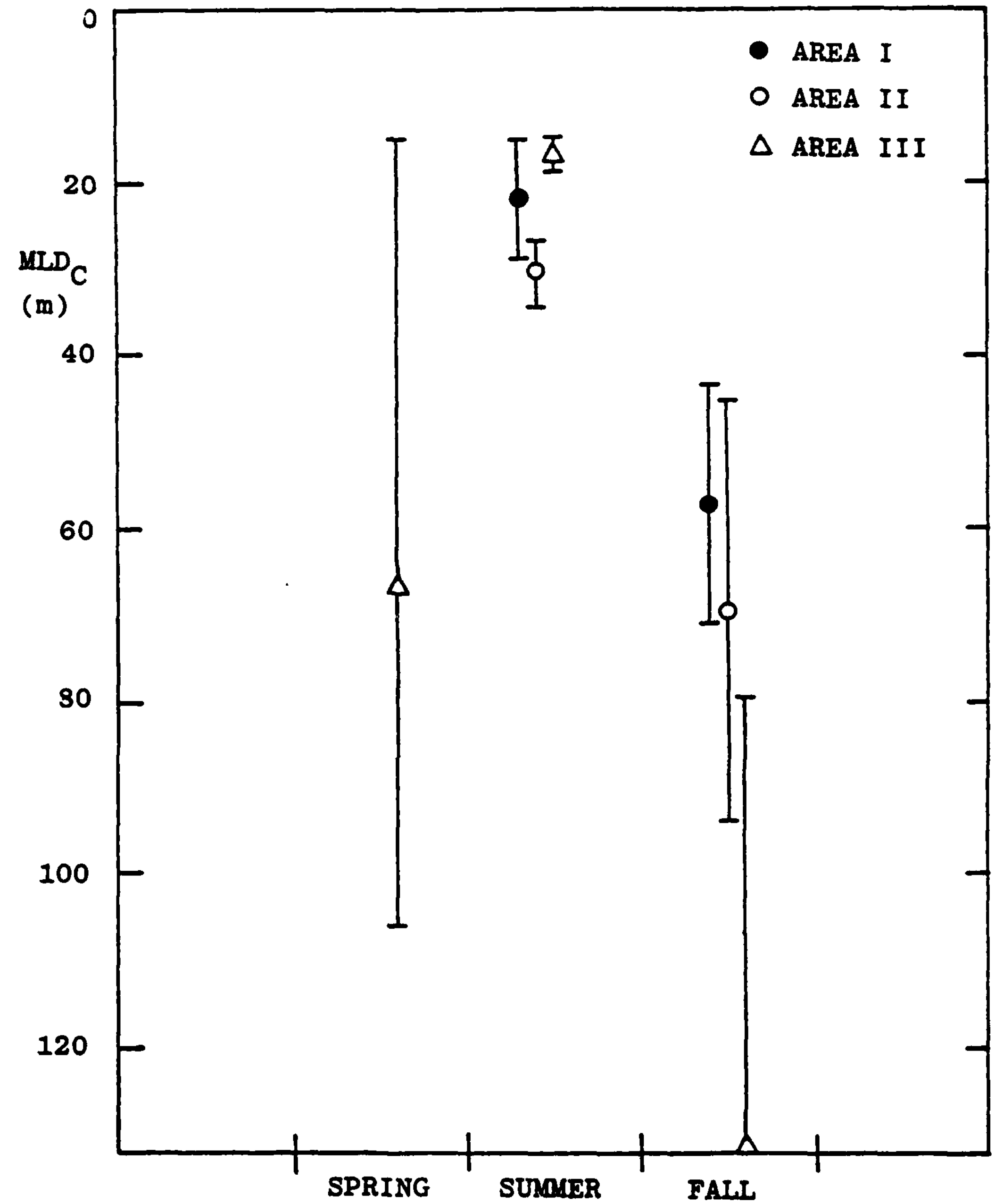

Figure 4.2 Dependence of MLD on area and season for sound speed criterion. Mean MLD_C and 95% confidence interval about mean.

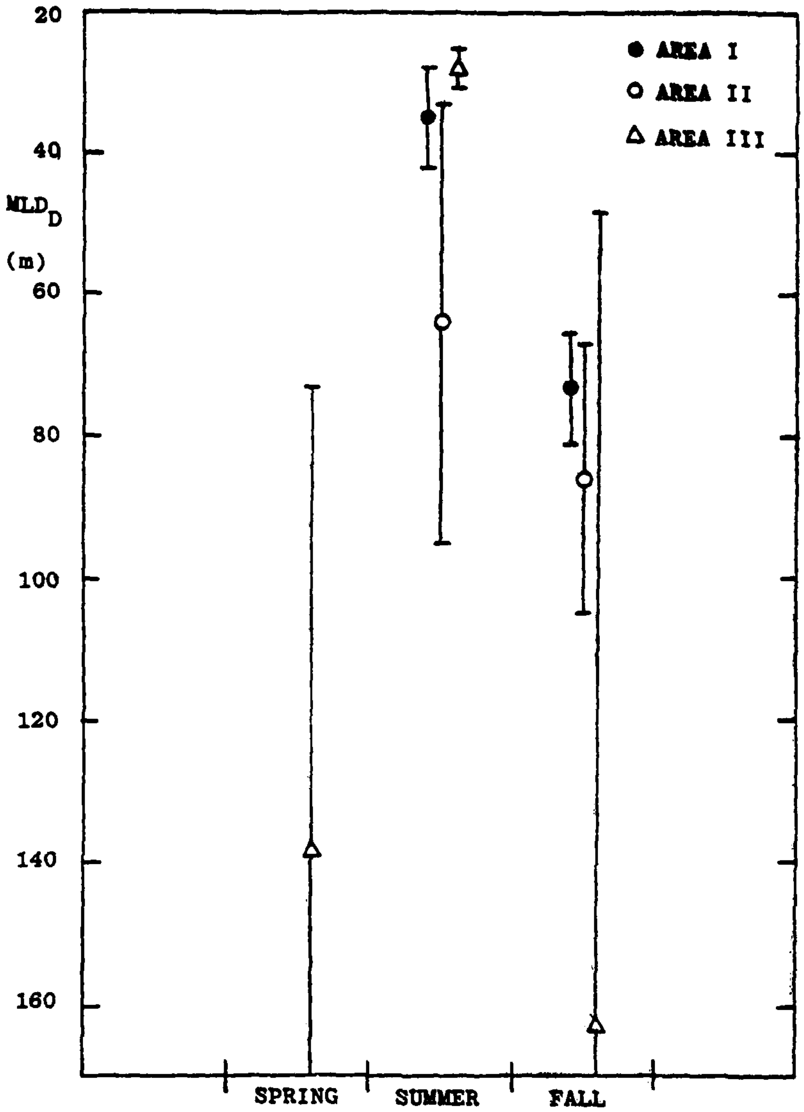

Figure 4.3 Dependence of MLD on area and season for density criterion. Mean MLD$_D$ and 95% confidence interval.

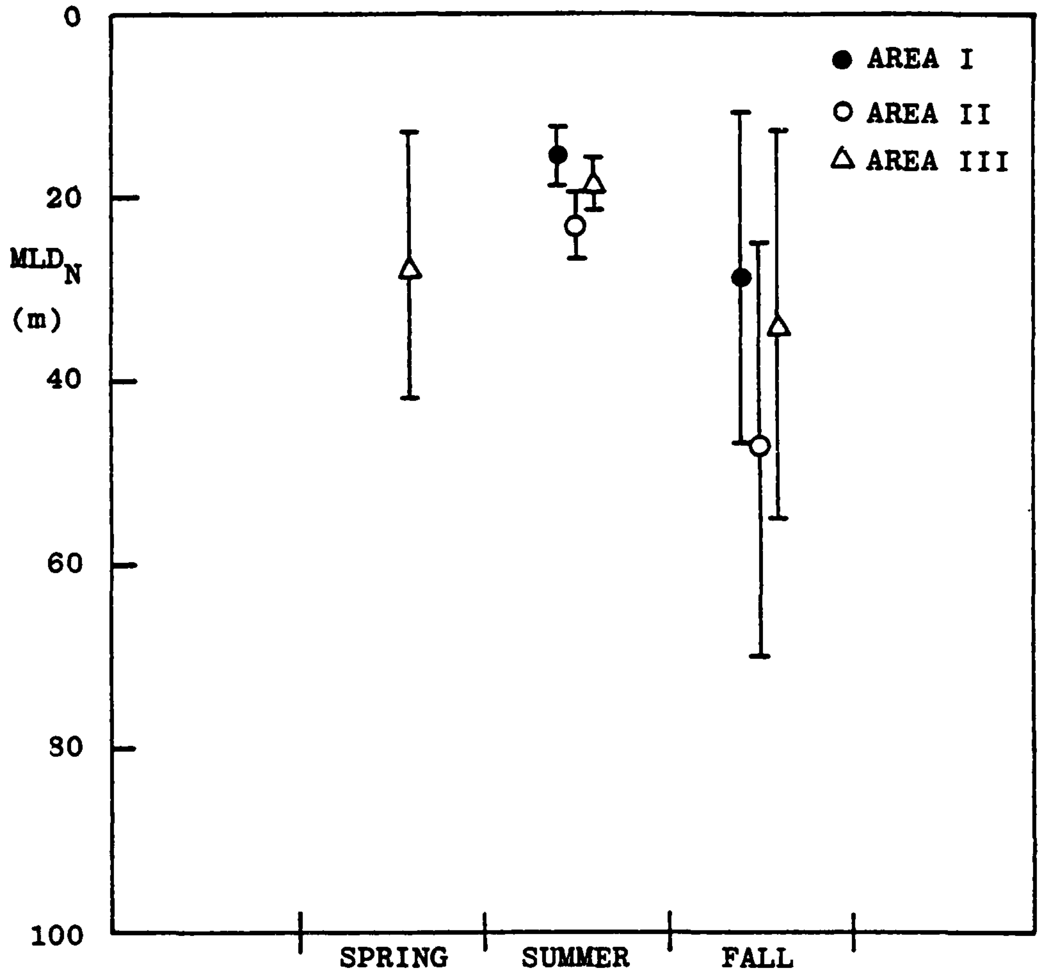

Figure 4.4 Dependence of MLD on area and season for stability criterion. Mean MLD_N and 95% confidence interval about mean.

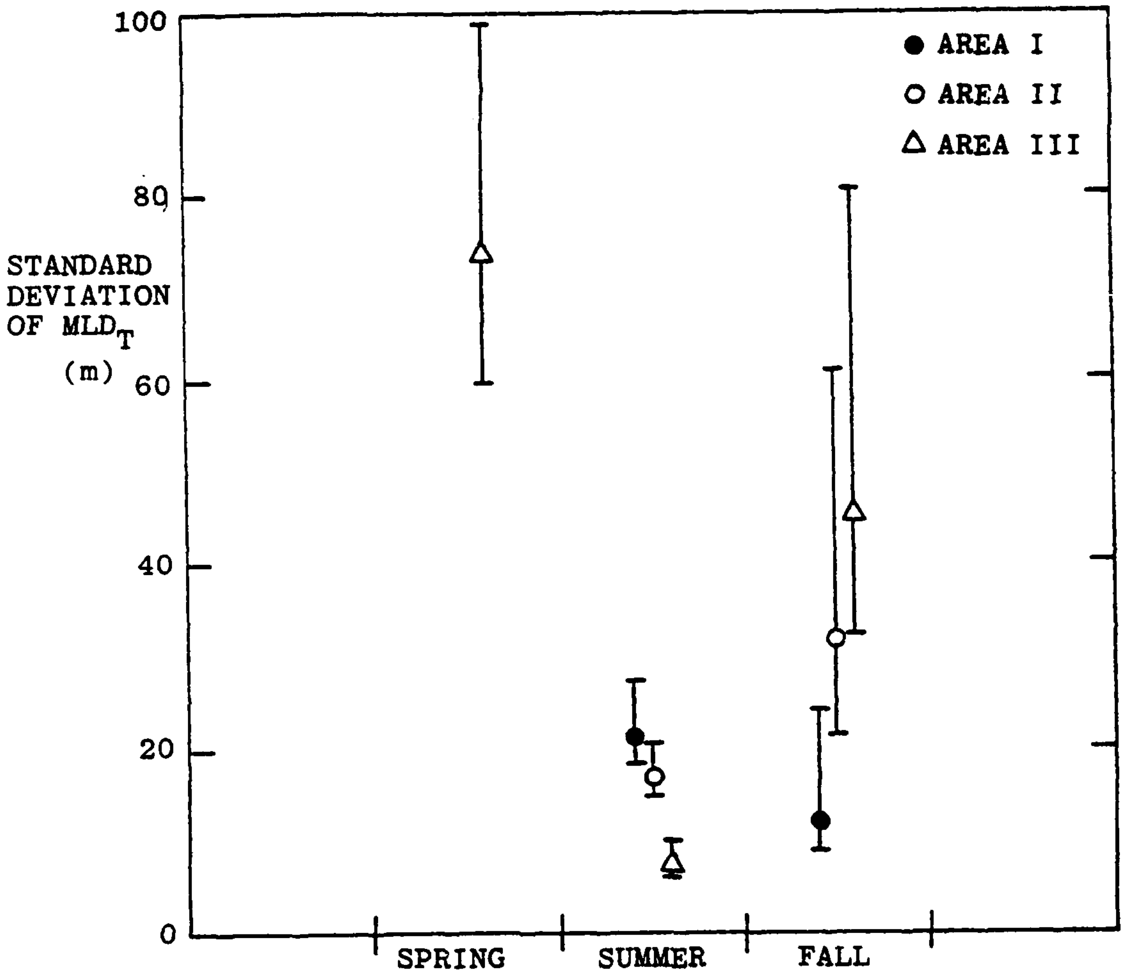

Figure 4.5 Dependence of MLD standard deviation on area and season for the temperature criterion. MLD$_T$ standard deviation and 95% confidence interval on the standard deviation.

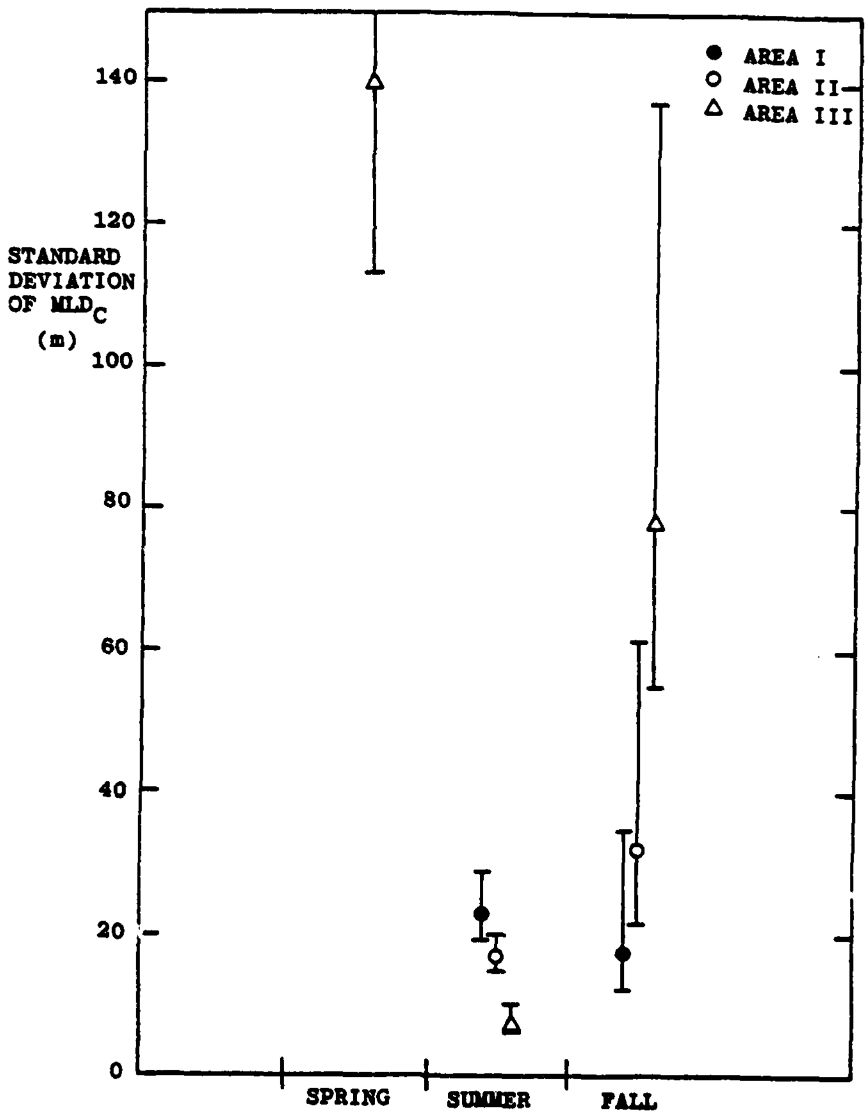

Figure 4.6 Dependence of MLD standard deviation on area and season for the sound speed criterion. MLD$_C$ standard deviation and 95% confidence interval on the standard deviation.

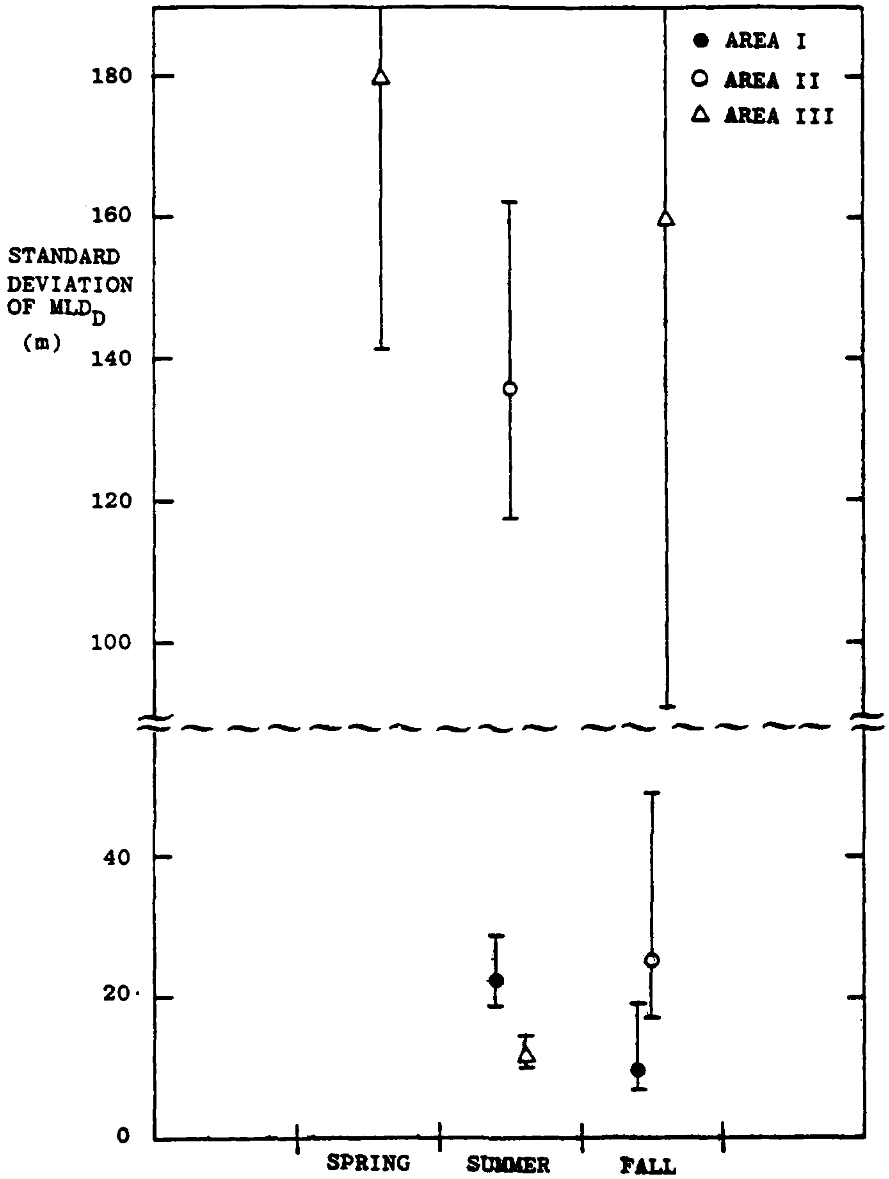

Figure 4.7 Dependence of MLD standard deviation and 95% confidence interval on area and season for the density criterion. Note break in vertical axis.

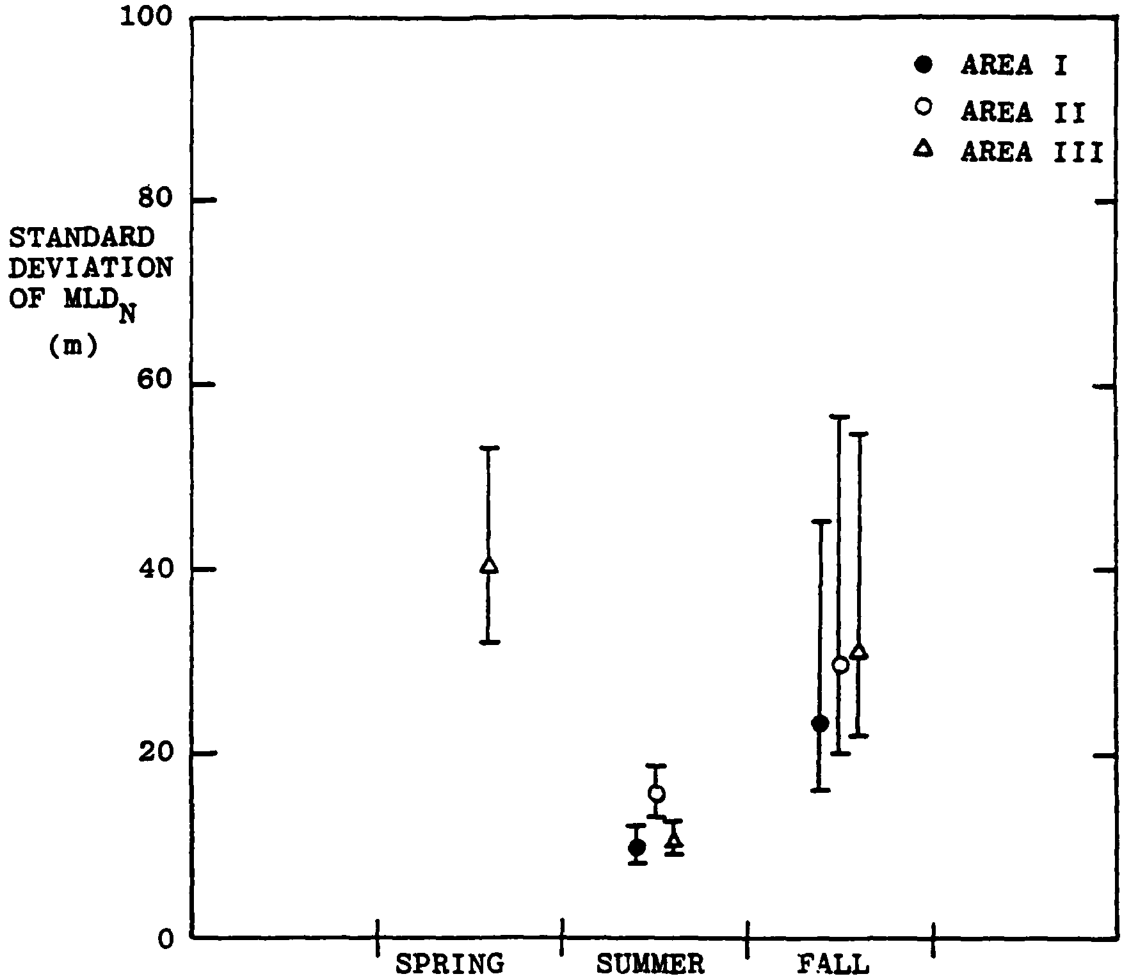

Figure 4.8 Dependence of MLD standard deviation on area and season for the stability criterion. MLD standard deviation and 95% confidence interval on the standard deviation.

the occasional recording of extremely deep MLDs (in excess of several hundred meters) combined with small sample sizes at those times of years.

The various definitions of MLD show the same increase in both mean and standard deviation in the non-summer months. Only the density definition of MLD in the summer in area II breaks the pattern. The increased mean and standard deviation for this definition is caused by two stations with large values for MLD_D (one with a value of 1070m). Further work should investigate these stations for possible problems with the data or the implementation of the density criterion. Although it must now be considered unlikely, the possibility of layers actually homogeneous in density with such fantastic thickness must also be reviewed.

4.2 GAUSSIANITY OF MLD DISTRIBUTIONS

The chi-square goodness-of-fit test is applied to determine the probability that a particular sample distribution is drawn from a Gaussian population. Table 4.2 presents the results of these tests. The null hypothesis, that an MLD distribution is Gaussian, will be rejected whenever the probability of occurrence of a chi-square value greater than or equal to the computed test statistic is less than 0.05. Table 4.2 shows the significance level attained in each test of the null hypothesis. Using this criterion the distributions of the following classes and definitions can be considered non-Gaussian: MLD_T and MLD_C for area I, summer; MLD_C, MLD_D, MLD_N for area II, summer; all definitions for area III, spring; MLD_N for area III, summer; all definitions for area I, all seasons combined; all definitions for area II, all seasons combined; all definitions for area III, all seasons combined; and all definitions for all area, all seasons combined. The fall season distributions do not contain enough values to perform the chi squared test. The distributions that can still be considered Gaussian are: MLD_D and MLD_N for area I, summer; MLD_T for area II, summer; and MLD_T, MLD_C and MLD_D for area III, summer.

4.3 MLD DEPENDENCE ON SEASON, AREA AND DEFINITION

Non-Gaussian distributions can be tested for significant differences in location (mean and median) by use of

TABLE 4.2
CHI SQUARE TEST OF GAUSSIANITY

* distribution considered Gaussian

CLASS/DEFINITION	CHI-SQUARE STATISTIC	DEGREES OF FREEDOM	SIGNIFICANCE LEVEL
Summer, Area I			
T	30.69	2	<.005
C	59.20	2	<.005
D	0.64	2	.82 *
N	3.70	2	.12 *
Fall, Area I			
	insufficient data		
Summer, Area II			
T	7.23	4	>.10 *
C	10.43	4	.03
D	158.94	4	<.005
N	16.34	4	<.005
Fall, Area II			
	insufficient data		
Spring, Area III			
T	47.60	2	<.005
C	61.70	2	<.005
D	44.19	2	<.005
N	35.94	2	<.005
Summer, Area III			
T	3.12	4	.65 *
C	5.17	4	.41 *
D	3.34	4	.63 *
N	10.12	4	.03
Fall, Area III			
	insufficient data		

TABLE 4.2 (continued)

CLASS/DEFINITION	CHI SQUARE STATISTIC	DEGREES OF FREEDOM	SIGNIFICANCE LEVEL
All Seasons, Area I			
T	6.69	2	.01
C	13.40	2	<.005
D	6.58	2	.01
N	6.80	2	.01
All Seasons, Area II			
T	13.12	4	.01
C	18.79	4	<.005
D	126.69	4	<.005
N	20.09	4	<.005
All Seasons, Area III			
T	138.23	4	<.005
C	166.42	4	<.005
D	229.30	4	<.005
N	95.30	4	<.005
All Seasons, All Areas			
T	175.63	4	<.005
C	269.27	4	<.005
D	305.36	4	<.005
N	83.78	4	<.005

non-parametric statistical methods. These methods do not depend upon the characteristics of the probability density functions of the distributions. The differences in MLD distributions from different areas and seasons can be tested using the Mann-Whitney two sample test, which does not require an equal number of observations in each sample. MLD distributions based on different definitions were compared using the Wilcoxon Signed Rank Test. The Hodges-Lehmann estimator was used for differences in the mean MLD and the associated confidence interval for the difference in the mean MLD.

The seasonal dependence of MLD is examined first. The Mann Whitney test results are given in table 4.3. The significance level indicates the probability that the test statistic could be produced from two distributions which come from the same population. When this value drops to 5% or less, then the distributions are considered significantly different. Those distributions not considered different are marked by a double asterisk, while nearly different cases are marked with a single asterisk. The table also contains an estimate of the difference in the means, along with upper and lower 95% confidence limits on the estimate. Plots of the estimated difference in the means and the 95% confidence intervals are presented in figure 4.9a, b, and c.

Summer and fall distributions (figure 4.9a) are significantly different for all areas and for all criteria except N. The difference is about 45 $\pm$ 10 m in areas I and II (fall being deeper) where it is independent of criterion (excluding N). The difference is greater in area III (about 70 $\pm$ 29 m), more variable and more dependent on criterion. In summer, area III has the shallowest mean MLD; in winter, the deepest (see figures 4.1 to 4.3). How this characteristic may be related to frontal zone dynamics in the Iceland Faroe Front is not clear.

The lack of a seasonal variation in MLD_N distributions points to a serious problem with that criterion. It is likely that noise still in the data is generating layers of high N values where none actually exist (see the structure still apparent in the smoothed σ_T profile, figure 2.5). This suggests that smoothing to only 5 m is not sufficient to remove all the time lag problems in the data. Such noise will tend to trigger the MLD_N algorithm prematurely, and hence explain the shallow nature and seasonal independence of the MLD_N distributions.

TABLE 4.3
SEASONAL DIFFERENCES BY MANN WHITNEY TESTS

* marginally insignificant difference

** insignificant difference

SEASON, AREA CRITERION	SIGNIFICANCE LEVEL	MEAN DIFFERENCE	95% LOWER BOUND	95% UPPER BOUND
Fall-Summer, Area I				
T	<.0014	41	30	49
C	<.0014	42	28	51
D	<.0014	42	26	53
N	.1038**	7	-2	30
Fall-Summer, Area II				
T	<.0014	50	28	62
C	<.0014	49	29	62
D	<.0014	48	35	59
N	.0038	16	5	38
Fall-Summer, Area III				
T	<.0014	67	13	88
C	<.0014	93	79	115
D	<.0014	74	33	111
N	.2843**	6	-6	27
Spring-Summer, Area III				
T	<.0014	9	3	16
C	.0055	7	1	14
D	<.0014	19	7	99
N	.1230**	2	-2	7
Fall-Spring, Area III				
T	.0475*	45	-3	75
C	<.0014	84	60	103
D	.2148**	28	-42	94
N	.4443**	2	-9	25

The summer-spring comparison (figure 4.9b) shows significant differences for temperature and density, and a nearly significant difference for sound speed. As before, stability does not respond to the seasonal change. Spring MLDs are about 10m deeper, on average, than summer MLDs.

The spring-fall differences are significant for the sound speed criterion and marginally significant for the temperature criterion. The density distribution does not show a significant difference. As before, the MLD_N values are insensitive to seasonal differences.

The dependence of MLD on area is examined next. The Mann Whitney test results are given in table 4.4, and the mean differences and 95% confidence limits are presented in figures 4.10a, b and c.

In summer, area II is significantly deeper than area I for all criteria (figure 4.10a). Large confidence intervals are associated with the mean difference of the density MLDs because there is a great deal of variability in the differences due to the deep observations of MLD in area II in the summer under that criterion. In fall, area II is significantly deeper than area I for temperature and stability and nearly significantly for sound speed. Area II is deeper than area I by about 10m in the summer and 20m in the fall.

Area III distributions of MLD cannot be considered different from those of area I for any criterion in summer or any criterion but sound speed in fall.

In summer, area III is significantly shallower than area II for all criteria by an approximate value of 10m. In fall, only the sound speed gives a significant difference. In this case, area III is deeper than area II.

Finally, the dependence of MLD on criterion is examined. The temperature definition is taken arbitrarily as a standard.

The differences between the MLD means for the sound speed and temperature criteria as a function of season and area are presented in figure 4.11a. Except for fall in area III, the MLD_C values tend to be 6 m $\pm$ 2 m shallower than MLD_T values. The discrepancy in area III during the fall is significant and would require more study to relate to oceanographic properties.

TABLE 4.4
AREA DIFFERENCES BY MANN WHITNEY TESTS

* marginally insignificant differences

** insignificant differences

AREA, SEASON CRITERION	SIGNIFICANCE LEVEL	MEAN DIFFERENCE	95% LOWER BOUND	95% UPPER BOUND
Area II-Area I, Summer				
T	<.0014	11	5	16
C	<.0014	11	5	17
D	.0080	10	-3	23
N	.0019	6	1	10
Area II-Area I, Fall				
T	.0351	22	-26	37
C	.0516*	22	-11	36
D	.0122	19	6	32
N	.0721**	15	-17	49
Area III-Area I, Summer				
T	.3557**	0	-5	4
C	.5120**	0	-3	4
D	.0594*	-5	-12	2
N	.0853**	3	0	7
Area III-Area I, Fall				
T	.1922**	26	-37	53
C	<.0014	52	27	92
D	.1093**	23	-39	267
N	.4840**	2	-21	35
Area III-Area II, Summer				
T	<.0014	-13	-17	-8
C	<.0014	-12	-17	-7
D	<.0014	-20	-30	-11
N	.0436	-3	-7	1
Area III-Area II, Fall				
T	.3121**	7	-55	32
C	.0044	37	11	85
D	.3121**	15	-53	249
N	.1190**	-16	-35	13

The differences in MLD mean values for the density and temperature criteria as a function of area and season are presented in figure 4.11b. For areas I and II, the MLD_D means are about 5 m deeper than the MLD_T means. For area III, the difference in the means is much greater and much less certain. Stated another way, in area III the density criterion MLDs respond much more to the seasonal cycle than the temperature MLDs.

The difference between temperature and stability (figure 4.11c) shows once again the failure of the MLD_N means to respond to the seasonal cycle.

Overall (figure 4.12), the sound speed MLDs do not differ from the temperature MLDs, the density MLDs are deeper and the stability MLDs are shallower.

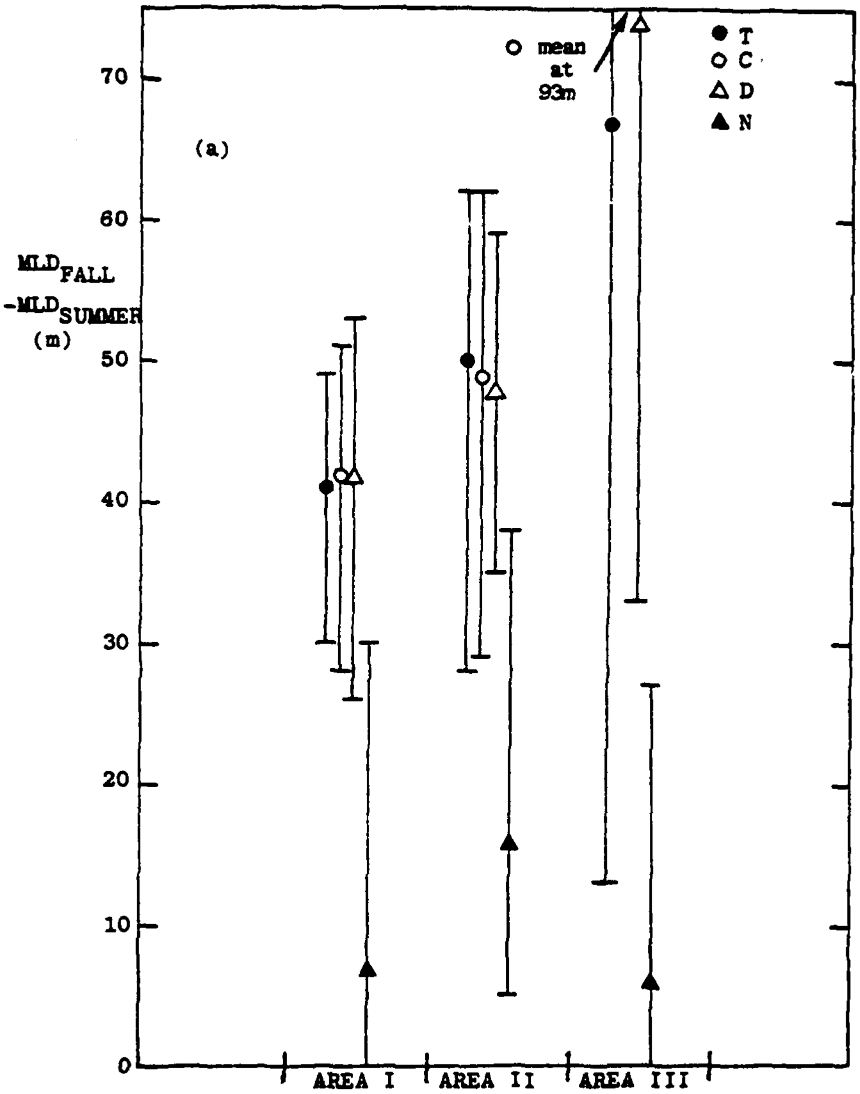

Figure 4.9 Seasonal dependence of MLD as a function of area and criterion. Symbols represent criteria and position on horizontal axis represents area. Within an area symbols are offset for clarity. a) fall-summer.

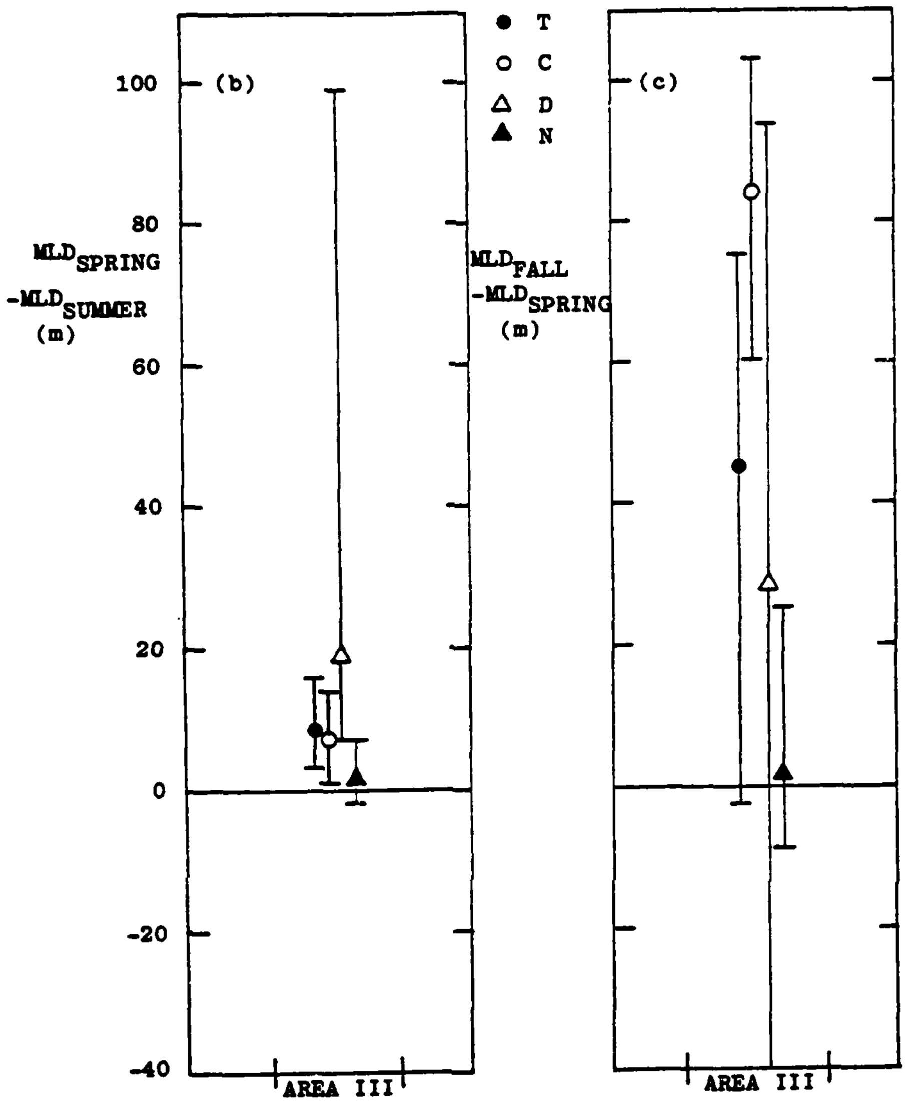

Figure 4.9 b) spring-summer. c) fall-spring. Note change of scale and large uncertainties of comparisons involving spring.

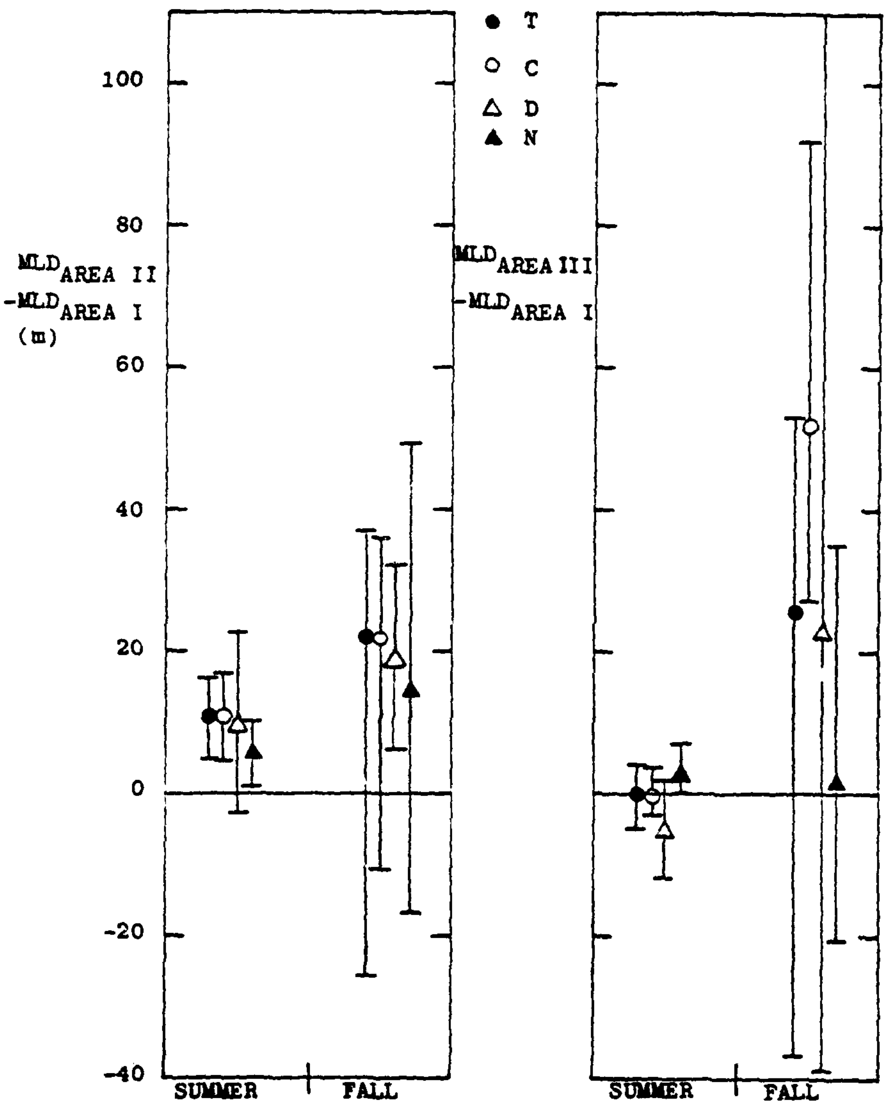

Figure 4.10 Area dependence of MLD as a function of season and criterion. Symbols denote criteria and horizontal position represent season. Within a season symbols are offset for clarity. a) Area II - Area I. b) Area III - Area I.

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MIXED LAYER DEPTH DISTRIBUTIONS FROM SVSTD DATA.(U)
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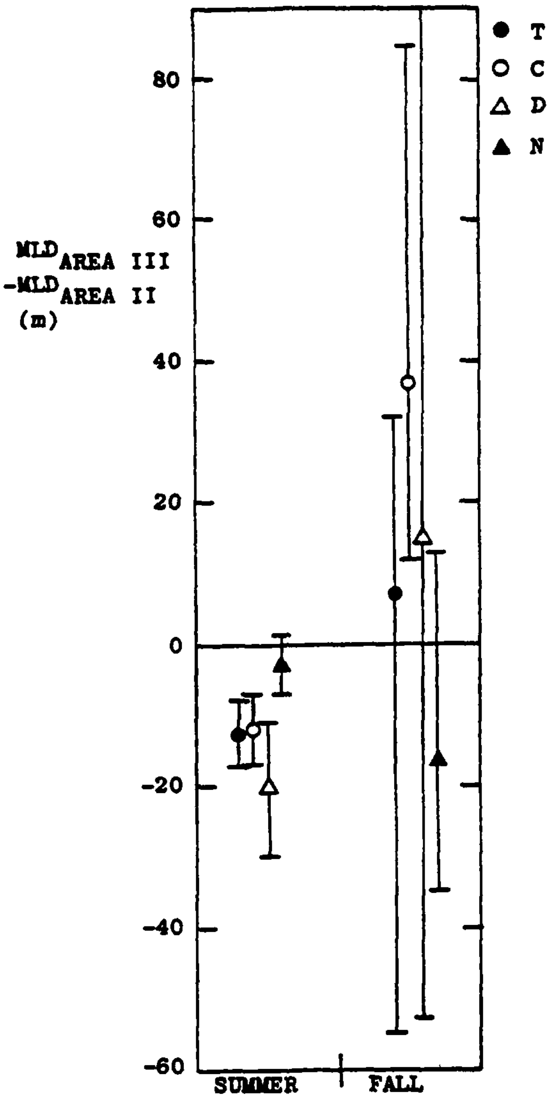

Figure 4.10 c) Area III - Area II.

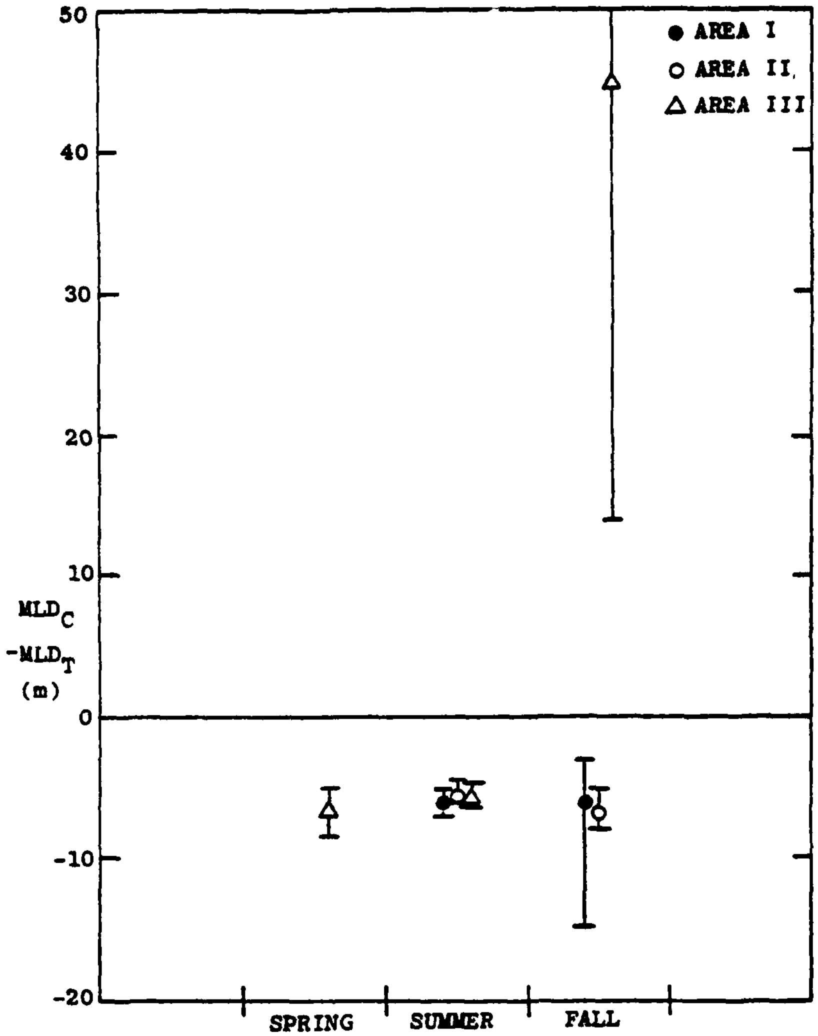

Figure 4.11a Difference between sound speed and temperature criteria as a function of area and season. Mean difference and 95% confidence interval.

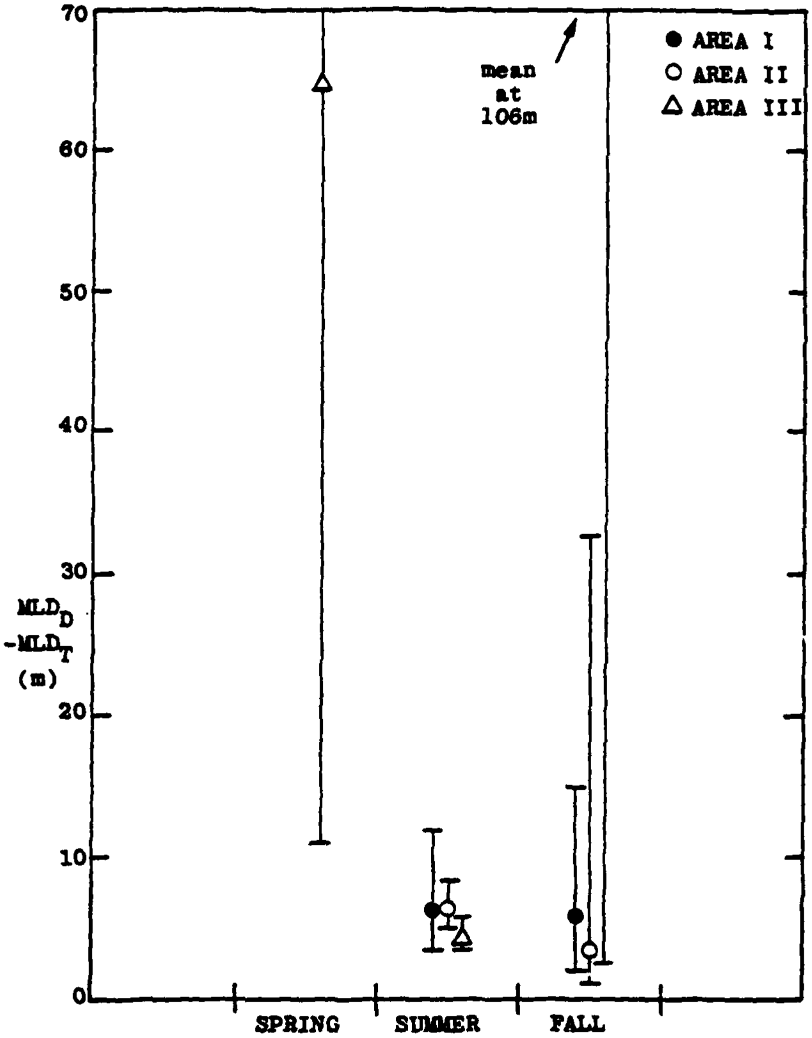

Figure 4.11b Difference between density and temperature criteria as a function of area and season. Mean difference and 95% confidence interval.

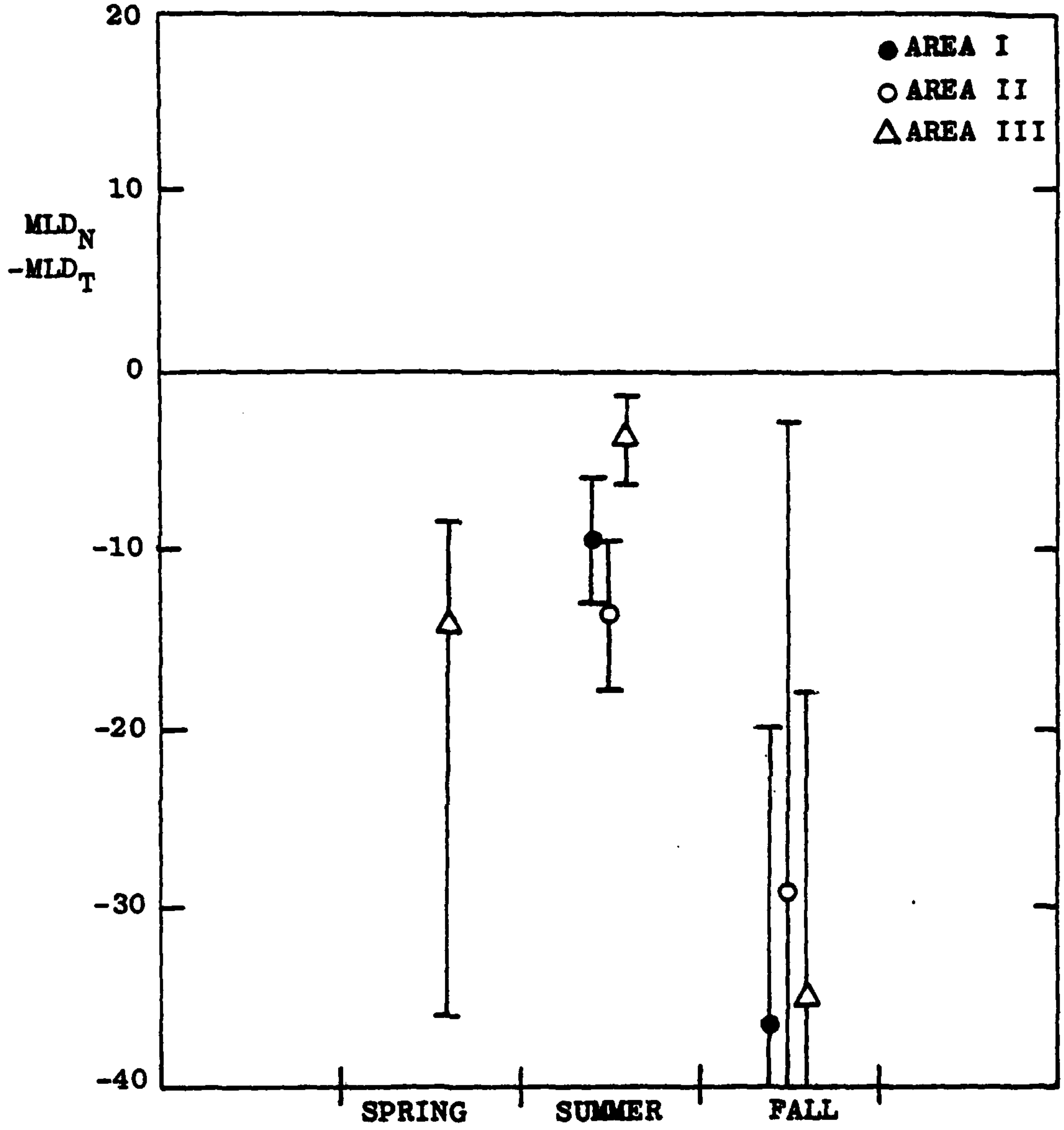

Figure 4.11 c) Difference between stability and temperature criteria as a function of area and season. Mean MLD difference and 95% confidence interval.

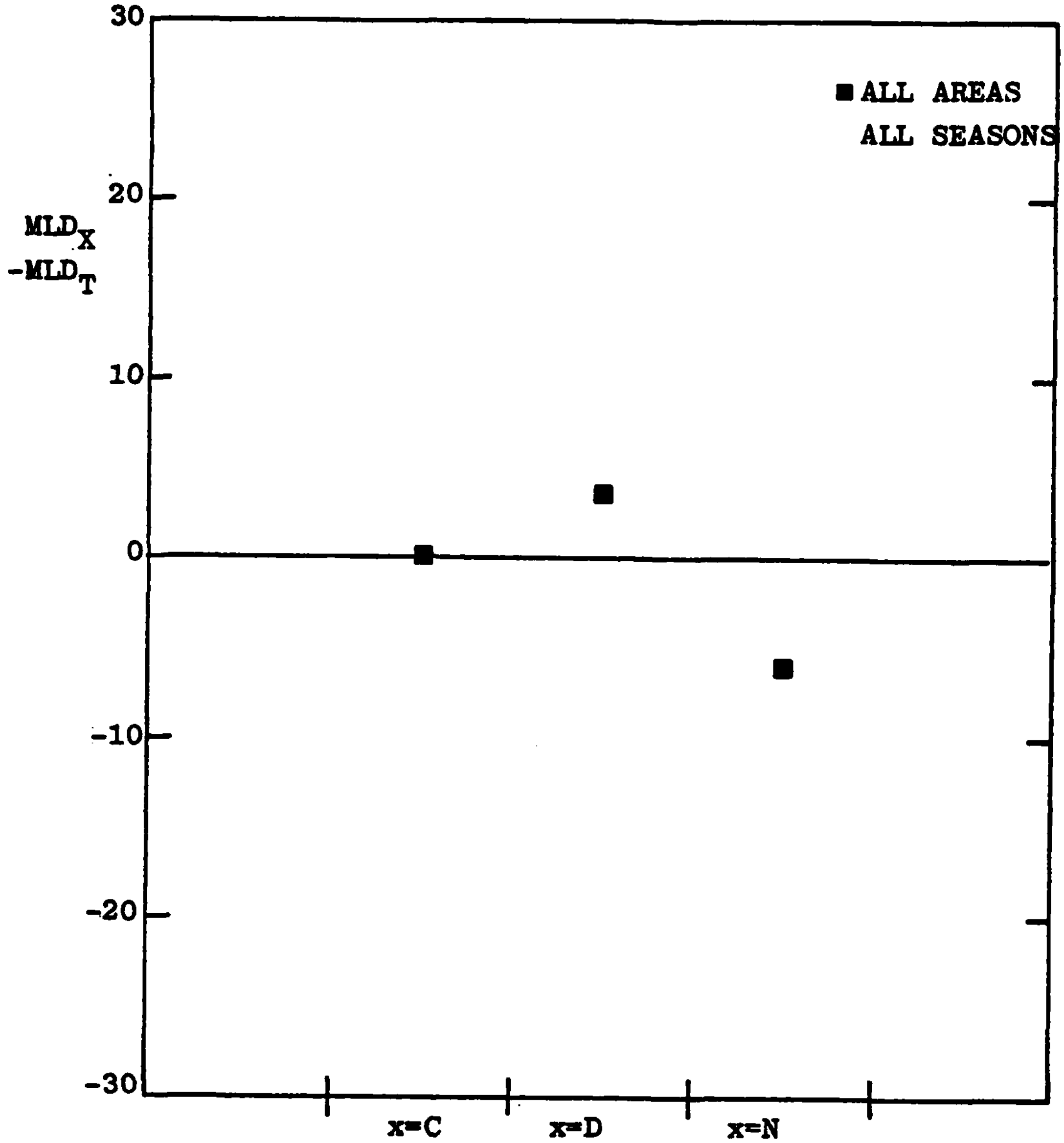

Figure 4.12 Dependence of MLD on criterion. All data for all seasons and areas combined. The sound speed criterion is not significantly different than the temperature. At the .001 level of significance the MLD_Ds are deeper, and the MLD_Ns are shallower, than the MLD_Ts.

Section 5
CONCLUSIONS

Five conclusions can be drawn from this work.

1. The greatest variation of MLD occurs with changes of season and amounts to an increase of 40m or more from summer to fall.

2. There is relatively slight but still significant variation of MLD with area. The Iceland Flank MLDs are about 10m deeper than either the Rockall Trough or Iceland Faeroe Frontal Zone in the summer and perhaps even more in the fall. There is not a significant difference between the Rockall Trough and the Iceland Faeroe Frontal Zone.

3. The definition of MLD based on stability is not sensitive to the seasonal variations, but seems to be affected by noise in the density profile introduced by time lag problems and not removed by 5m filtering.

4. Except for Area III in the spring and fall, the difference between the other definitons of MLD are relatively independent of area and season. Area III is also remarkable in having more deviations in MLD than Area I in the fall.

5. The large values of MLD in summer in Area II are suspect. These occur at stations 15 and 18 of cruise 932014.

Section 6
RECOMMENDATIONS

Based on the work performed here three tasks for further work can be identified. The first improves the present analysis, the second attempts to generalize the results and the third applies to future survey planning.

6.1 IMPROVEMENTS

Some of the MLD criteria should be redefined to be more consistent with applications.

The present definition of the stability MLD should not be used in future analyses as it is too sensitive to noise in the data. All MLD_N distributions should be recalculated with a new definition that is triggered by Brunt-Vaisala peaks in excess of 3 cph (2 cph is presently used).

The definition of the sound speed MLD should take into account the sound speed gradient above the maximum. Without a sufficient increase of sound speed with depth, surface ducting of sound energy will not occur. A sensitivity test of sound energy ducting as a function of sound speed gradient in the mixed layer must be performed. Then MLD_C should be recalculated with a requirement that gradient above the sound speed maximum exceed a minimum value. Then the resulting distribution of MLD_C will pertain to surface ducting.

The present analysis will also be improved by simply eliminating bad stations. Two summertime stations have been identified as suspect. These should be examined more closely to look for causes for the discrepancy between their MLD values and the values of MLD from other stations in the area. If unrealistic measurements are to blame the stations should be dropped.

In order to better characterize a particular distribution of MLDs (only MLD_T need be characterized if the relationships with the other criteria are known, see below) more needs to be known than the fact that the distribution is non-Gaussian. By plotting the third and fourth moments of the sample distribution, an analytical distribution (Binomial, Poissan, etc.) can be selected that is most appropriate for the data. This last step does not lead to a more complete understanding of the processes leading to the distributions of MLDs, it just makes a more complete description easier to specify.

6.2 GENERALIZING RESULTS

It would be very useful if MLDs by the various definitions could be predicted from the values of MLD according to the temperature criterion. Temperature profiles are both simpler and much less expensive to obtain (an expendable bathythermograph, XBT, can be used instead of an SVSTD). XBT measurements are more plentiful in the historical data set. For this reason it is highly recommended that more research be performed to correlate MLD_T to MLD_C, MLD_D and MLD_S. The data set provided for the present study is already useful to make the correlations for summer conditions.

The relationship can be investigated using three approaches. First, look at the equations of state relating sound speed, density and density gradient to temperature (T) and salinity (S) to determine how the various criteria should be related for a given T-S relationship. Assume some simple T-S curves and predict the correlation of MLD_T to MLD_C, MLD_D and MLD_S. Second, use the STD data in the area to define the actual T-S curve(s) and use these to calculate a second set of correlations between MLD_T and MLD_C, MLD_D and MLD_S. See if these differ significantly from the correlations computed using the simplified T-S relations. Finally, compute the actual correlations between MLD_T and MLD_C, MLD_D and MLD_S and see if these are consistent with the equations of state and the observed or simplified T-S curves.

6.3 FUTURE SURVEY PLANS

To make useful correlations in other seasons more data must be taken. There are statistical methods to determine the number of stations that must be occupied in a particular time-space window in order to characterize the distribution of some property (e.g. MLD) in that window.

In addition, statistical methods exist that can provide sampling strategies to address area characterizations. That is, they address the question of how large the time-space window mentioned above should be. These methods typically rely on estimates of correlation lengths and correlation times. Some of these correlation scales can be determined from individual cruises among the data provided for the present study. Correlation times, specifically, will require additional data sets, preferrably from moored instruments as used in the JASIN area.

Appendix A
COMPUTER PROGRAMS FOR MLD DEFINITIONS

This appendix lists the FORTRAN statements that are used to select MLDs from arrays of pressure (P, in dbar) temperature (T, in ^{o}C) and salinity (S, in 0/00 for the calculation of sound speed, density and Brunt-Väisälä frequency). In these routines, N is the number of elements in the P, T and S arrays. The value of mixed layer depth is returned (TMLD, SSMLD, DMLD or BVMLD) as is the index of the array element (IMLD) associated with that depth. For the calculation of BVMLD, a value of the local gravitational acceleration is passed as the variable G. The calculations of sound speed, density and Brunt-Väisälä frequency are detailed in section 2 of this report.

A.1 FORTRAN SUBROUTINE FOR MLD_T

```
      SUBROUTINE TEMMLD (P, T, S, N, TMLD, IMLD)
      DIMENSION P(1), T(1), S(1)
      If ((P(1)-5.0).GE.0.5) GO TO 500
      DO 10 I=1,N
C     FIND 5 M FIRST
      IF (P(I)-5..GE.0.5) GO TO 20
      I5=I
      T5=T(I)
      GO TO 10
C     CHECK AGAINST T VALUE AT 5 DB
   20 TDIF=ABS(T(I)-T5)
      IF (TDIF.LT.0.2) GO TO 10
      TGRAD=ABS((T(I)-T(I-1))/(P(I)-P(I-1)))
C     IF TGRAD LE 5.E-3 KEEP LOOKING
      IF (TGRAD.LE.5.E-3) GO TO 10
C     STOP----DESIRED VALUES FOUND
      TMLD=P(I)
      IMLD=I
      RETURN
   10 CONTINUE
  500 TMLD=-10.
      IMLD=00
      RETURN
      END
```

A.2 FORTRAN SUBROUTINE FOR MLD_C

```
      SUBROUTINE SMLD(P,T,S,N,SSMLD,IMLD)
      DIMENSION P(1),T(1),S(1)
      DIMENSION SS (20000)
      ERR=.5
      IF((P(1)-5.0).GE.0.5) GO TO 500
      M=1
      SSMAX=0.0
      DO 10 I=1,N
      IF(P(I).LT.5.0) GO TO 10
C     ROUND SOUND SPEED BECAUSE ADJ VALUES MAY BE SIMILAR
      IS=(SOUND(P(I),T(I),S(I))+.05)*10.0
      SS(I)=IS/10.0
C     CHECK FOR A NEW MAXIMUM
      IF(SS(I).LT.SSMAX) GO TO 95
      SSMAX=SS(I)
      M=I
      GO TO 10
   95 CONTINUE
      SSDIFF=SSMAX-SS(I)
C     CHECK WHETHER VALUES FOUND
      IF(SSDIFF.GE.ERR) GO TO 99
      GO TO 10
   99 SSMLD=P(M)
      IMLD=M
      RETURN
   10 CONTINUE
  500 CONTINUE
      SSMLD=-10.
      IMLD=0
      RETURN
      END
```

A.3 FORTRAN SUBROUTINE FOR $MLD_{\sigma T}$

```
      SUBROUTINE DENMLD(P,T,S,N,DMLD,IMLD)
      DIMENSION P(1),T(1),S(1)
      IF((P(1)-5.0).GE.0.5) GO TO 500
      I5=1000
      DGMAX=0.0
      DO 10I=1,N
      IF((P(I)-5.0).GE..5) GO TO 20
      I5=I
      CALL SIGGT(T(I),S(I),SO,ST5)
      STOLD=ST5
      GO TO 10
   20 CALL SIGGT(T(I),S(I),SO,ST)
C     CHECK AGAINST SIGMA T VALUE AT 5 DBARS TO SEE IF FOUND
      IF((ST-ST5).LT.0.02) GO TO 99
      DG=ST-STOLD
      IF(DG.LE.DGMAX) GO TO 30
      DGMAX=DG
      IDGMX=I
      GO TO 99
   30 IF(DGMAX.LE.0.0) GO TO 99
      DGDIF=DGMAX-DG
C     IF DGDIF LT ERROR IN DG THEN KEEP LOOKING
      IF(DGDIF.LE.0.01) GO TO 99
      IMLD=IDGMX
      DMLD=P(IMLD)
      RETURN
   99 STOLD=ST
   10 CONTINUE
  500 DMLD=-10.
      IMLD=0
      RETURN
      END
```

A.4 FORTRAN SUBROUTINE FOR MLD_N

```
      SUBROUTINE BMLD(P,T,S,N,BVMLD,IMLD,G)
      DIMENSION P(1),T(1),S(1)
      DIMENSION BV(2000),PNSQ(2000)
      IF(N.GT.2000) N=2000
      ERR=.5
      IF(P(1)-5..GE..5) GO TO 500
      PNSQ(1)=2.0
      CALL BVSQ(P,T,S,G,N,BV,PNSQ)
      BVMAX=0.
      IBMX=0
      DO 10 I=1,N
      IF(BV(I).LT.0.0) GO TO 199
      BV(I)=SQRT(BV(I))
      GO TO 10
  199 BV(I)=0.0
   10 CONTINUE
      DO 200 I=1,N
C     FIND BV MAX VALUE
      IF(BV(I).LE.2.0.AND.BVMX.LE.0.0) GO TO 200
      IF(P(I).LT.5.0) GO TO 200
      IF(BV(I).LE.BVMAX) GO TO 30
      BVMAX=BV(I)
      IBMX=I
      GO TO 200
   30 IF((BVMAX-BV(I)).LE.ERR) GO TO 200
      IMLD=IBMX
      BVMLD=P(IMLD)
      RETURN
  200 CONTINUE
  500 BVMLD=-10.
      IMLD=0
      RETURN
      END
```

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ABBREVIATIONS

cph	cycles per hour
dbar	decibar(s)
m	meter(s)
sec	seconds

ACRONYMS

MLD	mixed layer depth
NAVOCEANO	Naval Oceanographic Office
SAI	Science Applications, Inc.
SVSTD	sound velocity, salinity, temperature, depth *in situ* continuously recording probe

SYMBOLS

^{o}C	degrees Celsius
$^{o}/oo$	parts per thousand
Area I	Rockall Trough
Area II	Iceland Flank
Area III	Iceland Faroe Frontal Zone
C	sound speed
Cl	chlorinity
D	density
g	gravitational acceleration
N	Brunt-Väisälä Frequency
P	pressure
PP	effective pressure for adiabatic lapse rate calculation
PR	reference pressure
S	salinity
T	temperature
Z	depth
α	in situ specific volume
γ	adiabatic lapse rate
θ	potential temperature
ρ	density
σ_T	specific gravity anomaly
ϕ	latitude

FILME

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