

A COMPARISON OF BATHY MESSAGES WITH XBT SOURCE DATA
FROM THE HAWAII TO TAHITI SHUTTLE EXPERIMENT

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By

Peter C. Morton

Thesis Committee:

Klaus Wyrtki, Chairman
Brent Gallagher
E. D. Stroup

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THESIS COMMITTEE

Klaus Beyl

Chairman

Edward D. King

Brent Gallagher

ABSTRACT

The quality of bathy messages from the Hawaii to Tahiti Shuttle Experiment was determined to be poor: 13.8% of all radio-transmitted temperature-depth pairs were in error by at least 0.5°C , and 9.5% of all pairs were in error by more than 20 meters. The source of these errors was determined to be, overwhelmingly, shipboard coding inaccuracies. Two methods of error detection were developed and found to be partially successful: 20% of all depth errors in the thermocline greater than 20 meters and 31.6% of all temperature errors greater than 1°C in the mixed and deep layers were found to be detectable. Despite the general poor quality of the bathy message data, it is found that bathy messages may be useful for crude estimates of heat storage and geostrophic velocities.

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SECTION I INTRODUCTION

1.1 BATHY MESSAGES AND THE BATHY MESSAGE PROGRAM

A bathy message is a radio-transmitted representation of a bathythermograph record. A bathythermograph record gives temperature as a continuous function of depth. The instrument generally used to produce a bathythermograph record is the expendable bathythermograph (XBT). Occasionally a retrievable bathythermograph (BT) is employed. Information encoded in a bathy message includes the ship's call sign, cruise number, position, time, date, observation number, station number and instrument (XBT or BT). Throughout this paper the term bathy point shall refer to a radio-transmitted temperature-depth pair. The temperature is read to the nearest tenth of a degree Celsius and the depth is read to the nearest whole meter. Temperatures at the sea surface, at the deepest point measured, and at several points in between are recorded. Less than twenty points must be used to describe temperatures in the upper 500 meters.

The Bathy Operational Program is a part of the Integrated Global Ocean Station System (IGOSS), a joint effort of the Intergovernmental Oceanic Commission (IOC) and the World Meteorological Organization (WMO). The purpose of the Bathy Program is to provide international real-time communication of ocean temperature data. Bathy messages are exchanged through the Global Telecommunication System (GTS) of the World Weather Watch (WWW) of the WMO.

The availability of bathy message data from the Hawaii to Tahiti Shuttle Experiment has provided an excellent opportunity to evaluate the Bathy Message Program. During the Shuttle Experiment (Wyrcki et al., 1981) data from XBT observations were encoded on bathy message logs. These logs were then transmitted via Coastal Radio Stations into the GTS. Transmitted bathy message information, recorded on Fleet Numerical Oceanographic Center (FNOC) tapes, was available for comparison with the original XBT data. More than 800 bathy messages were recorded during the Shuttle Experiment.

1.2 PURPOSE OF THIS STUDY

The purpose of this comparison of the Shuttle Experiment XBT data with the corresponding FNOC bathy message data is three-fold:

- (1) to make a statistical evaluation of IGOSS data transmission accuracy;
- (2) determine the reliability of products prepared from bathy message data;
- (3) establish guidelines for detecting and correcting errors.

1.3 CLASSIFICATION OF ERROR

There are three types of errors which can appear in bathy message data (Huber, 1979):

- (a) Physical errors caused by instrument inaccuracies. Such errors occur at the time of observation. An XBT thermistor failure is an example of a physical error which can occur in situ. An improperly calibrated or malfunctioning recorder will also appear as a physical error.
- (b) Coding errors resulting from human error when an observer enters a wrong value or incorrectly encodes information on a bathy log.
- (c) Transmission errors which may occur whenever data is transferred from one place to another, or from one storage space to another. Included as transmission errors are incomplete and/or duplicated messages.

1.4 GUIDELINE FOR DETECTING ERRORS

The frequency of transmission and coding errors was determined by comparing bathy message data with the corresponding original XBT traces

and noting the discrepancies. A check was then run on the bathy radio logs to determine the origin of the error. A transmission error was distinguishable by a correct and complete bathy radio log and an incomplete or erroneous bathy message. Coding errors appeared on the radio log as well as on the bathy message.

Two tests were established for detecting errors from the bathy trace alone:

1. Regional upper and lower limits for temperatures at fixed (5 m interval) depths were established using all available NORPAX XBT data. Bathy temperature values falling outside of these limits were then checked to determine whether they resulted from coding or transmission errors.
2. Temperature increases of 0.5°C or more with increasing depth were noted. If a temperature proved to be the result of a coding or transmission error then this error was considered detectable.

Coding and transmission errors resulting in incorrect information on FNOC tapes had the appearance of physical errors on the bathy message trace. The two tests described above might, therefore, be used to detect physical as well as transmission and coding errors. However the effectiveness of the two aforementioned tests could not be determined because XBTs which were obviously incorrect were not transmitted as bathy messages. Thus all errors in the bathy message data set which

were detectable could be determined to be the result of either coding or transmission inaccuracies.

1.5 RELIABILITY OF BATHY MESSAGE PRODUCTS

The ultimate goal of the Bathy Program is the acquisition, on an international scale, of real-time data for the production of timely oceanographic products. The influence of errors on certain of these products, specifically dynamic height, geostrophic velocity, and heat storage will be discussed below.

After errors in the bathy message data have been detected by the above mentioned method, some errors falling within the prescribed limits remain undetected. The effect of such hidden errors on the quality of oceanographic products derived from bathy message data will be determined by comparing these products with those produced from the corresponding original XBT data.

1.6 THE DATA SET

Bathy messages received by FNOC from the central equatorial Pacific during the period of the Hawaii to Tahiti Shuttle Experiment were provided on digital tapes. All bathy data were then entered on 9 track 1600 b.p.i. ASCII tape in order to be compatible with the Hawaii Institute of Geophysics (H.I.G.) HARRIS 800 system. All XBTs recorded during the Shuttle Experiment had previously been digitized using the

H.I.G. inhouse digitizer and this information had been stored on 9 track 1600 b.p.i. ASCII tape.

1.7 REMOVAL OF DUPLICATE AND UNMATCHED BATHY MESSAGES

Each bathy message is identified by the latitude, longitude, date and time of the corresponding XBT station. A listing of all bathy messages received for each cruise occasionally revealed more than one bathy message for an XBT. Often one of these messages would be incomplete. Duplicated messages possibly result when a radio operator at a Coastal Radio Station receives a garbled transmission from a shipboard operator and asks for a repeat (D. McLain, personal communication). Duplicated messages were easily recognized and removed. Comparisons of cruise-by-cruise listings of bathy messages with the corresponding XBTs revealed a number of bathy messages for which no XBT information was available. These unmatched bathy messages were removed from the data set.

Bathy logs were essential for determining if a bathy message error resulted from a transmission or a coding error. All information to be transmitted in a bathy message was first recorded in a bathy log. Discrepancies between bathy logs recorded aboard the observation ship and bathy messages recorded by FNOC resulted from errors occurring after coding of the bathy message. Such errors, occurring during the transfer of information, were defined to be transmission errors. On the other hand, if information contained in a bathy log was consistent

with the information contained in the bathy message but differed from the corresponding XBT, it was determined that a coding error had occurred. A total of 760 bathy message logs from the Hawaii-Tahiti Shuttle cruises were available for cruises 5-12 and cruises 14-15. No logs were available from cruises 1-4 and 13, although bathy messages were received from these cruises. Logs were available for the latter portion of cruise 15 while bathy messages were received by FNOG for the first half of the cruise only. Thus no bathy message from cruise 15 could be matched with its respective log.

A total of 802 bathy messages were received by FNOG from the Shuttle cruises. Of these, 79 were duplicates. Often a repeated message contained a grossly incomplete message (e.g., two points). Of the remaining 723 bathy messages all but 15 could be paired with the parent XBTs, yielding 708 bathy messages which were successfully matched with corresponding XBTs. No bathy logs were available for 180 of these 708 bathy message-XBT pairs, leaving a total of 528 bathy message/bathy log/XBT sets for analysis.

1.8 DIGITIZATION OF XBTs

XBTs from the Shuttle Experiment had been digitized by recording temperature-depth pairs along each XBT trace every 10 m and every 0.5°C. Thus an XBT trace extending from the surface to 400 m over temperatures ranging from 28°C to 10°C was digitized by a minimum of 77 points. The trace was also digitized at the apex of each significant

temperature spike (small scale temperature changes with depth or an unsteady signal from the thermistor will produce sharp peaks or 'spikes' in the XBT trace). Typically, 90 temperature-depth pairs were recorded per XBT for the upper 400 m.

SECTION II ANALYSIS OF ERROR

2.1 PRELIMINARY ANALYSIS

The accuracy of an XBT is dependent on the thermal structure of the water column through which the XBT falls. While the overall system accuracy of an XBT is, roughly, $\pm 0.2^{\circ}\text{C}$ and ± 5 m (Anderson, 1980), the depth of a specific isotherm in a weak thermal gradient is more poorly determined than the depth of an isotherm in a sharp thermal gradient. Conversely, the temperature at a specific depth in a weak thermal gradient is better determined than the temperature at a specific depth within a strong thermal gradient. For example, Shuttle XBTs frequently recorded temperature changes of more than 15°C over depth changes of less than 50 m. Within such a sharp temperature gradient a system accuracy of ± 5 m means that temperatures at specific depths cannot be known more accurately than $\pm 1.5^{\circ}\text{C}$. On the other hand, Shuttle XBTs commonly recorded surface mixed layers with temperature changes of a few tenths of a degree over depth changes of 80 m or more. For such weak thermal gradients an XBT system accuracy of $\pm 0.2^{\circ}\text{C}$ means that the depth of a specific isotherm has an uncertainty of many tens of meters.

An error analysis of bathy messages produced from XBTs must consider the dependency of XBT accuracy on the thermal structure in which the XBTs were deployed. The waters of the central equatorial Pacific consist of a warm shallow mixed layer of almost uniform temperature separated from a region of cold deep water by a sharp gradient of

temperature in the thermocline (Fig.1). Temperature gradients in each of these three layers are, on the average, sufficiently different to warrant a separate analysis of error in each layer.

For analysis each bathy message was divided into three layers utilizing characteristics of the mean thermal structure. The mixed layer was defined as the region extending from the sea surface to the first depth with temperature less than the sea surface temperature by 1°C or more. The thermocline region was designated from the bottom of the mixed layer to the first depth with temperature less than or equal to 12°C . Choice of the depth of the 12°C isotherm as the bottom of the thermocline is justified as follows:

The shape of the mean temperature-depth profile in the deep layer is almost a straight line. At about the depth of 12°C the profile begins to depart from this line. Thus, while this depth does not correspond to the bottom of the thermocline for all stations, the depth of 12°C represents, on the average, a lower limit for the bottom of the thermocline. The deep layer was defined from the bottom of the thermocline to 400 m, a depth to where the majority of the XBT casts extended.

The mean difference between XBT and bathy message temperatures, at 5 m intervals, in each of the three layers was calculated for each station. Histograms of these mean differences for each layer were compiled for each cruise (Tables 1, 2, 3). Most mean differences fell within $\pm 0.5^{\circ}\text{C}$ for all layers. The means of these (mean) temperature differences were within $\pm 0.25^{\circ}\text{C}$ for all cruises for all three layers

with two exceptions: the histograms of mean temperature differences for the thermocline layer in Cruises 13 and 14 were centered near $+0.4^{\circ}\text{C}$ (Table 1). It is noted here that, first, there are differences in bathy message quality between the cruises and, second, temperature differences in the sharp thermal gradient of the thermocline are larger than temperature differences in the weaker thermal gradients of the mixed and deep layers. Histograms for the mixed and deep layers for all cruises were sharply peaked near 0.0°C (Tables 2, 3).

Each bathy message-XBT pair was linearly interpolated to give temperature values at 5 m intervals. Each pair was then plotted in a temperature versus depth graph utilizing the Versatec plotter so that the fit of the bathy message to the XBT could be seen. In addition a plot of the difference between the XBT and the corresponding interpolated bathy message temperatures at 5 m intervals was superimposed.

2.2 EFFECTS OF INTERPOLATION

In some of the bathy message-XBT comparisons to follow the digitized Shuttle XBTs were first linearly interpolated to give temperature values at 5 m depth intervals. In comparing these interpolated XBTs to bathy messages it is necessary to determine how much of the difference between the two data sets is due to interpolation alone. To determine the contribution from computational effects of linear interpolation, XBTs from cruises 4 and 7 were linearly interpolated to give

temperature values at 5 m intervals. Since the XBTs were first digitized to 10 m intervals before being interpolated to 5 m intervals, a comparison of temperature values at depth intervals that are multiples of 10 m would be biased. Therefore a depth interval of 3 m was chosen for this test.

Temperature values at 3 m depth intervals were determined by linear interpolation for both the interpolated and uninterpolated sets. The mean difference in temperature ((digitized)-(digitized and interpolated to 5 m intervals)) was calculated at each three meter depth interval from zero to 462 m for both cruises. These differences were found to be quite small. For the 155 mean differences calculated for Cruise 4, only 15 exceeded 0.02°C . The size of the mean temperature difference at only one depth was greater than 0.06°C (0.13°C). Ninety-nine of the 155 mean temperature differences were equal to zero for Cruise 4. Only 22 of 155 standard deviations of these mean differences were 0.10°C or greater. The largest standard deviation observed was 0.35°C . In Cruise 7, 109 of the 155 mean differences were equal to zero. Five of the mean temperature differences exceeded 0.02°C . The largest mean temperature difference determined for Cruise 7 was 0.09°C . Sixteen of the 155 standard deviations of the mean temperature differences in Cruise 7 were 0.10°C or more. The largest observed standard deviation was 0.27°C .

The effects of linear interpolation on the depth of specific isotherms was also examined for Cruises 4 and 7. The depths of all isotherms

from five to 28°C at temperature intervals of 1°C were found for both the digitized and the digitized, interpolated data sets. It was found that the mean differences (digitized-(digitized and interpolated)) in isotherm depth were small. In Cruise 4 the largest mean depth difference observed was 0.36 m, and the largest standard deviation of mean depth difference was 1.26 m. In Cruise 7 the greatest size of the mean depth difference was 0.46 m. The largest observed standard deviation was 1.47 m.

Based on the above tests, it is concluded that the uncertainties introduced by linearly interpolating the XBT data to 5 m depth intervals are quite small. On the average, linear interpolation contributes less than 0.01°C to the difference in temperature at a specified depth, and less than 0.3 m to the difference in depth of a specified isotherm.

2.3 EXPECTED ERROR DUE TO THE SHAPE OF THE XBT CURVE

All available Shuttle XBTs were interpolated to 5 meter intervals and the mean temperature at each depth was then determined. The resulting mean XBT profile is shown in Figure 1. This mean profile cannot be interpreted as being anything more than loosely representative of a region extending across 40 degrees of latitude. For example an XBT cast in the waters of the North Equatorial Countercurrent would show a more pronounced temperature gradient in the thermocline than the mean. Conversely an XBT taken at 17°S would indicate a less pronounced

thermal gradient in the thermocline than is shown for the mean. Nonetheless certain features of the mean profile lend themselves to a statement about bathy message error.

In Figure 1 it is seen that above roughly 130 meters (20°C) the mean profile is concave upwards (d^2Z/dT^2 is negative) and below 130 meters the mean profile is concave downwards (d^2Z/dT^2 is positive). An operator producing a bathy message from such an XBT profile using only a dozen points to define the curve is likely to produce errors resulting from the paucity of points, as shown in Figure 2.

While the magnitude of the errors so produced cannot be known from this simple analysis, it is possible to determine the sign. Define the quantity T^*

T^* = temperature difference (XBT-BM) at fixed depth.

From Figure 2 it is possible to state that, on the average, T^* will be positive above 130 meters (20°C) and negative below 130 m. Define the quantity D^*

D^* = difference in depth (XBT-BM) of a fixed isotherm.

Again from Figure 2 it is seen that, on the average, D^* will be negative above 130 m and positive below 130 m.

The size of the inaccuracies produced during the digitization process as the result of using a limited number of points to define the curve varies from profile to profile. For example, a trace with many

inflections or spikes would require a bathy point at each apex. Similarly many points might be required to define a smoothly curving trace. Human judgement plays a large role in determining the size of inaccuracies produced. A person digitizing an XBT who fails to properly indicate the position of an inflection point will produce an error even if the bathy point chosen lies on the XBT trace.

2.4 EFFECTS OF HUMAN ERROR IN DIGITIZATION

The scale of the Sippican XBT analogue recorder is, itself, a source of bathy error distortion. That is, an operator who makes a mistake of 1 mm in the horizontal direction while digitizing the trace will cause an error in temperature of 0.2°C . The temperature scale factor in the following discussion is equal to $0.2^{\circ}\text{C}/\text{mm}$. A 1-mm mistake in the vertical direction creates an error of 3.7-3.8 m (the scale on the Sippican recording paper decreases slightly with increasing depth). Thus the depth scale factor is $3.7 \text{ m}/\text{mm}$ or $3.8 \text{ m}/\text{mm}$, depending on the depth.

An estimate was made of the effects of small coding inaccuracies on the quality of bathy message accuracy based on a simple geometric analysis using features of the mean temperature-depth profile.

In Figure 3 E_h is the allowable human error (in millimeters). An operator who records a bathy point a perpendicular distance E_h from the

analogue trace will produce a temperature error given by

$$T^* = E_h^* (\text{temperature scale factor}) \sin(\tan^{-1} dZ/dT). \quad (1)$$

The depth error D^* produced by the operator error E_h is given by

$$D^* = E_h^* (\text{depth scale factor}) \cos(\tan^{-1} dZ/dT). \quad (2)$$

In the equations above dZ/dT is the local first derivative of the analogue trace. Equations 1 and 2 apply for small E_h only.

Except for the regions near the top and bottom of the thermocline, the mean profile can be represented by three straight lines, one each in the mixed, thermocline, and deep layers. In Table 4 the slope, dZ/dT , in each of the three layers is approximated by

$$\Delta Z/\Delta T = ((\text{bottom depth} - \text{top depth}) / (\text{bottom temperature} - \text{top temperature})).$$

The average mixed layer depth is taken to be 60 m, and the bottom of the thermocline occurs, on the average, at a depth of about 220 m.

In Table 4 $(\Delta Z/\Delta T)_{\text{trace}}$ is the slope on the analogue trace corresponding to $\Delta Z/\Delta T$:

$$(\Delta Z/\Delta T)_{\text{trace}} = (\Delta Z/\Delta T) * (\text{temperature scale factor} / \text{depth scale factor}).$$

The angle in Figure 3 is given by

$$\Theta = \tan^{-1}((\Delta Z/\Delta T)_{\text{trace}}).$$

It can be seen from Table 4 and equations (1) and (2) that for a human inaccuracy of 0.5 mm the estimated expected depth error is about 0.3 m in the mixed layer, 1.7 m in the thermocline layer, and, approximately, 0.6 m in the deep layer. The estimated expected temperature error due to a human inaccuracy of 0.5 mm is about 0.1°C in the mixed and deep layers, and 0.05°C in the thermocline. An XBT has an instrumental accuracy of, approximately, $\pm 5 \text{ m} \pm 0.2^{\circ}\text{C}$ (Anderson, 1980). In comparison with XBT instrumental accuracy it is seen that the expected depth error in the mixed and deep layers and the expected temperature error in the thermocline due to a human inaccuracy of 0.5 mm are negligible. However the expected depth error in the thermocline and the expected temperature error in the mixed and deep layers make a small but possibly significant contribution to bathy message inaccuracy.

2.5 BATHY POINT TEMPERATURE AND DEPTH INACCURACIES

The 708 bathy message-XBT pairs were examined to determine the range of bathy point temperature and depth errors for all bathy points from the surface to a depth of 400 m. The XBT data set used in this comparison was interpolated to 5 m depth intervals. For each bathy point the difference between the temperature given by the bathy point and the temperature found by linear interpolation of the corresponding XBT to the depth of the bathy point was found. Any non-zero difference was termed an error. Depth errors were found for each bathy point by subtracting the depth given by the bathy point from the depth found by

linear interpolation of the corresponding XBT to the temperature given by the bathy point.

The results of temperature and depth comparisons reveal the overall poor quality of bathy message data from the Shuttle Experiment. Of the 7,694 bathy points examined for temperature differences, 1,061 (13.8%) had temperature differences exceeding 0.5 degrees Celsius. Of these, a total of 454 bathy points with temperature differences greater than 1°C were found. A total of 2,363 bathy points, or 30.7%, differed from the XBT temperature at the same depth by more than 0.2°C. Of the 7,674 bathy points analyzed, 3716 (46.3%) did not deviate from the calculated XBT temperature value by more than 0.1 degrees Celsius.

The results of the depth comparisons show that the number of significant depth differences is quite large. A substantial number, 1,188 of the 6,067 bathy points for which it was possible to calculate depth differences, had depth differences in excess of 10 m, and 574, or 9.5% of all depth differences examined exceeded 20 m. A total of 3,884 (64.0%) of the bathy points had depth differences of 5 m or less.

In conclusion a significant number of the bathy points examined gave temperatures which differed by more than 1.0°C from the temperatures found from the corresponding XBTs for the same depth. A substantial number of bathy points had depth differences greater than 20 m. On the basis of the above results it is concluded that, for any bathy point,

probability of the given temperature being incorrect by more than 0.5°C is 13.8% and the probability of the given depth having an inaccuracy greater than 10 m is 19.6%.

SECTION III DETECTION OF ERROR

3.1 DETECTION OF CODING AND TRANSMISSION ERROR

An effort was made to determine the source of the temperature errors found in the previous analysis. The temperature of each bathy point from the surface to the depth at which the message terminated was compared with the temperature value found by linearly interpolating the corresponding XBT at the depth of the bathy point. If the magnitude of this difference was greater than or equal to 1°C a check was made with the bathy log to determine whether the difference resulted from a coding inaccuracy.

Of the 708 stations which had both bathy messages and XBTs available, 282 stations were found to have a temperature difference of 1°C or more. A total of 494 temperature differences greater than 1°C were involved. This total includes, in addition to the 454 such points found previously, 40 points below 400 m.

The 528 matched bathy message-bathy log-XBT sets were examined to determine the source of these temperature differences. Of the 343 bathy points in this data set which were in error by more than 1°C , it was found that 46 resulted from transmission errors and 297 were the result of coding inaccuracies.

3.2 TRANSMISSION LOSSES

A total of 5,778 bathy points were recorded for the 528 stations for which bathy messages, radio logs, and matching XBTs were available. A check of the logs revealed that 208 points were lost in transmission. Thus only 96.4% of the points transmitted were received. Transmission losses affected 74 stations, or 14.0%. Frequently a transmission loss resulted in a truncated (short) message: transmission losses resulted in 31 bathy messages which did not reach a depth of 400 m (5.9% of all stations in the sample).

3.3 SHORT MESSAGES

The FNOG data were examined to determine the number of bathy messages which were complete to 400 m. Of the 708 bathy messages with paired XBTs, 100 were found to terminate at depths shallower than 400 m. All of the corresponding XBTs were complete to 400 m depth or more. Forty-five of these 100 bathys reached depths greater than 350 m, and 64 bathys recorded depths of 300 m or more. Eleven stations did not reach depths greater than 100 m.

The 528 stations from cruises 5-12 and cruise 14 which had matching XBTs, bathy messages, and logs were scrutinized to determine whether these short messages were the result of transmission errors or coding inaccuracies. Of 78 incomplete messages 37 were found to be the result of transmission error and 41 short messages were caused by coding error.

3.4 ERRORS IN POSITION AND TIME OF BATHY STATIONS

Statistics of the (XBT-BM) differences in position and time have been recorded in Table 5. The overall accuracy of the positions and times of stations, as received by FNOC, is fair. Six hundred seventy-nine of the 708 (97.6%) bathy messages examined recorded station times within 12 hours of the times recorded for the corresponding XBT's. Six hundred seventy of the 708 (94.6%) bathys reported the latitudes of their respective stations within 15' of the latitudes recorded for the XBTs. A total of 97.9% (693/708) of the longitudes given by bathy messages were correct. If it is assumed that space and time error statistics are independent then the joint probability that a bathy message gives the latitude and longitude to within 15' of the correct position and the time to within 12 hours is 90.1%.

Twelve bathy messages had time differences of 24 hours and one had a time difference of 48 hours. Twenty-four bathy messages had latitude errors and 8 had longitude errors of 1° or more. Cruise 13 alone accounted for 45.8% (11/24) of the latitude differences exceeding one degree.

Bathy message-XBT pairs for which bathy logs were available were examined to determine the source of errors and it was found that bathy message errors in position and time were predominantly the result of coding errors. Seventy-five percent (9/12) of the time errors greater than 12 hours, 70.0% (14/20) of all errors in latitude greater than

fifteen minutes, and 100% (14/14) of all longitude errors greater than fifteen minutes were the result of coding mistakes.

The correctness of the time and location of XBT stations recorded as bathy messages reported by the same ship can be checked using two criteria:

- (i) The difference in space between two stations divided by the difference in their respective times must be less than a reasonable maximum ship speed.
- (ii) Bathy messages sequential in space should also sequential in time.

The first criterion will, if a sufficiently large 'maximum ship speed' is chosen, give a determination with a high degree of certainty that an error has occurred. The second criterion assumes that a ship of opportunity will travel an approximately linear path in the open ocean. This assumption cannot always be valid. For example a ship traveling from west to east might suddenly veer north or even west to avoid a storm. The two criteria presented above allow a determination that an error may have occurred, but are not sufficient to determine absolutely that an error has occurred, or whether the possible error is a mistake in space or in time. Further it cannot always be known which of two sequential stations is the source of error.

XBT stations during the Tahiti Shuttle Experiment were, in general,

positioned 1.0° latitude apart. For a maximum ship speed of 12 knots (an arbitrary maximum ship speed for a research vessel) the minimum transit time between two consecutive stations separated a distance of 1.0° latitude is 5.0 hrs. The 707 BM-XBT pairs were scrutinized for time errors greater than 5.0 hours and space errors greater than or equal to 1.0° latitude. Criteria (i) and (ii) were applied to determine the detectability of these errors. The results are tabulated in Table 6. Fifteen of the 20 time errors greater than 5.0 hours (75%) were detectable (Table 6). Of 31 space errors greater than or equal to 1.0° latitude 19 (61.3%) were detectable.

A total of 10 space errors occurred because the sign of the latitude was incorrectly recorded on the bathy message. The respective dates, times, and longitudes of these stations were in logical sequence when compared with neighboring bathy messages. Thus it could have been determined from the bathy message information alone that the latitude was incorrect. If it is assumed that only one bit of information is the cause of the inaccuracy then the sign of the latitude is immediately suspect. Since changing the sign of the latitude allows these nine space errors to satisfy criteria (i) and (ii) it is concluded that these 9 errors are correctable. The tenth bathy message gave a latitude which, in addition to possessing the wrong sign, contained an error in magnitude. Thus, for this station, the detected error in latitude was found to be only partially correctable.

3.5 DETECTION OF INCORRECT BATHY POINTS

Detection of an error, regardless of its causes, requires that temperature or depth values exceed acceptable limits. Two methods of establishing these limits are:

- (i) from physical principles. To a first order the ocean is in hydrostatic balance. Coding and transmission errors may be detected if they result in physically unlikely temperature inversions.
- (ii) statistically. If an area of interest is rich in historical data acceptable limits may be set statistically.

The attractiveness of the first method is that incorrect bathy points are detected on physical grounds. A weakness of the second method is the assumption that the record is sufficiently complete to preclude the possibility that a bathy point falling outside of the maximum or minimum limits is, nonetheless, correct.

3.6 TEMPERATURE INVERSIONS IN THE NORPAX DATA

In order to determine realistic limits for physically plausible temperature inversions in the Central Equatorial Pacific, a study was made of the frequency of temperature inversions in the Shuttle XBT data. The depths at which temperature inversions began was examined

(Fig.4). Since the system temperature accuracy of an XBT is $\pm 0.2^{\circ}\text{C}$ (Anderson, 1980), a change in temperature of less than 0.2°C could be merely the result of XBT thermistor inaccuracy. In order to determine the temperature inversions which might be significant any increase in temperature of 0.1°C or more with increasing depth was noted. A maximum of 17 temperature inversions were observed to begin at the surface. Sixteen inversions began at a depth of 5 m. No more than 6 inversions were observed to begin at any single depth below 5 m. Eight of these temperature inversions involved a temperature increase of 0.50°C or more.

3.7 DETECTION OF ERROR BY TEMPERATURE INVERSION

Bathy messages were screened for temperature inversions of 0.5°C or more. A total of 38 were found. Visual inspection of the bathy message and XBT plots showed that 35 of the 38 'inversions' (92.1%) were caused by coding or transmission errors. One detected inversion was from an XBT which had been edited (truncated), suggesting that a physical error had occurred. If, as suspected, a physical error had occurred, then 36 of the 38 detected 'unlikely inversions' were indeed errors (94.7%). The two remaining inversions could not be positively identified as errors because inversions in the bathy record are consistent with inversions recorded by the XBT. Thus the possibility that these two temperature inversions are physical errors remains.

3.8 USEFULNESS OF THE TEMPERATURE INVERSION METHOD FOR BATHY ERROR DETECTION

At least 94.7% of all bathy message inversions of 0.5° C or more were determined to be errors, suggesting that an upper limit for temperature increases over increasing depth is a useful method of error detection. Reasonable limits must be set for the allowable ranges of inversion thickness and temperature increase with depth, but these limits can be taken to be sufficiently broad that they are only weakly dependent on the regional oceanography. This method succeeded in identifying 35 of the 494 bathy points (7.0%) deviating by 1° C or more from the corresponding XBT temperature at the same depth. Within the thermocline the temperature inversion test was successful in identifying 31.6% (24/76) of the bathy points whose temperatures were incorrect by more than 1° C. In the mixed and deep layers, 13.8% (11/80) of the bathy points with depths incorrect by more than 20 m were identified by this method. It is concluded that the temperature inversion test was partially successful in detecting bathy temperature differences in the thermocline.

3.9 A METHOD OF STATISTICAL DETECTION OF ERROR

Since 93% of the bathy points in error by 1° C or more could not be identified as unlikely temperature inversions, an attempt was made to determine whether upper and lower limits of temperatures at fixed depths, determined statistically from the regional data base, could be

established. To this end a review of the physical oceanography of the area was conducted.

3.10 THE MEAN PICTURE OF THE THERMAL STRUCTURE

The physical oceanography of the transequatorial region is well known and has been described previously (Wyrтки et al., 1977). The thermocline (13° to 25° C) is strongly developed between 5° S and 15° N. Poleward of 5° S and 15° N the isotherms spread increasingly apart. Ridges in the thermal structure at the equator and at 10° N and a trough at 5° N are associated with the geostrophic flows of the northern portion of the South Equatorial Current (0° to 5° N) and the eastward flowing North Equatorial Countercurrent (5° to 10° N). From 10° N to 20° N the downward sloping isotherms of the thermocline are associated with the North Equatorial Current. South of 5° S the isotherms of the thermocline slope downwards away from the equator in association with the South Equatorial Current. At the equator the Equatorial Undercurrent is characterized by a spreading of the isotherms.

3.11 THE LONG TERM VARIABILITY

The mean picture of the thermal structure of the transequatorial region, described above, is subject to great variation (Wyrтки et al., 1977). Occasionally the trough in the thermocline associated with the Countercurrent disappears altogether and the isotherms rise from

the southern hemisphere to the thermocline ridge near 10° N. At such a time the Countercurrent extends to the equator and the South Equatorial Current retreats into the southern hemisphere. At other times the ridge in the thermocline at 10° N subsides and the Countercurrent almost disappears. Infrequently the entire equatorial region may be covered with a layer of warm (29° C) water. The North Equatorial Current may split into branches and frequently contains eddies. Embedded in the westward flowing South Equatorial Current is occasionally found the eastward flowing South Equatorial Countercurrent. The northern portion of the South Equatorial Current is quite variable, responding to variations in the strength of the Southeast Trades and to lateral shifts of the North Equatorial Countercurrent.

3.12 SHORT TERM VARIABILITY

Short term variability of the thermal structure is revealed by AXBT transequatorial sections (Patzert et al., 1978). Depths of the 14° C and 18° C isotherms can vary by 25 m and more in two days. Spectral analysis of NODC data (Wyrtki et al., 1977) for the depths of the 18° C isotherm shows that energy was concentrated at a period of 4.5 days and a mean amplitude of 14 m. Time series of the eighteen degree isotherm also show fluctuations at the frequency of semi-diurnal tides with amplitudes of 5 m.

3.13 THE RESULTS OF STATISTICAL DETECTION OF ERROR

Because the transequatorial thermal structure shows great variability on time scales of days, seasons, and years, attempts at error detection based on deviation from some observed mean will achieve only limited success. Nonetheless an effort was made to detect bathy errors by determining the bathy points which fell outside of the observed maximum-minimum temperature envelope (Fig. 1) by 0.5° C. A total of seventeen such points were found. Nine of these points caused temperature differences of more than 1° C in the thermocline, and six points caused depth differences greater than 20 meters in the deep and mixed layers. Of these seventeen points found by statistical detection eight had already been detected by the 'unlikely temperature inversion test' discussed above. Thus a total of nine new errors were revealed.

3.14 CONCLUSION

Of the 80 points within the thermocline which had XBT-BM depth differences of more than 20 m, 16 (20%) were detected (11 by the inversion test and 7 by the statistical test). Of 76 points above or below the thermocline which had temperature differences (XBT-BM) greater than 1° C, 24 (31.6%) were detected.

Overall, a total of 45 of 494 (9.1%) incorrect bathy points known to be in error by 1° C or more were successfully detected from statistical and physical considerations. It is doubtful that more errors could be efficiently detected since increased restrictions in the limits of

allowable temperature ranges at fixed depth, allowable temperature inversion thicknesses, or ranges of temperature increase with depth would result in elimination of many good bathy points as well as further detection of bathy error.

It is concluded, based on the 708 XBT-BM pairs from the Tahiti Shuttle Experiment, that, for any given bathy message, there is a 90.5% (641 of 708 stations) probability that the depth values of all bathy points within the thermocline do not contain errors greater than 20 m, and that there is a 89.8% (636 of 708 stations) probability that all bathy points in the deep and mixed layers are correct to within 1°C.

SECTION IV PROPAGATION OF ERRORS IN BATHY PRODUCTS

4.1 HEAT STORAGE CALCULATIONS

Heat storage H in the upper 400 m was computed for the 605 matched bathy message-XBT pairs that extended to depths of 400 m or more:

$$H = \int_0^{400} Tdz$$

It can be seen that the difference (XBT-BM) in H (Table 7) also represents the sum of the temperature differences between each bathy message and corresponding XBT.

The difference in the resulting calculations of H between the two data sets was found to vary greatly between cruises. Cruise 14 showed the greatest mean difference, 102.1°C m. Cruise 5 had the smallest (absolute value) mean difference, 0.8°C m. Seven of the twelve cruises had mean differences greater than zero. The absolute value of the difference in H was less than 50°C m for 54.0% (327/605) of the stations examined (Table 7). For 79.2% (479/605) of the bathy message-XBT pairs the absolute value of the difference in H was 100 °C m or less. Typically, a value of H computed from a Shuttle XBT might be between 5000°C m and 7000°C m. If it is assumed that 2000°C m represents a characteristic value for the range of H values in the Central Equatorial Pacific, then an accuracy of $\pm 100^\circ\text{C m}$ represents an accuracy of about 5% of the range of H values.

The standard deviation of differences in H was also determined for each

cruise. The largest standard deviation, 178.2°C m , was recorded for Cruise 14 and the smallest, 32.3°C m , was recorded for Cruise 4. For 7 of the 12 cruises examined the standard deviation of differences in H were greater than 100°C m .

Since more than 79% of the H values calculated from the 708 bathy messages examined were within 100°C m of the H values calculated from the corresponding XBTs, 100°C m might be considered to be the typical inaccuracy of an H value determined from a bathy message. A difference of 100°C m represents, approximately, a difference of 10 Kcal cm^{-2} .

4.2 DIFFERENCE IN DYNAMIC HEIGHT COMPUTATIONS

Computation of dynamic height using a temperature-salinity relationship to determine density ($\sigma\text{-t}$) has been described by other authors (Emery, 1975; Wyrski, 1978). The temperature-salinity relationship used in the following computations of $\sigma\text{-t}$ was established from all available data between 145°W and 165°W for intervals of 5° latitude between 20°N and 20°S . In each of these intervals the salinity was specified at 0.2°C temperature intervals.

Dynamic height at the surface relative to 400 m was calculated for each bathy message-XBT pair extending to at least 400 m depth (605 total). The data sets used in this computation were interpolated to give temperature values at 5 m depth intervals. The computations (NODC User's Manual, 1974) proceeded by first determining the specific volume anomaly (δ)

$$\delta = \zeta_{s,t,p} - \zeta_{35,0,p}$$

and then computing the dynamic depth anomaly (D)

$$D = \sum_{i=1}^{91} 1/2(\delta_{i-1} + \delta_i) dp_i$$

$$dp = p_i - p_{i-1}$$

Dynamic height of the surface relative to 400 m is simply the dynamic depth anomaly at 400 m.

The distribution of differences (XBT-BM) of dynamic height at the surface relative to 400 m is centered near zero for cruises 4 through 12 (Table 8). The means of the differences in dynamic height for cruises 13 through 15 are about 15 dyn mm. The dynamic heights computed from the bathy messages tended to be lower than the corresponding XBT dynamic heights: 61% (369/605) of the differences in dynamic height (XBT - BM) were positive. Of the 605 (90.7%) dynamic height differences examined 549 were within 40 dyn mm of zero. A total of 523 (86.4%) of the differences were within 30 dyn mm of the origin, and 74.7% (452/605) were within 20 dyn mm of zero. Almost half (289) of the dynamic height differences (absolute values) were 10 dyn mm or less. Typical values of dynamic height at the surface relative to 400 m computed from Shuttle XBTs ranged between 800 and 1200 dyn mm. The change in dynamic height at the surface relative to 400 m observed in the Shuttle data over a distance of 1 degree of latitude was, usually, between 3 and 100 dyn mm. If 100 dyn mm is taken as a characteristic value of the change in dynamic height at the surface relative to 400 m

across a typical current, an accuracy of ± 20 dyn mm represents 20% of a typical value.

The standard deviation of the differences in dynamic height were calculated. Cruises 13 had the highest standard deviation of 51.2 dyn mm. All other cruises had standard deviations of less than 40 dyn mm.

4.3 COMPUTATION OF GEOSTROPHIC VELOCITIES

Geostrophic velocities resulting from differences in dynamic height are given by

$$u = -1/f \Delta D / \Delta Y$$

$$v = 1/f \Delta D / \Delta X$$

where ΔD is the difference in dynamic height between two stations, and ΔX is the difference in space between the two stations.

If 20 dyn mm is taken as the typical inaccuracy of a dynamic height computed from a bathy message then the resultant inaccuracy in a determination of geostrophic flow from two bathy messages is 8.8 cm sec⁻¹ at 3° latitude, 2.6 cm sec⁻¹ at 10° latitude, and 1.3 cm sec⁻¹ at 20° latitude.

SECTION 7 CONCLUSION

The overall quality of the bathy messages examined was poor. A substantial number (13.8%) of the bathy points were incorrect by more than 0.5°C . Only 30.7% of the points were within 0.2°C of the correct temperature. A significant number of points (9.5%) gave depth values incorrect by more than twenty meters, and 19.6% of all points were incorrect by at least ten meters. Of 708 stations examined 282 contained at least one bathy point in error by more than 1°C . A total of 494 such points were involved.

Coding errors were the primary cause of bathy message inaccuracies. Most (251/297) of the points in error by more than 1°C for which bathy logs were available were the result of coding errors. Coding errors were also responsible for most of the errors in position and time. Seventy-five percent (9/12) of the station times incorrect by more than twelve hours resulted from coding inaccuracies. Seventy percent (14/20) of the errors in latitude and 100% (14/14) of the errors in longitude greater than fifteen minutes were due to coding mistakes.

The two methods developed to detect errors were partially successful. In the thermocline, 32.4% (11/34) of the depth errors greater than 40 meters and 55.6% (5/9) of the depth errors greater than 100 meters were detected. Twenty percent (16/80) of the depth errors in the thermocline greater than 20 meters were found by these two methods. In the deep and mixed layers 31.6% (24/76) of the temperature errors greater than 1°C were detectable.

Despite the inaccuracies in the bathy message data set, bathy messages may be useful for crude estimates of geostrophic velocities. Of the 605 dynamic heights computed from bathy messages 549 differed from the dynamic height values for the corresponding XBTs by less than 40 dynamic millimeters. A total of 452 (74.7%) of the differences in dynamic heights were less than 20 dynamic millimeters. If 20 dynamic millimeters is taken as a typical inaccuracy in dynamic height computed from a bathy message, then the resulting inaccuracy in a computation of geostrophic flow is 8.8 cm s^{-1} at 3 degrees latitude, 2.6 cm s^{-1} at 10 degrees latitude, and 1.3 cm s^{-1} at 20 degrees latitude.

Bathy messages may be useful for heat storage computations when the magnitude of changes in heat storage are large. A total of 54.0% (327/605) of the bathy messages gave heat storage values differing from the corresponding XBTs by less than 50°C m and 79.2% (479/605) of the heat storage values computed from bathy messages were within 100°C m of the values determined from the respective XBTs.

REFERENCES

1. Anderson, E. R., Expendable Bathythermograph (XBT) Accuracy Studies, NOSC Technical Rep. 550, June 15, 1980.
2. Emery, W. J., Dynamic Height from Temperature Profiles, J. Phys. Oceanogr., 5, 369-375, 1975.
3. Firing, E., C. Fernander, J. Miller, Profiling Current Measurements From The Norpax Hawaii To Tahiti Shuttle Experiment, Hawaii Inst. Geophys. Rep. HIG-81-2, 1981.
4. Huber, K., Quality control procedures applied to IGOSS data at the Specialized Control Centre, FRG. Intergovernmental Oceanic Commission report no. 17 - supplement, 1979.
5. Integrated Global Ocean Station System Guide on Operational Instructions for the Reporting of Oceanographic Data (draft). IOC/Inf-398. UNESCO, October 1979.
6. Key to Oceanographic Records Documentation No. 1, User's Guide To NODC's Data Services, National Ocean and Atmospheric Administration, U.S. Department of Commerce, February, 1974.

7. Patzert, W. et al., AXBT Observations of Tropical Pacific Ocean Thermal Structure During the Hawaii/Tahiti Shuttle Experiment November 1977 to February 1978, SIO Ref. Series 78-24, September, 1978.
8. Scarsborough, J. B., Numerical Methods of Mathematical Analysis, 6th ed. Baltimore, Johns Hopkins Press, 1966.
9. Wyrтки, K. et al., Variability of the Thermal Structure in the Central Equatorial Pacific Ocean, Hawaii Inst. Geophys. Rep. HIG 77-1, 75 p, January, 1977.
10. Wyrтки, K., Monitoring The Strength of Equatorial Currents From XBT Sections and Sea Level, J. Geophys. Res., 83, 1935-1940, 1978.
11. Wyrтки, K., E. Firing, D. Halpern, R. Knox, G. J. McNally, W. C. Patzert, E. D. Stroup, B. A. Taft, R. Williams, The Hawaii to Tahiti Shuttle Experiment, Science, 211, 22-28, 1981.

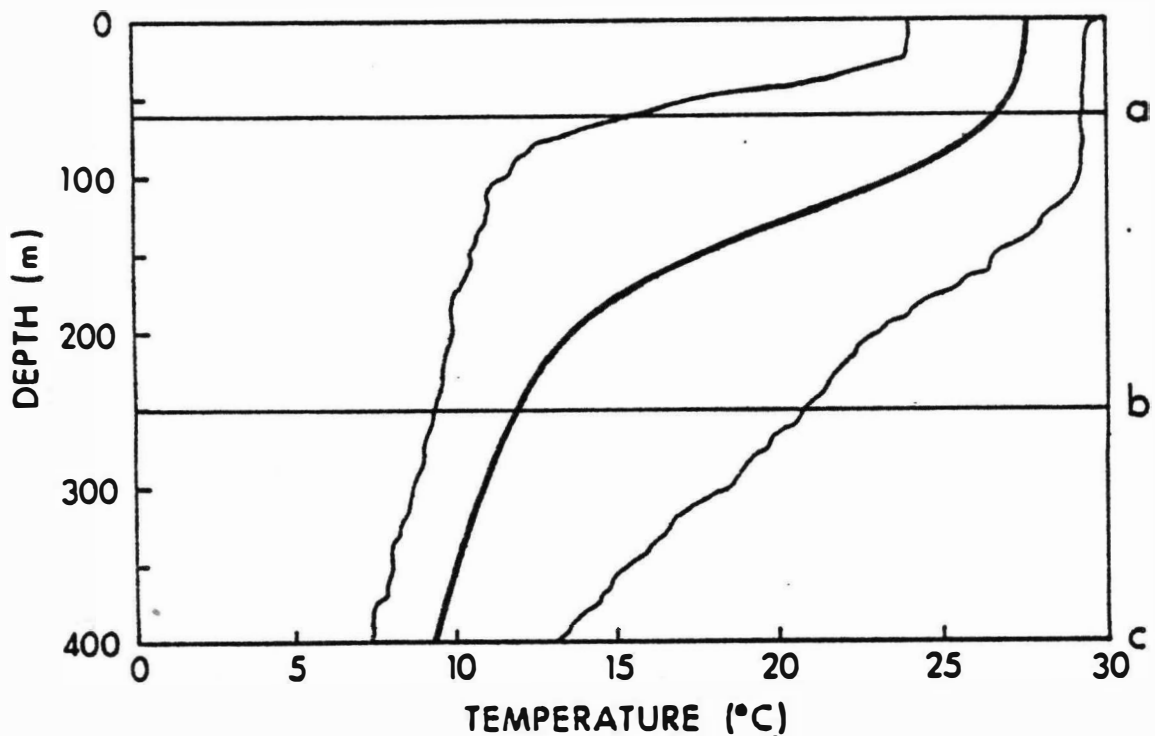


Figure 1. The mean temperature-depth profile compiled from 1061 Shuttle XBTs. Also shown are profiles composed of the maximum and minimum observed values. Line (a) indicates the depth of the top of the thermocline chosen for analysis. Line (b) indicates the depth chosen to represent the bottom of the thermocline, and (c) shows the depth at which analysis of error in the deep layer terminated.

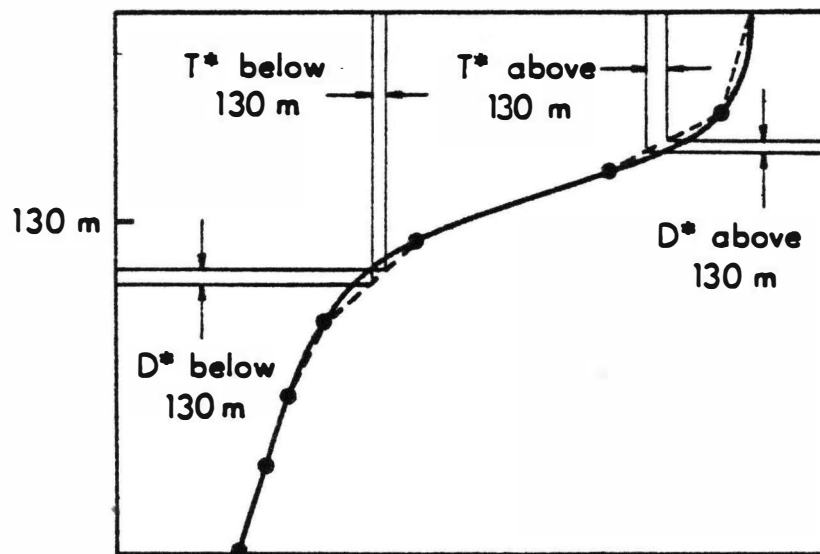


Figure 2. An illustration of the error resulting from the use of a finite number of points to define an XBT analog temperature-depth trace.

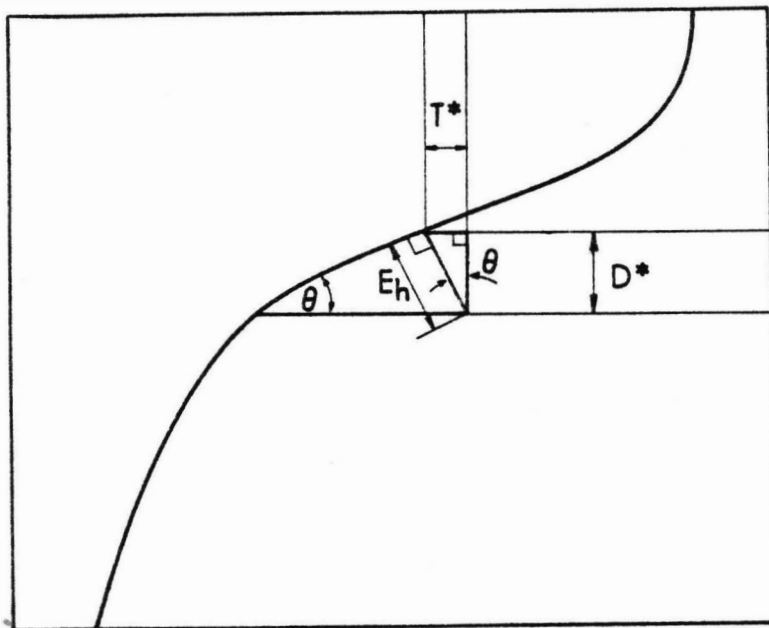


Figure 3. The error in depth, D^* , and the error in temperature, T^* , due to a human error, E_h , is shown.

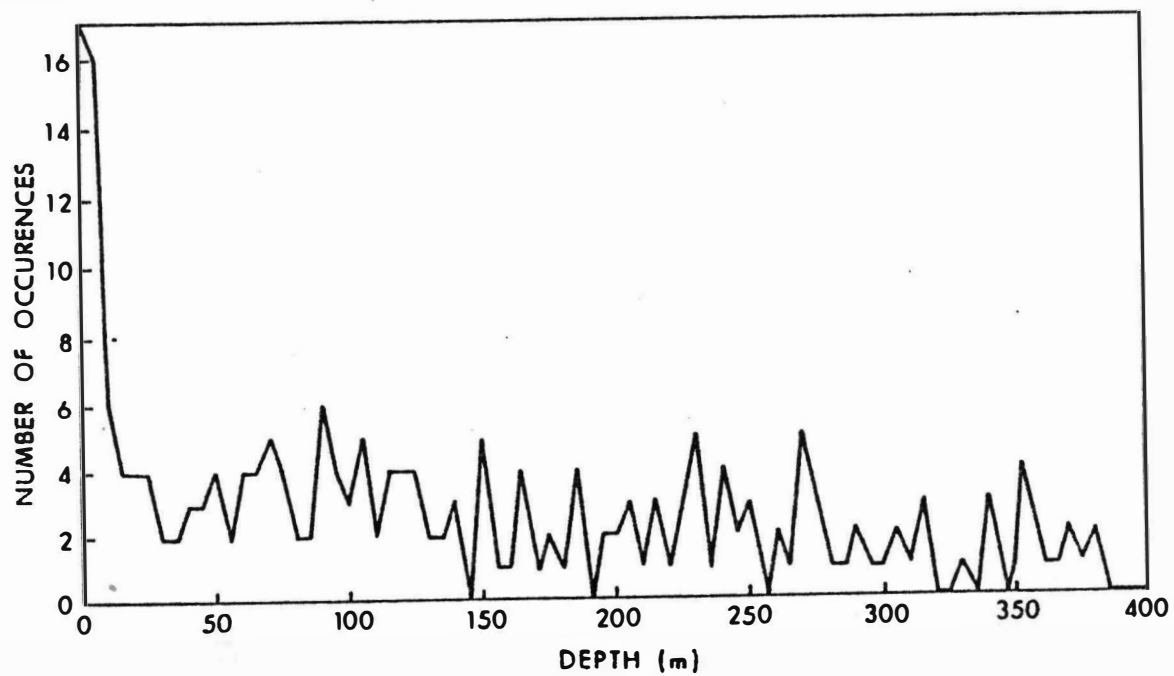


Figure 4. A histogram of depths, to the nearest 5 m, at which temperature inversions begin (compiled for 1061 Shuttle XBTs). Only temperature increases of 0.1°C or more with increasing depth are indicated.

Table 1. The distribution of the means of temperature differences (\bar{X}_{BT-BM}) at 5 m depth intervals within the thermocline layer at each station, compiled for 708 stations.

cruise interval	4	5	6	7	8	9	10	11	12	13	14	15	total
$\bar{X} \leq -2.0$					2		2	2		1	2		9
$-2.0 < \bar{X} \leq -1.8$												1	1
$-1.8 < \bar{X} \leq -1.6$					1				1		1		3
$-1.6 < \bar{X} \leq -1.4$					1	1		1					3
$-1.4 < \bar{X} \leq -1.2$					2		1		1	1			5
$-1.2 < \bar{X} \leq -1.0$					1	2		1	1		1		6
$-1.0 < \bar{X} \leq -0.8$		1	1	1	2			1		1			7
$-0.8 < \bar{X} \leq -0.6$		1	1				2	2	3	1	1	1	12
$-0.6 < \bar{X} \leq -0.4$	2	1	1	3	1	1	3	2	6	1	4	1	26
$-0.4 < \bar{X} \leq -0.2$	3		4	11	6	7	14	8	8	1	1	1	64
$-0.2 < \bar{X} \leq 0.0$	16	6	14	27	16	19	23	22	19	9	8	7	186
$0.0 < \bar{X} \leq 0.2$	15	12	13	16	18	24	7	14	12	13	9	17	170
$0.2 < \bar{X} \leq 0.4$	7	5	8	2	12	5	7	1	15	16	10	16	104
$0.4 < \bar{X} \leq 0.6$	1		1	1	2	5		5	7	6	3	9	40
$0.6 < \bar{X} \leq 0.8$	1		3	2	1				3	5	4	2	21
$0.8 < \bar{X} \leq 1.0$				1		1			1	3	4	4	14
$1.0 < \bar{X} \leq 1.2$			1		1		1	1			3	1	8
$1.2 < \bar{X} \leq 1.4$		1				1		1		3	2	2	10
$1.4 < \bar{X} \leq 1.6$										3	4		7
$1.6 < \bar{X} \leq 1.8$										1	2		3
$1.8 < \bar{X} \leq 2.0$									1	1	1		3
$\bar{X} > 2.0$						1		1	1		2	1	6
total number of stations considered	45	27	47	64	66	67	60	62	79	66	62	63	708

Table 2. The distribution of the means of temperature differences (XBT-BM) at 5 m intervals within the mixed layer at each station compiled for 708 stations.

cruise \ interval	4	5	6	7	8	9	10	11	12	13	14	15	total
$X \leq -2.0$								1					1
$-2.0 < X \leq -1.8$													
$-1.8 < X \leq -1.6$													
$-1.6 < X \leq -1.4$													
$-1.4 < X \leq -1.2$													
$-1.2 < X \leq -1.0$								1					1
$-1.0 < X \leq -0.8$			1							1			2
$-0.8 < X \leq -0.6$		1							1				2
$-0.6 < X \leq -0.4$				2				1	1	1		2	7
$-0.4 < X \leq -0.2$		2	1	8		2	3	14	3		1	1	36
$-0.2 < X \leq 0.0$	31	5	7	28	7	37	24	27	34	8	11	22	241
$0.0 < X \leq 0.2$	11	18	33	18	39	21	20	9	32	37	27	31	296
$0.2 < X \leq 0.4$	3		4	4	12	4	9	2	5	10	14	7	74
$0.4 < X \leq 0.6$		1	1	1	2	1		2		3	1	1	13
$0.6 < X \leq 0.8$					1	1	1	2	1	1	3	1	11
$0.8 < X \leq 1.0$				1	2			1	1	3	1		9
$1.0 < X \leq 1.2$					1		1			2			4
$1.2 < X \leq 1.4$								2					2
$1.4 < X \leq 1.6$					1						1		2
$1.6 < X \leq 1.8$							1						1
$1.8 < X \leq 2.0$				2	1	1					1		6
$X > 2.0$									1		1		6
total number of stations considered	45	27	47	64	66	67	60	62	79	66	62	63	708

Table 3. The distribution of the means of temperature differences (XBT-BM) in degrees centigrade at 5 m intervals within the deep layer, compiled for the 653 stations. Only stations with bathy messages complete to 250 m depth or deeper were considered.

cruise \ interval	4	5	6	7	8	9	10	11	12	13	14	15	total
$\bar{x} \leq -2.0$					1	2			1				4
$-2.0 < \bar{x} \leq -1.8$													
$-1.8 < \bar{x} \leq -1.6$								1			2		3
$-1.6 < \bar{x} \leq -1.4$						1							1
$-1.4 < \bar{x} \leq -1.2$					1			1		1			3
$-1.2 < \bar{x} \leq -1.0$					1								1
$-1.0 < \bar{x} \leq -0.8$		1						2			1		4
$-0.8 < \bar{x} \leq -0.6$						3	1				1	1	6
$-0.6 < \bar{x} \leq -0.4$			1	1	1		1	2	5			1	12
$-0.4 < \bar{x} \leq -0.2$	1	3	2	2	4	3	3	9	10	6	2	3	48
$-0.2 < \bar{x} \leq 0.0$	21	7	14	21	16	27	32	29	21	10	16	32	246
$0.0 < \bar{x} \leq 0.2$	11	5	17	14	27	26	18	15	33	39	28	18	251
$0.2 < \bar{x} \leq 0.4$		1	2	2	4	4	2	1	8	8	8	2	42
$0.4 < \bar{x} \leq 0.6$			1	1	2		1			2	2	1	10
$0.6 < \bar{x} \leq 0.8$		1	1	1		1	2	2			1	2	11
$0.8 < \bar{x} \leq 1.0$			4						1		1		6
$1.0 < \bar{x} \leq 1.2$			1										1
$1.2 < \bar{x} \leq 1.4$			1										1
$1.4 < \bar{x} \leq 1.6$													
$1.6 < \bar{x} \leq 1.8$			1										1
$1.8 < \bar{x} \leq 2.0$													
$\bar{x} > 2.0$			1		1								2
total number of stations considered	33	18	46	42	58	67	60	62	79	66	62	60	653

Table 4. The estimated expected error due to a human error of 0.5 mm in the three layers: mixed, thermocline, and deep.

layer	bottom depth	bottom temperature	top depth	top temperature	$\frac{\Delta z}{\Delta T}$	$\left(\frac{\Delta z}{\Delta T}\right)_{\text{trace}}$	θ	$\sin\theta$	$\cos\theta$	depth error	temperature error
mixed	50 m	27.2 ^o C	0 m	27.6 ^o C	$\frac{-50}{0.4}$	$\frac{-13}{2}$	81.3	0.99	0.15	0.29 m	0.10 ^o C
thermo- cline	190 m	14.3 ^o C	80 m	25.5 ^o C	$\frac{-110}{11.2}$	$\frac{-29}{56}$	27.4	0.46	0.89	1.69 m	0.05 ^o C
deep	380 m	9.7 ^o C	240 m	12.4 ^o C	$\frac{-140}{2.7}$	$\frac{-38}{13.5}$	70.4	0.94	0.34	0.63 m	0.09 ^o C

Table 5. The number of time and space errors out of a total of 708 bathy message-XBT pairs. The errors of the 528 bathy message/bathy log/XBT matched sets are classified as coding (C) or transmission (T) errors. '*' indicates that the bathy logs were not available.

cruise	number of time errors ≥ 24 hr	number of time errors > 12 hr	number of time errors > 12 hr due to		number of space errors $> 1^{\circ}$		number of space errors $> 0.5^{\circ}$		lat. errors $> 15'$ due to		total number of lat. errors $> 15'$	number of long. errors $> 15'$ due to		total number of long. errors $> 15'$
			C	T	lat.	long.	lat.	long.	C	T		C	T	
4	2	2	*	*	0	0	0	0	*	*	0	*	*	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	4	4	4	0	0	0	2	0	3	0	3	0	0	0
7	0	1	1	0	0	0	0	1	0	0	0	1	0	1
8	2	4	1	3	4	3	5	6	3	4	7	5	0	5
9	0	0	0	*	2	0	2	0	1	1	2	2	0	2
10	0	0	0	*	1	2	2	3	2	0	2	3	0	3
11	3	3	3	*	1	1	3	2	3	0	3	2	0	2
12	0	0	0	*	1	1	2	0	1	1	2	0	0	0
13	2	3	*	*	11	1	11	1	*	*	14	*	*	1
14	0	0	0	0	1	0	0	1	1	0	1	1	0	1
15	0	0	*	*	3	0	3	0	*	*	4	*	*	0
total	13	17	9	3	24	7	30	14	14	6	38	14	0	15

Table 6. The number of detectable time errors and correctable and detectable space errors out of a total of 708 bathy messages examined.

cruise	number of time errors ≥ 5 hr	number of detectable time errors ≥ 5 hr	number of space errors $\geq 1.0^{\circ}$	number of detectable space errors $\geq 1.0^{\circ}$	number of detectable and correctable space errors $\geq 1.0^{\circ}$
4	2	2	0	0	0
5	0	0	0	0	0
6	4	4	0	0	0
7	1	1	0	0	0
8	4	2	7	5	1
9	1	1	2	2	2
10	1	1	3	1	0
11	3	1	2	2	0
12	1	0	1	0	0
13	3	3	12	8	5
14	0	0	1	0	0
15	0	0	3	1	1
total	20	15	31	19	9

Table 7. The distribution of differences (XBT-BM) in heat storage H from the surface to 400 m compiled for 605 stations.

cruise interval	4	5	6	7	8	9	10	11	12	13	14	15	total
H < -200													
-200 ≤ H < -190					1			1					2
-190 ≤ H < -180							1						1
-180 ≤ H < -170													
-170 ≤ H < -160					1								1
-160 ≤ H < -150													
-150 ≤ H < -140				1									1
-140 ≤ H < -130						2			1			1	4
-130 ≤ H < -120			1		1								2
-120 ≤ H < -110							1	1					2
-110 ≤ H < -100	1			2	1								4
-100 ≤ H < -90	1	1	1				2	2	2				9
-90 ≤ H < -80				2		1		2	2	1			8
-80 ≤ H < -70			1		1		1	4	3			1	11
-70 ≤ H < -60			1	1	1	2	3	1	1			1	11
-60 ≤ H < -50	2		2	2			1	4	4		1	3	19
-50 ≤ H < -40	4	1	1	2	2	4	5	3	3		2		27
-40 ≤ H < -30	4		2	2	3	3	5	6	7	1	3	1	34
-30 ≤ H < -20	3	1	1	2	2	3	1	4	1	3	1	1	23
-20 ≤ H < -10	2	4	2	3	1	7	4	3	6	1	1		34
-10 ≤ H < 0	7		2	5	2	5	6	5	1	1	2	3	39
0 ≤ H < 10	1	1	2	6	2	4	4	2	4		1	2	29
10 ≤ H < 20	4	2	5	4	8	6	1	2	3	3	2	4	44
20 ≤ H < 30	2	1	3	2	5	6	4	2	3	5	2	8	43
30 ≤ H < 40	1	1	1	2	4	2	4	2	4	4	1	5	31
40 ≤ H < 50			3	2	2	3			2	4	3	3	23
50 ≤ H < 60	3	1	1		4	3	1		3	4	2	4	26
60 ≤ H < 70					2	2	1	1	2	6	6	2	22
70 ≤ H < 80			2	1	4	1		1	7	4	3	1	24
80 ≤ H < 90			1		2	1	1		2	1		2	10
90 ≤ H < 100			1		1		1		1	3	1	4	12
100 ≤ H < 110			1		2				2	1		5	11
110 ≤ H < 120			2					2	1		2	1	8
120 ≤ H < 130			1		1	1			1	3	2	1	10
130 ≤ H < 140					1					1	1	1	4
140 ≤ H < 150				1					1	1	4		7
150 ≤ H < 160						1	1			3	1	1	7
160 ≤ H < 170		1	1					1			1		4
170 ≤ H < 180			2						1				3
180 ≤ H < 190								1		2	1		4
190 ≤ H < 200								1		1	2	1	5
H ≥ 200	2	5	1	6	2	3	4	5	6	8	4		46
no. stations considered	33	17	46	42	58	59	50	55	73	59	53	60	605

Table 8. The distribution of the differences (XBT-BM) in dynamic depth anomaly, X, in dynamic millimeters at 400 m compiled for 605 stations.

interval	4	5	6	7	8	9	10	11	12	13	14	15	total
X < -100			1		1			1	1				4
-100 ≤ X < -95								1					1
-95 ≤ X < -90													
-90 ≤ X < -85					1								1
-85 ≤ X < -80								1					1
-80 ≤ X < -75													
-75 ≤ X < -70									1		1		2
-70 ≤ X < -65													
-65 ≤ X < -60						1							1
-60 ≤ X < -55							1	1					2
-55 ≤ X < -50								1			1		2
-50 ≤ X < -45										1			1
-45 ≤ X < -40					1		1		1				3
-40 ≤ X < -35		1										1	2
-35 ≤ X < -30		1			1	1		1					4
-30 ≤ X < -25			1	2	1		1						5
-25 ≤ X < -20		1		2	2	1		3	3			1	13
-20 ≤ X < -15			2	2	3	1	3	5	6				24
-15 ≤ X < -10	2		4	6	2	2	7	4	8	1	1	3	40
-10 ≤ X < -5	9	2	2	3	1	7	6	12	6		4	2	54
-5 ≤ X < 0	11	1	6	6	4	15	8	7	8	3	3	5	77
0 ≤ X < 5	4	7	2	12	7	9	7	5	9	6	5	8	81
5 ≤ X < 10	3	2	9	3	11	9	7	5	6	6	3	13	77
10 ≤ X < 15	4		5	2	7	6	4	1	9	9	9	6	61
15 ≤ X < 20			1	2	5	3	3	1	5	8	5	4	37
20 ≤ X < 25				5	2	2		1	3	3	1	8	25
25 ≤ X < 30			4	1	6		1	4	3	5	4	1	29
30 ≤ X < 35		1						1	2	5	4	1	14
35 ≤ X < 40			2			1					2	1	6
40 ≤ X < 45			1		1		1			2	3	1	9
45 ≤ X < 50		1	1		1					2		1	6
50 ≤ X < 55											2	1	3
55 ≤ X < 60										1	1	1	3
60 ≤ X < 65													
65 ≤ X < 70								1	1			1	3
70 ≤ X < 75						1				1	1	1	4
75 ≤ X < 80								1					1
80 ≤ X < 85													
85 ≤ X < 90													
90 ≤ X < 95													
95 ≤ X < 100									1				1
X ≥ 100				1	1					5	1		8
no. stations considered	33	17	46	42	58	59	50	57	73	59	51	60	605