VERIFICATION OF McDONNELL'S MIXED-LAYER DEPTH FORECASTING MODEL

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by

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B. S., Ohio University, 1958

Submitted in partial fulfillment
for the degree of

MASTER OF SCIENCE IN PHYSICAL OCEANOGRAPHY

from the

UNITED STATES NAVAL POSTGRADUATE SCHOOL
October 1966

ABSTRACT

A model based on Kitaigorodsky's application of similarity theory and modified by McDonnell to forecast the mixed-layer depth was studied. The model applies during the warming season and is based on the theory of similarity. The parameters involved in the model were determined from bathythermograph data recorded at Ocean Weather Stations November (latitude 30N, longitude 140W) and Bravo (latitude 56 30N, longitude 51W). Parameters were evaluated daily and grouped by months. Both seasonal and transitional MLD situations were treated.

From these parameters, the form of the dimensionless function P(N), claimed by Kitaigorodsky to be universal, was determined by least squares fit to be best approximated by a second order polynomial. Forecasting equations involving P(N) were developed for each month and tested with data from the following years for both OWS ships.

There is general agreement between the observed MLD and that found from the prediction equation based on the last year's P(N) for the same month and location. Month-to-month and spatial differences in P(N) cast considerable doubt on its universality, at least as determined by the parameters as currently defined.

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LIST OF SYMBOLS AND ABBREVIATIONS

ASW	anti-submarine warfare
BT	bathythermograph
C_p	specific heat of sea water at constant pressure
f	coriolis parameter
MLD	mixed-layer depth
MLD_s	seasonal mixed-layer depth
MLD_t	transitional mixed-layer depth
Q_s	excess heat in upper layer associated with seasonal thermocline
Q_t	excess heat in upper layer associated with transitional thermocline
TS	temperature at surface of ocean
W	representative maximum wind
β	coefficient of thermal expansion
ρ	density of sea water
ϕ	latitude
Ω	modified coriolis parameter (f x 10^4)
ω	angular velocity of earth

1. Introduction.

Extensive studies have been made on the ensonified bands of water in the sea in an effort to utilize better their potential for sound propagation. Sound transmission in the upper layers of the ocean is for the most part determined by the vertical temperature regime. The need for more information about this thermal structure to increase the effectiveness of our ASW equipment and perhaps develop new ideas from this knowledge is urgent.

Various methods have been devised for forecasting the ocean thermal structure. Statistical predictions of the thermocline depth and subsurface thermal structure have been the recent trend. The tools of this statistical approach have been either multiple linear-regression techniques or harmonic analysis of temperature cycles at various depths.

The bulk of applied research, however, is still based on either dynamical models or on parametric empirical relationships. Inherent in dynamical analysis is the problem of mathematical complexity if all processes are considered; if simplifying assumptions are made, the reality of the model becomes questionable. Forecasting techniques based on empirical relationships are only locally valid with monthly or seasonal adjustments required.

As pointed out by McDonnell [5] in his paper "Application of Similarity Theory to Forecasting the Mixed-Layer Depth of the Ocean", the theory of similarity represents an alternative approach in building a forecasting model. Kitaigorodsky [4] was the first to investigate the application of similarity theory as proposed by Monin and Obukhov [6] to predict the thermal structure in the upper layer of the ocean. In the development of this model, Kitaigorodsky assumed that purely thermal convection due to unstable density stratification was negligible and that vertical gradients of salinity are equal to zero. This imposed a seasonal limitation on the resulting equations. Generally speaking, a stable density stratification exists in the upper layer during the warming season when the thickness of the nearly isothermal layer can be considered mainly a function of wind mixing. Heat fluxes across the air-sea interface during the summer are positive (inward) and tend to build and strengthen the seasonal thermocline.

With these assumptions, McDonnell applied the method of Kitaigorodsky, with some modification of parameters to develop a practicable forecasting model. In McDonnell's conclusion a recommendation was made that future research be applied in determining the form of the dimensionless function P(N), inherent in the application of similarity theory, for various oceanic locations in order to test Kitaigorodsky's contention that P(N) is a universal function.

The present author studied two distinct geographical areas using McDonnell's mixed-layer depth forecasting model in an effort to establish the form of P(N). In this way, the form of the function P(N) could be better fixed and the possibility of its universality tested. Furthermore, the practicability of McDonnell's model and parameters could be tested if realistic mixed-layer depths could be forecast using his method.

2. Review of McDonnell's model.

McDonnell used data recorded at OWS Papa and the theory of similarity to develop a method of forecasting the mixed-layer depths associated with transitional and seasonal thermoclines during the warming season.

The mixed-layer depth (MLD) was defined as the depth at which water first became 1C colder than the water at the surface. Usually, this depth could be accepted as the top of the seasonal thermocline. Transitional thermoclines were identified as those having a temperature difference from the surface of less than 1C with a certain degree of permanence so as not to involve those of diurnal period. McDonnell considered the term "MLD" and depth of the thermocline synonymous and refers only to mixed-layer depths associated with either transitional or seasonal thermoclines. Only secular, non-advective, and non-divergent processes were considered as influencing the MLD. Other processes contribute to MLD behavior which deviates from the model.

The relationships developed by McDonnell are:

$$MLD = P(N)\frac{W^2}{Q\beta\Omega^2} \qquad (1)$$

$$N = \frac{Q\beta\Omega}{W} \qquad (2)$$

where: Q = total heat present or excess heat in the upper wind mixed-layer,

W = representative maximum wind,

Ω = coriolis parameter times 10^4 ($2\omega \sin\phi \times 10^4$)

β = coefficient of thermal expansion,

P = a dimensionless function of N with the form of a first degree polynomial.

To specify the form of P(N), equations (1) and (2) were solved for P(N) and N respectively. Then measured values of the parameters provided 200 paired values of P(N) and N which were plotted together. The form of P(N) was found by curve fitting to this plot. Seasonal and transitional MLD's were separately treated, a linear function P(N) being determined for each of these situations.

McDonnell pointed out that, if the parameters chosen truly represent the controlling processes, then the plot of P versus N would have little scatter. Large scatter indicates assumptions were inadequate, e.g., divergence and advection are certainly important during some intervals.

McDonnell's final equations incorporating the linear relationship for P(N) were:

$$MLD = 2.9\frac{W}{\Omega} - .25\times10^{-4}\frac{W^2}{Q\beta\Omega^2} \tag{3}$$

where

$$P(N) = 2.9N - .25\times10^{-4} \tag{4}$$

for transitional MLD and

$$MLD = 3.89\frac{W}{\Omega} - 6.1\times10^{-4}\frac{W^2}{Q\beta\Omega^2} \tag{5}$$

where

$$P(N) = 3.89N - 6.1\times10^{-4} \tag{6}$$

for the seasonal MLD.

3. Area study selection.

Several basic considerations governed the choice of the data used in this study. The first requirement was dependability, i.e., the measurements must be of acknowledged accuracy and recorded at a fixed location with appropriate frequency as nearly continuous as possible during the periods of interest; the second requirement was immediate availability, an important matter because of the limited time available for preparation of the study; the third requirement was that data be suitable to measure the phenomena the thesis attempts to describe, which means mainly that the effects of extraneous processes, such as internal wave activity, convection and advection be minimized or, at least, evaluated; and a fourth consideration was that the data come from geographically and climatologically dissimilar areas and from different times so that the possibility of a universal function and its application to forecasting could be examined.

The requirements having to do with quality, frequency and continuity are satisfactorily met by the data from OWS ships; in fact there are few other sources for suitable data. The particular weather ships from which data were used were chosen in large part because of their being on hand in large quantities, thus providing economy of both time and money.

Specifically, data available for the study represented two distinct geographical locations, one in the Atlantic (OWS Bravo 56 30N, 51W) and one in the Pacific (OWS November 30N 140W). In addition comparison was available with McDonnell's work at OWS Papa (50N, 145W).

According to Tully [8], OWS November is contained in the eastern extremity of the large Subtropic Region in which the mid-ocean flows are zonal and the waters respond to surface processes. Advection of thermal regimes are minimal since no major current system is present. The location coincides with the mean position of the permanent Pacific anticyclone for the summer months, but effects of convergence in deepening the MLD can be estimated from Fofonoff's [1] mass transport calculations.

OWS Bravo, however, located in the eastern sector of the Labrador Sea does not possess these ideal conditions. Random advective influences may be present due to meandering of adjacent current patterns.[1] Additionally, monthly mean patterns of atmospheric circulation show the presence of a deep low over this location; therefore horizontal divergence can be expected in the upper layers. To some extent, as at OWS November, this effect can be estimated.

[1](The West Greenland Current (warm) on the north and Labrador Current (cold) to the south could provide advective influences.)

4. Calculation of parameters.

The start of the warming season is evidenced by the onset of the seasonal thermocline; it remains in effect until after the autumn equinox when the seasonal thermocline settles to lower depths by convection and decays. Data to cover this period were selected from the months June through October.

To determine the parameter MLD, observed values of MLD were plotted against time for each month, MLD's being read directly from the BT trace. Plots were made with the time interval three hours, the normal spacing of BT observations aboard ocean weather stations (OWS) ships. Both seasonal and transitional MLD's were plotted from the six to eight BT's available per day. A smooth curve representing the top of the thermocline or actual MLD was then sketched connecting the plotted points. In this manner an observation time with a missing BT report could be assigned an interpolated MLD.

A mean MLD was computed from the four plotted MLD's during each twelve-hour interval starting with midnight Greenwhich. If more than one interpolated MLD was contained in the averaging process, the interval was not accepted. By assessing the MLD in this manner, the ambient variations due to internal waves hopefully were reduced.

To determine Q, a BT trace was selected from each 12-hour interval studied that best represented the mean seasonal (and transitional, if it existed) MLD for that interval. The value of the parameter Q was determined from this trace representing the total heat in the uppermost layer. A step-by-step procedure for determining the value of Q is explained in appendix I with appropriate illustrations. The technique used by the author represents a modification of McDonnell's method.

The parameter W (representative maximum wind) defined by McDonnell is an average of the five highest winds reported in a 24-hour period[1] that precedes the 12-hour interval of interest by up to 72 hours.

The values of β , the coefficient of thermal expansion, are listed in table 24 as given by Sverdrup [7]. The value of the parameter β is selected by entering table 24 with the surface temperature of the representative BT for the 12-hour interval being studied and the appropriate salinity.

Table 1 is a breakdown by OWS ship and month of the nearly 1500 BT's which provided the data for determining 628 paired values of P and N subsequently used in evaluating the form of the function P(N). Of the total paired values, 473 represent seasonal and 155 represent transitional thermoclines.

The following equations were used to obtain the paired values of P and N from the parameters calculated for each 12-hour interval.

$$P = (MLD)\,\frac{Q\beta\Omega^2}{W^2} \tag{1a}$$

$$N = \frac{Q\beta\Omega}{W} \tag{2}$$

Tables 2 through 12 give the values of the parameters and the corresponding paired values of P and N for each observation time. The only irregulatiry in this process was September 1960 at OWS Bravo where the available data represented only the first 10 and last 11 days of the month. During the 10 day segment missing, the surface temperature became

[1](Normally eight wind reports are available in a 24-hour interval)

TABLE 1

MONTHLY NUMBER OF BT DATA CARDS ANALYZED
AND NUMBER OF PAIRED VALUES DETERMINED

OWS NOVEMBER

MONTH	YEAR	# OF BT's ANALYZED	# OF MLD's SEASONAL	# OF MLD's TRANSIENT	# OF PAIRED VALUES SEASONAL	# OF PAIRED VALUES TRANSIENT
June	1957	96	96	55	35	19
July	1957	134	134	0	45	0
Aug.	1957	129	112	5	48	0
Sept.	1957	150	141	142	52	44
Oct.	1957	196	196	0	62	0

OWS BRAVO

MONTH	YEAR	# OF BT's ANALYZED	# OF MLD's SEASONAL	# OF MLD's TRANSIENT	# OF PAIRED VALUES SEASONAL	# OF PAIRED VALUES TRANSIENT
June	1960	176	157	114	50	17
July	1960	177	118	168	51	56
Aug.	1960	147	114	43	55	11
Sept.	1960	134	129	15	39	8
Oct.	1960	123	123	0	38	0

less by 3.5C and the MLD increased by over 30 meters, indicating that other processes than those considered in the model may be involved. Therefore the data for September were split into two segments and treated separately.

With this change of season, the heat fluxes across the air-sea interface, although not computed, may well be negligible. During the following month, October, (as the cooler continental air masses became more prominent) instability mixing due to density increases created by evaporation may influence the depth of this isothermal layer. The influence of evaporation, not considered in this model, would be indicated by the scatter in the paired values of P and N.

TABLE 2

PARAMETERS USED TO DETERMINE VALUES OF P AND N
FOR JUNE 1957 AT OWS NOVEMBER

DATE	W (KNOTS)	Q_s (Kg cal/cm^2)	Q_t	MLD_s (METERS)	MLD_t	TS (^oC)	P_s x 10^4	N_s	P_t x 10^4	N_t
060157	13.0	6.2		27.9		21.1	1.48	.94		
060157	12.6	4.8		27.3		22.2	1.22	.77		
060257	11.0	5.8		27.7		22.2	1.97	1.07		
060257	10.8	4.8		26.6		21.7	1.57	.87		
060357	10.2	4.9		24.6		22.2	1.71	.98		
060457	10.2	5.8		25.0		23.3	2.12	1.18		
060557	10.2	7.4	.76	26.3	8.8	23.3	2.83	1.50	.10	.15
060557	9.0	7.7	.68	23.8	10.9	22.8	3.34	1.74	.14	.15
060657	8.6	5.9	1.17	25.5	8.7	22.2	3.01	1.40	.20	.27
060657	10.6	6.3	1.05	24.8	10.0	22.8	2.05	1.21	.14	.20
060757	10.6	6.5	.68	26.4	13.1	22.2	2.25	1.25	.13	.14
060757	10.6	7.7	1.53	28.2	11.8	22.8	2.85	1.48	.24	.30
060857	10.6	5.4	1.32	24.0	11.7	22.8	1.71	1.79	.20	.26
060857	10.2	7.3	.65	21.7	8.9	22.8	2.25	1.45	.08	.14
060957	9.2	7.6	1.05	22.0	8.5	21.7	2.83	1.62	.14	.22
060957	8.6	6.7	1.35	22.2	7.6	22.2	2.97	1.57	.20	.31
061057	8.8	8.5	1.71	25.7	12.8	22.2	4.16	1.95	.42	.39
061057	8.8	9.5	2.55	27.0	11.8	23.2	5.04	2.24	.59	.60
061157	8.0	8.9	1.78	25.0	11.7	23.3	5.29	2.31	.49	.46
061157	7.2	7.6	2.04	23.7	10.1	22.4	5.14	2.14	.58	.57
061257	6.0	10.6	3.00	26.7	8.5	23.4	11.96	3.67	1.07	1.04
061357	7.0	11.4	2.68	27.0	9.1	23.6	9.54	3.38	.75	.79
061457	7.8	9.3	2.47	28.2	12.1	23.3	6.56	2.48	.74	.65
061457	9.2	9.1	1.77	28.6	13.7	21.8	4.41	1.95	.41	.38
061557	11.4		1.68		14.6	22.5			.28	.30
061757	12.6	9.0		23.8		22.2	1.99	1.45		
061757	12.6	11.4		28.1		22.1	2.98	1.83		
061857	13.8	11.6		25.9		22.1	2.33	1.71		
061957	14.8	11.9		31.1		22.2	2.49	1.63		
061957	14.6	11.7		27.8		22.5	2.25	1.63		
062057	14.2	8.9		29.2		21.7	1.84	1.24		
062057	14.8	12.3		28.2		21.8	2.28	1.63		
062157	14.8	11.6		27.5		22.1	2.14	1.59		
062157	14.8	10.7		29.8		21.8	2.09	1.42		
062257	14.0	10.7		30.3		22.1	2.37	1.51		
062257	14.2	12.9		31.3		22.1	2.96	2.05		

TABLE 3

PARAMETERS USED TO DETERMINE VALUES OF P AND N FOR JULY 1957 AT OWS NOVEMBER

DATE	W (KNOTS)	Q_s (Kg cal/cm^2)	Q_t (Kg cal/cm^2)	MLD_s (METERS)	MLD_t (METERS)	TS (^oC)	P_s x 10^4	N_s	P_t x 10^4	N_t
070957	16.3	12.09		34.2		23.8	2.37	1.55		
071057	14.3	11.0		36.0		23.9	2.94	1.60		
071057	12.2	9.8		42.3		23.8	4.23	1.67		
071157	10.8	8.4		40.3		23.7	4.41	1.61		
071157	9.8	9.5		41.2		23.8	6.19	2.02		
071257	7.2	13.2		42.0		24.1	16.77	3.94		
071257	6.0	11.2		47.9		24.9	23.37	4.01		
071357	6.4	10.9		38.5		24.3	16.06	3.67		
071357	6.4	12.0		44.2		24.4	20.31	4.03		
071457	6.0	11.6		37.1		24.9	18.74	4.15		
071457	6.0	10.1		38.3		24.0	16.34	3.62		
071557	10.2	13.0		41.2		24.3	8.07	2.73		
071557	14.4	10.5		39.1		24.3	3.11	1.57		
071657	18.4	11.9		40.3		24.2	2.22	1.39		
071657	19.6	11.5		39.6		24.2	1.86	1.27		
071757	22.6	13.3		35.9		24.2	1.47	1.27		
071757	22.0	9.7		35.3		24.1	1.11	.95		
071857	23.0	13.2		38.0		23.6	1.44	1.20		
071857	23.0	8.2		34.0		23.6	.80	.74		
071957	23.0	8.5		35.3		23.8	.87	.77		
071957	21.0	11.0		43.3		23.8	1.65	1.09		
072057	21.0	9.5		42.9		24.0	1.41	.98		
072057	21.0	12.0		44.5		23.6	1.84	1.18		
072157	19.8	9.8		41.2		23.8	1.56	1.03		
072157	20.0	9.6		44.4		23.7	1.62	1.00		
072257	20.0	11.0		39.2		23.6	1.63	1.14		
072257	19.6	10.7		43.6		23.9	1.84	1.14		
072357	18.4	9.0		41.0		23.9	1.66	1.02		
072357	13.0	9.3		44.1		23.8	3.68	1.49		
072457	12.2	9.6		35.7		23.6	3.50	1.64		
072457	13.4	10.3		43.6		23.4	3.79	1.60		
072557	14.2	11.8		44.4		24.0	3.95	1.78		
072557	14.2	13.2		49.2		24.2	5.05	2.00		
072657	16.6	12.1		50.5		24.1	3.47	1.57		
072657	16.8	11.0		46.4		24.1	2.84	1.41		
072757	16.8	10.7		47.4		23.5	2.73	1.32		
072757	15.2	11.4		47.0		23.8	3.53	1.56		
072857	18.8	9.3		39.8		21.4	1.50	.97		
072857	20.6	8.8		33.7		21.0	1.00	.84		
072957	20.6	12.3		44.7		21.6	1.86	1.17		
072957	20.6	8.1		36.7		20.7	.96	.75		
073057	19.8	13.0		47.7		21.3	2.27	1.29		
073057	19.4	13.8		49.3		21.7	2.59	1.39		
073157	17.8	12.5		48.6		21.4	2.75	1.38		
073157	18.0	12.3		48.7		21.4	2.63	1.33		

TABLE 4

PARAMETERS USED TO DETERMINE VALUES OF P AND N
FOR AUGUST 1957 AT OWS NOVEMBER

DATE	W (KNOTS)	Q_s (Kg cal/cm^2)	Q_t (Kg cal/cm^2)	MLD_s (METERS)	MLD_t (METERS)	TS (°C)	P_s x 10^4	N_s x 10^4	P_t x 10^4	N_t x 10^4
080157	19.0	11.1		40.8		21.4	1.80	1.14		
080157	19.8	13.1		50.9		21.5	2.44	1.30		
080257	19.8	13.5		51.8		21.7	2.56	1.34		
080257	19.8	12.7		48.5		21.5	2.25	1.26		
080357	17.8	12.4		43.4		21.5	2.71	1.37		
080357	17.0	13.9		54.1		21.4	3.74	1.61		
081157	10.0	12.2		49.0		22.5	8.83	2.47		
081157	10.0	10.0		37.8		22.9	5.59	2.02		
081257	9.6	11.5		37.1		23.6	7.03	2.49		
081257	9.4	14.8		35.4		23.6	9.01	3.27		
081357	9.6	15.1		44.4		23.7	11.06	3.27		
081357	9.6	15.5		47.2		23.7	12.07	3.35		
081457	11.8	22.0		54.8		23.8	13.16	3.88		
081457	13.0	15.9		53.2		23.8	7.60	2.55		
081557	13.8	22.5		49.3		23.8	8.86	3.40		
081557	13.8	17.5		44.7		23.8	6.25	2.64		
081657	13.8	18.3		41.6		23.7	6.08	2.76		
081657	11.8	13.3		39.8		23.6	5.78	2.34		
081757	11.2	13.5		39.2		23.7	6.42	2.51		
081757	10.2	17.9		40.1		23.7	10.49	3.65		
081857	10.0	18.5		50.0		23.9	14.06	3.84		
081857	9.4	17.9		41.5		23.6	12.78	3.97		
081957	9.4	18.4		37.9		23.8	12.15	3.55		
081957	9.4	18.4		37.9		23.8	12.00	4.08		
082057	10.4	14.8		42.9		23.9	8.93	2.96		
082057	10.4	19.3		46.8		23.9	12.70	3.86		
082157	10.4	14.4		44.9		23.9	9.08	2.88		
082157	10.4	11.4		39.2		23.9	6.28	2.28		
082257	9.4	14.6		42.8		23.7	10.74	3.23		
082257	9.0	19.3		48.7		23.8	17.64	4.45		
082357	10.4	18.1		47.3		23.9	12.03	3.62		
082357	11.4	19.7		47.1		24.0	10.85	3.59		
082457	11.8	19.8		53.0		24.0	11.45	3.49		
082457	11.8	19.0		49.8		24.0	10.32	3.35		
082557	11.8	23.8		55.7		24.0	14.47	4.19		
082557	11.8	23.5		53.5		23.9	13.73	4.15		
082657	13.2	28.4		59.5		24.1	15.31	4.28		
082657	13.6	20.7		54.1		23.9	9.21	3.16		
082757	13.4	18.1		42.9		23.8	6.57	2.81		
082757	13.9	22.6		47.9		23.8	8.51	3.38		
082857	12.6	21.6		39.1		23.6	8.09	3.56		
082857	11.4	21.5		42.3		23.9	10.63	3.93		
082957	10.4	14.1		38.3		23.8	7.59	2.83		
082957	10.0	11.7		30.5		23.6	5.43	2.44		
083057	10.2	16.9		42.3		24.0	10.45	3.45		
083057	9.8	22.5		46.3		24.2	17.01	4.93		
083157	7.8	17.7		46.5		24.1	21.20	4.87		
083157	6.0	23.7		49.1		24.1	50.69	8.48		

TABLE 5

PARAMETERS USED TO DETERMINE VALUES OF P AND N
FOR SEPTEMBER 1957 AT OWS NOVEMBER

DATE	W (KNOTS)	Q_s (Kg cal/cm^2)	Q_t	MLD_s (METERS)	MLD_t	TS (^{o}C)	P_s x 10^4	N_s	P_t x 10^4	N_t
090157	6.3	23.6	.46	45.7	8.5	23.3	41.31	7.80	.15	.15
090157	6.5	22.0	.97	36.6	15.2	23.3	28.96	7.04	.53	.31
090257	6.4	22.8	.56	57.0	9.8	23.3	48.23	7.46	.21	.18
090257	6.4	29.4	.77	59.4	12.2	23	64.81	9.56	.35	.25
090357	7.4	29.8	.83	67.1	9.1	22.8	55.50	8.38	.21	.24
090357	7.4	29.2	.78	61.0	10.7	23.3	49.45	8.21	.24	.22
090457	7.8	22.2	1.03	42.7	12.2	23.3	23.69	5.92	.32	.28
090457	7.8	25.7	1.38	48.8	16.8	23.3	31.34	6.85	.59	.36
090557	7.8	18.5	.54	27.4	6.1	23.9	12.67	4.93	.08	.14
090557	5.4	27.3	.93	45.7	9.1	23.3	65.03	10.54	.45	.36
090657	8.2	28.8	1.38	57.9	12.2	23.9	37.70	7.31	.38	.35
090657	9.2	26.5	.92	51.8	9.1	23.9	24.65	7.38	.15	.21
090757	10.5	28.2	1.15	51.8	11.6	23.9	20.15	5.58	.18	.22
090757	10.5	23.8	1.39	45.7	12.2	23.9	15.00	4.72	.24	.28
090857	11.2	21.4	.54	48.8	6.1	23.9	12.65	3.98	.04	.10
090857	11.2	24.8	1.44	45.7	18.3	23.9	13.73	4.61	.32	.26
090957	13.2	19.7	1.19	57.9	15.2	23.9	9.95	3.13	.15	.18
090957	14.2	29.4	2.01	59.4	24.4	23.3	13.17	4.30	.36	.29
091057	14.2	26.1	2.18	48.8	21.3	23.3	9.60	3.83	.35	.32
091057	14.2	22.4	1.07	36.6	25.9	23.9	6.18	3.29	.21	.15
091157	14.2	21.3	1.38	51.8	18.3	23.9	17.47	4.52	.40	.29
091157	19.8	24.1	1.68	51.8	17.1	23.3	19.76	5.12	.46	.36
091257	9.8	23.7	2.00	45.7	19.8	23.9	17.15	5.03	.63	.43
091257	9.8	28.6	1.92	48.8	20.7	23.9	22.09	6.07	.63	.40
091357	9.8	26.8	.85	57.9	9.1	23.9	48.13	7.96	.24	.25
091357	7.0	21.0	1.65	51.8	25.9	23.9	33.75	6.24	1.33	.49
091457	7.0	21.1	1.46	47.2	12.8	23.9	30.89	6.26	.59	.43
091457	7.0	20.6	1.18	45.7	21.3	23.9	29.20	6.12	1.24	.56
091557	9.8	25.8	1.10	56.4	12.8	23.3	23.03	5.47	.22	.24
091657	9.8	20.3	2.46	48.8	28.0	23.9	15.68	4.32	1.09	.53
091757	10.0	23.2	1.54	54.9	19.8	23.9	19.37	4.83	.46	.32
091757	10.2	24.6	2.18	61.0	18.3	23.9	21.92	5.01	.59	.45
091857	16.8	23.1	2.29	57.9	25.0	23.3	7.20	2.85	.31	.28
091857	16.8	23.0	1.57	57.9	30.5	23.9	7.17	2.85	.25	.19
091957	19.8	23.5	1.56	48.8	27.4	23.9	4.45	2.46	.29	.25
091957	19.8	22.9	2.45	39.6	30.5	23.9	3.52	2.41	.22	.21
092057	18.4	24.4	1.86	57.9	26.8	23.9	6.35	2.76		
092157	18.2	25.0		48.8		23.3	5.59	2.85		
092157	17.8	22.7	.85	48.8	21.3	23.3	5.32	2.66	.08	.10
092257	15.0	22.7	2.44	61.0	27.4	23.9	9.36	3.15	.45	.33
092357	9.0	25.7	2.39	64.6	30.5	24.4	32.14	6.14	1.41	.58
092357	9.0	28.7	2.54	64.0	27.4	23.9	34.46	6.64	1.31	.58

TABLE 5 (Cont'd)

DATE	W	Q_s	Q_t	MLD_s	MLD_t	TS	P_s	N_s	P_t	N_t
	(KNOTS)	(Kg cal/cm^2)		(METERS)		(°C)	x 104		x 104	
092457	6.0		2.45		27.4	24.4			2.92	.88
092557	7.0	20.0	1.36	61.0	29.9	23.9	37.85	5.94	1.26	.40
092557	8.0	23.6	1.87	67.1	33.5	24.4	38.80	6.34	1.53	.50
092657	10.6	27.2	2.17	54.9	24.4	24.4	20.84	5.51	.73	.45
092757	16.4	29.3		67.1		25.0	11.46	3.84		
092757	17.6	22.4		54.9		25.0	6.23	2.73		
092857	17.6	26.2		61.0		25.0	8.09	3.19		
092857	17.6	26.2		61.6		25.0	8.18	3.19		
092857	17.6	28.0		67.1		24.4	9.51	3.42		
093057	11.6	22.6		45.7		24.4	12.03	4.18		
093057	11.6	22.6		45.7		24.4	12.03	4.18		

TABLE 6

PARAMETERS USED TO DETERMINE VALUES OF P AND N
FOR OCTOBER 1957 AT OWS NOVEMBER

DATE	W (KNOTS)	Q_s (Kg cal/cm^2)	Q_t (Kg cal/cm^2)	MLD_s (METERS)	MLD_t (METERS)	TS (°C)	P_s x 10^4	N_s x 10^4	P_t x 10^4	N_t x 10^4
100157	10.6	19.3		30.2		24.6	8.13	3.91		
100157	10.0	24.3		36.0		24.7	13.72	5.22		
100257	10.6	22.2		35.6		24.4	11.03	4.50		
100257	13.6	25.8		35.1		24.4	7.67	4.08		
100357	13.8	21.0		36.6		24.5	6.33	3.26		
100357	13.9	27.7		44.2		24.7	9.93	4.28		
100457	14.6	23.5		42.2		24.3	7.30	3.46		
100457	16.2	26.4		48.5		24.8	7.67	3.51		
100557	16.0	22.8		39.8		24.3	5.56	3.06		
100557	16.2	23.2		50.1		24.4	6.95	3.08		
100657	15.3	19.8		34.0		24.4	4.51	2.77		
100657	14.2	23.6		39.4		24.3	7.23	3.55		
100757	17.4	22.2		40.9		24.2	4.71	2.75		
100757	21.0	24.1		44.9		24.2	3.84	2.47		
100857	22.0	23.0		42.4		24.1	3.17	2.24		
100857	21.8	22.3		40.4		24.3	2.98	2.20		
100957	22.0	28.4		46.3		24.4	4.26	2.77		
100957	21.8	21.6		37.1		24.5	2.65	2.13		
101057	17.6	22.4		43.8		24.3	4.97	2.73		
101057	14.8	20.9		41.7		24.3	6.23	3.03		
101157	14.8	20.5		38.0		24.2	5.57	2.98		
101157	14.8	22.4		42.3		24.1	6.78	3.25		
101257	14.2	26.1		44.7		24.2	9.07	3.95		
101257	13.8	26.4		45.2		24.2	9.83	4.11		
101357	10.0	19.6		46.9		24.3	14.42	4.21		
101357	9.2	22.2		43.5		24.2	17.89	5.19		
101457	11.2	20.4		40.6		24.1	10.35	3.91		
101457	12.0	21.4		41.8		23.9	9.45	3.72		
101557	12.0	21.8		44.3		23.3	10.20	3.79		
101557	12.0	19.0		39.6		22.8	7.71	3.22		
101657	10.8	21.7		45.3		22.8	12.45	4.07		
101657	10.8	21.3		43.1		21.8	11.30	3.88		
101757	9.2	20.8		42.3		22.8	15.36	4.59		
101757	8.6	20.2		39.8		22.4	16.05	4.76		
101857	8.6	20.0		44.0		21.7	17.07	4.58		
101857	9.4	21.6		44.0		22.2	15.89	4.65		
101957	7.0	20.1		41.9		22.2	25.39	5.82		
101957	10.6	22.2		43.1		22.2	12.58	4.25		
102057	14.2	22.3		39.8		22.5	6.51	3.19		
102057	15.2	25.5		42.7		22.3	6.95	3.41		

TABLE 6 (Cont'd)

DATE	W (KNOTS)	Q_s (Kg cal/cm^2)	Q_t	MLD_s (METERS)	MLD_t	TS (°C)	P_s x 10^4	N_s	P_t x 10^4	N_t
102157	16.6	27.2		49.0		22.5	7.14	3.32		
102157	18.0	24.8		42.3		22.5	4.79	2.80		
102257	19.8	23.0		43.9		22.2	3.81	2.36		
102257	19.8	23.2		44.3		22.4	3.88	2.37		
102357	19.8	25.7		47.6		21.7	4.43	2.55		
102357	19.4	26.6		49.2		22.5	5.14	2.78		
102457	16.8	25.3		53.7		22.0	6.90	2.96		
102457	11.6	24.1		44.4		22.2	11.66	4.21		
102557	12.6	24.5		57.0		22.1	12.99	3.83		
102557	12.6	23.5		46.3		22.4	10.13	3.79		
102657	12.6	21.4		43.8		21.8	8.47	3.34		
102657	12.6	22.2		44.7		22.0	8.97	3.46		
102757	10.0	25.2		55.0		22.2	20.47	5.12		
102757	10.6	20.5		44.1		22.5	11.89	3.92		
102857	10.6	25.5		50.5		22.1	16.93	4.89		
102857	10.8	25.4		50.4		22.1	16.21	4.76		
102957	9.4	24.6		53.3		21.9	21.30	5.14		
102957	9.0	22.0		52.8		21.9	20.57	4.80		
103057	7.4	21.5		51.9		21.9	29.29	5.71		
103057	12.0	23.2		50.7		22.2	12.07	3.92		
103157	16.2	27.5		61.0		21.9	9.17	3.34		
103157	17.2	27.2		56.0		21.8	7.39	3.11		

TABLE 7

PARAMETERS USED TO DETERMINE VALUES OF P AND N
JUNE 1960 AT OWS BRAVO

DATE	W	Q_s	Q_t	MLD_s	MLD_t	TS	P_s	N_s	P_t	N_t
	(KNOTS)	(Kg cal/cm^2)		(METERS)		(^{o}C)	x 10^4		x 10^4	
060160	22.6	2.41		54.9		5.0	.43	.15		
060160	25.4	2.94		50.6		4.5	.39	.16		
060260	25.8	2.95		54.9		5.0	.41	.16		
060260	25.8	4.82	.42	73.2	12.2	4.8	.89	.26	.01	.02
060460	20.0	4.02		48.8		4.8	.82	.28		
060460	20.0	4.15		39.6		4.8	.69	.29		
060560	20.0	5.65		36.6		5.0	.86	.39		
060560	23.2	4.79	1.18	67.1	24.4	5.0	.99	.30	.09	.07
060760	23.2	1.02		19.8		4.4	.06	.06		
060760	23.2	2.20		32.6		4.4	.22	.13		
060860	16.4	1.52		39.6		3.9	.37	.13		
060860	17.2	.76		25.6		4.4	.11	.06		
060960	17.2	.80		25.9		4.4	.12	.06		
060960	17.2	.75		21.3		4.4	.09	.06		
061060	17.2	.52		18.3		4.4	.05	.04		
061060	16.2	1.95		29.0		4.4	.36	.17		
061160	14.0	1.10		19.8		4.4	.19	.11		
061160	15.2	3.62		25.3		5.3	.66	.33		
061260	15.4	3.39		22.9		4.4	.55	.30		
061260	17.4	3.92		26.8		5.0	.58	.31		
061360	17.4	2.94		18.9		5.0	.31	.23		
061360	17.4	3.00		25.6		5.0	.42	.24		
061460	17.4	2.44		24.4		4.8	.33	.19		
061460	21.6	4.42		37.2		5.3	.59	.28		
061560	21.6	3.40		31.4		5.0	.38	.22		
061560	21.6	6.40		34.1		5.1	.78	.41		
061660	21.6	7.30		25.9		4.7	.68	.46		
061660	20.6	4.50		28.3		5.3	.50	.30		
061760	16.6	4.74		27.4		4.9	.79	.39		
061760	19.2	4.83		24.1		5.3	.53	.35		
061860	19.8	5.70		29.3		4.8	.71	.40		
061860	19.8	5.65		29.9		5.4	.72	.39		
061960	19.8	7.40		35.7		5.0	1.13	.51		
061960	19.2	6.70		35.4		5.8	1.07	.48		
062060	19.2	6.91	.76	31.1	6.1	5.4	.97	.49	.02	.05
062060	17.8	5.31	.61	25.0	4.6	6.1	.77	.48	.02	.05
062160	17.0	1.95	.93	27.4	9.1	6.0	1.21	.62	.05	.08
062160	13.2	7.56	.90	32.3	12.8	6.3	2.58	.87	.12	.10
062260	11.8	9.50	1.13	36.6	11.8	5.8	4.17	1.11	.23	.13
062260	9.6	8.97	1.83	33.5	16.8	5.6	5.45	1.28	.56	.26
062360	10.2		1.91		18.3	6.1			.62	.28
062360	10.2	8.67	1.43	34.7	14.3	5.6	4.83	1.17	.33	.19

TABLE 7 (Cont'd)

DATE	W (KNOTS)	Q_s (Kg cal/cm^2)	Q_t	MLD_s (METERS)	MLD_t	TS (°C)	P_s x 104	N_s	P_t x 104	N_t
062460	12.0		.98		12.8	5.7			.15	.11
062460	12.6	7.35	.97	29.0	16.8	5.6	2.25	.80	.17	.11
062560	14.0	7.60	2.90	35.1	14.6	5.6	2.27	.75	.36	.28
062560	14.0	8.37	2.17	33.5	11.9	5.8	2.39	.82	.22	.21
062660	14.0	10.89	3.28	35.1	18.3	6.1	3.59	1.18	.56	.35
062760	19.0	8.75		31.4		6.1	1.40	.70		
062760	19.0	8.12		32.0		6.1	1.32	.65		
062860	19.0	10.25		36.0		5.6	1.71	.74		
062960	14.8	11.50		33.5		6.1	3.24	1.18		
062960	14.8	7.28		25.9		6.1	1.58	.74		
063060	11.0	11.10		27.4		6.1	4.63	1.52		
063060	10.6		.90		16.8	6.2			.25	.13

TABLE 8

PARAMETERS USED TO DETERMINE VALUES OF P AND N
FOR JULY 1960 AT OWS BRAVO

DATE	W (KNOTS)	Q_s (Kg cal/cm^2)	Q_{t}	MLD_s (METERS)	MLD_t	TS (^{o}C)	P_s x 10^4	N_s	P_t x 10^4	N_t
070160	14.0	11.26	1.78	55.8	27.3	6.1	5.90	1.22	.46	.19
070160	14.0	13.25	1.66	57.4	26.2	6.7	7.14	1.43	.41	.18
070260	14.0	13.09	2.04	61.2	24.6	6.5	7.52	1.42	.47	.22
070260	12.6	13.92	2.74	63.4	34.4	6.7	10.23	1.67	1.09	.33
070360	12.2	13.64	2.54	67.8	38.3	6.3	11.43	1.69	1.20	.32
070360	13.2	10.13	3.53	57.4	31.7	6.7	6.14	1.16	1.18	.40
070460	13.2	13.75	2.80	68.4	31.7	7.2	10.81	1.72	1.02	.35
070460	13.2	15.05	3.05	65.6	32.8	7.2	11.35	1.88	1.15	.38
070560	12.4	14.88	.68	60.1	16.4	7.5	11.65	1.98	.15	.09
070560	12.4	14.77	4.05	71.1	27.3	6.9	12.57	1.80	1.32	.49
070660	14.4	14.72	3.77	73.8	35.5	6.7	9.64	1.55	1.19	.40
070660	18.2	13.24	4.66	79.3	30.1	7.1	6.35	1.20	.85	.42
070760	18.2	13.22	2.40	71.1	24.6	7.5	5.68	1.20	.36	.22
070760	18.2	15.72	3.34	65.6	27.3	7.6	6.49	1.48	.57	.31
070860	17.0	12.10	3.88	60.1	30.1	7.0	4.63	1.17	.74	.38
070860	12.6	10.35	2.80	54.7	27.3	7.2	7.14	1.35	.96	.37
070960	13.8	13.96	2.86	73.8	26.2	7.2	10.84	1.67	.79	.34
070960	13.8	15.74	3.92	76.6	30.6	7.2	12.68	1.88	1.26	.47
071060	13.8	12.47	3.81	65.6	23.0	7.2	8.60	1.49	.92	.45
071060	13.8	11.01	2.14	61.2	12.0	7.2	7.09	1.31	.27	.26
071160	13.8	15.56	1.74	79.3	16.4	7.9	13.50	1.93	.31	.22
071160	14.4	13.71	4.17	65.6	27.3	8.3	9.42	1.70	1.19	.52
071260	14.8	16.58	5.41	82.0	33.9	7.8	12.94	1.92	1.07	.63
071260	14.8		3.14		20.8	8.6			.67	.39
071360	14.8	16.44	2.44	76.6	23.5	8.1	12.49	1.99	.57	.29
071360	14.4	15.75	5.58	67.3	26.2	7.7	10.65	1.88	1.47	.66
071460	13.4	14.60	2.97	75.5	21.9	8.3	13.34	1.95	.79	.40
071460	13.4	15.29	5.00	67.8	25.7	8.0	12.03	1.96	1.49	.64
071560	13.4	15.52	5.52	71.1	27.9	8.1	13.35	2.07	1.86	.74
071560	13.0	16.43	5.08	67.3	27.3	8.3	14.22	2.26	1.78	.70
071660	12.0	14.13	4.90	82.0	24.6	8.3	17.48	2.10	1.82	.73
071660	12.0	19.45	6.63	87.5	32.8	8.3	25.68	2.90	3.28	.99
071760	14.6	16.45	6.22	65.6	37.2	8.3	11.00	2.01	2.36	.76
071760	22.8	13.14	4.62	60.1	35.5	8.3	3.30	1.03	.69	.36
071860	22.8	12.41	3.66	59.1	32.8	8.1	3.07	.97	.50	.29
071860	22.8	14.66	6.30	71.1	36.1	8.5	4.36	1.15	.95	.49
071960	20.0	17.57	7.52	76.6	44.8	8.3	7.31	1.57	1.83	.67
071960	20.2	15.14	6.32	62.9	37.7	8.2	5.07	1.34	1.27	.56
072060	22.0		5.40		36.1	7.5		.81	.40	
072060	22.0	18.88	6.68	68.4	45.9	7.8	5.56	1.47	1.32	.52
072160	17.4		2.37		19.7	7.8			.32	.23
072160	17.4	17.04	8.86	68.4	44.8	7.7	8.02	1.68	2.73	.87

TABLE 8 (Cont'd)

DATE	W	Q_s	Q_t	MLD_s	MLD_t	TS	P_s	N_s	P_t	N_t
	(KNOTS)	(Kg cal/cm^2)		(METERS)		(°C)	x 104		x 104	
072260	15.2	17.80		71.1		8.1	11.90	2.09		
072260	13.2	14.00		54.7		8.0	9.16	1.81		
072360	13.2	16.30		71.1		8.3	14.45	2.21		
072460	12.6	15.08	7.63	73.8	38.3	7.8	14.61	2.05	3.83	1.04
072460	13.6	14.20	6.55	61.2	35.5	8.6	10.56	1.93	2.82	.89
072560	13.6	17.86	7.81	71.1	42.1	8.2	14.92	2.35	3.86	1.03
072560	13.6	15.45	7.87	71.1	38.3	8.2	12.91	2.03	3.54	1.03
072660	10.0		.61		13.7	7.8			.17	.10
072660	7.0	18.27	7.42	73.8	49.2	8.5	59.70	4.66	16.13	1.89
072760	9.0		3.40		27.3	8.1			2.49	.68
072860	10.2		8.06		33.9	8.4			5.71	1.41
072860	11.0	17.85	6.73	68.4	32.8	8.7	22.67	3.00	4.10	1.13
072960	10.6	19.29	6.76	75.5	30.1	9.2	30.27	3.50	4.23	1.23
073060	10.6		2.52		19.1	9.1			1.00	.46
073060	10.4	22.12	6.14	76.6	31.7	9.4	36.59	4.09	4.20	1.13
073160	10.4		3.90		21.9	9.0			1.77	.69
073160	10.0	21.31	3.31	76.6	20.8	8.0	36.38	3.94	1.55	.61

TABLE 9

PARAMETERS USED TO DETERMINE VALUES OF P AND N FOR AUGUST 1960 AT OWS BRAVO

DATE	W (KNOTS)	Q_s (Kg cal/cm^2)	Q_t	MLD_s (METERS)	MLD_t	TS (°C)	P_s x 10^4	N_s	P_t x 10^4	N_t
080160	8.8	6.80		15.2		8.9	3.00	1.43		
080160	11.8	9.06		18.3		9.3	2.78	1.47		
080260	14.0	4.67		15.2		8.9	.81	.62		
080260	13.6	8.40		21.3		9.2	2.26	1.19		
080460	17.0	9.46		22.9		9.2	1.75	1.07		
080560	17.0	15.85		30.5		9.3	3.91	1.79		
080560	15.0	10.25		24.4		8.9	2.50	1.27		
080660	12.0	6.22		18.3		9.2	1.85	1.00		
080660	12.0	13.51		30.5		10.1	6.89	2.23		
080760	10.0	14.42	1.45	29.0	9.1	9.4	9.77	2.77	.31	.28
080760	12.5	13.72		25.9		9.5	5.31	2.11		
080860	15.2	22.96	3.96	44.2	12.2	9.7	10.56	2.99	.50	.52
080860	15.2	10.02		24.4		11.1	2.78	1.43		
080960	15.2	14.92		29.0		10.4	4.65	2.00		
081060	15.2	10.50		25.9		11.1	3.10	1.49		
081060	20.2	13.02		24.4		11.1	2.05	1.39		
081160	20.2	8.66		18.3		11.1	1.02	.93		
081160	16.0	12.33		21.3		11.4	2.70	1.67		
081260	14.0	8.14		15.2		11.7	1.70	1.29		
081260	12.0	10.82		18.3		11.8	3.70	2.00		
081360	12.0	8.15		15.8		11.9	2.41	1.50		
081360	12.0	12.30		19.8		11.7	4.55	2.27		
081460	15.6	13.06	.28	22.9	3.0	11.7	3.31	1.85	.01	.04
081460	15.6	11.66		21.3		11.6	2.75	1.65		
081560	15.6	15.20		29.0		11.1	4.77	2.11		
081560	15.6	14.64		27.1		11.6	4.39	2.08		
081660	15.2	16.50		30.5		11.7	5.86	3.40		
081660	13.8	20.37	6.55	38.4	18.3	11.7	11.05	3.27	1.69	1.05
081760	13.8	9.62		21.3		11.7	2.89	1.54		
081760	13.0	13.06		25.0		11.7	5.22	2.22		
081860	14.2	12.50		24.4		11.6	4.07	1.95		
081960	25.8	20.58		29.0		11.1	2.36	1.73		
081960	25.8	19.05		27.4		10.7	2.02	1.56		
082060	25.0	10.52	.25	23.5	9.1	11.4	1.04	.91	.01	.02
082060	20.0	12.90	.17	32.6	3.1	11.1	2.77	1.40	.01	.02
082160	13.4	21.30		39.6		11.1	12.36	3.44		
082160	10.4	12.00		18.3		11.1	5.34	2.50		
082260	14.8	17.30		26.8		11.1	5.57	2.53		
082360	14.8	15.28		21.3		11.7	4.00	2.28		
082460	15.2	15.25		25.0		11.7	4.44	2.22		
082460	15.2	15.52		25.6		11.7	4.63	2.26		
082560	15.2	9.33		18.3		11.7	1.99	1.36		
082560	11.8	12.62	.20	20.7	3.7	11.3	4.94	2.31	.02	.04

TABLE 9 (Cont'd)

DATE	W (KNOTS)	Q_s (Kg cal/cm^2)	Q_t	MLD_s (METERS)	MLD_t	TS (°C)	P_s x 104	N_s	P_t x 104	N_t
082660	11.8	19.60		36.6		11.7	13.86	3.68		
082660	11.8	22.62	.90	39.6	9.1	11.4	16.93	4.15	.15	.16
082760	11.8	21.70		37.8		11.7	15.85	4.07		
082760	9.8	16.88	.67	30.5	10.7	11.7	14.42	3.81	.20	.15
082860	9.8	19.62		33.5		11.9	18.41	4.43		
082860	9.8	18.78		32.0		12.1	17.20	4.33		
082960	9.4	19.07	1.00	32.0	11.3	12.2	19.00	4.59	.35	.24
082960	8.8	13.82		25.0		11.2	11.74	3.40		
083060	10.6	15.00	1.22	27.4	15.8	10.6	9.41	2.99	.44	.24
083060	16.0	16.90		22.9		10.6	3.89	2.23		
083160	19.4	17.15		27.4		10.4	3.10	1.81		
083160	19.4	16.00		26.5		10.1	2.80	1.68		

TABLE 10

PARAMETERS USED TO DETERMINE VALUES OF P AND N FOR SEPT. 01-09, 1960 AT OWS BRAVO

DATE	W (KNOTS)	Q_s (Kg cal/cm^2)	Q_t	MLD_s (METERS)	MLD_t	TS (°C)	P_s x 10^4	N_s	P_t x 10^4	N_t
090160	19.8	15.78		24.4		10.4	2.44	1.63		
090160	19.8	14.90		23.8		10.3	2.25	1.54		
090260	19.8	18.15		29.0		10.3	3.33	1.87		
090360	25.2	14.15		21.3		10.0	1.14	1.11		
090360	25.2	11.40		21.9		10.3	.98	.92		
090460	25.2	17.00		25.6		10.2	1.70	1.38		
090460	25.0	13.62		22.3		10.4	1.21	1.11		
090560	21.0	14.22		21.3		10.6	1.77	1.43		
090560	21.0	12.22		20.4		10.7	1.45	1.23		
090660	21.0	13.31		21.9		10.6	1.70	1.34		
090660	13.6	13.62		20.1		10.6	3.81	2.12		
090760	12.6	10.02		17.7		10.6	2.87	1.68		
090760	13.0	15.10		21.3		10.6	4.89	2.46		
090860	16.6	19.19	2.49	34.7	11.6	10.6	6.22	2.45	.27	.32
090860	19.2	24.26	11.38	42.7	21.3	10.6	7.23	2.67	1.69	1.25
091060	20.0	11.42		21.3		10.6	1.56	1.21		
091060	20.0	15.05		22.3		10.6	2.17	1.60		

TABLE 11

PARAMETERS USED TO DETERMINE VALUES OF P AND N FOR SEPT. 19-30, 1960 AT OWS BRAVO

091960	20.0	18.55		55.5		7.1	5.16	1.53		
092060	18.0	20.00		54.9		6.7	6.24	1.68		
092060	20.0	22.71	5.76	62.5	30.5	7.3	7.11	1.87	.88	.47
092160	27.0		7.70		30.5	7.1			.65	.47
092160	27.0	23.63	7.12	82.3	36.6	7.2	5.34	1.44	.72	.43
092260	27.0	10.23	2.71	42.7	24.4	6.8	1.10	.57	.17	.15
092260	27.0	11.55		39.6		7.1	1.26	.70		
092360	22.8	13.84	2.00	52.7	21.3	7.8	2.92	1.04	.17	.15
092360	15.0	19.31		56.4		7.3	9.69	2.12		
092460	19.8	20.22	2.64	61.0	18.3	7.1	6.30	1.68	.25	.22
092460	25.0	19.20		54.3		6.7	3.07	1.16		
092560	25.0	18.80		47.2		6.7	2.61	1.14		
092560	25.0	18.70		61.0		7.2	3.66	1.23		
092660	28.4	10.15		36.6		7.5	.92	.59		
092660	28.4	16.20		54.3		6.7	2.01	.86		
092760	30.0	16.10		58.5		6.6	1.93	.81		
092760	30.0	20.40		54.3		6.1	2.27	1.03		
092860	22.8	18.70		63.4		6.3	4.20	1.24		
092860	20.0	17.70		64.6		6.1	5.26	1.34		
092960	20.0	18.62		59.4		6.7	5.09	1.41		
092960	15.8	19.21		57.9		6.1	8.20	1.84		
093060	21.2	16.42		62.5		6.7	4.20	1.17		
093060	22.8	20.47		57.3		6.5	4.14	1.35		

TABLE 12

PARAMETERS USED TO DETERMINE VALUES OF P AND N
FOR OCTOBER 1960 AT OWS BRAVO

DATE	W (KNOTS)	Qs (Kg cal/cm^2)	Qt (Kg cal/cm^2)	MLD_s (METERS)	MLD_t (METERS)	TS (°C)	P_s x 10^4	N_s	P_t x 10^4	N_t
100260	25.5	19.75		56.4		6.1	3.15	1.17		
100360	27.0	19.05		58.8		6.0	2.83	1.07		
100460	25.0	18.62		55.5		5.8	2.76	1.02		
100460	25.0	18.80		55.5		6.7	3.07	1.14		
100560	20.0	20.40		54.3		5.9	4.63	1.40		
100560	16.8	17.78		59.4		6.1	6.89	1.60		
100660	18.2	15.25		51.2		6.3	4.34	1.27		
100660	19.6	17.55		59.4		6.0	5.08	1.38		
100760	19.6	19.95		62.5		6.1	5.97	1.54		
100760	19.6	15.32		47.2		5.6	3.14	1.07		
100860	25.0	18.45		59.4		5.0	2.93	1.01		
100860	25.0	17.72		57.9		5.8	2.74	.97		
100960	23.0	11.20		42.7		5.8	1.51	.67		
100960	20.0	15.71		50.9		6.1	3.68	1.19		
101060	17.0	15.31		46.6		6.0	4.54	1.36		
101160	20.0	10.38		39.6		5.7	1.72	.71		
101260	20.0	10.52		41.1		5.4	1.81	.72		
101360	20.0	15.80		48.8		6.0	3.55	1.20		
101460	22.0	15.55		47.9		5.9	2.57	.97		
101560	25.0	15.95		60.0		6.1	2.82	.97		
101660	25.0	17.95		58.8		5.8	2.82	.99		
101660	25.0	16.50		64.6		6.0	3.14	1.00		
101760	17.0	18.10		62.5		5.8	6.54	1.46		
101760	17.0	13.26		51.8		6.1	4.37	1.18		
101860	17.0	16.62		62.5		5.6	6.00	1.34		
101960	12.0	17.84		62.5		5.8	12.93	2.04		
102060	20.2	14.71		54.3		6.1	3.60	1.10		
102160	20.2	17.35		64.0		6.1	5.01	1.30		
102260	20.2	17.24		58.5		4.7	4.13	1.17		
102360	18.0	17.65		59.4		6.1	5.96	1.48		
102460	1.80	16.60		56.4		5.8	5.38	1.33		
102460	17.0	16.95		56.4		5.9	5.53	1.37		
102560	13.0	17.30		61.0		5.7	10.43	1.83		
102660	20.0	18.52		67.1		6.1	5.72	1.40		
102860	25.0	15.62		59.7		6.1	2.75	.95		
102960	22.0	14.40		67.1		6.1	3.67	.99		
103060	22.0	14.57		62.8		6.1	3.48	1.00		
103160	27.0	16.10		64.6		6.1	2.63	.90		

5. The form of the function P(N).

A least squares computer program was used to determine the polynomial of degree K which best fits (in the least squares sense) M data points. The best fit among those polynomials tested (through third order) was for K = 2 for each of three groups of points representing about one-fourth of all paired values of P and N. The coefficients of the polynomial were then computed for each month and tabulated in table 13, P(N) having the form below,

$$P(N) = a_2 N^2 + a_1 N + a_0 \tag{8}$$

The corresponding forecasting equation is

$$MLD = a_2 \beta Q + a_1 \frac{W}{\Omega} + a_0 \frac{W^2}{Q\beta\Omega^2} \tag{9}$$

McDonnell's criteria for acceptable data limited the number of his paired values to only 22 pairs for transitional MLD's and 29 pairs for seasonal MLD's. These data, as a result, were from various months of the warming season during the years 1958 through 1962. Because of the small number of paired values and the grouping of the seasonal and transitional paired values, only a linear regression separately done for the two categories was justified. These are equations (4) and (6) of McDonnell; they do not necessarily represent the most likely form of the function P(N).

The present author used both seasonal and transitional paired values together to obtain a single form for P(N). This was then incorporated into McDonnell's basic equation (1) and used to forecast both seasonal and transitional MLD's. Graph No. 1 represents the form of P(N) using

TABLE 13

COEFFICIENTS FOR EACH MONTH USED IN THE FORECASTING EQUATION

	$a_2 \times 10^{-4}$	a_1	$a_0 \times 10^{4}$
OWS November			
June	.721	.500	.094
July	1.117	.401	-.089
Aug.	.606	.726	.081
Sept.	.582	.928	-.030
Oct.	1.142	-2.890	4.235
OWS Bravo			
June	1.38	1.63	-.03
July	1.93	2.59	-.47
Aug.	.87	.36	.09
Sept. (1-10)	1.11	-.59	.48
Sept. (19-30)	1.66	1.13	-.12
Oct.	4.74	-4.83	2.95
OWS November (June through September)			
	.543	1.289	-.228
OWS Bravo (June through September)			
	.996	1.815	.023

a second-order polynomial as the best fit for the paired values determined by McDonnell at OWS Papa.

Graphs No. 2 through 12 are the curves of the function P(N) as determined for each month. All paired values are plotted on each scatter diagram.[1]

The scatter of the paired values is relatively small for most months indicating that McDonnell's model may well contain the correct combination of parameters. Usually the paired values of P and N for transitional situations were found near the origin with little scatter. During low wind conditions, the computation of P is very sensitive to small errors in wind speed which accounts for much of the excess scatter at large P. Additional scatter probably results from random fluctuations not removed by the averaging procedures described in section 4.

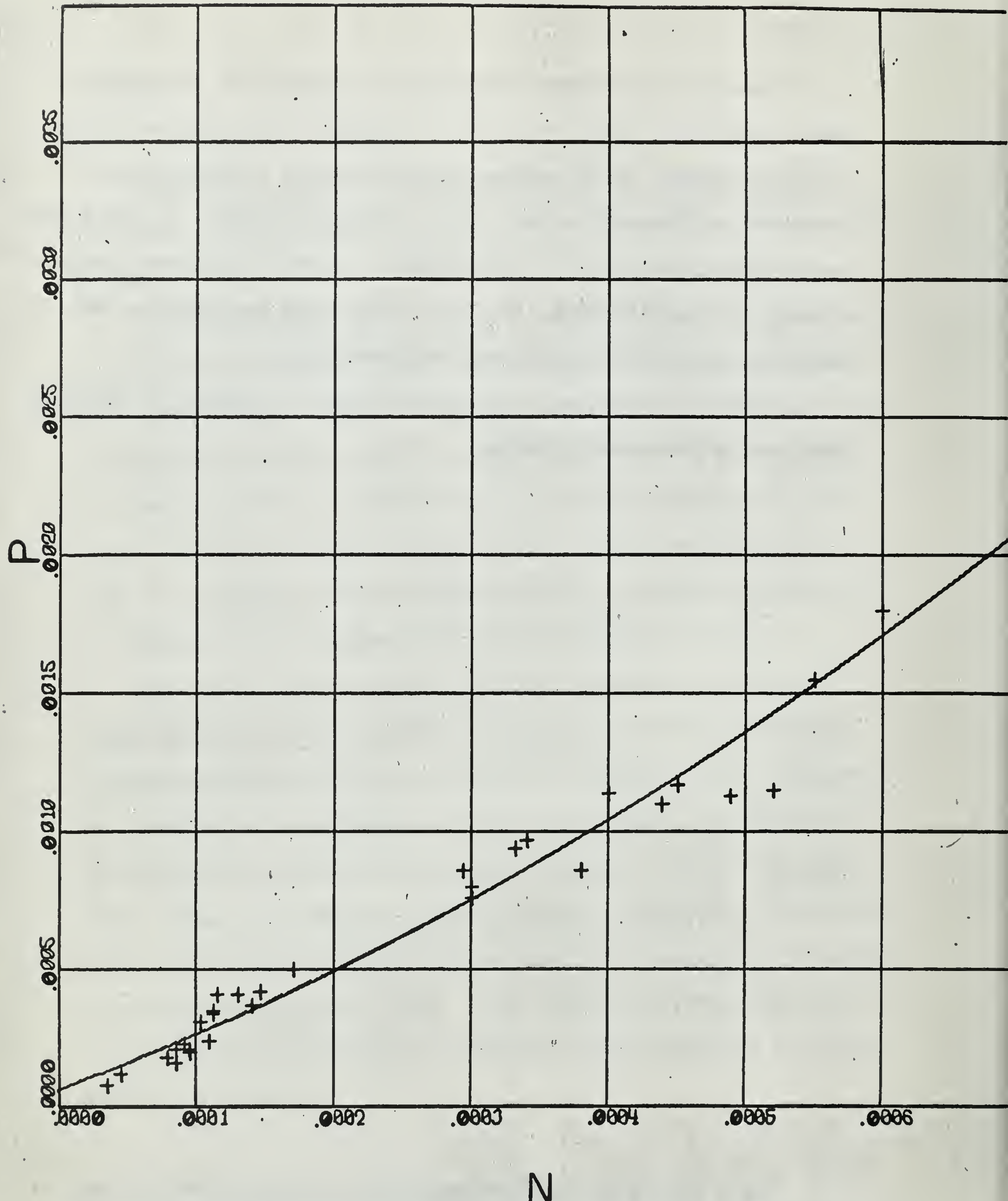
One can see that the monthly best fit curves have a variety of slopes apparently indicating the non-universality of P(N). However, systematic deviations due to contaminating influences (e.g. divergence), but included in the computation of the paired values, may account for the variations in slope of each monthly function. By analyzing incremental changes in P and N associated with small increases in Q and MLD, general conclusions concerning the influence of divergence and advection on the paired values can be made. This analysis indicates that reduction of the MLD by divergence or advection tends to diminish the slope dP/dN and vice versa.

[1](Graph No. 5 for September 1957 had 10 points which fell outside the scale. Graph No. 4 for August had one such point.)

Divergence of the Ekman transport was computed from the monthly Ekman transport at grid points in the vicinity of each location during the year studied. Meridional and zonal components of Ekman transport calculated by Fofonoff and Ross [1,2], were used for this. At OWS Bravo, maximum divergence was during August which has the least slope of any function for that OWS ship. The same correlations were noted at OWS November except that the divergence was negative.[1]

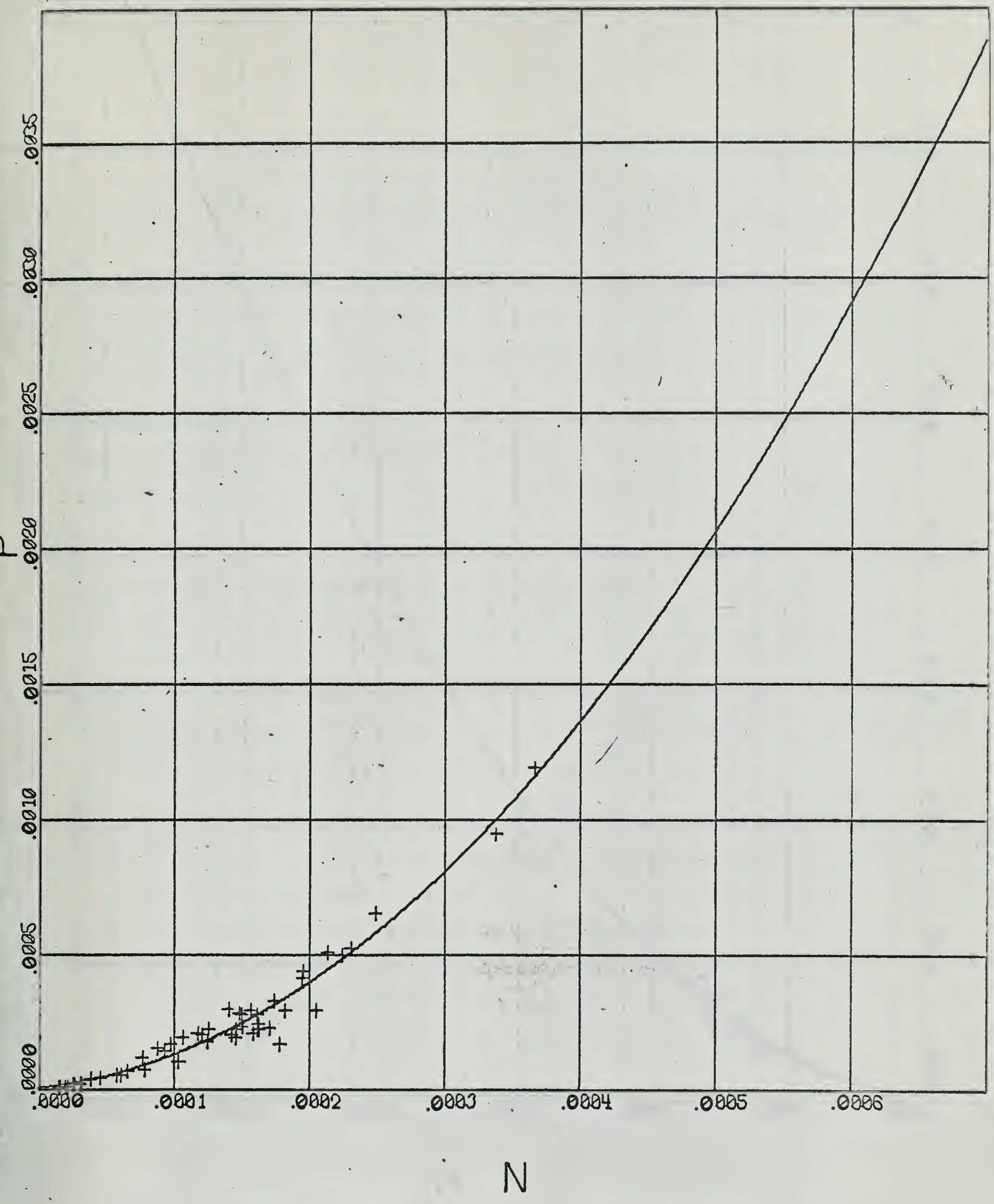
Systematic deviations in the paired values as a result of advection could not be evaluated as easily.

[1](July and August at OWS November were anamolous months in this respect.)



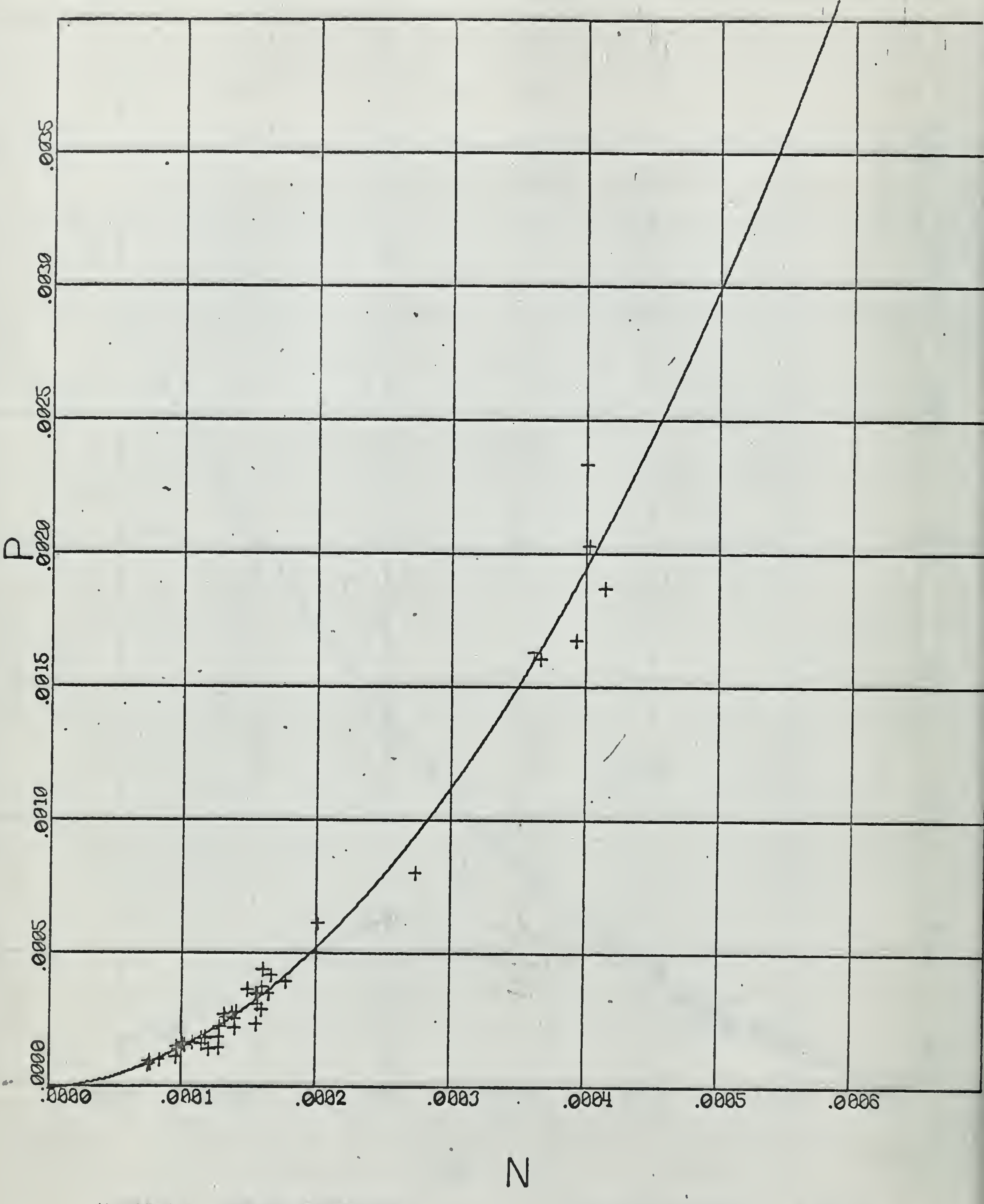
X-SCALE = 1.00E+00 UNITS/INCH.
Y-SCALE = 5.00E+00 UNITS/INCH.

LEAST SQUARES BEST FIT CURVE USING OWS PAPA
TRANSITIONAL AND SEASONAL DATA GRAPH NO 1

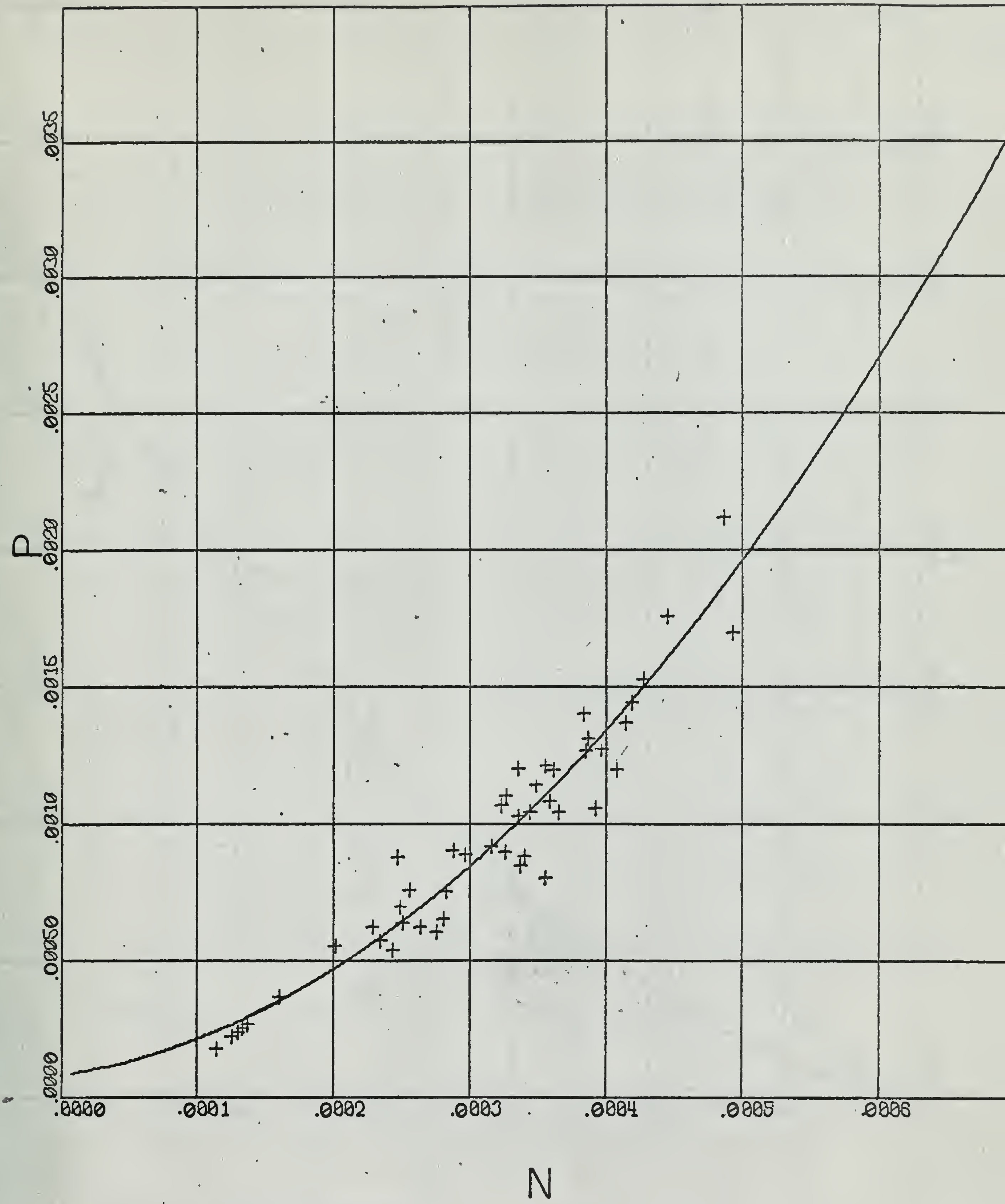


X-SCALE = 1.00E+00 UNITS/INCH.
Y-SCALE = 5.00E+00 UNITS/INCH.

LEAST SQUARES BEST FIT CURVE OWS NOVEMBER
30 00N 140 00W JUNE 1957 GRAPH NO 2

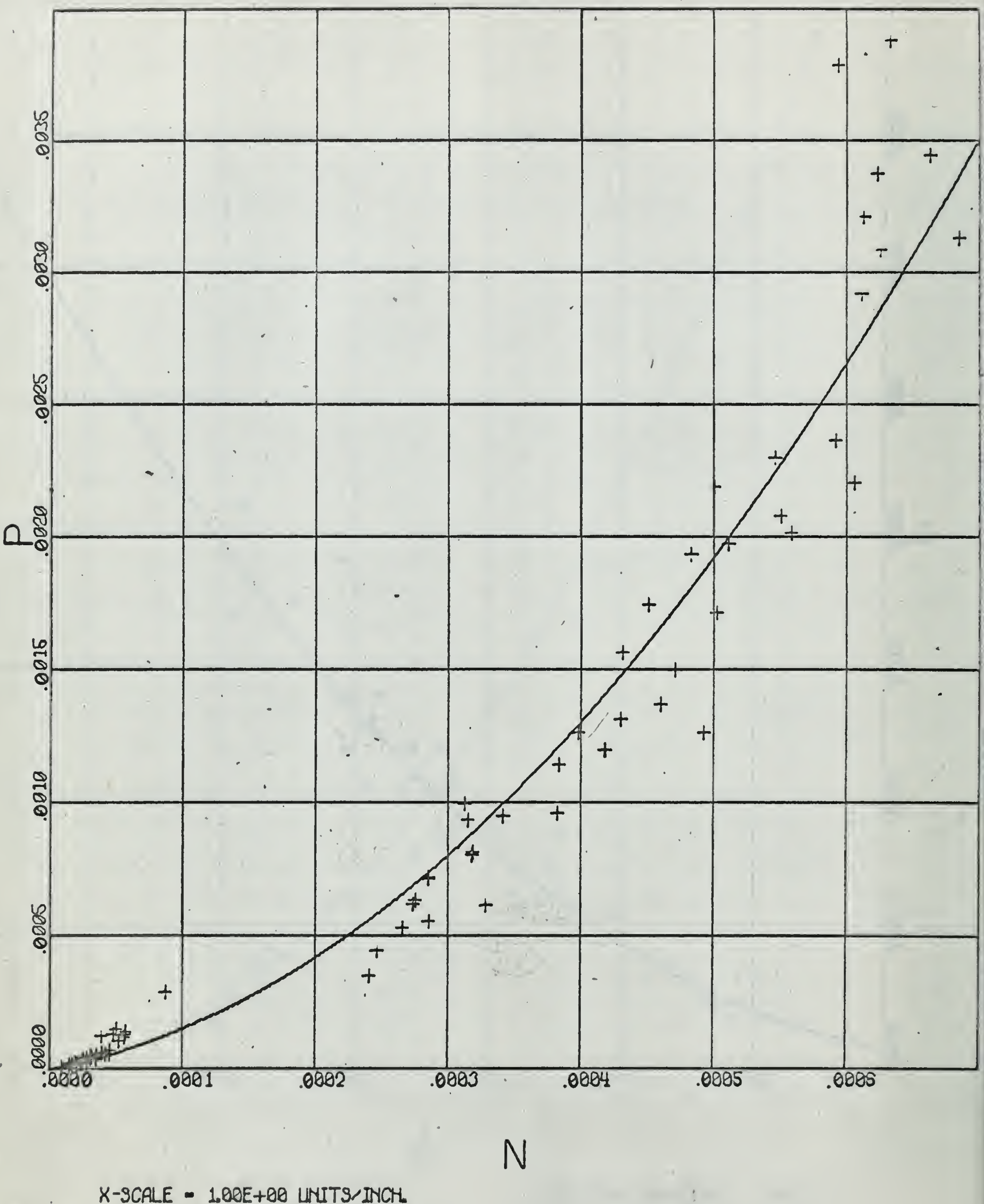


X-SCALE = 1.00E+00 UNITS/INCH.
Y-SCALE = 5.00E+00 UNITS/INCH.
LEAST SQUARES BEST FIT CURVE OWS NOVEMBER
30 00N 140 00W JULY 1957 GRAPH NO 3



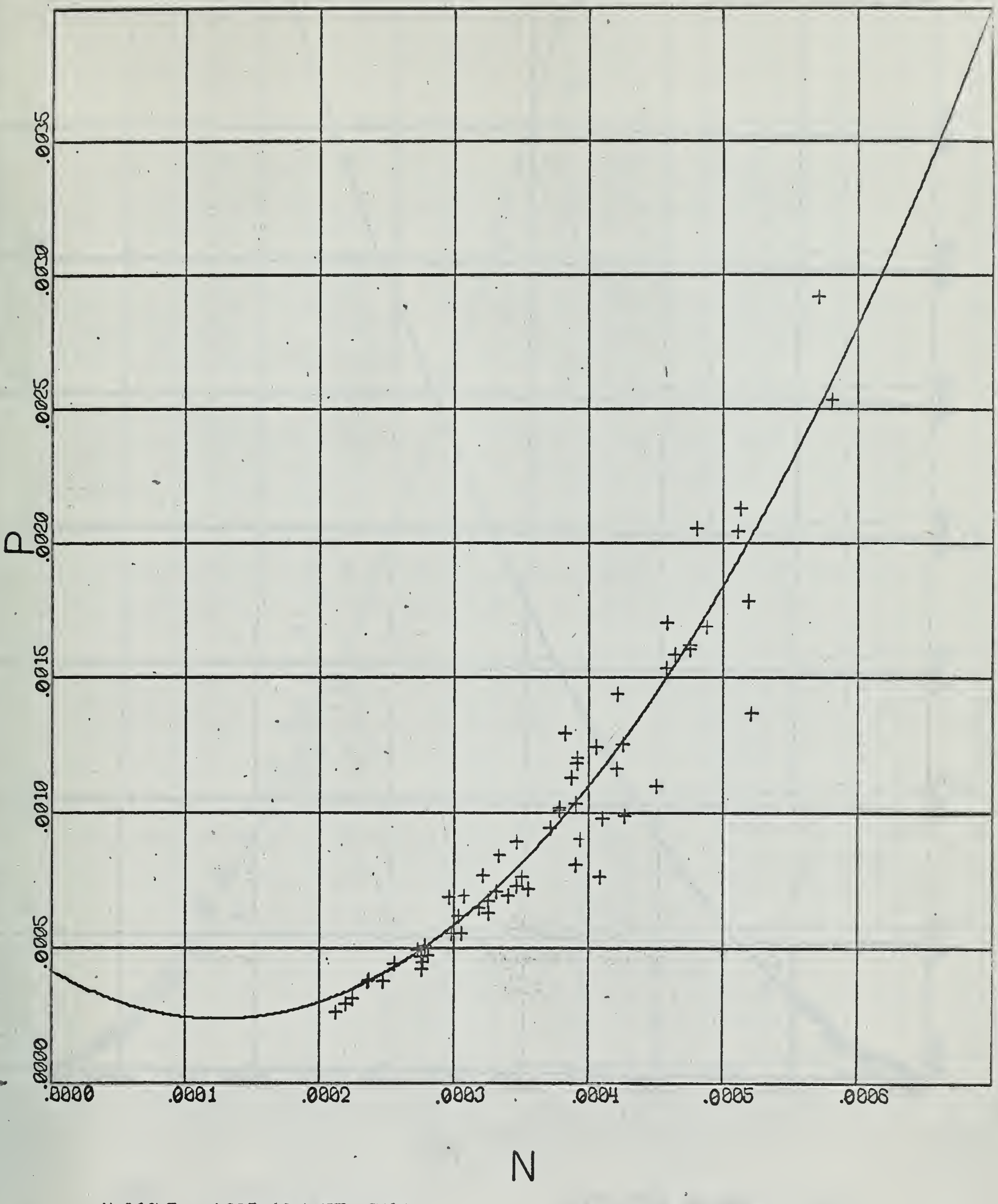
X-SCALE = 1.00E+00 UNITS/INCH.
Y-SCALE = 5.00E+00 UNITS/INCH.

LEAST SQUARES BEST FIT CURVE OWS NOVEMBER
30 00N 140 00W AUGUST 1957 GRAPH NO 4

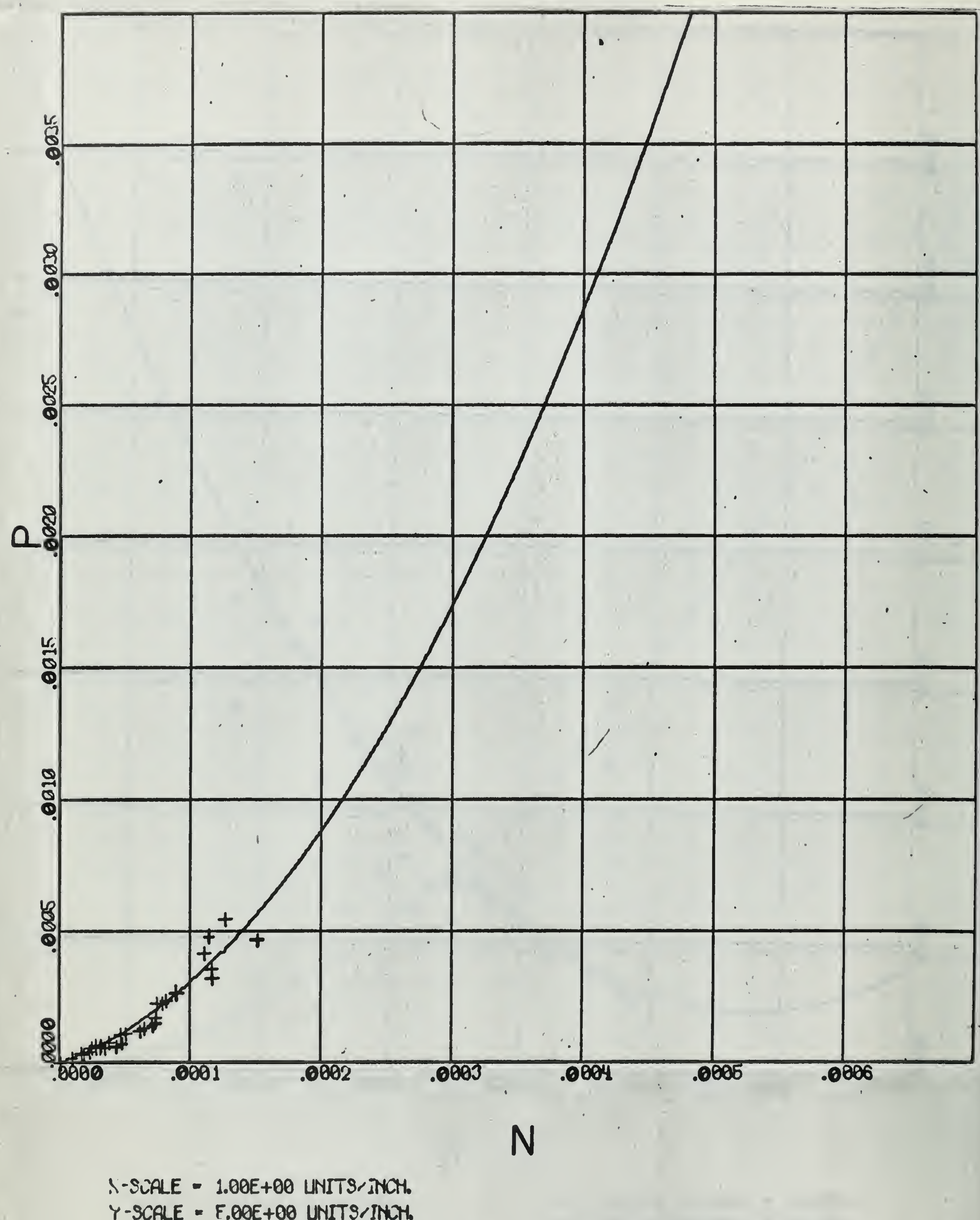


X-SCALE = 1.00E+00 UNITS/INCH.
Y-SCALE = 5.00E+00 UNITS/INCH.

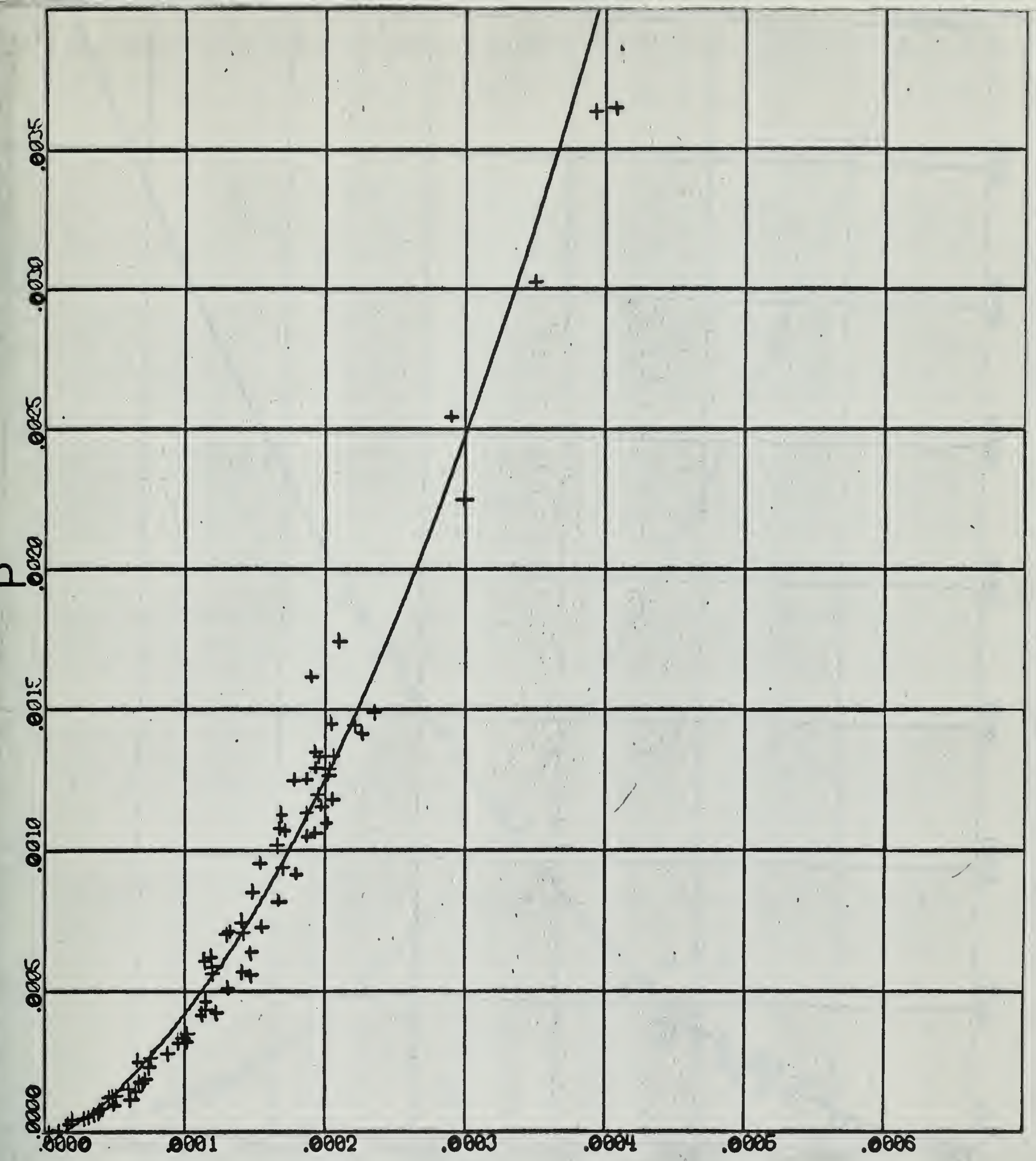
LEAST SQUARES BEST FIT CURVE OWS NOVEMBER
30 00N 140 00W SEPT. 1957 GRAPH NO 5



X-SCALE = 1.00E+00 UNITS/INCH.
Y-SCALE = 5.00E+00 UNITS/INCH.
LEAST SQUARES BEST FIT CURVE OWS NOVEMBER
30 00N 140 00W OCTOBER 1957 GRAPH NO 6



LEAST SQUARES BEST FIT CURVE FOR OWS BRAVO
56 30N 51 00W JUNE 1960 GRAPH NO 7



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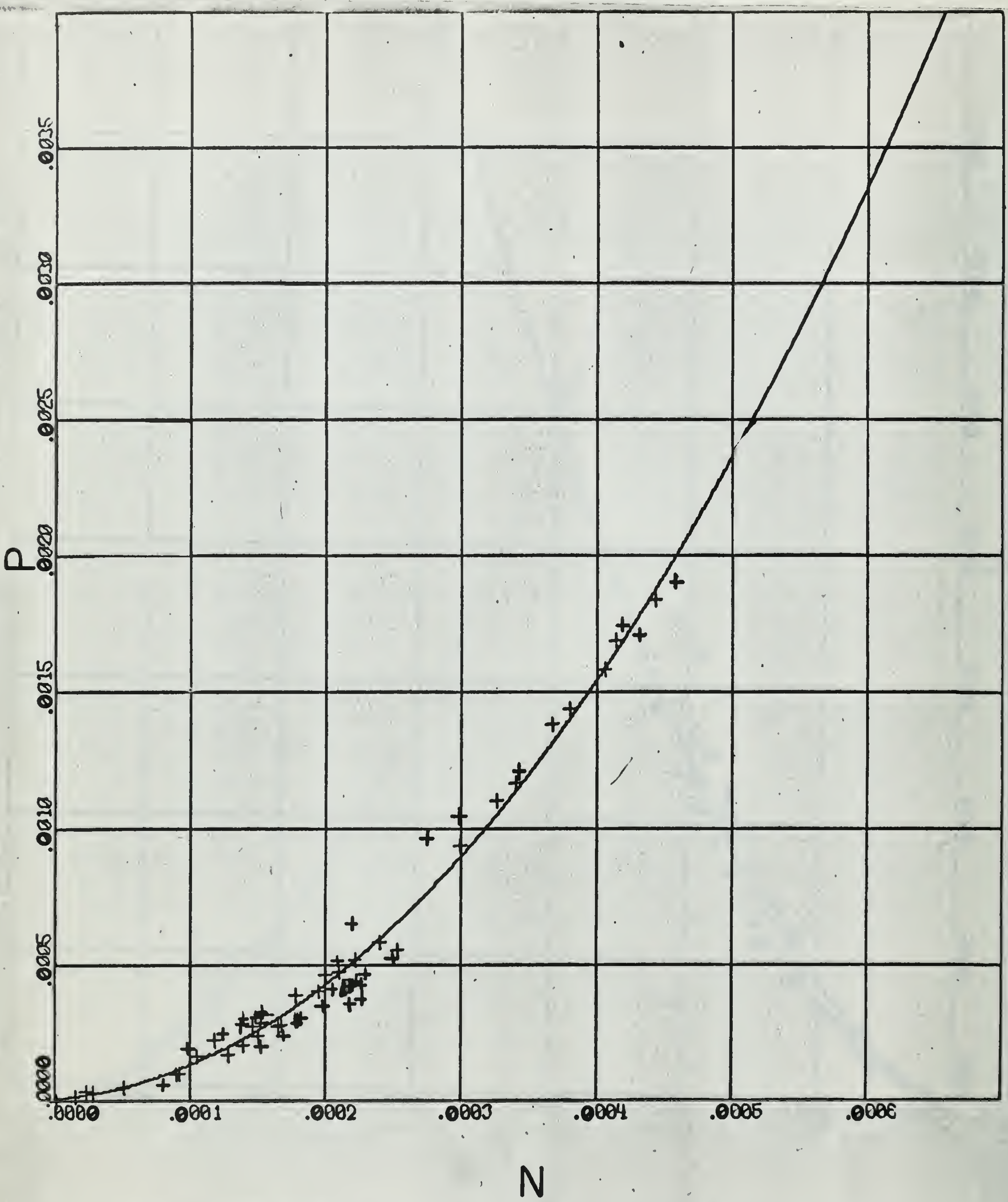
Y-SCALE = 5.00E+00 UNITS/INCH.

LEAST SQUARES BEST FIT CURVE FOR OWS BRAVO
56 30N 51 00W JULY 1960 GRAPH NO 8



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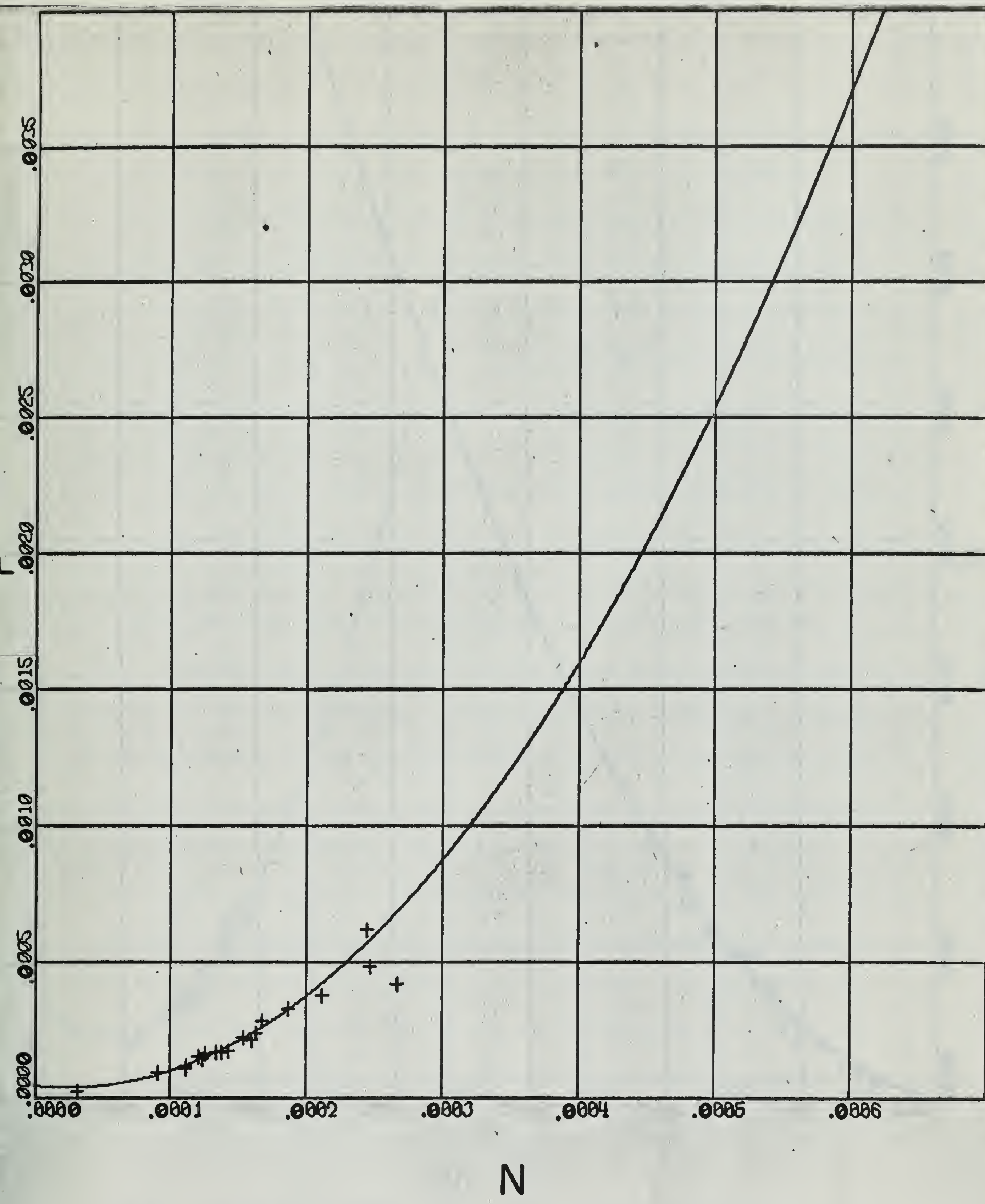
LEAST SQUARES BEST FIT CURVE FOR OWS BRAVO
56 30N 51 00W AUGUST 1960 GRAPH NO 9



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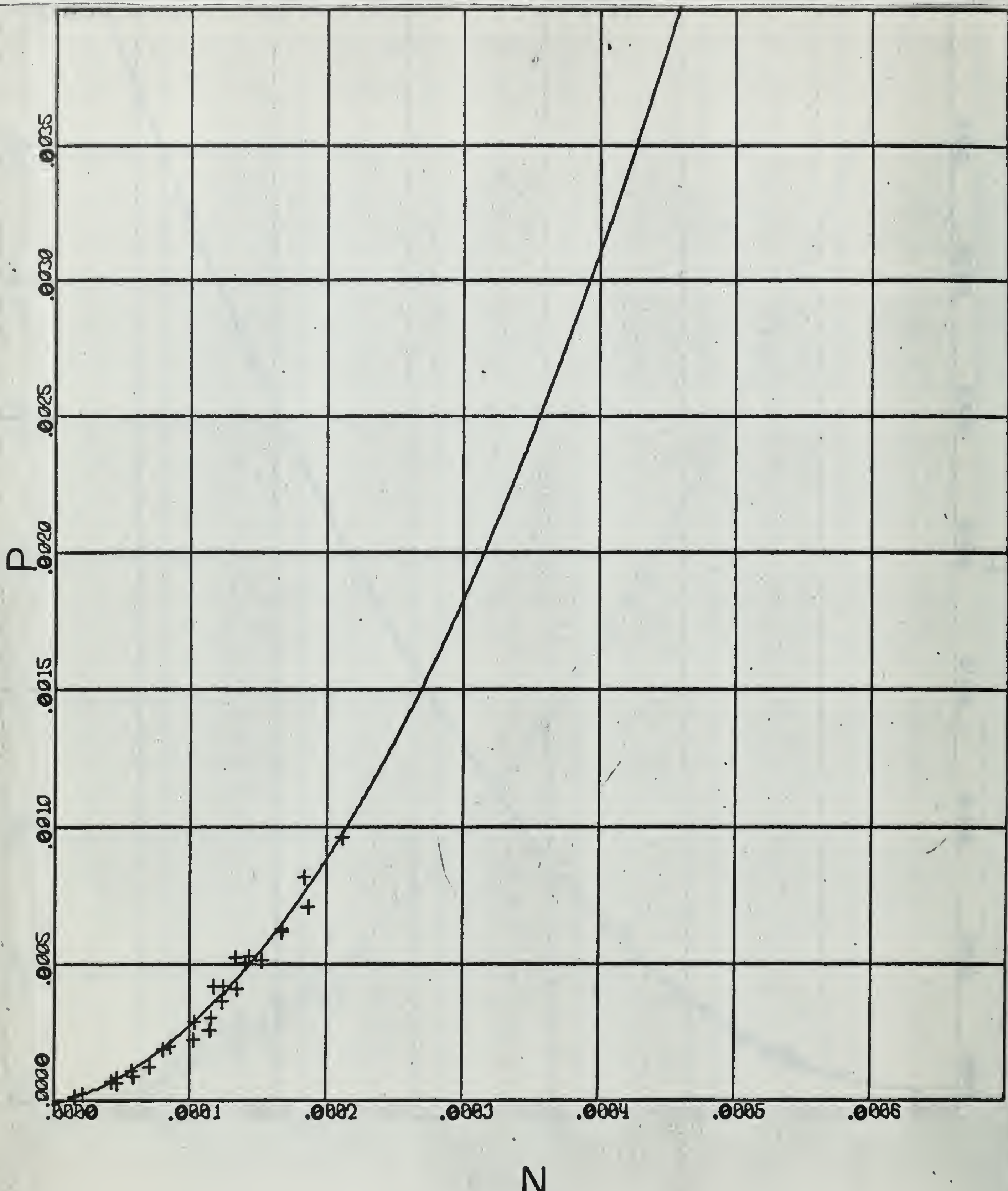
LEAST SQUARES BEST FIT CURVE FOR OWS BRAVO
01 THRU 09 SEPTEMBER 1960 GRAPH NO 10



X-SCALE = 1.00E+00 UNITS/INCH.
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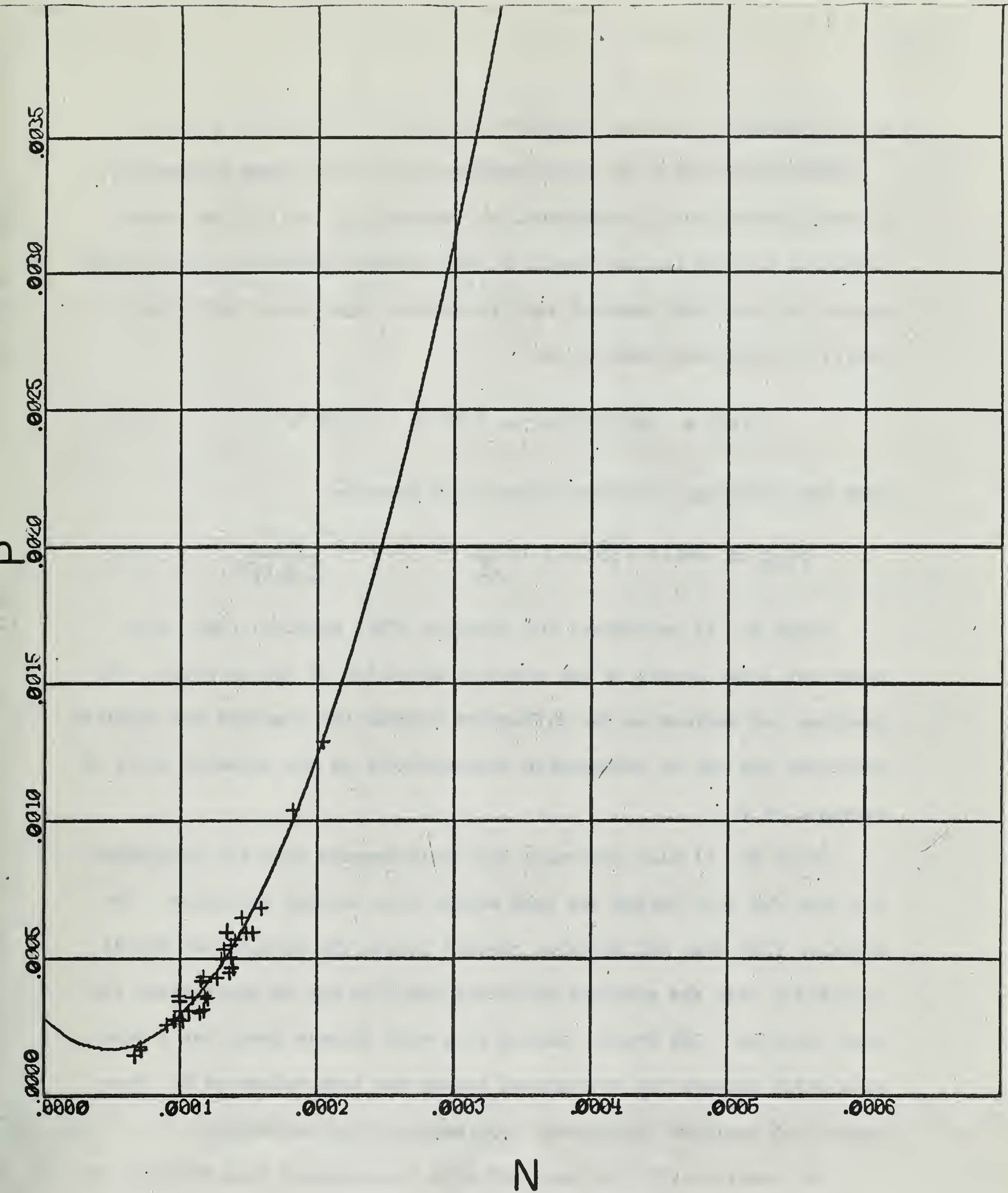
LEAST SQUARES BEST FIT CURVE FOR OWS BRAVO
19 THRU 30 SEPTEMBER 1960 GRAPH NO 11



LEAST SQUARES BEST FIT CURVE FOR OWS BRAVO
56 30N 51 00W OCTOBER 1960 GRAPH NO 12

6. A possible universal function.

The concept of a universal function P(N) as proposed originally by Kitaigorodsky was investigated by combining all of the 504 paired values of P and N for the months of June through September for both OWS ships. By the least squares best fit method, the second order polynomial for P(N) was found to be

$$P(N) = .422 \times 10^{4} N^{2} + 2.25\,N - .168 \times 10^{-4} \qquad (10)$$

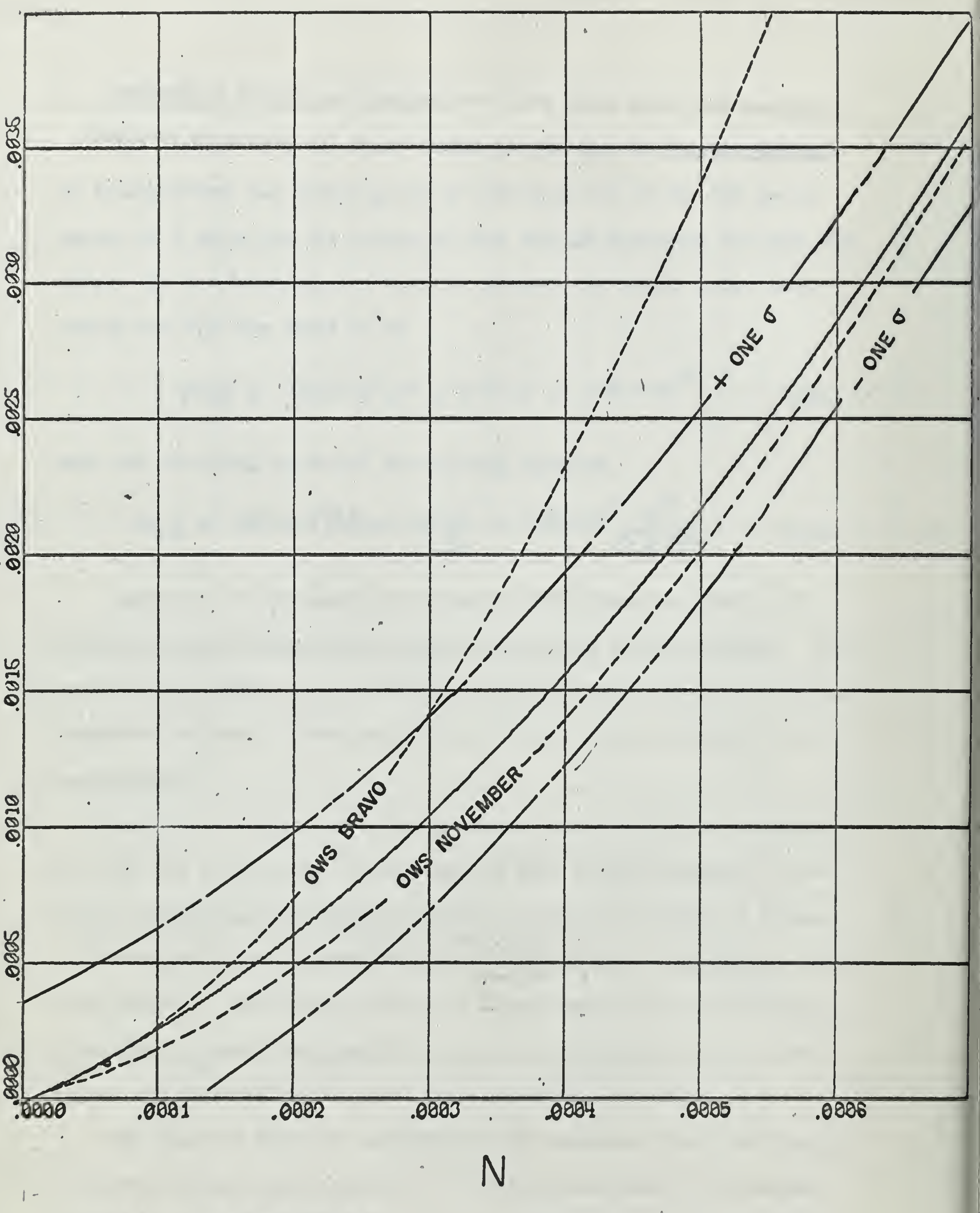
with the resulting universal forecasting equation,

$$MLD = .422 \times 10^{4} \beta Q + 2.25 \frac{W}{\Omega} - .168 \times 10^{-4} \frac{W^{2}}{Q \beta \Omega^{2}} \qquad (11)$$

Graph No. 13 represents the function P(N), equation (10), with upper and lower bounds of one standard deviation of the residues. The residues are defined as the difference between the computed and original ordinates and can be interpreted statistically as the standard error of estimate of P.

Graph No. 13 also indicates the least-squares best-fit polynomial for each OWS ship during the same months June through September. The function P(N) from OWS November remains inside the statistical bounds indicating that the proposed universal function may be appropriate for that location. OWS Bravo, located in a more dynamic area, has a function which exceeds the statistical bounds for high values of N. Processes not included in the model may explain this deviation.

The function P(N) for each OWS ship is estimated from the data of only one warming season and may well be unrepresentative. Investigation of other years may reveal a closer correlation between different locations and times which would strengthen the idea of a universal function as well as improve the estimates of the constants involved.



X-SCALE = 1.00E+00 UNITS/INCH.
Y-SCALE = 2.00E+00 UNITS/INCH.

LEAST SQUARES BEST FIT CURVE JUNE THRU SEPT
OWS NOV 1957 AND OWS BRAVO 1960 GRAPH NO. 13

7. Procedure for forecasting and testing.

Equation (9) can be used to forecast MLD's over any length of time for which the parameters can be accurately predicted. Data such as were used to determine the coefficients in (9) were available for the following years at both OWS ships. A continuous day-to-day forecast was used to test the appropriate monthly coefficients for equation (9).[1] In essence the forecast was a test of whether the curves P(N) for a given year and month were useful in predicting MLD's for the same month in some other year.

All BT's available for the preceding 24-hour period were used to calculate a mean observed MLD.[2] The parameters β , Q, and W were computed by the same methods used in determining the paired values P and N. Using the parameters β , Q, and W in the forecasting equation (9), with the proper coefficients for the month and location under study, a daily MLD was computed and compared to the 24-hour mean observed MLD. This process was continued day by day from the available data with the results listed in tables 14 through 22. A total of 169 forecasts were made, 20 representing MLD_t and 149 representing MLD_s.

Although forecasts for periods greater than 24 hours were not attempted, equation (9) is assumed to possess this utility. In an extended forecast, a mean value representing the heat flux across the air-sea

[1](Only a small number of observations was available for June and July 1958 at OWS November. August data for the same location were missing.)

[2](For comparison with the computed daily MLD, a 24-hour interval was necessary to provide additional BT data for averaging out non-periodic influences.)

interface per day could be applied to modify the parameter Q for heat accretion during the forecast interval. Monthly climatological data (Kimball [3])are available for certain oceanic areas that list the average net heat flux per day. More important, however, is an accurate wind prediction. Its importance can be seen by analyzing the terms with the coefficients a_2 and a_1 of equation (9) from table 13, and noting the expected changes in the parameters Q and W respectively. The average change in Q as a result of heat flux is at most about ten percent in a single day, based on approximately .4 Kg. cal/cm^2 per day influx at OWS November, while the change in W may range from 0 to 30 knots during the same interval. When considering forecast <u>changes</u> in the seasonal MLD, the term involving the coefficient a_2 then becomes negligible.

Therefore, daily increases in Q were not considered essential in forecasting seasonal MLD's. The fact that wind through mechanical mixing during the warming season is usually the dominant factor in forecasting changes of the seasonal MLD is clearly seen - assuming fluctuations created by internal waves have been averaged out.

The possible universal function derived from all paired values for June through September was not tested by forecasting.

TABLE 14

FORECAST OF MLD's FOR JUNE 1958 AT OWS NOVEMBER

DATE	W (KNOTS)	Q_s (Kg cal/cm^2)	Q_t	TS (^oC)	FORECAST MLD_s (METERS)	MLD_t	OBSERVED MLD_s (METERS)	MLD_t	FORECAST[1] $DIFF_s$ (METERS)	$DIFF_t$
062658	12.2	17.25		20.0	40.5		48.8		-8.3	
062758	16.8	14.58		20.0	39.6		39.6		.0	
062858	19.6	14.85		20.0	42.4		43.5		-1.1	
062958	20.8	16.25		20.0	45.1		45.9		- .8	
063058	20.2	17.30		20.0	47.2		46.6		.6	

Forecast seasonal MLD's within one standard deviation (3.1 meters) 80%

Forecast seasonal MLD's within two standard deviations (6.2 meters) 80%

TABLE 15

FORECAST OF MLD's FOR JULY 1958 AT OWS NOVEMBER

071058	18.6	9.26		20.0	38.9		32.0		6.9	
071158	18.6	6.64		20.0	32.5		30.3		2.3	
071258	14.2	9.20		20.0	35.4		38.7		-3.3	
071358	12.8	8.20		21.1	32.1		35.4		-3.3	
071458	10.6	9.60		21.3	35.1		37.2		-2.1	
071558	10.0	10.02		21.7	35.9		41.0		-5.1	

Forecast seasonal MLD's within one standard deviation (3.7 meters) 67%

Forecast seasonal MLD's within two standard deviations (7.2 meters) 100%

[1] (Negative values indicate forecast MLD's were too shallow)

TABLE 16

FORECAST OF MLD's FOR SEPTEMBER 1958 AT OWS NOVEMBER

DATE	W (KNOTS)	Q_s (Kg cal/cm^2)	Q_t	TS (^oC)	FORECAST MLD_s (METERS)	FORECAST MLD_t	OBSERVED MLD_s (METERS)	OBSERVED MLD_t	FORECAST $DIFF_s$ (METERS)	FORECAST $DIFF_t$
090158	23.8	12.60		23.3	4917		37.5		12.2	
090258	21.6	14.68		23.3	50.6		39.0		11.6	
090358	16.0	15.73		22.8	45.5		36.6		8.0	
090458	15.8	12.75		23.6	40.3		38.4		1.9	
090558	15.8	16.16		23.3	45.9		43.6		2.3	
090658	12.6	15.60		23.9	41.8		40.5		1.3	
090758	10.0	16.10		23.3	38.6		40.2		- 1.6	
090858	10.0	14.22		23.9	36.3		38.1		- 1.8	
090958	9.0	14.10	.65	23.9	34.8	10.0	36.6	9.1	- 1.8	.9
091058	8.0	14.44	.68	23.3	33.5	9.4	35.1	9.1	- 1.6	.3
091258	12.0	13.82		23.2	37.4		39.0		- 1.6	
091358	12.0	16.70		23.0	42.1		39.6		2.7	
091458	12.0	16.50		23.2	41.8		39.0		2.8	
091558	11.6	18.70		23.1	44.9		39.6		5.3	
091658	11.6	18.80		22.9	45.1		41.1		4.0	
091758	11.0	18.42		23.1	43.7		42.7		1.0	
091858	15.8	19.77		23.1	51.8		44.2		7.6	
091958	16.2	18.71		23.1	50.6		47.9		2.7	
092058	17.2	18.85		23.1	52.1		46.6		5.5	
092158	16.8	20.70		22.7	54.6		47.0		7.6	
092258	14.0	17.09		22.9	45.5		44.2		1.3	
092358	10.8	22.51		23.1	50.1		48.2		1.9	
092458	16.2	22.88		22.5	57.4		49.7		7.7	
092558	16.8	22.72		22.8	57.9		51.5		6.4	
092658	16.4	23.50		22.7	58.6		51.8		6.8	
092758	17.0	21.76		22.7	56.6		51.5		5.1	
092858	14.2	22.81		22.8	54.8		53.9		.9	
092958	10.6	24.19		22.7	52.5		51.5		1.0	
093058	10.0	24.00		22.7	51.5		54.9		- 3.4	

Forecast seasonal MLD's within one standard deviation (5.8 meters) 72%

Forecast seasonal MLD's within two standard deviations (11.6 meters) 97%

TABLE 17

FORECAST OF MLD's FOR OCTOBER 1958 AT OWS NOVEMBER

DATE	W (KNOTS)	Q_s (Kg cal/cm^2)	Q_t (Kg cal/cm^2)	TS (°C)	FORECAST MLD_s (METERS)	FORECAST MLD_t (METERS)	OBSERVED MLD_s (METERS)	OBSERVED MLD_t (METERS)	FORECAST $DIFF_s$ (METERS)	FORECAST $DIFF_t$ (METERS)
100158	9.8	20.27		22.7	39.1		48.8		- 9.7	
100258	11.6	21.85		22.6	41.0		47.9		- 6.9	
100358	9.5	21.90		22.7	43.7		48.8		- 4.1	
100458	8.4	20.38		22.9	41.3		47.2		- 5.9	
100558	7.6	23.90		22.9	52.7		54.9		- 2.2	
100658	6.0	20.85		22.9	47.4		51.8		- 4.4	
100758	6.0	24.15		23.3	57.2		54.9		2.3	
100858	7.0	27.82		23.2	65.6		60.7		4.1	
100958	10.4	22.40		23.3	46.6		54.9		- 8.3	
101058	11.8	26.35		23.2	52.0		57.0		- 5.0	
101158	11.0	25.65		23.1	51.3		54.9		- 3.6	
101258	6.0	25.45		22.9	61.1		57.9		3.2	
101358	6.0	25.00		23.1	59.2		56.4		2.8	
101458	6.0	28.52		22.9	70.4		65.5		4.9	
101558	7.2	23.05		22.8	51.1		53.3		- 2.2	
101658	9.4	25.00		22.6	52.2		57.0		- 4.8	
101758	16.8	27.55		22.7	50.2		57.9		- 7.7	
101858	19.6	28.45		22.8	51.3		60.4		- 9.1	
101958	15.2	25.10		22.7	45.8		54.9		- 9.1	
102058	15.2	27.60		22.6	51.2		57.9		- 6.7	
102158	15.2	27.12		22.9	50.3		57.3		- 7.0	
102258	12.0	27.95		22.5	53.8		61.0		- 7.2	
102458	16.0	25.93		22.2	45.7		59.7		-13.4	
102558	16.0	26.10		21.2	46.0		57.9		-11.9	
102658	15.2	26.10		22.1	46.3		54.9		- 8.6	
102758	15.2	28.60		21.9	51.8		64.0		-12.2	
102858	12.0	26.62		22.0	50.5		62.5		-12.0	
102958	16.8	28.40		21.9	50.3		61.0		-10.7	
103058	27.8	29.60		22.1	58.1		67.1		- 9.0	
103158	25.6	28.35		21.7	54.2		65.5		-11.3	

Forecast seasonal MLD's within one standard deviation (3.2 meters) 17%

Forecast seasonal MLD's within two standard deviations (6.4 meters) 43%

TABLE 18

FORECAST OF MLD's FOR JUNE 1961 AT OWS BRAVO

DATE	W (KNOTS)	Q_s ($Kg\ cal/cm^2$)	Q_t	TS (°C)	FORECAST MLD_s (METERS)	FORECAST MLD_t	OBSERVED MLD (METERS)	OBSERVED MLD_t	FORECAST $DIFF_s$ (METERS)	FORECAST $DIFF_t$
061961	26.0	6.35		6.1	44.1		36.6		7.5	
062061	23.0	3.79		6.7	35.2		32.9		2.3	
062161	23.0	3.25		6.1	33.9		27.4		6.5	
062261	17.2	2.38		6.7	25.3		15.2		10.1	
062361	16.8	4.58		6.7	29.4		18.3		11.1	
062461	16.4	4.08		6.7	28.0		21.3		7.7	
062561	18.6	4.10		6.7	30.7		31.7		-1.0	
062661	23.8	4.26		6.1	37.2		33.2		5.0	
062761	23.8	3.56		6.4	35.6		26.2		9.4	
062861	19.6	5.87	.48	6.1	33.4	14.8	31.1	9.1	3.3	5.7
062961	15.8	5.07	.59	6.7	29.1	15.8	30.5	9.1	-1.4	6.7
063061	10.0	5.85	.68	6.7	23.0	12.3	29.6	9.1	-6.6	3.2

Forecast seasonal MLD's within one standard deviation (6.6 meters) 58%

Forecast seasonal MLD's within two standard deviations (13.2 meters) 100%

TABLE 19

FORECAST OF MLD's FOR JULY 1961 AT OWS BRAVO

DATE	W (KNOTS)	Qs ($Kg\ cal/cm^2$)	Q_t ($Kg\ cal/cm^2$)	TS (°C)	FORECAST MLD_s (METERS)	FORECAST MLD_t (METERS)	(OBSERVED) MLD_s (METERS)	(OBSERVED) MLD_t (METERS)	FORECAST $DIFF_s$ (METERS)	FORECAST $DIFF_t$ (METERS)
070161	27.6	5.34		6.0	35.4		32.9		2.5	
070261	28.9	8.04		6.1	34.5		36.9		17.6	
070461	28.0	12.38		6.1	73.3		61.9		11.4	
070561	20.0	10.54		6.1	58.3		63.1		- 4.8	
070661	18.2	8.51		6.2	49.3		43.3		6.0	
070761	20.8	9.16		6.1	54.0		48.8		5.2	
070861	20.8	11.32		6.1	61.8		50.0		11.8	
070961	18.2	9.46		6.7	52.6		47.9		4.7	
071061	12.0	16.41		7.2	66.2		54.9		11.3	
071161	12.0	14.62	3.05	5.6	54.6	19.0	54.3	12.2	.1	6.8
071261	12.0	18.13	2.71	5.8	62.8	16.6	60.0	18.3	2.8	- 1.7
071361	18.0	18.45	3.10	5.6	73.6	15.9	65.5	32.0	8.1	-16.1
071461	20.0		5.72	5.6		35.5		33.5		2.0
071561	20.0		5.85	5.0		36.2		34.4		1.8
071661	15.0		6.83	5.6		37.6		31.4		6.2
071761	15.0		5.90	5.3		34.2		30.5		3.7
073061	8.0		8.00	7.2		35.9		26.2		9.7
073161	10.0		8.52	7.2		40.6		27.4		13.2

Forecast seasonal MLD's within one standard deviation (9.9 meters) 75%

Forecast seasonal MLD's within two standard deviations (19.8 meters) 100%

TABLE 20

FORECAST OF MLD's FOR AUGUST 1961 AT OWS BRAVO

DATE	W (KNOTS)	Q_s (Kg cal/cm^2)	Q_t (Kg cal/cm^2)	TS (^oC)	FORECAST MLD_s (METERS)	FORECAST MLD_t (METERS)	OBSERVED MLD_s (METERS)	OBSERVED MLD_t (METERS)	FORECAST $DIFF_s$ (METERS)	FORECAST $DIFF_t$ (METERS)
080161	18.0	7.10		9.5	16.8		21.3		- 4.5	
080361	16.0	6.52		8.3	14.7		22.9		- 8.2	
080461	14.0	6.83	1.23	7.8	13.7	12.5	24.4	17.2	-10.7	.3
080561	12.0		1.84	6.7		9.3		15.2		-5.9
080661	12.0		1.50	7.8		9.5		13.7		-4.2
080761	10.0		1.50	7.8		7.7		13.7		-6.0
080861	13.8		1.00	7.8		5.9		10.7		-4.8
080961	17.4	3.14		8.3	13.3		21.3		- 8.0	
081061	20.0		2.20	7.8		16.4		10.7		5.7
081261	20.0	8.14		6.7	17.1		25.0		- 7.9	
081361	13.6	11.00		6.7	16.7		32.0		-15.3	
081461	14.4	7.95		6.7	14.1		27.4		-13.3	
081561	14.4	5.94		7.2	12.8		24.4		-11.6	
081661	11.0	8.75		7.2	14.2		24.4		-10.2	
081761	12.0	8.31		7.8	14.5		24.4		- 9.9	
081861	19.2	7.65		7.8	17.1		24.4		- 7.3	
081961	19.6	8.18		8.9	18.5		24.4		- 6.9	
082061	19.0	8.80		7.6	18.2		29.0		-10.8	
082161	19.0	11.12		8.3	21.2		30.5		-10.3	
082261	15.2	9.22		8.9	17.7		30.5		-12.8	
082361	15.8	12.14		9.4	22.1		32.0		- 9.9	
082461	19.8	16.20		9.3	29.3		36.0		- 6.7	
082561	23.6	15.32		8.3	28.1		37.2		- 9.1	
082661	27.0	17.10		9.3	33.1		38.1		- 5.0	
082761	24.8	16.12		9.3	30.9		39.0		- 8.1	
082861	22.6	16.02		8.3	28.5		35.1		- 6.6	
082961	20.5	18.95		9.5	32.9		37.2		- 4.3	
083061	15.0	14.40		8.9	24.1		34.1		-10.0	
083161	14.2	14.70		8.9	24.1		29.6		- 5.5	

Forecast seasonal MLD's within one standard deviation (5.6 meters) 17%

Forecast seasonal MLD's within two standard deviations (11.2 meters) 83%

TABLE 21

FORECAST OD MLD's FOR SEPTEMBER 1961 AT OWS BRAVO

DATE	W (KNOTS)	Q_s (Kg cal/cm^2)	Q_t (Kg cal/cm^2)	TS (°C)	FORECAST MLD_s (METERS)	FORECAST MLD_t (METERS)	OBSERVED MLD_s (METERS)	OBSERVED MLD_t (METERS)	FORECAST $DIFF_s$ (METERS)	FORECAST $DIFF_t$ (METERS)
090161	17.6	13.39		8.9	19.0		27.4		- 8.4	
090261	15.8	16.30		7.8	21.3		29.0		- 7.7	
090361	20.0	15.41		9.2	27.6		32.0		- 9.4	
090461	20.0	13.53		8.3	18.9		27.4		- 8.5	
090561	18.0	16.30		8.9	23.0		30.5		- 7.5	
090661	17.2	18.00		9.4	26.6		32.9		- 6.3	
091061	19.0	18.20		7.8	23.8		38.1		-14.3	
091261	15.0	23.05		8.3	32.5		44.2		-11.7	
091361	15.0	25.80		8.3	36.7		45.1		- 8.4	
091761	15.0	22.60		8.4	31.8		41.1		- 9.3	
091861	20.0	23.91		7.8	31.5		47.5		-16.0	
091961	20.0	24.89		7.8	32.9		45.7		-12.8	
092161	21.0	24.10		7.8	31.8		47.2		-15.4	
092261	20.2	25.95		7.8	34.4		57.9		-23.5	
092361	16.4	26.30		7.8	35.5		57.9		-23.4	
092461	19.4	26.60		8.3	37.1		54.9		-17.8	
092561	20.0	24.95		8.3	34.5		54.9		-20.4	
092661	20.0	26.20		8.3	36.4		57.9		-21.5	
092761	15.0	26.30		8.3	37.5		67.1		-29.6	
092961	22.0	23.90		7.6	31.3		67.7		-36.4	

Forecast seasonal MLD's within one standard deviation (11.5 meters) 40%

Forecast seasonal MLD's within two standard deviations (23.0 meters) 80%

TABLE 22

FORECAST OF MLD's FOR OCTOBER 1961 AT OWS BRAVO

100261	28.0	24.85		7.2	97.4		76.2		21.2	
100361	28.0	23.65		7.2	91.9		76.2		15.7	
100461	20.0	18187		6.7	65.9		50.3		15.6	
100561	18.0	16.42		5.8	51.3		42.7		8.6	
100661	19.0	17.21		6.7	60.2		51.2		9.0	
100761	22.0	17.40		5.6	55.0		53.9		1.1	
100861	25.0	17.65		5.6	57.8		51.8		6.0	
101161	22.0	17.68		5.6	55.7		67.1		-11.4	
101261	26.0	19.27		5.6	61.9		64.0		- 2.2	
101461	20.0	13.55		5.6	45.3		64.0		-18.7	
101561	20.0	15.42		5.6	49.0		67.1		-18.1	

Forecast seasonal MLD's within one standard deviation (10.6 meters) 45%

Forecast seasonal MLD's within two standard deviations (21.2 meters) 100%

8. Evaluating the results.

Table 23 is a condensation of the statistical analysis of predicted MLD_s in relation to the observed MLD_s. Deviations of the forecast from the observed MLD are compared with the standard deviation (σ) of the daily mean of the observed MLD_s for each month. Statistics were not obtained for transient MLD situations since too few of these occurred during any month for a statistical analysis. Persistence forecasts from day to day were used for comparison.

Except for the month of October[1], OWS November had a large percentage of forecasts (72%) within one σ, which is significant in that the average σ (5 meters) is small.

For the same months at OWS Bravo only 40 percent of the forecasts were within one σ (9 meters). The inability of equation (9) to forecast accurately the MLD may be related to factors, such as divergence, not included in the model. Use of additional paired values P and N for each month should improve forecasts based on the resulting function P(N). Extension of the monthly study into other years should bring about further improvement, as random contaminating processes are smoothed out by increase in sample size.

[1](October was omitted to avoid months containing possible convective mixing.)

TABLE 23

COMBINED STATISTICAL ANALYSIS OF FORECASTS FOR SEASONAL MLD's

MONTH	YEAR	OWS	# OF FCSTS	% FCSTS WITHIN ONE σ [1]	% FCSTS WITHIN TWO σ	σ (METERS)
June	1958	November	5	80 (50)	80 (75)	3.1
July	1958	November	6	67 (60)	100 (80)	3.7
Sept.	1958	November	29	72 (100)	97 (100)	5.8
Oct.	1958	November	30	17 (62)	43 (83)	3.2
June	1961	Bravo	12	75 (73)	100 (100)	6.6
July	1961	Bravo	12	58 (82)	100 (82)	9.9
Aug.	1961	Bravo	24	17 (91)	83 (100)	5.6
Sept.	1961	Bravo	20	40 (100)	80 (100)	11.5
Oct.	1961	Bravo	11	45 (85)	100 (90)	10.6

Overall average of forecast seasonal MLD's within one σ 45 (82) %

Overall average of forecast seasonal MLD's within two σ 81 (92) %

[1] (Values in parentheses are statistical analysis of forecasts by persistence.)

9. Conclusions and acknowledgement.

As a result of this study concerning the application of a proposed mixed-layer depth forecasting model, the following conclusions can be made.

(1) Persistence gives the best short term prediction of MLD in the locations studied. If no recent observations are available, predictions utilizing a previous year's P(N) and accurate wind forecasts are useful.

(2) The dimensionless coefficient P(N), inherent in the application of similarity theory, is best approximated by a second-degree polynomial.

(3) A single function can be used to represent P(N) for both seasonal and transitional MLD's.

(4) During the warming season, changes in the MLD are mainly influenced by variations in the wind speed.

(5) The concept of a universal function P(N) proposed by Kitaigorodsky may be valid, but its determination requires considerable refining of existing data to remove contaminating influences.

For his invaluable aid in the preparation of this manuscript, the author is deeply indebted to Associate Professor J. B. Wickham, Department of Meteorology and Oceanography, U. S. Naval Postgraduate School, Monterey.

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APPENDIX I

METHOD USED FOR DETERMINING THE PARAMETER Q

The parameter Q is defined as

$$Q = \rho C_p (\text{AREA}) \times 10^{-1}$$

where the factor (AREA) is given by the integral $\int_{T_1}^{T_2} Z dt$, T_1 and T_2 being the temperatures of the "isothermal" layer (see fig. 1, slide 1) below and above the thermocline (either seasonal or transitional), and Z is the depth from the surface to the temperature curve. Density is represented by ρ and C_p is the specific heat at constant pressure.

In evaluating the factor (AREA), the most difficult step is the choice of T_1. It is that temperature, where the water becomes isothermal or nearly so. The isothermal condition may continue to great depth or exist in only a thin layer between temperature gradients. Frequently this layer is difficult to distinguish, in which case reference must be made to adjacent BT slides to establish at least a nearly isothermal condition. In any case the subjectivity in calculating Q by this procedure probably contributes to scatter of the curves P(N).

Once T_1 and T_2 are determined, (AREA) is found by replacing $\int_{T_1}^{T_2} Z dt$ by an equivalent rectangle with the area $\overline{Z}\,(T_2 - T_1)$. The depth of $\overline{Z}$ is determined by a horizontal line drawn through the thermocline such that equal areas will result above and below $\overline{Z}$ (see fig. 1, slide 4).

For OWS November during the warming season $\rho C_p = .975$ (cal/Ccm^3) for an average salinity of 32.5°/oo and can be considered constant. For OWS Bravo $\rho C_p = 1.01$ (cal/Ccm^3) for an average salinity of 34.5°/oo.

A constant factor was calculated that included ρC_p and a change of dimensions (from British to Metric and from Fahrenheit to Centigrade) enabling direct computation of Q from the BT slide. This factor was 1/6.05 for OWS November and 1/5.9 for OWS Bravo.

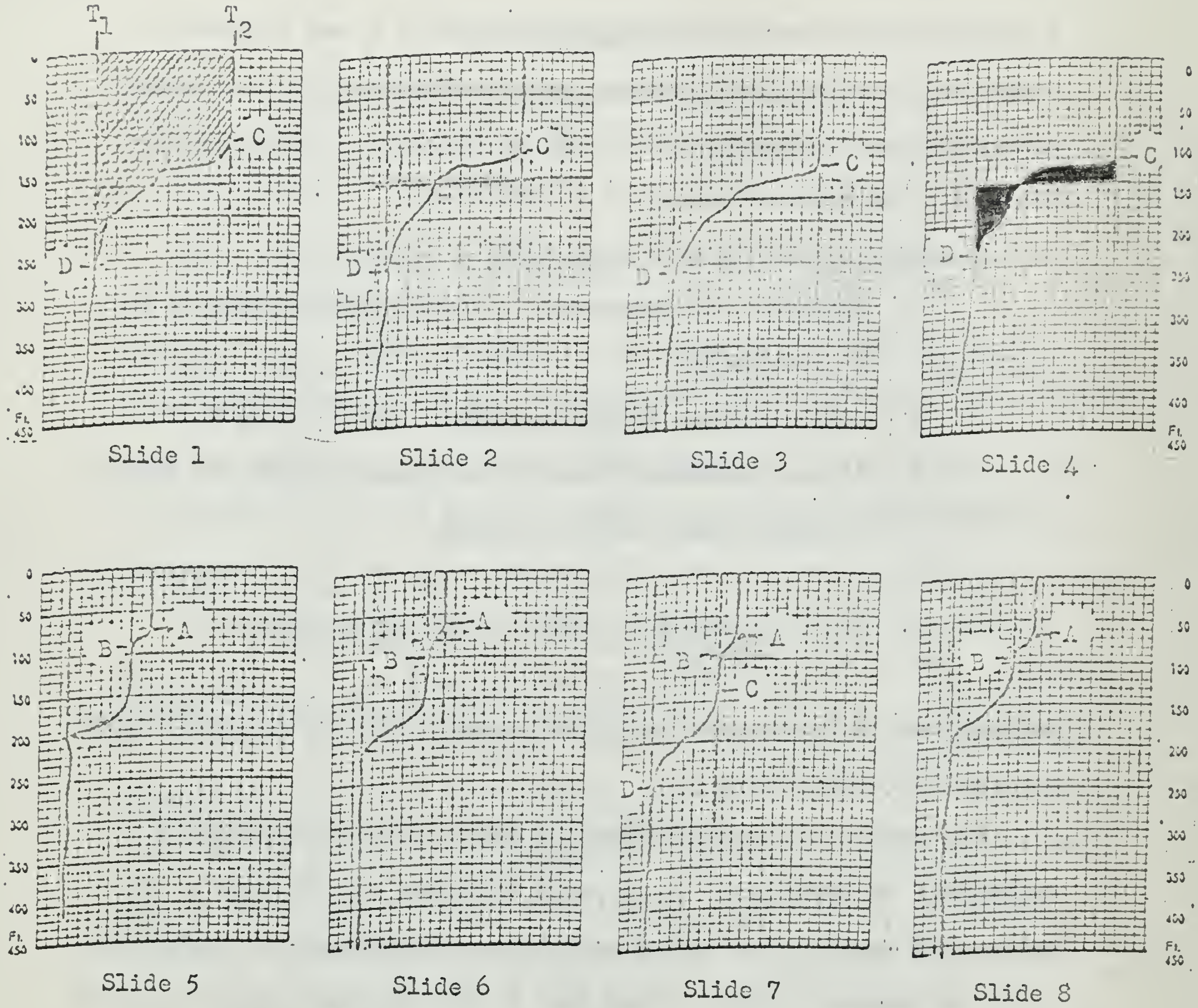
A sample calculation of Q_s from slide 4 follows:

1. Determine the difference in temperatures between T_2 and T_1. (13.8°F)
2. Read the depth of the horizontal line $\bar{Z}$. (150 Ft)
3. If this slide were from OWS Bravo data, divide the product of steps 1 and 2 by 5.9, giving

$$Q_s = \frac{(13.8)(150)}{5.9} \times 10^{-1} = 35 \text{ (kg cal/cm}^2\text{)}$$

Calculations of Q_t are done in the same manner and usually are an order of magnitude less than Q_s.

This method outlined represents a modification to McDonnell's technique. He constructed T_1 so as to intersect the BT trace at 200 meters (656 feet). This method soon became unreasonable in evaluating Q for two reasons. First, excess heat in the uppermost layer was poorly represented. Q represented the excess heat in the layer above 200 meters. Secondly, Q could be evaluated realistically only on slides from deep BT's which are seldom used. The present author's method, although subjective, better represents the excess heat in the mixed-layer under study.



A -the transitional mixed-layer depth (MLD_t).

B -the intersection of vertical (T_1) with the BT trace for transitional situations.

C -the seasonal mixed-layer depth (MLD_s).

D -the intersection of the vertical (T_1) with the BT trace for seasonal situations.

Figure 1

Representation of the AREA used in calculating the parameter Q

TABLE 24

COEFFICIENT OF THERMAL EXPANSION ($\beta \times 10^4$) OF SEA WATER

AT SEA LEVEL FOR DIFFERENT TEMPERATURES AND SALINITIES

SALINITY 0/00

TEMPERATURE (°C)	30	31	32	33	34	35
5	1.01	1.04	1.06	1.08	1.11	1.14
6	1.12	1.15	1.17	1.19	1.22	1.24
7	1.23	1.26	1.28	1.30	1.33	1.35
8	1.34	1.37	1.39	1.41	1.44	1.45
9	1.45	1.48	1.50	1.52	1.55	1.56
10	1.57	1.59	1.61	1.63	1.65	1.67
11	1.67	1.69	1.72	1.73	1.75	1.76
12	1.77	1.80	1.82	1.83	1.84	1.86
13	1.87	1.89	1.91	1.93	1.94	1.95
14	1.97	1.99	2.01	2.02	2.03	2.04
15	2.06	2.08	2.09	2.11	2.13	2.14
16	2.15	2.16	2.17	2.19	2.21	2.23
17	2.23	2.24	2.26	2.28	2.30	2.31
18	2.32	2.33	2.35	2.37	2.39	2.40
19	2.41	2.42	2.44	2.46	2.47	2.48
20	2.50	2.51	2.53	2.55	2.56	2.57
21	2.58	2.59	2.61	2.63	2.64	2.65
22	2.67	2.68	2.69	2.71	2.72	2.73
23	2.75	2.76	2.77	2.79	2.80	2.81
24	2.83	2.84	2.86	2.87	2.88	2.89
25	2.92	2.93	2.94	2.95	2.96	2.97

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1. ORIGINATING ACTIVITY *(Corporate author)* U. S. Naval Postgraduate School Monterey, California	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE
Verification of McDonnell's Mixed-Layer Depth Forecasting Model

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

5. AUTHOR(S) *(Last name, first name, initial)*
KELLEY, Robert D.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
October 1966	72	8

8a. CONTRACT OR GRANT NO. N/A	9a. ORIGINATOR'S REPORT NUMBER(S) N/A
b. PROJECT NO.	
c.	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* N/A
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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
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13. ABSTRACT

A model based on Kitaigorodsky's application of similarity theory and modified by McDonnell to forecast the mixed-layer depth was studied. The model applies during the warming season and is based on the theory of similarity. The parameters involved in the model were determined from bathythermograph data recorded at Ocean Weather Stations November (latitude 30N, longitude 140W) and Bravo (latitude 56 30N, longitude 51W). Parameters were evaluated daily and grouped by months. Both seasonal and transitional MLD situations were treated.

From these parameters, the form of the dimensionless function P(N), claimed by Kitaigorodsky to be universal, was determined by least squares fit to be best approximated by a second order polynomial. Forecasting equations involving P(N) were developed for each month and tested with data from the following years for both OWS ships.

There is general agreement between the observed MLD and that found from the prediction equation based on the last year's P(N) for the same month and location. Month-to-month and spatial differences in P(N) cast considerable doubt on its universality, at least as determined by the parameters as currently defined.

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