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COMMISSION (of UNESCO)

WORLD METEOROLOGICAL
ORGANIZATION

Ad Hoc MEETING OF THE IGOSS TASK TEAM ON QUALITY CONTROL FOR AUTOMATED SYSTEMS
Marion, Massachusetts, USA, 3-6 June 1991

SUMMARY REPORT

SC/92/WS/31

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1. ORGANIZATION OF THE MEETING

1.1 OPENING OF THE MEETING

The Ad Hoc Meeting of the IGOSS Task Team on Quality Control for Automated Systems (TT/QCAS) was opened at 9:30 am, 3 June 1991 by Mr. R. Bailey and Mr. J. Withrow, Co-Chairmen of the Task Team. Mr. B. Walsh, President of Sippican, welcomed the participants on behalf of Sippican emphasizing Sippican's interest in developing high quality oceanographic instrumentation. He noted that the expendable bathythermograph (XBT) is and always has been the core Sippican product. He expressed Sippican's interest in the work of the Task Team and wished them good luck in their endeavors. Mr. J. Withrow welcomed the participants on behalf of the Intergovernmental Oceanographic Commission (IOC) and the World Meteorological Organization (WMO) Secretariats and Miss M. Jenard welcomed the participants on behalf of the US IGOSS Organization. Mr. R. Bailey emphasized the need to finalize the XBT fall rate study and produce recommendations to the IGOSS Ship-of-Opportunity and WOCE/TOGA XBT/XCTD meetings in October 1991. The Co-Chairmen thanked Sippican for its excellent local arrangements and pleasant working facilities.

1.2 ADOPTION OF THE AGENDA

Mr. J. Withrow introduced the Agenda noting that the Agenda could be changed at this time or at any time during the meeting. The Meeting decided that the temperature equation should be considered in conjunction with the fall rate equation. Otherwise, the Agenda was adopted as shown in Annex I.

1.3 WORKING ARRANGEMENTS

The Meeting adopted the working arrangements for the Meeting as presented by the Co-Chairmen and agreed to adjust it as necessary, including the establishment of drafting groups to address specific questions.

2. BACKGROUND

Mr. D. Bixby, Vice President of Quality Control at Sippican presented the history of Sippican's development of the expendable bathythermograph. He paid particular attention to early testing of the XBT and the methods used to develop and verify the XBT fall rate equation. He also reported on the various Quality Control activities conducted by Sippican to insure continuity and quality on the Sippican XBT production line.

Mr. J. Hannon, Director of Marketing at Sippican then took the Meeting on a tour of the XBT, XCTD and other products' production facilities. The Meeting found that this tour provided insight that was particularly helpful during their deliberations.

3. PRESENTATION OF FIELD WORK

Presentations were given by the following individuals and are represented in Document IOC/INF-888 Add.

Mr. M. Whalen
Mr. R. Bailey
Mr. M. Szabados
Dr. K. Hanawa
Dr. A. Sy
Mr. P. Rual

4. GENERAL DISCUSSION

4.1 FALL RATE EQUATION

The possibility of an error in the depth equation for expendable bathythermographs was first reported by Flierl and Robinson (1977). Since that time several papers have supported this hypothesis. The TT/QCAS initiated an effort in 1989 to conduct sufficient testing under controlled conditions to adequately quantify the problem and develop a revised equation.

Each XBT was conducted as close in time as possible to the CTD in order to make the inter-comparison. Most comparisons were made during the downcast of the CTD but in no case was data utilized that was taken more than 10 minutes after the CTD. Calibrated CTDs were used throughout the testing. Data was processed using several different methods to arrive at revised coefficients. Temperature independent methods utilized by Hanawa, Rual and Bailey were deemed more reliable than the temperature dependent method utilized by Szabados and Sy.

Figure I shows the a and b coefficients obtained by present and past contributors for T-7 type probes, using temperature independent methods of analysis, compared to Hanawa and Yoshikawa (1991) overall new estimate for the fall rate equation. Sufficient T-4 and T-6 data analyzed by temperature independent methods was unavailable to be included in the analysis. All results lie within a +/- 10 meters envelope of maximum deviation from this new estimate. This deviation is now within the manufacturer's specifications for depth accuracy (5 meters or +/- 2% of depth, whichever is the largest). Table I shows the actual values for each case for Figure I as well as past and present results for T-7, T-6, and T-4 type probes using the various methods of analysis. It is noted that the a and b coefficients obtained from the 1990 XBT fall rate independent evaluation by Szabados and Sy using equal test procedures and XBT probes wet calibrated by Sippican showed that the probes were falling at a slower rate. It was speculated that the wet calibration procedure used to calibrate the probes might have contributed to this deviation. Sippican will evaluate the effects of wet calibration on the XBT fall rate during their upcoming field test in late June 1991.

Despite the difference in data processing techniques, there was very close correlation between the results of all contributors. It was shown that a solution to the problem was possible. The Meeting concluded that based on the results a new depth equation was possible that would place the XBT inside its design specifications. While the diverse methods were used to arrive at the revised coefficients served to verify the results, it was deemed necessary by the Meeting to adopt a single method of data processing and re-process all the data according to that method. K. Hanawa agreed to re-process the data using a refinement of his method and all members of the Task Team agreed to forward their data to him. The Meeting also noted that Sippican was going to conduct extensive inter-comparison tests on the XBT within the next month and it wanted to include these results in the analysis. Thus, the Meeting decided to follow the action plan shown in Paragraph 6 below. The Meeting felt that it would be better to take these actions to refine their results so that the recommended revision to the equation would stand up to rigorous review. The Meeting agreed that K. Hanawa's overall analysis should be developed into a scientific report for publication and defence in a scientific journal.

The Meeting was asked by Sippican to review the cruise plan for their up-coming XBT/XCTD test cruise. The Meeting made comments and provided guidance based on experience gained during their field work.

4.2 RESISTANCE TO TEMPERATURE CONVERSION

The Meeting noted that several equations are existent for converting the resistance of the XBT thermistor to temperature. The Meeting examined this issue with Sippican and Sippican agreed to provide the Meeting with the temperature equation for its probes (Annex III).

Mr. D. Bixby described the way in which thermistors are constructed and the difference between the thermistors in the XBT and the expendable conductivity temperature depth (XCTD) sensor.

5. OTHER ISSUES

The Meeting was concerned that some of the equipment currently available has not been properly tested and calibrated. The experience of the Task Team indicates that users should carefully evaluate acquisition of all hardware and software components to ensure that they are compatible and that they meet the manufacturers' specifications.

5.1 BOWING

Mr. R. Bailey opened this agenda item and described the bowing problem. The problem occurs only with a certain types of controllers (Bailey et. al., 1989) (Annex IV). The Meeting observed that the problem was related to mismatches between design specifications of the XBT probe and controller circuit design and was not restricted to the upper layer where it is more easily observed but can occur throughout the cast.

The Sippican bridge circuit used in all Sippican recorders sends approximately 80 to 120 microamperes through the A-wire and the thermistor to sea water ground and an equal amount of current through the B-wire directly to sea water ground. The insulation integrity of the wire is specified to be sufficient to keep wire current leakage to sea water insignificant relative to the above thermistor currents. If one were to use a thermistor measuring circuit that sent 12 microamperes of current though the thermistor, one would need a ten times improvement in XBT wire insulation impedance to achieve the same wire leakage performance. Wire leakage affects will be dramatically increased when using the 12 microampere measurement circuit. In addition, the speed that XBT wire can "heal" will be slowed at the lower current level. This correlates with previous findings by NOAA that the incidence of bowing in the Bathy Systems XBT controller is a result of low current utilized by this controller.

Based on the explanation presented by Sippican, the Meeting recommended that controllers utilizing the amperage recommended by Sippican for use with Sippican's probes be used. Other controllers should be rigorously tested and extensively compared with simultaneous CTD casts to ensure data quality and reliability. The Meeting also noted that data exhibiting this phenomenon is highly suspect and should be handled accordingly.

5.2 EXPENDABLE CONDUCTIVITY TEMPERATURE DEPTH (XCTD)

Sippican presented the current status of the XCTD probe. It was pointed out that recent problems observed in the Baldridge tests in January 1991 (significant noise in the temperature and salinity readings) had been solved due to probe modification and introduction of the MK 12 controller and that all that remained was at sea testing. This was expected to be accomplished during cruises in June and September of this year. Sippican agreed to distribute the results of these tests to meeting participants.

The Meeting noted that the Ship-of-Opportunity community required a 20 kt XCTD as most Ships-of-Opportunity travel faster than the present 10 kt design speed. Sippican noted that the lower speed probe could be launched from a higher speed platform, but the probe would not reach its 1000 meter design depth because it would run out of wire. At present, only a 10 kt version has been developed by Sippican, but a 20 kt version would hopefully be developed and tested by September 1991.

Future Task Team activity with regard to the XCTD will be addressed at the September meeting dependent on availability of a production 20 kt version of the XCTD.

5.3 SIPPICAN MS-DOS IEEE TIMING PROBLEM

Mr. R. Bailey presented this agenda item. His paper on this subject is contained in Annex V.

This problem was passed to Sippican. Sippican noted that the problem was caused by a change to the software driver for the Metrobyte card used in their MK 9 controller. Sippican noted that this change was made by Metrobyte and Sippican was not aware of the change. The change significantly increased the time-out resulting from a no data indication from the Metrobyte board. This delay resulted in errors in the start of descent timing of the cast resulting in a significant and unpredictable depth error in the cast. The software problem was corrected by Sippican through a change in its software. The chance of the problem's future occurrence was removed through the development of the MK 12 controller which does not use the Metrobyte board. The action recommended by Sippican is contained in Annex VI. Data collected under this condition should be considered highly suspect and handled accordingly.

The Meeting noted the need in the community to keep records of controllers and software in the automated collection of data for use in the event that problems arise. It also invited Sippican to utilize the OMNET mailing list IGOSS.XBT to disseminate bulletins regarding the performance of its equipment. This mailing list reaches almost all IGOSS Ship-of-Opportunity Managers.

5.4 NEW XBT PROBES

The Task Team has become aware that there are new manufacturers of XBT-type probes. It is unaware of any independent evaluation of probes other than those manufactured by Sippican or by a company under license to Sippican. The Task Team recommends that users of newly designed probes carefully examine the performance of those probes against known standards such as calibrated CTDs.

6. FUTURE WORK

Based on the results of the general discussion, the Meeting decided that good progress had been made but that a few unforeseen details needed to be resolved. The Meeting decided to take the following actions:

Action	Completion Date
Forward all raw data to K. Hanawa for reprocessing in accordance with procedures developed by the meeting.	June 1991
Sippican to conduct additional XBT test cruise to determine principally the effects of pre-calibration by immersion, probe to probe variability, and nose piece drag factors.	June 1991
K. Hanawa to distribute data to the participants for re-evaluation and review over telemail.	August 1991
Participants to meet again immediately prior to the IGOSS Ship-of-Opportunity Meeting to discuss and finalize results from K. Hanawa's analysis (Appendix).	September 1991

The Meeting examined the long-term need for inter-comparisons and on-going quality control efforts. It agreed that comparisons should be conducted periodically to ensure that systematic or other errors do not creep into the measurements. Sippican agreed to provide probes on a case by case basis for Task Team testing.

7. APPROVAL OF THE REPORT

The meeting approved the Summary Report.

8. CLOSURE OF THE MEETING

The Meeting was informed that the results of this Meeting and follow-up work will be presented at the Ship-of-Opportunity Meeting (1-4 October 1991), the WOCE/TOGA XBT/XCTD Committee (October 1991), and the Sixth Session of the Joint IOC-WMO Committee for IGOSS (November 1991).

The Co-Chairmen thanked the participants and Sippican for their contribution and co-operation.

The Meeting closed at 4:30 pm on Thursday, 6 June 1991.

APPENDIX

SUMMARY REPORT ON THE EVALUATION OF THE SIPPICAN/TSK XBT FALL RATE EQUATION

1. INTRODUCTION

The possibility of an error in the depth equation for expendable bathythermographs (XBTs) was first reported by Flierl and Robinson (1977). Since that time several investigators have obtained revised equations for the fall rate equation using a number of different techniques. The TT/QCAS initiated an effort in 1989 to conduct sufficient testing to adequately quantify the problem and develop a revised equation for universal use in the community.

2. PREVIOUS AND INITIAL RESULTS

The fall rate equation for the XBT is given by the manufacturer to be

$$z = a\,t - b\,t^2 \qquad \text{Eqn.1}$$

where a and b are constants, t is the time elapsed (secs) since the start of descent of the probe, and z is the depth of the probe at time (t). For T-7, T-6, T-4 type probes, the equation is

$$z = 6.472\,t - 0.00216\,t^2 \qquad \text{Eqn.2}$$

Table 1 shows the revised a and b coefficients obtained by past and present investigators for the T-7, T-6, and T-4 types of Sippican XBT probes. These results were obtained by comparing the XBT to standard CTDs. The XBTs have been generally found to fall faster than stated by the manufacturer. Methods which are not independent of temperature error (i.e., not temperature error free) are considered to be inaccurate revisions of the coefficients. The wet calibration procedures used by Sy and Szabados in their 1990 evaluations are considered to have lead to erroneous revised coefficients (subject to verification) which have the probes falling slower that given by the manufacturer.

Figure 1 shows the a and b coefficients obtained by past and present investigators for T-7 type probes. Shown on the figure are contours of maximum deviations in depth, relative to the revised equation of Hanawa and Yoshikawa (1991), for different combinations of a and b from the fall rate equation. Despite the different methods of analysis, most revised values lie within the +/- 10 metres envelope of maximum deviation in depth from the Hanawa and Yoshikawa (1991) equation. These results were deemed as encouraging in relation to the hope of arriving at a new universal equation. The Task Team therefore decided to reanalyze all available XBT-CTD comparison data according to a temperature independent method developed in discussions at an Ad Hoc Meeting of the Task Team in June, 1991, at Marion, Massachusetts, USA.

3. REVISED EQUATION FOR THE SIPPICAN T-7 XBT

The method adopted for the detection of depth errors was a modification of the temperature independent methods individually developed by Hanawa and Yasuda (1991) and Rual (1991). The data used in the analysis were XBT-CTD comparison data collected by 4 institutions since 1985: CSIRO (principal investigator (PI)-Rick Bailey); NOAA/NOS (PI-Mike Szabados); ORSTOM (PI-Pierre Rual); and Tohoku University (PI-Kimio Hanawa). Each XBT was conducted as close in time as possible to the downcast of the CTD to minimize temporal variations in the temperature field during the tests. Figure 2 shows the locations of the various XBT-CTD comparison experiments, and Table 2 gives the details of the experiments.

Figure 3 shows the distribution of depth differences between the XBT and CTD as detected from the 126 profiles used in the analysis. The upper panel shows the frequency distribution of depth differences detected at each 25m interval from 100m to 750m. The scale of the bars is shown in the lower left hand corner. The lower panel shows the profile of the mean depth difference. The close circles denote mean values and the vertical bars are twice the standard deviation. The T-7 XBT is found to be falling faster than specified by the manufacturer. The mean depth difference between the XBT and CTD is approximately 26m at 750m, which is approximately an error of 3.5% of the depth. The T-7 XBT is seen to exceed the depth accuracy specified by the manufacturer (+/- 5m or 2% of the depth, whichever is the largest) from approximately 125m onwards.

From the observed depth differences, the revised equation for the Sippican T-7 XBT was calculated to be

$$z = 6.733\ t - 0.00254\ t^2 \qquad \text{Eqn.2}$$

There was insufficient data to make any conclusions on a revised equation for T-6 and T-4 probes. Preliminary results, however, indicate no significant difference in the equation to that derived for the T-7. Further data will be collected for the T-4 in the next 4-6 months before any conclusions are made.

4. RECOMMENDATIONS

The task team made the following recommendations regarding the present fall rate equation and its future work programme.

1. IGOSS should continue using the existing equations for Sippican XBT probes until:

   - Existing international organizations make a decision on the appropriate solution regarding any change to the fall rate equations taking into account recommendations from the scientific community

   - An international co-ordinated effort to implement the solution is in place and an implementation date is set.

   - A scientific paper to be produced by the Task Team has been reviewed by the scientific community and published in the literature.

2. New codes (or code groups) are required for the JJXX and data center data sets to track probe types to facilitate corrections, etc.

3. Continued evaluations of fall rates for other types of expendable probes and those produced by other manufactures are required.

4. Coordinated ongoing random testing of all manufacturers's XBT's is required.

5. The terms of reference of the Task Team should be reviewed to provide for annual meetings of the group involved in these studies to permit them to consult on the results of their activities and revise their plan of action.

5. REFERENCES

Flierl, G. and A.R. Robinson, 1977: XBT measurements of the thermal gradient in the MODE eddy. J. Phys. Oceanogr., 7, 300-302.

Hanawa, K. and Y. Yoshikawa, 1991: Re-examination of depth error in XBT. J. Atmos. Oceanic Technol., 8, 422-429.

Hanawa, K. and T. Yasuda, 1991: Additional Evidence of XBT depth error using the probes from the Japanese licensed manufacturer. Paper presented at the Ad Hoc Meeting of the IGOSS Task Team on Quality Control for Automated Systems, June 1991, Marion, Massachusetts, USA.

Rual, P., 1991: XBT Depth Correction. Paper presented at the Ad Hoc Meeting of the IGOSS Task Team on Quality Control for Automated Systems, June 1991, Marion, Massachusetts, USA.

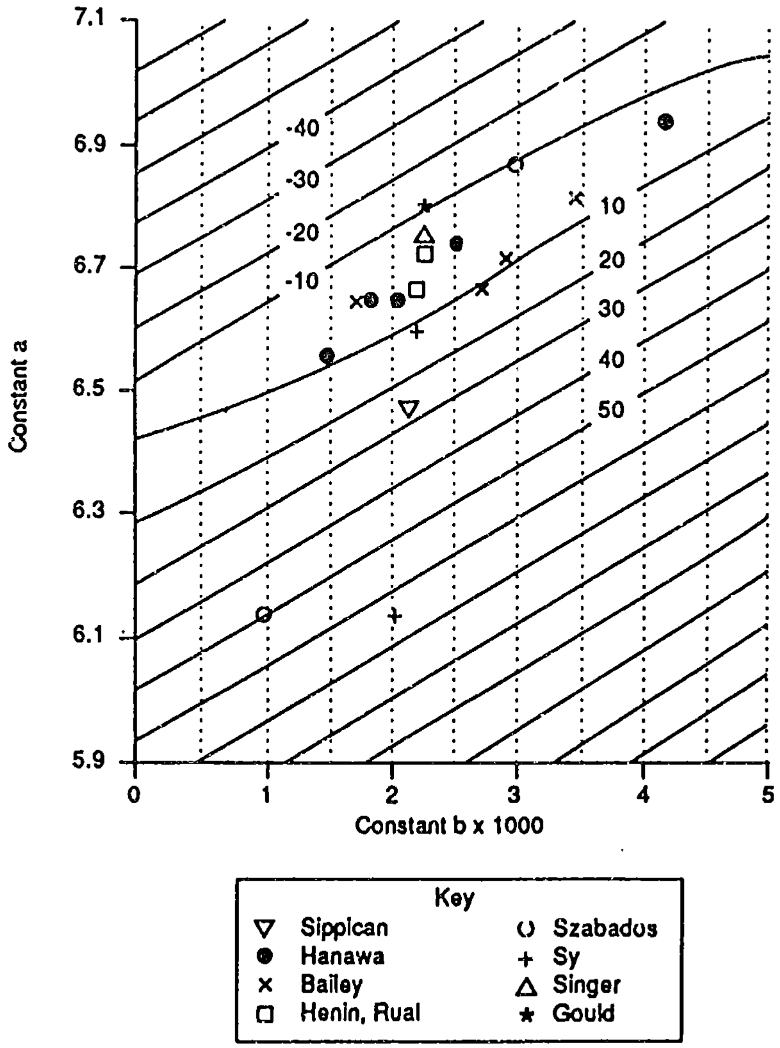


Figure 1 - a + b Co-efficient for indicated XBT studies

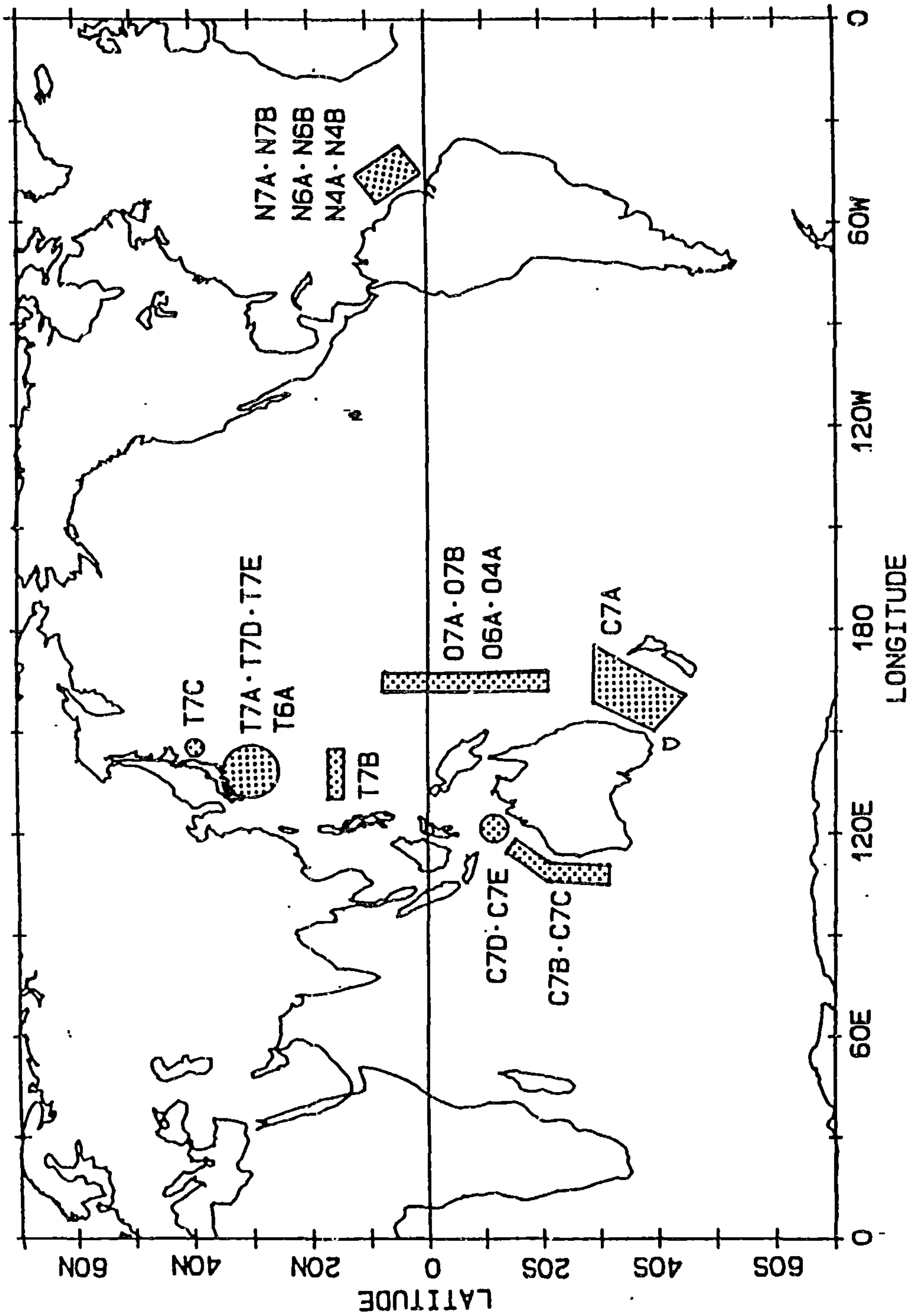
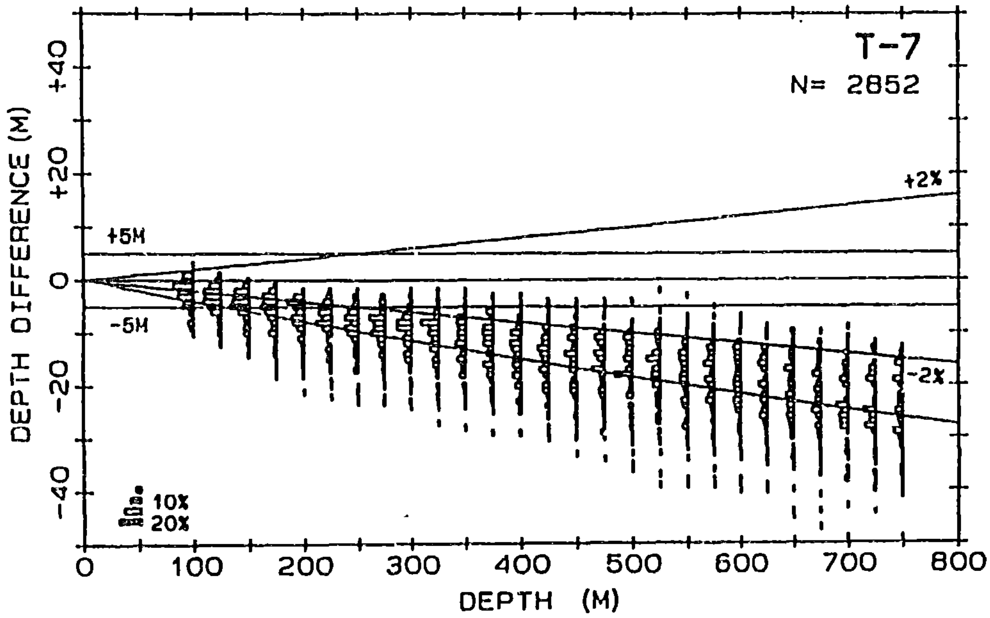


Figure 2 - Locations of XBT-CTD comparison studies



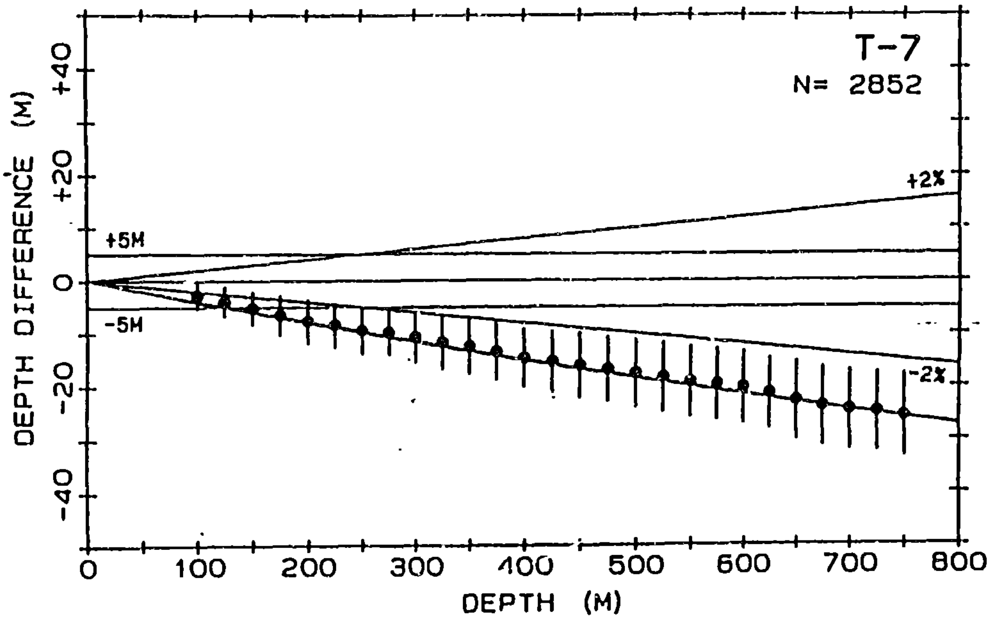


Figure 3 - Distribution of depth differences from the 126 XBT-CTD profiles used in the analysis

Summary of Newly Derived Coefficients for Fall Rate Equations (T-7, T-6, T-4 XBTs)

Table 1 -

$$Zx = a \cdot t - b \cdot 10^{-3}\ t^2$$

Author	Area	Year	Type	Manufac.	Number	Linear Correc %	a	b	Remarks
Hanawa	N. Pacific	1985	T-7	TSK	12		6.741	2.53	Temp. Error
		1987	T-7	TSK	7		6.652	2.03	Free
		1987	T-7	TSK	8		6.941	4.13	
		1989	T-7	TSK	10		6.562	1.48	
		1991	T-7	TSK	4		6.655	1.84	
		1989	T-6	TSK	9		6.553	1.38	
Bailey	S. Pacific	1989	T-7	Sippican	12		6.824	3.46	Temp. Error
	Trop. Indian	1987	T-7	Sippican	8		0.720	2.92	Free
		1987	T-7	Sippican	7		6.645	1.76	
		1987	T-7	Sippican	6		6.665	2.70	
Singer	Trop. Atlantic	1985-1986	T-7	Sippican	25		6.754	2.25	Temp. Error Dependent
Gould	Atlantic(?)	1989(?)	T-7	Plessey	19	5	6.796	2.27	XBT Bottom Hi
Sy	N. Atlantic	1989	DB	Sippican	12	2	6.601	2.20	Temp. Error Fr (Wet Calibratio
Szabados	Trop. Atlantic	1988	T-7	Sippican	7		6.867	2.98	Surf Temp. Err
			T-6	Sippican	7		6.751	1.15	Subtracted
			T-4	Sippican	6		6.812	1.76	(Temp. Error
Henin	Eq. Pacific	1987	T-4	Sippican	35	5	6.796	2.27	Dependent)
Rual	Eq. Pacific	1989	T-7	Sippican	22	3	6.666	2.22	Temp. Error
			T-7	Sippican	11	4	6.731	2.25	Free
			T-4+ T-6	Sippican	16	3	6.666	2.22	
Sy*	N. Altantic	1990	T-7	Sippican	12	-5.1	6.142	2.05	Wet Calibration
			T-6	Sippican	12	-5.8	6.097	2.03	Batch.
			T-4	Sippican	12	-5.5	6.116	2.04	Surf Temp. Err
Szabados*	Trop. Atlantic	1990	T-7	Sippican	14		6.107	0.97	Subtracted
			T-6	Sippican	8		5.982	0.87	(Temp. Error
			T-4	Sippican	8		6.087	0.39	Dependent)

*Subject to Verification

Table 2 - Summary of CTD-XBT comparison experiment for T-7 probles

Total number of probes is 126

Institution	Data set name	Number of XBTs	XBT manufacturer	Experimental date	Cruise name
CSIRO	C7A	12	Sippican	August-September 1989	V1089
	C7B	8	Sippican	March 1987	V0487
	C7C	7	Sippican	March 1987	same as C7B
	C7D	3	Sippican	November 1987	V1087
	C7E	3	Sippican	November 1987	same as C7D
NOAA/NOS	N7A	7	Sippican	July 1988	STACS
	N7B	6	Sippican	July 1988	same as N7A
ORSTOM	O7A	22	Sippican	June-July 1989	SURTROPAC
	O7B	12	Sippican	December 1989	SURTROPAC
TOHOKU	T7A	15	TSK	December 1985	KH-85-5
	T7B	9	TSK	February 1987	KH-87-1
	T7C	8	TSK	September 1987	KT-87-13
	T7D	10	TSK	June 1989	KT-89-9
	T7E	4	TSK	January-February 1991	KH-91-1

Data-set name	XBT data converter used	CTD used	Remarks
C7A	MK-9	Neil Brown	
C7B	MK-9	Neil Brown	suffered by bias-like error
C7C	SA-810	Neil Brown	suffered bowing problem
C7D	MK-9	Neil Brown	
C7E	MK-9	Neil Brown	
N7A	MK-9	Neil Brown III	
N7B	MK-9	Neil Brown III	
O7A	?	SEABIRD model 9	
O7B	?	SEABIRD model 9	
T7A	handmade(ORI)	Neil Brown IIIb	suffered by bias-like error
T7B	handmade(ORI)	Neil Brown IIIb	
T7C	Z-60-II	Neil Brown IIIb	
T7D	Z-60-II	Neil Brown IIIb	
T7E	Z-60-II	Neil Brown IIIb	

ANNEX I

AGENDA

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ANNEX II

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ANNEX III

TEMPERATURE TO RESISTANCE EQUATION

Sippican XBT Recorders

The Sippican recorder bridge circuit contains a linearization resistor which corrects for the thermistor response with an inverse function to create a bridge output voltage increasing linearly with temperature and accurate to approximately to plus or minus 0.5 degrees Centigrade. All present Sippican recorders then correct the plus or minus 0.5 degree error in the host computer. Old recorders such as the Mk-2A used a non-linear temperature grid on the chart paper output to make the correction.

Thermistor Temperature to Resistance Equation:

$$T = \frac{1}{A + B \ln R + C(\ln R)^3}$$

A = 1.28928665692E-3
B = 2.35498902711E-4
C = 9.55620646318E-8

T is temperature in Kelvin
R is the thermistor resistance

Comments of XBT bowing:

The Sippican Bridge circuit used in all Sippican recorders sends approximately 80 to 120 microamperes through the A-wire and the thermistor to seawater ground and an equal amount of current through the B-wire directly to sea water ground. The insulation integrity of the wire is specified to be sufficient to keep wire current leakage to sea water insignificant relative to the above thermistor currents. If one were to use a thermistor measuring circuit that sent 12 microamperes of current through the thermistor, one would need a ten times improvement in XBT wire insulation impedance to achieve the same wire leakage performance. Wire leakage affects will be dramatically increased when using the 12 microampere measurement circuit. In addition, the speed that XBT wire can "heal" will be slowed at the lower current level.

ANNEX IV

RELEVANCE TO TOGA OF SYSTEMATIC XBT ERRORS

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Introduction

Over recent years expendable bathythermographs (XBTs) have become increasingly relied upon in large-scale oceanographic research programs. An assessment of the accuracy of XBTs, and the systems used to drive them, is therefore essential.

The depth accuracy of XBTs has been the subject of many studies [1,2,3,4]. These studies have proposed alternative fall-rate equations to the one specified by the manufacturer on the basis of the errors observed in the depth of the XBT. Other investigators [5,6] have concentrated on the temperature calibration of the probe thermistors in an effort to improve the accuracy of XBTs.

The aims of this study are to:

- provide further calibrations of XBTs and XBT systems by comparing them with conductivity-temperature-depth (CTD) sensors.
- evaluate the applicability of the various depth-correction algorithms mentioned above.
- examine the implications of the observed depth and temperature errors to a large-scale research program such as TOGA (Tropical Ocean and Global Atmosphere).

Instrumentation and Methods

Two types of digital XBT systems were calibrated against the RV *Franklin*'s Neil Brown CTD Profiler during separate voyages in 1987 (Table 1). Both types of XBT system are used in the CSIRO's Ship-of-Opportunity Program (SOOP). The MK-9 XBT system was used in two configurations for the calibration experiments; with the *Franklin*'s PDP-11 data logging system, and with an HP-85 microcomputer as deployed on ships-of-opportunity. Deep Blue XBTs, from the same batch, were used throughout the calibrations.

The CTD station positions are shown in Fig. 1. Typically, XBTs were dropped 10–20 minutes prior to the descent of the CTD profiler at each station.

The temperature profiles recorded by the CTD Profiler for both voyages are shown in Fig. 2.

Depth and Temperature Errors

(a) *Depth Errors*

Figs. 3(a) and 4(a) give examples of the average temperature error ($T_{XBT}-T_{CTD}$) as a function of depth for two of the XBT System/CTD calibration experiments. The characteristic shape of both profiles of temperature error is similar to that found in the experiments of Hanawa and Yoritaka[4]. They found the negative errors in temperature to be mainly due to the errors in depth that result from the XBT falling faster than specified by the manufacturer's fall-rate equation. The largest errors in temperature correspond to the depths of large temperature gradient in the temperature profiles (cf Fig. 2). This is where the depth error due to an incorrect fall-rate has its largest effect.

Figs 3(b) and 4(b) give examples of the average temperature error ($T_{XBT}-T_{CTD}$) as a function of depth for the same two calibration experiments, however, the depths of the XBTs have been corrected according to the depth-correction algorithm developed by Hanawa and Yoritaka[4]. This algorithm proved to be the most successful at reducing the mean and rms temperature errors for each of the three calibration experiments. The rms temperature error was consistently reduced from above to below the accuracy of the XBT (±0.15°C). The depth-correction algorithm according to Heinmiller et al.[1], on the other hand, actually increased the rms temperature error for each case.

Unfortunately, some errors in temperature still remain at depths corresponding to large temperature gradients, even after the data has been corrected according to Hanawa and Yoritaka[4]. The fall-rate correction of Hanawa and Yoritaka[4] is therefore not totally applicable in the waters of this study, although it does improve the data.

(b) *Temperature Errors*

Start-up Transients: Large start-up transients in the upper 4 m were observed for the SEAS II XBT System (Fig. 5), and to a lesser extent for the MK-9 XBT System. The mean difference between the first temperature digitisation (0.6 m) and the temperature at 3.9 m (commonly used as the sea surface temperature due to such transients) was -9.50 ± 10.08°C for the SEAS II XBT System, compared to 0.41 ± 0.30°C for the MK-9 XBT System.

SEAS II Mixed Layer Anomaly (Bowing): The need for the comparison of XBT data with a precision CTD sensor was first invoked by the observation of anomalies in the mixed layer temperature profiles recorded by SEAS II XBT Systems deployed in the CSIRO SOOP in the western tropical Pacific. A gradual increase, or "bowing", in temperature was observed as opposed to an isothermal profile. An example is given in Fig. 6. Such anomalies were not present in the data recorded by the MK-9 XBT Systems.

The upper 200 m of the temperature profiles recorded by the SEAS II XBT System and the CTD Profiler during FR0487 are shown in Figs 7(a) and 7(b) respectively. The gradient in temperature in the mixed layer for a single XBT and its corresponding CTD are highlighted to emphasize the "bowing" problem. The corresponding average error in temperature ($T_{XBT}-T_{CTD}$) in the mixed layer as a function of depth is shown in Fig. 7(c). The mean SEAS II XBT temperature in the mixed layer starts less than and finishes greater than the mixed layer temperature given by the CTD. On examination of each individual XBT/CTD comparison, however, the start and finish temperatures of the SEAS II XBT System were found to be randomly distributed in relation to the CTD mixed layer temperature. In some cases the SEAS II temperature starts above the CTD mixed layer temperature and finishes further above it. In other cases, it may start below it and finish equal to it.

The above results indicate a possible drift problem with the electronics of the SEAS II XBT System. The temperature errors may also extend deeper than the mixed layer. We can only distinguish the problem in the mixed layer where the real temperature gradient is zero.

Implications for TOGA

(a) Isotherm Depth Errors

If we assume the corrected depth (z') from Hanawa and Yoritaka[4] to be the true depth of the XBT, then Fig. 8 shows the depth error (z–z') as a function of depth, where z is the depth of the XBT given by the manufacturer. The depth accuracy of the XBT at any given depth is also shown. A 20°C isotherm depth of 200 m, for example, will be measured by an XBT as occurring at a depth of approximately 192.5 m — an error of 7.5 m. The depth error exceeds 25 m at a depth of 800 m, and exceeds the depth accuracy of the XBT (5 m or 2% of the depth, whichever is greater) at a depth of approximately 135 m.

(b) Dynamic Height Errors

Table 2 shows the mean error in dynamic height (D_{XBT}–D_{CTD}) relative to 200 m, 400 m and 700 m for the three calibration experiments. The errors are small both before and after the correction for depth of the XBT. Values range from –0.019 dyn m to 0.001 dyn m. Fortunately, the largest temperature gradients in the tropics are shallow enough for errors in temperature, which affect the dynamic height, to be small. The error in depth, which affects the temperature error, is relatively small at these shallower depths.

The depth correction from Hanawa and Yoritaka[4] successfully reduces the error in dynamic height for the MK-9 XBT System, but increases it for the SEAS II XBT System. The additional positive errors in temperature caused by the "bowing" problem of the SEAS II XBT System are possibly cancelling some of the negative errors in temperature that result from errors in depth. The dynamic height error, which depends on temperature, is therefore reduced for the SEAS II XBT System.

(c) Mixed Layer Temperature Errors

A mixed layer bowing index, defined as the maximum temperature of a profile minus the temperature at 5 m, was used to estimate the typical magnitude and frequency of the mixed layer anomaly recorded by the SEAS II XBT Systems deployed in the CSIRO SOOP. The results for the XBT data recorded in 1987 are given in Table 3. Potentially, 34.4% of the data had errors greater than the temperature accuracy of the XBT (±0.15°C). Some profiles recorded indexes of 0.7°C (Fig. 6) and above.

Fig. 9 shows the error in monthly heat storage rates as a function of the potential error in mixed layer temperature due to "bowing". The errors are shown for two characteristic mixed layer depths (MLD). Given the mean index for 1987 from Table 3 of 0.22°C, the corresponding error in the monthly heat storage rate is approximately 18 W/m^2 for a mixed layer depth of 100 m. This is an unacceptable source of error in heat budget studies.

(d) Sea Surface Temperature Errors

The shallowest depth that should be used to estimate sea surface temperature (SST) from an XBT is 3.9 m due to start-up transients. Large errors in SST will be observed otherwise.

Conclusions

- The depth-correction algorithm according to Hanawa and Yoritaka[4] proved the most effective in reducing the mean and rms temperature errors for this data set. However, as neither this correction nor the other corrections that were applied completely reduced the temperature errors observed between the XBTs and CTD Profiler, further studies on the factors that vary the fall-rate of XBTs between different locations will need to be undertaken before a generally applicable depth-correction algorithm will be found. This will have to be done for each type of XBT probe.

- Temperature errors observed in the mixed layer, due to the "bowing" problem associated with the SEAS II XBT System, are a significant source of error for TOGA. A thorough engineering analysis of the electronics of this system is recommended before future use of the system. On the results of this study, CSIRO has replaced the SEAS II units in its SOOP with MK-9 XBT Systems.

References

1. Heinmiller, R., C. Ebbesmeyer, B. Taft, D. Olson and O. Nikitin (1983): Systematic errors in expendable bathythermograph (XBT) profiles. *Deep-sea Research* 30, 1185–1196.

2. Seaver, G., and S. Kuleshov (1982): Experimental and analytical error of the expendable bathythermograph. *Journal of Physical Oceanography* 12, 592–600.

3. Green, A. (1984): Bulk dynamics of the expendable bathythermograph (XBT). *Deep-sea Research* 31, 415–426.

4. Hanawa, K. and H. Yoritaka (1987): Detection of systematic errors in XBT data and their correction. *Journal of the Oceanographical Society of Japan* 43, 68–76.

5. Georgi, D., J. Dean and J. Chase (1980): Temperature calibration of expendable bathythermographs. *Ocean Engineering* 7, 491–499.

6. Roemmich, D. and B. Cornuelle (1987): Digitisation and calibration of the expendable bathythermograph. *Deep-sea Research* 34, 299–307.

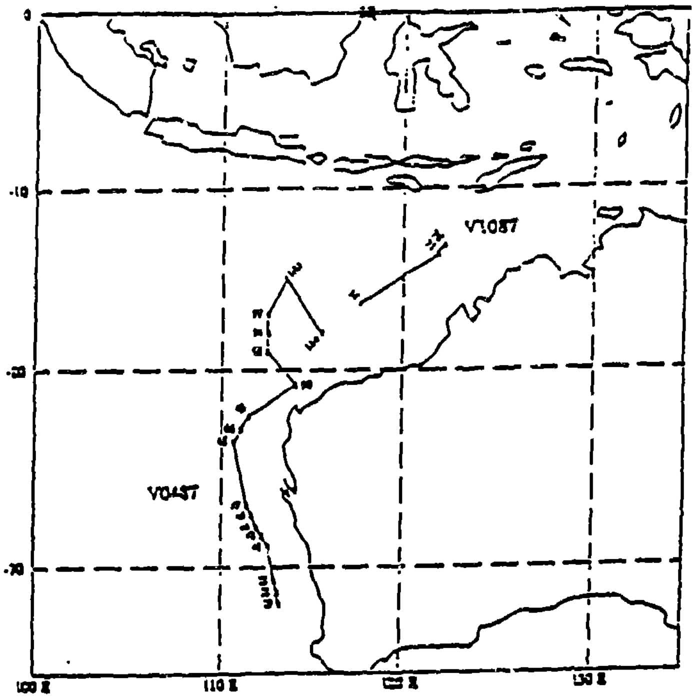


Fig. 1. RV *Franklin* V0487 and V1087 CTD station positions.

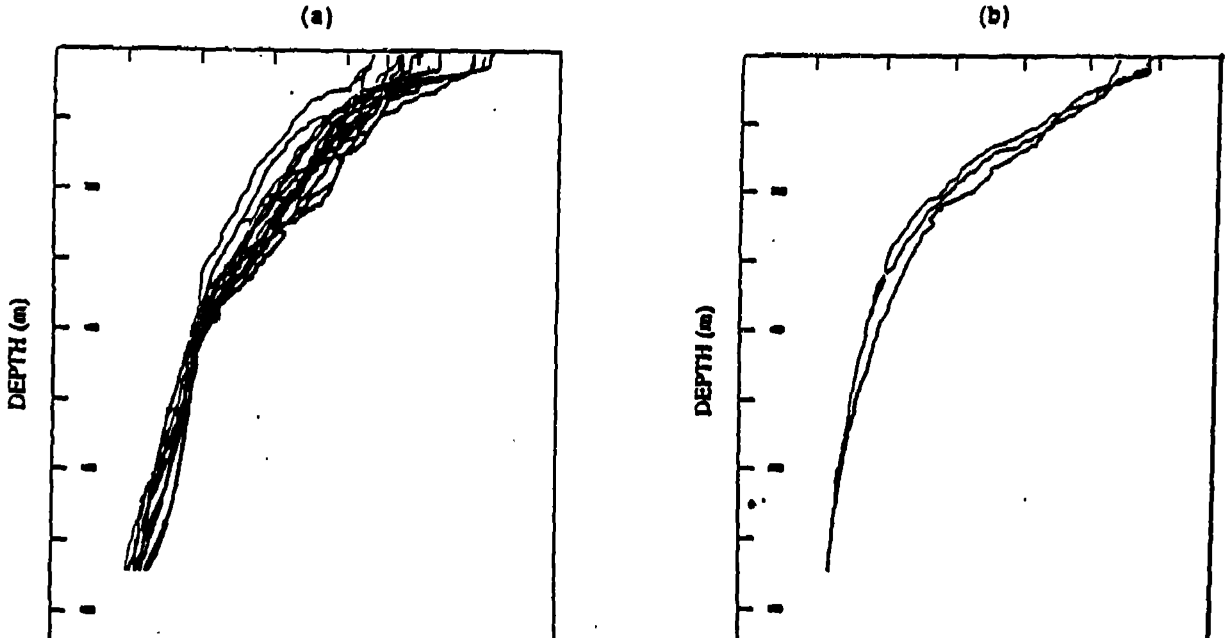
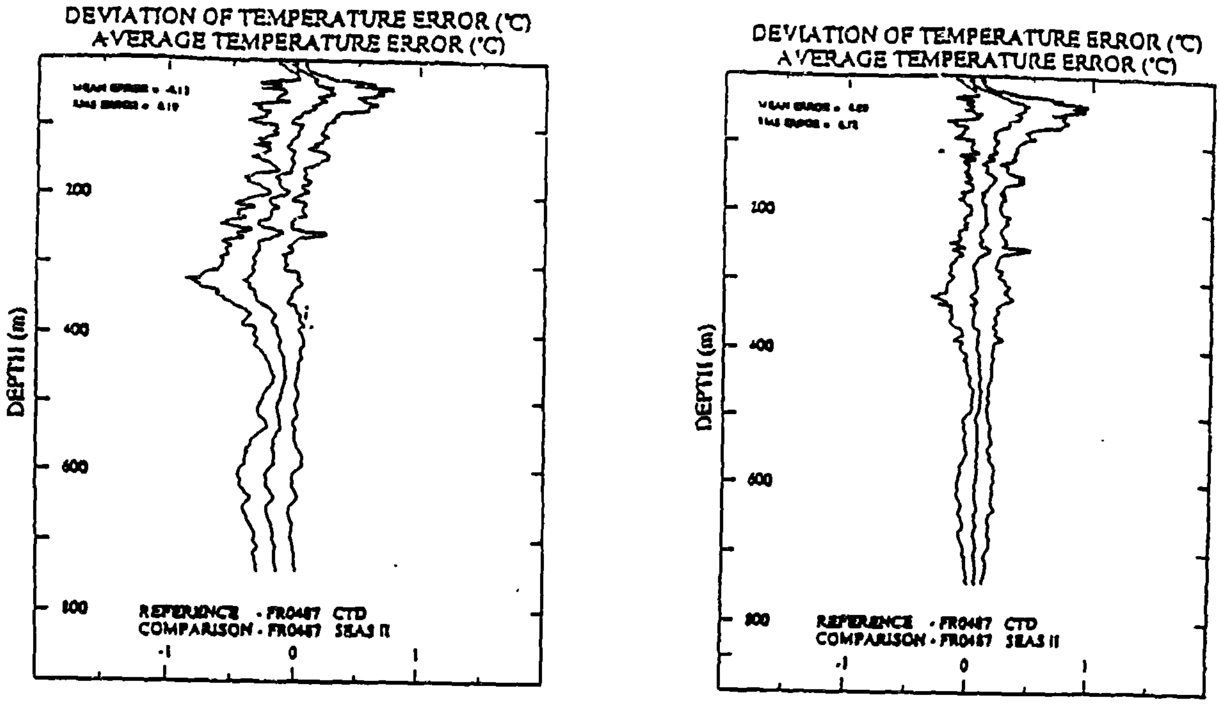
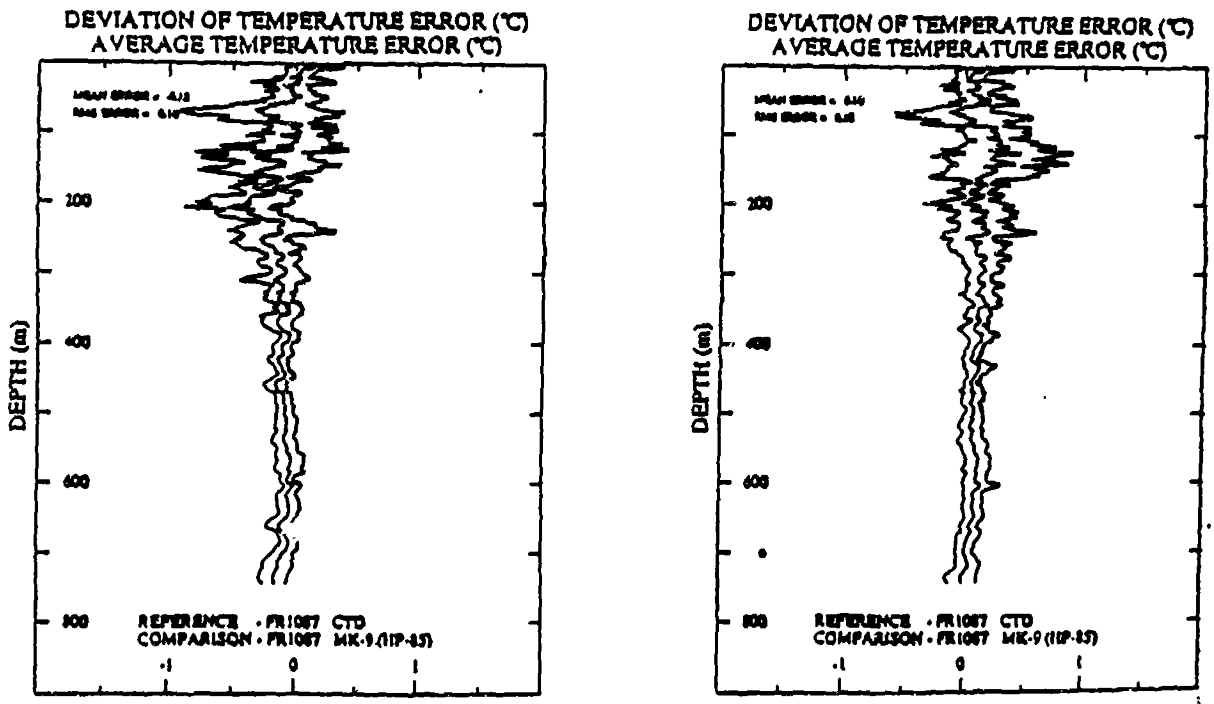


Fig. 2 CTD temperature profiles: (a) FR0487; (b) FR1087.



(a) (b)

Fig. 3. Average temperature error profiles ($T_{XBT}-T_{CTD}$) for XBT/CTD comparisons on FR0487 using the SEAS II XBT System; (a) depth uncorrected; (b) depth corrected according to Hanawa and Yoritaka[4].



(a) (b)

Fig. 4. Average temperature error profile ($T_{XBT}-T_{CTD}$) for XBT/CTD comparisons on FR1087 using the MK-9 XBT System: (a) depth uncorrected; (b) depth corrected according to Hanawa and Yoritaka[4].

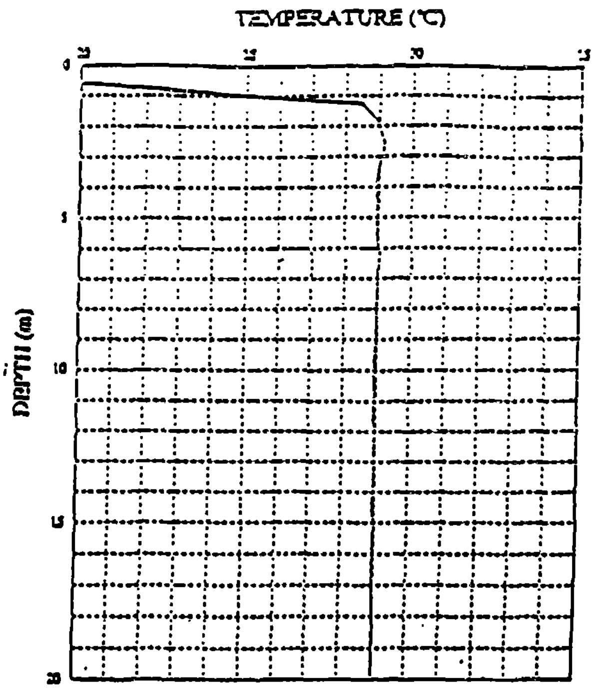


Fig. 5. Example of a start-up transient from a SEAS II XBT System.

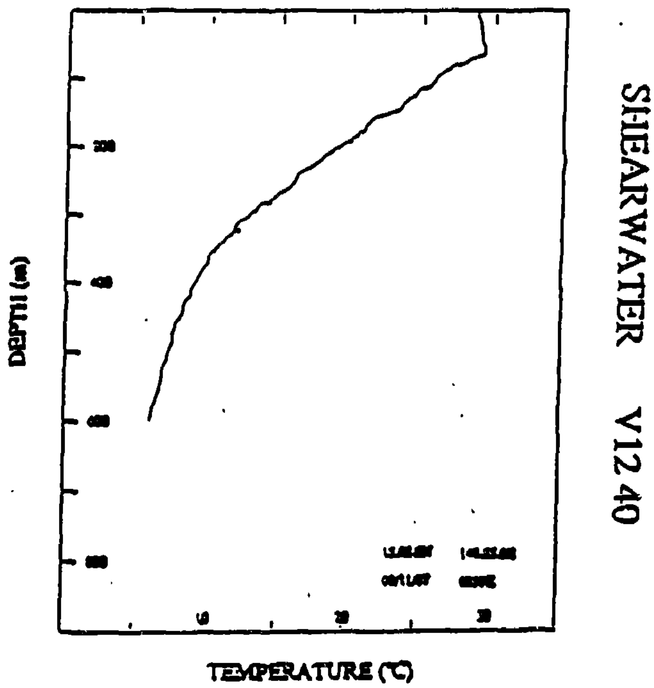


Fig. 6. Example of a mixed layer anomaly recorded by a SEAS II XBT System.

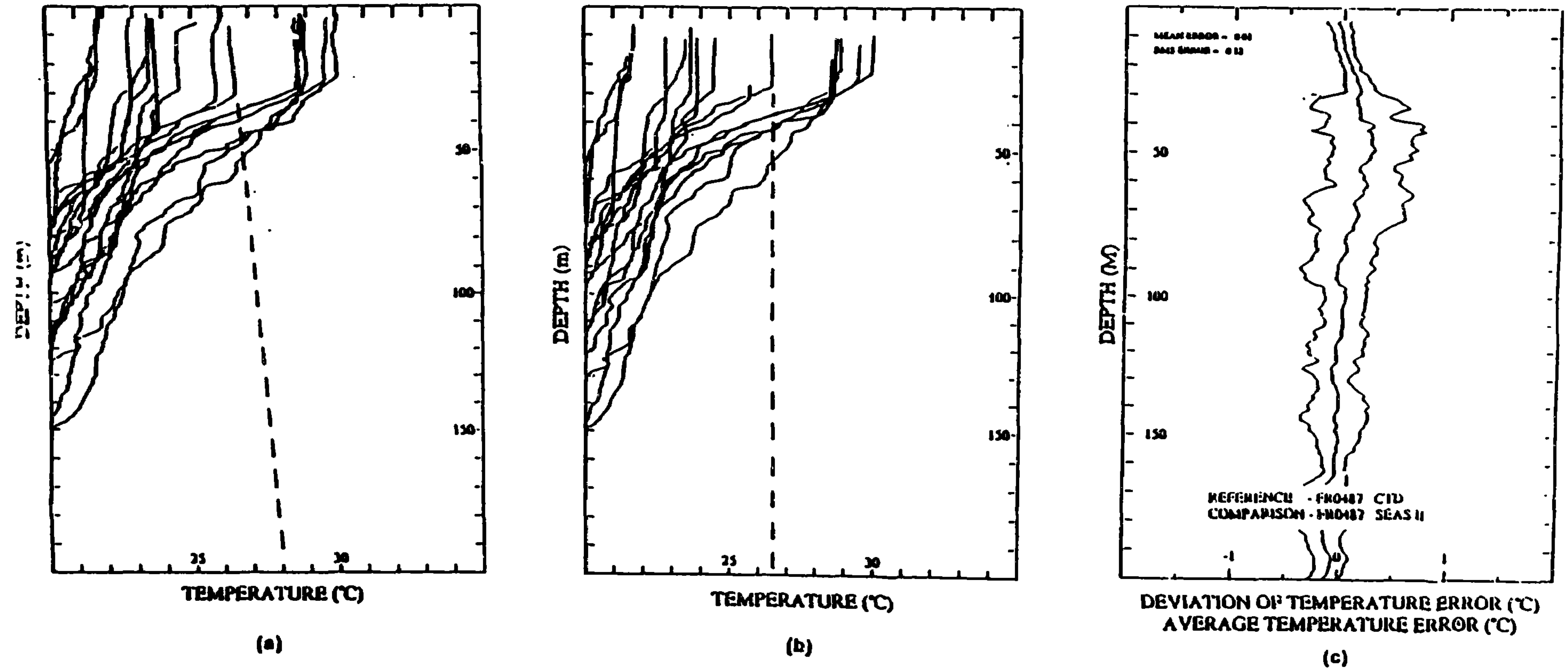


Fig. 7. (a) SEAS II temperature profiles (upper 200 m) for FR0487; (b) CTD temperature profiles (upper 200 m) for FR0487; (c) corresponding average temperature error profile (upper 200 m)

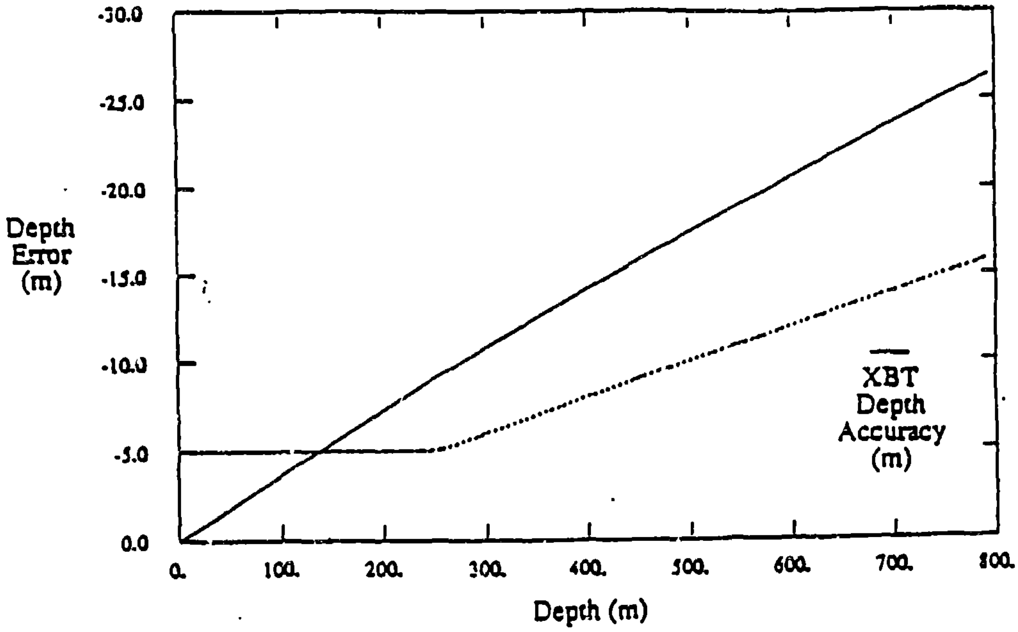


Fig. 8. Depth error of the XBT as a function of depth.

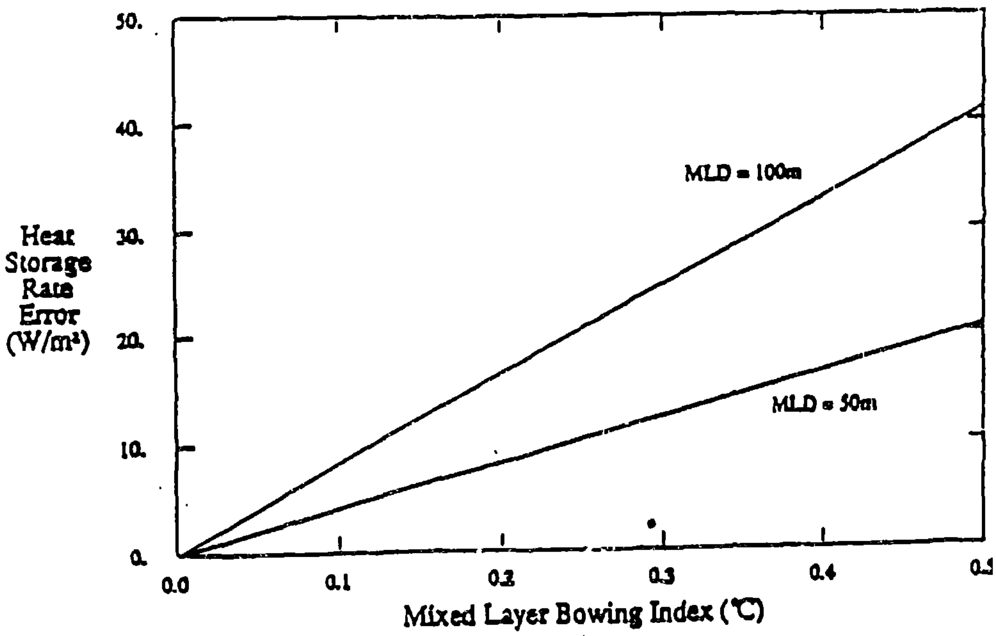


Fig. 9. Error in monthly heat storage rate due to the "bowing" problem of the SEAS II XBT System.

Table 1

Calibration Experiment #	Voyage	XBT System Description	XBT Type	Number of XBTs	Number of Corresponding CTDs
1	FR0487	SEAS II/Bathy Systems SA-810 (HP-85)	Deep Blue	17	17
2	FR1087	Sippican MK-9 (HP-85)	Deep Blue	14	3
3	FR1087	Sippican MK-9 (PDP-11)	Deep Blue	12	3

Table 2

DYNAMIC HEIGHT ERROR

Voyage	XBT System	Error in Dynamic Height Relative to 200 m (dyn m)		Error in Dynamic Height Relative to 400 m (dyn m)		Error in Dynamic Height Relative to 700 m (dyn m)	
		Mean	Standard Dev.	Mean	Standard Dev.	Mean	Standard Dev.
FR0487	SEAS II/Bathy Systems SA-810 (HP-85)	0.001 (0.007)	0.007 (0.008)	-0.009 (0.010)	0.013 (0.013)	-0.012 (0.020)	0.013 (0.014)
FR1087	Sippican MK-9 (HP-85)	-0.011 (0.004)	0.007 (0.006)	-0.012 (0.011)	0.009 (0.009)	-0.016 (0.012)	0.011 (0.011)
FR1087	Sippican MK-9 (PDP-11)	-0.011 (0.003)	0.008 (0.009)	-0.013 (0.008)	0.008 (0.008)	-0.019 (0.009)	0.012 (0.011)

( ) after XBT depth correction according to Hanawa and Yoritaka[4].

Table 3

SEAS II MIXED LAYER ANOMALY ANALYSIS 1987
(Estimate)

Index = $T_{max} - T_{5\ meters}$

Total number of drops = 1739
Total number of anomalous drops = 1223
Mean Index for anomalous drops = 0.22

Index Bin	Index >	Range ≤	Frequency	Percentage of Total Drops
0.1	0.05	0.15	625	35.94
0.2	0.15	0.25	315	18.12
0.3	0.25	0.35	133	7.65
0.4	0.35	0.45	44	2.53
≥0.5	0.45	—	106	6.10
			TOTAL = 1223	TOTAL = 70.34

ANNEX V

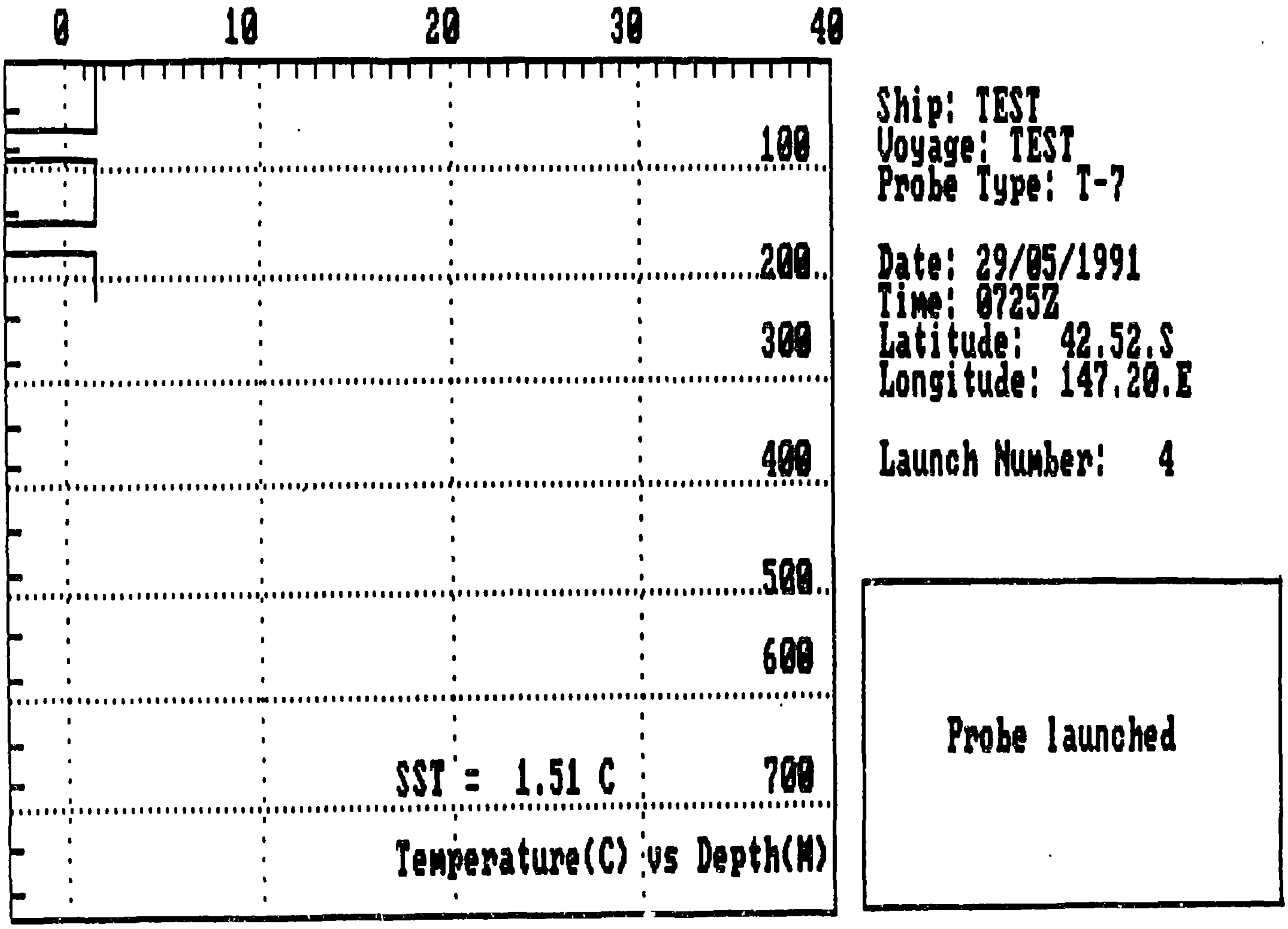
ERRORS IN START OF DESCENT TIMING IN XBT DATA ACQUISITION EQUIPMENT

During testing of the XBT Data Acquisition Equipment on the bench it was discovered that there is a random delay between contact being made between the test canister and earth (in real deployment this occurs when the probe hits the water), and the computer recording the first data point. It had been reported by other users that this delay was in the region of 0.3 - 0.6 seconds resulting in a depth error of up to 2 metres. However, the delay on our own equipment appeared to be considerably more than this with certain equipment configurations, sometimes up to 3 sec. Subsequently it was found that Sippican had failed to notify us that the GPIB driver (file GPIBDVR.COM on the program disk) supplied with V4.0 of their software was incompatible with V3.x firmware/V4.x software and that a previous version of the driver should be used. The correct version is dated 22/12/85, but some 500 profiles had been recorded by four of the Voluntary Observing Ships using the incorrect driver (6/10/88). All these profiles thus had a random delay resulting in faulty depths.

The purpose of these tests was to determine the nature of the delay (mean, std dev.), both in the correct and incorrect versions so that an attempt could be made to correct the faulty data.

A timing device was constructed by the electronics lab which is placed in the earth lead from the test canister to the Sippican Mk9 Unit. The switch on the test canister is left on 'launch' and the switch on the timer replaces this function. The timing device, when switched on, operates a simple on/off switch and can be set to any time between 1 sec and 255 sec. by means of dip switches. When switched on the circuit is completed and the computer starts to record data from the test canister. After a set period (10 sec. was chosen for efficiency) the circuit is broken and the computer records negative values from the test canister until the timer makes the circuit again. Tests were carried out specifying T-10, T-4 and T-7 probe types.

From each profile thus obtained the time at which the data went negative was calculated. Since data is collected at the rate of 10Hz (one data point every 0.1 sec) this should occur at the 100th data point. This figure was compared with the actual number of recorded data points up to the data going negative and the delay calculated. The timer was also tested by calculating the number of data points recorded during the second on/off cycle of each profile. A histogram of the distribution for each set of tests was also produced.


0
10
20
30
40
100
200
300
400
500
600
700
SST = 1.51 C
Temperature(C) vs Depth(M)
Ship: TEST
Voyage: TEST
Probe Type: T-7
Date: 29/05/1991
Time: 0725Z
Latitude: 42.52.S
Longitude: 147.20.E
Launch Number: 4
Probe launched

Results

Test number	N	Mean delay (sec)	Std. Dev. (sec)	Mean depth error (metres)
1	100	2.22	0.72	13.90
2	100	2.16	0.80	13.92
* 3	100	2.27	0.76	14.60
4	100	2.60	0.54	16.28
5	100	0.34	0.18	2.14
6	100	0.24	0.07	1.49
7	100	0.36	0.19	2.34
8	100	0.44	0.18	2.81
9	100	0.41	0.20	2.61
* 10	100	1.69	0.81	10.82
* 11	100	2.25	0.60	14.45
*Composite 3,10,11	300	2.07	0.77	13.29

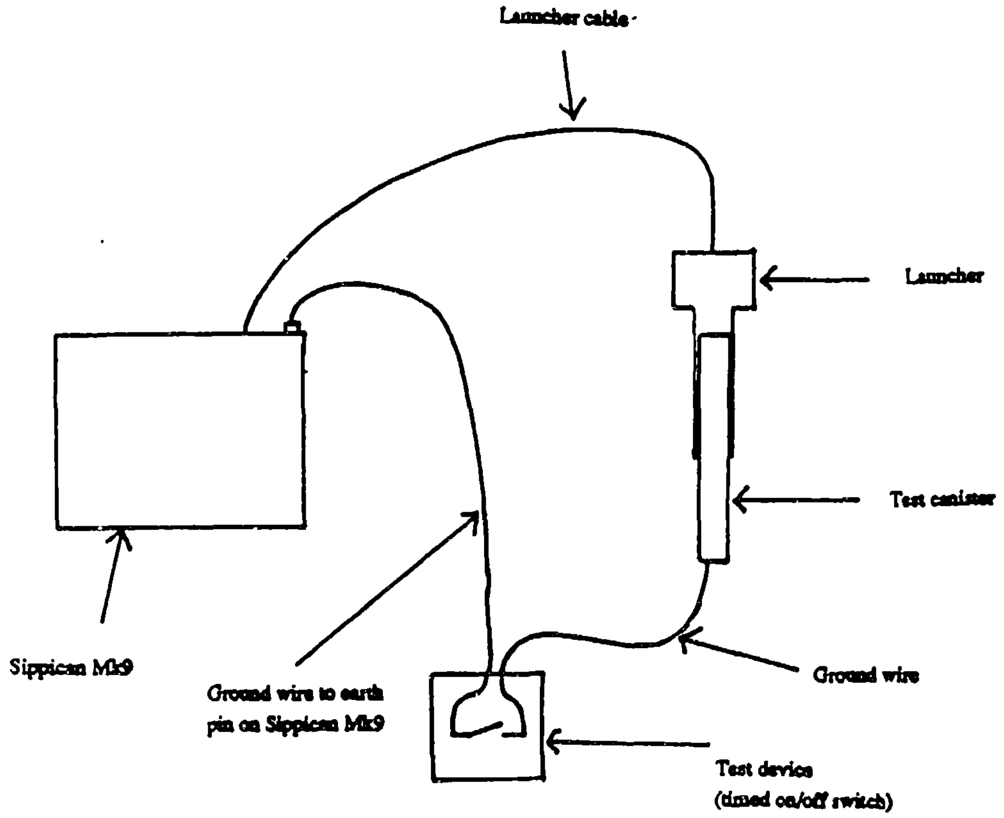
Equipment configurations examined.

Eleven tests were conducted, each of 100 profiles. All but one were conducted on the Toshiba T1200 computer as used on the CSIRO Voluntary Observing Ships; one test used a Toshiba T3200sx computer. The data acquisition program used is the Sippican Ver 4.0 program, in both its original form (dated 26/10/89) and the CSIRO version (dated 19/10/90). Tests were done using both the R3.0 and the R3.1 versions of the firmware ROM supplied by Sippican.

Test number	GPIB driver	Data Acquisition program	Sippican firmware rom	Probe type	Computer Toshiba
1	'88	26/10/89	3.0	T10	T1200
2	'88	26/10/89	3.0	T4	T1200
* 3	'88	26/10/89	3.0	T7	T1200
4	'88	19/10/90	3.0	T10	T1200
5	'85	19/10/90	3.1	T10	T1200
! 6	'85	02/01/91	3.1	T10	T3200sx
7	'85	26/10/89	3.0	T7	T1200
8	'85	26/10/89	3.1	T7	T1200
9	'85	19/10/90	3.1	T7	T1200
* 10	'88	26/10/89	3.0	T7	T1200
* 11	'88	26/10/89	3.0	T7	T1200

* These tests have the same components as those in use on the CSIRO Voluntary Observing Ships which produced the faulty data, giving a total of 300 tests.

! This latest version of the CSIRO Data Acquisition Program is comparable to the 19/10/90 version for the purposes of these tests.



Schematic diagram of test equipment.

ANNEX VI

INTERMITTENT DEPTH OFFSET CAUSED BY TRIGGER DELAY

Product: MK9 Data Acquisition Software
Version: Version V4.x February 1989
Component: MK9 Firmware V3.x

Intermittent Depth Offset Caused by Trigger Delay

Overview

A previous dispatch, October 1989, discussed a perceived problem with the MetraByte software driver. It appeared that the newer version of the GPIBDVR.COM, REV3.00, caused some strange behavior for the V3.x firmware/V4.x software combination. The recommended fix was to revert to an older version of the GPIBDVR.COM, REV1.20.

During a routine bench checkout of a MK9 recorder system (including a new PC), the operator noticed a varying delay between seawater activation and the appearance of a trace on the screen. Also, on occasion, the trace would stop prior to reaching terminal depth.

Problem

A customer reported a problem with the V3.x firmware. The customer was performing simultaneous drops comparing a MK9 system to a homemade XBT interface box. Typically, the two profiles matched quite well. However, occasionally the Sippican MK9 profile would exhibit a slight depth offset. The customer investigated the problem by connecting a common XBT simulator to two MK9 systems. One system used the V2.x firmware and the other system used the V3.x firmware. The V3.x system exhibited an intermittent delay between the activation of the seawater return and the audible indication of a probe launch. The delay time, as measured with a stopwatch, was approximately .2 to .3 seconds. The V2.x system never exhibited this behavior.

Analysis

A MK9 system was configured with the V3.x firmware and connected to a PC running the V5.x acquisition software. The older GPIBDVR.COM program (REV1.20) was resident.

The first goal of the investigation was to accurately measure the time between the start of the first A/D sample and the transmission of this sample to the PC. A logic analyzer was attached to the following signals:

1. Start-of-Descent logic signal, XBT PCB.
2. BUSY logic signal, XBT PCB.
3. NDAC GPIB handshake signal, Controller PCB.

The first measurement showed that the Start-of-Descent signal remained active for 10 milliseconds. This time period is normal since the the overall delay time between sensing seawater return and starting the measurement cycle consists of 9 millisecond SOD delay and a 1 millisecond front-end delay. The BUSY logic signal from the A/D convertor went active 100 milliseconds after the Start-of-Descent signal went inactive. This time period is normal since the conversion for the first sample is not started until the fixed sample period has expired (100 milliseconds). The BUSY logic signal remained active for approximately 77 milliseconds, the normal conversion time for the A/D convertor. The time of interest is the time between the start of BUSY active and the first active NDAC signal. The expected time was approximately the conversion time of the A/D convertor since the data should be transmitted immediately after the conversion is completed. However, a sample of ten trials showed a wide variance of times ranging from 76.8 mS to as great as 399.1 mS. The maximum allowable time was 177 mS. The problem as reported by the customer was duplicated.

The same setup was repeated for the V2.x firmware. The critical times ranged from 76.78 mS to 132.8 mS. The V2.x firmware exhibits the variability but does not exceed the 177 mS limit; hence, the V2.x firmware appears to work fine.

The examination of the code differences between V2.x and V3.x shows a single instruction added to the V3.x code. However, it seems inconceivable that a single instruction can cause such a difference. The investigation continued at the PC software level.

Various combinations of code rewrites and GPIBDVR.COM revisions produced a solution that eliminates the intermittent trigger delay and provides consistent performance.

Solution

The problem appears to be with the adjustment of the transfer time-out period for the MetraByte driver. The MetraByte TIMEOUT command controls the time-out period for GPIB command and data transfer activity. The time-out is specified as an integer multiplier. The effect of the integer multiplier depends on the revision level of the driver.

For REV1.20, the default time-out is specified as 0.6 seconds and the integer multiplier is specified as 1.5 seconds for PC/AT and 3.5 seconds for PC/XT computers. The specified times will vary with the PC's clock speed. For REV3.00, the default time-out is specified as 2 seconds and the integer multiplier as 56 milliseconds.

Due to the variability of the integer multiplier effect, the MK9 application must be able to differentiate between the two driver revisions. In addition, the REV3.00 driver requires a Bus Clock Speed parameter. The default clock speed is 4 MHz.

The solution consists of an additional function and two calls to the MetraByte TIMEOUT subprogram. The new function, written in Microsoft C, checks for the existence and revision of the MetraByte driver. If the driver is resident, a global variable is set to indicate the resident revision level, REV1.20 or REV3.00. A call to the TIMEOUT subprogram is performed just prior to the prelaunch cycle and once again before probe launch. The integer multiplier is selected for the optimum performance for the resident driver. In addition, if REV3.00 is resident, the SYSCON command is enhanced with the CLOCK parameter set to 8 MHz. The calls to TIMEOUT are used in the XBT, XSV, and AXBT measurement subprograms.

The above described fixes are incorporated into the V5.1 maintenance release.

Restricted distribution

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ADDENDUM TO THE SUMMARY REPORT

SUBMITTED PAPERS

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ADDENDUM TO THE SUMMARY REPORT **Page**

The presentation given by M. Whalen, Sippican, Inc. is available upon request from Sippican, Inc.

EXAMINATION OF ERRORS IN XBT DEPTHS

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Introduction

Temperature profiles recorded by expendable bathythermographs (XBTs) may potentially suffer from three sources of error. One is associated with the accuracy of the thermistor and probe assembly in measuring temperature, the second stems from problems with the electronic measuring and digitising circuitry, and the third involves errors in the probe's inferred depth from its measured time of descent.

In this study the XBT fall rate as given by the manufacturer is examined using a series of XBT/CTD comparisons. While temperature errors associated with the observed depth errors of the XBT are discussed, temperature errors associated with the probe assembly or recording equipment are not specifically examined in detail.

Field Measurements

The XBT/CTD comparisons were carried out during several voyages of the R.V.Franklin in 1987 and 1989. Two types of digital XBT recording systems were used (Sippican Mk-9 and Bathy Systems SA-810) in conjunction with the R.V.Franklin's Neil Brown CTD Profiler. The Sippican Mk-9 XBT system was driven by two different computer configurations, although, both configurations basically used the same software. Sippican Deep Blue T-7 type probes were used throughout the study.

The locations, times, and dates for each XBT/CTD comparison are given in Fig.1 and Table 1. The data have been divided into separate data sets depending on the XBT system configuration. All XBT/CTD comparisons shown have a time difference between the XBT and CTD launch (downcast only) of less than or equal to ten minutes. This minimizes the effects of any temporal variabilty present in the thermal structure in the regions being sampled. The temperature profiles recorded by the CTD Profiler associated with each voyage (and appropriate data sets) are given in Figs 2a-2c.

Method of Analysis

Hanawa and Yoritaka (1987) developed a method for determining depth errors of the XBT which is independent of any systematic temperature difference between the XBT and CTD. Their method was adopted for this analysis. By forming the temperature depth derivative of both the XBT and CTD data, similar gradient features (in the form of maxima and minima) can be observed and compared between the XBT and CTD traces. These features are more easily discernible than the associated features in the original temperature profiles. The depth of a feature observed by an XBT can then be compared to the actual depth as measured by the CTD to obtain the depth error in the XBT.

The data were initially low passed filtered and differentiated according to the method given by Kaiser and Reed (1977). The filter parameters were set such that, at a sampling rate of $0.6\ m^{-1}$, the cut off wavelength is 19.2 m. The amplitude error of the filter was chosen so that the difference between raw data and filtered data is minimal, while also minimising the number of data points lost near the surface due to the filter weights. A figure of 160 db was found adequate for this purpose.

Depth Errors

Figure 3 shows, for all the data analysed, the difference in depth of temperature features observed by the XBT and the CTD as a function of the assumed depth of the XBT. The depth error increases with the assumed depth of the XBT. This implies the XBT is actually falling at a faster rate than that given by the manufacturer's equation for the fall rate of the XBT.

Figure 4 shows the actual depths of the temperature features observed as a function of time for all the data sets combined. The solid line represents the manufacturer's depth/time relationship. For a Deep Blue T-7 type probe, the equation for the assumed depth (z) of the probe at time t is given by

$$z = 6.472\ t - 0.00216\ t^2 \qquad \text{(Eqn.1)}$$

A parabolic regression of CTD depth against XBT time will give a new fall rate equation whose coefficients better reflect the fall rate of the probe. Table 2 shows the new fall rate equations given by this analysis for the combined data set and for each data set treated independently. Figure 5 shows the differences in depths given by the manufacturer's fall rate equation compared to the newly obtained fall rate equation for the combined data set. At 800 metres, the difference is approximately 20 metres.

As can be seen from table 2, the coefficients for the depth equation have uncertainties associated with them. One way of depicting such uncertainties is to calculate coefficients from subsets of the data. That is, if we randomly select 20 CTD XBT comparisons from the available data, then perform a least squares regression to obtain a depth equation, we can do this in ${}^{30}C_{20}$ possible ways. The values obtained for the depth equation should be spread over a confidence ellipse. Figure 6 shows the results from such an experiment. The coefficients are distributed within an eliptical region, and the density of points indicates an high degree of certainty of the estimate.

Temperature Errors

XBT depth error may be thought of as introducing a temperature error into the data. That is, even if the probe is capable of measuring temperature accurately, the temperature will be assigned to the wrong depth. By plotting the difference between XBT and CTD temperature data, as a function of depth, we may assess whether the new fall rate equation reduces the temperature error. XBT data used for the temperature error comparison consisted of depths calculated from the manufacturer's fall rate equation (i.e. depth uncorrected), depth corrected XBT data using the coefficients from a particular data set, and depth corrected XBT data using the coefficients obtained from the entire data set.

Figures 7a-7c show the temperature differences as a function of depth for data set A. If we consider Figure 7a showing the mean temperature error over all depths (uncorrected), it is clear the depth error, especially in the main thermocline, causes a significant temperature error. This is evidenced by the gradient between 80 and 700 metres of the temperature error. After depth correction this gradient has been reduced (Figures 7b and 7c).

An analysis of the variances of the data was performed, whereby the standard deviation within and between the data was calculated. If the depth correction coefficients reduce the depth error, we would expect the standard deviation of the temperature error within a cast as a function of depth to be reduced. The standard deviation between casts should remain unchanged if the temperature error is due to random error.

Table 3 summarises the analysis of variance carried out for the data, and also shows the mean temperature error and the sum squared deviations over all depths. The standard deviation within the samples has been reduced in the corrected data sets, while the standard deviation between samples remains constant.

Data set A reveals that the depth correction does reduce the temperature variability within a cast as well as the mean and sum squared deviations. The XBT system used to record data set B had a constant temperature offset problem associated with an hardware fault, hence the large temperature errors before and after depth correction. Depth correcting this data set does reduce the variability, and leaves a constant temperature error as would be expected. The Bathy Systems SA-810 XBT system used to record data set C exhibited the bowing problem associated with these units. This is an harware problem which manifests itself as a gradual and inconsistent drift or increase in temperature with depth, which is most noticeable in the mixed layer. The depth corrected data exhibits a positive temperature bias, as would be expected from the nature of the bowing.

Discussion

The analysis has shown that depths calculated from the manufacturers depth equation are in error when the depth temperature profiles are compared to a standard instrument such as a CTD. It has been shown that this systematic error leads to an uncertaintity in temperature, and that depth correcting the XBT data with a modified fall equation improves the temperatures when they are also compared to a CTD.

As yet, however, no measure of probe to probe variability has been explored. Voyage 1087 provided data (data sets D and E) where two XBT systems were operated in tandem. Probes were launched almost simultaneously.

Figure 8 shows the difference in absolute depth at which each system on Voyage 1087 encountered particular temperature features. The results indicate the uncertainty in absolute depth increases with depth, and that the variations can almost be 10 metres at 600 metres. This error represents a real probe to probe fall rate error and may in fact place limits on the absolute depth accuracy of the XBT.

References

Hanawa, K. and H. Yoritaka (1987): Detection of systematic errors in XBT data and their correction. *Journal of the Oceanographical Society of Japan* 43, 68-76.

Kaiser, J.F. and W.A. Reed (1977): Data smoothing using low-pass digital filters. *Rev. Soc. Instrum.* 48, 1447-1457

Data Set & Voyage#	Date	XBT Time	CTD Time	System	Location	
A	19-08-89	17:57	18:03	1	43.14.0S	160.54.0E
	27-08-89	04:16	04:21		28.47.0S	172.50.0E
	29-08-89	10:47	10:51		28.15.0S	167.01.0E
	30-08-89	16:27	16:34		28.15.0S	164.06.0E
V1089	31-08-89	22:50	22:56		28.14.0S	160.38.0E
	11-09-89	23:43	23:49		34.25.0S	153.37.0E
	13-09-89	20:57	21:01		34.24.0S	158.53.0E
	14-09-89	18:24	18:29		34.25.0S	161.59.0E
	16-09-89	02:06	02:10		34.25.0S	166.52.0E
	20-09-89	23:26	23:32		38.00.0S	162.01.0E
	22-09-89	22:18	22:22		37.59.0S	156.04.0E
	24-09-89	08:02	08:08		39.01.0S	152.39.0E
B	14-03-87	03:03	03:11	1	31.10.0S	113.07.0E
	17-03-87	03:20	03:29		28.04.0S	111.55.0E
	17-03-87	16:04	16:11		27.00.0S	111.22.0E
	20-03-87	06:06	06:16		23.44.0S	110.37.0E
V0487	20-03-87	23:29	23:38		22.25.0S	111.26.0E
	23-03-87	20:24	20:32		19.00.0S	112.30.0E
	24-03-87	15:04	15:10		16.59.0S	112.29.0E
	25-03-87	12:52	13:00		14.59.0S	113.30.0E
C	14-03-87	03:02	03:11	2	31.10.0S	113.07.0E
	17-03-87	03:19	03:29		28.04.0S	111.55.0E
	20-03-87	23:29	23:38		22.25.0S	111.26.0E
	23-03-87	20:22	20:32		19.00.0S	112.30.0E
V0487	24-03-87	15:02	15:10		16.59.0S	112.29.0E
	25-03-87	12:50	13:00		14.49.0S	113.30.0E
	27-03-87	08:39	08:43		18.02.0S	115.31.0E
D	05-11-87	05:35	05:38	3	16.21.0S	117.41.0E
V1087	12-11-87	07:07	07:17		13.41.0S	121.42.0E
	12-11-87	18:12	18:18		13.11.0S	122.02.0E
E	05-11-87	05:29	05:38	1	16.21.0S	117.41.0E
V1087	12-11-87	07:09	07:17		13.41.0S	121.42.0E
	12-11-87	18:11	18:18		13.11.0S	122.02.0E

Table 1. Data used in analysis of XBT depth error problem. The system types are: 1) Sippican Mk9 with a PDP-11 computer, 2) Bathy Systems SA-810 with a HP-85, and 3) Sippican Mk9 with a HP-85.

Data Set	Depth Equation Coefficients	
	A	B
A	6.824 (+/- 0.09306) t	- 0.003462 (+/- 0.0009781) t^2
B	6.720 (+/- 0.07574) t	- 0.002917 (+/- 0.0006626) t^2
C	6.645 (+/- 0.09326) t	- 0.001758 (+/- 0.0008645) t^2
D+E	6.665 (+/- 0.07281) t	- 0.002698 (+/- 0.0006797) t^2
F (All Data)	6.774 (+/- 0.04405) t	- 0.003288 (+/- 0.0004057) t^2

Table 2. Fall rate equation coefficients.

Data Set	Standard Dev Within Samples			Standard Dev Betw Samples			Mean			SSD		
	a	b	c	a	b	c	a	b	c	a	b	c
A	.185	.092	.099	.079	.082	.081	-.216	-.007	-.051	.017	.002	.003
B	.136	.145	.125	.141	.145	.145	-.589	-.400	-.371	.007	.001	.002
C	.214	.173	.174	.046	.047	.049	-.065	.140	.163	.021	.012	.013
D+E	.149	.102	.107	.056	.061	.064	-.100	.055	.103	.010	.003	.003

Table 3. Mean temperature errors: a = depth uncorrected; b = depth corrected using new fall rate equation for associated data set; c = depth corrected using new fall rate equation for combined data set.

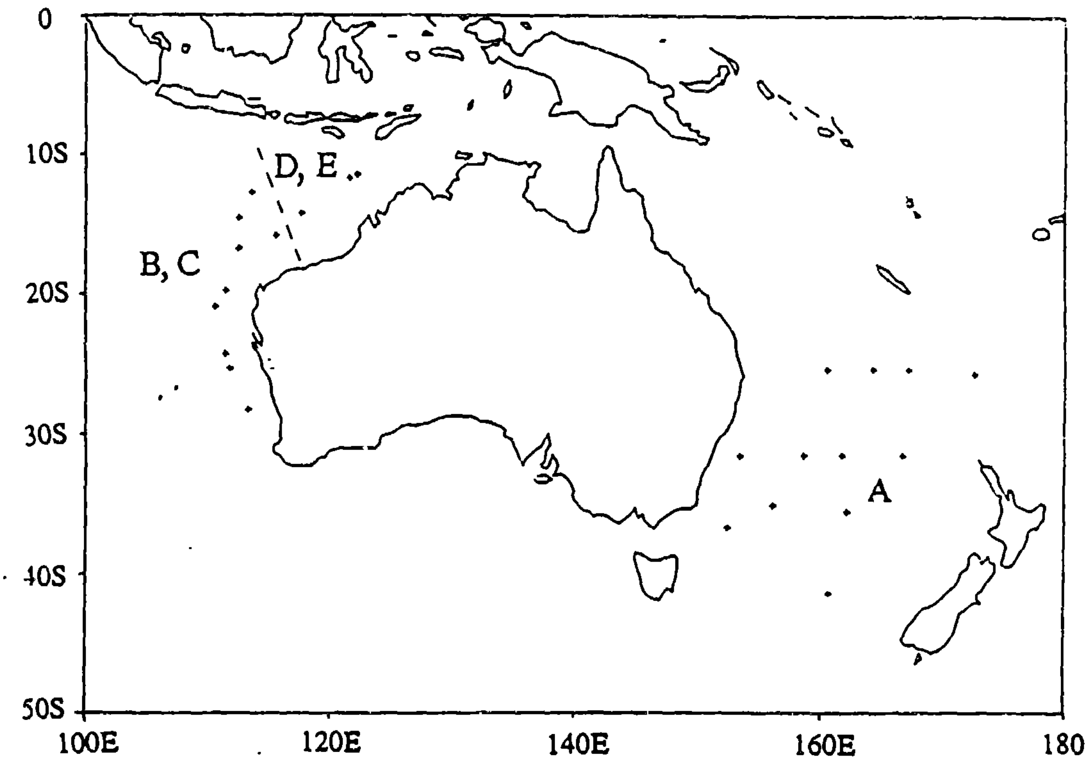

Figure 1. CTD station positions. General locations for data sets A,B,C,D, and E are indicated.

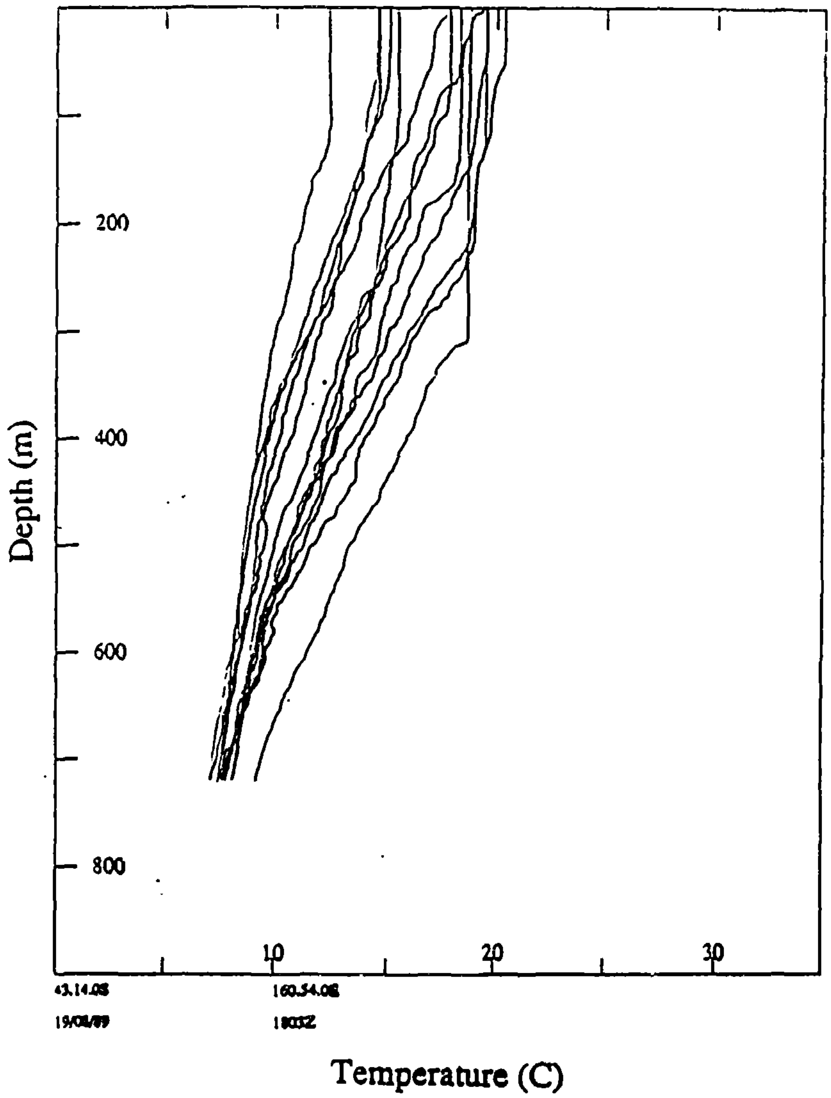

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Figure 2a. CTD temperature profiles for data set A.

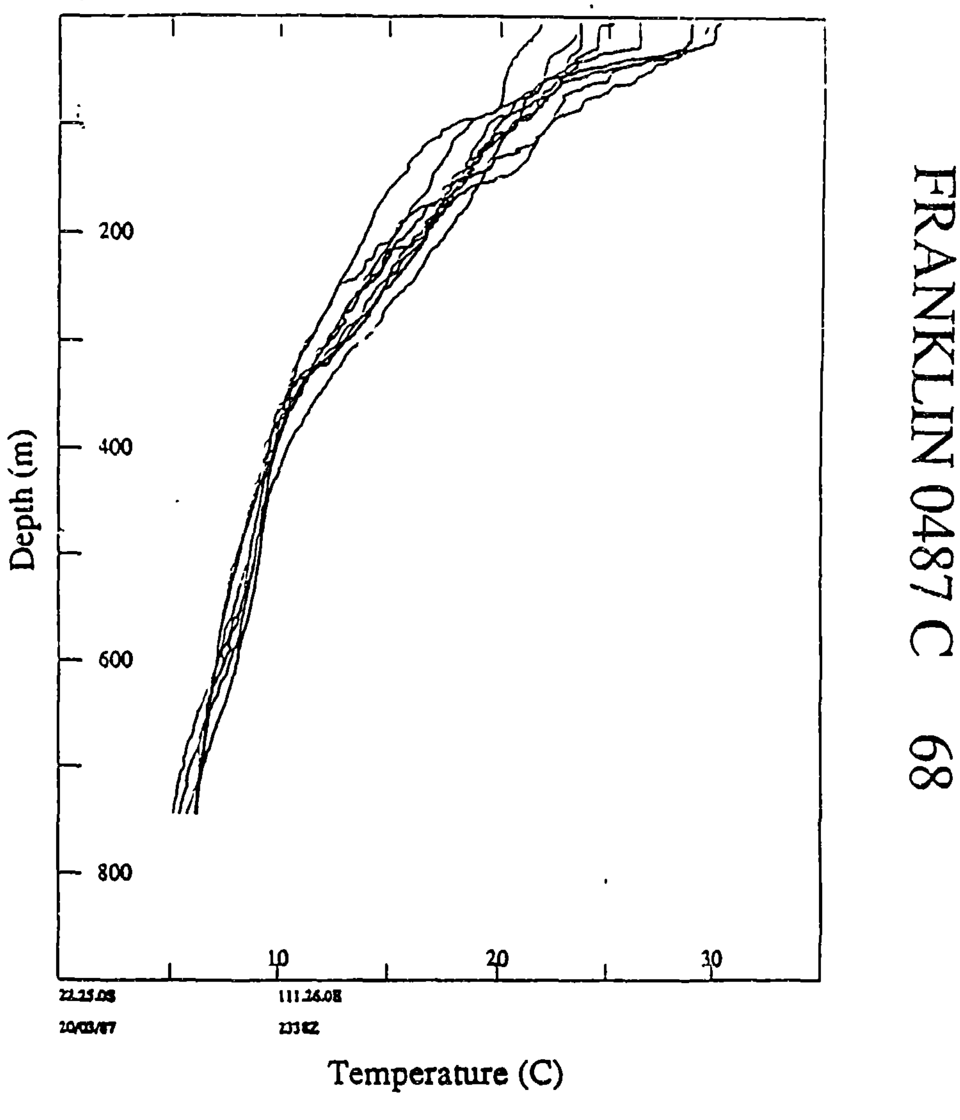

Figure 2b. CTD temperature profiles for data sets B & C.

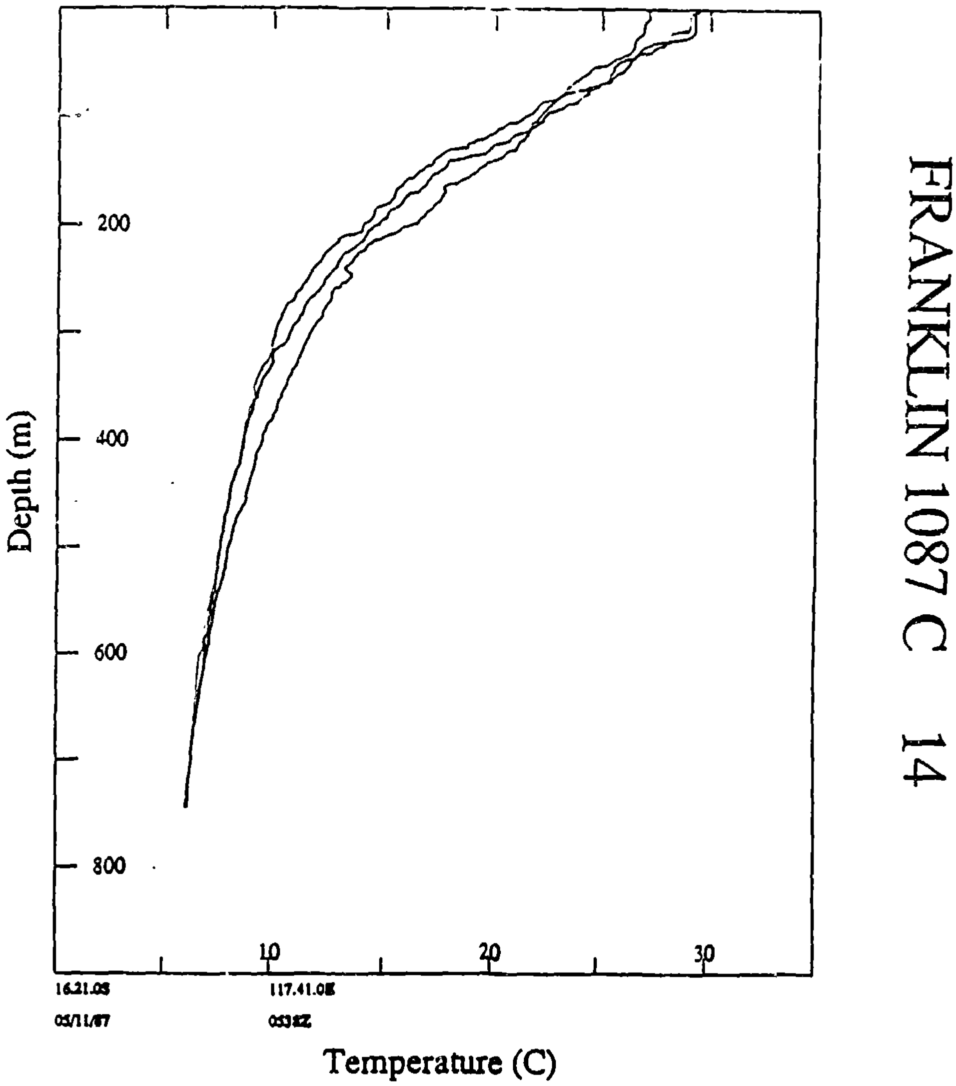

Figure 2c. CTD temperature profiles for data sets D & E.

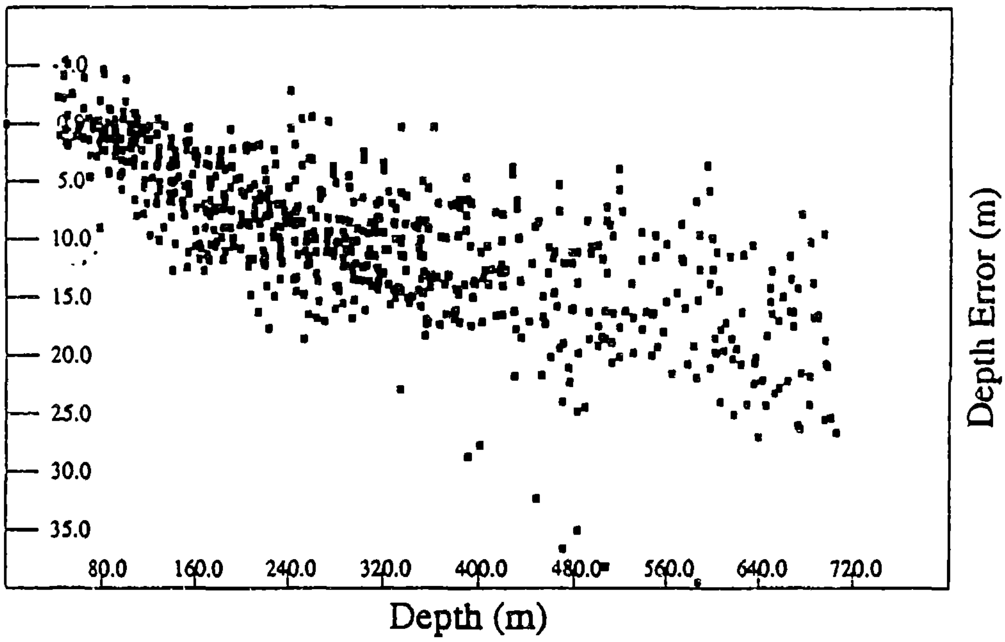

Figure 3. Scatter diagram of the error in the depth of the XBT as a function of the assumed depth of the XBT given by the manufacturer.

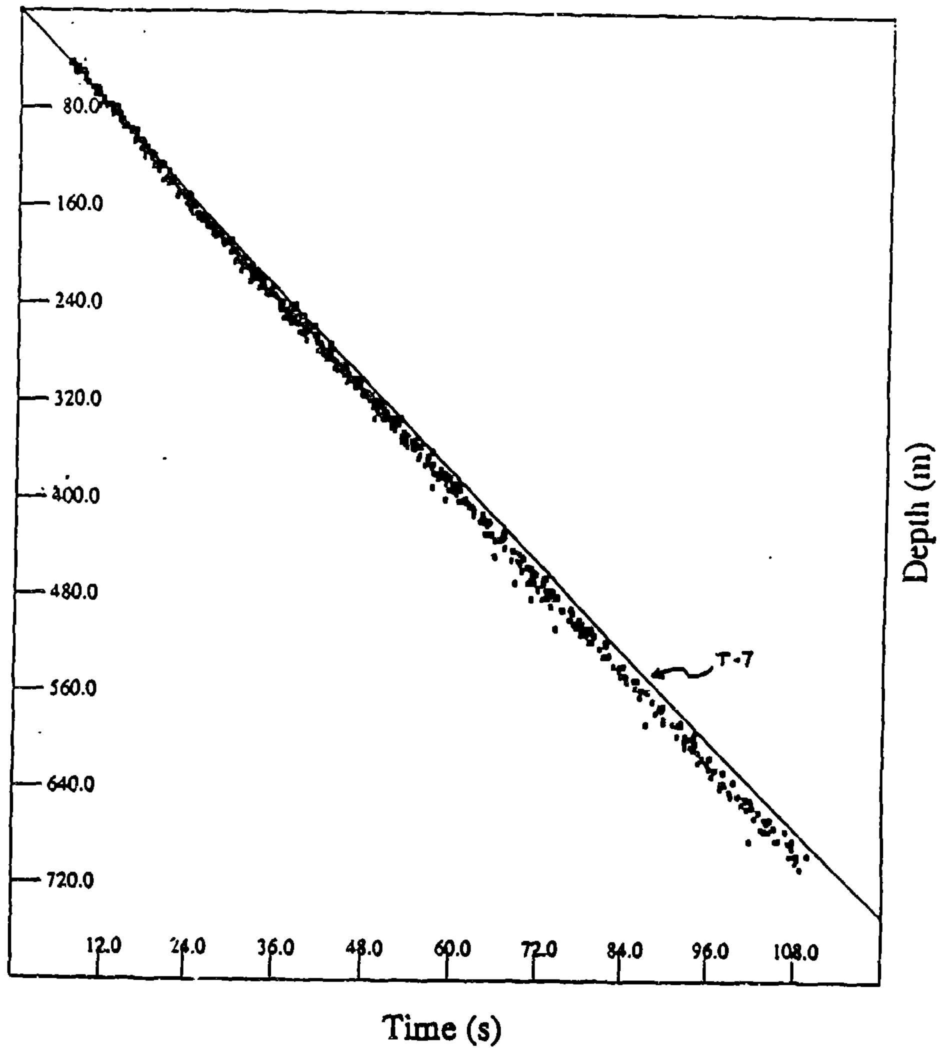

Figure 4. Scatter diagram of the actual depths of the XBT as a function of elapsed time. The solid line is the manufacturer's depth/time relationship for a T-7 type XBT probe.

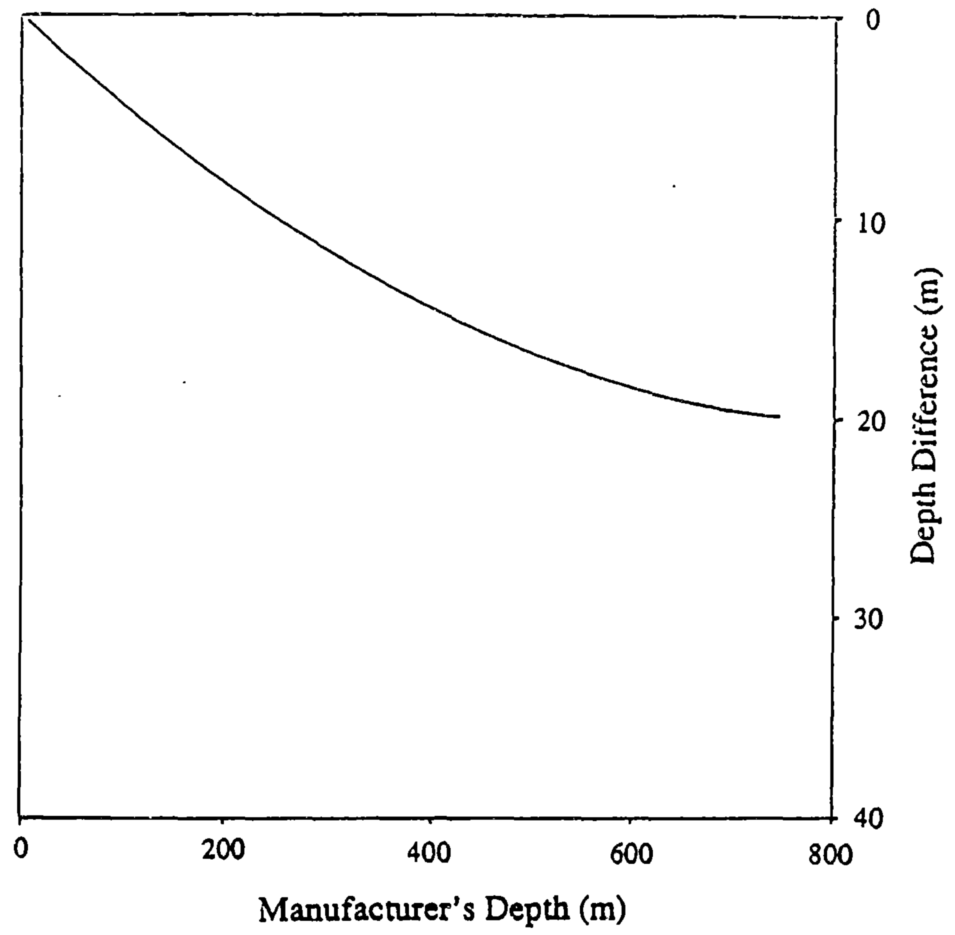

Figure 5. Depth difference between fall rate equation obtained for all data in this study and manufacturer's fall rate equation.

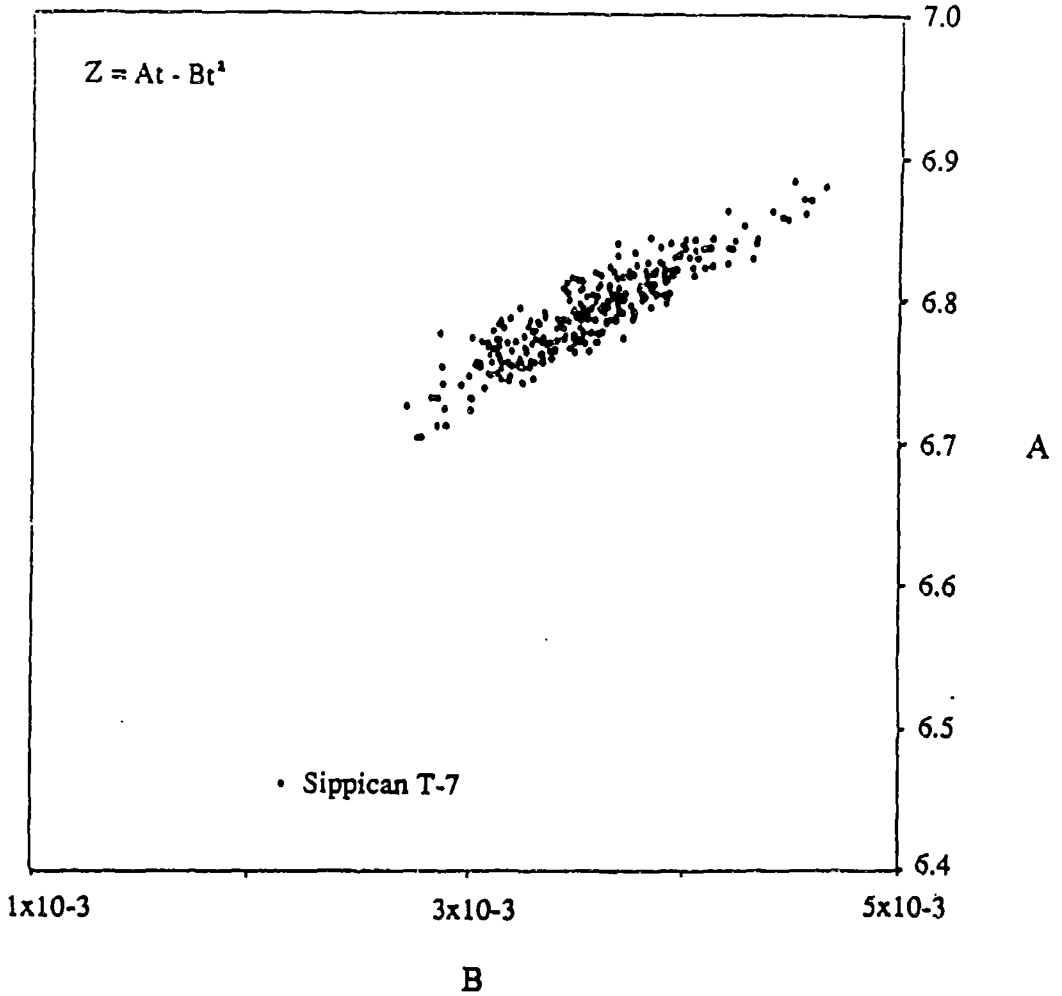

Figure 6. Confidence elipse analysis for new fall rate equation coefficients.

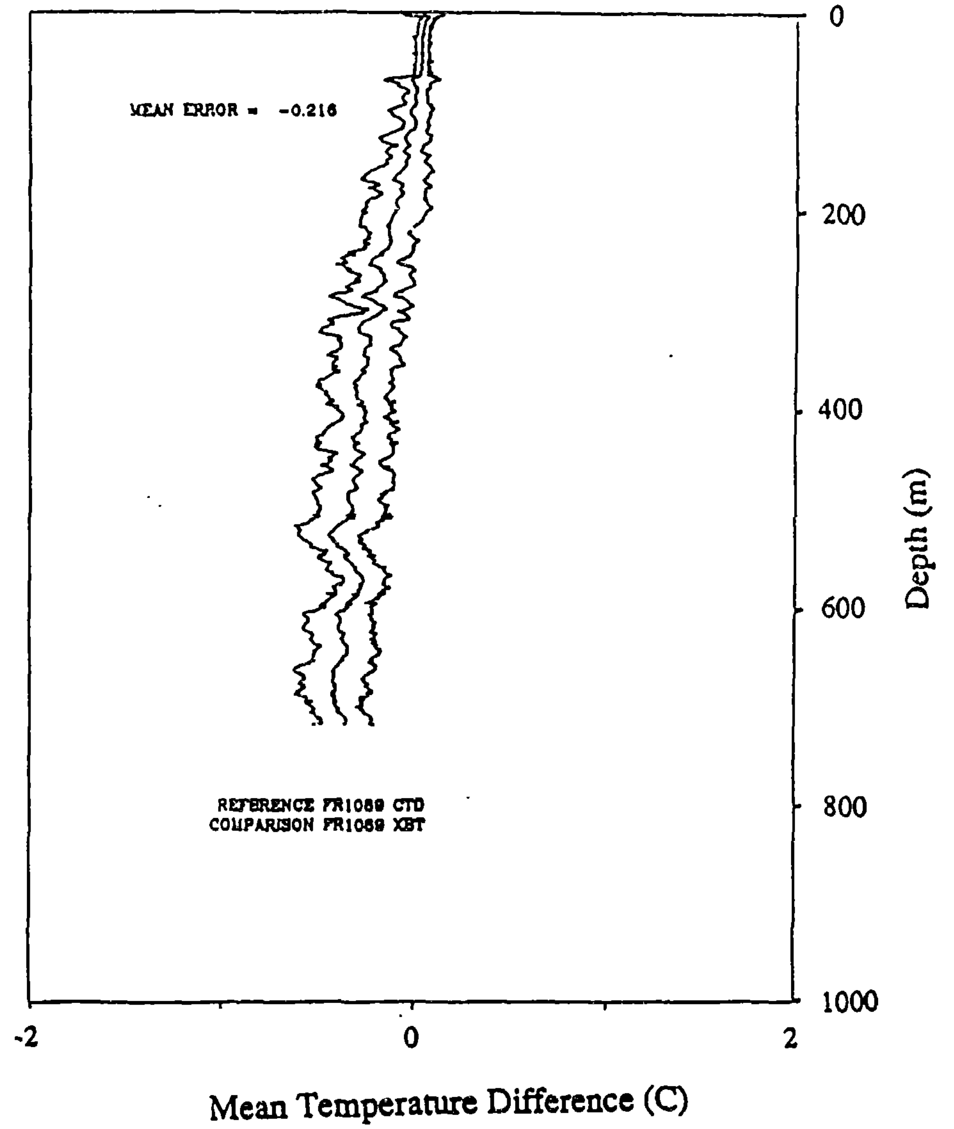

Figure 7a. Average temperature error profile (T_{XBT} - T_{CTD}) for data set A: depth uncorrected.

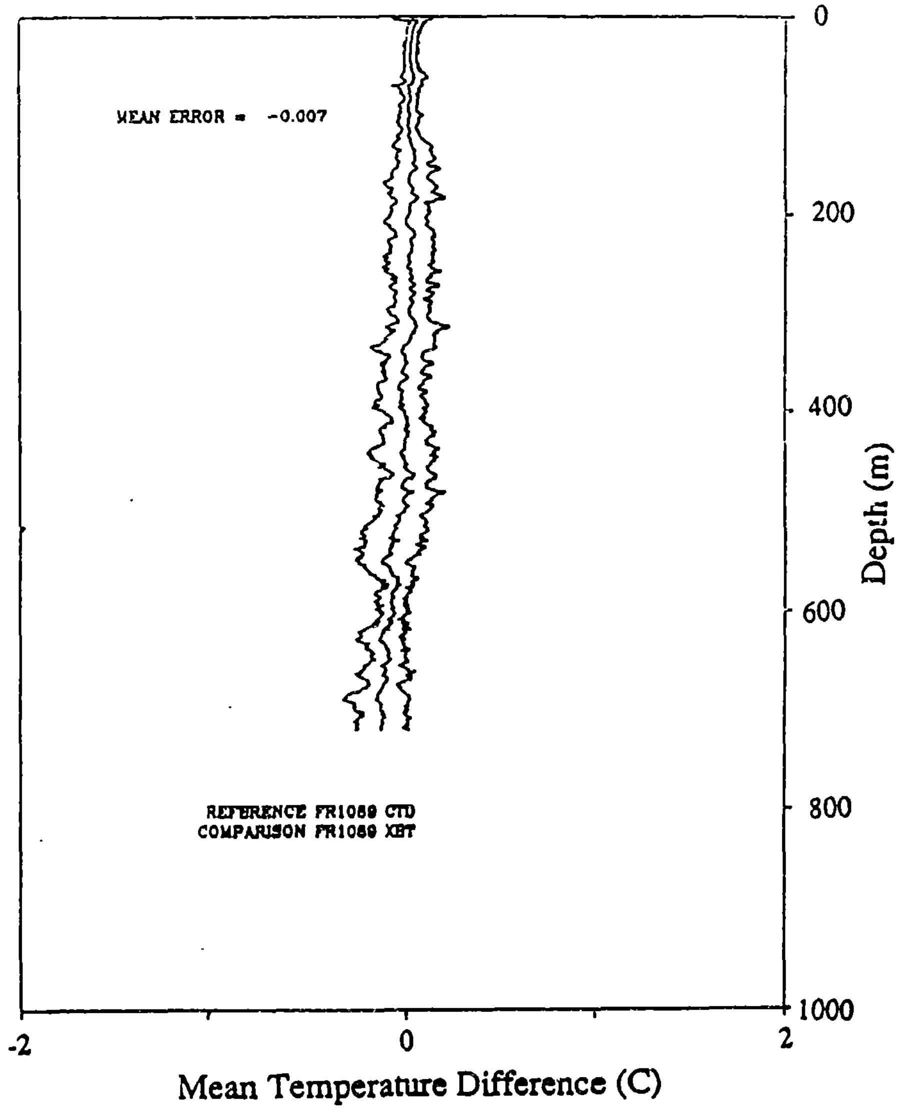

Figure 7b. Average temperature error profile (T_{XBT} - T_{CTD}) for data set A: depth corrected using fall rate coefficients calculated for data set A.

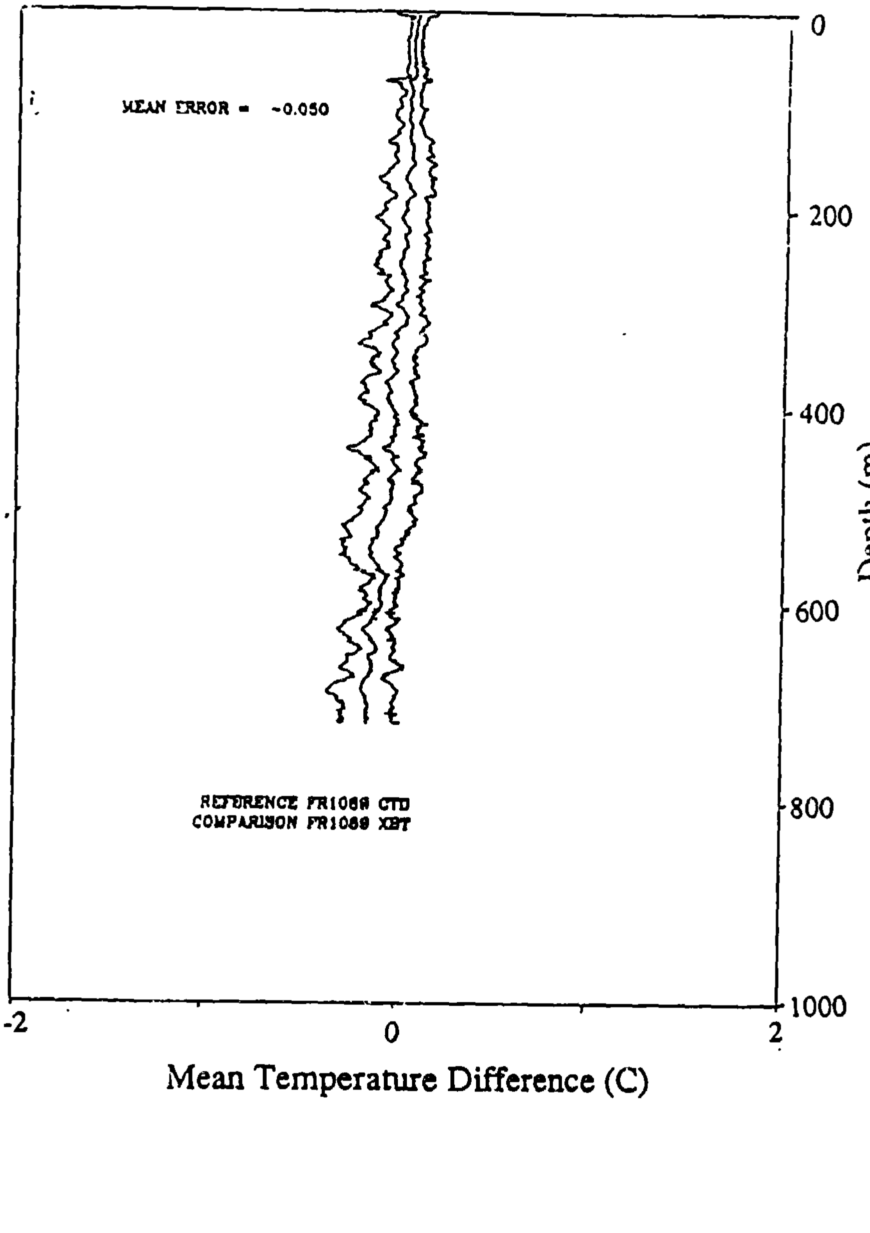

Figure 7c. Average temperature error profile (T_{XBT} - T_{CTD}) for data set A: depth corrected using fall rate coefficients calculated for combined data set (F).

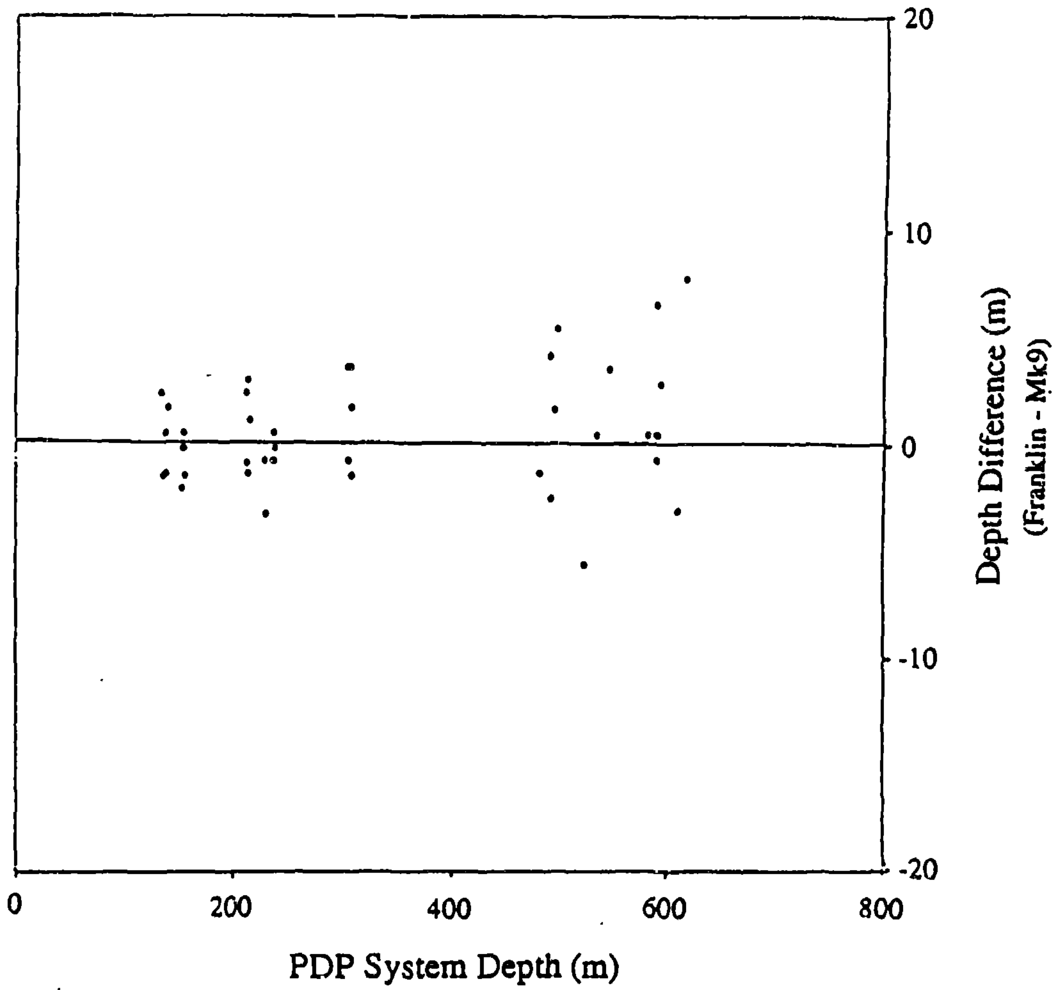

Figure 8. Probe to probe variabilty.

Evaluation of
The Expendable Bathythermographic(XBT)
Fall Rate Equation

by
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June, 1991

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Introduction

This data report presents the results of an evaluation of the Sippican Corporation's empirical XBT depth (fall rate) equation for T-04, T-06, and T-07 probes by the National Oceanic and Atmospheric Administration (NOAA), National Ocean Service (NOS). This evaluation is, in conjunction with an international effort, being coordinated by the IOC-IGOSS Task Team on Quality Control. With the growing awareness of the importance of the ocean thermal structure as a factor in the world's climate, it is imperative that the ocean science community quantify it's means of monitoring the ocean's thermal properties. For the XBT, which is used for the majority of upper ocean temperature measurements, the depth of the temperature measurement is computed from time of probe descent using the following empirical equation established 25 years ago by Sippican:

$$\text{Depth} = 6.472*T - 0.00216*T^2 \quad ,\text{where } T = \text{sample rate} * \text{sample no.}$$

The accuracy specifications for the XBT probe are +/- 2 percent or +/- 5 meters (whichever is greater) for depth and +/- 0.15 degree Celsius for temperature. The accuracy of Sippican's XBT fall rate equation has been questioned over the past decade (Seaver and Kuleskov, 1982; Heinmiller et al., 1983; Hanawa and Yoritaka, 1987; Szabados and Wright, 1989; Bailey and Meyers 1989; Henin, 1989; Sy and Ulrich, 1990).

The XBT test was carried out on the NOAA Vessel MT Mitchell during a January-March 1990 Subtropical Atlantic Climate Study (STACS) cruise. The evaluation was conducted in the Atlantic Ocean in the region Northeast of Brazil (Figure 1). During the cruise 38 CTD casts were taken and 23 of these were used in the XBT-CTD comparison. A total of 66 XBT's were launched. The Sippican MK-9 XBT analog-to-digital controller was the XBT controller used for the evaluation. A Sippican MK-2 analog recorder was also included in the test to evaluate any potential bias inherent in analog vs digital XBT recording technology. Of the 66 XBT's launched, 45 were recorded with the MK-9 and 21 were recorded with the MK-2.

Also included in this report are results from an earlier STACS cruise (July 1988) which took place in the same general location in the Atlantic aboard the NOAA Vessel Whiting. During that cruise four XBT analog-to-digital controllers, including one sippican MK-9, were evaluated (Szabados and Wright, 1989). To evaluate any potential difference in the performance of XBT's from one production lot to another, results from 20 XBT drops recorded during the MK-9 1988 XBT-CTD comparison are included in this report.

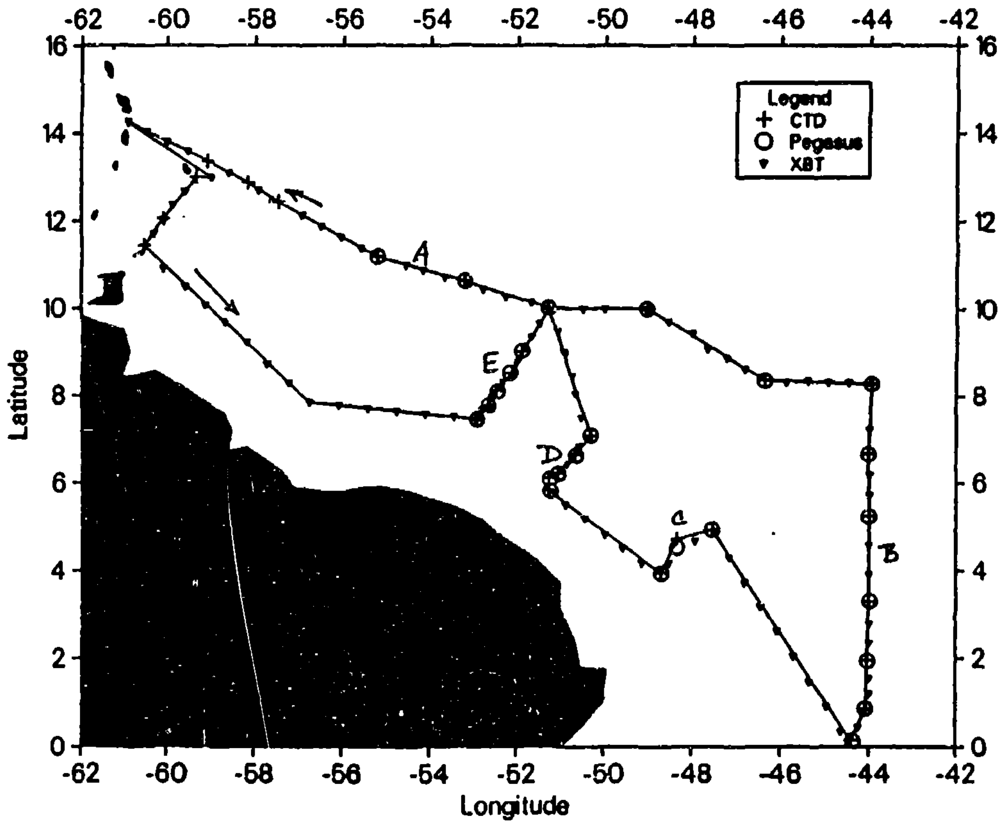


Figure 1 STACS January - March 1990 Cruise Track

METHODS AND PROCEDURES

In October 1989, at the IGOSS International Ship-Of-Opportunity Meeting in Hamburg, a decision was made to conduct an internationally coordinated experiment to evaluate the XBT fall rate equation. Field tests were to be conducted in different ocean regions by a number of principal investigators in the XBT VOS community. To ensure a controlled test, participants were requested to coordinate the experiment using similar test procedures. A copy of those guidelines are included in Appendix A.

For the NOAA test a Sippican MK-9 XBT controller utilizing the Shipboard Environmental data Acquisition System (SEAS) III software was used. For the temperature standard a Neil Brown Mark III CTD was used. The MK-9 was calibrated by NOS and the CTD was calibrated by the Northwest Regional Calibration Center, in accordance with NOAA Calibration Procedure for CTD Sensors (NOIC-CP-04A). Based on CTD calibration results, CTD pressure error from 0 to 700 meters is 2 decibars, and the temperature error is 0.002 degree Celsius. The XBT probes for this test provided by Sippican had been "wet" calibrated in a temperature bath. Since it is not possible to measure the "true" depth of a descending XBT probe, but rather compare the XBT measurement to a CTD, there are some inherent limitations using the CTD as the reference measurement. Some of these limitations include errors as a result of inaccuracies in the CTD temperature and pressure (depth) measurement and any anomalies that may be introduced during CTD data processing. It is also recognized that the XBT and CTD do not descend at the same rate and therefore do not measure the water column simultaneously. The XBT descends at a faster rate of 6.5 m/sec then the winched controlled CTD descent rate of 0.5 m/sec. The response time of the XBT thermistor is 63 percent of a step change in temperature in 1 meter of water, with 95 percent of a step change in temperature in 3 meters (Sippican, 1983). To eliminate the effect of hysteresis in the response of the CTD, XBT's were launched only during the down cast of the CTD.

The procedure for launching the XBT's for both the MK-9 and Mk-2 tests was as follows: launch a T-04 probe when the CTD was at 100 meters, followed by the launching of T-06 and T-07 probes. There was a deviation from this launching procedure early in the test after a high number of probes failed due to inclement weather. The high failure rate of the probes is attributed to poor launching conditions resulting from the rolling and pitching of the vessel in six to eight foot seas. The revised procedure was to drop three of the same type of probe at a particular CTD station. The MK-2, analog recorder experienced an electrical failure about two-thirds the way into the test. The XBT logs for the MK-9 and MK-2 during the February 1990 test are provided in Appendix B. For the MK-9 data, only probes that descended to at least 300 meters for T-04 and T-06 probes and to 400 meters for T-07 probes were used in the analysis. This resulted in only 30 XBT drops for the MK-9 and 18 XBT drops for the MK-2 from the February 1990 test being included in the analysis. In contrast, during the July 1988 test when the seas were calm, there were only five probe failures out of 250 XBT's launched. The procedures for collecting the 20 XBT MK-9 drops from the 1988 test were similar to the 1990 test with the following exceptions: only one XBT was launched during a CTD cast when the CTD was at the thermocline, and the XBT's used were not calibrated. The number of XBT's by probe type from each test used in the analysis are listed in Table 1.

TABLE 1
PROBE TYPE AND NUMBER USED IN ANALYSIS

CRUISE	SYSTEM	T-04	T-06	T-07	TOTAL
JUL 1988	MK-9	6	7	7	20
FEB 1990	MK-9	8	8	14	30
FEB 1990	MK-2	7	11	0	18

The output from the MK-9 was digitally recorded on a PC compatible computer using SEAS III software, while the MK-2 recorded on paper tape. The MK-2 was provided by Sippican. The MK-2 analog paper tape was digitized by NOAA's National Oceanographic Data Center (NODC) on an OGTCO digitizer. Digitizing procedures at NODC require two passes of each XBT trace which must agree within a maximum deviation of 0.02 inches. The result of this digitizing process is "significant data points." The MK-9 processes data at 0.65 meter increments. CTD data were recorded at 1 decibar increments.

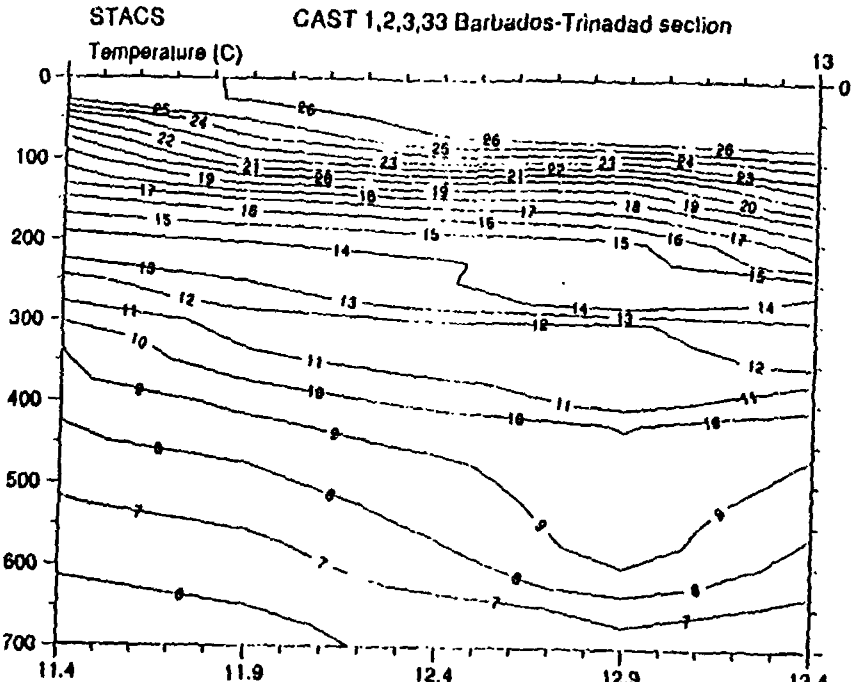
To compute error in the XBT fall rate, the following procedures were used. First, to minimize the effect of any temperature error, temperatures for the XBT were compared with the CTD in the isothermal region of the mixed layer. Any temperature differences between the CTD and the XBT in this region were subtracted from the XBT data. Next, to determine any error in the MK-9 XBT depth, a computer program was developed to "best-fit" the XBT data to the CTD data. This best-fit analysis of the XBT profile to the CTD was found by shifting a 50-meter segment of the XBT data by 1-meter increments up and down until the least mean differences between the XBT and CTD temperatures were determined. The depth error was then computed from the number of meters that the original XBT data were moved to best-fit the CTD. Results of the best-fit analysis are included in Appendix C. Care must be taken when interpreting this analysis in a mixed layer since a small offset in temperature error not removed from the XBT data could erroneously indicate a large depth error. In the non-mixed layers this method worked quite well. To determine any depth offset for the MK-2 data, the computed significant XBT data points were manually compared with the CTD data on a graph and any offset was determined using a Gerber Variable Scale.

Results

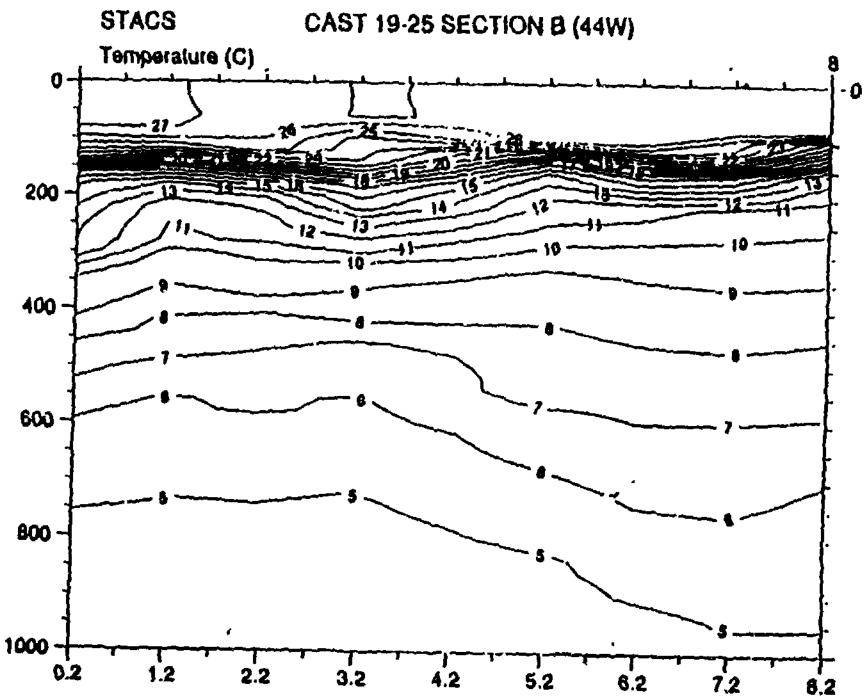
The temperature structure for the region during the STACS January-March 1990 cruise is shown in Figure 2 (a) for the Western boundary and in Figure 2 (b) for the Eastern boundary of the test area. Surface temperatures ranged from 25 to 26 degrees Celsius, while temperatures at 500 meters ranged from 7 to 9 degrees Celsius. A strong thermocline was present at about 100 to 200 meters, and a strong mixed layer was observed above the thermocline with a gradual temperature gradient below the thermocline. Figure 3 illustrates the general salinity structure for the region during the test. The salinity ranged from about 36 ppt at the surface to 35 ppt at 500 meters. The XBT evaluation was carried out during the February portion of the cruise.

During the July 1988 STACS cruise, the surface temperatures ranged from 27 to 29 degrees Celsius. Temperatures at 500 meters ranged from 6 to 8 degrees Celsius. The thermocline was characteristically found at 50 to 200 meters. Below the thermocline there were steps in the temperature structure which provided excellent features to compare any offset between the XBT and CTD temperature traces. The salinity at the surface generally ranged from 30 to 35 ppt. In some areas the surface salinity was lower, which was attributed to fresh water discharge from the Amazon River. At about 100 meters the salinity increased to 36 ppt and then decreased to 34 ppt at 500 meters.

As shown in Table 2, the accuracy of the XBT thermistor was found to be better than the +/- 0.15 Celsius specified by the manufacturer. The mean temperature difference between the XBT and CTD in the mixed layer above the thermocline was 0.029 for the 1988 test and 0.026 for the 1990 test. These results agree with a previous study by Georgi et al. (1980) indicating that the temperature difference (standard minus probe thermistor temperature) of the XBT probe ranges from +0.048 to -0.045 degrees



(a)



(b)

Figure 2 STACS JAN. - MAR. 1990 Cruise:
(a) Temperature Contours Along Western Boundary
(b) Temperature Contours Along Eastern Boundary

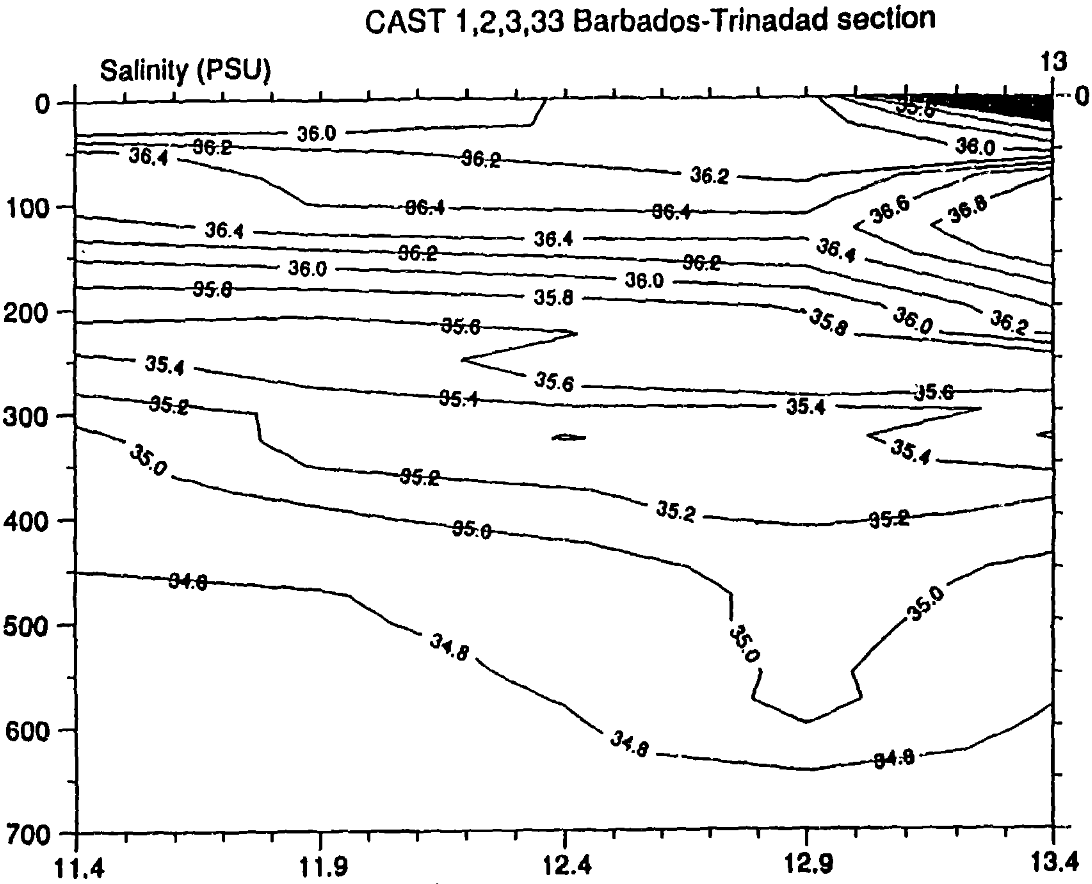


Figure 3 STACS JAN. - MAR. 1990 Cruise: Salinity Contours Along CTD Stations 1,2,3,33 (Barbados - Tinadad section)

TABLE 2
MEAN TEMPERATURE DIFFERENCES BETWEEN THE XBT AND CTD IN THE MIXED LAYER (DEGREES CELSIUS)

STACS CRUISE	MEAN	STANDARD DEVIATION
July 1988	.029	.046
Feb. 1990	.026	.043

Celsius. Since larger temperature differences were observed during the test with those probes excluded from the data analysis, because of either wire stretch or wire insulation failure, errors greater than those indicated in this report could be present in XBT data sets if not properly quality controlled.

The XBT depth errors (XBT Depth - CTD Depth) are summarized in Figures 4 through 7 and Tables 3 through 6. The computed depth error during the February 1990 and July 1988 cruises for T-04, T-06, and T-07 probes showed two opposing trends (Figure 4). For the 1988 data the XBT probe was underestimating the depth (falling faster), while the 1990 data indicated that the XBT probe was over-estimating depth (falling slower). These XBT depth errors are greater than the manufacturer's specification. In addition, the different trends indicate a possible unknown cause for the bias in both data sets. Figures 5 (a) and (b) show an example of the difference between the CTD-XBT temperature profiles for the 1988 and 1990 tests.

As shown in Figure 6, the data collected utilizing the MK-2 analog recorder agreed well with the data processed through the MK-9 controller. This suggests there should be no significant errors in the XBT data archives as a result of the change during the past decade from analog to digital recording technology.

During the 1990 cruise, the T-04 and T-07 probes had similar mean depth errors, where the mean depth error for each probe type differed by only about one meter. The T-06 probe mean depth error was greater by several meters than the T-04 and T-07 probes in regions deeper than 100 meters. In the region of 300 to 400 meters, mean depth errors of the T-04 and T-07 probes ranged 15 to 17 meters, while the mean depth error of the T-06 probe ranged from 21 to 25 meters. During the 1988 cruise the T-04 and T-07 mean depth errors agreed to within one meter. While the T-06 probe mean depth error agreed with those of the T-04 and T-07 by about a two meters.

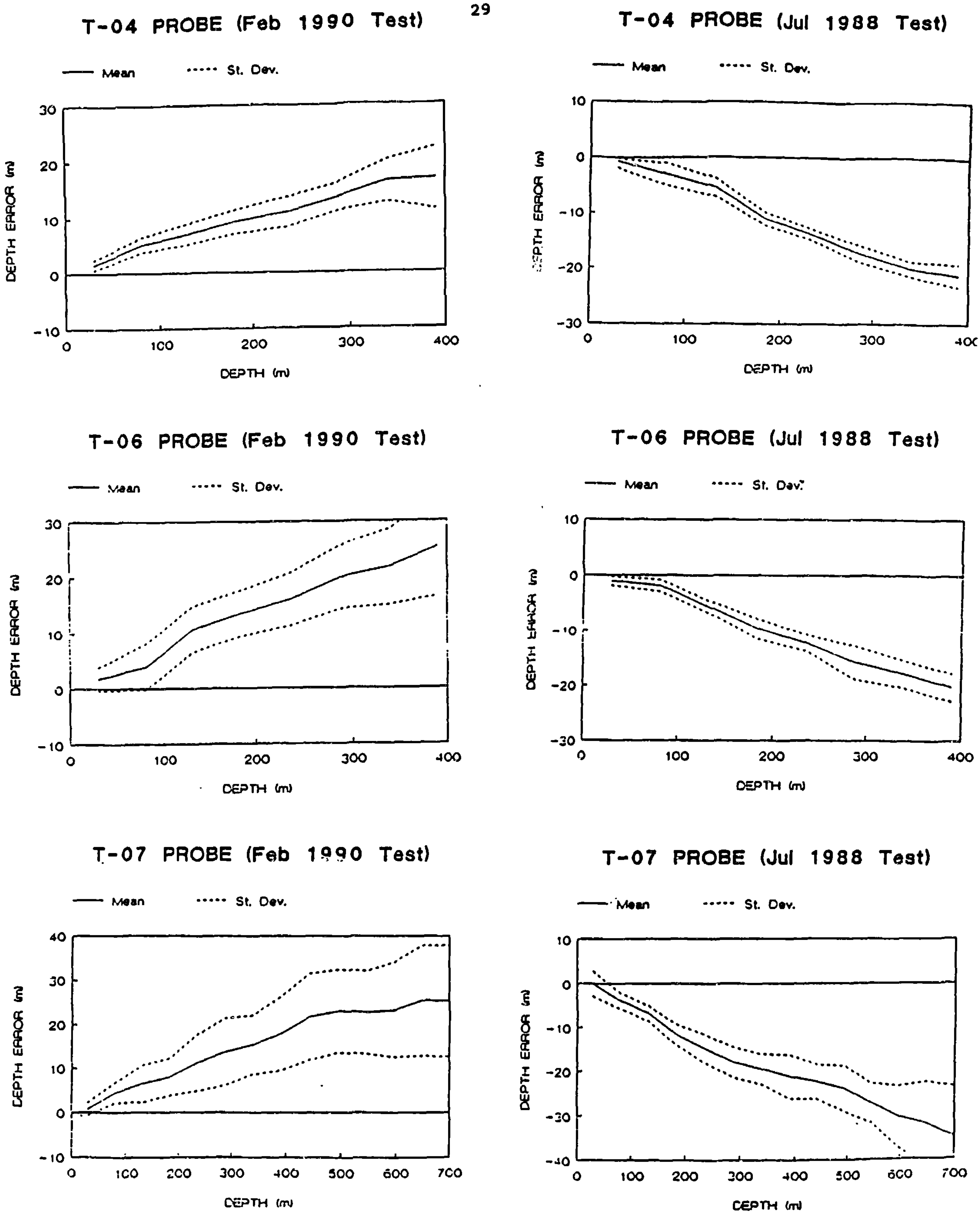
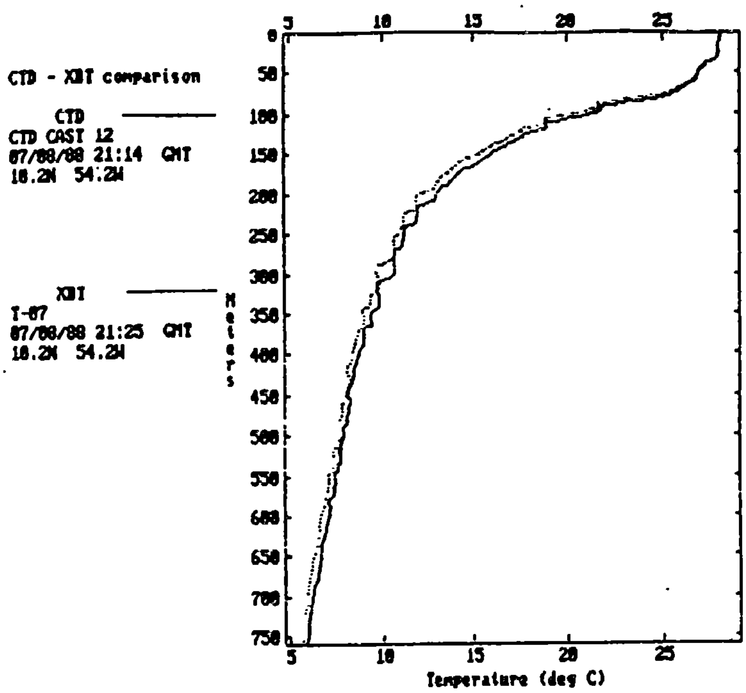
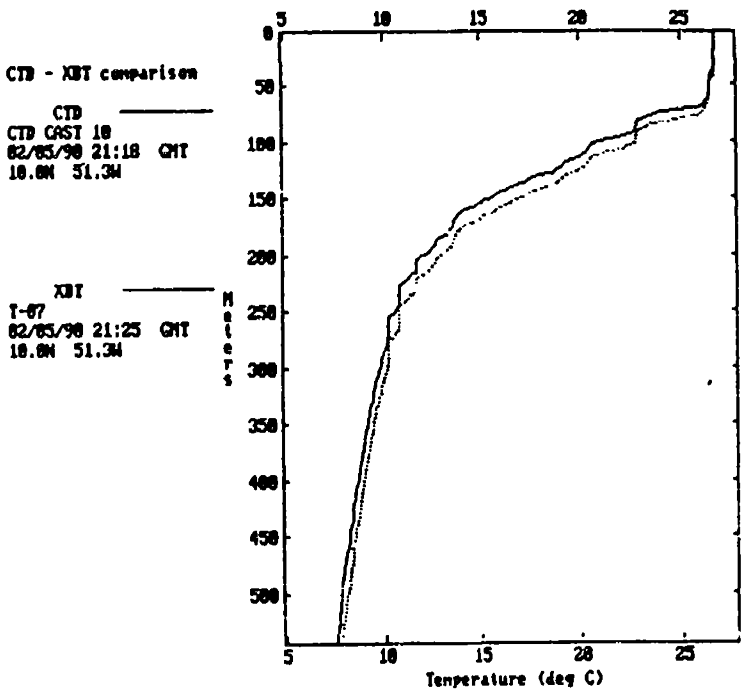


Figure 4 Depth Error for T-04, T-06, and T-07 Probes (MK-9 only)



(a)



(b)

Figure 5 (a) Sample XBT-CTD Profile for July 1988 Test
(b) Sample XBT-CTD Profile for Feb. 1990 Test

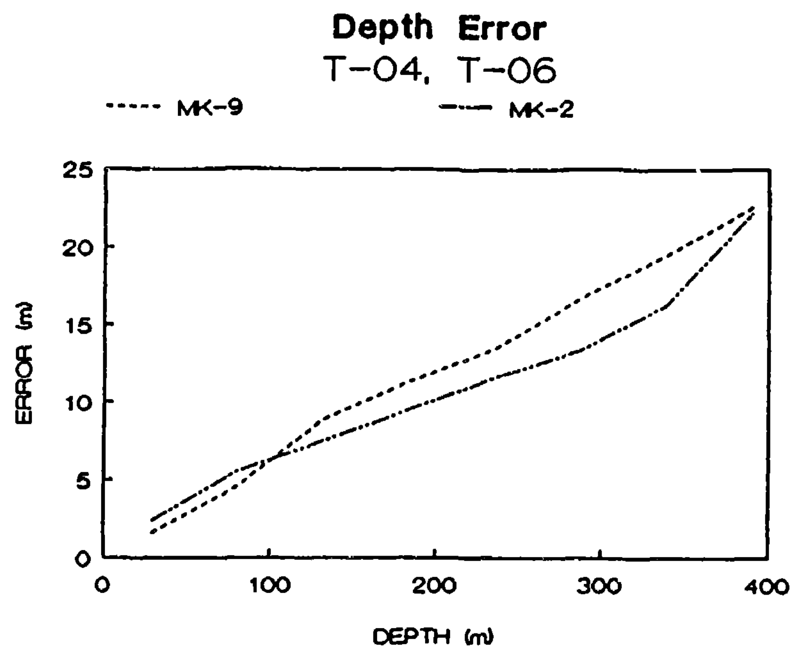


Figure 6.0 Mean Depth Error For MK-2 and MK-9 Recording Systems

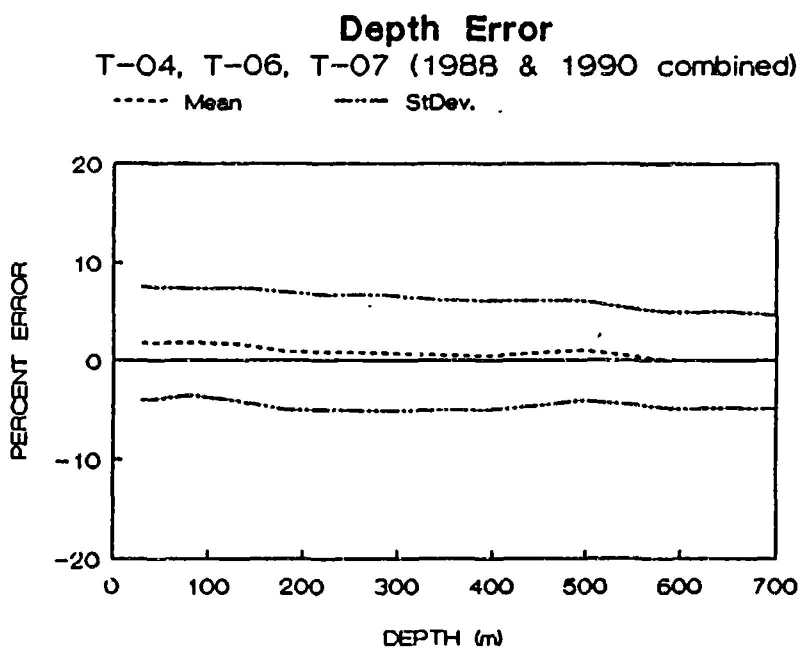


Figure 7 Percent Depth Error For Combined 1988 and 1990 Data Set

TABLE 3
XBT DEPTH ERROR (METERS)
STACS CRUISE 1988
MK-9

	T-04		T-06		T-07		T-4, T-6, T-7	
DEPTH	MEAN	ST DEV	MEAN	ST DEV	MEAN	ST DEV	MEAN	ST DEV
29.08	-0.66	0.51	-0.99	0.81	-0.00	2.86	-0.55	1.75
80.56	-2.98	1.99	-1.85	1.06	-3.98	1.81	-2.93	1.80
132.41	-5.46	1.63	-5.67	1.10	-6.81	1.76	-6.01	1.56
183.97	-11.09	1.16	- 9.64	1.78	-11.63	2.34	-10.77	1.96
235.24	-14.06	0.97	-12.20	1.48	-14.75	3.21	-13.65	2.34
287.49	-17.37	1.50	-15.74	3.05	-17.87	3.44	-16.98	2.86
338.82	-20.02	1.32	-17.86	2.49	-19.43	3.43	-19.06	2.64
390.48	-21.17	2.04	-20.27	2.49	-21.12	4.95	-20.84	3.31
441.84					-22.39	3.88	-22.39	3.88
493.51					-23.98	5.15	-23.98	5.15
545.50					-27.27	4.42	-27.27	4.42
596.56					-30.41	6.94	-30.41	6.94
648.52					-32.05	9.45	-32.05	9.45
700.16					-35.02	11.39	-35.02	11.39

TABLE 4
XBT DEPTH ERROR (METERS)
STACS CRUISE 1990
MK-9

	T-04		T-06		T-07		T-4, T-6, T-7	
DEPTH	MEAN	ST DEV	MEAN	ST DEV	MEAN	ST DEV	MEAN	ST DEV
29.08	1.49	0.92	1.73	2.10	0.85	1.39	1.25	1.52
80.56	5.21	1.37	3.97	4.14	4.54	2.29	4.56	2.68
132.41	7.08	1.87	10.68	4.10	6.53	4.19	7.78	4.00
183.97	9.32	2.18	13.54	4.11	8.16	4.25	9.90	4.30
235.24	10.93	2.70	16.02	4.73	11.35	6.49	12.48	5.55
287.49	13.53	2.48	19.98	5.70	13.76	7.66	15.35	6.61
338.82	16.38	3.75	21.84	6.79	15.39	6.69	17.44	6.66
390.48	16.87	5.55	25.43	8.90	17.87	8.33	20.04	8.69
441.84					21.73	9.80	21.73	9.80
493.51					23.01	9.42	23.01	9.42
545.50					22.70	9.46	22.70	9.46
596.56					23.30	10.78	23.30	10.78
648.52					25.40	12.51	25.40	12.51
700.16					25.26	12.61	25.26	12.61

TABLE 5
XBT DEPTH ERROR (METERS)
STACS CRUISES 1988 & 1990 COMBINED
MK-9

	T-4, T-6, T-7	
DEPTH	MEAN	ST DEV
29.08	0.53	1.70
80.56	1.56	4.36
132.41	2.26	7.64
183.97	1.63	10.87
235.24	2.03	13.77
287.49	2.42	16.95
338.82	2.23	19.07
390.48	2.26	21.81
441.84	3.56	23.85
493.51	5.38	25.20
545.50	2.70	26.95
596.56	0.28	29.53
648.52	0.78	31.97
700.16	0.57	33.48

TABLE 6
XBT DEPTH ERROR (METERS)
STACS CRUISE 1990
MK-2

	T-04		T-06		T-04,T-06	
DEPTH	MEAN	ST DEV	MEAN	ST DEV	MEAN	ST DEV
29.08	2.3	1.1	2.5	-	2.4	0.7
80.56	4.6	3.8	7.1	2.7	5.6	3.5
132.41	6.1	3.9	8.4	3.1	7.5	3.4
183.97	7.9	6.5	10.7	4.4	9.6	5.3
235.24	8.7	6.4	13.5	4.8	11.6	5.8
287.49	11.7	7.9	14.7	6.2	13.4	6.6
338.82	12.0	10.0	19.4	5.3	16.3	8.0
390.48	16.9	15.1	27.4	7.2	22.2	11.2

While for both the 1988 and the 1990 cruises, the mean XBT depth error for all probes exceeded the two percent error specified, the standard deviation around the mean depth error was within two percent. This suggests that if the bias for each data set is removed, the standard XBT depth error could be within two percent.

The result of combining the two MK-9 data sets for 1988 and 1990 and computing the mean depth error and standard deviation for the 50 probes (14 T-04, 15 T-06, and 21 T-07) is provided in Table 5 and Figure 7. The corresponding low mean depth error for the combined data set can be misleading. Rather, it is the standard deviation for the XBT depth error for the combined data set that provides the best insight to the extent of the depth offset. From the surface to 700 meters, the standard deviation of the XBT depth to the CTD depth ranged 4.9 to 5.9 percent.

DISCUSSION

From this study and others it is clear that the XBT probes T-04, T-06 and T-07 descend at a rate different than specified by the standard XBT fall rate equation. This deviation in the fall rate is greater than the manufacturers specification. The tendency for the probe to fall at a faster rate, as indicated in the July 1988 STACS data, has been identified in previous studies (Seaver and Kuleskov, 1982; Heinmiller et al, 1983; Hanawa and Yoritaka, 1987; Henin, 1989). The results of the February 1990 STACS data, indicating that the probe is falling at a rate slower than the standard fall rate equation, remains an anomaly. Dean Roemmich (pers. comm.) has found that probes that have been "wet" calibrated have a tendency to fall at a slower rate than those not calibrated. This might explain the anomaly since the probes used during the February 1990 test were "wet" calibrated. The hypothesis that "wet" calibration of XBT probes may affect the XBT fall rate will be being tested during an upcoming June-July 1991 STACS cruise.

As previously discussed, the uncorrected XBT depth error has been shown to be 4.9 to 5.9 percent. Removing the systematic bias from a data set can reduce the standard depth error to about two percent. The important role the XBT plays in the measurement of the ocean's upper thermal structure mandates that the cause for these XBT-CTD depth offsets be identified and reduced.

Several possible explanations exist for these findings; although somewhat improbable, they should be considered: First, errors can be introduced by the XBT controller quartz clock. This is unlikely since the MK-2 and MK-9 showed the same results. Secondly, errors in CTD temperature-depth measurements should be considered. Although the errors for the calibrated Neil Brown CTD Mark III are too small to account for the large differences, a malfunction of the CTD is not being ruled out. An evaluation of the CTD is being conducted by AOML. Thirdly, differences in temperature and salinity structure of the water column may account for variation in the XBT fall rate. If this is the case, the significant difference found in the fall rate in the STACS region under a relatively small difference in density structure would then suggest a larger deviation in the XBT fall rate when compared to XBT-CTD evaluations at different latitudes. This possibility will be considered when the principal investigators, participating within the IGOSS Task Team on Quality Control, meet to evaluate the standard XBT fall rate equation and jointly review the results from the individual XBT-CTD tests conducted in different ocean water masses. Fourthly, possible batch-to-batch manufacturing differences in XBTs need to be considered. Fifthly, the way XBT probes are handled and stored needs to be considered. Such procedures as probe launch height (above the sea surface) and manner of handling probes (e.g., "wet calibrated") may affect probe performance.

Last but not least the adequacy of the existing coefficients of the Sippican fall rate equation need to be considered. Fitting new coefficients to the equation has shown to provide better agreement between the XBT and CTD data. The possibility of deriving new coefficients will be done in conjunction with the combined findings with the other members of IOC-IGOSS Task Team on Quality Control.

ACKNOWLEDGEMENTS

I would like to express my sincere thanks to Darren Wright (NOAA/NOS) who conducted the XBT field effort for this evaluation. I would also like to thank Bob Molinari and Mark Bushnell (NOAA/AOML) for the CTD data, the temperature and salinity contour plots for the STACS cruises, and the opportunity to conduct the evaluation during the STACS cruises. I appreciate the calibrated XBT probes and MK-2 provided by Jim Hannon (Sippican Corp.) I would also like to thank Patrick McHugh, Patricia Davey, and Mary Shihadeh who assisted in the preparation of this report.

References

Bailey, R.J., H.E. Phillips and G. Meyers
"Relevance to TOGA of Systematic XBT Errors." Unpublished manuscript presented at Third Session of the Joint IOC-WMO Meeting for Implementation of IGOSS XBT Ship-of-Opportunity Programmes, Hamburg, F.R.G., 16-20 October 1989.

Georgi, D., J. Dean and J. Chase
"Temperature Calibration of Expendable Bathythermographs." Ocean Engineering, Vol. 7, pp 491-499, 1980.

Hanawa, K. and H. Yoritaka
"Detection of Systematic Errors in XBT Data and Their Correction." J. of Oceanographical Society of Japan, Vol. 43, pp 66-76, 1987.

Heinmiller, R.H., Ebbesmeyer, C.C., Taft, B.A., Olson, D.B., and O.P. Nikitin
"Systematic Errors in Expendable Bathythermograph (XBT) Profiles." Deep Sea Research, 30, 1185-1197, 1983.

Henin, C.
"Experimental Error of Expendable Bathythermography in the Western Tropical Pacific" (unpublished manuscript). Surtropac Group, Orstrom, Noumea, 1989.

Seaver, G.A. and S. Kuleshov
"Experimental and Analytical Error of the Expendable Bathythermograph." Journal of Physics and Oceanography, 12, 592-600, 1982.

Singer, J.
"A Note on the Error Observed in Electronically Digitized T-7 XBT Data." Submitted to J. of Atmospheric and Oceanic Tech., 1990

Sippican Ocean Systems
"Operation/Maintenance Manual MK-9 Digital XBT/XSV System." September 1983.

Sy, A. and J. Ulrich
North Atlantic Ship of Opportunity XBT Programme 1989 - Data Report. Wissenschaftlich-Technische Berichte aus dem Deutschen Hydrographischen Institut, 1990.

Szabados, M. and D. Wright
Field Evaluation of Real-Time XBT Systems. Unpublished manuscript presented at Third Session of the Joint IOC-WMO Meeting for Implementation of IGOSS XBT Ship-of-Opportunity Programmes, Hamburg, F.R.G., 16-20 October 1989.

APPENDIX A
TEST PROCEDURES

TEST PROCEDURES FOR EVALUATION OF THE XBT FALL RATE EQUATION

I. INTRODUCTION

The accuracy of the standard fall rate (depth) equation that SIPPICAN, INC., recommends for use with their XBT's, particularly the T-4, T-6, and T-7 models has been questioned in the literature over the last 10 years. Four recent independent tests by Hanawa, Szabados, Bailey, and Henin present further evidence that the XBT probe appears to fall faster and at higher rate than previous indicated. If a problem does exist, it has community wide implications and must be addressed accordingly. In May 1989, at the TOGA AD Hoc Panel of XBT Experts meeting in Noumea, New Caledonia, the National Ocean Service (NOS) has agreed to take the lead in organizing a community wide effort to accurately assess the problem, determine its potential impact and develop suitable recommendations for its resolution. In October 1989, at the IGOSS International Ship-of-Opportunity Meeting in Hamburg, a decision was made to conduct an internationally coordinated experiment to evaluate the XBT fall rate equation. Field tests will be conducted in different oceans by a number of individuals in the XBT VOS community and a database of all the data will be constructed. A list of principle investigators is provided in Appendix A. This collective XBT and corresponding CTD data will be evaluated to determine the magnitude of the possible depth offset problem and used to recommend a course of action if necessary. The evaluation of the data will be a collaborative effort with the results being presented in a joint report. A meeting is being planned to coincide with the TOGA International Science Meeting in Hawaii in July 1990, to discuss the status and preliminary results of the evaluation of the XBT fall rate equation.

II. SCOPE

The purpose of this experiment is to accurately assess the XBT fall rate equation, determine any equation inadequacies, and if necessary recommend a suitable resolution to the XBT community.
The experiment will be repeated in several different ocean regions to assess any possible influence of density structure on the XBT fall rate. To ensure a controlled test, participants will arrange and coordinate the experiment in their region using test procedures provided below. Each participant will be provided with a case of calibrated T-4, T-6, and T-7 probes, a Sippican MK-9 (if needed), and IBM compatible software to run with the MK-9 (if needed).

XBT and CTD data, and the results of the calibration will be forwarded to NOS for inclusion in a central data base. NOS will in turn provide each participant with the full data set, calculated depth errors, and revised coefficients of the fall rate equation based on polynomial regression analysis. Each participant will evaluate and interpret the results and cooperatively prepare a report.

III. PROCEDURES

B. STANDARDS

1. All XBT data will be evaluated relative to a field standard. The field standard to be used will be a CTD. The CTD will be calibrated before and after the test. Each investigator will apply corrections to their CTD data, based on the calibration, before forwarding to NOS. The CTD data temperature, salinity, and depth will be forwarded to the address provide in section III.5, on a MS-DOS compatible 5 1/4 or 3 1/2 inch floppy disk (high density can be used) using the format specified in Appendix B.

2. Each XBT controller will under go a calibration check. Recommended standards for the XBT controller calibration check are provided in Appendix C. Any MK-9 provided by Sippican will under go a calibration check by NOS before being distributed. To minimize potential system bias by varies types of XBT controllers the MK-9 XBT controller from Sippican will be exclusively used. This by no means is an endorsement of the Sippican's MK-9, but reflects an experimental control. XBT controllers will be made available by Sippican for the duration of the experiment to those participants without an available MK-9. IBM PC compatible software for use with the MK-9 will be made available by NOS if needed. Computers will be the responsibility of each participant.

3. A case (12 probes) of each type of probe (T-4, T-6, and T-7) will be provided to each participant. Probes will be provided and calibrated by Sippican. To keep track of probe failures a log of the probe serial numbers associated with each drop should be maintained and forwarded with the data. All the XBT data from these tests will be recorded for later evaluation.

4. All participants contact Mike Szabados on telemail (M.SZABADOS), or by phone (202-673-3957) to arrange for the shipment of probes and if necessary a MK-9.

5. XBT data will be sent to NOS unedited on MS-DOS compatible floppy disks. All XBT data will be forward in the ASCII format specified in Appendix B. If the software provided by NOS is used, the raw data disk can be sent directly without reformatting. The mailing address for all data is:

   NOAA/NOS/OOD
   1825 CONNECTICUT AVENUE
   ROOM 618
   WASHINGTON, D.C. 20235
   ATTENTION: DARREN WRIGHT

6. To also evaluate any potential bias from analogy to digital

technology, NOS will include the use of the Sippican MK-2 analogy in their field tests.

B. FIELD PROCEDURES

The following field procedures should be used by all participants.

1. During each CTD cast three XBT's (T-4,T-6, and T-7) will dropped during the descent of the CTD.

2. Record XBT probe serial number, location, date, and time in XBT log book.

2. The XBT system should be set up for a drop prior to the descent of the CTD.

3. When the CTD is at a depth of 100 meters the T-4 probe should be first released. XBT probes will be dropped only during the down cast of the CTD.

4. Upon completion and recording of the T-4 drop, the T-6 probe should be setup and launched as soon possible.

5. Likewise the T-7 probe should be launched upon completion of the T-6 drop.

6. Make sure all XBT data is processed and saved on disk. Due to this dropping scheme, the CTD station should be at a ocean depth of at least 800 meters.

7. All CTD data should be saved for later use in the evaluation of the XBT data.

APPENDIX A

PRINCIPLE INVESTIGATORS

The following is a list of principle investigators. Participation by additional investigators is encouraged.

Rick Bailey
CSIRO Division of Oceanography
Telemail: G.MEYERS (OMNET)

Jim Hannon
Sippican Ocean Systems Inc.
Telemail: SIPPICAN

Pierre Rual
ORSTOM
Telemail: ORSTOM.NOUMEA

Alexander Sy
Deutsches Hydrographisches Institut
Telemail: DHI.HAMBURG

Michael Szabados and Darren Wright
NOAA/National Ocean Service
Telemail: M.SZABADOS

APPENDIX B

DATA FORMATS

(Note: all data to be exchanged on MS-DOS compatible floppy disks in ASCII format. If the software provided by NOS is used, the raw XBT data disk can be initially sent directly to NOS without reformatting.)

1. CTD DATA EXCHANGE FORMAT

a. Each CTD cast data saved in a separate file.

b. Each CTD file has a header record with the following information (pad with blank spaces if necessary):

Investigators Name (position 1 to 15th character)
CTD Cast Number (17th to 27th character)
Date (MO/DA/YR) (36th to 43th character)
Time GMT (HH:MM) (45th to 49th character)
Latitude (to tenths, hemisphere) (51th to 55th char.)
Longitude (to tenths, hemisphere) (57th to 62nd char.)

c. CTD data record format
(Forward data in the upper 800 meters only)
(Use CTD data from the down cast only)

Temperature (to hundredths deg. C) (1 to 6th character)
Depth (meters to hundredths) (8th to 13th character)
Salinity (part per thousand) (15th to 19th character)

Example CTD File format:

```
SZABADOS        CTD CAST 01         02/18/90 13:30 08.9N 035.7W
 28.67    1.00 34.85
 28.43    2.00 34.85
 28.33    3.00 34.85
 28.29    4.00 34.86
 28.28    5.00 34.86
 28.26    6.00 34.86
 28.21    7.00 34.85
 27.98    8.00 34.85
 27.97    9.00 34.85
 27.96   10.00 34.85
   .       .     .
   .       .     .
  9.15  400.00 37.65
   .       .     .
   .       .     .
```

2. XBT DATA EXCHANGE FORMAT

a. Each XBT drop saved in a separate file.

b. Each XBT file has a header record with the following information (pad with blank spaces if necessary):

```
Investigators Name (position 1 to 15th character)
CTD Cast Number  (17th to 27th character)
XBT Probe Type   (30th to 34th character)
Date  (MO/DA/YR) (36th to 43th character)
Time GMT (HH:MM) (45th to 49th character)
Latitude (to tenths, hemisphere) (51th to 55th char.)
Longitude (to tenths, hemisphere) (57th to 62nd char.)
```

c. XBT data record format

```
Temperature (to hundredths deg. C) (1 to 6th character)
Depth (meters to hundredths) (8th to 13th character)
```

Example XBT File Format

```
SZABADOS        CTD CAST 01  T-04  02/18/90 13:30 08.9N 035.7W
 28.67   0.65
 28.43   1.29
 28.33   1.94
 28.29   2.59
 28.28   3.24
 28.26   3.88
   .      .
   .      .
   .      .
  7.23 420.22
   .      .
   .      .
```

APPENDIX C.
XBT SYSTEM CALIBRATION CHECK PROCEDURES

Each of the XBT controllers should be tested to determine if the system is operating properly. One way to check the accuracy of the XBT controller is to use a Sippican IA8 Test Canister. This test canister is set at a specific resistance/temperature. If the temperature output of the controller being tested is not within +/- 0.1 C of the test probe temperature, the controller should not be used in the test. A second way to check the accuracy of the XBT controller is over a temperature (resistance) range using a decade box. The temperature range should be as follows, the temperatures are in parentheses:

```
Resistance
   18094 - (-2.000 C) +/- .1 C
   17287 - (-1.100 C) +/- .1 C
   16329 -  0.000 C +/- .1 C
   12679 -  5.000 C +/- .1 C
    9948 - 10.000 C +/- .1 C
    7274 - 16.660 C +/- .1 C
    6247 - 20.000 C +/- .1 C
    5000 - 25.000 C +/- .1 C
    4024 - 30.000 C +/- .1 C
    3350 - 34.000 C +/- .1 C
    3193 - 35.550 C +/- .1 C
```

If a system tests outside these limits it should not be used in the test. Results of the calibration check should be recorded.

APPENDIX B
XBT LOG SHEETS
STACS FEB 1990 CRUISE

XBT'S LAUNCHED USING MK-9 CONTROLLER

CTD CAST	PROBE TYPE	XBT DROP	SERIAL #	COMMENTS
1	T-06	1	No Rec	OPERATOR ERROR
2	T-04	2	599943	NONE
2	T-06	3	280207	NONE
2	T-07	4	678571	NONE
3	T-04	5	599944	WIRE BREAK 450M
3	T-06	6	280218	WIRE BREAK 430M
3	T-07	7	678570	NONE
4	T-06	8	280213	NONE
4	T-06	9	280216	CUT OFF AT 450
4	T-06	10	280217	CUT OFF AT 230
5	T-04	11	599941	CUT AT 370
5	T-04	12	599935	NONE
5	T-04	13	599936	CUT AT 320M
6	T-04	14	599940	CUT OFF AT 325
6	T-04	15	599938	CUT OFF AT 375
6	T-04	16	599937	CUT OFF AT 450
9	T-04	17	599740	CUT OFF AT 50M
9	T-04	18	599732	NONE
9	T-04	19	599933	NONE
10	T-04	20	599737	CUT OFF 325
10	T-04	21	599738	CUT OFF AT 300
10	T-07	22	678569	CUT OFF AT 550
11	T-06	23	280228	NONE
11	T-06	24	280224	NONE
11	T-06	25	28022u	NONE
12	T-06	26	280229	NONE
12	T-06	27	280225	NONE
12	T-06	28	280221	CUT OFF AT 300M
14	T-07	29	678577	CUT AT 250M
15	T-07	30	678576	CUT AT 250M
15	T-07	31	678575	NONE
15	T-07	32	678572	NONE
16	T-07	33	678579	NONE
16	T-07	34	678580	CUT AT 450M
19	T-07	35	678628	CUT AT 460M
19	T-07	36	678627	CUT AT 440M
20	T-07	37	678625	NONE
20	T-07	38	678624	NONE
20	T-07	39	678623	WIRE STRETCH
22	T-07	40	678620	CUT AT 750
22	T-07	41	678621	CUT AT 150M
22	T-07	42	678622	NONE
23	T-07	43	678619	NONE
23	T-07	44	678618	CUT AT 450
23	T-07	45	678617	CUT AT 700

XBT'S LAUNCHED USING MK-2 RECORDER

CTD CAST	PROBE TYPE	XBT DROP	SERIAL #	COMMENTS
4	T-06	1	280210	MK-2 ALIVE AGAIN
4	T-06	2	280212	NONE
4	T-06	3	280215	CUT OFF AT 230
5	T-06	4	280211	CUT AT 360
5	T-06	5	280208	NONE
5	T-06	6	280209	CUT AT 275
6	T-04	7	599934	CUT OFF AT 325
6	T-04	8	599939	CUT OFF AT 375
6	T-04	9	599942	CUT OFF AT 450
9	T-04	10	599729	CUT OFF AT 50M
9	T-04	11	599730	NONE
10	T-04	12	599734	NONE
10	T-04	13	599739	NONE
10	T-04	14	599735	CUT OFF AT 360
11	T-06	15	280227	NONE
11	T-06	16	280223	NONE
11	T-06	17	280219	NONE
12	T-06	18	280222	NONE
12	T-06	19	280226	NONE
12	T-06	20	262065	CUT OFF AT 300M
14	T-07	21	678574	MK-2 FAILED

APPENDIX C
BEST FIT ANALYSIS

SZABADOS CTD CAST 17 T-04 07/10/88 06:29 7.6N 49.9W

Depth Range (meters)			Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error wit Depth Uncorrected (C
6.0	to	53.7	0.00	0.04 +/- 0.02	0.04 +/- 0.02
57.7	to	105.4	-2.98	0.04 +/- 0.03	0.31 +/- 0.08
109.4	to	157.1	-5.97	0.19 +/- 0.10	0.91 +/- 0.10
161.0	to	208.7	-11.93	0.05 +/- 0.07	0.61 +/- 0.09
212.7	to	260.4	-13.91	0.01 +/- 0.03	0.37 +/- 0.09
264.4	to	312.0	-17.87	0.02 +/- 0.03	0.30 +/- 0.05
316.0	to	363.6	-21.85	0.01 +/- 0.02	0.31 +/- 0.02
367.6	to	415.3	-22.83	0.02 +/- 0.01	0.26 +/- 0.05

Uncorrected Depth	Corrected Depth
29.73	29.73
81.85	84.83
133.04	139.01
184.60	196.53
236.51	250.42
288.12	305.99
340.07	361.92
391.72	414.55

SZABADOS CTD CAST 18 T-04 07/10/88 12:55 7.1N 49.0W

Depth Range (meters)	Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error with Depth Uncorrected (C)
5.0 to 52.7	-1.99	0.02 +/- 0.02	0.05 +/- 0.03
56.7 to 104.4	-3.98	0.08 +/- 0.04	0.51 +/- 0.11
108.4 to 156.1	-8.94	0.21 +/- 0.14	1.27 +/- 0.20
160.1 to 207.7	-13.91	0.08 +/- 0.08	0.46 +/- 0.05
211.7 to 259.4	-18.87	0.04 +/- 0.04	0.25 +/- 0.04

Uncorrected Depth	Corrected Depth
29.08	31.07
80.56	84.54
132.41	141.35
183.97	197.88
235.24	254.11

SZABADOS CTD CAST 19 T-04 07/10/88 19:01 6.7N 48.5W

Depth Range (meters)	Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error with Depth Uncorrected (C)
5.0 to 52.7	-1.00	0.06 +/- 0.04	0.06 +/- 0.03
56.7 to 104.4	-5.97	0.06 +/- 0.05	0.55 +/- 0.11
108.4 to 156.1	-7.95	0.16 +/- 0.08	1.38 +/- 0.20
160.1 to 207.7	-12.91	0.06 +/- 0.07	0.68 +/- 0.06
211.7 to 259.4	-15.89	0.03 +/- 0.03	0.30 +/- 0.04
263.4 to 311.0	-19.86	0.01 +/- 0.02	0.21 +/- 0.02
315.0 to 362.7	-20.85	0.02 +/- 0.01	0.28 +/- 0.03
366.6 to 414.3	-21.83	0.04 +/- 0.02	0.20 +/- 0.03

Uncorrected Depth	Corrected Depth
29.08	30.08
80.56	86.53
132.41	140.36
183.97	196.88
235.24	251.13
287.49	307.35
338.82	359.67
390.48	412.31

SZABADOS CTD CAST 20 T-04 07/10/88 23:47 6.2N 48.5W

Depth Range (meters)			Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error wit Depth Uncorrected (C
5.0	to	52.7	0.00	0.05 +/- 0.03	0.05 +/- 0.03
56.7	to	104.4	-1.99	0.06 +/- 0.04	0.09 +/- 0.04
108.4	to	156.1	-4.97	0.16 +/- 0.08	0.87 +/- 0.12
160.1	to	207.7	-9.93	0.07 +/- 0.07	0.66 +/- 0.10
211.7	to	259.4	-12.91	0.01 +/- 0.03	0.24 +/- 0.08
263.4	to	311.0	-17.88	0.01 +/- 0.02	0.34 +/- 0.05
315.0	to	362.7	-18.86	0.01 +/- 0.02	0.25 +/- 0.05
366.6	to	414.3	-20.84	0.04 +/- 0.03	0.26 +/- 0.04

Uncorrected Depth	Corrected Depth
29.08	29.08
80.56	82.55
132.41	137.38
183.97	193.90
235.24	248.15
287.49	305.37
338.82	357.68
390.48	411.32

SZABADOS CTD CAST 21 T-04 07/11/88 04:28 5.8N 48.7W

Depth Range (meters)	Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error wit Depth Uncorrected (C
5.0 to 52.7	-1.00	0.06 +/- 0.03	0.06 +/- 0.03
56.7 to 104.4	-3.98	0.05 +/- 0.04	0.30 +/- 0.11
108.4 to 156.1	-4.97	0.16 +/- 0.07	0.96 +/- 0.20
160.1 to 207.7	-9.93	0.03 +/- 0.06	0.34 +/- 0.09
211.7 to 259.4	-13.90	0.06 +/- 0.06	0.44 +/- 0.06
263.4 to 311.0	-15.89	0.02 +/- 0.03	0.23 +/- 0.03
315.0 to 362.7	-18.86	0.03 +/- 0.02	0.15 +/- 0.05
366.6 to 414.3	-18.86	0.03 +/- 0.03	0.15 +/- 0.03

Uncorrected Depth	Corrected Depth
29.08	30.08
80.56	84.54
132.41	137.38
183.97	193.90
235.24	249.14
287.49	303.38
338.82	357.68
390.48	409.34

SZABADOS CTD CAST 22 T-04 07/11/88 9:00 5.3N 48.9W

Depth Range (meters)	Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error with Depth Uncorrected (C)
5.0 to 52.7	-1.00	0.02 +/- 0.02	0.04 +/- 0.03
56.7 to 104.4	-2.99	0.05 +/- 0.03	0.33 +/- 0.08
108.4 to 156.1	-5.96	0.20 +/- 0.11	1.19 +/- 0.23
160.1 to 207.7	-10.93	0.02 +/- 0.06	0.40 +/- 0.09
211.7 to 259.4	-13.90	0.02 +/- 0.03	0.36 +/- 0.13
263.4 to 311.0	-16.88	0.01 +/- 0.02	0.39 +/- 0.09
315.0 to 362.7	-20.85	0.01 +/- 0.02	0.25 +/- 0.06
366.6 to 414.3	-23.82	0.04 +/- 0.05	0.15 +/- 0.05

Uncorrected Depth	Corrected Depth
29.08	30.08
80.56	83.55
132.41	138.37
183.97	194.90
235.24	249.14
287.49	304.37
338.82	359.67
390.48	414.30

SZABADOS CTD CAST 23 T-04 07/11/88 13:00 5.0N 49.1W

Depth Range (meters)	Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error wit Depth Uncorrected (C
5.0 to 52.7	-1.00	0.02 +/- 0.02	0.04 +/- 0.03
56.7 to 104.4	0.00	0.05 +/- 0.03	0.05 +/- 0.03
108.4 to 156.1	-2.98	0.24 +/- 0.13	0.55 +/- 0.11
160.1 to 207.7	-10.93	0.19 +/- 0.18	0.60 +/- 0.11
211.7 to 259.4	-13.90	0.05 +/- 0.06	0.26 +/- 0.05
263.4 to 311.0	-15.89	0.02 +/- 0.03	0.25 +/- 0.03
315.0 to 362.7	-18.86	0.02 +/- 0.02	0.12 +/- 0.02
366.6 to 414.3	-18.86	0.02 +/- 0.02	0.24 +/- 0.04

Uncorrected Depth	Corrected Depth
29.08	30.08
80.56	80.56
132.41	135.39
183.97	194.90
235.24	249.14
287.49	303.38
338.82	357.68
390.48	409.34

SZABADOS CTD CAST 03 T-06 07/06/88 23:43 8.5N 57.5W

Depth Range (meters)			Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error with Depth Uncorrected (C)
5.0	to	52.7	-1.00	0.01 +/- 0.01	0.04 +/- 0.02
56.7	to	104.4	-1.00	0.04 +/- 0.03	0.10 +/- 0.05
108.4	to	156.1	-4.97	0.09 +/- 0.06	0.32 +/- 0.06
160.1	to	207.7	-7.94	0.06 +/- 0.04	0.52 +/- 0.04
211.7	to	259.4	-10.92	0.04 +/- 0.03	0.58 +/- 0.10
263.4	to	311.0	-13.90	0.04 +/- 0.03	0.34 +/- 0.10
315.0	to	362.7	-15.88	0.04 +/- 0.02	0.41 +/- 0.07
366.6	to	414.3	-17.86	0.08 +/- 0.05	0.46 +/- 0.08

Uncorrected Depth	Corrected Depth
29.08	30.08
80.56	81.56
132.41	137.38
183.97	191.91
235.24	246.16
287.49	301.39
338.82	354.70
390.48	408.34

SZABADOS CTD CAST 04 T-06 07/07/88 02:31 8.7N 57.3W

Depth Range (meters)			Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error wit Depth Uncorrected (C
5.0	to	52.7	-1.00	0.03 +/- 0.03	0.03 +/- 0.03
56.7	to	104.4	0.00	0.04 +/- 0.02	0.04 +/- 0.02
108.4	to	156.1	-4.97	0.06 +/- 0.05	0.40 +/- 0.06
160.1	to	207.7	-7.94	0.04 +/- 0.03	0.47 +/- 0.05
211.7	to	259.4	-9.93	0.06 +/- 0.03	0.56 +/- 0.13
263.4	to	311.0	-12.91	0.05 +/- 0.03	0.34 +/- 0.08
315.0	to	362.7	-15.88	0.05 +/- 0.03	0.37 +/- 0.08
366.6	to	414.3	-16.87	0.10 +/- 0.05	0.47 +/- 0.09

Uncorrected Depth	Corrected Depth
29.08	30.08
80.56	80.56
132.41	137.38
183.97	191.91
235.24	245.17
287.49	300.40
338.82	354.70
390.48	407.35

SZABADOS CTD CAST 05 T-06 07/07/88 05:57 9.0N 57.1W

Depth Range (meters)	Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error with Depth Uncorrected (C)
5.0 to 52.7	0.00	0.01 +/- 0.03	0.01 +/- 0.03
56.7 to 104.4	-1.99	0.04 +/- 0.03	0.19 +/- 0.06
108.4 to 156.1	-5.96	0.05 +/- 0.05	0.42 +/- 0.05
160.1 to 207.7	-8.94	0.05 +/- 0.04	0.71 +/- 0.08
211.7 to 259.4	-11.92	0.03 +/- 0.04	0.56 +/- 0.14
263.4 to 311.0	-14.90	0.03 +/- 0.03	0.47 +/- 0.07
315.0 to 362.7	-17.87	0.04 +/- 0.03	0.35 +/- 0.08
366.6 to 414.3	-20.84	0.07 +/- 0.06	0.31 +/- 0.05

Uncorrected Depth	Corrected Depth
29.08	29.08
80.56	82.55
132.41	138.37
183.97	192.91
235.24	247.16
287.49	302.39
338.82	356.69
390.48	411.32

SZABADOS CTD CAST 06 T-06 07/07/88 09:57 9.5N 56.9W

Depth Range (meters)			Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error with Depth Uncorrected (C)
5.0	to	52.7	-1.99	0.01 +/- 0.02	0.06 +/- 0.03
56.7	to	104.4	-2.99	0.04 +/- 0.03	0.28 +/- 0.05
108.4	to	156.1	-6.96	0.12 +/- 0.07	0.52 +/- 0.08
160.1	to	207.7	-12.91	0.07 +/- 0.06	1.03 +/- 0.11
211.7	to	259.4	-13.90	0.15 +/- 0.10	0.71 +/- 0.14
263.4	to	311.0	-20.86	0.03 +/- 0.04	0.39 +/- 0.04
315.0	to	362.7	-19.85	0.07 +/- 0.02	0.28 +/- 0.05
366.6	to	414.3	-22.83	0.08 +/- 0.04	0.36 +/- 0.06

Uncorrected Depth	Corrected Depth
29.08	31.07
80.56	83.55
132.41	139.37
183.97	196.88
235.24	249.14
287.49	308.35
338.82	358.67
390.48	413.31

SZABADOS CTD CAST 07 T-06 07/07/88 14:32 9.9N 56.7W

Depth Range (meters)	Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error with Depth Uncorrected (C)
5.0 to 52.7	-1.99	0.01 +/- 0.02	0.05 +/- 0.03
56.7 to 104.4	-1.99	0.04 +/- 0.02	0.18 +/- 0.05
108.4 to 156.1	-6.96	0.15 +/- 0.11	0.63 +/- 0.07
160.1 to 207.7	-10.93	0.03 +/- 0.05	0.81 +/- 0.08
211.7 to 259.4	-11.92	0.08 +/- 0.06	0.37 +/- 0.11
263.4 to 311.0	-12.91	0.06 +/- 0.03	0.29 +/- 0.09
315.0 to 362.7	-14.89	0.03 +/- 0.02	0.41 +/- 0.09
366.6 to 414.3	-19.85	0.03 +/- 0.03	0.20 +/- 0.05

Uncorrected Depth	Corrected Depth
29.08	31.07
80.56	82.55
132.41	139.37
183.97	194.90
235.24	247.16
287.49	300.40
338.82	353.71
390.48	410.33

SZABADOS CTD CAST 08 T-06 07/07/88 18:36 10.3N 56.4W

Depth Range (meters)			Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error with Depth Uncorrected (C)
5.0	to	52.7	0.00	0.02 +/- 0.02	0.02 +/- 0.02
56.7	to	104.4	-1.99	0.08 +/- 0.05	0.16 +/- 0.07
108.4	to	156.1	-5.96	0.09 +/- 0.06	0.76 +/- 0.08
160.1	to	207.7	-9.93	0.09 +/- 0.06	0.68 +/- 0.09
211.7	to	259.4	-13.90	0.04 +/- 0.05	0.35 +/- 0.12
263.4	to	311.0	-18.87	0.04 +/- 0.03	0.33 +/- 0.07
315.0	to	362.7	-21.84	0.02 +/- 0.02	0.35 +/- 0.03
366.6	to	414.3	-23.82	0.03 +/- 0.02	0.24 +/- 0.04

Uncorrected Depth	Corrected Depth
29.08	29.08
80.56	82.55
132.41	138.37
183.97	193.90
235.24	249.14
287.49	306.36
338.82	360.66
390.48	414.30

SZABADOS CTD CAST 09 T-06 07/07/88 23:32 10.7N 56.2W

Depth Range (meters)	Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error with Depth Uncorrected (C)
5.0 to 52.7	-1.00	0.01 +/- 0.02	0.03 +/- 0.02
56.7 to 104.4	-2.99	0.06 +/- 0.04	0.21 +/- 0.06
108.4 to 156.1	-3.97	0.16 +/- 0.06	0.54 +/- 0.07
160.1 to 207.7	-8.94	0.05 +/- 0.05	0.60 +/- 0.08
211.7 to 259.4	-12.91	0.06 +/- 0.05	0.45 +/- 0.10
263.4 to 311.0	-15.89	0.03 +/- 0.03	0.31 +/- 0.07
315.0 to 362.7	-18.86	0.02 +/- 0.02	0.22 +/- 0.04
366.6 to 414.3	-19.85	0.03 +/- 0.02	0.19 +/- 0.03

Uncorrected Depth	Corrected Depth
29.08	30.08
80.56	83.55
132.41	136.38
183.97	192.91
235.24	248.15
287.49	303.38
338.82	357.68
390.48	410.33

SZABADOS CTD CAST 10 T-07 07/08/88 04:40 11.2N 55.9W

Depth Range (meters)			Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error wit Depth Uncorrected (C
5.0	to	52.7	-1.99	0.03 +/- 0.02	0.07 +/- 0.03
56.7	to	104.4	-3.98	0.06 +/- 0.04	0.34 +/- 0.07
108.4	to	156.1	-4.97	0.11 +/- 0.05	0.53 +/- 0.05
160.1	to	207.7	-8.94	0.05 +/- 0.05	0.59 +/- 0.04
211.7	to	259.4	-9.93	0.07 +/- 0.04	0.35 +/- 0.10
263.4	to	311.0	-14.90	0.05 +/- 0.04	0.33 +/- 0.12
315.0	to	362.7	-14.89	0.04 +/- 0.03	0.22 +/- 0.06
366.6	to	414.3	-18.86	0.03 +/- 0.03	0.19 +/- 0.05
418.2	to	465.9	-18.85	0.03 +/- 0.02	0.18 +/- 0.04
469.9	to	517.5	-18.85	0.03 +/- 0.02	0.22 +/- 0.03
521.4	to	569.0	-24.80	0.04 +/- 0.03	0.23 +/- 0.05
573.0	to	620.6	-26.78	0.04 +/- 0.03	0.18 +/- 0.05
624.6	to	672.2	-27.76	0.07 +/- 0.04	0.32 +/- 0.04
676.1	to	723.7	-30.73	0.03 +/- 0.03	0.19 +/- 0.03

Uncorrected Depth	Corrected Depth
29.08	31.07
80.56	84.54
132.41	137.38
183.97	192.91
235.24	245.17
287.49	302.39
338.82	353.71
390.48	409.34
441.84	460.69
493.51	512.36
545.50	570.30
596.56	623.34
648.52	676.28
700.16	730.89

SZABADOS CTD CAST 11 T-07 07/08/88 11:38 10.7N 55.1W

Depth Range (meters)			Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error with Depth Uncorrected (C)
5.0	to	52.7	-1.99	0.04 +/- 0.03	0.09 +/- 0.04
56.7	to	104.4	-2.99	0.08 +/- 0.05	0.24 +/- 0.08
108.4	to	156.1	-5.96	0.21 +/- 0.11	0.53 +/- 0.09
160.1	to	207.7	-10.93	0.05 +/- 0.05	0.80 +/- 0.14
211.7	to	259.4	-13.90	0.06 +/- 0.05	0.35 +/- 0.11
263.4	to	311.0	-14.90	0.06 +/- 0.04	0.28 +/- 0.10
315.0	to	362.7	-16.88	0.06 +/- 0.04	0.31 +/- 0.08
366.6	to	414.3	-13.89	0.06 +/- 0.04	0.20 +/- 0.06
418.2	to	465.9	-17.86	0.04 +/- 0.03	0.23 +/- 0.06
469.9	to	517.5	-19.85	0.04 +/- 0.03	0.15 +/- 0.03
521.4	to	569.0	-22.81	0.04 +/- 0.03	0.30 +/- 0.04
573.0	to	620.6	-24.79	0.05 +/- 0.04	0.27 +/- 0.08
624.6	to	672.2	-21.81	0.02 +/- 0.02	0.17 +/- 0.06
676.1	to	723.7	-24.78	0.04 +/- 0.02	0.27 +/- 0.03

Uncorrected Depth	Corrected Depth
29.08	31.07
80.56	83.55
132.41	138.37
183.97	194.90
235.24	249.14
287.49	302.39
338.82	355.70
390.48	404.37
441.84	459.70
493.51	513.36
545.50	568.31
596.56	621.35
648.52	670.33
700.16	724.94

SZABADOS CTD CAST 12 T-07 07/08/88 21:25 10.2N 54.2W

Depth Range (meters)	Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error with Depth Uncorrected (C)
5.0 to 52.7	-1.99	0.02 +/- 0.02	0.05 +/- 0.02
56.7 to 104.4	-3.98	0.15 +/- 0.07	0.61 +/- 0.15
108.4 to 156.1	-7.95	0.13 +/- 0.07	0.69 +/- 0.07
160.1 to 207.7	-13.91	0.04 +/- 0.05	0.78 +/- 0.07
211.7 to 259.4	-16.88	0.07 +/- 0.06	0.41 +/- 0.08
263.4 to 311.0	-20.86	0.03 +/- 0.03	0.47 +/- 0.12
315.0 to 362.7	-22.83	0.05 +/- 0.02	0.40 +/- 0.08
366.6 to 414.3	-28.78	0.05 +/- 0.04	0.33 +/- 0.04
418.2 to 465.9	-27.79	0.04 +/- 0.02	0.23 +/- 0.04
469.9 to 517.5	-30.76	0.04 +/- 0.02	0.27 +/- 0.03
521.4 to 569.0	-31.74	0.04 +/- 0.01	0.31 +/- 0.02
573.0 to 620.6	-39.67	0.03 +/- 0.02	0.34 +/- 0.02
624.6 to 672.2	-40.64	0.04 +/- 0.03	0.33 +/- 0.04
676.1 to 723.7	-49.56	0.03 +/- 0.04	0.30 +/- 0.03

Uncorrected Depth	Corrected Depth
29.08	31.07
80.56	84.54
132.41	140.36
183.97	197.88
235.24	252.12
287.49	308.35
338.82	361.65
390.48	419.26
441.84	469.63
493.51	524.27
545.50	577.24
596.56	636.23
648.52	689.16
700.16	749.72

SZABADOS CTD CAST 13 T-07 07/09/88 4:56 9.7N 53.3W

Depth Range (meters)			Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error with Depth Uncorrected (C)
5.0	to	52.7	0.00	0.05 +/- 0.04	0.05 +/- 0.04
56.7	to	104.4	-1.00	0.07 +/- 0.04	0.11 +/- 0.05
108.4	to	156.1	-4.97	0.09 +/- 0.06	0.55 +/- 0.07
160.1	to	207.7	-8.94	0.04 +/- 0.05	0.41 +/- 0.05
211.7	to	259.4	-10.92	0.08 +/- 0.09	0.52 +/- 0.12
263.4	to	311.0	-13.90	0.01 +/- 0.03	0.34 +/- 0.10
315.0	to	362.7	-16.88	0.02 +/- 0.03	0.34 +/- 0.10
366.6	to	414.3	-18.86	0.09 +/- 0.08	0.32 +/- 0.06
418.2	to	465.9	-21.83	0.03 +/- 0.03	0.33 +/- 0.05
469.9	to	517.5	-25.80	0.02 +/- 0.02	0.26 +/- 0.03
521.4	to	569.0	-28.77	0.02 +/- 0.02	0.23 +/- 0.02
573.0	to	620.6	-30.74	0.02 +/- 0.01	0.21 +/- 0.02
624.6	to	672.2	-34.70	0.03 +/- 0.02	0.16 +/- 0.02
676.1	to	723.7	-32.71	0.02 +/- 0.01	0.11 +/- 0.02

Uncorrected Depth	Corrected Depth
29.08	29.08
80.56	81.56
132.41	137.38
183.97	192.91
235.24	246.16
287.49	301.39
338.82	355.70
390.48	409.34
441.84	463.67
493.51	519.31
545.50	574.27
596.56	627.30
648.52	683.22
700.16	732.87

SZABADOS CTD CAST 14 T-07 07/09/88 11:14 9.2N 52.7W

Depth Range (meters)			Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error wi Depth Uncorrected (
5.0	to	52.7	-1.00	0.07 +/- 0.04	0.08 +/- 0.04
56.7	to	104.4	-3.98	0.10 +/- 0.05	0.44 +/- 0.10
108.4	to	156.1	-5.96	0.11 +/- 0.05	0.61 +/- 0.08
160.1	to	207.7	-10.93	0.06 +/- 0.05	0.60 +/- 0.10
211.7	to	259.4	-16.88	0.03 +/- 0.04	0.66 +/- 0.14
263.4	to	311.0	-19.86	0.01 +/- 0.03	0.48 +/- 0.10
315.0	to	362.7	-21.84	0.01 +/- 0.02	0.36 +/- 0.12
366.6	to	414.3	-24.81	0.03 +/- 0.03	0.44 +/- 0.07
418.2	to	465.9	-26.79	0.03 +/- 0.02	0.30 +/- 0.07
469.9	to	517.5	-28.78	0.02 +/- 0.02	0.30 +/- 0.03
521.4	to	569.0	-32.73	0.02 +/- 0.02	0.33 +/- 0.04
573.0	to	620.6	-37.69	0.02 +/- 0.02	0.33 +/- 0.02
624.6	to	672.2	-44.61	0.04 +/- 0.04	0.27 +/- 0.03
676.1	to	723.7	-48.57	0.02 +/- 0.02	0.20 +/- 0.02

Uncorrected Depth	Corrected Depth
29.08	30.08
80.56	84.54
132.41	138.37
183.97	194.90
235.24	252.12
287.49	307.35
338.82	360.66
390.48	415.29
441.84	468.63
493.51	522.29
545.50	578.23
596.56	634.25
648.52	693.13
700.16	748.73

SZABADOS CTD CAST 15 T-07 07/09/88 18:01 8.6N 51.6W

Depth Range (meters)			Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error with Depth Uncorrected (C)
5.0	to	52.7	5.96	0.11 +/- 0.06	0.17 +/- 0.09
56.7	to	104.4	-4.97	0.14 +/- 0.08	0.44 +/- 0.17
108.4	to	156.1	-8.94	0.16 +/- 0.10	1.05 +/- 0.11
160.1	to	207.7	-14.90	0.10 +/- 0.07	1.21 +/- 0.14
211.7	to	259.4	-17.88	0.07 +/- 0.06	0.59 +/- 0.06
263.4	to	311.0	-17.88	0.02 +/- 0.02	0.32 +/- 0.04
315.0	to	362.7	-18.86	0.01 +/- 0.02	0.22 +/- 0.02
366.6	to	414.3	-18.86	0.03 +/- 0.03	0.14 +/- 0.02
418.2	to	465.9	-19.85	0.01 +/- 0.02	0.17 +/- 0.02
469.9	to	517.5	-19.85	0.02 +/- 0.01	0.15 +/- 0.02
521.4	to	569.0	-22.81	0.02 +/- 0.02	0.13 +/- 0.03
573.0	to	620.6	-22.81	0.01 +/- 0.01	0.09 +/- 0.04
624.6	to	672.2	-22.80	0.02 +/- 0.02	0.11 +/- 0.02
676.1	to	723.7	-23.79	0.00 +/- 0.01	0.20 +/- 0.02

Uncorrected Depth	Corrected Depth
29.08	23.12
80.56	85.53
132.41	141.35
183.97	198.87
235.24	253.12
287.49	305.37
338.82	357.68
390.48	409.34
441.84	461.69
493.51	513.36
545.50	568.31
596.56	619.37
648.52	671.32
700.16	723.95

SZABADOS CTD CAST 16 T-07 07/10/88 00:20 8.2N 50.8W

Depth Range (meters)	Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error with Depth Uncorrected (C
5.0 to 52.7	0.99	0.03 +/- 0.02	0.03 +/- 0.03
56.7 to 104.4	-6.96	0.15 +/- 0.09	0.55 +/- 0.23
108.4 to 156.1	-8.94	0.07 +/- 0.06	1.47 +/- 0.30
160.1 to 207.7	-12.91	0.03 +/- 0.06	0.88 +/- 0.16
211.7 to 259.4	-16.88	0.02 +/- 0.04	0.42 +/- 0.07
263.4 to 311.0	-22.84	0.02 +/- 0.03	0.27 +/- 0.06
315.0 to 362.7	-23.83	0.02 +/- 0.02	0.33 +/- 0.03
366.6 to 414.3	-23.82	0.05 +/- 0.04	0.31 +/- 0.04
418.2 to 465.9	-23.82	0.02 +/- 0.02	0.35 +/- 0.03

Uncorrected Depth	Corrected Depth
29.08	28.09
80.56	87.52
132.41	141.35
183.97	196.88
235.24	252.12
287.49	310.33
338.82	362.65
390.48	414.30
441.84	465.66

SZABADOS CTD CAST 02 T-04 01/31/90 17:45 12.1N 60.1W

Depth Range (meters)	Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error with Depth Uncorrected (C)
5.0 to 52.7	0.99	0.03 +/- 0.02	0.03 +/- 0.02
56.7 to 104.4	4.97	0.04 +/- 0.02	0.28 +/- 0.18
108.4 to 156.1	5.96	0.09 +/- 0.07	0.82 +/- 0.51
160.1 to 207.7	8.95	0.07 +/- 0.04	0.51 +/- 0.33
211.7 to 259.4	10.93	0.04 +/- 0.03	0.26 +/- 0.16
263.4 to 311.0	14.90	0.04 +/- 0.03	0.40 +/- 0.25
315.0 to 362.7	17.87	0.05 +/- 0.04	0.47 +/- 0.29
366.6 to 414.3	17.87	0.10 +/- 0.06	0.56 +/- 0.34

Uncorrected Depth	Corrected Depth
29.08	28.09
80.56	75.59
132.41	126.45
183.97	175.02
235.24	224.31
287.49	272.59
338.82	320.95
390.48	372.61

SZABADOS CTD CAST 10 T-07 07/08/88 04:40 11.2N 55.9W

Depth Range (meters)			Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error wit Depth Uncorrected (C
5.0	to	52.7	-1.99	0.03 +/- 0.02	0.07 +/- 0.03
56.7	to	104.4	-3.98	0.06 +/- 0.04	0.34 +/- 0.07
108.4	to	156.1	-4.97	0.11 +/- 0.05	0.53 +/- 0.05
160.1	to	207.7	-8.94	0.05 +/- 0.05	0.59 +/- 0.04
211.7	to	259.4	-9.93	0.07 +/- 0.04	0.35 +/- 0.10
263.4	to	311.0	-14.90	0.05 +/- 0.04	0.33 +/- 0.12
315.0	to	362.7	-14.89	0.04 +/- 0.03	0.22 +/- 0.06
366.6	to	414.3	-18.86	0.03 +/- 0.03	0.19 +/- 0.05
418.2	to	465.9	-18.85	0.03 +/- 0.02	0.18 +/- 0.04
469.9	to	517.5	-18.85	0.03 +/- 0.02	0.22 +/- 0.03
521.4	to	569.0	-24.80	0.04 +/- 0.03	0.23 +/- 0.05
573.0	to	620.6	-26.78	0.04 +/- 0.03	0.18 +/- 0.05
624.6	to	672.2	-27.76	0.07 +/- 0.04	0.32 +/- 0.04
676.1	to	723.7	-30.73	0.03 +/- 0.03	0.19 +/- 0.03

Uncorrected Depth	Corrected Depth
29.08	31.07
80.56	84.54
132.41	137.38
183.97	192.91
235.24	245.17
287.49	302.39
338.82	353.71
390.48	409.34
441.84	460.69
493.51	512.36
545.50	570.30
596.56	623.34
648.52	676.28
700.16	730.89

SZABADOS CTD CAST 05 T-04 02/03/90 15:40 7.8N 52.6W

Depth Range (meters)	Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error with Depth Uncorrected (C)
5.0 to 52.7	0.99	0.03 +/- 0.03	0.04 +/- 0.03
56.7 to 104.4	6.95	0.03 +/- 0.02	0.66 +/- 0.44
108.4 to 156.1	5.96	0.07 +/- 0.04	0.67 +/- 0.42
160.1 to 207.7	5.97	0.02 +/- 0.02	0.54 +/- 0.39
211.7 to 259.4	5.96	0.03 +/- 0.02	0.07 +/- 0.07
263.4 to 311.0	9.93	0.03 +/- 0.02	0.14 +/- 0.09
315.0 to 362.7	10.92	0.03 +/- 0.01	0.06 +/- 0.04
366.6 to 414.3	8.94	0.02 +/- 0.02	0.06 +/- 0.05

Uncorrected Depth	Corrected Depth
29.08	28.09
80.56	73.61
132.41	126.45
183.97	178.00
235.24	229.28
287.49	277.56
338.82	327.90
390.48	381.54

SZABADOS CTD CAST 06 T-04 02/03/90 18:28 7.8N 52.7W

Depth Range (meters)	Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error wi Depth Uncorrected (
5.0 to 52.7	1.99	0.01 +/- 0.01	0.02 +/- 0.02
56.7 to 104.4	6.95	0.04 +/- 0.03	0.77 +/- 0.49
108.4 to 156.1	9.94	0.09 +/- 0.04	1.53 +/- 0.96
160.1 to 207.7	10.93	0.04 +/- 0.03	0.48 +/- 0.32
211.7 to 259.4	13.91	0.06 +/- 0.05	0.18 +/- 0.13
263.4 to 311.0	14.90	0.01 +/- 0.02	0.06 +/- 0.05

Uncorrected Depth	Corrected Depth
29.08	27.09
80.56	73.61
132.41	122.47
183.97	173.04
235.24	221.33
287.49	272.59

SZABADOS CTD CAST 09 T-04 02/05/90 05:31 9.0N 51.9W

Depth Range (meters)	Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error wit Depth Uncorrected (C
5.0 to 52.7	1.99	0.00 +/- 0.05	0.01 +/- 0.03
56.7 to 104.4	5.96	0.01 +/- 0.04	0.04 +/- 0.04
108.4 to 156.1	5.96	0.14 +/- 0.07	0.84 +/- 0.53
160.1 to 207.7	8.95	0.03 +/- 0.03	0.82 +/- 0.51
211.7 to 259.4	10.93	0.05 +/- 0.03	0.49 +/- 0.31
263.4 to 311.0	11.92	0.02 +/- 0.02	0.22 +/- 0.14
315.0 to 362.7	15.89	0.02 +/- 0.01	0.35 +/- 0.21
366.6 to 414.3	18.86	0.06 +/- 0.04	0.42 +/- 0.26

Uncorrected Depth	Corrected Depth
29.08	27.09
80.56	74.60
132.41	126.45
183.97	175.02
235.24	224.31
287.49	275.57
338.82	322.93
390.48	371.62

SZABADOS CTD CAST 09 T-04 02/05/90 00:36 9.0N 51.9W

Depth Range (meters)			Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error with Depth Uncorrected (C)
5.0	to	52.7	0.99	0.02 +/- 0.07	0.03 +/- 0.05
56.7	to	104.4	3.97	0.02 +/- 0.02	0.05 +/- 0.05
108.4	to	156.1	6.96	0.20 +/- 0.09	0.90 +/- 0.56
160.1	to	207.7	11.93	0.05 +/- 0.05	1.07 +/- 0.66
211.7	to	259.4	13.91	0.05 +/- 0.04	0.67 +/- 0.42
263.4	to	311.0	15.89	0.05 +/- 0.03	0.32 +/- 0.20
315.0	to	362.7	17.87	0.03 +/- 0.02	0.43 +/- 0.26
366.6	to	414.3	21.84	0.08 +/- 0.05	0.51 +/- 0.32

Uncorrected Depth	Corrected Depth
29.08	28.09
80.56	76.59
132.41	125.45
183.97	172.04
235.24	221.33
287.49	271.60
338.82	320.95
390.48	368.64

SZABADOS CTD CAST 10 T-04 02/05/90 21:30 10.0N 51.3W

Depth Range (meters)	Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error wi Depth Uncorrected (
5.0 to 52.7	2.98	0.03 +/- 0.05	0.04 +/- 0.05
56.7 to 104.4	4.97	0.07 +/- 0.04	0.55 +/- 0.37
108.4 to 156.1	6.96	0.05 +/- 0.03	0.75 +/- 0.46
160.1 to 207.7	8.95	0.06 +/- 0.03	0.58 +/- 0.36
211.7 to 259.4	9.94	0.08 +/- 0.06	0.28 +/- 0.19
263.4 to 311.0	12.91	0.04 +/- 0.03	0.21 +/- 0.13

Uncorrected Depth	Corrected Depth
29.08	26.10
80.56	75.59
132.41	125.45
183.97	175.02
235.24	225.30
287.49	274.58

SZABADOS CTD CAST 02 T-06 01/31/90 17:50 12.1N 60.1W

Depth Range (meters)	Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error with Depth Uncorrected (C)
5.0 to 52.7	4.97	0.02 +/- 0.04	0.03 +/- 0.03
56.7 to 104.4	6.95	0.07 +/- 0.04	0.41 +/- 0.27
108.4 to 156.1	9.94	0.17 +/- 0.13	1.32 +/- 0.81
160.1 to 207.7	14.91	0.08 +/- 0.05	0.87 +/- 0.54
211.7 to 259.4	18.88	0.06 +/- 0.03	0.33 +/- 0.21
263.4 to 311.0	21.85	0.04 +/- 0.02	0.45 +/- 0.28
315.0 to 362.7	21.84	0.08 +/- 0.04	0.46 +/- 0.29
366.6 to 414.3	20.85	0.15 +/- 0.09	0.67 +/- 0.41

Uncorrected Depth	Corrected Depth
29.08	24.11
80.56	73.61
132.41	122.47
183.97	169.06
235.24	216.36
287.49	265.64
338.82	316.98
390.48	369.63

SZABADOS CTD CAST 04 T-06 02/03/90 03:00 7.5N 53.0W

Depth Range (meters)	Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error wit Depth Uncorrected (C
5.0 to 52.7	1.99	0.01 +/- 0.05	0.01 +/- 0.05
56.7 to 104.4	3.97	0.14 +/- 0.07	0.43 +/- 0.28
108.4 to 156.1	6.96	0.11 +/- 0.05	0.96 +/- 0.60
160.1 to 207.7	8.95	0.06 +/- 0.04	0.35 +/- 0.23
211.7 to 259.4	13.91	0.03 +/- 0.03	0.10 +/- 0.07
263.4 to 311.0	15.89	0.03 +/- 0.02	0.24 +/- 0.15
315.0 to 362.7	16.88	0.04 +/- 0.03	0.21 +/- 0.13
366.6 to 414.3	25.81	0.05 +/- 0.03	0.19 +/- 0.12

Uncorrected Depth	Corrected Depth
29.08	27.09
80.56	76.59
132.41	125.45
183.97	175.02
235.24	221.33
287.49	271.60
338.82	321.94
390.48	364.67

SZABADOS CTD CAST 04 T-06 02/03/90 03:10 7.5N 53.0W

Depth Range (meters)	Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error with Depth Uncorrected (C)
5.0 to 52.7	4.97	0.01 +/- 0.03	0.02 +/- 0.03
56.7 to 104.4	9.94	0.09 +/- 0.06	1.10 +/- 0.71
108.4 to 156.1	14.91	0.21 +/- 0.12	2.18 +/- 1.33
160.1 to 207.7	18.88	0.09 +/- 0.06	0.96 +/- 0.61
211.7 to 259.4	18.88	0.03 +/- 0.02	0.12 +/- 0.10
263.4 to 311.0	19.86	0.02 +/- 0.02	0.26 +/- 0.17
315.0 to 362.7	19.86	0.01 +/- 0.01	0.23 +/- 0.16
366.6 to 414.3	20.85	0.02 +/- 0.02	0.14 +/- 0.09

Uncorrected Depth	Corrected Depth
29.08	24.11
80.56	70.62
132.41	117.50
183.97	165.09
235.24	216.36
287.49	267.63
338.82	318.96
390.48	369.63

SZABADOS CTD CAST 11 T-06 02/06/90 21:56 7.1N 50.3W

Depth Range (meters)			Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error wi Depth Uncorrected (
5.0	to	52.7	0.99	0.01 +/- 0.03	0.01 +/- 0.03
56.7	to	104.4	0.00	0.00 +/- 0.01	0.00 +/- 0.01
108.4	to	156.1	7.95	0.15 +/- 0.07	0.72 +/- 0.50
160.1	to	207.7	10.93	0.13 +/- 0.07	2.06 +/- 1.26
211.7	to	259.4	11.92	0.05 +/- 0.03	0.60 +/- 0.40
263.4	to	311.0	14.90	0.01 +/- 0.02	0.17 +/- 0.12
315.0	to	362.7	17.87	0.01 +/- 0.02	0.15 +/- 0.10
366.6	to	414.3	20.85	0.01 +/- 0.01	0.12 +/- 0.08

Uncorrected Depth	Corrected Depth
29.08	28.09
80.56	80.56
132.41	124.46
183.97	173.04
235.24	223.32
287.49	272.59
338.82	320.95
390.48	369.63

SZABADOS CTD CAST 11 T-06 02/06/90 22:05 7.1N 50.3W

Depth Range (meters)	Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error with Depth Uncorrected (C)
5.0 to 52.7	0.00	0.01 +/- 0.02	0.01 +/- 0.02
56.7 to 104.4	8.94	0.01 +/- 0.01	0.01 +/- 0.02
108.4 to 156.1	6.96	0.06 +/- 0.04	0.67 +/- 0.45
160.1 to 207.7	9.94	0.26 +/- 0.12	1.69 +/- 1.04
211.7 to 259.4	9.94	0.03 +/- 0.04	0.53 +/- 0.35
263.4 to 311.0	15.89	0.01 +/- 0.03	0.17 +/- 0.11
315.0 to 362.7	16.88	0.00 +/- 0.01	0.14 +/- 0.09
366.6 to 414.3	18.86	0.02 +/- 0.02	0.11 +/- 0.07

Uncorrected Depth	Corrected Depth
29.08	29.08
80.56	71.62
132.41	125.45
183.97	174.03
235.24	225.30
287.49	271.60
338.82	321.94
390.48	371.62

SZABADOS CTD CAST 11 T-06 02/06/90 22:12 7.1N 50.3W

Depth Range (meters)			Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error wit Depth Uncorrected (C
5.0	to	52.7	0.99	0.01 +/- 0.02	0.02 +/- 0.03
56.7	to	104.4	0.00	0.00 +/- 0.01	0.00 +/- 0.01
108.4	to	156.1	7.95	0.11 +/- 0.06	0.77 +/- 0.53
160.1	to	207.7	10.93	0.20 +/- 0.09	2.00 +/- 1.22
211.7	to	259.4	13.91	0.04 +/- 0.03	C.75 +/- 0.49
263.4	to	311.0	18.87	0.01 +/- 0.03	0 20 +/- 0.13
315.0	to	362.7	20.85	0.01 +/- 0.01	0.17 +/- 0.11
366.6	to	414.3	20.85	0.02 +/- 0.02	0.13 +/- 0.08

Uncorrected Depth	Corrected Depth
29.08	28.09
80.56	80.56
132.41	124.46
183.97	173.04
235.24	221.33
287.49	268.62
338.82	317.97
390.48	369.63

SZABADOS CTD CAST 12 T-06 02/07/90 03:32 6.7N 50.7W

Depth Range (meters)	Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error with Depth Uncorrected (C
5.0 to 52.7	0.00	0.01 +/- 0.02	0.01 +/- 0.02
56.7 to 104.4	0.00	0.01 +/- 0.01	0.01 +/- 0.01
108.4 to 156.1	17.89	0.05 +/- 0.02	1.52 +/- 1.04
160.1 to 207.7	19.87	0.30 +/- 0.16	3.51 +/- 2.12
211.7 to 259.4	24.84	0.21 +/- 0.12	1.60 +/- 0.99
263.4 to 311.0	32.77	0.06 +/- 0.04	1.05 +/- 0.64
315.0 to 362.7	37.73	0.06 +/- 0.04	0.40 +/- 0.25
366.6 to 414.3	45.66	0.06 +/- 0.04	0.29 +/- 0.18

Uncorrected Depth	Corrected Depth
29.08	29.08
80.56	80.56
132.41	114.52
183.97	164.10
235.24	210.40
287.49	254.72
338.82	301.09
390.48	344.82

SZABADOS CTD CAST 12 T-06 02/07/90 03:37 6.7N 50.7W

Depth Range (meters)			Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error wi Depth Uncorrected (
5.0	to	52.7	0.00	0.01 +/- 0.04	0.01 +/- 0.04
56.7	to	104.4	1.98	0.01 +/- 0.02	0.02 +/- 0.02
108.4	to	156.1	12.92	0.06 +/- 0.03	1.24 +/- 0.85
160.1	to	207.7	13.91	0.19 +/- 0.10	2.32 +/- 1.40
211.7	to	259.4	15.90	0.11 +/- 0.07	0.88 +/- 0.55
263.4	to	311.0	19.86	0.04 +/- 0.03	0.57 +/- 0.36
315.0	to	362.7	22.84	0.06 +/- 0.04	0.30 +/- 0.19
366.6	to	414.3	29.78	0.05 +/- 0.04	0.20 +/- 0.14

Uncorrected Depth	Corrected Depth
29.08	29.08
80.56	78.58
132.41	119.49
183.97	170.06
235.24	219.34
287.49	267.63
338.82	315.98
390.48	360.70

SZABADOS CTD CAST 02 T-07 01/31/90 17:26 12.1N 60.1W

Depth Range (meters)	Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error with Depth Uncorrected (C)
5.0 to 52.7	0.00	0.01 +/- 0.01	0.01 +/- 0.01
56.7 to 104.4	-1.00	0.03 +/- 0.02	0.07 +/- 0.03
108.4 to 156.1	1.00	0.26 +/- 0.13	0.27 +/- 0.16
160.1 to 207.7	7.95	0.07 +/- 0.05	0.45 +/- 0.29
211.7 to 259.4	10.93	0.06 +/- 0.04	0.22 +/- 0.14
263.4 to 311.0	10.92	0.06 +/- 0.04	0.41 +/- 0.24
315.0 to 362.7	10.92	0.08 +/- 0.05	0.42 +/- 0.25
366.6 to 414.3	12.91	0.12 +/- 0.06	0.42 +/- 0.26
418.2 to 465.9	22.82	0.06 +/- 0.03	0.41 +/- 0.25
469.9 to 517.5	21.82	0.03 +/- 0.02	0.30 +/- 0.19
521.4 to 569.0	15.87	0.02 +/- 0.02	0.24 +/- 0.15
573.0 to 620.6	18.84	0.03 +/- 0.02	0.21 +/- 0.13
624.6 to 672.2	21.81	0.03 +/- 0.03	0.22 +/- 0.14
676.1 to 723.7	23.78	0.03 +/- 0.02	0.15 +/- 0.10

Uncorrected Depth	Corrected Depth
29.08	29.08
80.56	81.56
132.41	131.41
183.97	176.02
235.24	224.31
287.49	276.57
338.82	327.90
390.48	377.57
441.84	419.02
493.51	471.69
545.50	529.63
596.56	577.72
648.52	626.71
700.16	676.38

SZABADOS CTD CAST 10 T-07 02/05/90 21:25 10.0N 51.3W

Depth Range (meters)			Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error wit Depth Uncorrected (C
5.0	to	52.7	3.97	0.01 +/- 0.03	0.03 +/- 0.03
56.7	to	104.4	8.94	0.08 +/- 0.04	0.91 +/- 0.60
108.4	to	156.1	11.93	0.08 +/- 0.05	1.37 +/- 0.83
160.1	to	207.7	13.91	0.06 +/- 0.04	0.98 +/- 0.60
211.7	to	259.4	17.88	0.07 +/- 0.05	0.49 +/- 0.31
263.4	to	311.0	20.85	0.02 +/- 0.02	0.32 +/- 0.20
315.0	to	362.7	25.82	0.02 +/- 0.02	0.33 +/- 0.20
366.6	to	414.3	30.77	0.03 +/- 0.03	0.28 +/- 0.17
418.2	to	465.9	34.73	0.01 +/- 0.01	0.29 +/- 0.18
469.9	to	517.5	38.68	0.01 +/- 0.01	0.34 +/- 0.21

Uncorrected Depth	Corrected Depth
29.08	25.11
80.56	71.62
132.41	120.48
183.97	170.06
235.24	217.36
287.49	266.64
338.82	313.00
390.48	359.71
441.84	407.11
493.51	454.83

SZABADOS CTD CAST 15 T-07 02/08/90 04:34 5.8N 51.3W

Depth Range (meters)			Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error with Depth Uncorrected (C)
5.0	to	52.7	2.98	0.01 +/- 0.04	0.03 +/- 0.04
56.7	to	104.4	5.96	0.03 +/- 0.02	0.19 +/- 0.13
108.4	to	156.1	8.95	0.11 +/- 0.06	1.76 +/- 1.08
160.1	to	207.7	11.93	0.06 +/- 0.04	0.68 +/- 0.43
211.7	to	259.4	14.90	0.02 +/- 0.03	0.37 +/- 0.19
263.4	to	311.0	19.86	0.02 +/- 0.02	0.89 +/- 0.56
315.0	to	362.7	22.84	0.04 +/- 0.03	0.44 +/- 0.27
366.6	to	414.3	24.82	0.03 +/- 0.02	0.22 +/- 0.15
418.2	to	465.9	30.76	0.02 +/- 0.02	0.66 +/- 0.40
469.9	to	517.5	31.74	0.01 +/- 0.01	0.37 +/- 0.24
521.4	to	569.0	35.70	0.01 +/- 0.01	0.70 +/- 0.43
573.0	to	620.6	40.65	0.02 +/- 0.02	0.31 +/- 0.20
624.6	to	672.2	45.60	0.04 +/- 0.03	0.20 +/- 0.13
676.1	to	723.7	45.58	0.01 +/- 0.01	0.14 +/- 0.09

Uncorrected Depth	Corrected Depth
29.08	26.10
80.56	74.60
132.41	123.46
183.97	172.04
235.24	220.34
287.49	267.63
338.82	315.98
390.48	365.66
441.84	411.08
493.51	461.77
545.50	509.80
596.56	555.91
648.52	602.92
700.16	654.58

SZABADOS CTD CAST 15 T-07 02/08/90 04:49 5.8N 51.3W

Depth Range (meters)	Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error wit Depth Uncorrected (C
5.0 to 52.7	2.98	0.01 +/- 0.03	0.03 +/- [illegible].03
56.7 to 104.4	5.96	0.02 +/- 0.02	0.21 +/- 0[illegible]4
108.4 to 156.1	9.94	0.12 +/- 0.05	1.85 +/- 1.[illegible]
160.1 to 207.7	11.93	0.07 +/- 0.05	0.72 +/- 0.4[illegible]
211.7 to 259.4	15.90	0.07 +/- 0.04	0.40 +/- 0.20
263.4 to 311.0	17.87	0.03 +/- 0.02	0.81 +/- 0.51
315.0 to 362.7	22.84	0.05 +/- 0.03	0.46 +/- 0.29
366.6 to 414.3	24.82	0.03 +/- 0.02	0.21 +/- 0.14
418.2 to 465.9	30.76	0.02 +/- 0.02	0.64 +/- 0.38
469.9 to 517.5	31.74	0.02 +/- 0.01	0.36 +/- 0.23
521.4 to 569.0	36.69	0.03 +/- 0.01	0.71 +/- 0.44
573.0 to 620.6	38.67	0.02 +/- 0.02	0.30 +/- 0.19
624.6 to 672.2	41.64	0.04 +/- 0.03	0.18 +/- 0.12
676.1 to 723.7	39.64	0.01 +/- 0.02	0.13 +/- 0.08

Uncorrected Depth	Corrected Depth
29.08	26.10
80.56	74.60
132.41	122.47
183.97	172.04
235.24	219.34
287.49	269.62
338.82	315.98
390.48	365.66
441.84	411.08
493.51	461.77
545.50	508.81
596.56	557.89
648.52	606.88
700.16	660.52

SZABADOS CTD CAST 16 T-07 02/09/90 04:35 3.9N 48.7W

Depth Range (meters)	Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error with Depth Uncorrected (C)
5.0 to 52.7	0.00	0.01 +/- 0.03	0.01 +/- 0.03
56.7 to 104.4	5.96	0.01 +/- 0.02	0.16 +/- 0.12
108.4 to 156.1	8.95	0.08 +/- 0.04	1.36 +/- 0.86
160.1 to 207.7	8.95	0.05 +/- 0.04	0.77 +/- 0.49
211.7 to 259.4	7.95	0.05 +/- 0.04	0.38 +/- 0.25
263.4 to 311.0	6.95	0.05 +/- 0.03	0.19 +/- 0.13
315.0 to 362.7	23.83	0.07 +/- 0.03	0.30 +/- 0.18
366.6 to 414.3	34.74	0.06 +/- 0.05	0.18 +/- 0.13
418.2 to 465.9	31.75	0.02 +/- 0.02	0.07 +/- 0.04
469.9 to 517.5	27.77	0.06 +/- 0.03	0.43 +/- 0.26
521.4 to 569.0	30.74	0.04 +/- 0.02	0.46 +/- 0.28

Uncorrected Depth	Corrected Depth
29.08	29.08
80.56	74.60
132.41	123.46
183.97	175.02
235.24	227.29
287.49	280.54
338.82	314.99
390.48	355.74
441.84	410.09
493.51	465.74
545.50	514.76

SZABADOS CTD CAST 16 T-07 02/09/90 04:45 3.9N 48.7W

Depth Range (meters)	Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error wit Depth Uncorrected (C
5.0 to 52.7	0.00	0.01 +/- 0.05	0.01 +/- 0.05
56.7 to 104.4	5.96	0.01 +/- 0.02	0.16 +/- 0.12
108.4 to 156.1	14.91	0.18 +/- 0.07	2.10 +/- 1.30
160.1 to 207.7	15.90	0.06 +/- 0.03	1.24 +/- 0.78
211.7 to 259.4	12.92	0.08 +/- 0.06	0.62 +/- 0.39
263.4 to 311.0	9.93	0.03 +/- 0.03	0.29 +/- 0.19
315.0 to 362.7	17.87	0.04 +/- 0.03	0.24 +/- 0.15
366.6 to 414.3	17.87	0.03 +/- 0.02	0.07 +/- 0.05

Uncorrected Depth	Corrected Depth
29.08	29.08
80.56	74.60
132.41	117.50
183.97	168.07
235.24	222.32
287.49	277.56
338.82	320.95
390.48	372.61

SZABADOS CTD CAST 19 T-07 02/11/90 14:09 0.2N 44.4W

Depth Range (meters)			Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error with Depth Uncorrected (C)
5.0	to	52.7	0.00	0.00 +/- 0.02	0.00 +/- 0.02
56.7	to	104.4	4.97	0.05 +/- 0.03	0.23 +/- 0.17
108.4	to	156.1	6.96	0.16 +/- 0.11	1.08 +/- 0.73
160.1	to	207.7	9.94	0.06 +/- 0.04	0.64 +/- 0.41
211.7	to	259.4	9.94	0.06 +/- 0.03	0.19 +/- 0.13
263.4	to	311.0	12.91	0.04 +/- 0.03	0.32 +/- 0.23
315.0	to	362.7	12.91	0.12 +/- 0.08	0.60 +/- 0.38
366.6	to	414.3	14.89	0.07 +/- 0.05	0.15 +/- 0.11

Uncorrected Depth	Corrected Depth
29.08	29.08
80.56	75.59
132.41	125.45
183.97	174.03
235.24	225.30
287.49	274.58
338.82	325.91
390.48	375.59

SZABADOS CTD CAST 19 T-07 02/11/90 14:15 0.2N 44.4W

Depth Range (meters)			Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error wit Depth Uncorrected (C
5.0	to	52.7	0.00	0.03 +/- 0.03	0.03 +/- 0.03
56.7	to	104.4	4.97	0.03 +/- 0.02	0.23 +/- 0.18
108.4	to	156.1	6.96	0.14 +/- 0.06	0.96 +/- 0.65
160.1	to	207.7	7.95	0.15 +/- 0.10	0.62 +/- 0.39
211.7	to	259.4	28.81	0.22 +/- 0.13	0.70 +/- 0.43
263.4	to	311.0	34.75	0.11 +/- 0.07	0.56 +/- 0.36
315.0	to	362.7	18.87	0.05 +/- 0.04	0.95 +/- 0.58
366.6	to	414.3	20.85	0.06 +/- 0.04	0.18 +/- 0.13

Uncorrected Depth	Corrected Depth
29.08	29.08
80.56	75.59
132.41	125.45
183.97	176.02
235.24	206.43
287.49	252.74
338.82	319.95
390.48	369.63

SZABADOS CTD CAST 20 T-07 02/11/90 23:00 0.9N 44.1W

Depth Range (meters)	Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error with Depth Uncorrected (C)
5.0 to 52.7	0.00	0.01 +/- 0.03	0.01 +/- 0.03
56.7 to 104.4	4.97	0.02 +/- 0.02	0.21 +/- 0.16
108.4 to 156.1	5.96	0.10 +/- 0.04	0.95 +/- 0.61
160.1 to 207.7	6.96	0.04 +/- 0.03	0.59 +/- 0.38
211.7 to 259.4	8.94	0.03 +/- 0.03	0.23 +/- 0.16
263.4 to 311.0	14.90	0.03 +/- 0.02	0.46 +/- 0.31
315.0 to 362.7	14.90	0.03 +/- 0.02	0.10 +/- 0.09
366.6 to 414.3	13.90	0.02 +/- 0.01	0.14 +/- 0.10
418.2 to 465.9	16.87	0.04 +/- 0.02	0.28 +/- 0.17
469.9 to 517.5	21.82	0.04 +/- 0.02	0.22 +/- 0.15
521.4 to 569.0	21.82	0.03 +/- 0.02	0.38 +/- 0.23
573.0 to 620.6	22.80	0.04 +/- 0.02	0.05 +/- 0.06
624.6 to 672.2	27.76	0.04 +/- 0.01	0.15 +/- 0.10
676.1 to 723.7	27.75	0.02 +/- 0.01	0.16 +/- 0.10

Uncorrected Depth	Corrected Depth
29.08	29.08
80.56	75.59
132.41	126.45
183.97	177.01
235.24	226.30
287.49	272.59
338.82	323.92
390.48	376.58
441.84	424.97
493.51	471.69
545.50	523.68
596.56	573.76
648.52	620.76
700.16	672.41

SZABADOS CTD CAST 20 T-07 02/11/90 23:10 0.9N 44.1W

Depth Range (meters)			Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error wi Depth Uncorrected (C
5.0	to	52.7	0.00	0.01 +/- 0.03	0.01 +/- 0.03
56.7	to	104.4	3.97	0.01 +/- 0.01	0.15 +/- 0.11
108.4	to	156.1	4.97	0.03 +/- 0.02	0.84 +/- 0.54
160.1	to	207.7	4.97	0.03 +/- 0.02	0.45 +/- 0.29
211.7	to	259.4	5.96	0.03 +/- 0.02	0.15 +/- 0.11
263.4	to	311.0	9.93	0.02 +/- 0.02	0.31 +/- 0.21
315.0	to	362.7	6.95	0.01 +/- 0.02	0.04 +/- 0.05
366.6	to	414.3	10.92	0.01 +/- 0.01	0.12 +/- 0.08
418.2	to	465.9	12.90	0.02 +/- 0.01	0.20 +/- 0.13
469.9	to	517.5	14.88	0.03 +/- 0.01	0.16 +/- 0.11
521.4	to	569.0	14.88	0.02 +/- 0.02	0.27 +/- 0.17
573.0	to	620.6	15.87	0.02 +/- 0.03	0.02 +/- 0.04
624.6	to	672.2	16.86	0.03 +/- 0.01	0.11 +/- 0.07
676.1	to	723.7	17.84	0.02 +/- 0.01	0.10 +/- 0.06

Uncorrected Depth	Corrected Depth
29.08	29.08
80.56	76.59
132.41	127.44
183.97	179.00
235.24	229.28
287.4[illegible]	277.56
338.[illegible]	331.87
390.48	379.56
441.84	428.94
493.51	478.63
545.50	530.62
596.56	580.69
648.52	631.66
700.16	682.32

SZABADOS CTD CAST 22 T-07 02/13/90 22:48 3.3N 44.0W

Depth Range (meters)	Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error with Depth Uncorrected (C)
5.0 to 52.7	0.00	0.01 +/- 0.02	0.01 +/- 0.02
56.7 to 104.4	3.97	0.04 +/- 0.03	0.32 +/- 0.21
108.4 to 156.1	4.97	0.02 +/- 0.02	0.10 +/- 0.08
160.1 to 207.7	4.97	0.13 +/- 0.07	0.72 +/- 0.49
211.7 to 259.4	8.94	0.07 +/- 0.06	0.53 +/- 0.34
263.4 to 311.0	11.92	0.05 +/- 0.03	0.57 +/- 0.35
315.0 to 362.7	12.91	0.03 +/- 0.03	0.43 +/- 0.28
366.6 to 414.3	14.89	0.03 +/- 0.02	0.23 +/- 0.17
418.2 to 465.9	17.86	0.02 +/- 0.02	0.54 +/- 0.33
469.9 to 517.5	19.84	0.01 +/- 0.01	0.19 +/- 0.13
521.4 to 569.0	21.82	0.01 +/- 0.01	0.21 +/- 0.13
573.0 to 620.6	22.80	0.01 +/- 0.01	0.19 +/- 0.12
624.6 to 672.2	23.80	0.02 +/- 0.02	0.11 +/- 0.08
676.1 to 723.7	23.78	0.01 +/- 0.01	0.10 +/- 0.06

Uncorrected Depth	Corrected Depth
29.08	29.08
80.56	76.59
132.41	127.44
183.97	179.00
235.24	226.30
287.49	275.57
338.82	325.91
390.48	375.59
441.84	423.98
493.51	473.67
545.50	523.68
596.56	573.76
648.52	624.72
700.16	676.38

SZABADOS CTD CAST 22 T-07 02/13/90 22:56 3.3N 44.0W

Depth Range (meters)	Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error wit Depth Uncorrected (C
5.0 to 52.7	0.00	0.01 +/- 0.02	0.01 +/- 0.02
56.7 to 104.4	1.98	0.04 +/- 0.02	0.20 +/- 0.13
108.4 to 156.1	0.00	0.02 +/- 0.03	0.02 +/- 0.03
160.1 to 207.7	1.00	0.12 +/- 0.07	0.14 +/- 0.09
211.7 to 259.4	4.97	0.05 +/- 0.05	0.30 +/- 0.19
263.4 to 311.0	6.95	0.04 +/- 0.03	0.37 +/- 0.23
315.0 to 362.7	8.94	0.03 +/- 0.02	0.28 +/- 0.18
366.6 to 414.3	10.92	0.01 +/- 0.02	0.17 +/- 0.13
418.2 to 465.9	11.91	0.02 +/- 0.02	0.34 +/- 0.21
469.9 to 517.5	12.89	0.01 +/- 0.01	0.12 +/- 0.08
521.4 to 569.0	14.88	0.01 +/- 0.01	0.14 +/- 0.09
573.0 to 620.6	14.87	0.01 +/- 0.01	0.13 +/- 0.09
624.6 to 672.2	15.87	0.01 +/- 0.01	0.06 +/- 0.05
676.1 to 723.7	17.84	0.01 +/- 0.01	0.06 +/- 0.04

Uncorrected Depth	Corrected Depth
29.08	29.08
80.56	78.58
132.41	132.41
183.97	182.97
235.24	230.27
287.49	280.54
338.82	329.88
390.48	379.56
441.84	429.93
493.51	480.62
545.50	530.62
596.56	581.69
648.52	632.65
700.16	692.32

SZABADOS CTD CAST 23 T-07 02/13/90 23:26 5.2N 44.0W

Depth Range (meters)			Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error with Depth Uncorrected (C)
5.0	to	52.7	0.99	0.00 +/- 0.02	0.01 +/- 0.02
56.7	to	104.4	2.98	0.01 +/- 0.01	0.11 +/- 0.10
108.4	to	156.1	1.99	0.13 +/- 0.06	0.45 +/- 0.30
160.1	to	207.7	2.98	0.03 +/- 0.03	0.12 +/- 0.09
211.7	to	259.4	4.97	0.03 +/- 0.02	0.08 +/- 0.05
263.4	to	311.0	5.96	0.02 +/- 0.01	0.13 +/- 0.08
315.0	to	362.7	4.97	0.02 +/- 0.01	0.09 +/- 0.06
366.6	to	414.3	4.97	0.02 +/- 0.01	0.05 +/- 0.04
418.2	to	465.9	6.95	0.02 +/- 0.01	0.05 +/- 0.03
469.9	to	517.5	8.93	0.02 +/- 0.01	0.05 +/- 0.04
521.4	to	569.0	11.90	0.01 +/- 0.01	0.13 +/- 0.08
573.0	to	620.6	11.90	0.03 +/- 0.01	0.12 +/- 0.07
624.6	to	672.2	9.92	0.02 +/- 0.01	0.07 +/- 0.05
676.1	to	723.7	5.94	0.02 +/- 0.02	0.05 +/- 0.04

Uncorrected Depth	Corrected Depth
29.08	28.09
80.56	77.58
132.41	130.42
183.97	180.99
235.24	230.27
287.49	281.53
338.82	333.85
390.48	385.51
441.84	434.89
493.51	484.58
545.50	533.60
596.56	584.66
648.52	638.60
700.16	694.22

SZABADOS CTD CAST 23 T-07 02/13/90 23:34 5.2N 44.0W

Depth Range (meters)			Depth Error (meters)	Mean Temp. Error with Depth Corrected (C)	Mean Temp. Error wit Depth Uncorrected (C
5.0	to	52.7	0.99	0.00 +/- 0.01	0.01 +/- 0.02
56.7	to	104.4	3.97	0.02 +/- 0.01	0.12 +/- 0.11
108.4	to	156.1	3.98	0.11 +/- 0.05	0.83 +/- 0.53
160.1	to	207.7	4.97	0.03 +/- 0.03	0.21 +/- 0.14
211.7	to	259.4	5.96	0.03 +/- 0.02	0.12 +/- 0.08
263.4	to	311.0	8.94	0.01 +/- 0.02	0.21 +/- 0.13
315.0	to	362.7	10.92	0.01 +/- 0.01	0.23 +/- 0.14
366.6	to	414.3	12.91	0.02 +/- 0.02	0.11 +/- 0.08

Uncorrected Depth	Corrected Depth
29.08	28.09
80.56	76.59
132.41	128.43
183.97	179.00
235.24	229.28
287.49	278.55
338.82	327.90
390.48	377.57

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Reexamination of the Depth Error in XBT Data

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ABSTRACT

By using the accumulated datasets of CTD-XBT comparison experiments since 1985, the depth errors for both T-7 and T-6 probes were reexamined. All the XBT probes used here were manufactured by the Tsurumi-Seiki Company, Limited, Japan. The same method as that of Hanawa and Yoritaka was adopted for the detection of depth error. The empirical depth-time equation for T-7 probes newly obtained from an average of all datasets was very similar to that by Hanawa and Yoritaka: depth difference between the corrected and uncorrected data was about 25 m at 800 m. The new equation for T-6 probes based on a single dataset also showed that the depth difference between the corrected and uncorrected data was greater than 10 m at 500 m. It was confirmed that the free-fall velocity estimated by the XBT manufacturer considerably underestimates the actual velocity for both T-7 and T-6 probes.

1. Introduction

An expendable bathythermograph (XBT) measurement is very convenient and suitable for rapid surveys and monitoring of the subsurface temperature structure. Since the procedure for XBT measurements is very easy, XBTs have been used extensively by volunteer observing ships. In the Tropical Ocean Global Atmosphere (TOGA) World Ocean Circulation Experiment and (WOCE) projects, extensive XBT measurements from ships of opportunity as well as from research vessels are underway and are being planned. However, several investigators have pointed out that there are systematic errors in XBT temperature profiles compared with those obtained by more accurate devices such as STD and CTD. For example, Flierl and Robinson (1977), Heinmiller et al. (1983), Hanawa and Yoritaka (1987, hereafter HY), and more recently Yoshida et al. (1989) and Singer (1990) reported on the depth error; i.e., error in the computed free-fall velocity of XBT probes. On the other hand, Roemmich and Cornuelle (1987) examined the error in temperature itself.

Among them, HY proposed the new empirical depth-time equation for XBT T-7 probes (760 m) based on a new detection method for estimating depth error. However, they used only a single comparison dataset made at a single site in 1985. Since then, the authors have conducted three comparison experiments for T-7 probes and one for T-6 probes (460 m) with CTDs at different times and in different water masses. The purpose of the present study is to reexamine the depth error in XBT data using these accumulated datasets.

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2. Data and procedure of depth-error detection

a. *CTD-XBT comparison experiments*

Since 1985 the authors have undertaken the CTD-XBT comparison experiments on cruises of the R/V *Hakuho Maru* and the R/V *Tansei Maru*, which belong to the Ocean Research Institute (ORI), University of Tokyo. Table 1 is the summary of comparison experiments. In all comparison experiments, the Neil Brown CTD-IIIb was used, which has been calibrated by the Physical Oceanography group, ORI, University of Tokyo. Those for T-7 probes were conducted four times (datasets A–D), including that reported by HY, and the experiment for T-6 probes was done once (dataset E). All the XBT probes used here were made by the Japanese licensed manufacturer, the Tsurumi-Seiki Company Limited. Except for thermistors that are imported from the Sippican Inc., United States, all parts of XBT probe are manufactured in Japan.

The experimental procedures used were the same as in HY. After stopping the ship, the CTD fish was lowered at a descent rate of about 1 m s^{-1}. When the fish reached about 100–200 m in depth, the XBT probe was launched. Since the XBT T-7 (T-6) probes finish measuring within about 130 s (70 s), the XBT profiles in the deeper part are taken about 10 (6) min earlier than the CTD profiles. For dataset C, XBT measurements were made every 5 min during one CTD cast: at one CTD station, four XBT probes were launched.

TABLE 1. Summary of CTD-XBT comparison experiments.

Dataset	Probe type	Number of XBTs	Number of CTD stations	Date	Cruise[a]	Experimental sea area
A	T-7	12	12	December 1985	KH-85-5	around 30°N,135°E
B	T-7	7	7	February 1987	KH-87-1	along 15°N line
C	T-7	8	2	September 1987	KT-87-13	east of Japan
D	T-7	10	10	June 1989	KT-89-9	south of Japan
E	T-6	9	9	June 1989	KT-89-9	south of Japan

Dataset	XBT data converter used	CTD used
A	handmade (ORI)[b]	Neil Brown IIIb[c]
B	handmade (ORI)	Neil Brown IIIb
C	Z-60-II[d]	Neil Brown IIIb
D	Z-60-II	Neil Brown IIIb
E	Z-60-II	Neil Brown IIIb

[a] KH and KT are the cruises of the R/Vs *Hakuho Maru* and *Tansei Maru*, respectively.
[b] See Kitagawa et al. (1981).
[c] Neil Brown Company, Limited.
[d] Murayama-Denki Company, Limited.

Figure 1 shows the locations where the five CTD-XBT comparison experiments were conducted, and Fig. 2 shows the CTD temperature profiles obtained in those comparison experiments. Datasets A and D for T-7 probes, and the dataset E for T-6 probes (the same cruise as D) were taken south of Japan in the northwestern part of the North Pacific subtropical gyre. Dataset B is from the northern part of the North Equatorial Current and dataset C is from the water between the North Pacific subtropical and subpolar gyres; the

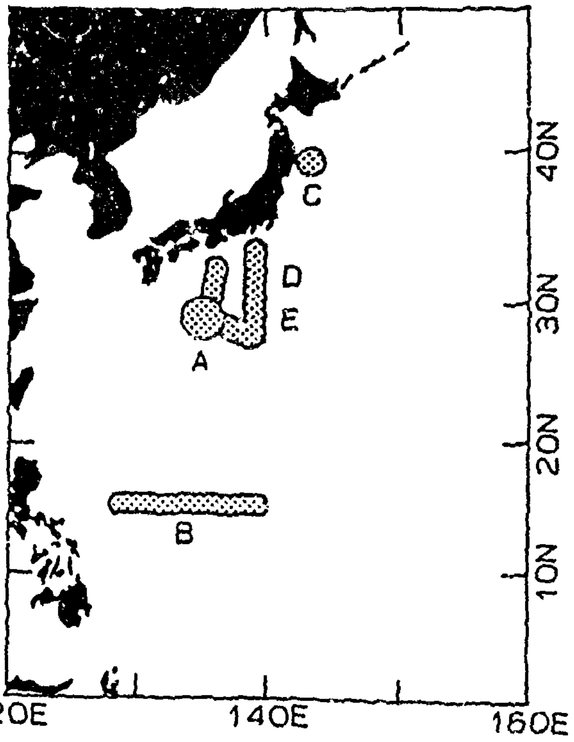

FIG. 1. Locations where CTD-XBT comparison experiments were conducted. Dataset E for T-6 probes was obtained from the same cruise as dataset D for T-7 probes. See Table 1.

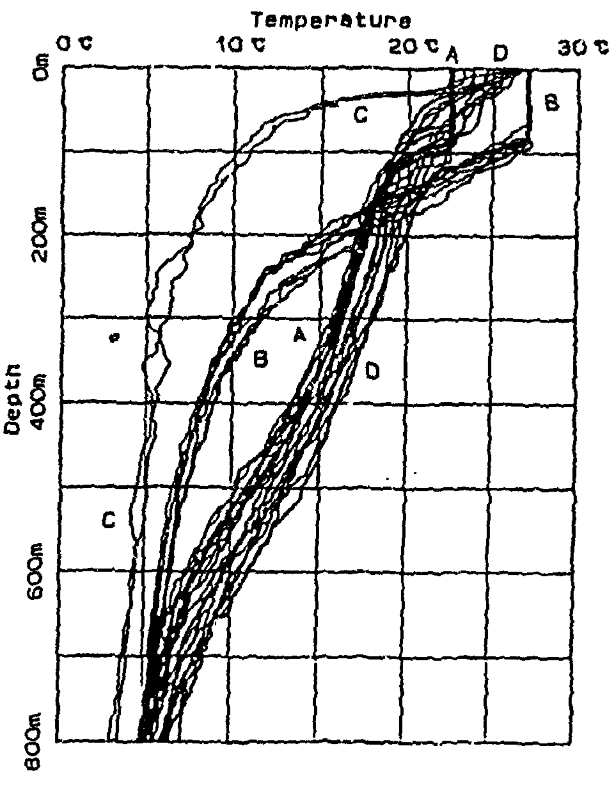

FIG. 2. All CTD temperature profiles for the datasets A-D.

Oyashio and Kuroshio confluence area. It is seen that the temperature profiles are very different in each of the water masses.

b. Procedure of the depth-error detection

The data processing used to determine the depth error is almost the same as in HY. First, both XBT and CTD temperature data were resampled at vertical intervals of 1 m: these are regarded as the "raw" data. At this stage, since the CTD measures pressure, the pressure-depth conversion of the CTD data was made by using the following approximate relation as in HY:

$$z_C = 0.993 p_C, \qquad (1)$$

where z_C is the CTD depth in meters and p_C is the CTD pressure in decibars. Here we chose a density of 1.0275, which lies between 300 and 500 m deep to approximate the density of the upper ocean. This is adequate for our purpose.

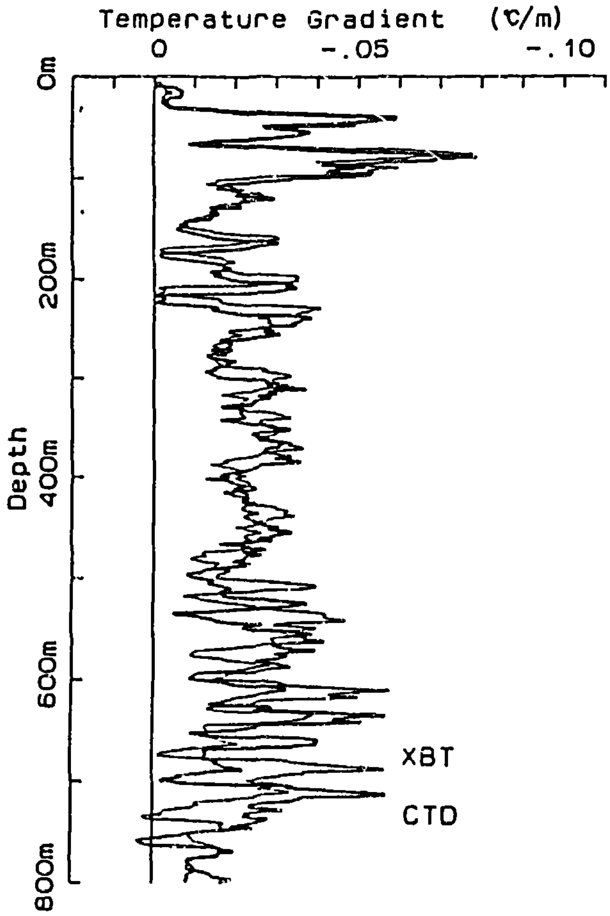

FIG. 3. Example of temperature gradient profiles calculated from the filtered data. Thick and thin lines correspond to CTD and XBT temperature gradients, respectively.

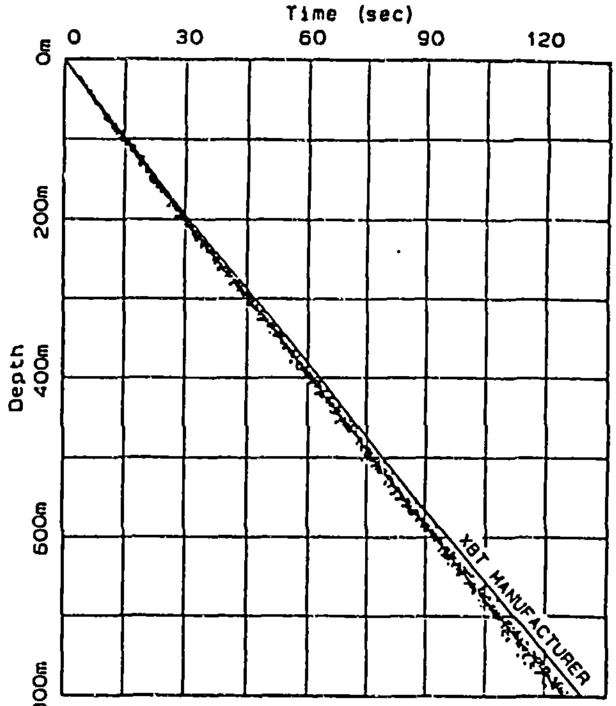

FIG. 4. Scatterplot of the true depths of XBT probes as a function of elapsed time. The full line without dots in the figure denotes the depth-time relationship given by the XBT manufacturer, Eq. (2).

To calculate depth for the XBT probes, the depth-time equation provided by the XBT manufacturer was used at this stage:

$$z_X = 6.472t - 2.160 \times 10^{-3}t^2, \qquad (2)$$

where z_X denotes the XBT depth in meters, and t is the elapsed time in seconds from the time when the XBT probe hits the sea surface.

Next, a simple running average, i.e., box-car filter with 11 points (spacing 10 m of CTD data), was applied to the raw data in the present study, although HY adopted a low-pass filter having a cutoff scale of 30 m and a full-power scale of 60 m. From these filtered temperature profiles, the temperature gradients were calculated. Figure 3 shows an example of CTD and XBT temperature gradient profiles.

Then, the depths of maximum and minimum values of the gradients were selected as the markers, and the differences between two corresponding markers were determined. Identification of the CTD marker and the corresponding XBT marker was made by eye. As is evident in Fig. 3, the corresponding maxima or minima used as markers are easily recognized. The number of markers was 20–30 points for one XBT profile. At this stage, the markers were selected to provide an even distribution along the entire profile; i.e., 3–5 markers per 100 m for the T-7 probes. As a result, a total of about 1000 markers was used for T-7 probes for all

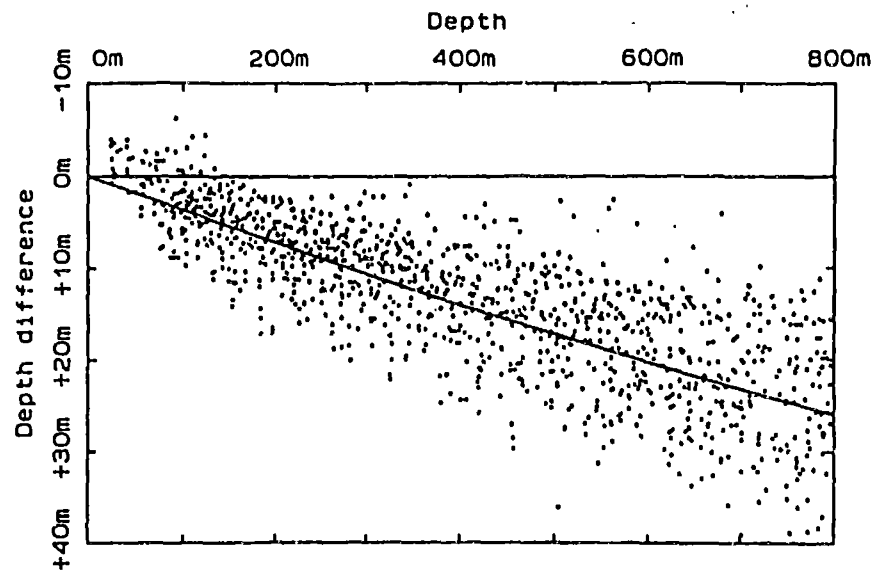

FIG. 5. Scatterplot of depth difference (ordinate) between the true depth of markers and the depth calculated from the equation provided by the XBT manufacturer, Eq. (2) (abscissa). The solid line denotes the depth difference according to the newly estimated empirical depth-time equation (3).

profiles in the present study. Finally, the relation between the elapsed time and the "true" depth, i.e., CTD depth, was examined as described in the next section.

3. Depth-time equation for T-7 probes

a. Depth-time equation for all datasets

Figure 4 shows the scatterplot of the true depths of XBT probes versus elapsed time. The full line without dots in the figure denotes the relationship given by the XBT manufacturer in Eq. (2). In Fig. 5, the ordinate denotes the depth differences between the "true" depths of markers and the depths calculated from Eq. (2), and the abscissa denotes the depth estimated by Eq. (2). Although there is significant scatter in the depth differences for the markers over the entire depth of the profile, this figure clearly shows that an XBT probe falls faster than the fall rate given by the XBT manu-

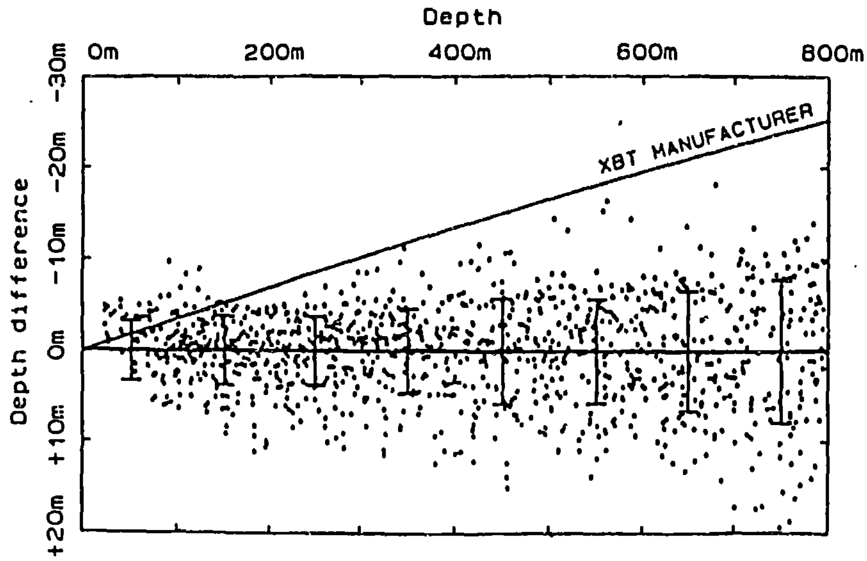

FIG. 6. Scatterplot of the depth difference of the markers to the newly estimated depth-time equation (3). The error bars (plus/minus are standard deviation) are drawn every 100 m.

facturer. The mean value of the depth difference at 700 m is greater than 20 m, which exceeds the accuracy for XBTs stated by XBT manufacturer; i.e., 5 m and/or 2% (Seaver and Kuleshov 1982).

The depth-time equation that best describes all T-7 datasets is estimated by the least-squares method to be

$$z_X = 6.711t - 2.454 \times 10^{-3}t^2, \quad (3)$$

which is also drawn in Figs. 4 and 5 by the solid line surrounded by dots. Here, we assumed that there is no bias component; i.e., no constant term in the depth-time equation. The standard deviation of the XBT markers from surface to 800 m was 5.33 m. This equation is "fortunately" almost the same as that proposed by HY who used only the dataset A in the present study; i.e.,

$$z_X = 6.715t - 2.449 \times 10^{-3}t^2. \quad (4)$$

Figure 6 shows the scatterplot of the depth difference of the markers with the newly estimated equation (3). The standard deviations are drawn every 100 m of true depth in Fig. 6 and show gradual increasing with increasing depth. The standard deviation from the surface to 100 m is not so small and the actual depths of the probes are shallower in this layer than those estimated by both Eqs. (2) and (3). Although there may be several reasons, it is plausible that it takes some time for the probes to reach their terminal velocity of about 6.7 m s^{-1}. Its delay time may depend on the attitude of the probes when they hit the surface, and on the darting of the XBT launcher above the sea surface. In addition, this large scatter may be partly due to the disturbances in the shallower layer caused by the ship screw, the descent of the CTD fish, and due to the existence of large internal waves in the seasonal thermocline.

b. Depth-time equation for the individual datasets

The depth-time equation for each dataset was also determined as follows:

$$\text{Dataset A: } z_X = 6.741t - 2.528 \times 10^{-3}t^2, \quad (5)$$

$$\text{Dataset B: } z_X = 6.652t - 2.030 \times 10^{-3}t^2, \quad (6)$$

$$\text{Dataset C: } z_X = 6.941t - 4.133 \times 10^{-3}t^2, \quad (7)$$

$$\text{Dataset D: } z_X = 6.562t - 1.476 \times 10^{-3}t^2. \quad (8)$$

Reexamination of dataset A used in HY showed that three data were unsuitable for comparison; that is, two XBT data suffered wire stretching (see Fig. 6 in HY) and one CTD profile was very noisy. Therefore, since

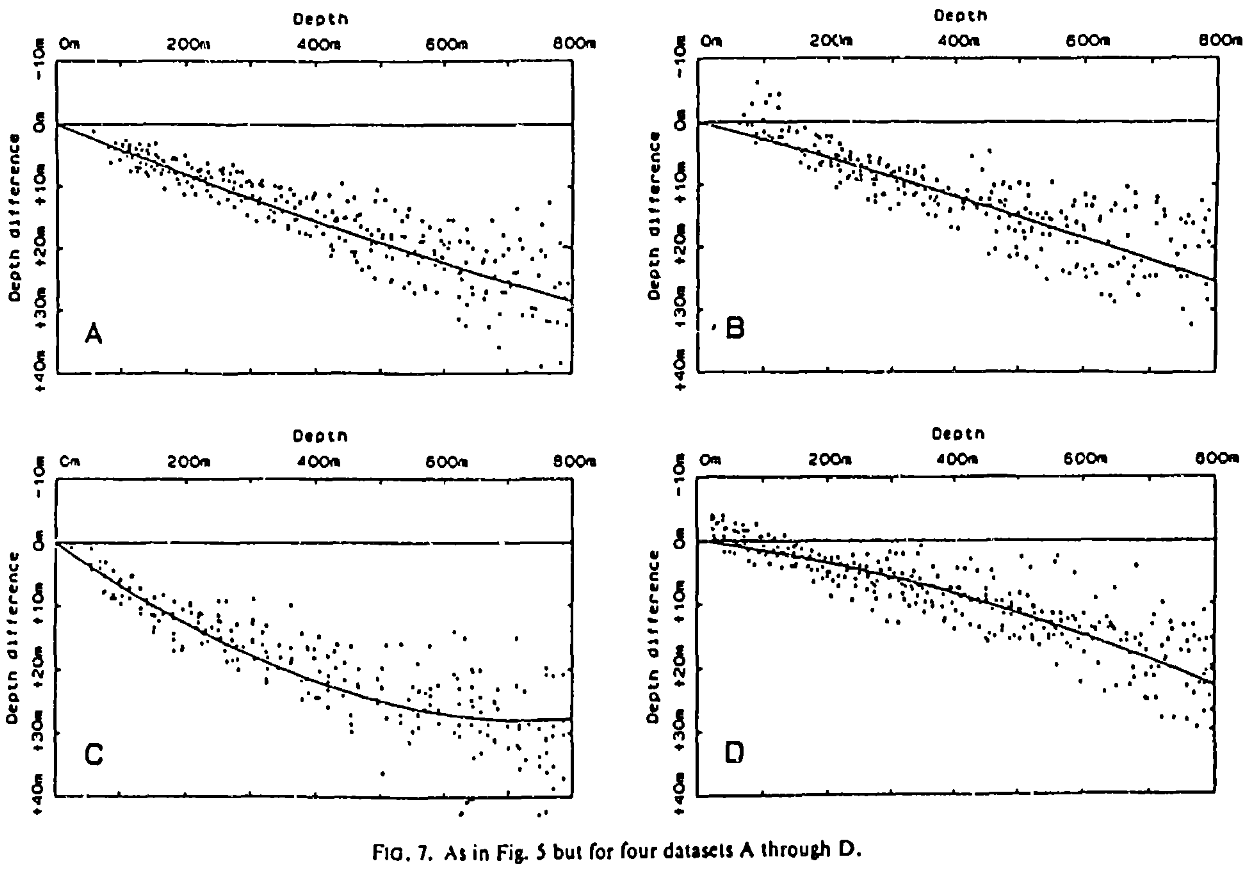

FIG. 7. As in Fig. 5 but for four datasets A through D.

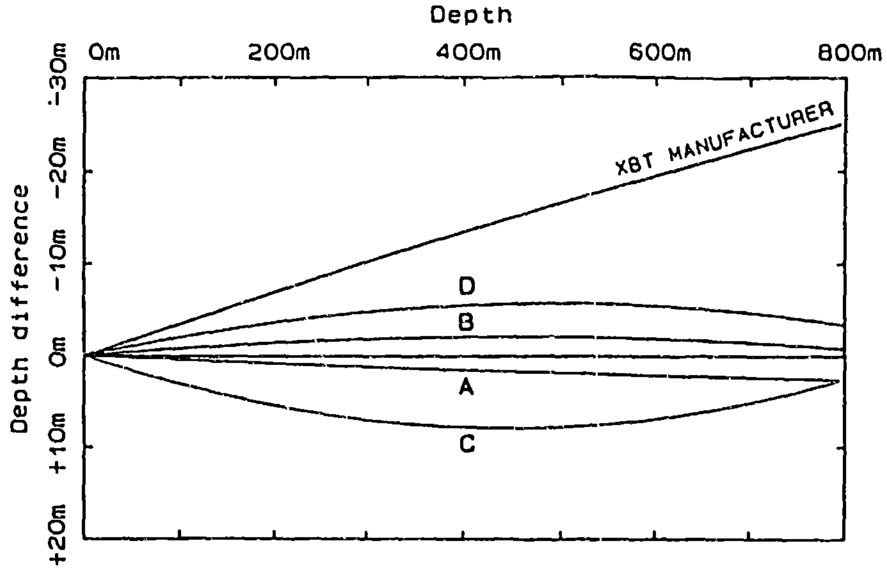

FIG. 8. Difference among four equations individually estimated for four datasets A through D.

three data were discarded in the present analysis, Eq. (5) is slightly different from Eq. (4) by HY.

Figure 7 shows the scatterplot of depth difference as in Fig. 5 but for four datasets A through E. Each panel shows that the markers largely scatter and the standard deviations for depth intervals of 100 m also increase from upper to deeper layers (not shown here). However, an individual dataset seems to have its own systematic tendency. Figure 8 shows the relationship among four equations (5)–(8) to Eq (3). It shows that XBTs of datasets A and C fall faster than Eq. (3), while those of datasets B and D fall slower. Since mean vertical temperature profiles depend on the sites of the comparison experiment as seen in Fig. 2, the difference in the sea water viscosity, i.e., the drag coefficient for the XBT probes, may be a possible explanation for the difference in Eqs. (5)–(8).

Assuming that at low temperatures water has high viscosity, XBTs of datasets B and C suffer higher drag compared with those of datasets A and D, because water temperatures in experimental sites of datasets B and C are relatively lower than those in datasets A and D as seen in Fig. 2. Therefore, it can be expected that XBTs of datasets B and C fall much slower than those of datasets A and D. However, Fig. 8 shows that XBTs of dataset C fall fastest among four datasets, while those of dataset D fall slowest. Those of datasets of A and B fall with velocity between the above two datasets; that is, it is concluded that tendency of XBT fall rate as shown in Fig. 8 cannot be explained from the viewpoint of water viscosity, and we must search for another reason.

Since the XBTs used here were made at different times (different lots), there may be small but systematic changes in shape and weight of the probes. Here, it is very interesting to point out that the relationship between the two constants a and b (positive value), multiplied by t and t^2, respectively, in the depth–time equation, has a quasi-linear relationship as shown in

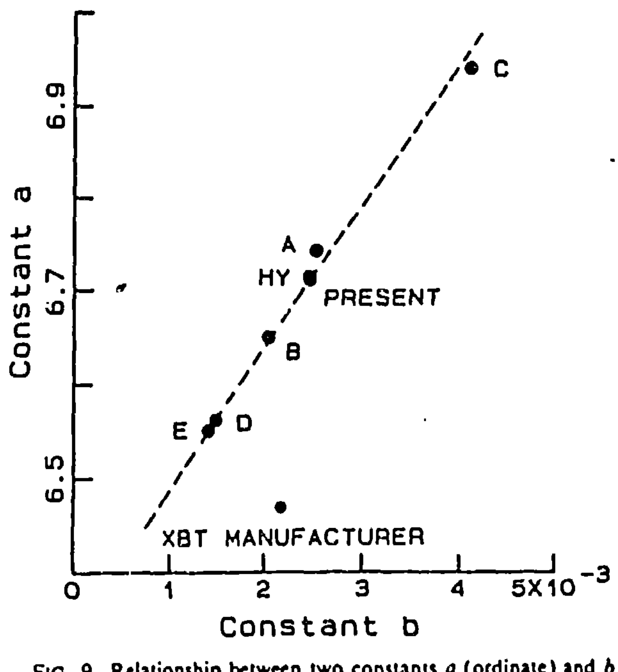

FIG. 9. Relationship between two constants a (ordinate) and b (abscissa), which are multiplied by t and t^2, respectively, in the depth–time equations. Symbols denote datasets. That for T-6 probes (dataset E) is also presented.

Fig. 9. The constant a can be regarded as the free-fall velocity at the initial stage (very close to the terminal velocity), while constant b reflects the temporal rate of velocity due to the reduction of the probe weight by releasing wire.

The most plausible cause, which explains the above relationship between constants a and b, may be attributed to the differences in the enamel thickness used on the probe wire; that is, when the wire is thick in diameter and is thinly coated with enamel, the weight per unit length of wire is heavier and the buoyancy of the whole probe is small compared with the standard one. Therefore, this probe can fall faster at the initial state—i.e., larger constant a—but it becomes slower rapidly because of the faster reduction of the probe weight by the release of heavier wire—i.e., larger b. On the other hand, when the wire is thin in diameter and is thickly coated with enamel, the probe falls slower at first, and keeps its velocity to the later stage because of the situation opposite from the situation described above. This situation will lead to smaller constants a and b.

The Japanese XBT manufacturer (Mr. S. Suzuki, personal communication,) recognizes that it is very difficult to make wire with uniform diameter and enamel coating. Actually, they find that wire weight in water shows largest scatter among the parts of probe. Here, it should be noted that the total weight of the

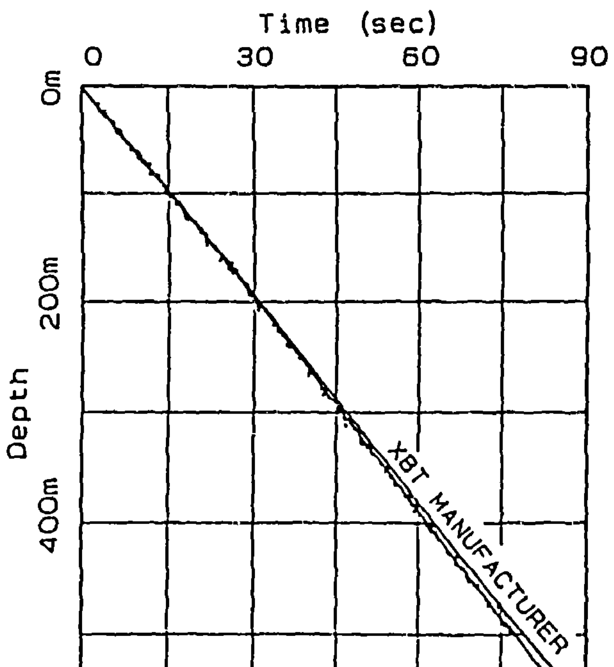

FIG. 10. As in Fig. 4 but for T-6 probes (dataset E).

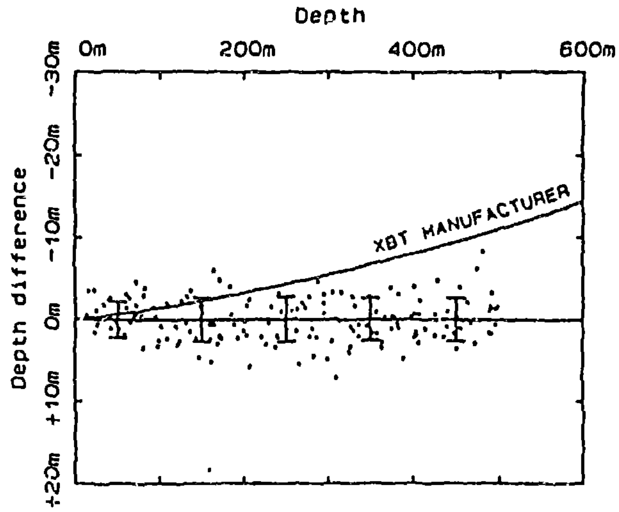

FIG. 11. As in Fig. 6 but for T-6 probes (dataset E).

XBT probe is inspected *only in air* by an XBT manufacturer and is adjusted by reeling wire, i.e., wire length.

The above discussion is just qualitative, and quantitative verification must be made by using some physical model. However, its task is beyond the scope of the present study.

4. Depth–time equation for T-6 probes

The depth error was also examined for the XBT T-6 probes (dataset E). Figure 10, as in Fig. 4, shows the relation between the true depths of XBT probes and the elapsed time. This figure also shows that an XBT T-6 probe falls faster than the fall rate given by the XBT manufacturer, as well as the T-7 probe. The mean value of the depth difference at 450 m is about 10 m, which also exceeds the accuracy for XBTs stated by XBT manufacturer. From these data, the following depth–time equation was obtained:

$$z_X = 6.553t - 1.378 \times 10^{-3}t^2. \qquad (9)$$

The scatter of the markers, which is almost independent on depth, is rather small compared with those for T-7 probes as shown in Fig. 11. The mean standard deviation of the markers from surface to 500 m was 2.53 m. Note that constants a and b in Eq. (9) also lie on the line of a quasi-linear relationship between constants a and b for T-7 probes, as shown in Fig. 9. Since dataset E consists of only nine probes, more data for T-6 probes are needed to confirm this equation.

5. Concluding remarks

In the present study, the free-fall velocities of T-7 and T-6 probes were reexamined using data from five CTD-XBT comparison experiments since 1985. Following the method adopted by HY, it was confirmed that the free-fall velocity estimated by the XBT manufacturer considerably underestimates the actual velocity for the T-7 probes, as was pointed out by HY. The new empirical depth–time equation [Eq. (3)] for T-7 probes obtained by using all the datasets was almost the same as that obtained by HY. However, the empirical equations for individual datasets were different from each other, and seem to have a systematic tendency. A new depth–time equation for T-6 probes was also obtained as Eq. (9).

Since XBTs used here were made by the Japanese licensed manufacturer, it goes without saying that the comprehensive CTD–XBT comparison experiments at different times and in different water masses with XBTs manufactured by all makers would be very useful.

Finally, the authors must comment on the use of the newly estimated equations (3) and (9); that is, although an individual investigator is invited to use the newly estimated equations for individual studies, XBT data sent to the national or international XBT data centers should be those calculated by a single, internationally accepted, equation, i.e., that provided by the XBT manufacturer, Eq. (2). The existence of mixed data in the database must be absolutely avoided.

Acknowledgments. The authors would like to express their sincere thanks to all scientists, the captain, officer and crew in the cruises of KH-85-5, KH-87-1, KT-87-13, and KT-89-9, by the R/Vs *Hakuho Maru* and *Tansei Maru*. Thanks are extended to Mr. S. Suzuki, Tsurumi-Seiki Company, Limited, for his response to the authors' questions and requests. The authors also acknowledge comments by an anonymous reviewer.

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REFERENCES

Flierl, G., and A. R. Robinson, 1977: XBT measurements of the thermal gradient in the MODE eddy. *J. Phys. Oceanogr.*, 7, 300–302.

Heinmiller, R. H., C. C. Ebbesmeyer, B. A. Taft, D. B. Olson and O. P. Nikitin, 1983; Systematic errors in expendable bathythermograph (XBT) profiles. *Deep-Sea Res.*, 30, 1185–1196.

Hanawa, K., and H. Yoritaka, 1987: Detection of systematic errors in XBT data and their correction. *J. Oceanogr. Soc. Japan*, 43, 68–76.

Kitagawa, S., K. Taira and T. Teramoto, 1981: A digital data logger for the XBT. *La mer*, 19, 165–170. [Japanese with English abstract and captions.]

Roemmich, D., and B. Cornuelle, 1987: Digitization and calibration of the expendable bathythermograph. *Deep-Sea Res.*, 34, 299–307.

Seaver, G. A., and A. Kuleshov, 1982: Experimental and analytic error of the expandable bathythermograph. *J. Phys. Oceanogr.*, 12, 592–600.

Singer, J. J., 1990: On the error observed in electronically digitized T-7 XBT data. *J. Atmos. Oceanic Technol.*, 7, 603–611.

Yoshida, J., T. Suzuki, H. Sudo and M. Matsuyama, 1989: Corrected of XBT depth error. *J. Tokyo Univ. Fish.*, 76, 55–63. [Japanese with English abstract and captions.]

**PAPER TO BE PRESENTED
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Additional evidence of XBT depth error using the probes from the Japanese licensed manufacturer

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Abstract

New CTD-XBT comparison are presented which provide additional evidence of XBT depth error and support previous results (Hanawa and Yoritaka, 1987: Hanawa and Yoshikawa, 1991). New data processing procedures by which the depth errors are automatically detected are adopted.

The relationship between the scatter of the quadratic depth-time equation coefficients and the depth difference is also discussed. It is shown that when the two constants have a certain relationship, the depth differences between the plural depth-time equations are small, even if the two constants of those equations have apparently very different values.

1. Introduction

When CTD and XBT measurements are conducted repeatedly along an observational line, the pseudo-undulation of the isotherms ("XBT wave") appears in vertical temperature cross section. This is obviously due to depth error in the XBT data and has already been pointed out by several authors.

Hanawa and Yoritaka (1987, hereafter XY1) and Hanawa and Yoshikawa (1991, HY2) reported that the actual fall rate of XBT probes made by the Japanese licensed manufacturer Tsurumi-Seiki Co LTD is much faster than that estimated by the depth-time equation provided by the XBT manufacturer. A recent report by Singer (1990) reached nearly the same conclusion, using the XBT probes manufactured by Sippican Inc. USA.

After HY2, an additional CTD-XBT comparison experiment was conducted in the sea south of Japan by the Physical Oceanography

Laboratory at Tohoku University. In this report, we will describe the results of this comparison experiment. Although there is the manual handling stage in the data processing procedures adopted in HY1 and HY2, in the present analysis we adopted newly developed procedures, by which the depth error is automatically detected by computer. Lastly, the relationship between the scatter of two coefficients of the quadratic depth-time equations and the depth difference is briefly discussed.

2. The comparison experiment and newly adopted data processing procedures

a) CTD-XBT comparison experiment

The CTD-XBT comparison experiment was conducted on the Tokyo-Ogasawara Line Experiment (TOLEX) line by the R/V Hakuho Maru (KH-91-1 OMLET Cruise), in February 1991 (see Fig. 1). TOLEX is the monitoring program of the Kuroshio current system made by the Physical Oceanography Laboratory, Tohoku University. XBT measurements have been conducted bimonthly since August 1988 using a ferry shuttling from Tokyo to the Ogasawara Islands.

The experimental procedures and the apparatus used were the same as reported in HY2. Although seven XBT T-7 probes were dropped at seven CTD stations, only four profiles were used since the others were inappropriate due to wire stretching and noise problems. In this report we will refer to these data as dataset E. Note that dataset E in HY2 was data from T-6 probes.

Figure 2(a) shows the CTD temperature profiles and Fig. 2(b) shows the temperature difference between CTD data and XBT data calculated by the depth-time equation provided by the XBT manufacturer.

b) Data processing procedures adopted

To avoid manual handling in the detection of depth error used in HY1 and HY2, new data processing procedures were adopted. The actual procedures are as follows.

1. From the observed raw data, 1m-interval temperature data are calculated using a linear interpolation scheme for both CTD and XBT data. CTD pressure data are converted to depth data by using the approximate relation equation (Eq. (1) of HY2). The XBT depths are calculated from the depth-time equation provided by the XBT manufacturer (Eq. (2) of HY2).

2. A simple running average with a box-car filter of 11 points

(spacing 10m of CTD data) is applied to both sets of 1m-interval data.

3. Temperature gradients (hereafter TG) are calculated from both filtered CTD and XBT data.

4. From the surface to the deepest layer, 21 succesive points of CTD-TG data are compared with 21 succesive points of the XBT-TG data at various depths. Depth differences (DD: usually XBT depths are shallower than CTD depths) at the minimum value of TG differences between the two are determined. In the present analysis, central depths of CTD-TG data are set at intervals of 5m from 10m to 790m: 157 data.

5. The elapsed times at the depths of (CTD depths minus DD) are calculated by the depth-time equation used in estimation of depths of XBT data.

6. Using the dataset of true depths versus the elapsed times, a new depth-time equation is estimated by the method of least squares.

7. From the new equation, 1m-interval XBT temperature data are calculated from the observed raw data.

8. Stages 2 through 5 are repeated.

9. After the above processing is completed for all comparison data, a new equation is estimated using the datasets of true depths versus the elapsed times.

3. Results and comparison with the previous results

Figure 3 shows the scatter plot of the true depths of XBT probes as a function elapsed time. Although there are a few points far from the estimated relation, it shows reasonable dependence on some depth-time relation. The newly estimated depth-time equation for dataset E is,

$$Z_x = 6.655\underline{t} - 1.844\text{x}10^{-3}\underline{t}^2. \quad (1)$$

Figure 4 shows the temperature difference profiles between CTD and XBT data, whose depths are calculated by Eq. (1). Compared with Fig. 2(b), it clearly shows that the new equation, Eq. (1) can give a good estimation of XBT depths obtained in the present experiment.

Figure 5 shows the relationship between the two coefficients a and b, re-drawn from Fig. 9 of HY2. The two coefficients of the the present equation (1) lie near dataset B.

4. Relationship between the scatter of the coefficients and the depth difference

In this section we will show that, when two coefficients, a and b, in the depth-time equation which is estimated for some data set, have a special relationship for values of the reference equation or those of other data sets, depth differences estimated by the two equations are not so large.

a) Distribution of depth differences on coefficients a-b plane

Figure 6(b) shows profiles of the depth difference between the depth calculated by the reference equation and the other equations with four combinations of coefficients a and b, which are specified on the a-b plane of Fig. 6(a), Cases I through IV. Constants a and b of the reference equation were selected as 6.711 and 2.454×10^{-3} respectively, which correspond to those of Eq. (3) in HY2, i.e., a unified equation for datasets A through D. Coefficients a and b of Case I (II) were selected as though both a and b are smaller (greater) than those of the reference equation. On the other hand, coefficients of Case III (IV) were set as though when a is greater (smaller) than the reference equation, b is smaller (greater).

In Case I (II), the depth difference is negative (positive) from the surface to about 600m, it then crosses zero line and changes to the positive (negative) side. Although coefficients a and b of Cases I and II are apparently very different from the reference values, the actual depth difference is within plus/minus 10m from the surface to the reference depth of 770m. On the other hand, in Case III (IV), the depth difference gradually increases in a positive (negative) direction from surface, and at the reference depth of 770m it is greater than 10m. Although coefficients a and b of Cases III and IV are very similar to the reference values compared with Cases I and II, they do not mean directly that the depth difference is small. That is, the combination of coefficients a and b is essential to know how the depth difference behaves.

Figure 7 shows two types of representation of the depth difference on the a-b plane. The left panel, Fig. 7(a), shows the distribution of the standard deviation (root-mean-square) of depth differences between the depths calculated by the reference equation and the depth calculated by the other combinations of a and b. The right panel (Fig. 7(b)) shows the distribution of the maximum values of depth differences. Both panels show that when coefficients a and b have some special relationship, the depth difference is not so large. This special relationship between coefficients a and b can be roughly represented as,

$$a = 6.475 + 0.1x(b \times 1000). \tag{2}$$

Note that this relation equation, of course, depends on a and b from the reference equation. The existence of the situation mentioned above simply reflects the character of the quadratic depth-time equation.

b) Coefficients a and b for individual profiles

So far, the empirical depth-time equations were estimated by using all the markers for all XBT profiles, e.g., Eq. (4) in HY1, Eq. (3) in HY2 and Eq. (1) of the present study. The depth-time equations for individual profiles were estimated and coefficients a and b in those equations are plotted in Fig. 8. It is shown that constants a and b for individual profiles in individual data sets also have a quasi-linear relationship.

Almost all combinations of coefficients shown in Fig. 8 are distributed in the region where the depth differences are not so large. This fact is lucky for XBT users, since this means that users are able to make a single unified equation like Eq. (3) in HY2.

Why do coefficients a and b scatter along this region? HY2 speculated that it reflects the scatters of the wire weight and the enamel coating on it. Although the authors believe that this is a basic cause, it seems that Fig. 8 suggests the existence of additional causes, because the scatterness is too large. However, the authors can not specify it yet.

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References

Hanawa, K. and H. Yoritaka, 1987: Detection of systematic errors in XBT data and their correction. J. Oceanogr. Soc. Japan, 32, 68-76.

Hanawa, K. and Y. Yoshikawa, 1991: Re-examination of depth error in XBT data. J. Atmos. Oceanic Technol., 8(3), in press.

Singer, J.J., 1990: On the error observed in electronically digitized T-7 XBT data. J. Atmos. Oceanic Technol., 7, 603-611.

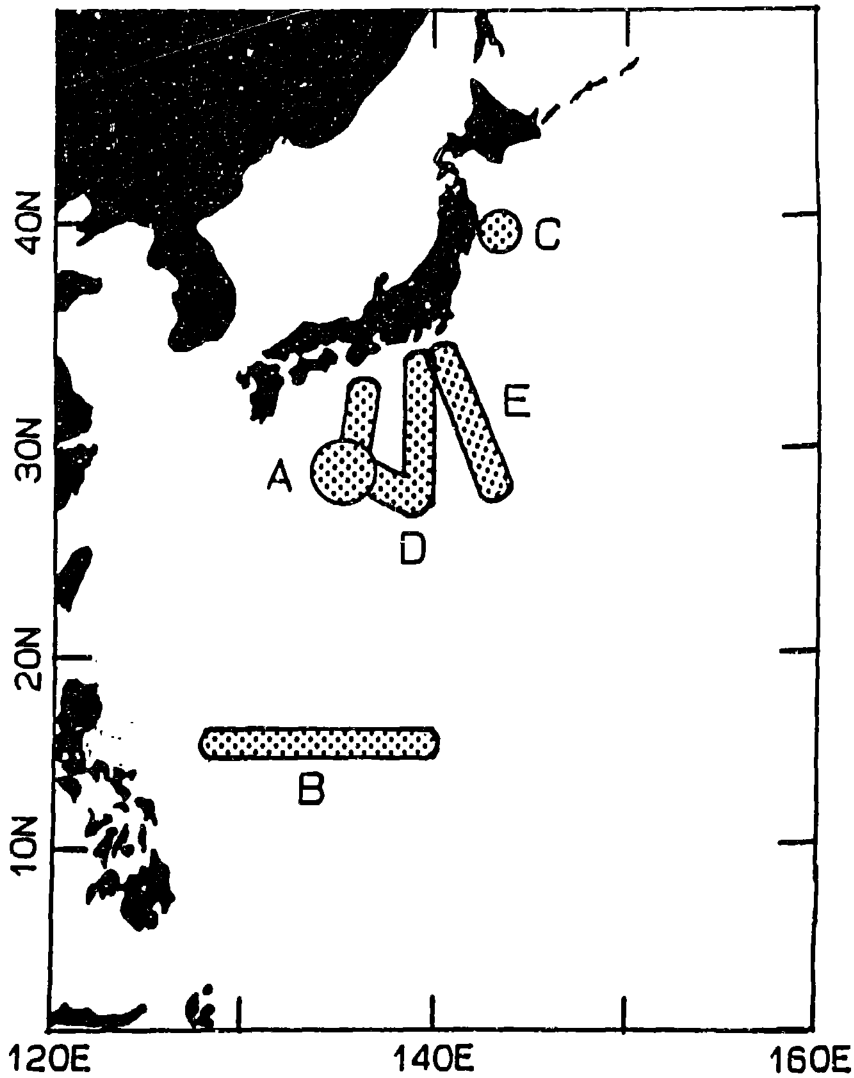

Fig. 1. Locations where CTD-XBT comparison experiments were conducted. Datasets A through D were reported in HY2.

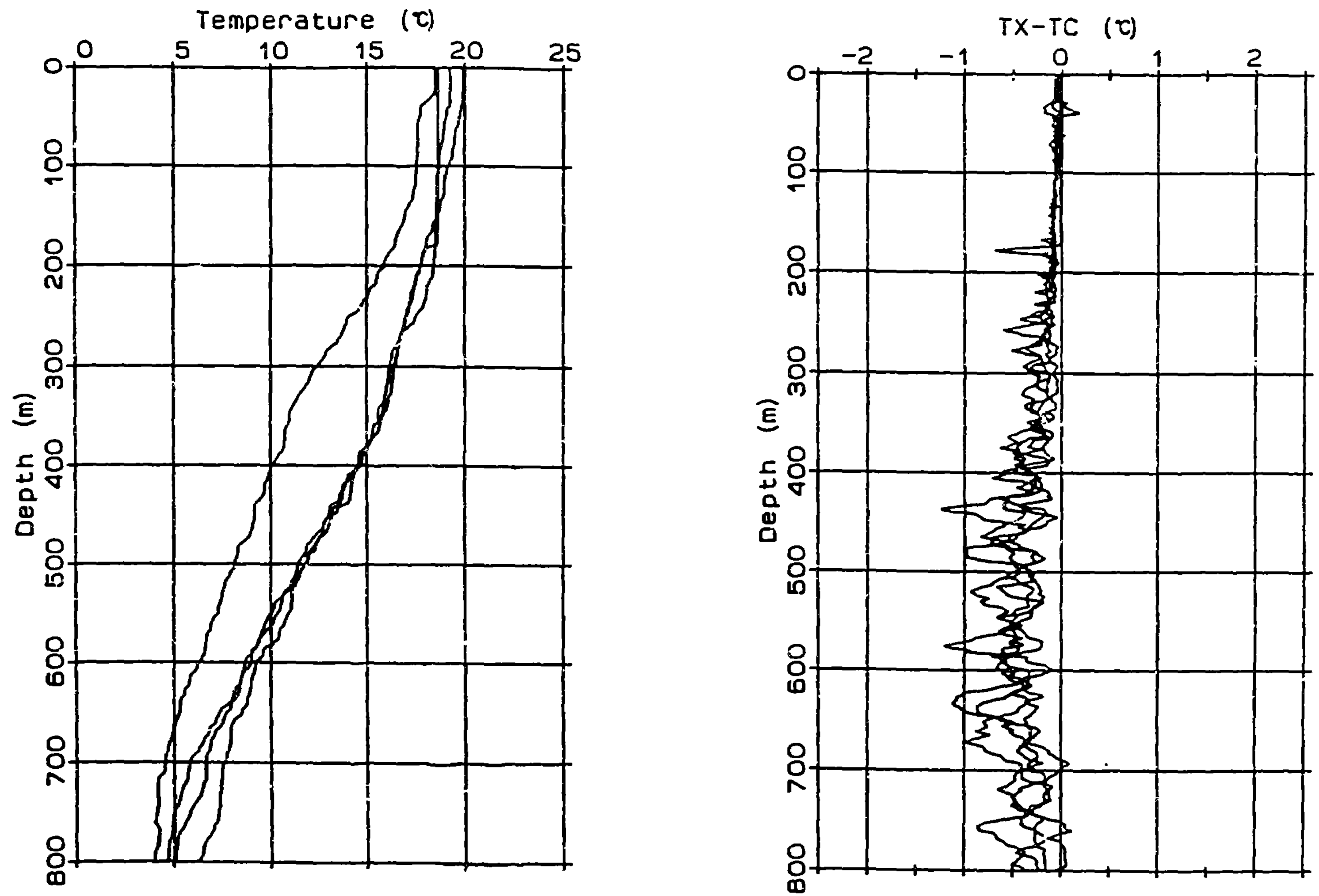

Fig. 2. (a) CTD temperature profiles of dataset E and (b) temperature differences of XBT and CTD data.

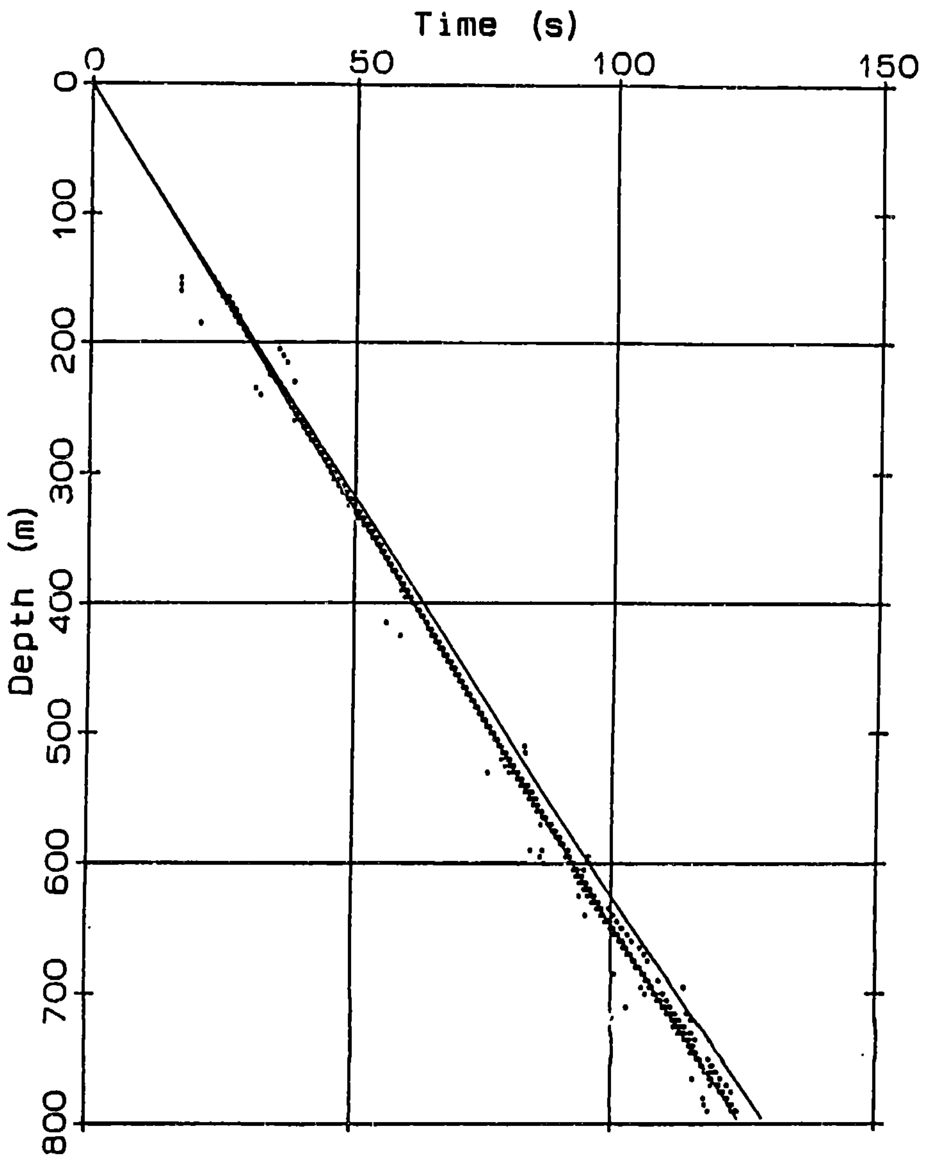

Fig. 3. Scatter plot of the true depths of XBT probes as a function elapsed time. The data of true depth (CTD depth) and elapsed time are obtained at 5m intervals in CTD depth.

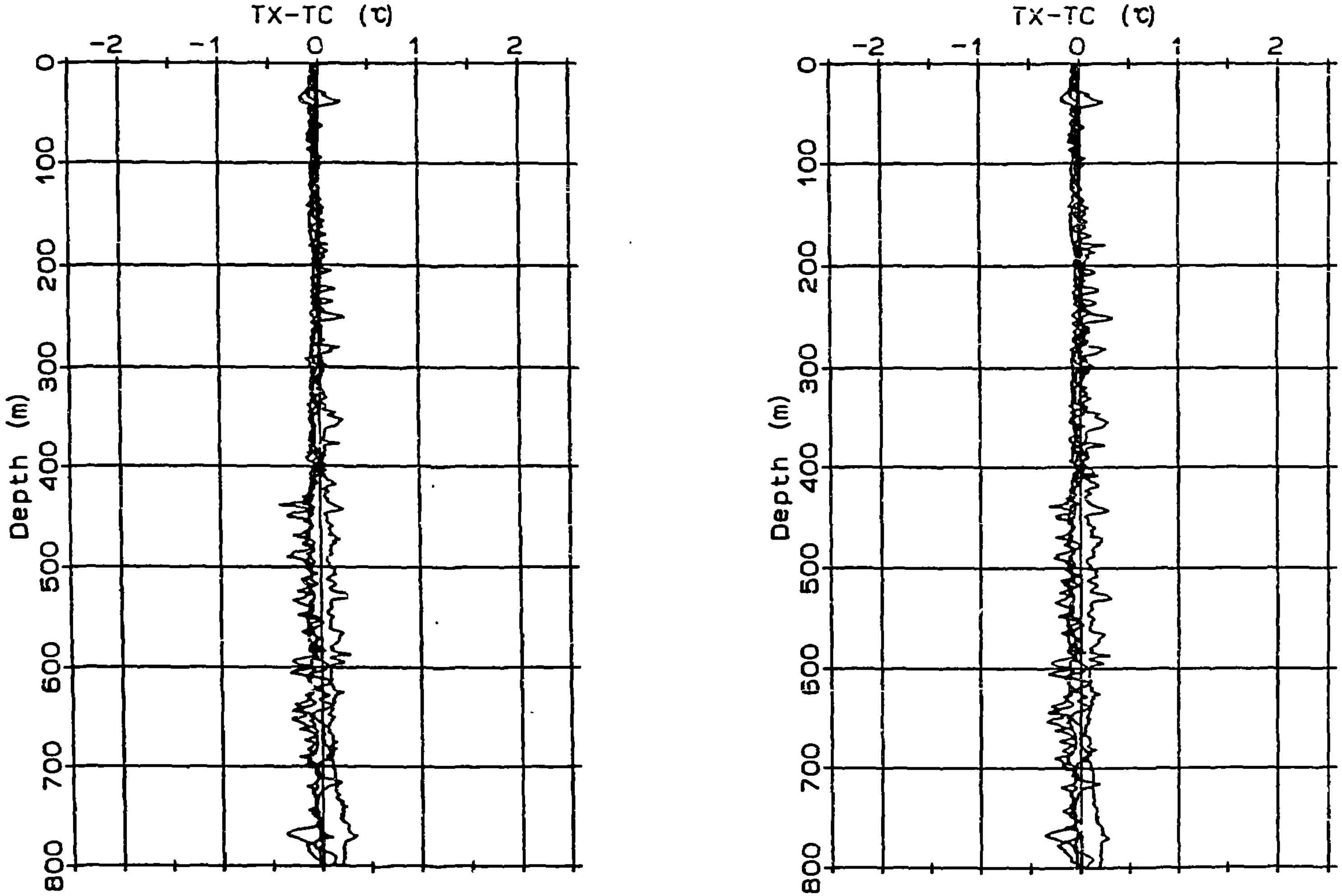

Fig. 4. (a) As in Fig. 2(b) but for using the XBT temperature data estimated by Eq. (1). (b) As in (a) but for those estimated by Eq. (3) in HY2.

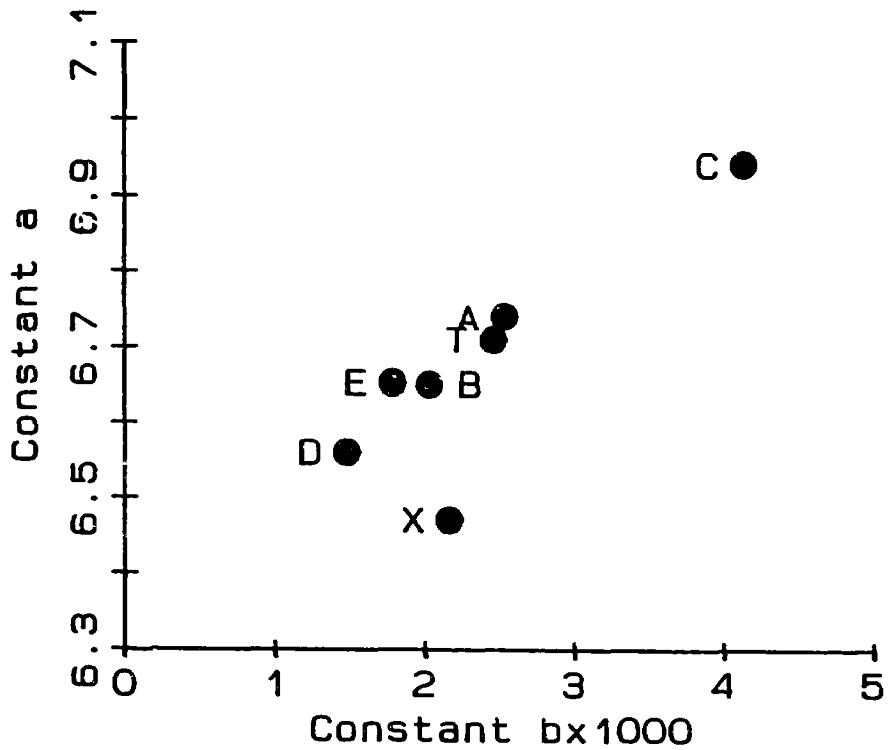

Fig. 5. Relationship between constants a and b of depth-time equation for T-7 probe (same as Fig 9 of HY2). T means an unified equation for datasets A through D (Eq. (3) in HY2) and X denotes that provided by XBT manufacturer.

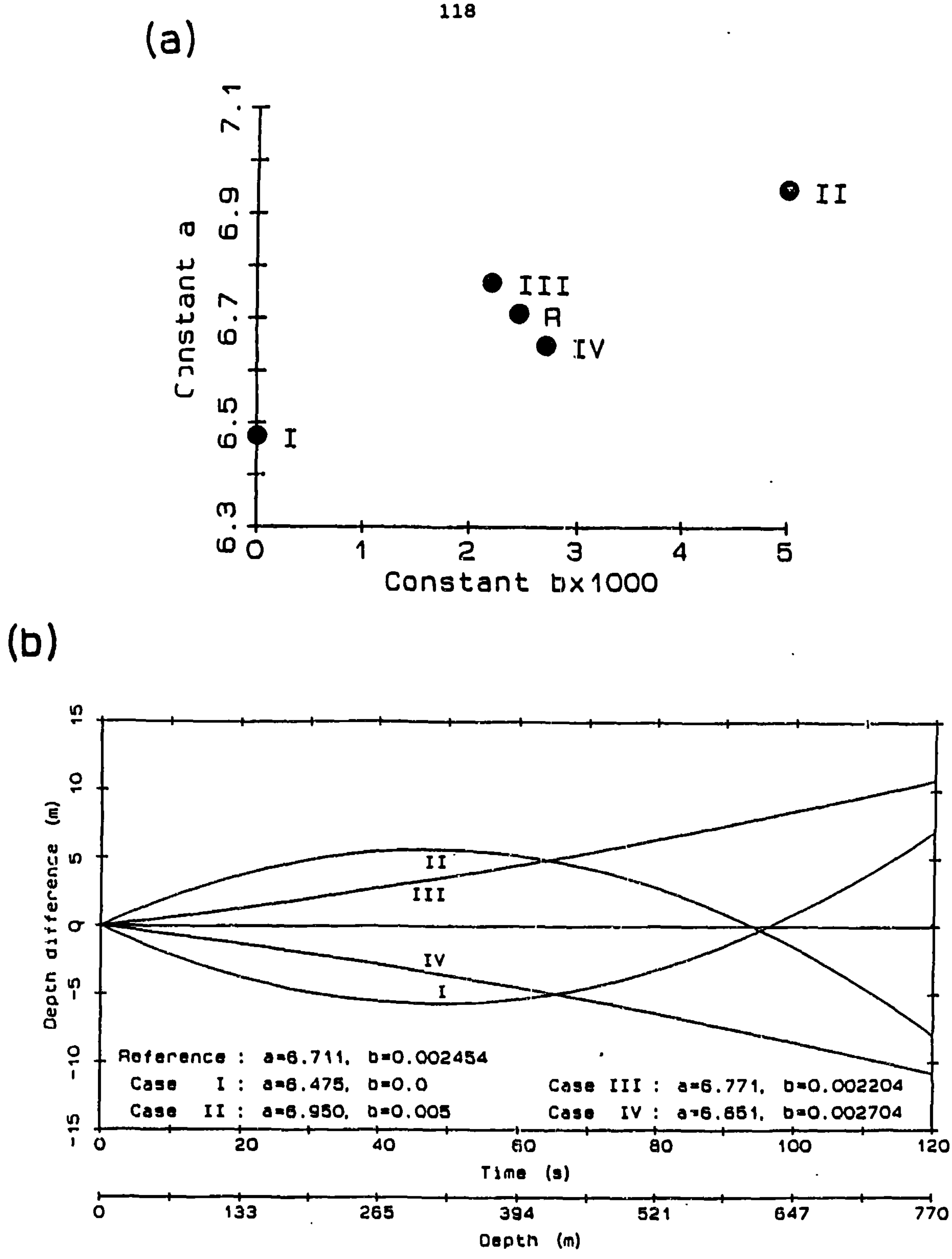

Fig. 6. (a) Combinations of a and b selected to show examples of depth difference: the reference equation and Cases I through IV. Symbol R denotes the reference equation which is same as T in Fig. 5(a). (b) Profiles of depth difference for each case from the reference equation. The depth of abscissa is calculated by the reference equation.

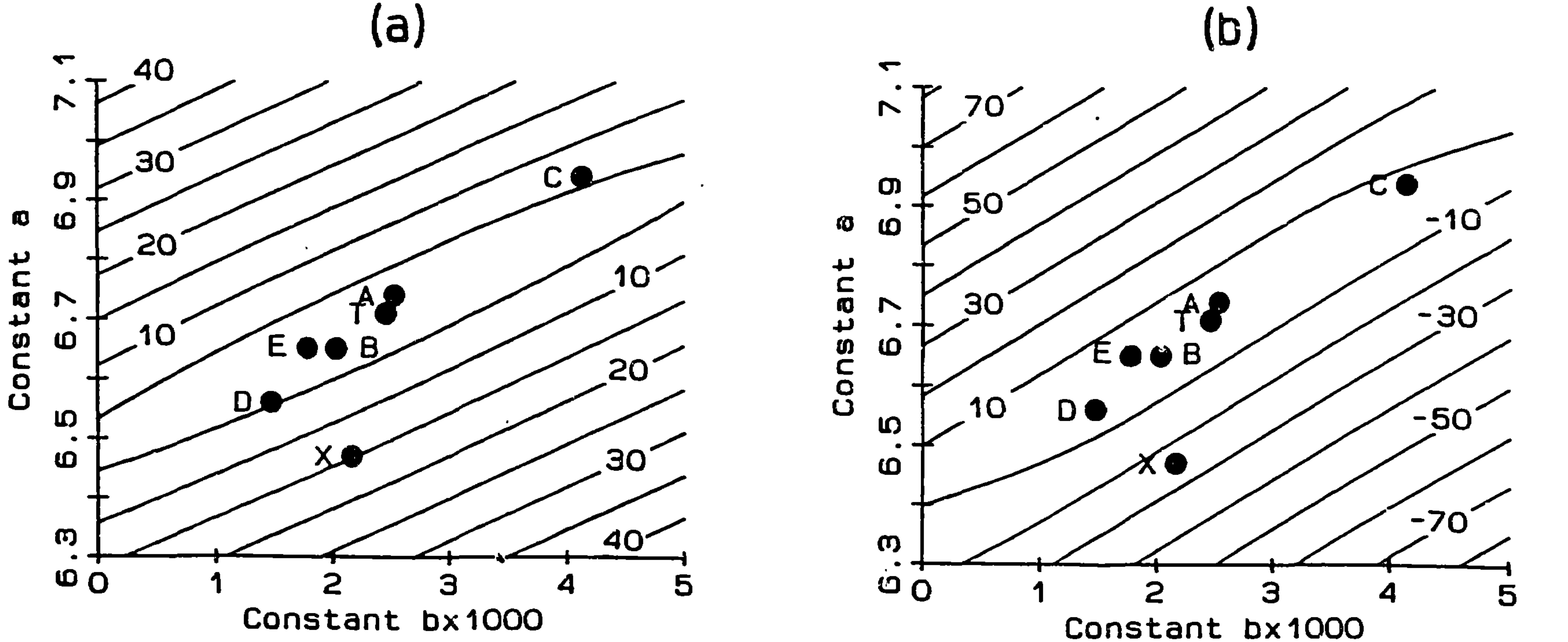

Fig. 7. Distribution of depth difference on the constants a-b plane. (a) Standard deviation (root-mean-square) of depth difference from the reference equation. Units in meter. (b) Maximum value of depth difference. Units in meter. Note that zero contour does not exist between contours of 10m and -10m.

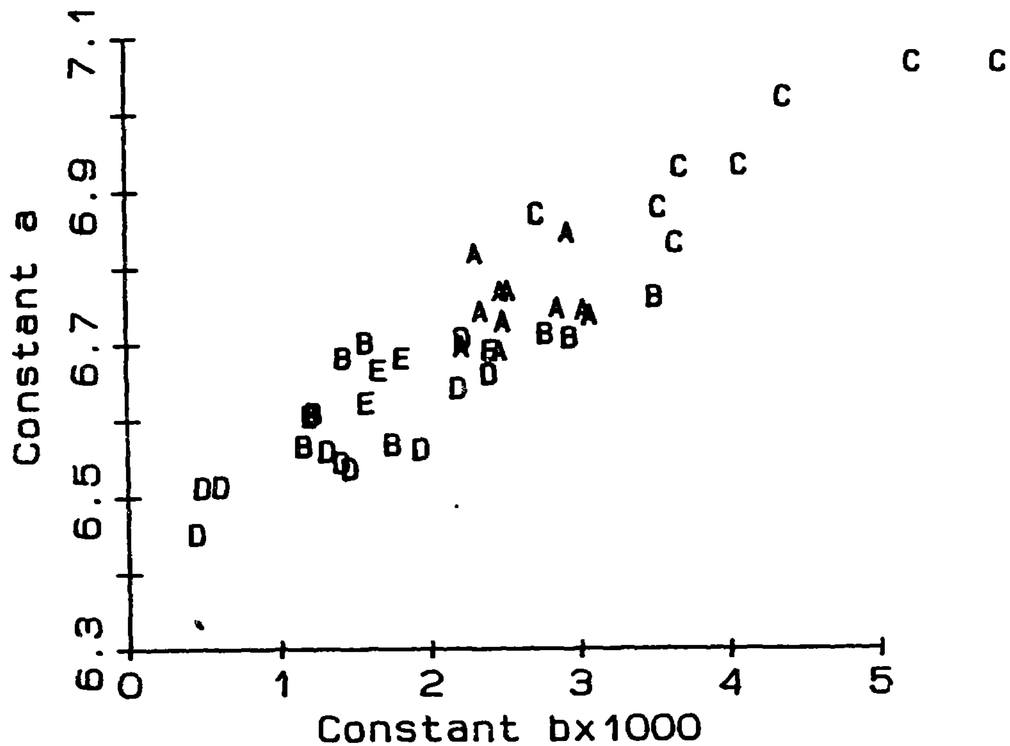

Fig. 8. As in Fig. 5 but for individual data.

Report on Field Tests in 1990 on the evaluation of the XBT Depth Fall Rate Equation

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At the IGOSS Ship-of-Opportunity Meeting in Hamburg, 16 - 20 October, 1989, it was decided to conduct an internationally co-ordinated experiment to evaluate the XBT depth fall rate equation. The goal was to carry out controlled XBT-CTD comparisons in different ocean regions to assess any possible influence of hydrographic structures on the fall rate of XBTs. NOAA/NOS took the lead in organizing a community-wide effort. Appropriate test procedures to ensure a controlled test were drafted by M.Szabados. According to these guidelines, only Sippican Mk-9 controllers and calibrated probes should be used to minimize the system bias.

The Bundesamt fuer Seeschiffahrt und Hydrographie (BSH, formerly DHI) participated in this experiment. All measurements were carried out in the Skagerrak on June 20, 1990 during a cruise onboard R.V. "Gauss". The position of the test site was 58° 16'N, 9° 31'E, the water depth was 680 m. At the same position an in-situ XBT-CTD comparison was carried out in July 1989 using a Bathy Systems controller and fresh water laboratory calibrated T-7 (deep blue) probes. The result of this test (12 probes) highlighted the known underestimation (probes falling faster than calculated) of the depth fall rate formula (Sy and Ulrich, 1990). However, in contrast to the results of previous studies by other groups, the depth fall rate error was within the accuracy range specified by Sippican as +/- 2 % of depth or +/- 5 m (whichever is greater). In order to verify these 1989 results and to collect data from a hydrographically rather unusual ocean area, the same site was selected for the 1990 depth fall rate evaluation experiment.

The Skagerrak is situated in the inner end of the Norwegian Trench between Norway and Denmark that cuts into the shelf, and has the topography of a large fjord (sill depth 270 m, maximum depth about 700 m). The hydrographic situation is governed by low saline outflow to the west (Norwegian Current) in the top layer, and below by a compensatory inflow of high saline water of Norwegian Sea and Atlantic origin. The Norwegian Current which follows the Norwegian coast is mainly fed by the very low saline Baltic Current (20 - 25 ‰) leaving the Baltic Sea through the Kattegat and following the Swedish coast towards the north. Outside these currents, North Sea and Atlantic waters (> 35 ‰) enter the Skagerrak along the Danish coast. This weak current, often called the Jutland Current, joins the Norwegian Current at the eastern end of the Skagerrak, though on average a cyclonic circulation is found in the top layer (Fig. 1). These different currents cause density to be governed by salinity rather than temperature. In addition, there is a considerable amount of fresh water inflow along the northern and eastern coasts, in particular during the spring run off. In summer, the temperature field is characterized by a three-layer system: a flat warm layer at the sea surface due to seasonal warming of the upper part of a deep mixed layer of several hundred meters depth, and below that is a layer with a weak thermocline extending to the bottom.

The field test was carried out in line with the test procedures drafted by Szabados (see Szabados (1991) for a copy of the guidelines). The calibrated Sippican Mk-9 controller and acquisition software was provided by NOAA/NOS. One case each of T-4, T-6, and T-7 probes was provided by Sippican, Inc. All the probes used were calibrated (salt water bath) by Sippican about six months before the test. After the field work, the raw XBT data (unchanged) and CTD data (reformatted) were forwarded to NOAA/NOS to be analysed using standard techniques developed by Szabados (1991).

Two CTDs were used as a reference: a standard Neil Brown NBIS MkIII and a self-containing (autonomous) SIS CTD plus 1000 (SIS Sensoren Instrumente Systeme GmbH, Kiel, Germany) mounted at the NBIS. The SIS (p, T and C), but not the NBIS, was calibrated before the cruise. In addition, in-situ water samples were taken using a rosette water sampler and the temperature measured using electronic reversing thermometers. The results are satisfactory for SIS (no in-situ corrections were necessary), but they show significant deviations from the NBIS salinity and temperature. It is for this reason and because of the better pressure resolution (0.01 dbar), pre-cruise calibration, easier data handling (internal data processing) and the good quality of the results of in-situ comparison that the SIS values are used for the analysis. The manufacturer's specification (accuracy: temp. 0.005 °C, sal. 0.02, pres. 0.05 % fs) is satisfactory for the purpose. Except for the reformatting procedure, no external data processing was necessary. The pressure sensor is self-adjusting at the sea surface, and 1 dbar was chosen as the vertical storage resolution.

While measurements were being taken, the vessel was stationary. The horizontal distance between XBT and CTD traces was about 30 m. XBT probes were not seen striking the CTD body or its single conducting wire. The running XBT wire was kept free of the ship's hull. The weather conditions were excellent, dry and calm. 12 CTD casts (lowering speed 1 m/s) and 36 XBT drops were carried out. One CTD cast failed but no XBT drop failed. The T-4 and T-7 probes' serial numbers showed a remarkable large range unlike those for T-6:

T-4: # 042 752 - 044 673 (12 probes)
T-6: # 282 931 - 282 942 (12 probes)
T-7: # 674 027 - 675 982 (12 probes)

The temperature field at the test site had no features such as series of steps or inversions which can be used to calculate the depth differences between CTD and XBT profiles as a function of depth for the whole depth range. Nevertheless, significant results (at least qualitatively) were obtained and are summarized below. The CTD-XBT comparison is quasi temperature error free because temperature differences between CTD and XBT profiles in the mixed layer were substracted from the XBT data. After this correction the residual mean temperature difference in the mixed layer between 100 m and 200 m is more than one order of magnitude smaller than at the upper part of the thermocline layer (350 m). The overall results are as follows:

> CTD minus XBT temperatures in the seasonal thermocline (gradient about 1°C/m) show large values in the order of -1 °C to -2 °C indicating that the fall rate equation is overestimated at the beginning of the probe's descent. As SST differences are close to zero or small (except for 3 T-7 traces which show large positive temperature differences between the sea surface and the mixed layer and thus are subject to malfunction), it is concluded that the data acquisition system worked accurate.

- the temperature differences in the mixed layer are close to zero which is indicative of sufficient temperature error correction.

- also the temperature differences at the step-like onset of the main thermocline at about 350 m show a negative maximum and remain negative. It can thus be concluded that the depth fall rate equation overestimates XBT depths for the whole trace.

- the mean XBT depth error (Δz = z(XBT) - z(CTD)) at 350 m is estimated as
  T-4: 20.0 m +/- 3.4 m
  T-6: 17.7 m +/- 4.5 m
  T-7: 19.7 m +/- 7.6 m

That the tests show how probes fall significantly slower than calculated by the drop rate equation corresponds to Szabados' (1991) findings. He carried out XBT field tests during a Sub- tropical Atlantic Climate Study (STACS) cruise northeast of Brazil between January and March 1990. These results do not, however, correspond to any other past or recent drop rate error estimates published in the literature. Their validity must therefore be questioned but they cannot be completely rejected as long as plausible explanations are found for this discrepancy. Szabados (1991) does discuss some possible explanations but they must be ruled out:

- effect of ocean region: the hydrography of the STACS region is completely different from that of the Skagerrak. Previous XBT tests in the STACS area (Szabados and Wright, 1989) and in the Skagerrak (Sy and Ulrich, 1990) showed opposite results as in 1990 (underestimation of the depth fall rate).

- XBT data acquisition system: for both experiments NOAA's acquisition system was used. A Mk-2 analog recorder included in the STACS 1990 field test, however, showed the same result.

- CTD system: two different and independently calibrated CTDs were used so CTD malfunction can be ruled out.

weather: the weather situation was different. Inclement weather in the STACS area caused a high drop failure rate whereas calm weather in the Skagerrak provided excellent launch conditions.

The probes themselves must therefore be regarded as the source of error. For both field tests probes from the same batch were used (M. Szabados, pers. comm.) and production differences can be considered a reason for why the probes fall at a slower rate. This argument, however, is difficult if not impossible to prove because no weight check has been carried out.

The calibration of all probes used was done in Sippican's XCTD salt water calibration baths (J. Hannon, per. comm.). Wet calibration of probes is not unusual. Roemmich and Cornuelle (1987) concluded from their experiences that calibration procedures are not destructive. They used fresh water. Salt water, however, has a corrosive effect on zinc given enough time to react. Corrosion of the probe's zinc nose surface increases its roughness and frictional resistance which affects the probe's characteristics. The effects of the salt water calibration can thus be regarded as a feasible explanation for the unusual result of the depth fall rate evaluation in 1990.

References:

Roemmich D. and B. Cornuelle (1987): Digitization and calibration of expendable bathythermograph. Deep-Sea Res., 34, 299-307.

Sy, A. and J. Ulrich (1990): North Atlantic ship of opportunity XBT programme 1989. Data report. Wissensch.-Techn. Ber. aus dem DHI, 1990-2, 89 pp.

Szabados M. and D. Wright (1989): Field evaluation of real-time XBT systems. Unpublished manuscript presented at Third Session of the Joint IOC-WMO Meeting for Implementation of IGOSS XBT Ship-of-Opportunity Programmes, Hamburg, F.R.G., 16-20 October 1989.

Szabados M. (1991): Evaluation of the expendable bathythermograph (XBT) fall rate equation. Data report. National Ocean Service, 6010 Executive Boulevard, Room 925, Rockville, MD 20852.

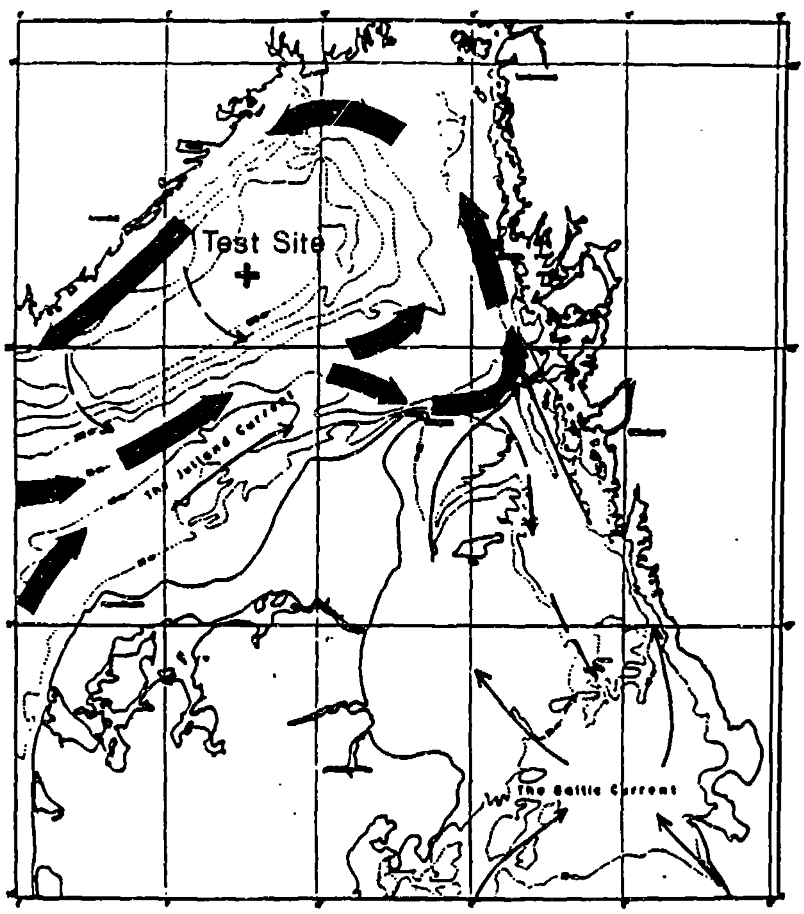


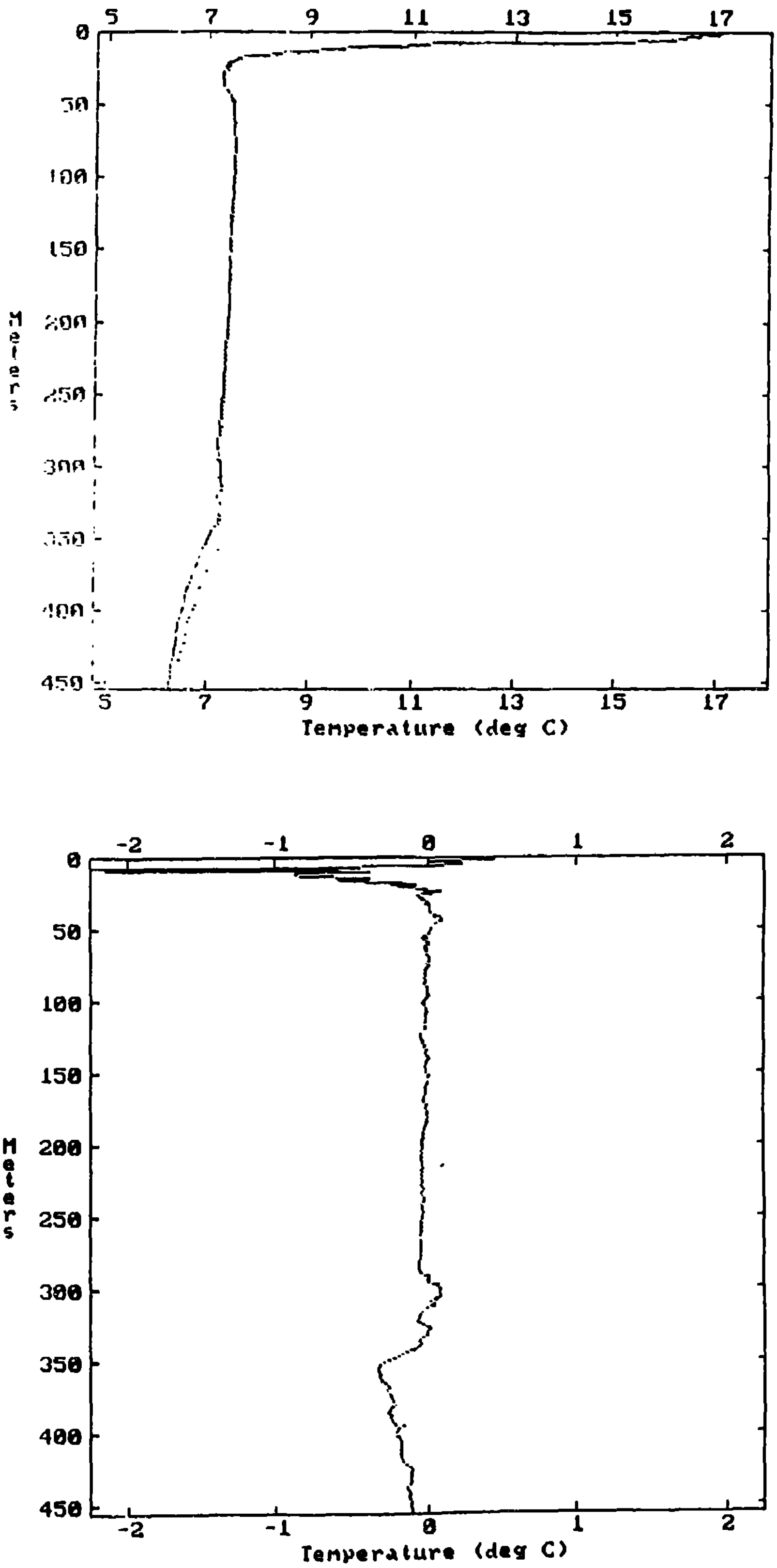
Fig. 1: XBT test region, Surface currents after Svansson, 1975.

Fig. 2: Sample for CTD and XBT (dotted line) profiles and CTD minus XBT profiles compared with CTD cast # 4 (start time 12:38)

a) for T-4 (start time 12:42)

b) for T-6 (start time 12:45)

c) for T-7 (start time 12:48)


5
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100
150
200
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300
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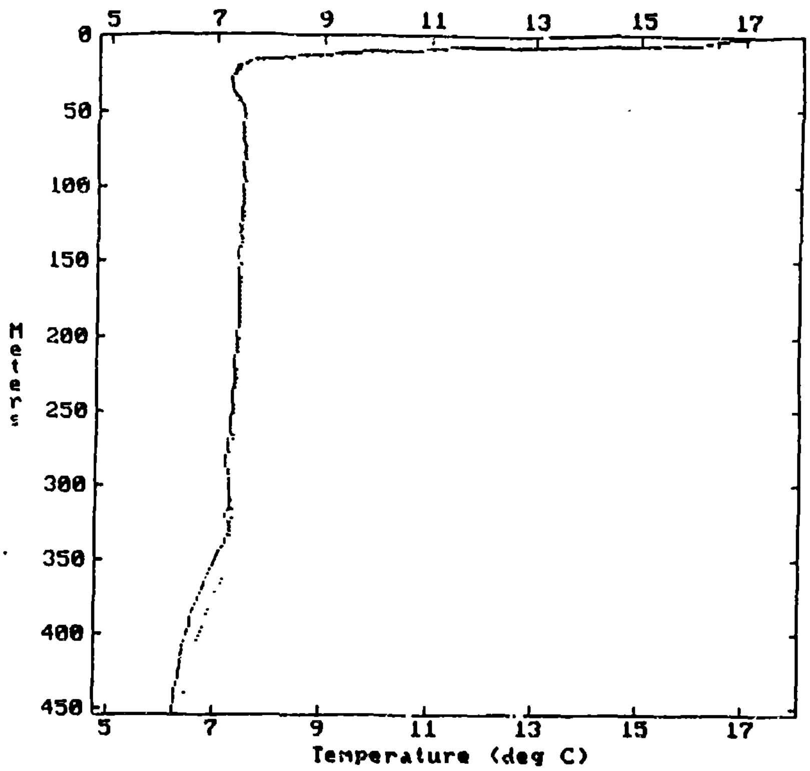
Meters
Temperature (deg C)
-2
-1
0
1
2
Temperature (deg C)

a)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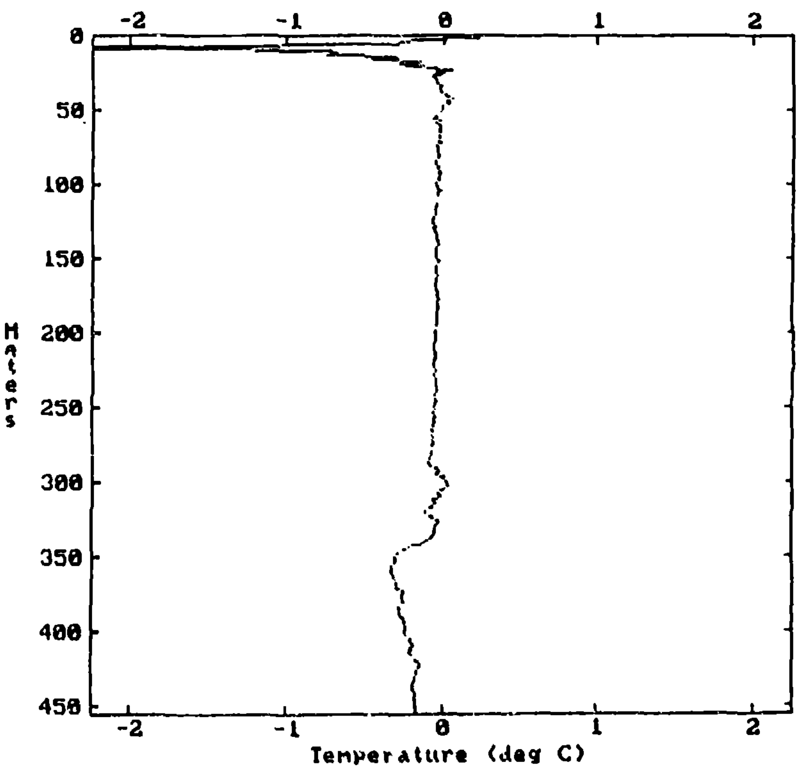
Temperature (deg C)

b)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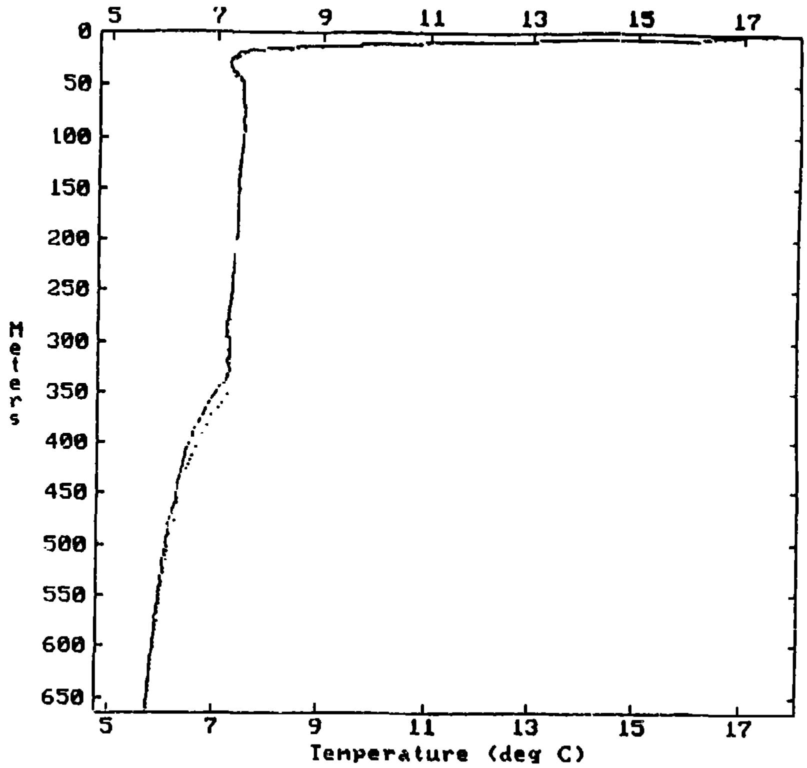
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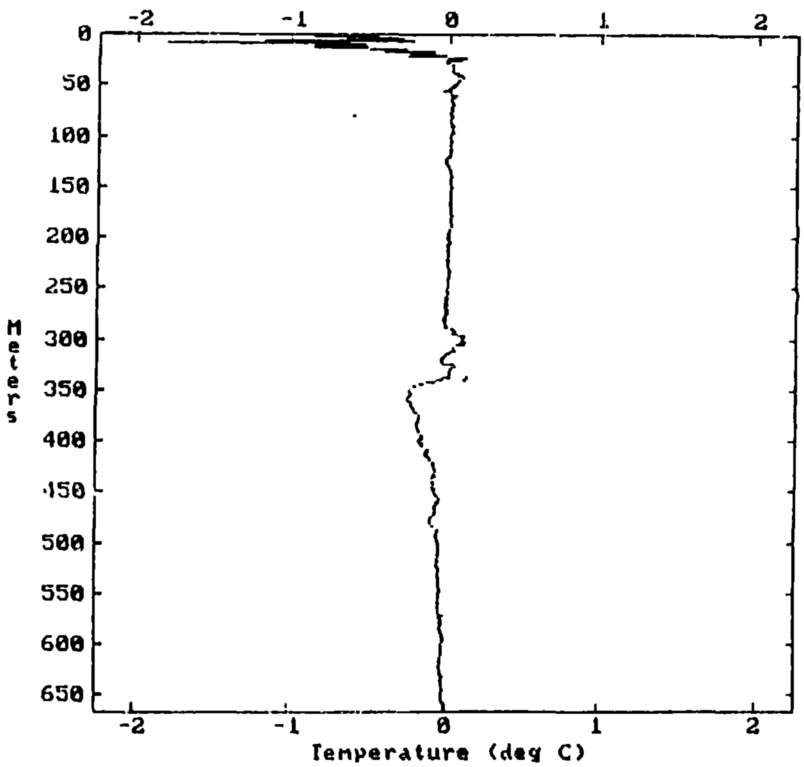
Meters
Temperature (deg C)

c)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Meters
Temperature (deg C)

XBT DEPTH CORRECTION

Pierre RUAL

(ORSTOM, May 1991)

Introduction

Within the framework of the TOGA programme, the SURTROPAC group of ORSTOM, Noumea, made several XBT-CTD comparisons during the SURTROPAC cruises in the western tropical Pacific, along 165°E between 20°S and 10°N. Henin (1989) tested 35 Sippican T4 probes in january 1987, which resulted in a linear depth correction of the Sippican depth formula with a coefficient of 1.05 between 80m and 400m, and almost no surface offset (1.25m).

In this note are presented two more test experiments with Sippican probes:

- 22 T7 probes in July 1989,
- 2 T6, 14 T4 and 11 T7 in December 1989.

A short comparison with some other results, from different areas, will follow and a new depth formula will be proposed.

Methods

Two methods have been experimented in order to compare a CTD profile to an XBT profile. Each method focused on depth comparison and are independent of any temperature error between the two profiles. The temperature error may, after correction of the depth, be computed as a by-product.

In these two methods, the basic principle is to detect the temperature steps of the XBT and CTD profiles and then to match their depths. Only the fact that abrupt changes in the temperature gradient exist, is important. The magnitude of these changes is not taken into account, this is how the methods are independent of the temperature error.

Second derivative zero crossing method

In order to detect abrupt temperature changes, the vertical temperature gradient and vertical second derivative are computed. The zero crossings of the second derivative correspond to the temperature gradient extrema (Figure 1). The zero crossing depths of the XBT and CTD profiles are then automatically matched by minimalization of the XBT depth error within two limits.

Following several authors (Henin 1989, Hanawa & Yoritaka 1987, Singer 1990, Sy & Ulrich 1990), a linear correction of the Sippican depth formula is correct to the first order (Figure 2). So a linear regression is used to adjust a correction coefficient to the Sippican depth formula with the addition of a surface offset if necessary.

The critical phase of this method is the matching procedure. If the profiles are noisy or if there are too many discrepancies between the XBT and CTD profiles, the automatic matching procedure becomes very difficult and may be erroneous.

Minimum integral of the temperature error vertical gradient method

In order to avoid the critical XBT-CTD depth matching phase, another method has been developed. The XBT minus CTD temperature error is computed for the whole profile, then the vertical gradient of that temperature error is also computed (Figure 3).

Simultaneous identical temperature changes in the XBT and CTD profiles induce no change in the temperature error and the temperature error vertical gradient remains equal to zero. But if a depth error occurs in the XBT profile, the simultaneous temperature changes are no longer at the same depth and an abrupt temperature error change is created between the shallower and the deeper depth. This induces two opposite spikes on the temperature error vertical gradient. These spikes are depth error dependent and will disappear when the depth error is corrected. So an easy way to correct the XBT depth is to compute the integral of the absolute temperature error gradient for different depth correction coefficients. The correct coefficient will be detected by a sharp minimum of the integral, due to the disappearance of the depth error dependent peaks (Figure 4).

Such a method suppose that, in the first order, there is no surface offset and that the depth correction is linear. This may be checked with the first method using the zero crossing depth matching.

Results

Twenty two T7 probes, from Sippican, were tested in July 1989. In December 1989, two T6, fourteen T4 and eleven T7 were also tested under the same conditions, against a SEABIRD CTD (model 09). The CTD sensors were calibrated by the manufacturer just prior to the experiments, their accuracy and drift are about an order of magnitude better than those of the XBT probes.

The results from these experiments are shown in Table 1. The two methods gave a similar result for the July experiment with T7 probes, so only one result appears in the table. In December 1989, the two T6 and the 14 T4 probes were processed together as the test results were very comparable. The two methods produced a similar result for the T4-T6 batch of probes, and this result is identical to the T7 result of the July 1989 experiment: a 3% depth correction coefficient.

The T7 result of the December 1989 experiment is also identical if only the first 500 meters are considered. If the lower part of the profiles, below the thermocline, is taken into account, then the correction coefficient is significatively different: 4% instead of 3% with a standard error of 0.25% (an example is given in Figure 5). It means, at least for this batch of probes, that the linear correction hypothesis is not correct, and a polynomial best fit should be used. In July 1989, there was not such a difference with the T7 probes tested.

The zero crossing method computes also the surface offset of the depth correction. It is very close to zero both for the T7 and the T4 probes (respectively 0.5m and -0.4m). So one needs only to apply a simple correction coefficient to the Sippican depth formula:

$$z = k * (6.472\, t - 2.16*10E\text{-}3\, t*t)$$

t: time in seconds

z: depth in meters

If k = 1.03 the formula becomes: $z = 6.666\, t - 2.22*10E\text{-}3\, t*t$

or $z = (3\, t - 10E\text{-}3\, t*t) * 20/9$ a nice simple formula!

If k = 1.04 then the formula is: $z = 6.731\, t - 2.25*10E\text{-}3\, t*t$

Comparison with previous results

Henin with T4 probes and Szabados & Wright with T4, T6 and T7 probes, used a similar method, attributing the temperature difference to a depth error, and found a 5% correction coefficient (Table 2). Henin tested the probes in the western tropical Pacific and Szabados & Wright in the western tropical Atlantic. Gould (1990) found the same coefficient for the T7 he tested with a completely different method. But Sy & Ulrich (1990), with Deep Blue probes tested in the cold waters of the Norwegian trench, found no depth error. Hanawa & Yoritaka (1987), in the western north Pacific, and Singer (1990) found a correction coefficient close to 3.5% for T7 probes.

Conclusion

The depth error is found to be from 0% to 5%, with a diversity of methods, areas and probe types or batches. Taking into account the 1% standard deviation found in this study (Table 1), which confirm the 2% dispersion specification given by Sippican, a 3% correction coefficient may be proposed as a general formula. The new depth formula proposed is: $z = (3\,t - 10E\text{-}3\,t*t) * 20/9$

References

Henin C., 1989, Experimental error of expandable bathythermograph in the western tropical Pacific. Communication to the 1st session of the TOGA XBT ad hoc panel of experts, Noumea, N. Caledonia, june 1989. 9 pages, unpublished manuscript.

Gould W.J., 1990, Depth error in T-7s. WOCE Newsletter, 10, 10-11.

Hanawa K. and H. Yoritaka, 1987, Detection of systematic errors in XBT data and their correction. J. Ocean. Soc. Japan, 43, 68-76.

Singer J.J., 1990, On the error observed in electronically digitized T-7 XBT data. J. Atm. Ocean. Tech., 7, 603-611.

Sy A. and J. Ulrich, 1990, North Atlantic ship of opportunity XBT programme, 1989 Data report. Scien. Tech. Rep. of Deutsches Hydrographisches Inst., 1990-2, 87 pages.

Sy A., 1991, WOCE hydrographic operations and methods, XBT measurements. 20 pages, unpublished manuscript.

Szabados M. and D. Wright, 1989, Field evaluation of real-time XBT systems. Summary of of ship-of-opportunity programmes and technical reports. Third Joint IOC-WMO meeting for implementation of IGOSS XBT SOOP programmes, Hamburg, Germany, oct. 16-20 1989, 141-153.

Legends

Figure 1: Temperature vertical second derivative zero crossing method: *i)* the XBT and XTD profiles zero crossings are computed, *ii)* the depths of XBT and CTD zero crossings are matched for a same temperature step, *iii)* and a linear regression is computed to correct the XBT depths to the CTD depths.

Figure 2: XBT T-4 Sippican probe depth error versus CTD depth with a linear correction coefficient correction curve of 1.05 (from Henin 1989).

Figure 3: Temperature difference vertical gradient method: *i)* the gradient of the difference between the XBT temperature and the CTD temperature is computed, *ii)* the sum of the gradient absolute values is computed, *iii)* the whole process is iterated for different XBT depth correction coefficients, and the correct coefficient is the coefficient that produce the lower sum because, if there is no depth error, the depth error dependent gradient spikes disappear.

Figure 4: from right to left, CTD profile + 7°C, XBT profile, vertical gradient of the temperature difference XBT - CTD + 5°C, temperature difference XBT - CTD. *a)* with no correction, *b)* with the correction coefficient that gives the minimum value of the sum of the temperature difference vertical gradients (no more depth error dependent spikes).

Figure 5: As for figure 4 but with two different XBT depth correction coefficients, *a)* correcting the upper part of the profile, *b)* the deeper part of the profile.

Table 1: XBT depth correction coefficients (in percentage) and their standard deviations, for the different experiments and methods used in this study.

Table 2: Summary of some XBT depth correction coefficients published recently.

Table 1

XBT correction coefficients & standard deviations

Exp.	T7		T4		Limits of Adjust.	Method
	cor%	dev.	cor%	dev		
July 89	3.0	1.0	-	-	10m -> Max-50m,	2 methods
Dec. 89	2.9	1.2	2.9	1.0	8m -> 520m,	zero crossing
Dec. 89	4.0	0.8	3.0	0.8	250m -> Max-50m,	integral

Table 2

XBT correction coefficients %

Author	T7	T4	Comments
Henin	-	5	80m -> 400m, temp. dif. method
Szabados	5	5	idem for T6, temp. dif. method
Gould	5	-	-> 700m, bottom hit comparison
Rual	4	-	250m -> 900m, temp. steps met.
Hanawa	3.4	-	temp. steps method
Singer	3.3 to 3.7	-	cited by Sy (1991)
Rual	3	3	10m -> 520m temp. steps method
Sy	0 (Deep Blue)	-	temp. dif. method

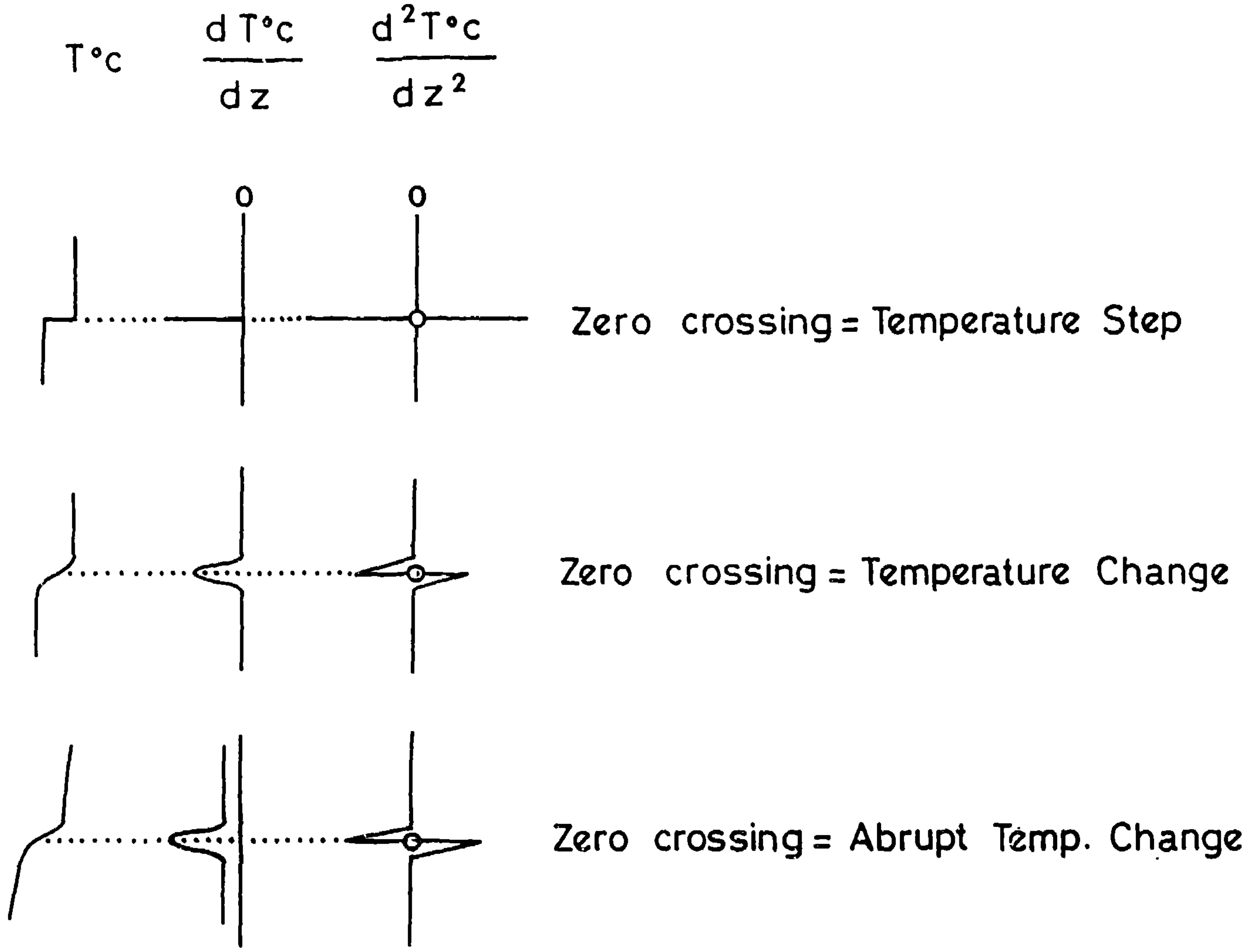
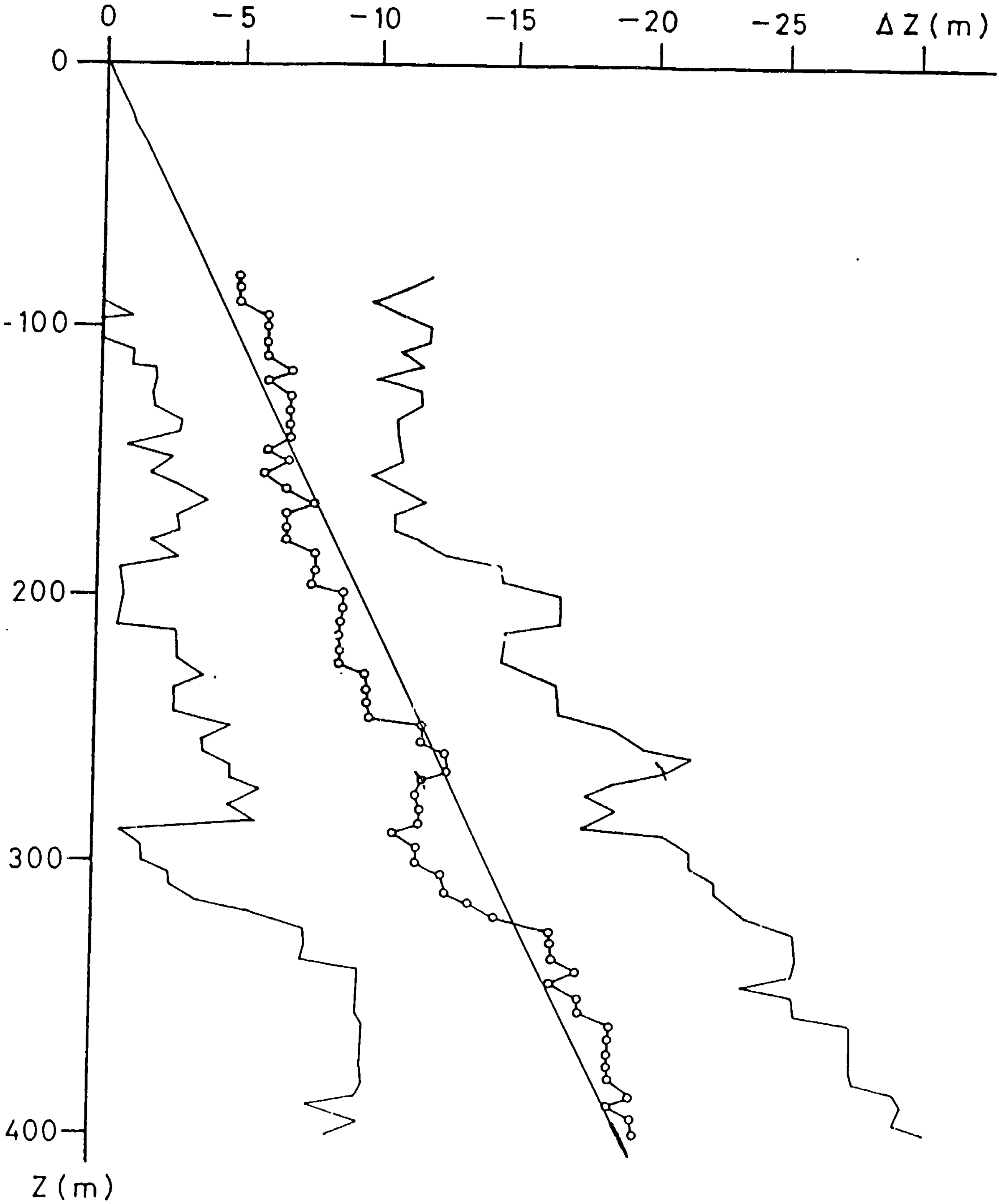
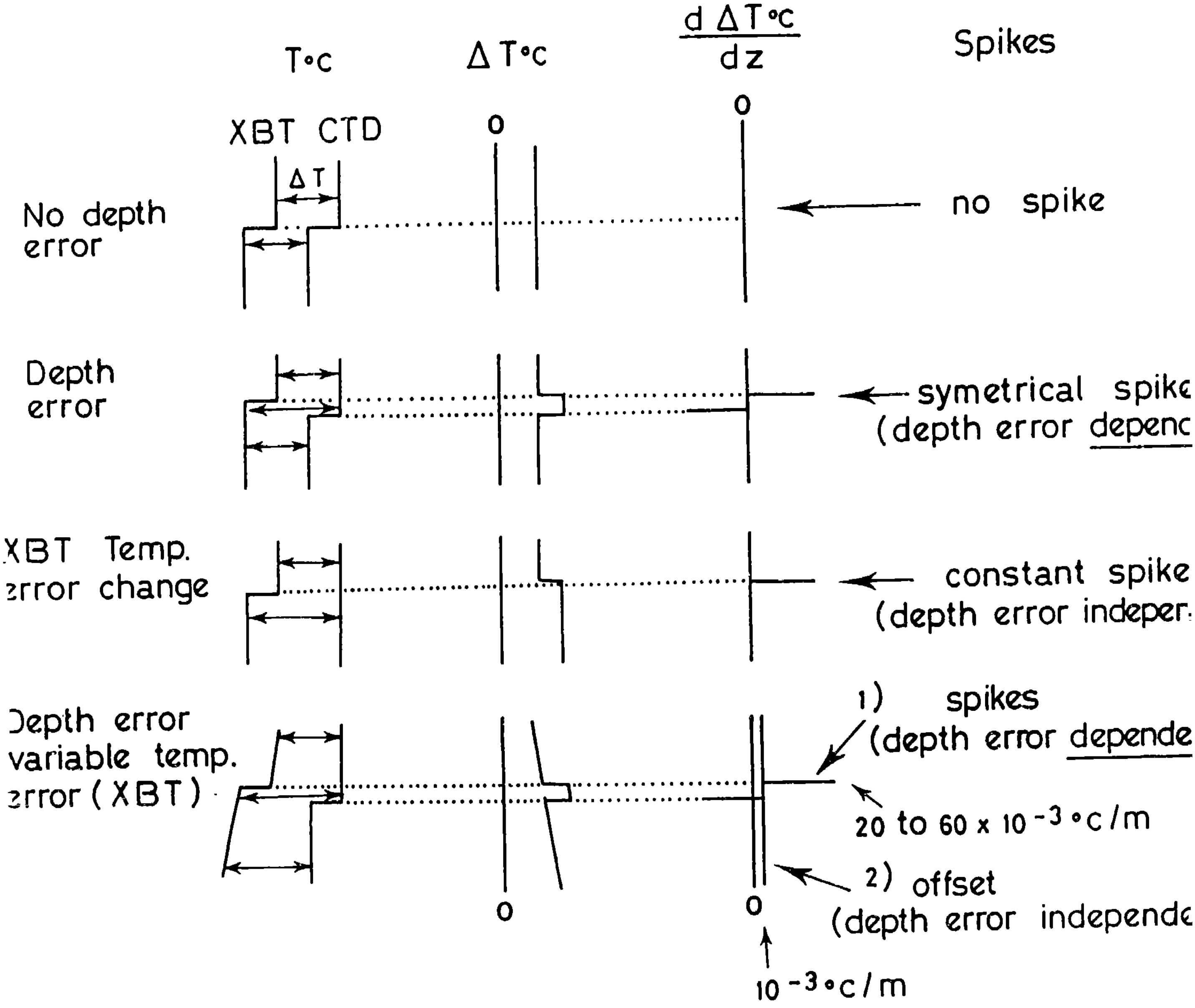

T°c
d T°c / dz
d²T°c / dz²
0
0
Zero crossing = Temperature Step
Zero crossing = Temperature Change
Zero crossing = Abrupt Temp. Change

fig 1



'g 2



T°c
XBT CTD
ΔT
ΔT°c
d ΔT°c / dz
Spikes
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0
No depth error
no spike
Depth error
symetrical spik
(depth error depenc
XBT Temp. error change
constant spike
(depth error indeper
Depth error variable temp. error (XBT)
1) spikes
(depth error depende
20 to 60 x 10 -3 °c/m
2) offset
(depth error independe
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0
10 -3 °c/m

fig 3

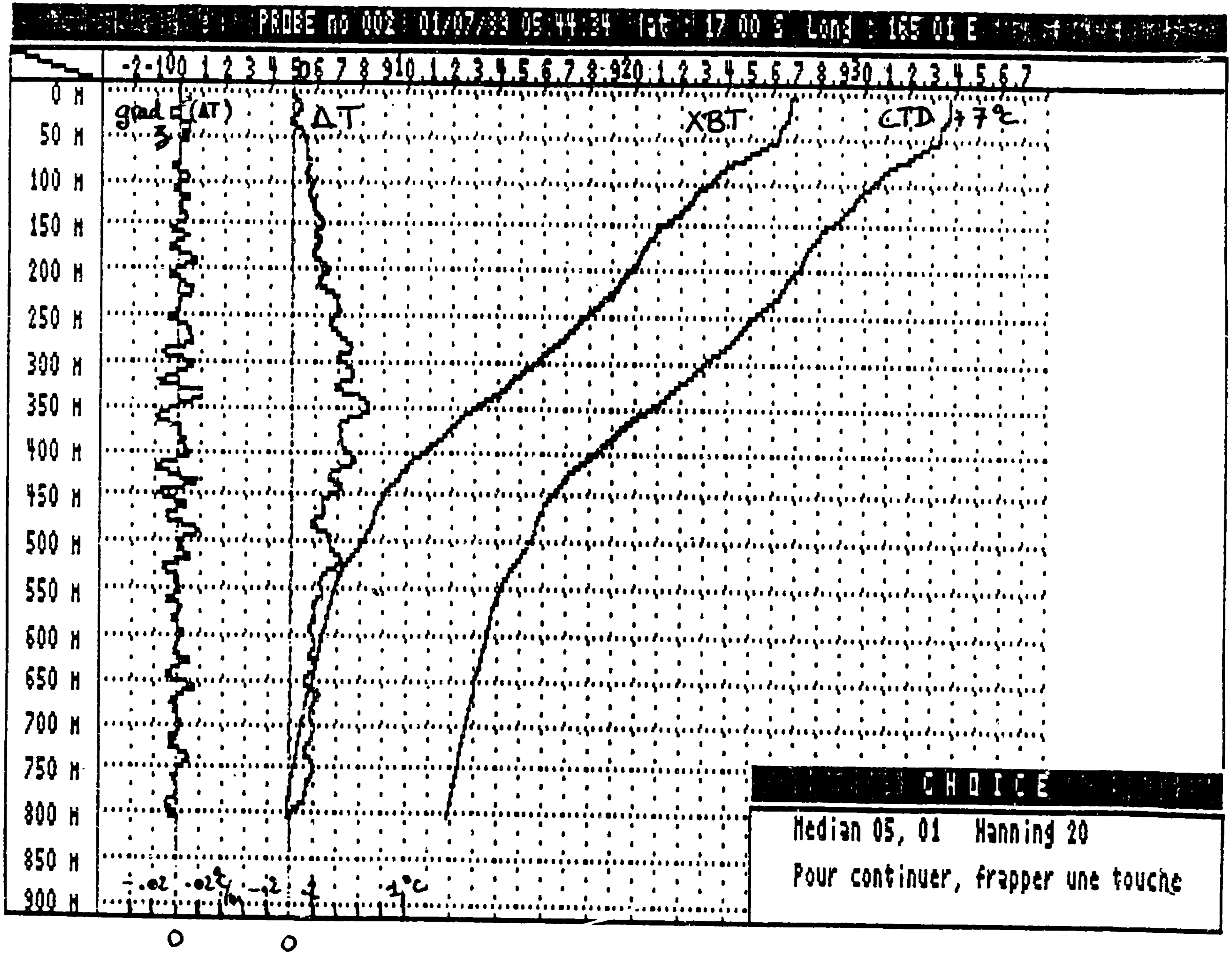
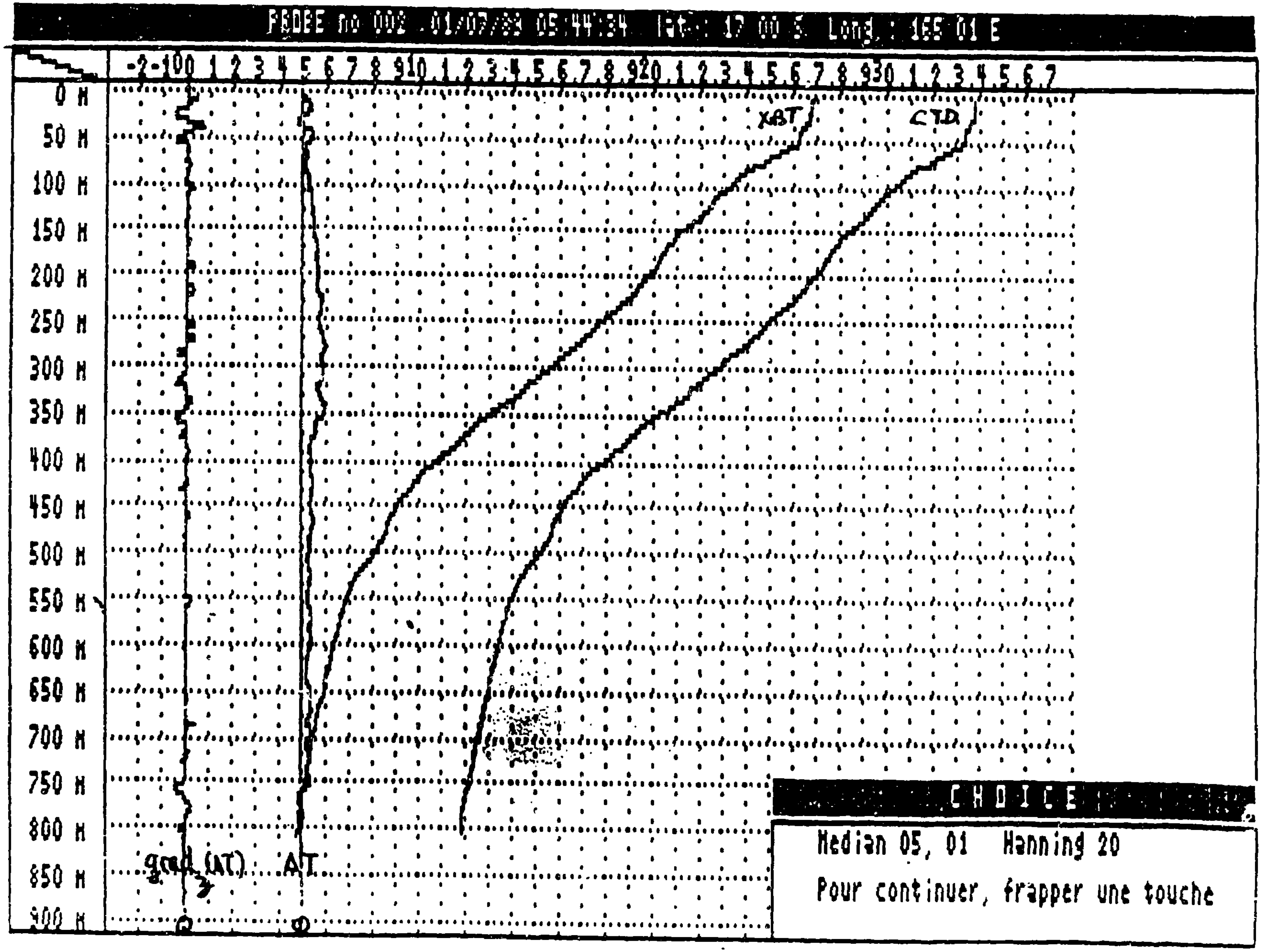


Figure 4 a No Correction



Correction +2.2 %

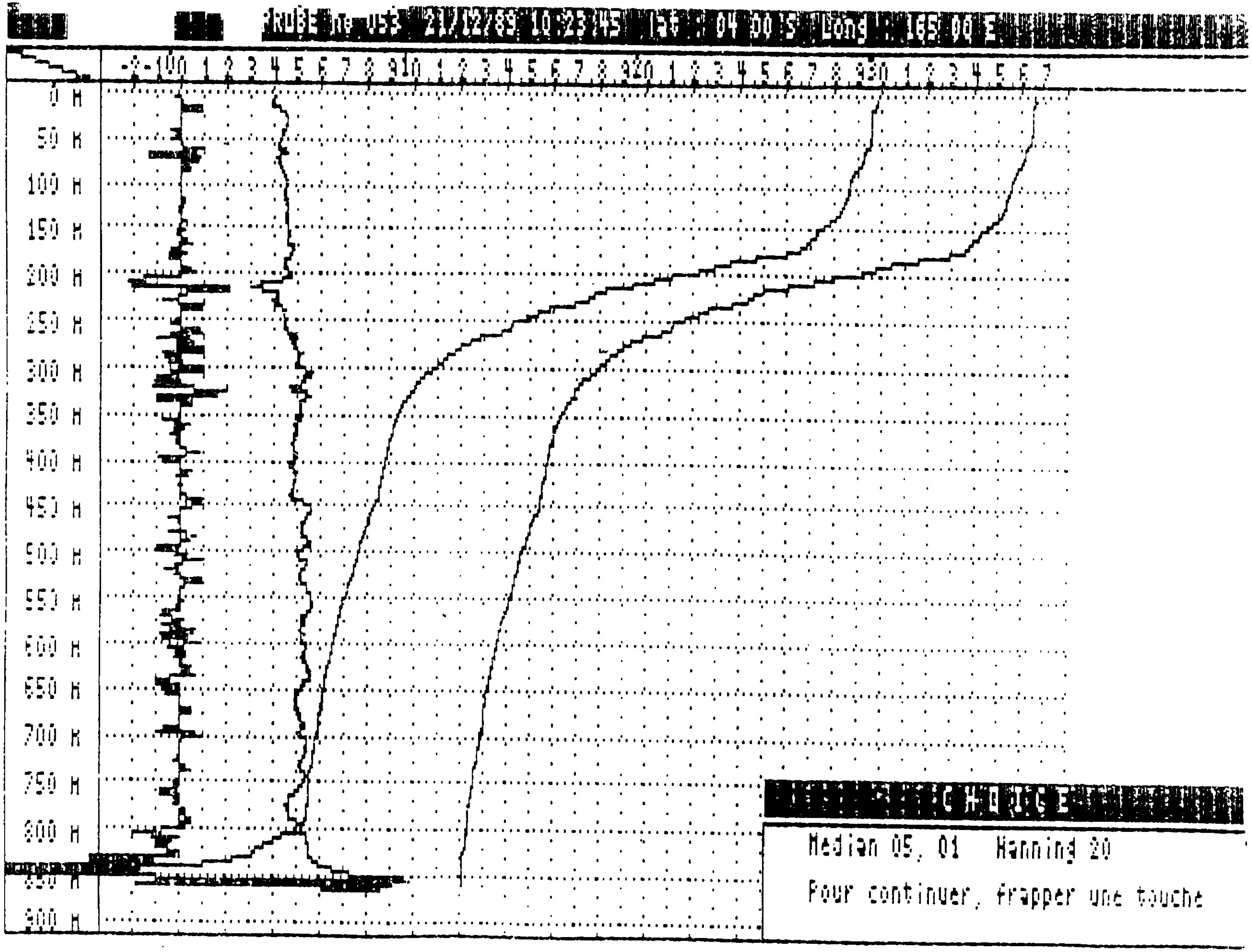


Fig 5 a cor = 1.2%

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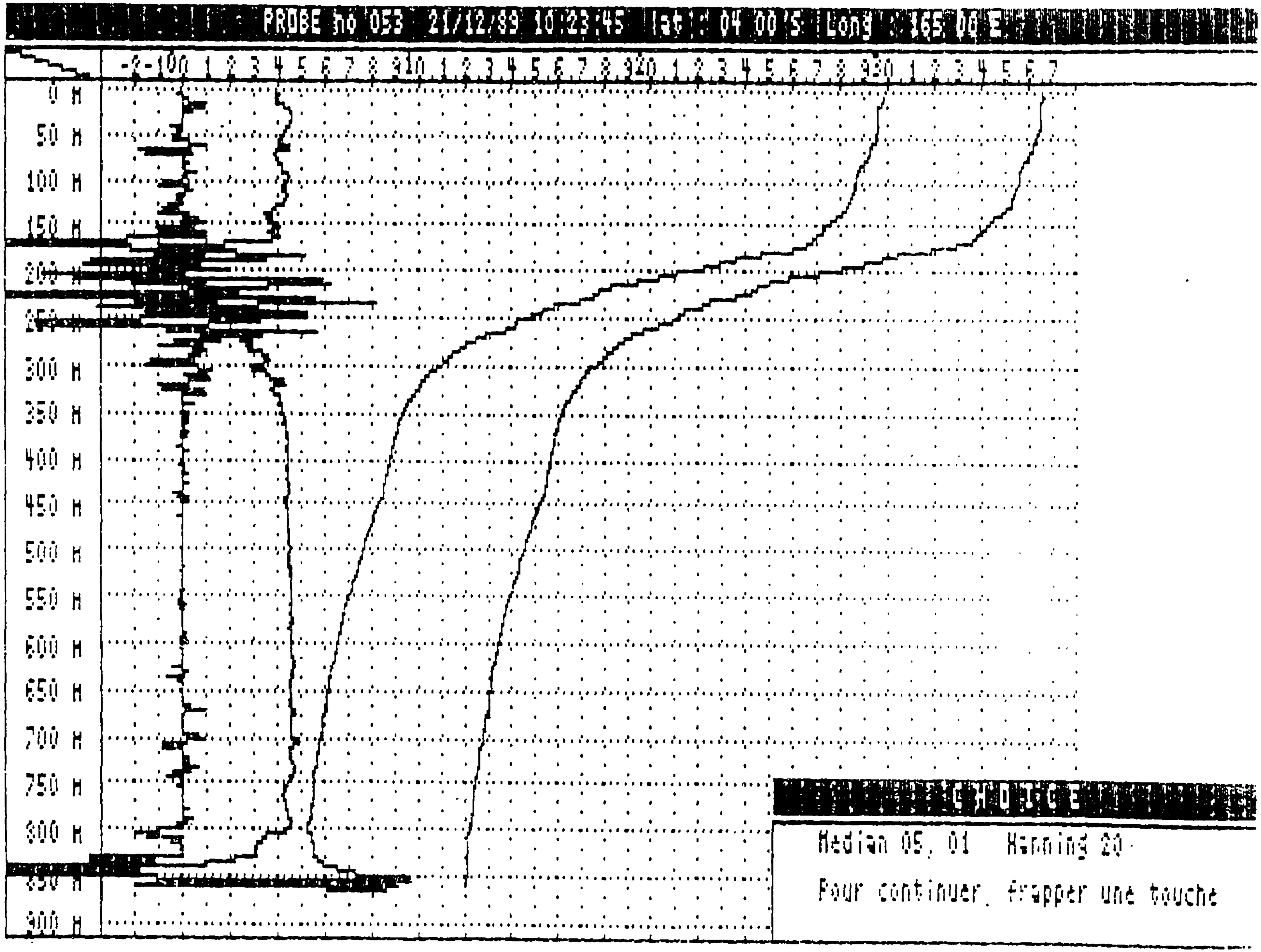
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100 M
150 M
300 M
350 M
400 M
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500 M
550 M
600 M
650 M
700 M
750 M
800 M
900 M
Median 05, 01 Hanning 20
Pour continuer, frapper une touche