THE MATTHEWS TABLES — 35 YEARS LATER

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Echo Sounders measure the time for a sound wave to travel from the ship's transducer to the ocean floor, and utilizing a constant for the speed of sound (usually 1 463 m/sec in the Pacific Ocean) express the product of the travel time and the speed as water depth. Because of local variations in the sound speed, depth errors from — 2 to 400 m can occur in the Pacific (figure 1). This problem was recognized by HECK and SERVICE of the U.S. Coast and Geodetic Survey upon examining their data from a prototype echo sounder in 1923. With the help of G. W. MCEWEN of Scripps Institution of Oceanography, they developed tables (HECK and SERVICE, 1924) for computation of sound speed from measurements of the temperature-salinity structure of the ocean. These computations were based on Newton's theoretical equation relating sound speed to the elasticity and density of the medium. In the case of sea water, these properties are functions of temperature, salinity and pressure.

HECK and SERVICE (*op. cit.*) speculated that areas of the ocean could be found with similar sound speed structure, thereby reducing the burden of frequent temperature-salinity measurements in support of echo sounding. The Matthews Tables (1939), currently in use for deep sea echo sounding corrections, are based on this concept. Using the oceanographic station data available at the time, MATTHEWS divided the world ocean into 52 classes of acoustic structure. For each of these classes he prepared a table of corrections versus depth which in effect express the departure of the local, vertically integrated sound speed from the sound speed "used" by the echo sounder (e. g. 1 463 m/s). His tables include maps which show the geographic areas where the 52 tables are applicable.

In addition to these echo sounding correction (hereafter abbreviated "correctors") tables, MATTHEWS also presented tables for the determination of sound speed as a function of temperature, salinity and depth. The latter tables of course are basic to the preparation of the correctors. For the sound speed tables, MATTHEWS also used the Newtonian equation, and he, as had HECK and SERVICE, pointed out the weakness of the water compressibility data, necessary for the practical application of Newton's equation. MATTHEWS estimated that his sound speeds were accurate to within about

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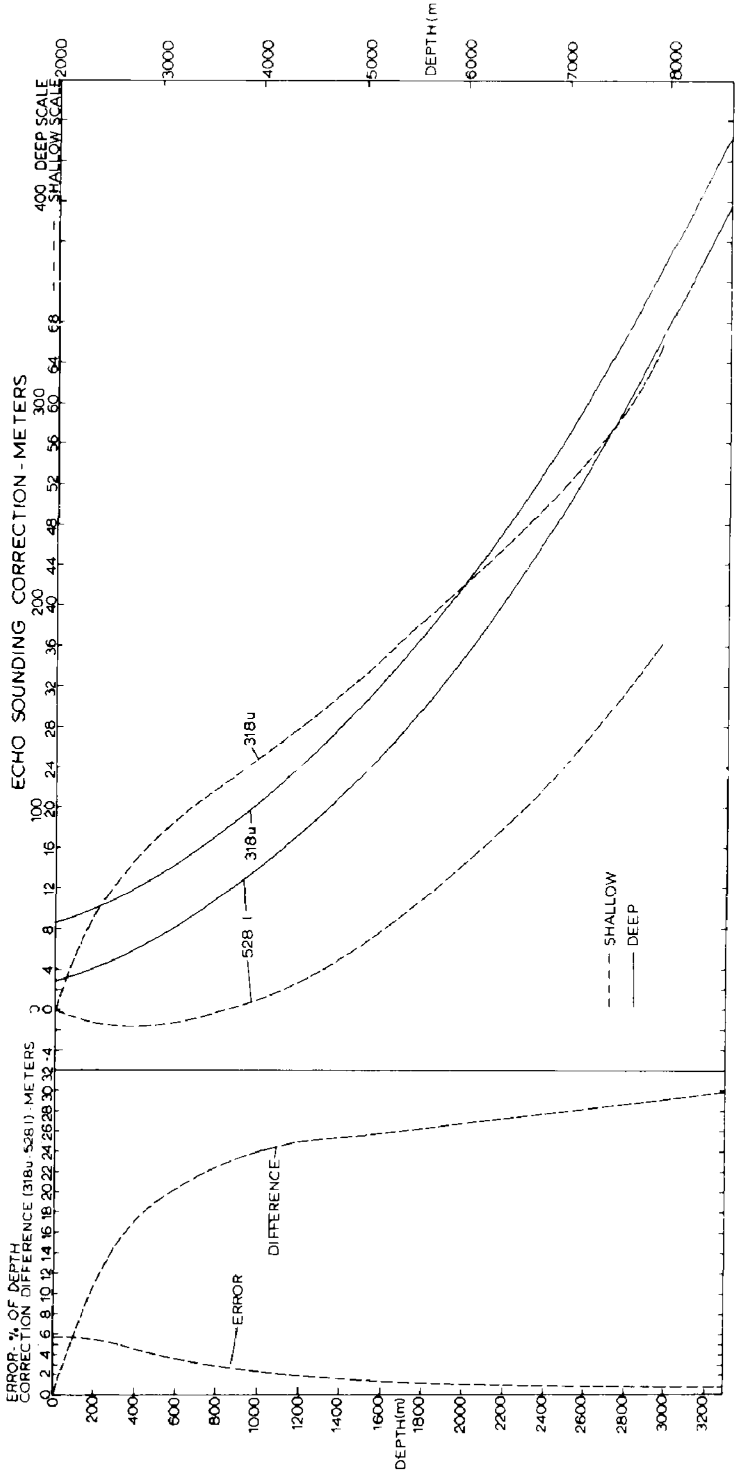


FIG. 1. — **Right** : Echo Sounding Corrections plotted versus depth, required in two areas (318 u and 528 l) of the Pacific to compensate for local departures in sound velocity from the instrument constant, 1 463 m/sec.

Left : The magnitude of depth error (in metres and in % of depth) if one misapplied the correction data for the two areas. These two areas are representative of the approximate extremes in echo sounding conditions in the Pacific. Area 318 u is bounded by 5°-10° S 170°-180° E; area 528 l is bounded by 60°-65° S, 120°-130° W.

0.1 %, but recommended that direct measurements be made to verify his results. Thus the validity of the Matthews Tables is therefore dependent on two major factors. Of primary importance was his solution to the sound speed problem. Then, his knowledge of the ocean's physical properties and his ability to map its acoustic structure becomes important. Since 1939 considerable progress has been made in laboratory measurements of the speed of sound in sea water and the delineation of the physical properties of the ocean through oceanographic surveys. This paper examines the impact of this work on the Matthews Tables.

THE SPEED OF SOUND IN SEA WATER

As early as 1951 laboratory measurements of sound speed at atmospheric pressure (Weissler and Del Grosso, 1951) showed that the Matthews sound speed tables yielded speeds about 3 m/sec too slow. Byer (1954) showed that the error was due to a too high value for the isothermal compressibility of sea water at low pressure, thus validating the concern

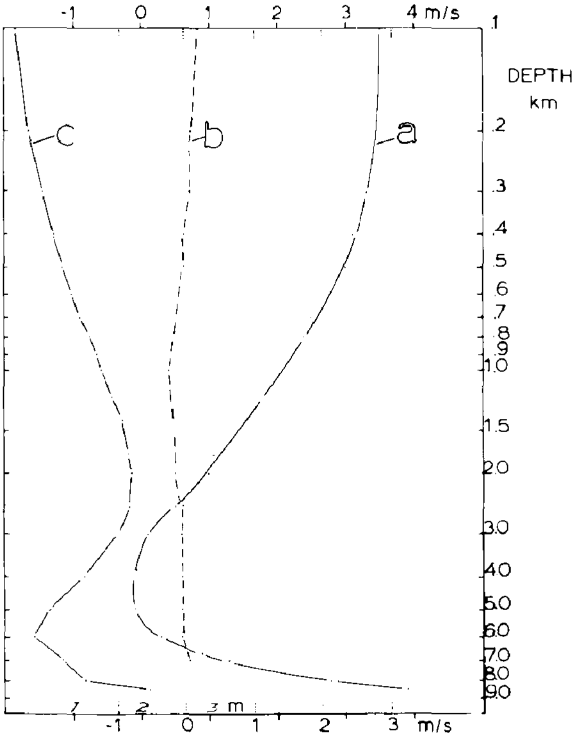


Fig. 2. — Curve "a" is the difference between sound speeds computed for waters at 28° S, 176° W, by two methods : Wilson's (1960b) minus Matthews' (1939). Curve (b) is a similar comparison of Wilson's (1960b) minus Del Groso and Mader's (1972). (Use upper abscissa scale for curves "a" and "b"). Curve "c" shows the error in echo *sounding corrections, in metres, for conditions at the same site, if one uses* Matthews' method in lieu of Wilson's as modified by Lovett (1969) (Use lower abscissa scale, slanted numerals). The lower abscissa scale, upright numerals, shows the effect of the Lovett adjustment on the curve "a" data.

expressed by MATTHEWS and by HECK and SERVICE. By the late '50s the results of WEISSLER and DEL GROSSO had been confirmed by many other measurements including those of WILSON (1960 a, 1960 b), which included measurements at elevated pressures (up to 1 000 kg/cm^2) to simulate the effect of depth in the ocean. The National Oceanographic Data Center (NODC) adopted WILSON's 1960-b equation about 1963, and thereafter routinely computed sound speeds for all oceanographic data sets. Curve "a" of figure 2 compares sound speeds computed from Wilson's formula with those from Matthews tables for a deep station in the South Pacific. The difference shows a definite dependence on depth (pressure). Thus the "deficit" speed of the Matthews tables is in fact an "excess" speed in the depth range 3 500-5 400 m. Measurements subsequent to 1960 both in the laboratory and field proved that Wilson's equation yields speeds too high apparently as a result of several problems, including a sound diffraction phenomena not recognized in the earlier study. LOVETT (1969) reviewed many of these later measurements and proposed that within the range of physical conditions encountered at sea, that Wilson's equation (*) be used, but that 0.65 m/sec be subtracted from the result. LOVETT's recommended 0.65 m adjustment was based principally on comparison of sound speed measurements on distilled water, supplemented by analysis of a few long range measurements at sea.

Recently DEL GROSSO and MADER (1972) reported laboratory measurements using an instrument markedly different in principle from WILSON's and most other investigators. DEL GROSSO and MADER included several equations, relating sound speed to temperature, salinity and pressure, with increasing "goodness of fit" with the number of terms utilized. Curve "b" of figure 2 compares sound speeds computed with the Del Grosso-Mader equation VII (18 terms) with those computed from Wilson's 1960 b equation for conditions at a typical deep oceanographic station. The differences are very close to the 0.65 m/sec adjustment proposed by LOVETT, thus adding strong support to the utility of LOVETT's proposal.

The shifted abscissa at the lower margin of figure 2 reflects this 0.65 m/sec adjustment. With the LOVETT adjustment, WILSON's speeds are somewhat closer to MATTHEWS and the depth range where WILSON's speeds exceed MATTHEWS is reduced, As indicated by curve "c" of figure 2, the use of MATTHEWS' sound speeds results in a small (maximum 2.1 m at 8 500 m), positive depth error (sounding too shoal). It is concluded that although MATTHEWS' sound speeds contain a systematic error, their use is not an important source of error in computations of echo sounding corrections.

(*) Lovett applied his adjustment to Wilson's 1960a equation rather than the generally accepted 1960b equation. For echo sounding problems the difference is negligible.

MAPPING OF THE OCEAN'S VERTICAL SOUND SPEED STRUCTURE

The second of MATTHEWS problems was, in essence, the mapping of the ocean's thermal-haline structure, and the conversion of the thermal-haline structure to a vertically integrated sound speed computed from the surface to progressively greater depths. The latter, "mean vertical sound speeds", were used to compute the echo sounder correction tables. MATTHEWS found that within an acceptable error tolerance he could represent the ocean by 52 classes of structure. The accuracy of this work was directly dependent on the store of oceanographic station data available in the 1930's. MATTHEWS does not inventory his data base other than in general terms, however a contempory compilation (VAUGHN 1937) of oceanographic stations shows a total of 1946 stations in the Pacific. As of 1967 Pacific Ocean stations

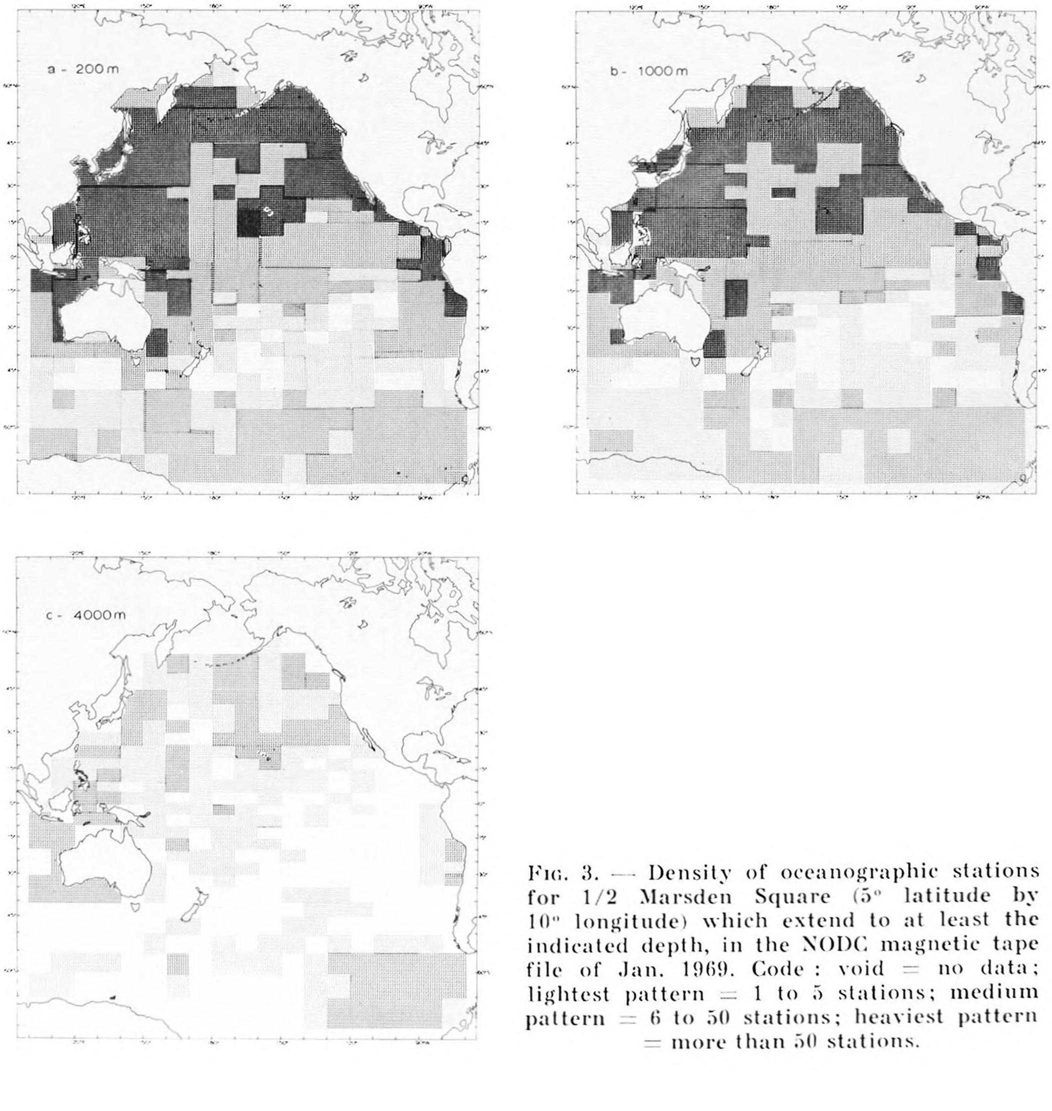
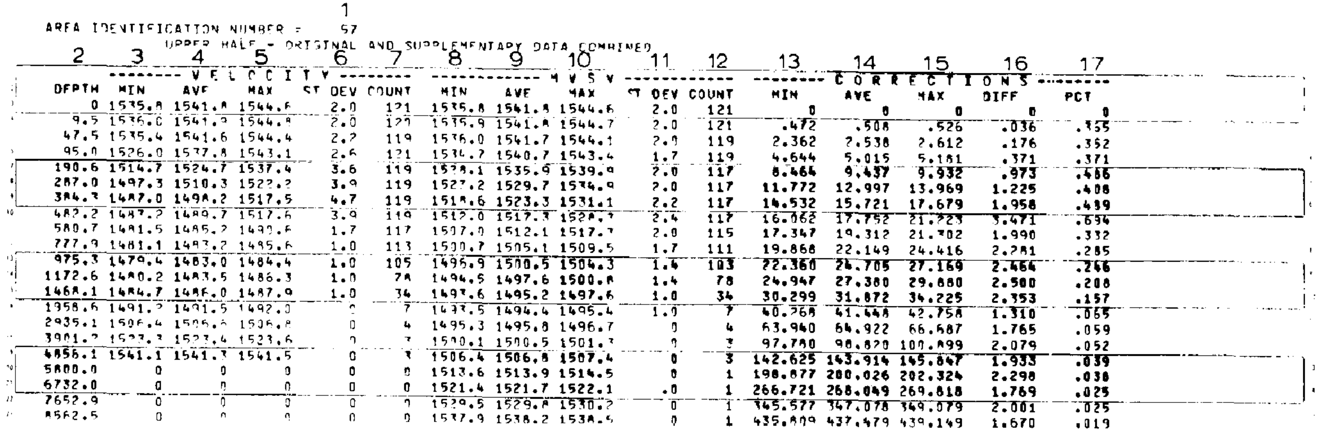


FIG. 3. — Density of oceanographic stations for 1/2 Marsden Square (5° latitude by 10° longitude) which extend to at least the indicated depth, in the NODC magnetic tape file of Jan. 1969. Code : void = no data; lightest pattern = 1 to 5 stations; medium pattern = 6 to 50 stations; heaviest pattern = more than 50 stations.



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                                    1
AREA IDENTIFICATION NUMBER =       57
                 UPPER HALF - ORIGINAL AND SUPPLEMENTARY DATA COMBINED
      2      3      4      5        6      7      8      9     10       11     12      13      14      15      16      17
        --------- V E L O C I T Y ---------     ------------- M V S V -------------    --------- C O R R E C T I O N S ---------
   DEPTH    MIN    AVE    MAX   ST DEV  COUNT    MIN    AVE    MAX   ST DEV  COUNT    MIN     AVE     MAX    DIFF     PCT
       0 1535.8 1541.8 1544.6     2.0    121  1535.8 1541.8 1544.6     2.0    121       0       0       0       0       0
     9.5 1536.0 1541.9 1544.8     2.0    121  1535.9 1541.8 1544.7     2.0    121    .472    .508    .526    .036    .355
    47.5 1535.4 1541.6 1544.4     2.2    119  1536.0 1541.7 1544.1     2.0    119   2.362   2.538   2.612    .176    .352
    95.0 1526.0 1537.8 1543.1     2.6    121  1534.7 1540.7 1543.4     1.7    119   4.644   5.015   5.181    .371    .371
   190.6 1514.7 1524.7 1537.4     3.6    119  1528.1 1535.9 1539.9     2.0    117   8.464   9.437   9.932    .973    .466
   287.0 1497.3 1510.3 1522.2     3.9    119  1527.2 1529.7 1534.9     2.0    117  11.772  12.997  13.969   1.225    .408
   384.3 1487.0 1498.2 1517.5     4.7    119  1518.6 1523.3 1531.1     2.2    117  14.532  15.721  17.679   1.958    .489
   482.2 1487.2 1489.7 1517.6     3.9    119  1512.0 1517.3 1528.7     2.4    117  16.062  17.752  21.223   3.471    .694
   580.7 1481.5 1485.2 1490.6     1.7    117  1507.0 1512.1 1517.3     2.0    115  17.347  19.312  21.302   1.990    .332
   777.9 1481.1 1483.2 1485.6     1.0    113  1500.7 1505.1 1509.5     1.7    111  19.868  22.149  24.416   2.281    .285
   975.3 1479.4 1483.0 1484.4     1.0    105  1496.9 1500.5 1504.3     1.4    103  22.360  24.705  27.169   2.464    .246
  1172.6 1480.2 1483.5 1486.3     1.0     78  1494.5 1497.6 1500.8     1.4     78  24.947  27.380  29.880   2.500    .208
  1468.1 1484.7 1486.0 1487.9     1.0     34  1493.6 1495.2 1497.6     1.0     34  30.299  31.872  34.225   2.353    .157
  1958.6 1491.2 1491.5 1492.0       0      7  1493.5 1494.4 1495.4     1.0      7  40.268  41.448  42.758   1.310    .065
  2935.1 1506.4 1506.6 1506.8       0      4  1495.3 1495.8 1496.7       0      4  63.940  64.922  66.687   1.765    .059
  3901.2 1523.3 1523.4 1523.6       0      3  1500.1 1500.5 1501.3       0      3  97.780  98.820 100.899   2.079    .052
  4856.1 1541.1 1541.3 1541.5       0      3  1506.4 1506.8 1507.4       0      3 142.625 143.914 145.847   1.933    .039
  5800.0      0      0      0       0      0  1513.6 1513.9 1514.5       0      1 198.877 200.026 202.324   2.298    .038
  6732.0      0      0      0       0      0  1521.4 1521.7 1522.1      .0      1 266.721 268.049 269.818   1.769    .025
  7652.9      0      0      0       0      0  1529.5 1529.8 1530.2       0      1 345.577 347.078 349.079   2.001    .025
  8562.5      0      0      0       0      0  1537.9 1538.2 1538.5       0      1 435.809 437.479 439.149   1.670    .019
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EXPLANATORY NOTES

1. Marsden Square No. 57 (upper half: 15°-20°N, 150°-160°E). In text 1/2 Marsden Square is called a "Sorting Area."
2. Fathometer Depth = True Depth - Average Corrector.
3. Minimum insitu velocity (m/sec) computed at indicated fathometer depth.
4. Average insitu velocity (m/sec) computed at indicated fathometer depth.
5. Maximum insitu velocity (m/sec) computed at indicated fathometer depth.
6. Standard deviation (m/sec) of all velocities computed at indicated fathometer depth.
7. Number of computed velocities (number of oceanographic stations having valid temperature and salinity data interpolated or observed at that fathometer depth.
8. Minimum mean vertical sound speed (m/sec) computed from the surface to indicated fathometer depth.
9. Average mean vertical sound speed (m/sec) computed from surface to indicated fathometer depth.
10. Maximum mean vertical sound speed (m/sec) computed from surface to indicated fathometer depth.
11. Standard deviation of mean vertical sound speed computed from the surface to indicated fathometer depth.
12. Number of valid oceanographic stations which extend to the indicated fathometer depth.
13. Minimum echo sounding correction for the indicated fathometer depth.
14. Average echo sounding correction for the indicated fathometer depth.
15. Maximum echo sounding correction for the indicated fathometer depth.
16. The greater difference (m) between the average and the maximum or minimum corrector.
17. The difference (see note 16) expressed in terms of percent of the true depth (Fathometer Depth + Average Corrector).

Fig. 4. — Example of echo sounding correction data computed from the NODC station file of Jan. 1969.

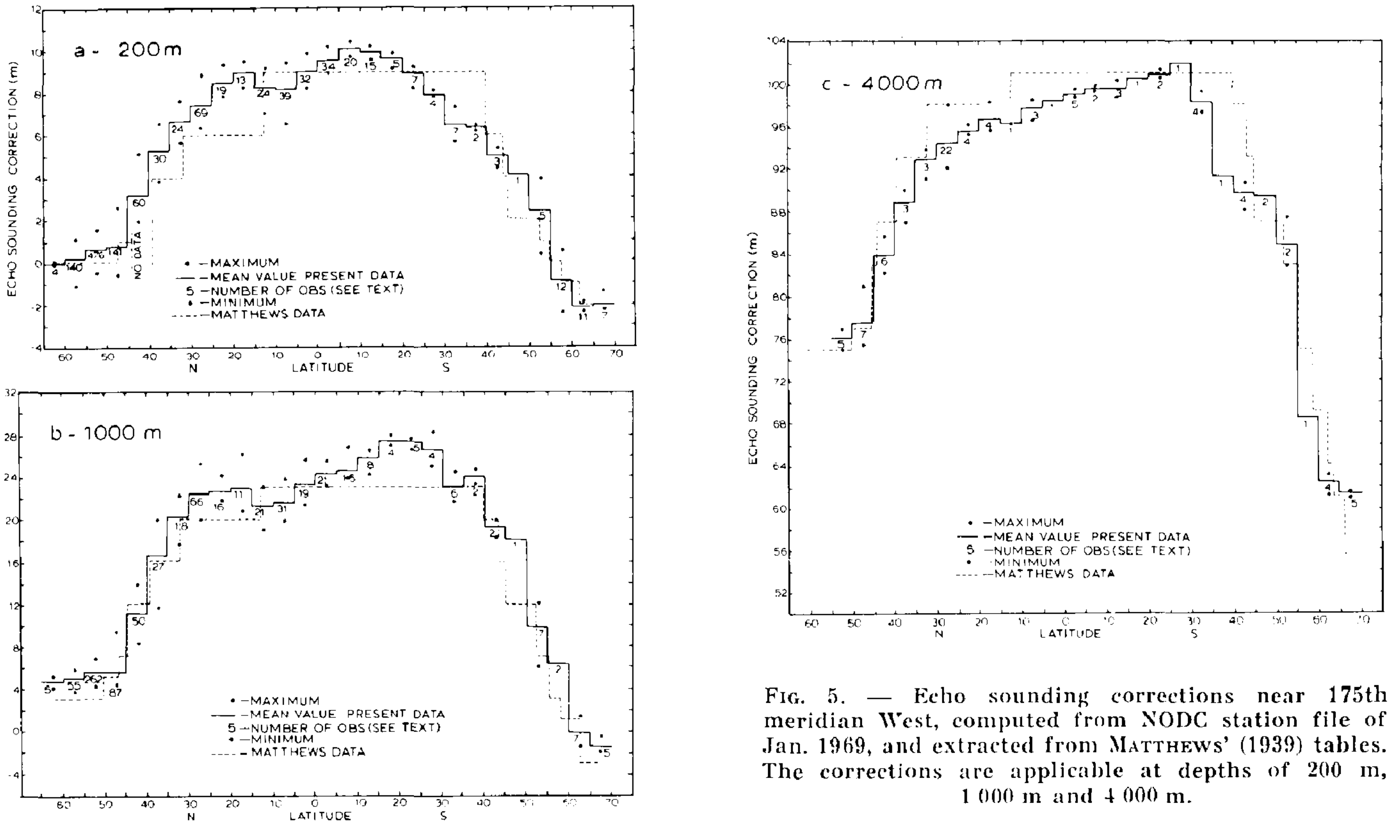

FIG. 5. — Echo sounding corrections near 175th meridian West, computed from NODC station file of Jan. 1969, and extracted from MATTHEWS' (1939) tables. The corrections are applicable at depths of 200 m, 1 000 m and 4 000 m.

on the magnetic tape file of NODC numbered more than 125 000. Unfortunately the areal distribution had not benefited proportionately, see below :

Oceanographic stations 1937 and 1967 - Pacific Ocean

Year	Total Sta.	% Area Covered (*)	% W. Pacific (**)
1937 (VAUGHN)	1 946	77	46
1967 (NODC)	125 453	96+	72

(*) % Area covered = % of the 1/2 Marsden Squares (5° Lat. × 10° Long.) in the Pacific which contain 1 or more oceanographic stations. The actual area in a Marsden Square varies by a factor of 4 between 0 and 60° Latitude.

(**) % W. Pacific = % West of 160° E.

The very large concentration in the West Pacific increased even more so after 1937; by 1967 fifty percent of all the Pacific stations on file were

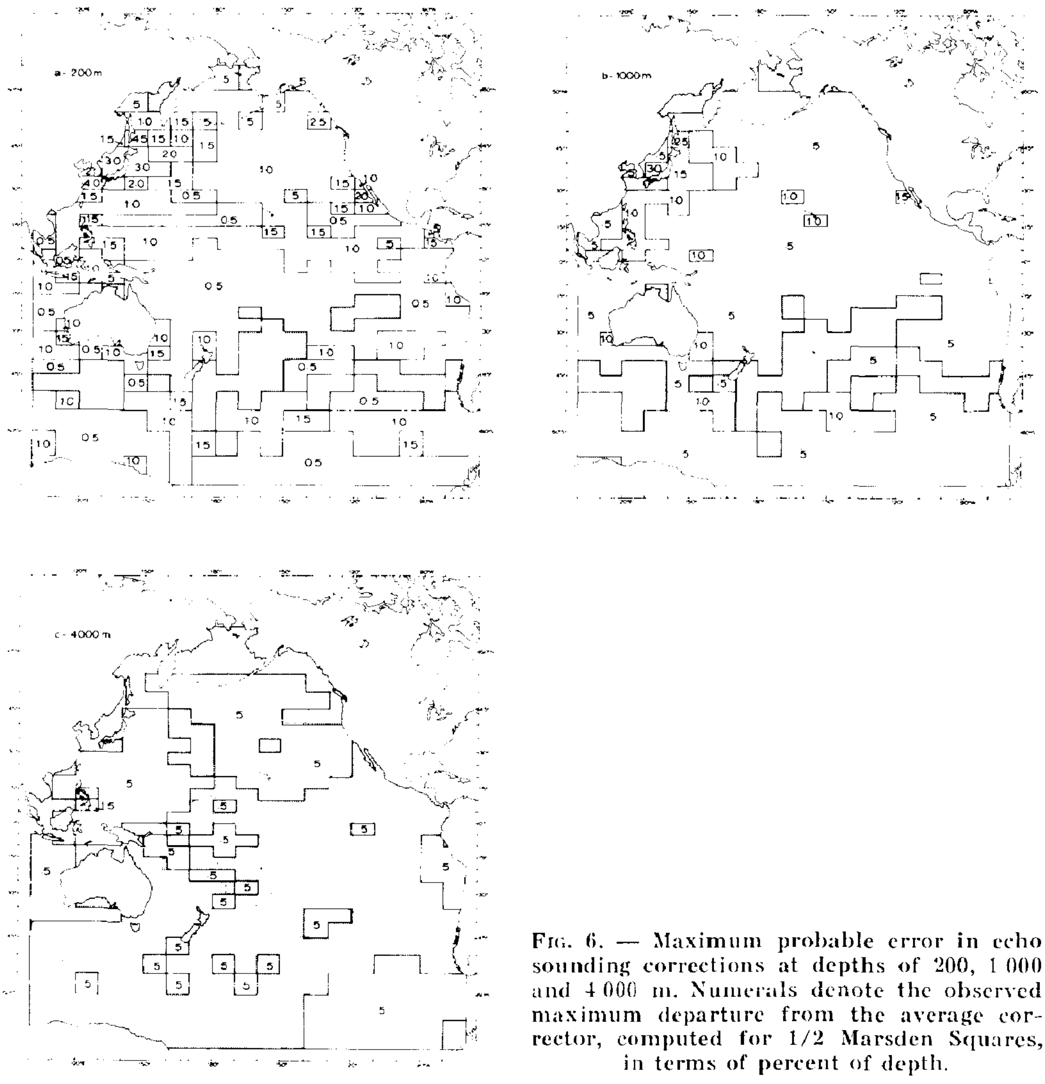

FIG. 6. — Maximum probable error in echo sounding corrections at depths of 200, 1 000 and 4 000 m. Numerals denote the observed maximum departure from the average corrector, computed for 1/2 Marsden Squares, in terms of percent of depth.

within 600 miles of Tokyo. Despite this bias there was a substantial improvement in station coverage throughout the Pacific as the area coverage figures show. Figure 3 shows the distribution of stations by depth and numerical density. Although data density is still weak, in some areas sufficient data are now available to permit one to evaluate Matthews' correctors, including time changes.

The NODC Pacific Ocean oceanographic station file of 1967 (plus a supplementary file of 30 000 additional stations which were added to the records by January 1969) was used to compute echo sounding corrections for each 1/2-Marsden Square (*). The method employed was a modification of the system described by RYAN and GRIM, (1968). An example of the results is given in figure 4. In essence, the computer program computes for each S.A. the average, the maximum and the minimum mean vertical sound speed (MVSS) from the surface to selected depths from all stations located in the S.A. Correctors are computed for the average, maximum and minimum MVSS. The results are tabulated at "fathometer depths" rather than true depths (**). In order to obtain provisional correctors for those S.A. where depths exceed oceanographic observations, two (one for N. Pacific — one for S. Pacific) arbitrary sound speed structures for the interval 5 000-9 000 m were appended to those stations having valid data to at least 4 000 m. The correctors computed from the NODC data file are compared directly with Matthews correctors along a meridional section near 175 °W, at three depths — 200, 1 000 and 4 000 m (figure 5) to test the validity of his class boundaries. Also, the limit of variability of the correctors is presented (figure 6) to show the magnitude of the corrector error within each S.A. which results from space and time dependent causes.

CLASS BOUNDARIES

The meridional sections (figure 5) reveal significant differences in the pattern of the corrector vs latitude curves. Whereas Matthews characterized the Central Pacific as having a constant corrector value between 12° N and 40° S, the data at 200 and 1 000 m show well defined double maxima, separated by a minimum near 10° N. The 4 000 metre data form an asymmetric curve having a single pronounced maximum at about 30° S.

The cause of the patterns exhibited by the 1969 data is clearly indicated in the temperature and salinity sections presented by REID (1965) in his figures 2 and 3. The corrector curves for the 200 and 1 000 m depths (figure 5) closely approximate the shape of REID's 12 °C isotherm, (inverted) showing the strong influence of the water temperature on the sound speed. Near 10° N upwelling of cooler, less saline, intermediate water reduces

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(*) A quadrangular area measuring 5° of latitude by 10° of longitude, hereafter the 1/2 Marsden Square will be called the 'Sorting Area', abbreviated "S.A.".

(**) Fathometer depth = true depth — corrector. In use, a 4th order polynomial equation is written expressing correctors as a function of fathometer depths. The equation is then used to solve for the corrector at any fathometer depth.

sound speeds, causing the minimum in the corrector curves at this latitude. At the 4 000 m level (figure 5) the minimum is masked by the integrating effect of the deep water column. The higher temperature and salinity in the South Pacific, detectable at all levels to 4 000 m causes the single maxima near 30° S.

In higher latitudes (N of 30° N, S of 40° S) the two sets of data display the same general pattern but disagree somewhat in amplitude at all three levels. The general features of the Southern Ocean and Sub-Arctic Pacific were known to MATTHEWS and are represented in his data.

An estimate of the practical significance of the difference between the comparable curves can be reached by considering the difference or "error" in terms of its relationship to depth, or true corrector, At 200 m (figure 5 a) the maximum difference between the two curves or "error" is 3 m (15 to 20° N and 35 to 40° S) which amounts to 1.5 % of the depth and is as much as 50 % of the corrector. At 1 000 m (figure 5 b) the maximum "error" is 4 m (15 to 20° S) which is less than 0.5 % of the depth and about 18 % of the corrector. At 4 000 m the maximum "error" is 8 to 10 m (35 to 40° S), about 0.25 % of the depth and about 10 % of the corrector.

As anticipated, the correctors calculated from the new data are larger than MATTHEWS, due in part to the use of WILSON's faster sound speeds. As figure 2 suggests, the same relationship should exist at 4 000 m (figure 5) but the reverse is true. MATTHEWS tabulated his computed mean vertical sound speed along with his correctors in his tables. In a routine check of his correctors I found I could not reproduce the tabulated values utilizing the listed speeds. My calculations yield values 3 to 5 m less than his (at 4 000 m) with the difference increasing exponentially with depth. The cause of this discrepancy is unknown.

SPACE AND TIME CHANGES IN CORRECTORS IN SORTING AREAS

The computer program used to process the 1969 NODC data file computed the maximum and minimum as well as the average corrector at each of the selected depths in the S.A. (figure 4). To the degree that the NODC file contains stations representative of the full spectrum of oceanographic conditions in the S.A., the *difference* between the average corrector (which is the one employed in processing soundings) and the more distant of the maximum or minimum value is a measure of the greatest error one could expect in using the average corrector. This difference, called here maximum probable error (*) (MPE), is presented at the three depths 200, 1 000 and 4 000 m in figure 6. The contour interval is 0.5 % of the depth; a value occasionally cited as the precision of the older echo sounders.

(*) Where sufficient oceanographic stations exist, the MPE should be based on a better statistical value such as the standard deviation. The latter is computed by the program but in view of the paucity of data is useful only in few S.A.

Figure 3 is useful in evaluating the validity of the corrector variability data (figure 6) in that the density of stations is a crude index of the adequacy of coverage. In high latitudes, however, the number of stations has less significance relative to seasonal coverage, as severe weather conditions may concentrate all surveys in one season.

MPE AT 200 m

At the 200 m level (figure 6 a) a very large portion of the tropical and subtropical region displays MPEs not greater than 0.5 % (1 m) in the corrector. Data density is good, and it is concluded that averaged correctors are valid. By inference, Matthews correctors in this depth range should also be free of large errors due to time dependent changes in the environment. Excessively large MPEs are present in the N.W. Pacific where the current systems (Kuroshio and Oyashio) result in very large space and time gradients. In these areas precision echo sounding requires local, contemporary measurements of water properties.

MPE AT 1000 m

At the 1 000 m level (figure 6 b), MPE within the S.As tend to be lower, due to the reduced influence of the upper layers to which space and time changes are largely confined. However, in the vicinity of Japan, spacial variations associated with the strong current systems result in unacceptably large MPEs, precluding the use of the average data. The very large MPE (1.5 %) in the area dissected by Baja California is a result of the anomalous water properties (contrasted with oceanic conditions) in the Gulf of California caused by topographic isolation and Colorado River discharge.

MPE AT 4000 m

At the 4 000 m level, (figure 6 c), the data density is very low in some of the S.A. (where the hachured pattern indicates no data on variability, one station was available). At 4 000 m the MPE is uniformly low, not greater than 0.5 % (20 m), owing to the integrating effect of depth due to the relative constancy of properties at great depths. For example, at 3 500 m Knauss (1962) shows a maximum range of less than 1 °C (less than 5 m/sec) throughout the entire Pacific. A notable exception occurs in the S.A. which includes part of the Philippine Trench and Sulu Basin. Here a difference of more than 8 °C (about 34 m/sec) extends from 2 200 to 4 000 m. This unique situation is the cause of the 1.5 % (60 m) MPE shown in figure 6 c in the southern Philippines. MATTHEWS also recognized this phenomena and assigned a unique designator, Area 40, to the Sulu Sea. Fortunately this is a singular situation, and elsewhere in figure 6 c, time and space changes within a S.A. are not important at 4 000 m.

CONCLUSIONS

The considerable body of sound speed measurements since 1950 has resulted in an authoritative series of equations (DEL GROSSO and MADER, 1972) for the relationship between water properties and sound speeds. The WILSON (1960 b) equation in common usage today, gives reasonably accurate values provided the LOVETT (1965) adjustment is included. MATTHEWS' (1939) speeds are systematically in error but not enough to seriously affect routine echo sounding correctors.

A test of MATTHEWS' class boundaries near 175° W, using the NODC oceanographic station file as of 1969, shows that more variability exists between 12° N and 40° S than the MATTHEWS maps indicate. The Matthews correctors are generally valid but in isolated areas are in error up to 50 % of their value (but a small percent of the depth). This discrepancy is probably due to the paucity of data on oceanographic conditions in 1939.

A puzzling problem arose in attempting to check Matthews' correctors from the tabulated data from which they were apparently computed. Caution is suggested in using the source data.

Despite the enormous increase in oceanographic stations since 1939, in much of the Pacific one cannot, with confidence, define the areal and temporal variations in correctors. Maximum-probable-error chartlets, computed from the NODC data, indicate that with correctors computed from data averaged over 5° latitude by 10° longitude quadrangles, that corrector errors will normally be less than 0.5 % of depth. However, the error problem is greatly accentuated at the interface between intense current systems and where topographic entrapment of water masses occur. In suspected areas, local measurements of water conditions are advisable.

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