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QUANTITATIVE ANALYSIS OF SOME BATHYTHERMOGRAPH ERRORS

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ABSTRACT

A statistical study of errors associated with the bathythermograph (BT) has been made from data obtained during eight 3-week cruises to ocean weather stations (OWS) DELTA and ECHO. Simultaneous observations using reversing thermometers, bucket thermometers, and injection thermometers and nine sets of observations using two connected BT's were analyzed. BT instrument bias varies with depth as much as 1°F with maximum error occurring in the thermocline. One pair of BT's recorded standard errors that varied from 0.20° to 0.61°F with depth and averaged 0.34°F.

Mean differences between reversing thermometer reference temperatures and BT, bucket, and injection thermometer temperatures were computed. Comparison of these differences indicate that ship injection thermometers averaged 1°F high; the BT's and bucket thermometers recorded sea surface temperature with approximately the same degree of accuracy, averaging within 0.5°F of the reference temperature.

At present, BT observations are processed by the National Oceanographic Data Center without correcting for instrument bias. Comparisons between uncorrected data and data containing a temperature correction factor (TCS) based on bucket thermometer readings indicate that the correction factor increases the average accuracy of the observation; however the increase in accuracy is small. Accuracy

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FOREWORD

Effective thermal structure analyses and predictions for the Antisubmarine Warfare Environmental Prediction System (ASWEPS) of the U.S. Naval Oceanographic Office require accurate data from many sources. An important source of subsurface temperature data for such analyses and predictions is the mechanical bathythermograph. This instrument, originally designed for operational use, was known to be of only approximate accuracy. The quantitative magnitude of instrumental errors was not known when the ASWEPS program was instituted. The Naval Oceanographic Office, in connection with its field research surveys, has conducted a number of field experiments to determine the magnitude of certain bathythermograph errors. The results of these experiments are presented in this report.

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INTRODUCTION

Nearly 800,000 bathythermograph (BT) observations have been obtained by various agencies. These BT's, taken over a period of about 20 years, are extremely valuable for oceanographic research.

BT data were originally used in qualitative studies of temperature-depth relationships. Emphasis for the use of BT data has gradually shifted from qualitative contributions to more demanding and exacting quantitative requirements. Several types of errors which influence quantitative statistical analyses became apparent during a study of BT data taken at ocean weather station ECHO (reference 1).

The most comprehensive study of BT errors is that of Bralove and Williams (reference 2). Their report defines various types of errors associated with the BT, suggests ways of measuring the magnitude of some of these errors, and concludes with recommendations to improve the quality of BT data. However, quantitative analysis determining magnitude of the errors is not given. One of the statistical analyses presented in this report was suggested by the Bralove and Williams study.

Stewart (reference 3) performed laboratory tests on six newly calibrated mechanical BT's in an attempt to evaluate their measuring capabilities. These tests showed that it was not possible to attain the specified full depth range accuracy of 1 percent. A more reasonable accuracy is 5 percent of full depth range. Also, the specified accuracy of ±0.1°F was found to be more like ±0.5°F.

Winterfeld (reference 4), in a study of correcting instrument bias by means of a reference temperature, states that most of the BT data on file at the National Oceanographic Data Center have been adjusted by using reference temperatures. The references were either injection temperatures obtained during the cruise or bucket temperature readings obtained specifically for bias adjustment. Winterfeld also indicates that differences between simultaneously recorded BT and injection sea surface temperatures are extremely variable, and that the calculated temperature correction (TCS, temperature correction slide) for BT bias "could not be assumed to be a true instrument bias; i.e., it could not be assumed that the reference temperatures are plausible. In fact, for many cruises the injection temperature records must have a bias of greater magnitude than the bias of the BT instrument. Thus, it must be concluded that a certain percentage of processed BT cruises in the NODC archives have, despite the TCS adjustment, a considerable bias in the adjusted BT temperatures. In fact, in many cases the adjustment must have introduced into the BT observation a bias of greater magnitude than the bias of the BT instrument."

Winterfeld also found that simultaneous BT and bucket thermometer sea surface temperatures generally were in agreement, and that no large variations were evident. This implies that bucket temperatures are more accurate than injection temperatures for use as BT reference temperatures.

Saur (reference 5), after comparing 6,826 pairs of bucket and injection temperatures, reported that injection temperature observations varied erratically among ships, cruises, and on individual ships at different speeds. These results indicated that injection temperatures average about 1°F higher than actual surface temperatures. Injection thermometers from five ships were in error as much as 3.9°F.

Undoubtedly, an injection temperature used as a reference to correct BT bias introduces considerable error. The BT is subject to additional errors: (1) delay in temperature response, (2) limited accuracy of temperature and pressure sensing elements, (3) temperature errors introduced by the pressure element lag, (4) error due to the field operator, (5) errors imposed by the corrections applied during processing of the slide, (6) inaccurate grid calibration, and (7) reading, coding, and key-punching errors.

The relationship between the overall error and its various components can be written as follows:

$$E = \sqrt{(\Delta E_1)^2 + (\Delta E_2)^2 + - - - (\Delta E_7)^2}$$

where ΔE represents various errors.

This study is designed to determine the magnitude of these errors.

OBSERVATIONAL PROGRAM

The data used in this report were obtained aboard U.S. Coast Guard cutters during five cruises to OWS DELTA (44N, 41W) and three cruises to OWS ECHO (35N, 48W). The dates for each patrol are indicated in table 1. During each 3-week cruise, routine BT observations were taken. In addition, oceanographic stations taken at OWS DELTA provided useful comparative data for this analysis. Several types of observations were taken specifically for this study. Paired BT observations were taken during ECHO cruises I and II and DELTA cruises I and II.

During DELTA II and III injection temperatures were read by an oceanographer. During all cruises injection temperatures were read by the ship's engineer.

TABLE 1

SUMMARY OF OCEAN WEATHER STATION CRUISES

DELTA I	June 1962
DELTA II	September-October 1962
DELTA III	November-December 1962
DELTA IV	March-April 1963
DELTA V	June-July 1963
ECHO I	November 1958
ECHO II	February-March 1959
ECHO V	January-February 1963

Bucket thermometers were calibrated before each cruise to insure accuracy of .1°F. Two bucket thermometers were used during DELTA I, II, and III. Procedure called for measuring the temperature of a bucket of surface water with two bucket thermometers. Whenever the two instruments disagreed by more than .2°F, both thermometers were replaced. During DELTA I, II, and III the thermometers remained in the bucket for as much as 4 minutes while the BT was lowered and recovered. During DELTA V and ECHO V a single bucket thermometer was read after stabilizing for about 30 seconds. During DELTA IV and ECHO V the USCGC CASCO was outfitted with special thermistor probes 3 feet below the water line (reference 6). Probe readings were used as reference temperatures.

Temperature measurements by use of reversing thermometers and BT's were made according to procedures outlined in reference 7. Half-hourly BT observations and 6-hourly Nansen casts were taken during all cruises. A cast normally requires 1 to $1\frac{1}{2}$ hours to complete. The BT schedule was interrupted during Nansen casts and was resumed on completion of each cast.

BT sea surface temperatures were checked against bucket temperatures. The two values generally agreed within a few tenths of a degree. Whenever the two disagreed by a few degrees, the BT was replaced. The BT was also replaced when the surface depth error exceeded 40 feet or when the BT trace showed hysteresis.

Recorded temperatures of reversing thermometers were generally an average reading of two instruments. However, if a pair of instruments disagreed by more than .06°C, the most plausible temperature was accepted. In some cases, when the protected thermometer was paired with an unprotected thermometer, only one reading was available.

Table 2 shows the numbers of sea surface temperature observations recorded by reversing thermometers on each cruise. The percentage of observations which were averaged from two thermometers are also indicated.

TABLE 2

NUMBER OF SEA SURFACE TEMPERATURE OBSERVATIONS RECORDED BY REVERSING THERMOMETERS

Cruise	Total Number of Obs.	Two Thermometers Used	
		No.	Percent
DELTA I	31	4	13
DELTA II	72	63	88
DELTA III	65	47	72
DELTA IV	77	77	100
DELTA V	49	44	90
ECHO V	58	58	100
	352		

ANALYSIS OF PAIRED BT DATA

During two patrols to OWS DELTA and two to OWS ECHO, paired BT observations were obtained by connecting two BT's together with brass holders. An oceanographic winch was used at DELTA, and a BT winch was used at ECHO. As indicated in table 3, 9 sets of data each containing from 8 to 38 observations were made with paired BT's. After routine processing by NODC, these observations were coded and punched on IBM cards.

As discussed by Bralove and Williams (reference 2), the extent to which two temperature observations represent true ocean variability, as opposed to random errors of the two sensors, can be estimated by computing the correlation coefficient, r.

$$r = \left[\frac{\sum_{i=1}^{N} X_i Y_i - \frac{\sum_{i=1}^{N} X_i \sum_{i=1}^{N} Y_i}{N}}{\sum_{i=1}^{N} X_i^2 - \frac{(\sum_{i=1}^{N} X_i)^2}{N}} \right] \frac{\sigma_x}{\sigma_y}$$

where

x_i = reading of first instrument
y_i = reading of second instrument
N = number of observations
σ_x = standard deviation of x_i
σ_y = standard deviation of y_i

As r approaches unity, variations in the readings of both instruments are a measure of the variations present in the ocean. If the correlation is low, the variations of both instruments are related to the instrument bias, and conclusions concerning ocean variability are limited.

The correlation coefficient does not indicate relative reliability of the two BT's. The relative magnitude of the standard deviations must be considered. If the instruments are reliable, standard deviations should be approximately equal. For the most part, the equality represents actual variations in the ocean. If the standard deviations are not approximately equal, then one of two conditions is evident: (1) a very small standard deviation may indicate that one measurement is being recorded several times (reading error) or (2) one instrument is less accurate and less reliable than the other.

When the correlation coefficient is high and the standard deviations are equal, the resulting standard errors of estimate are low and the two instruments are reliable to the accuracy of the standard error of estimate. The standard errors of estimate, S_x and S_y, can be computed as follows:

$$S_x = \sigma_x (1 - r^2)^{1/2}$$
$$S_y = \sigma_y (1 - r^2)^{1/2}$$

When the correlation coefficient is low and standard deviations are nearly equal but low, there may be negligible ocean variability. When the correlation coefficient is low and standard deviations are high, at least one of the two instruments is highly biased. If the standard deviations are unequal, the instrument with the higher standard deviation is probably in error. An inspection of the statistics from the nine sets of paired BT observations in table 3 indicates wide variability in instrument response.

Whenever the correlation coefficient for one pair of instruments is consistently high for all depths, the two standard deviations are expected to be nearly equal. However, this was not true in all cases. In the nine sets of paired observations, five coefficients (1,2,3,5,9) averaged more than .70 for all depths. Only one of these five (2) has a majority of the differences between the paired standard deviations equal to or less than .1°F.

The first two sets of observations were taken during ECHO I during a period (November 1958) when a definite seasonal thermocline existed. The magnitude of standard deviations should increase sharply in the vicinity of the thermocline with reliable instruments, yet they should be nearly equal for any given depth. This appears to occur between 320 and 360 feet. If one instrument responds faster than the other, there should be a marked difference between the standard deviations. This appears to occur at 280 feet. The instrument common to both sets (12914) appears to have a slower rate of response.

Bralove and Williams stated that "when two standard deviations are unequal, probably the instrument with the higher standard deviation is in error." If this statement is assumed to be true, then the first two sets of observations indicate that BT 12914 is more accurate to a depth of about 360 feet and is less accurate at greater depths than the other instruments.

TABLE 3

COEFFICIENT OF CORRELATIONS, STANDARD DEVIATIONS, AND STANDARD ERRORS OF ESTIMATE OF PAIRED BT OBSERVATIONS (TEMPERATURE IN °F)

PAIRED SET	OWS ECHO, NOVEMBER 1958										OWS ECHO, MARCH 1959				
	1					2					3				
BT SERIAL NUMBER	12914 VS 12151					12914 VS 12164					12257 VS 12202				
Depth	r	σ_x	σ_y	S_x	S_y	r	σ_x	σ_y	S_x	S_y	r	σ_x	σ_y	S_x	S_y
0	.71	.24	.44	.17	.31	.64	.32	.38	.25	.29	.74	.52	.32	.35	.21
40	.78	.27	.42	.17	.27	.78	.35	.38	.21	.23	.75	.52	.30	.35	.20
80	.80	.32	.42	.20	.26	.81	.33	.39	.19	.23	.75	.51	.27	.34	.18
120	.78	.31	.42	.19	.26	.77	.32	.39	.21	.25	.75	.50	.28	.33	.18
160	.83	.32	.46	.18	.25	.73	.32	.38	.22	.26	.81	.53	.27	.31	.16
200	.71	.39	.58	.27	.41	.65	.32	.35	.24	.27	.81	.53	.30	.31	.17
240	.64	.39	.45	.30	.35	.66	.32	.32	.24	.24	.78	.53	.31	.33	.20
280	.81	.32	.55	.19	.32	.85	.33	.56	.17	.29	.79	.54	.29	.33	.18
320	.96	.91	.98	.27	.29	.82	.64	.84	.37	.49	.76	.54	.27	.35	.18
360	.94	1.36	1.28	.45	.43	.83	.96	1.02	.53	.57	.44	.52	.28	.47	.25
400	.93	1.52	1.19	.54	.42	.92	.84	.68	.34	.27	.68	.49	.27	.36	.19
440	.94	1.10	.78	.39	.28	.88	.69	.63	.33	.30	.64	.44	.27	.34	.21
480	.91	.91	.65	.38	.27	.91	.58	.52	.24	.22	.61	.44	.27	.35	.22
520	.84	.74	.51	.40	.28	.87	.50	.44	.25	.22	.69	.45	.29	.33	.21
560	.54	.47	.40	.40	.34	.83	.44	.41	.25	.23	.50	.45	.25	.39	.21
600	.61	.61	.45	.60	.44	.86	.40	.39	.20	.20	.52	.42	.25	.35	.21
640	.71	.64	.42	.45	.29	.81	.37	.39	.22	.23	.61	.47	.37	.37	.29
680	.68	.64	.43	.47	.31	.86	.40	.38	.20	.19	.89	.62	.46	.28	.21
720	.56	.62	.45	.51	.37	.63	.43	.36	.33	.28	.91	.82	.57	.34	.24
760	.65	.68	.58	.52	.45	.62	.42	.33	.33	.26					
800	.77	.66	.51	.42	.33	.56	.41	.30	.34	.25					
N	38					18					18				

PAIRED SET	OWS ECHO, MARCH 1959														
	4					5					6				
BT SERIAL NUMBER	12202 VS 12330					12257 VS 12220					12220 VS 12202				
Depth	r	σ_x	σ_y	S_x	S_y	r	σ_x	σ_y	S_x	S_y	r	σ_x	σ_y	S_x	S_y
0	.12	.31	.39	.31	.39	.81	1.08	.72	.63	.42	.14	.80	1.00	.79	.98
40	.36	.35	.20	.32	.19	.80	1.04	.73	.62	.44	.65	.38	.23	.29	.17
80	.31	.34	.22	.33	.21	.80	1.05	.76	.63	.46	.69	.24	.18	.18	.13
120	.21	.37	.24	.36	.23	.82	1.07	.77	.61	.44	.57	.24	.19	.20	.15
160	.11	.38	.22	.37	.22	.85	1.06	.79	.56	.42	.57	.25	.20	.20	.16
200	-.06	.34	.22	.34	.22	.84	1.08	.76	.59	.41	.49	.24	.17	.21	.15
240	-.15	.38	.22	.32	.22	.83	1.08	.74	.60	.41	.52	.25	.19	.22	.16
280	-.30	.28	.21	.27	.20	.84	1.08	.74	.59	.41	.67	.25	.19	.19	.14
320	-.48	.29	.20	.26	.18	.84	1.06	.75	.57	.41	.63	.21	.19	.17	.14
360	-.39	.31	.24	.29	.22	.84	1.07	.75	.59	.41	.63	.22	.18	.17	.14
400	.01	.22	.16	.22	.16	.84	1.08	.75	.59	.41	.63	.22	.17	.17	.13
440	-.31	.29	.25	.28	.24	.85	1.07	.75	.57	.40	.55	.22	.16	.19	.14
480	-.31	.32	.24	.30	.24	.84	1.05	.76	.58	.42	.50	.23	.18	.20	.15
520	-.40	.32	.23	.29	.21	.83	1.04	.78	.59	.44	.47	.21	.18	.19	.16
560	-.41	.31	.26	.29	.24	.83	1.05	.76	.59	.43	.48	.15	.21	.13	.19
600	-.30	.29	.27	.28	.26	.80	.99	.72	.59	.43	.35	.22	.19	.21	.18
640	-.24	.28	.27	.27	.27	.80	.94	.69	.56	.41	.29	.23	.18	.22	.17
680	.47	.18	.30	.16	.27	.09	.96	.72	.95	.71	.46	.24	.22	.21	.20
720	.48	.17	.28	.15	.25	.43	.74	.79	.66	.71	.74	.36	.33	.24	.22
760											.90	.46	.50	.20	.22
800											.82	.48	.49	.27	.28
N	13					20					17				

PAIRED SET	OWS ECHO, MARCH 1959					OWS DELTA JUNE 1962					OWS DELTA SEPT 1962				
	7					8					9				
BT SERIAL NUMBER	12220 VS 12330					13819 VS 13823					12646 VS 12174				
Depth	r	σ_x	σ_y	S_x	S_y	r	σ_x	σ_y	S_x	S_y	r	σ_x	σ_y	S_x	S_y
0	-.38	.35	.27	.32	.25	.70	.68	1.04	.49	.75	.97	1.47	1.33	.38	.34
40	-.35	.34	.27	.32	.25	.40	.58	.76	.53	.70	.97	1.47	1.31	.37	.34
80	-.29	.29	.29	.28	.28	.51	.85	.83	.73	.71	.97	1.44	1.27	.35	.33
120	-.32	.30	.30	.28	.28	.52	.80	.82	.69	.70	.93	1.40	1.16	.52	.43
160	-.41	.22	.33	.20	.30	.51	.76	.76	.65	.65	.93	1.67	1.40	.61	.51
200	-.32	.21	.36	.19	.34	.21	.51	.81	.50	.79	.95	1.75	1.55	.54	.48
240	-.27	.26	.36	.25	.35	.40	.34	.85	.31	.78	.97	1.99	1.93	.45	.44
280	-.11	.28	.35	.28	.35	.32	.33	.83	.31	.78	.99	1.86	1.67	.26	.23
320	-.10	.31	.35	.31	.35	.31	.37	.86	.35	.82	.99	1.82	1.65	.28	.25
360	-.50	.31	.30	.27	.26	.61	.37	.87	.29	.69	.99	2.22	2.03	.27	.24
400	-.56	.32	.30	.26	.25	.63	.40	.90	.31	.70	.99	2.21	2.11	.30	.29
440	-.35	.36	.27	.34	.25	.69	.58	1.02	.42	.73	.99	2.34	2.22	.36	.34
480	-.43	.39	.27	.35	.24	.69	.63	1.03	.46	.75	.99	2.44	2.24	.29	.27
520	-.39	.37	.25	.35	.23	.64	.58	.98	.44	.75	.99	2.47	2.31	.30	.25
560	-.24	.38	.27	.37	.26	.64	.49	.90	.40	.74	.99	2.42	2.17	.22	.23
600	-.32	.37	.27	.35	.25	.52	.39	.86	.33	.73	.99	2.23	2.02	.32	.29
640	-.35	.37	.30	.35	.28	.35	.43	.77	.40	.72	.99	2.12	1.88	.33	.29
680	-.35	.39	.27	.37	.25	.24	.42	.74	.41	.72	.99	2.02	1.77	.33	.29
720						.21	.38	.74	.37	.66	.98	1.86	1.66	.35	.34
760						.25	.34	.69	.33	.67	.99	1.71	1.55	.28	.25
800						-.05	.42	.64	.42	.64	.98	1.62	1.40	.31	.27
N	8					23					22				

The seventh set of observations would also indicate that BT 12330 is slightly more accurate than BT 12220 from the surface through 40 feet and from 360 through 680 feet and is less accurate from 160 through 320 feet.

The third through seventh sets of paired observations (table 3) were taken at OWS ECHO during March 1959 using four different instruments. Little temperature change with depth occurred at this time. Thus, the instruments were not subjected to a severe test. Correlation coefficients and standard deviations were expected to be low. Negative correlations observed in the fourth and seventh sets indicated possible instrument bias in BT 12330. In spite of the low correlations, paired standard deviations were relatively low and nearly equal, indicating acceptable instrument performance and low ocean variability.

Correlations and standard deviations for all depths in the fifth set were the highest of all sets taken during ECHO II. Although the third set shows that BT 12257 was slightly biased and the seventh set shows that BT 12220 performed within acceptable limits, both instruments apparently suffered damage during collection of the fifth set, resulting in large standard deviations. The data indicated that sets 3 and 7 were recorded before set 5.

Results of the sixth set of observations are unusual in that the correlation and standard deviations for the surface temperature are of a completely different order of magnitude than those for all other depths. The correlation is very low and standard deviations are two to six times larger than those at the other depths. BT prints indicate that this discrepancy results from inaccurately read sea surface temperature owing to blurred traces.

The eighth and ninth sets of observations were taken at OWS DELTA during June and September 1962, respectively. During June, the thermal structure was quite variable; however, the seasonal thermocline was not completely established. During September, the seasonal thermocline was fully developed.

The eighth set of observations exhibits a relatively low correlation. BT 13823 appears to have considerable instrument bias, because its mean standard deviation for most depths is .3°F greater than that of BT 13819.

The ninth set of observations exhibits extremely high correlation at all depths and the largest standard deviations of any set. Because of their magnitude, the paired standard deviations appear to be approximately equal. Thus, for this pair of instruments, the standard error of estimate corresponds to random instrument errors. The mean standard error for BT 12646 is .36°F. The mean error of BT 12174 is .32°F.

For many years prior to 1963, the processing procedure for all bathythermograms included an average sea surface temperature correction factor called TCS. (TCS = Mean reference temperature - Mean BT temperature)

Reference temperatures are generally obtained with an injection thermometer, although each BT is equipped with a small, inexpensive mercury thermometer. During survey operations a more reliable mercury, "bucket" thermometer is used. The TCS value, added to the surface temperature and photographed with each bathythermogram, was assumed to represent instrument bias and to be constant with depth.

In order to obtain a quantitative measure of instrument bias variation with depth and to obtain a clearer understanding of the effect of adding a TCS, the means ($\overline{X}$) and standard deviations (S.D.) of the differences between the nine sets of paired BT observations were computed for several depths. These data are presented in table 4. The mean differences are also shown in figure 1(A and B). The first seven sets of observations have the TCS included in the calculations. The National Oceanographic Data Center has not included the TCS factor in processing BT's since 1963. Thus the eighth and ninth sets do not contain this factor.

Analysis of table 4 indicates that the TCS generally improves the mean sea surface temperature reading. Surface temperature differences for the first through seventh sets of observations vary between 0.0° and 0.32°F, whereas the mean differences for the eighth and ninth sets are 0.44° and 0.81°F, respectively. The question arises of whether the TCS decreases the differences between the two observations as depth increases. The means ($\overline{X}$) in table 4 indicate an improvement of about .2°F at all depths. The samples used in this study are too small for valid conclusions. Ideally, all nine sets of paired observations should have been processed both with and without the TCS.

The results also indicate that instrument bias varies with depth and between pairs of instruments. The mean differences for the first set of observations range from .31° at the surface to 1.30°F at 400 feet, a difference of 1°F. Mean differences for the eighth set range from .37° to .53°F, a difference of only .16°F. The ninth set, which exhibited a high correlation coefficient, has mean differences ranging from .42° to .81°F, a difference of .39°F.

COMPARISON OF TEMPERATURE SENSORS WITH REVERSING THERMOMETER DATA

Several analytical comparisons between bucket, injection, and BT temperatures (references 4, 5) have qualitative conclusions which agree with those of this report. However, since these analyses were not based on absolute reference temperatures and assumed that bucket temperatures were free of bias, their quantitative results are limited.

As indicated in table 2, 352 sea surface temperature observations were recorded with reversing thermometers at DELTA and ECHO. In addition, many reversing thermometer observations were made to a depth of 900 feet. The reversing thermometer is considered to be an extremely accurate instrument as free of instrument bias as any temperature sensor presently available for oceanographic measurements.

TABLE 4

MEAN AND STANDARD DEVIATIONS OF DIFFERENCES BETWEEN PAIRED BATHYTHERMOGRAPH OBSERVATIONS AT INDICATED DEPTHS

(°F)

Paired Set	1		2		3		4		5		6		7		8		9	
BT Serial Number	12914 12151		12914 12164		12257 12202		12202 12330		12257 12220		12220 12202		12220 12330		13819 13823		12646 12174	
Depth (feet)	$\bar{X}$	S.D.	$\bar{X}$	S.D.	$\bar{X}$	S.D.	$\bar{X}$	S.D.	$\bar{X}$	S.D.	$\bar{X}$	S.D.	$\bar{X}$	S.D.	$\bar{X}$	S.D.	$\bar{X}$	S.D.
0	.31	.25	.04	.19	-.29	.32	.00	.32	.20	.39	.25	.35	.21	.41	-.44	.56	.81	.40
40	.38	.24	.11	.16	-.22	.30	-.02	.21	.25	.37	.24	.17	.19	.39	-.52	.56	.80	.40
80	.39	.22	.13	.17	-.19	.25	-.10	.23	.29	.38	.33	.23	.14	.36	-.50	.64	.77	.40
120	.44	.25	.15	.20	-.12	.22	-.19	.26	.36	.38	.29	.22	.05	.32	-.45	.61	.77	.55
160	.48	.23	.18	.20	-.08	.24	-.21	.28	.42	.38	.31	.20	.01	.27	-.50	.53	.60	.42
200	.50	.28	.25	.26	-.07	.22	-.26	.29	.45	.39	.32	.22	-.06	.29	-.48	.64	.67	.44
240	.61	.30	.28	.26	-.02	.23	-.28	.29	.51	.43	.34	.20	-.11	.29	-.37	.59	.75	.46
280	.66	.36	.24	.31	.04	.25	-.32	.29	.50	.40	.32	.20	-.11	.28	-.43	.60	.55	.32
320	.89	.29	.62	.49	.09	.28	-.42	.29	.51	.41	.32	.19	-.08	.31	-.50	.57	.52	.30
360	1.07	.46	.82	.67	.14	.37	-.39	.33	.53	.43	.31	.18	-.13	.30	-.40	.50	.48	.31
400	1.30	.60	.62	.36	.15	.26	-.50	.29	.54	.43	.32	.20	-.17	.35	-.43	.50	.49	.32
440	1.06	.47	.49	.32	.09	.20	-.38	.30	.52	.42	.35	.22	-.19	.37	-.43	.53	.59	.38
480	1.00	.43	.33	.24	.09	.20	-.42	.27	.48	.45	.35	.21	-.29	.26	-.37	.55	.53	.35
520	.94	.41	.31	.22	.06	.19	-.37	.29	.46	.43	.34	.20	-.25	.33	-.37	.58	.46	.31
560	.90	.45	.33	.23	.02	.24	-.36	.33	.43	.41	.38	.24	-.31	.31	-.42	.60	.45	.34
600	.83	.35	.26	.21	.02	.22	-.37	.30	.45	.45	.38	.26	-.29	.27	-.46	.53	.46	.34
640	.79	.47	.26	.23	.04	.25	-.33	.29	.40	.45	.38	.26	-.26	.35	-.45	.50	.43	.35
680	.88	.44	.20	.19	.00	.18	-.38	.29	.30	.33	.43	.25	-.26	.36	-.50	.57	.47	.33
720	.89	.46	.11	.26	-.08	.27	-.37	.26	.33	.39	.45	.26	-.24	.32	-.53	.55	.42	.32
760	.93	.50	.09	.26							.46	.37			-.53	.51	.46	.30
800	.85	.42	.04	.25							.62	.30			-.46	.57	.45	.34
840	.97	.51	.05	.26							.55	.50			-.41	.53	.65	.36
X.	.71		.27		.10		.28		.15		.41		.35		.45		.61	

Thus, comparisons using reversing thermometer observations as absolute reference temperatures should be quite meaningful. However, it is recognized that reversing thermometer observations may contain some bias. A survey ship is generally rolling during the approximately 5 minutes required for a reversing thermometer to adjust to its surroundings. Thus, the thermometer is not located within the same water mass but is continually moving vertically through a column of water. The observation is actually an average temperature taken over a 5- to 10-minute period within a water column as much as 3 meters in thickness.

Reversing thermometer temperatures were tabulated for each cruise. Temperatures were also measured with several other instruments, including an injection thermometer (read by ship's engineer and an oceanographer), bucket thermometer, BT (read in the field), BT (uncorrected print), and BT (TCS added).

Reversing thermometer observations and comparative observations were generally made within 10 minutes of each other; however, some paired observations were taken as much as one-half hour apart.

Means, standard deviations, and confidence limits (t_{98}) of differences between simultaneous observations made with various temperature sensors are presented in table 5. The mean difference between reversing thermometer and bucket thermometer observations during all cruises was slightly less than .5°F. Mean bucket observations were always lower than reversing thermometer observations. The mean difference between reversing thermometer observations and values measured with a hull-mounted probe submerged 3 feet (DELTA IV and ECHO V) was nearly .4°F, only .1°F better than the bucket thermometer. However, the standard deviation of differences was less than half that of the bucket thermometers. Thus, it appears that thermistor probes give somewhat more accurate and consistent reference temperatures than bucket thermometers.

Means and standard deviations of the differences for DELTA V and ECHO V are slightly smaller than the mean results for all cruises. This apparently indicates that stabilization of bucket thermometers for about 4 minutes introduces a slight error.

The statistics of all cruises indicate that injection temperatures exceed measured surface temperatures by reversing thermometers by about 1°F, approximately the same value found by Saur (reference 5). With the exception of DELTA II, injection thermometer observations were higher than reversing thermometer observations.

Saur hypothesizes that incrustation or fouling, poor exposure of the well to water flow, possible air space within the well, and heat conduction by metal fittings produce greater injection thermometer bias than warming of the water before it reaches the thermometer well. Saur also noted that each injection thermometer exhibited a trip bias, i.e, the injection thermometer error varied from trip to trip. This variation was also indicated by data collected by the USCGC CHINCOTEAGUE

MEANS, STANDARD DEVIATIONS, AND CONFIDENCE LIMITS OF DIFFERENCES BETWEEN SIMULTANEOUS TEMPERATURE READINGS (°F) BY TWO TEMPERATURE SENSORS

			DELTA I			DELTA II			DELTA III			DELTA IV			DELTA V			ECHO V				
			$\bar{X}$	CL	σ_{x-y}	$\bar{X}$	CL	σ_{x-y}	$\bar{X}$	CL	σ_{x-y}	$\bar{X}$	CL	σ_{x-y}	$\bar{Y}$	CL	σ_{x-y}	$\bar{X}$	CL	σ_{x-y}	$\bar{X}.$	$\bar{X}..$
1.	Reversing Thermometer - Bucket Thermometer	0 meters	-.02	±.28	.66	-.66	±.20	.71	-.87	±.23	.73	.38*	±.08*	.27*	-.24	±.13	.41	.37* -.56	±.04* ±.12	.13* .38	.47	.53
2.	Reversing Thermometer - Injection Thermometer (Engineer)	8 meters	.30	.43	.87	-.43	.23	.77	.98	.57	1.17	1.03	.38	.62	ND			1.19	.11	.34	.98	.75
3.	Injection Thermometer (Oceanographer) - Injection Thermometer (Engineer)	8 meters	ND			.13	.24	.75	.18	±.06	.85	ND			ND			ND				
4.	Reversing Thermometer - BT (Read in the Field)	0 meters	.02	±.45	1.00	-.32	-.48	1.38	.21	±.20	.58	-.63	.14	.45	-.64	.22	.69	.58	.22	.55	.40	.77
5.	Reversing Thermometer - BT (Uncorrected Print)	0 meters	.09	±.34	.72	-.54	.21	.64	1.99	-.54	1.55	-.66	.17	.63	.90	.27	.72	.12	.17	.41	.62	.77
6.	Reversing Thermometer - BT (Corrected Print)	0 meters	.25	±.31	.75	.68	±.21	.65	.53	±.22	.64	-.72	.20	.74	.29	.10	.26	.44	.20	.49	.46	.59
7.	Reversing Thermometer - BT (Uncorrected Print)	1 - 50 meters	.36	±.18	.40	-.86	.41	1.22	1.20	1.36	1.53	-.40	±.36	.54	NC			.32	.34	.38	.63	.81
8.	Reversing Thermometer - BT (Corrected Print)	1 - 50 meters	.01	±.19	.41	.29	.39	1.16	-.27	.65	.72	-.33	±.46	.69	NC			.35	±.36	.41	.25	.68
9.	Reversing Thermometer - BT (Uncorrected Print)	51 - 75 meters	ND			-.74	.41	1.28	1.97	.94	1.45	-.55	±.37	.64	NC			.46	.37	.45	.93	.95
10.	Reversing Thermometer - BT (Corrected Print)	51 - 75 meters	ND			.28	.44	1.38	.28	.48	.55	-.72	±.56	.96	NC			.76	.37	.44	.51	.81
11.	Reversing Thermometer - BT (Uncorrected Print)	76 -100 meters	-.23	±.31	.56	-.73	.46	1.36	.98	.37	2.02	-.46	±.28	.70	NC			.21	.31	.35	.52	1.00
12.	Reversing Thermometer - BT (Corrected Print)	76 -100 meters	-.49	±.39	.70	.25	.48	1.43	.44	.18	.50	-.70	±.40	1.02	NC			.54	.29	.32	.48	.80
13.	Reversing Thermometer - BT (Uncorrected Print)	101 -150 meters	.39	±.25	.51	-1.07	.56	1.51	1.91	.42	2.64	-.70	±.32	.66	NC			-.02	.34	.38	.82	1.10
14.	Reversing Thermometer - BT (Corrected Print)	101 -150 meters	-.48	±.42	.84	.23	.54	1.44	-.02	.39	2.48	-.61	±.33	.67	NC			.28	.29	.32	.32	1.16
15.	Reversing Thermometer - BT (Uncorrected Print)	151 -200 meters	ND			-.76	.37	.99	1.10	.65	.73	-1.08	±.43	1.31	NC			.43	.29	.42	.84	.86
16.	Reversing Thermometer - BT (Corrected Print)	151 -200 meters	ND			.23	.53	1.41	-.91	.98	1.10	-1.26	±.45	1.36	NC			.75	.33	.48	.79	1.09
17.	Reversing Thermometer - BT (Uncorrected Print)	201 -274 meters	ND			-.89	.29	.57	1.23	.22	1.25	-.73	±.27	.72	NC			.03	.22	.33	.72	.72
18.	Reversing Thermometer - BT (Corrected Print)	201 -274 meters	ND			.40	.20	.39	-.78	.17	.93	-.87	±.35	.93	NC			.35	.30	.44	.60	.67
19.	Mean Difference - (Uncorrected Data)	All Depths	.27		.55	.80		1.08	1.48		1.60	.65		.74	.90		.72	.23		.39		
20.	Mean Difference - (Corrected Data)	All Depths	.31		.68	.34		1.13	.46		.99	.74		.91	.29		.26	.50		.41		

CL	- Confidence Limits ($t_{98}\,\sigma_{x-y}\sqrt{1/N}$)
NC	- Not Calculated
ND	- No Data
$\bar{X}$	- Mean Differences Between Indicated Sensors
$\bar{X}.$	- Mean of the Row Means
$\bar{X}..$	- Mean of the Row Standard Deviations
σ_{x-y}	- Standard Deviation of the Differences
*	- Sea Surface Temperature Thermistor Probe was used rather than a bucket thermometer.

during DELTA II and III. During DELTA II injection temperatures averaged .43°F greater than reversing thermometer temperatures. During DELTA III injection temperatures averaged .98°F less than reversing thermometer temperatures.

One possible source of injection thermometer error could be faulty observation by the ship's engineer. During DELTA II and III the injection thermometer was read by an oceanographer and the engineer at approximately the same time. The mean differences between these simultaneous observations, .13° and .18°F, are insignificant; however, large standard deviations (.75 and .85) indicate considerable variation between observations. Differences of this magnitude are understandable in view of the fact that the injection temperature dial on the CHINCOTEAGUE is calibrated in 2°F intervals and is inconveniently located among pipes about 18 inches below the deck level.

Winterfeld (reference 4) concluded that the time-consuming and costly process of computing a BT bias correction (TCS) is not warranted when injection readings are used as reference temperatures. Unadjusted BT readings are probably more accurate. Since July 1963, NODC has not applied the TCS factor to observations even if bucket reference temperatures were available. Since NODC-processed BT observations are used extensively for research, it was necessary to determine the effect of eliminating the TCS factor when bucket temperatures are available.

Reversing thermometer observations from DELTA and ECHO cruises were used as absolute temperature values for comparison with simultaneously recorded BT observations. Reversing thermometer observations for each cruise were compared with sea surface temperatures read from the BT in the field. Comparisons were also made between the reversing thermometer observations at the depth of the nansen bottle and the corrected and uncorrected BT prints.

Simultaneous observations for each cruise were divided into groups of 25- or 50-meter depth intervals. The mean, standard deviation, and confidence limits (t_{98}) of the differences were then computed (table 5). The results give no answer as to the effect of the TCS. In many cases the TCS adjustment increased the mean temperature error, even when bucket thermometer values were considered to be reliable.

The mean difference for all cruises surprisingly indicated that BT surface temperatures read by an oceanographer in the field are slightly more accurate, although less consistent, than bucket temperatures. BT temperatures were significantly more accurate than bucket temperatures during DELTA II and III.

Normally, the field oceanographer read the BT trace using the manufacturer's grid setting. Occasionally, when a large variance (2° or 3°F) existed between bucket and BT temperatures, the grid was adjusted.

To determine whether the TCS decreased or increased the error for a large sample of data, the means and standard deviations of the differences between corrected and uncorrected values of all observations from the six cruises were computed. The mean difference was .56°F for the uncorrected data and .44°F for corrected data. The standard deviation was .84°F for the uncorrected data and .73°F for the corrected data. Although the TCS appears to improve the accuracy of BT data, the improvement is small.

In general, Winterfeld (reference 4) and Saur (reference 5) concluded that a mercury bucket thermometer was more reliable and more accurate than an injection thermometer. However, Winterfeld notes that the air-sea temperature difference in DELTA II data affects bucket temperatures but does not affect reversing thermometer temperatures.

To determine whether air-sea temperature difference affects bucket temperature, the data from the DELTA cruises and the ECHO V cruise were plotted. The graphs were constructed by plotting reversing thermometer surface temperature minus bucket temperature against the reversing thermometer value minus air temperature (figures 2, 3, 4, 6, and 7). Figures 5 and 8 use a 3-foot temperature probe reference instead of the bucket temperature.

In addition, correlation coefficients were computed (table 6). The correlation between air-sea temperature differences and bucket temperature readings is high. The correlation is low when a probe 3 feet below the surface is used as a reference temperature. Winterfeld concludes that bucket values are affected by air temperature. The bucket thermometer probably records the true sea surface temperature, and a temperature gradient related to the air-sea temperature difference exists in the uppermost foot of water.

TABLE 6

CORRELATION COEFFICIENTS - REVERSING
THERMOMETER SURFACE TEMPERATURE MINUS BUCKET THERMOMETER TEMPERATURE
VERSUS REVERSING THERMOMETER SURFACE TEMPERATURE MINUS AIR TEMPERATURE

Cruise	Correlation
DELTA I	.57
DELTA II	.74
DELTA III	.72
DELTA IV (3-foot probe)	.10
DELTA V	.80
ECHO V	.66
ECHO V (3-foot probe)	.16

It may be concluded that reference temperatures for BT bias corrections must be obtained at an independent check point located at some depth rather than at the surface.

ERRORS RELATED TO DIGITIZED BT DATA

BT's in original stored form are not adaptable to high-speed computer analysis techniques. A punchcard format was developed for analysis of these data. Reading, coding, and punching of BT's on IBM cards introduce additional potential sources of error. These errors may be divided into two classes: (1) gross reading or key-punch error and (2) small reading variations. Key-punch operators generally have highly efficient verification techniques. Therefore, no attempt was made to separate and evaluate this type of error.

Hazelworth (reference 1) described the SERC punchcard format which has been used by the Naval Oceanographic Office for several research projects. The SERC punchcard contains water temperature in degrees and tenths (°F) at 20-foot intervals to 360 feet and at 40-foot intervals at greater depths. A study of a large number of punchcards indicated that the most common type of error made by the reader-coder was inaccuracy in reading the temperature by 5° or 10°F. Errors of this magnitude can significantly influence a statistical analysis and must be eliminated. A computer can be programmed to filter them out.

In order to evaluate coding error and reading accuracy, 100 to 200 bathythermograms from each of five ocean weather stations that were coded and on punchcards were reread by several readers. The means and standard deviations of differences between the two readings were computed (table 7).

TABLE 7

MEANS AND STANDARD DEVIATIONS OF DIFFERENCES BETWEEN TWO READINGS OF THE SAME BATHYTHERMOGRAMS

Ocean Weather Station	Number of Individual Readings	Mean Differences	Standard Deviation of Differences
BRAVO	1736	.039	.07
CHARLIE	2751	.072	.18
DELTA	1586	.076	.10
ECHO	3081	.246	.31
HOTEL	6086	.063	.14

Table 7 indicates that different individuals usually read BT prints with a variation of less than .1°F. Some variation can be attributed to differences in reading ability and to the inconsistent quality of BT prints.

CONCLUSIONS

The object of this study was investigation of the accuracy of BT instruments used in routine survey operations. All observations were taken by trained oceanographers using accepted survey procedures to record the thermal structure with a maximum degree of accuracy. No attempt was made to determine maximum possible errors. It is apparent that a properly used BT yields sufficiently accurate results for many research projects. The average sea surface temperature error is .4°F.

It has generally been accepted that a BT has an instrument bias that is constant with depth. Paired BT observations indicate that the bias is not constant but varies with depth, being as much as 1.0°F and averaging about 0.5°F. Complete compensation for this bias appears to be impossible. An accurate reference temperature could be used for partial compensation. A ship's injection thermometer is not as accurate as the average BT and should not be used to determine instrument bias. Bucket thermometer observations do not significantly improve the accuracy of BT data.

The reference temperature should not be measured at the sea surface owing to possible existence of a near surface temperature gradient. A reference depth of at least 3 feet appears to give satisfactory results. An accurate temperature probe placed in the injection pipe also should give acceptable results while the vessel is underway. Further temperature sensor research is indicated, such as was performed in reference 6.

Errors related to digitized BT data are quite large and therefore can be screened out by a computer program. Variations between individual readings of identical BT prints will average less than .1°F and are considered to be insignificant.

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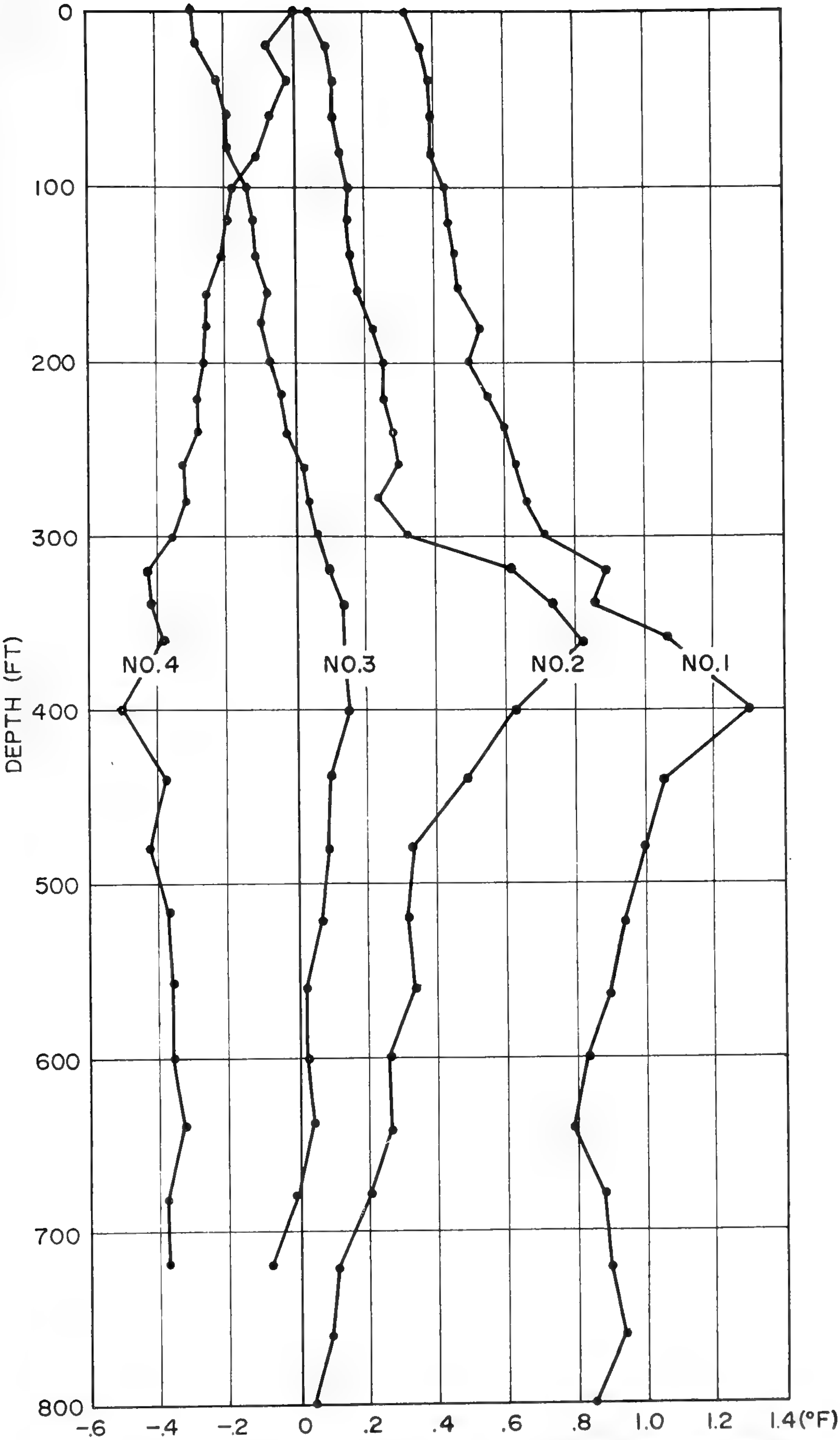

FIGURE 1A MEAN TEMPERATURE DIFFERENCES OF PAIRED BATHYTHERMOGRAPHS AT SELECTED DEPTHS

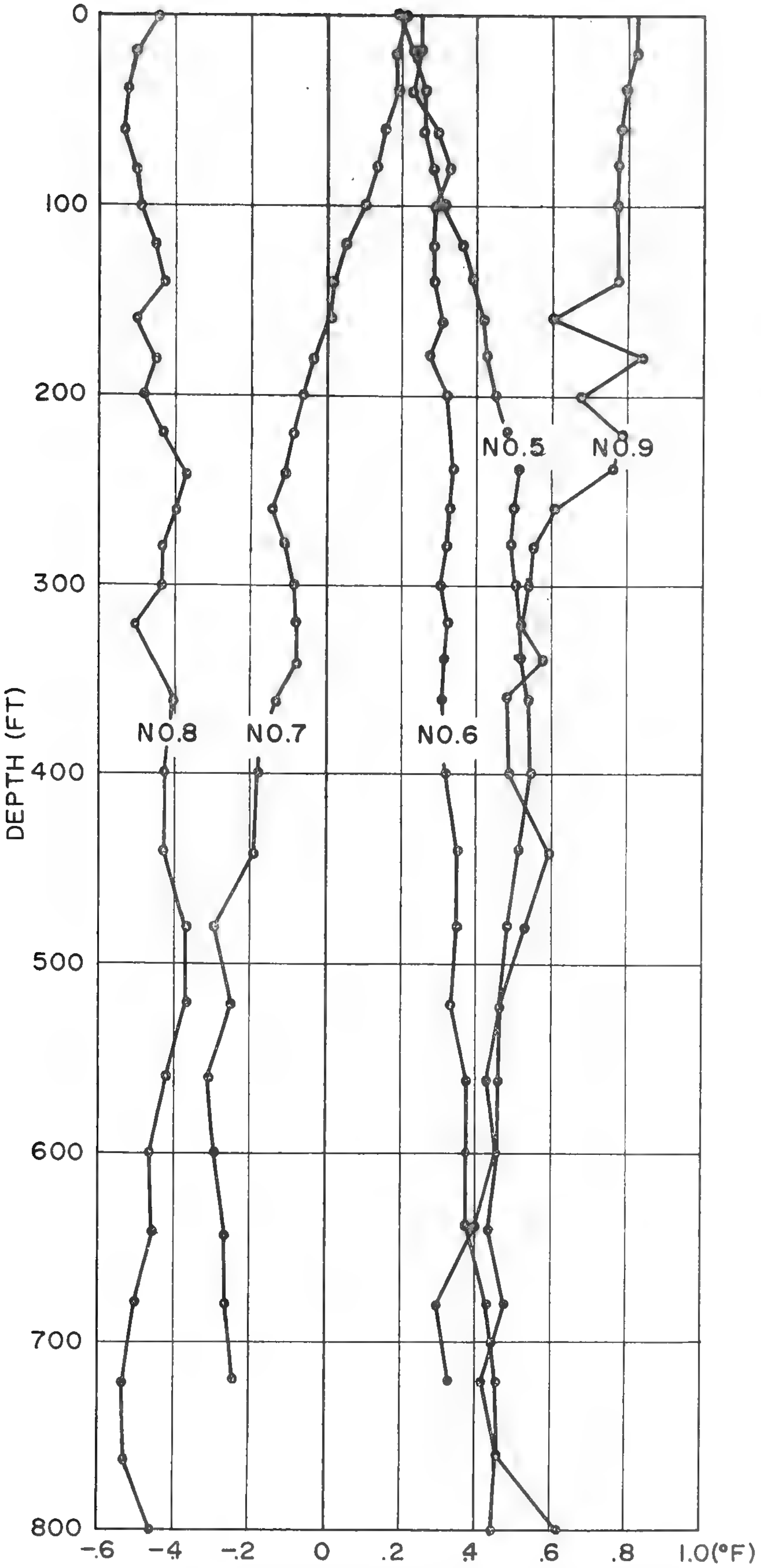

FIGURE IB MEAN TEMPERATURE DIFFERENCES OF PAIRED BATHYTHERMOGRAPHS AT SELECTED DEPTHS

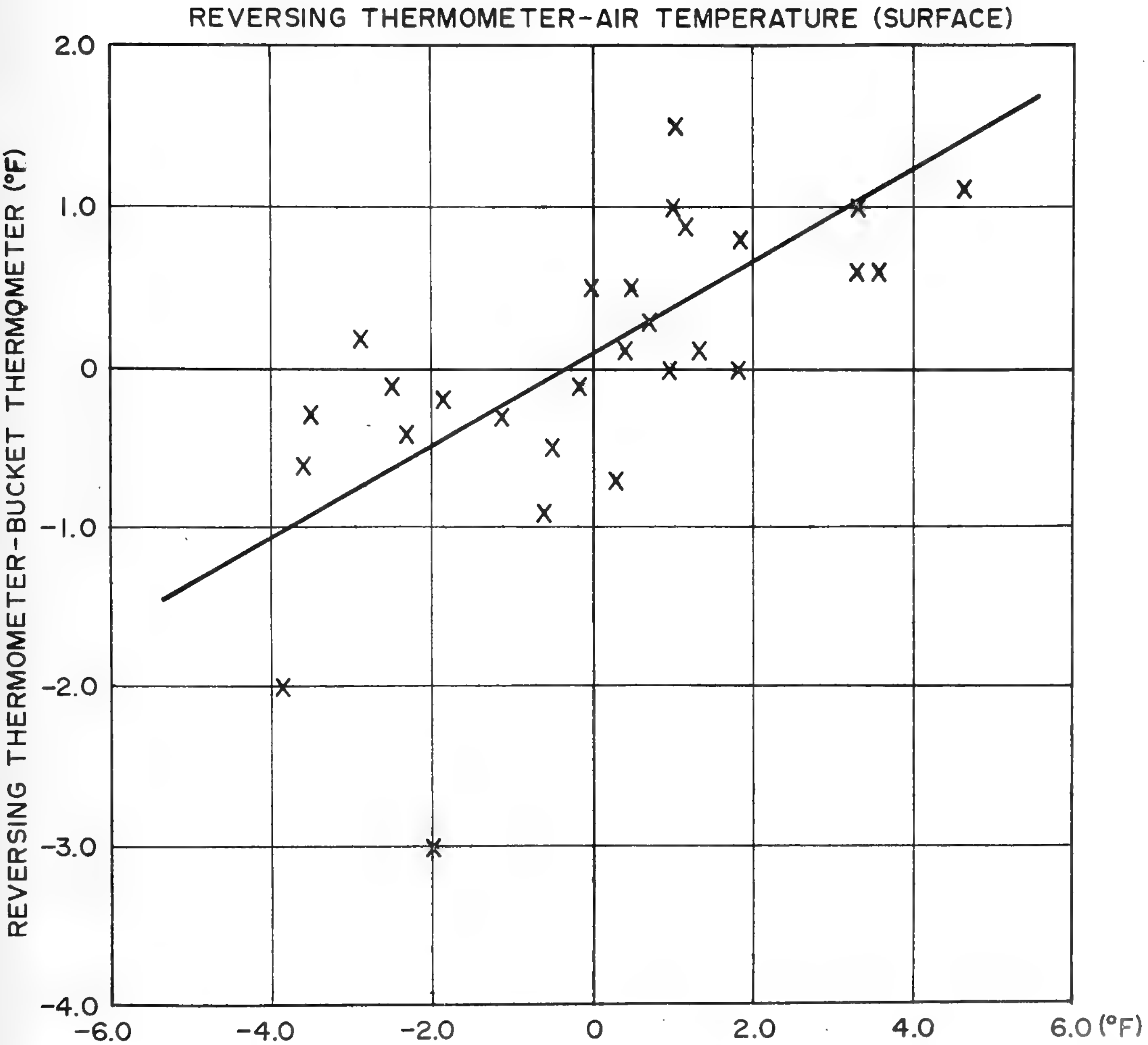

FIGURE 2 EFFECT OF AIR-SEA TEMPERATURE DIFFERENCE ON BUCKET TEMPERATURES-DELTA I

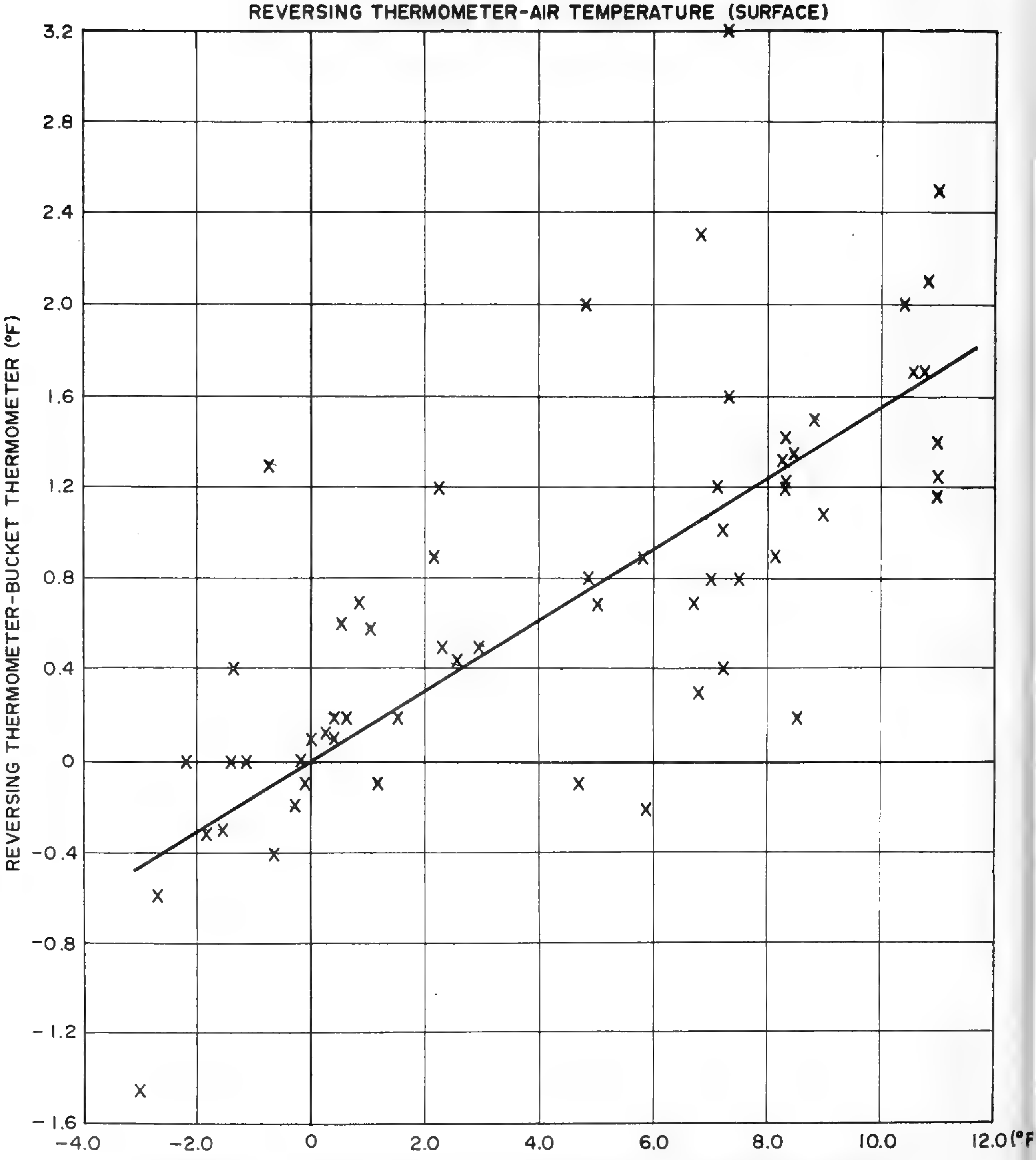

FIGURE 3 EFFECT OF AIR-SEA TEMPERATURE DIFFERENCE ON BUCKET TEMPERATURES-DELTA II

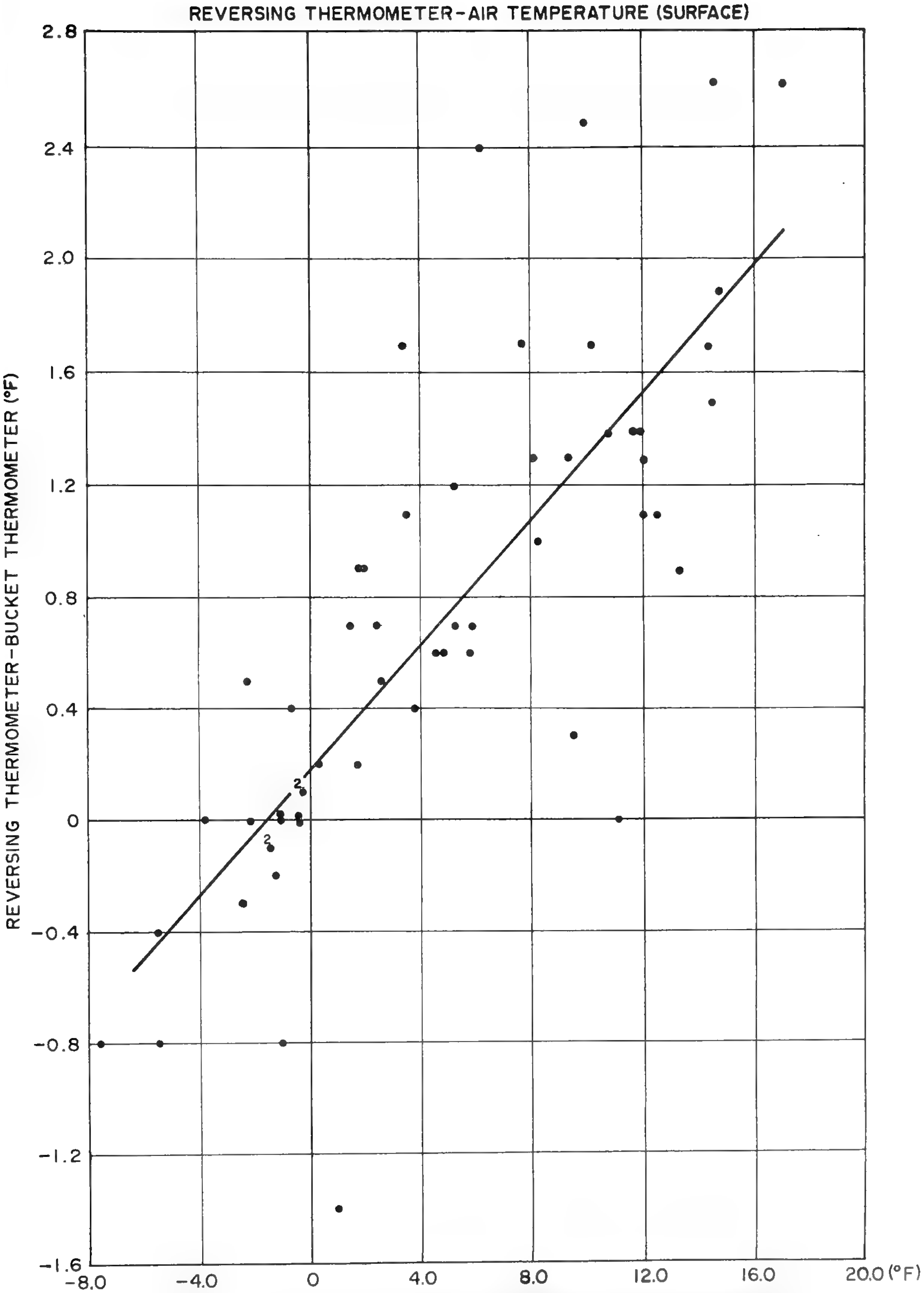

FIGURE 4 EFFECT OF AIR-SEA TEMPERATURE DIFFERENCE ON BUCKET TEMPERATURES-DELTA III

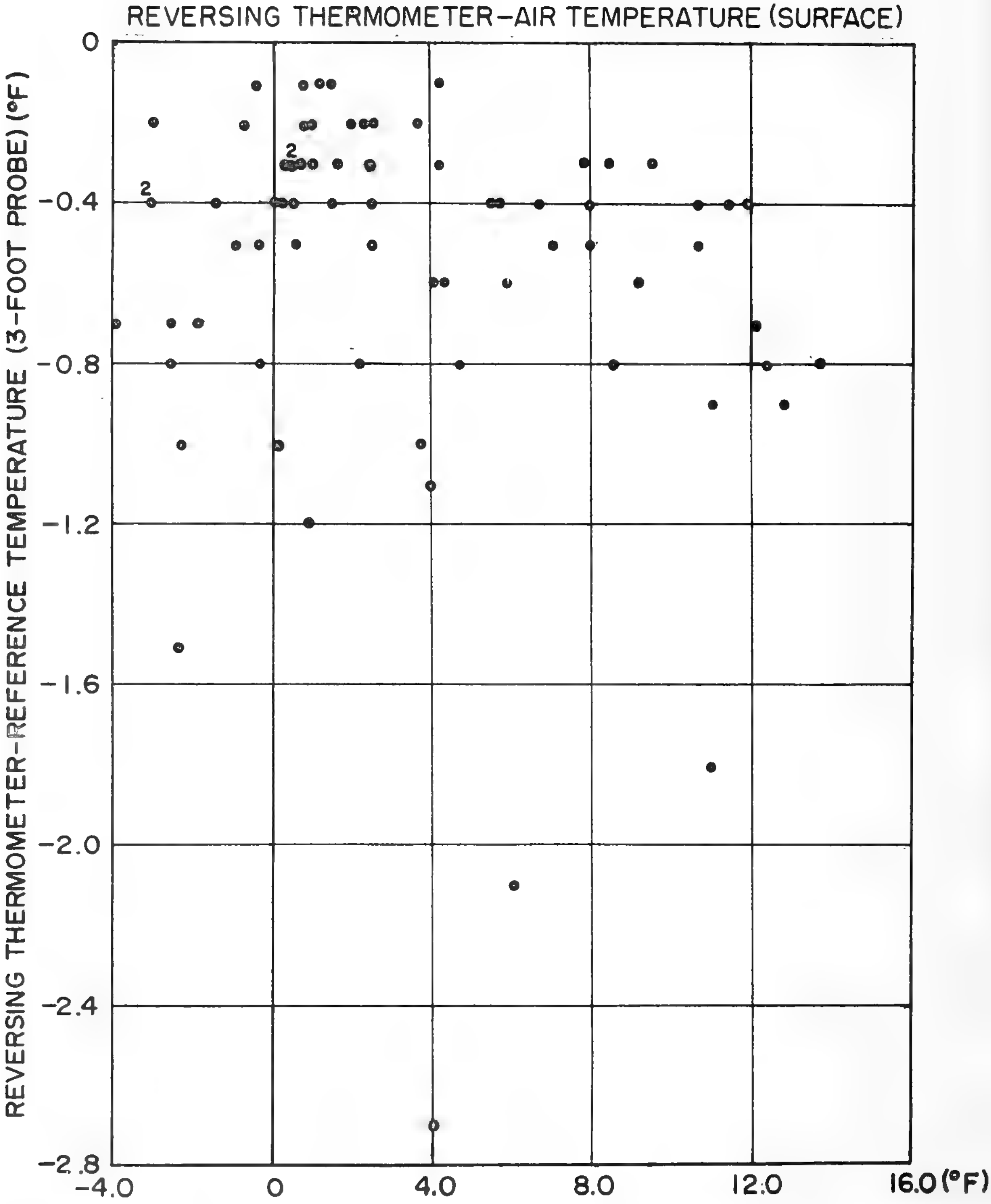

FIGURE 5 EFFECT OF AIR-SEA TEMPERATURE DIFFERENCE ON REFERENCE TEMPERATURES—DELTA IV

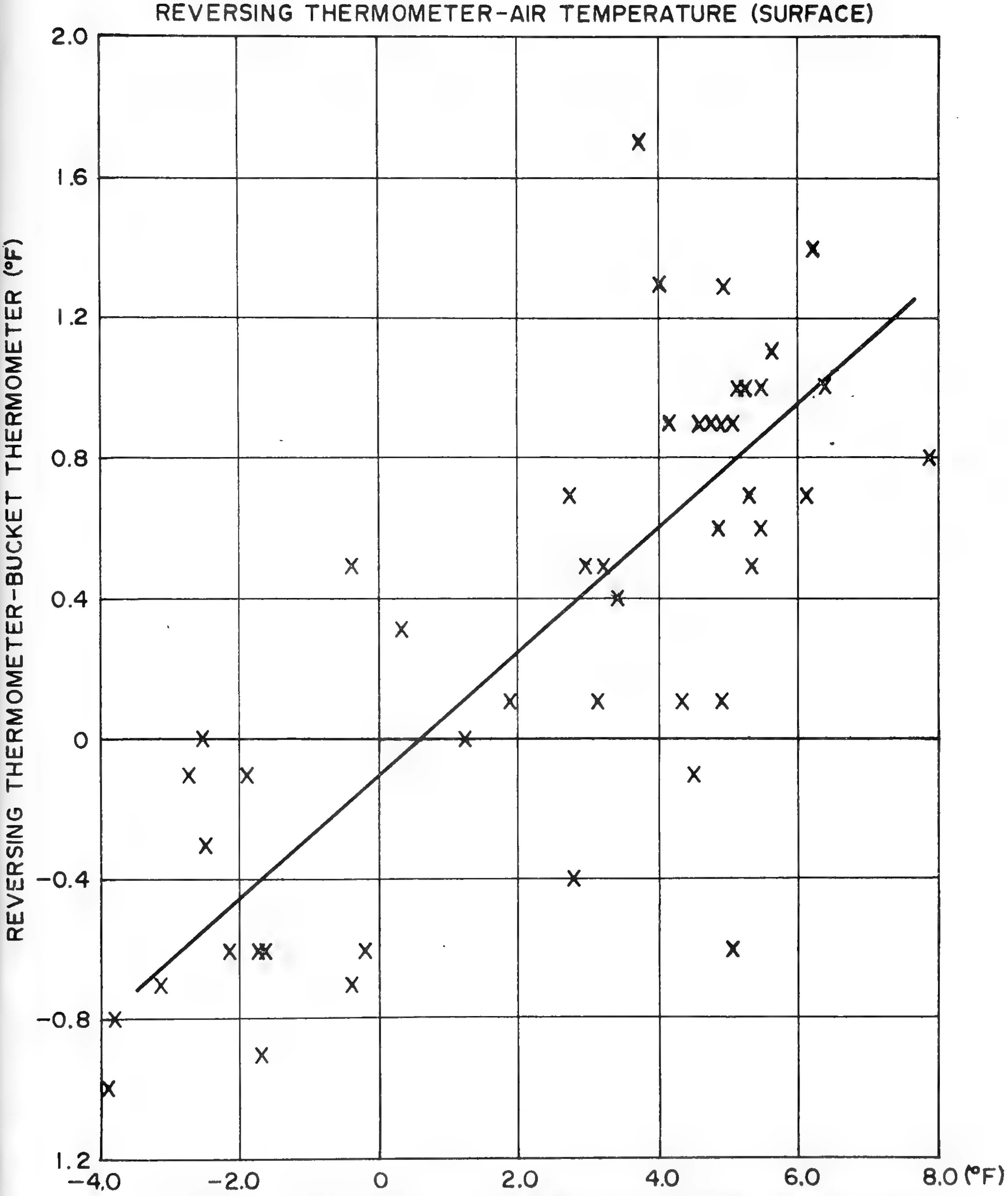

FIGURE 6 EFFECT OF AIR-SEA TEMPERATURE DIFFERENCE ON BUCKET TEMPERATURES-DELTA V

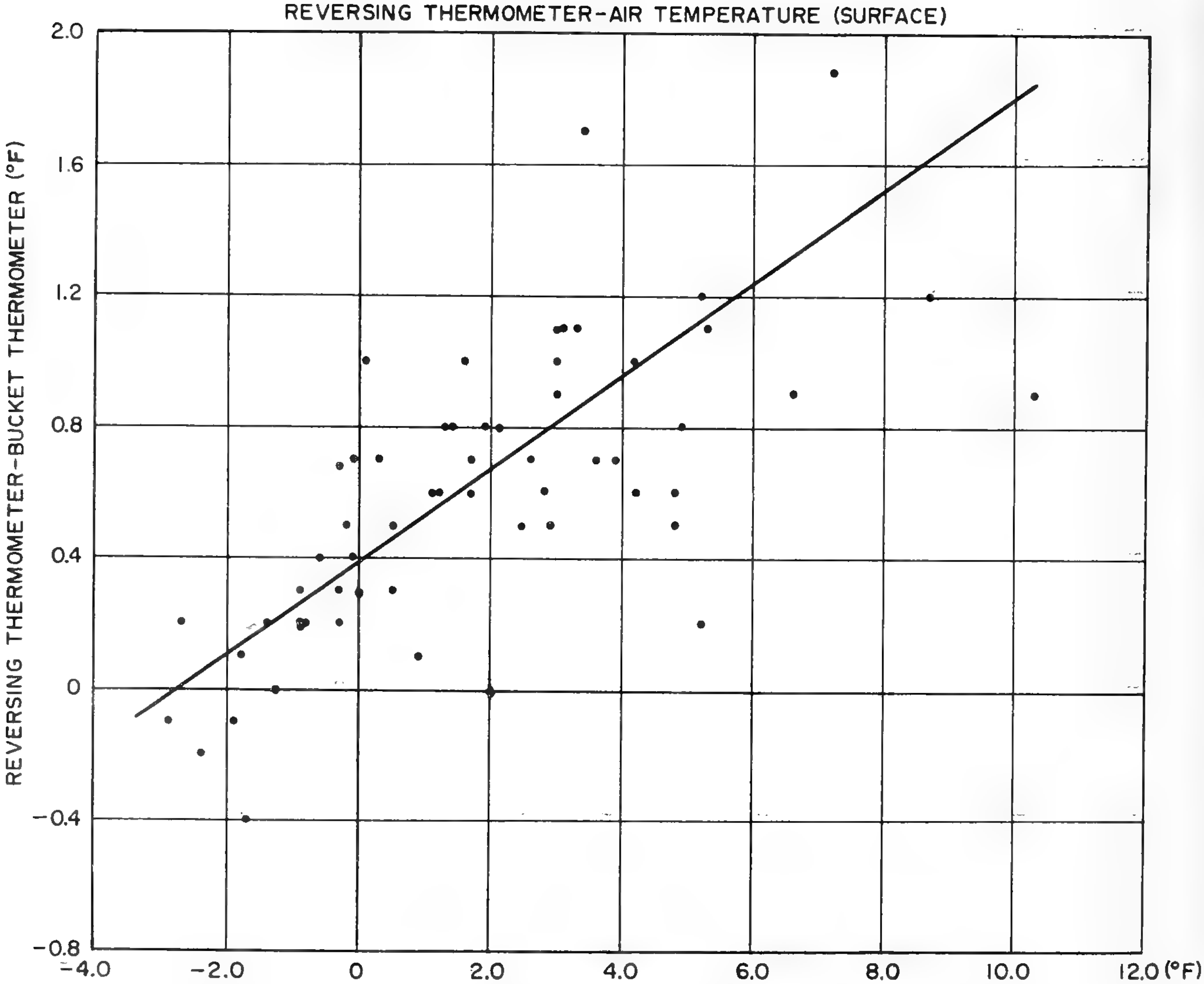

FIGURE 7 EFFECT OF AIR-SEA TEMPERATURE DIFFERENCE ON BUCKET TEMPERATURES-ECHO V

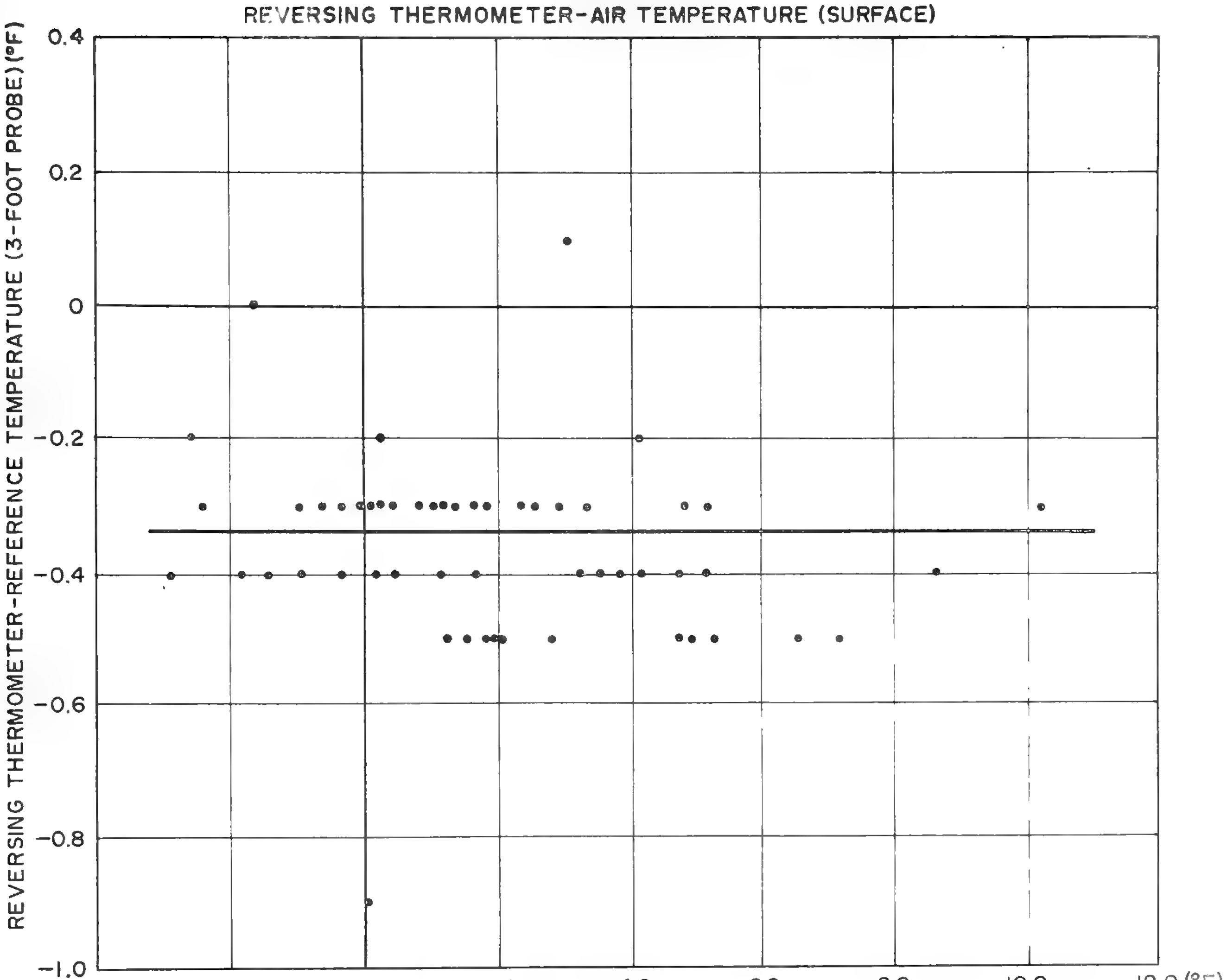

FIGURE 8 EFFECT OF AIR-SEA TEMPERATURE DIFFERENCE ON REFERENCE TEMPERATURE

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13. ABSTRACT A statistical study of errors associated with the bathythermograph (BT) has been made from data obtained during eight 3-week cruises to ocean weather stations (OWS) DELTA and ECHO. Simultaneous observations using reversing thermometers, bucket thermometers, and injection thermometers and nine sets of observations using two connected BT's were analyzed. BT instrument bias varies with depth as much as 1°F with maximum error occurring in the thermocline. One pair of BT's recorded standard errors that varied from 0.20° to 0.61°F with depth and averaged 0.34°F.

Mean differences between reversing thermometer reference temperatures and BT, bucket, and injection thermometer temperatures were computed. Comparison of these differences indicate that ship injection thermometers averaged 1°F high; the BT's and bucket thermometers recorded sea surface temperature with approximately the same degree of accuracy, averaging within 0.5°F of the reference temperature.

At present, BT observations are processed by the National Oceanographic Data Center without correcting for instrument bias. Comparisons between uncorrected data and data containing a temperature correction factor (TCS) based on bucket thermometer readings indicate that the correction factor increases the average accuracy of the observation; however, the increase in accuracy is small. Accuracy of several examples was decreased by correction.

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	ROLE	WT	ROLE	WT	ROLE	WT
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Bathythermograph Data						
OCEANOGRAPHIC EQUIPMENT						
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3. BT accuracy
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