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HYDROGRAPHIC SURVEYS OFF PLYMOUTH IN 1959 AND 1960

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(With Text-figs. 1–11)

The physical and chemical properties of sea water in the English Channel have been studied for the last 70 years (Dickson, 1892; Kyle, 1903; Matthews, 1905, 1909, 1911; Jee, 1919, 1920, 1921; Atkins, 1923*a*, *b*, 1925, 1926*a*, *b*, 1928, 1930, 1953; Harvey, 1923, 1925*a–c*, 1930, 1934; Lumby, 1923, 1924, 1935; Cooper, 1933*a–c*, 1938, 1958, 1960; Armstrong & Atkins, 1950; Armstrong & Harvey, 1950; Armstrong, 1954, 1955, 1957*a*, *b*, 1958*a*, *b*; Armstrong & Butler, 1959, 1960*a*, *b*, 1962; Armstrong & Boalch, 1961). The movement of the water has been investigated directly with drift bottles and current meters (Garstang, 1898; Carruthers, 1924, 1926, 1930, 1934, 1935; Carruthers, Lawford, Veley & Gruning, 1951), or by indirect methods (Gehrke, 1907; Dietrich, 1950, 1951; Cooper, 1960*a*, *b*). These investigations have shown that water of high salinity enters the western end of the English Channel from the Atlantic Ocean and flows eastward through the Straits of Dover into the North Sea. The inflow of Atlantic water appears to be intermittent, and the variability of the salinity at the mouth of the Channel is probably a consequence of variable water movements in the East Atlantic. A suggestion by Le Danois (1923) that Atlantic water at the mouth of the Channel was replaced in 1922 and 1923 by water from the Irish Sea is unlikely in view of the high salinities observed up channel in those years (Harvey, 1925*a*). Harvey calculated from the rate of movement of high-salinity water that its movement was 1·2 miles per day in 1908 and 1·6 in 1921. Carruthers (1924) found a rate of 1·5 miles per day from bottom-trailing drift bottles released in mid-channel in 1923. However, water movement may be very variable. Current measurements at the Varne Light Vessel near Dover (Carruthers, 1935) have shown that they are constant neither in speed nor direction and the easterly movement may be halted or temporarily reversed by strong winds.

The Plymouth Laboratory is conveniently placed for work at the western end of the English Channel, and quite early in the century effort was being concentrated on a few fixed positions which had been designated as International Hydrographic Stations after being first worked by Matthews in 1902. In particular, station E1 at 50° 02′ N., 4° 22′ W., which was 22 miles out, could be reached from Plymouth, several hours' work done and the return to port made in one day. Atkins did much of his work on nutrient elements and on the penetration of light into sea water at this position in this manner. A survey of his in 1924 showed that phosphate concentrations over a large area at the mouth of the Channel were fairly uniform and that station E 1 might be taken as typical of a large area. Atkins therefore worked the station as regularly as he was able, and regular work has been continued by others at the Plymouth Laboratory. Records of salinity and temperature at station E 1 go back to 1902, and of phosphate and silicate to 1921 and 1922 respectively. Other chemical work has been done from time to time such as determinations of nitrate (Harvey, 1926, 1928); nitrate, nitrite, ammonia, oxygen, excess base, carbon dioxide (Cooper, 1933*a–c*); total phosphorus (Harvey, 1948; Armstrong & Harvey, 1950); suspended matter (Armstrong & Atkins, 1950; Armstrong, 1958*b*); iron (Armstrong, 1957*b*); ultra-violet absorption (Armstrong & Boalch, 1961).

TABLE 1. CHANGES IN WATER MASS SAMPLED AT STATION E1 (50° 02′ N. 4° 22′ W.)

Date	Nature of change
11 Mar. 1952	Layering, 0–25 m σ_t 27·20, 35–70 m σ_t 27·35
21 Oct.–20 Nov. 1952	Salinity 35·22 ‰ fell to 35·14, silicate 1·93 μg at Si/l. fell to 1·24
11 May–8 June 1953	Silicate 1·22 rose to 3·02
10 Aug.–8 Sept. 1953	Silicate 2·36 rose to 3·41 (greater than in January)
19 Jan.–16 Feb. 1954	Salinity 35·31 rose to 35·37, silicate 4·70 fell to 2·83
13 July–11 Aug. 1955	Unseasonable fall in temperature, silicate 1·87 rose to 2·94
18 Oct. 1955	Silicate 3·11 higher than in January (2·12)
17 Nov.–21 Dec. 1955	Silicate 3·68 fell to 3·26
26 Mar.–22 Aug. 1956	High salinity (> 35·4)
16 July–21 Aug. 1957	Salinity 35·20 fell to 35·13
21 Jan.–18 Feb. 1958	Salinity 35·23 fell to 35·10, silicate 3·93 rose to 4·67

Some of the observations over periods of a few years have been summarized (Atkins, 1953; Cooper, 1938; Southward, 1960), though this is not easy because of the unavoidable irregularity of sampling.

That station E 1 is not necessarily typical of the western end of the Channel appeared in a survey of 1947, when quite large variations in phosphate were found (Cooper, 1958). Since 1947 the reliability of phosphate determinations was improved as a result of an investigation into the method and the use of a photoelectric absorptiometer (Harvey, 1948). An improved method for silicate was put into use in 1950 (Armstrong, 1951), and it also became possible to work the station at more regular intervals. Before long it could be seen that fluctuations in the properties of water sampled at the station were occurring because of changes in the water mass. Some examples are given in Table 1. If the rate of water movement at this station is 1 or 2 miles per day, it follows that quite large differences in the properties of the water may be found over distances of 20 or 30 miles. It was decided therefore to survey an area about 30 miles square to see what degree of non-uniformity existed in it. In 1959 two cruises, one in winter and one in summer, were undertaken. These gave such interesting results that six more cruises were done in 1960. It was hoped that these cruises would serve two purposes: to show to what extent results at station E1 were typical of the adjacent area, and also to give information on the hydrography of a part of the English Channel of interest to biologists at the Plymouth Laboratory. These cruises supplement the routine monthly cruises to station E1, the results from which are reported separately (Armstrong & Butler, 1960*a*, *b*, 1962).

In planning the survey we wished to be able to complete the sampling rapidly so that a synoptic view could be obtained and also arrange if possible that the distance between stations was greater than the probable movement of the water by tides and currents. These aims were fulfilled, we think, by taking an area which could be covered in 2 days, and by spacing the stations more than 5 miles apart. This spacing follows from the tidal information in Admiralty Chart 1598, which indicates that in the south-western corner of the area (chart position 14) water movement at spring tides would be just under 5 miles. When steaming round a network of stations on a zig-zag course it is very likely that adjacent positions will be worked at one or more multiples of half a tidal period. In the network chosen, stations were fixed at intervals of 10′ of latitude or longitude, which are 10 and $6\frac{1}{2}$ sea miles respectively. Tidal movement, at least at spring tides, is not therefore negligible, and introduces some distortion into the isotherms and isohalines which we have drawn in our diagrams as if the stations were sampled simultaneously. We do not think that this distortion is important. A further very slight possible distortion is caused by other movement of the water during the 2 days taken on the cruise.

In order to restrict the number of chemical analyses and also to simplify the presentation of the results, three depths only were sampled. Since nutrient determinations at the surface are neither very reliable nor interesting only temperature and salinity were measured at that level. Nutrient determinations were done at 10 and 50 m, which were supposed, in this area, to be sufficiently representative of the epi- and hypothalassa. The depth of water varies from about 55 m at the north-east corner to 85 m at the south-west, and shelves downward gently to the south-west.

WORKING METHODS

Navigation was by the 'Decca' system so that the positions of stations were probably accurate to ±0·1 mile. Steaming time between stations was about 1 h. The time taken for the January 1959 survey (21 stations) was 25 h. The subsequent cruises (32 stations) took about 40 h. The route through the stations was as indicated in Fig. 1, except in March 1960 when the network was worked after a cruise to the westward and was entered at the south-west corner. Stations were then worked on a zig-zag route going east along the 49° 40′ parallel, west along 49° 50′ N., east along 50° 00′ N., and west along 50° 10′ N.

Surface temperature and a sample for salinity were taken with a towed sampler (Lumby, 1927, 1928) which was hauled inboard just as the ship stopped at each station. Temperatures and samples for analysis were taken at 10 and 50 m with reversing bottles (with paired protected reversing thermometers) on a single hoist. In summer, a bathythermograph was attached to the hydrographic wire just below the 50 m bottle. The ship was stopped for 10–15 min.

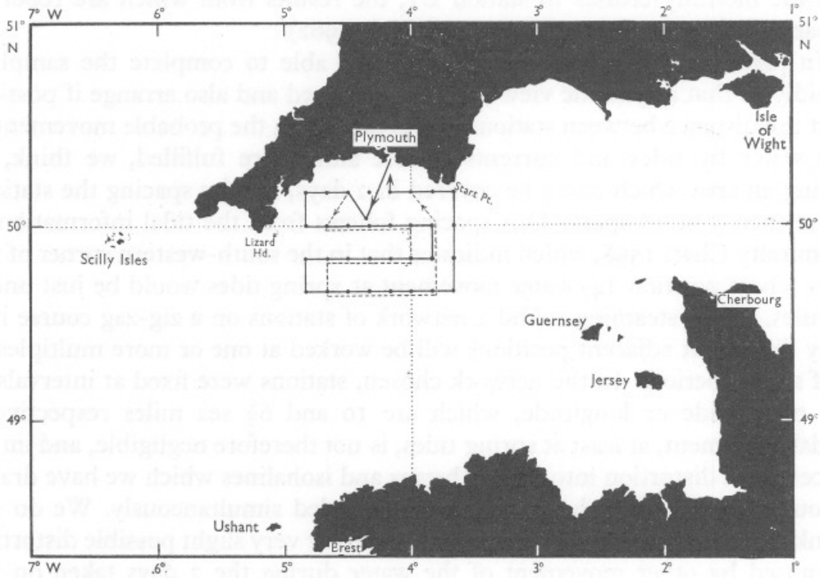

Fig. 1. Western end of English Channel, showing area surveyed.

Salinities were determined until July 1960 by chlorinity titration by the Government Chemist, Department of Scientific and Industrial Research. From that time onward, they were done in this laboratory by electrical conductivity, using the National Institute of Oceanography thermostat salinity meter. Phosphate and silicate were determined by molybdenum blue methods. Phosphate samples were preserved with chloroform and kept in a cold store until they could be analysed. Analyses were usually completed within 72 h. of collection of samples.

RESULTS

The eight cruises which were made started on 13 January and 24 June 1959, and 4 January, 9 March, 4 May, 6 July, 11 October and 20 December 1960. It is hoped that the detailed results will appear in the *Bulletin Hydrographique* of the International Council for the Exploration of the Sea. The presentation here is graphical and we have omitted some of the winter results when differences at the three depths were negligible, and some of the summer nutrient values which are so low as to make it difficult to draw meaningful contours.

January 1959 (Figs. 2, 3)

Observations for this cruise are given in full in order to show their reliability and the good agreement which can be obtained between sets of measurements. The isothermals run roughly east and west with the southern part of the area about 1° C warmer than the coastal part. Salinity, density, phosphate and silicate all show a tongue of water projecting south-eastward from station E1, and readily distinguishable by its lower salinity and higher phosphate and silicate contents. These properties suggest that it contains land-drainage water, and the south-easterly extension may indicate that this mass of water may be pushed eastward by general water movement in the area, being banked against the slope of the bottom and elongated. The dotted line on the density diagrams show the 40-fathom contour taken from the chart. A rough calculation shows that to lower the salinity in the area to the values shown would require a rainfall of about 20 cm in the catchment area of the rivers draining into the area.

June 1959 (Figs 4, 5)

The isotherms run mostly north and south, and at 0 and 10 m the water to the west is 2° C warmer than to the east. Temperature gradients are very steep in places. At 50 m the warmer water is to the east, the difference being about 1·8° C. This reversal of gradients is a consequence of the mixing process which, it is evident, occurs as the incoming water crosses the area. It appears that warm water of high salinity is entering the north-west corner near Lizard Point, with well marked layering giving a thermocline at 20 m. As this water moves across the area mixing takes place and the thermocline becomes more shallow and the temperature of the bottom water rises. Phosphate concentrations were too low to draw useful diagrams but those for silicate are given. They show, to the west, lower silicate in the upper layers, and to the east, the vertical homogeneity caused by mixing.

January 1960 (Figs. 6, 11)

Results at 10 m only are shown. The 50 m observations are very similar; this applies also in March, October and December. Isotherms and isohalines run roughly east and west; there is no sign of the tongue of low-salinity water found in January 1959. (There had been very rough weather for 8 weeks before this cruise, with south-westerly gales, and this may have caused lateral mixing in the area.) Phosphate is relatively high throughout the area, with a patch of high-phosphate water surrounding station E1. Silicate is higher near the coast. The temperature and salinity diagrams indicate that warmer more saline water is entering the area from the south-east.

March 1960 (Figs. 6, 11)

Again, isotherms and isohalines run roughly east and west, and high nutrient concentrations are found near the coast. Over much of the area the salinity has increased by about 0·1 % since January.

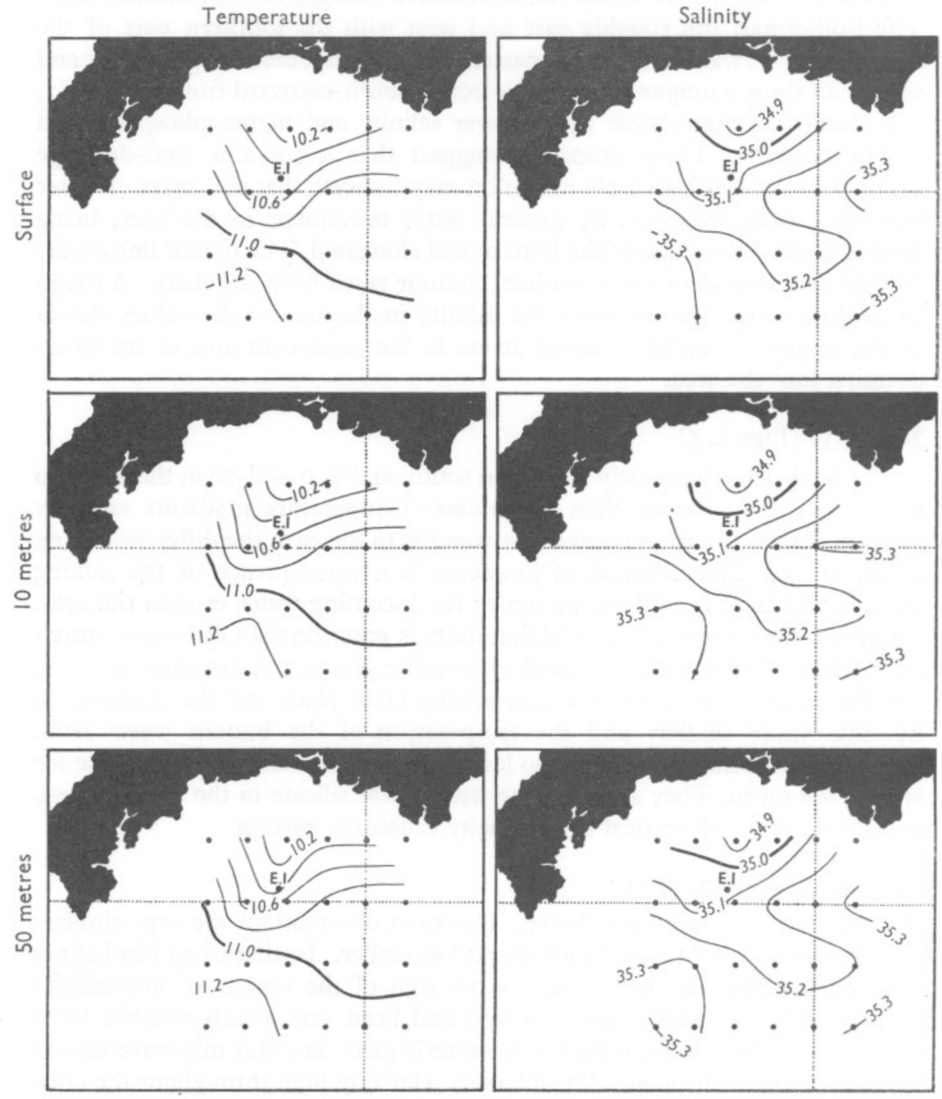

Fig. 2. Temperature (° C) and salinity (‰), January 1959.

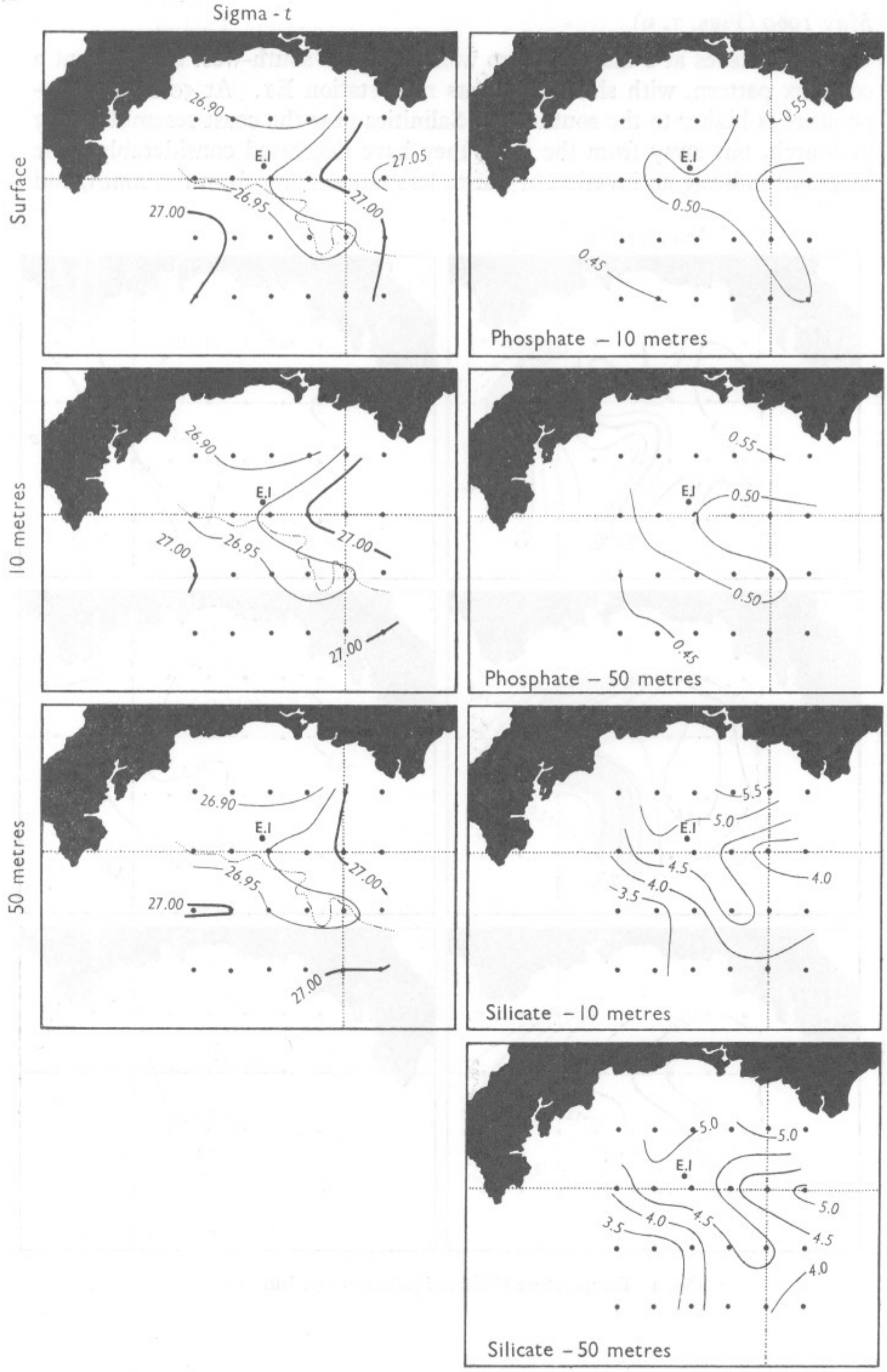

Fig. 3. Density (σ_t), phosphate (μgatom P/l.) and silicate (μgatom Si/l.), January 1959.

May 1960 (Figs. 7, 9)

Temperatures at 0 and 10 m are warmer to the south-west and present a complex pattern, with sharp gradients near station E1. At 50 m the temperature is higher to the south-east. Salinities near the coast resemble those in March, but away from the coast they have decreased considerably. The diagrams indicate an invasion of warm, less saline water from the south, and

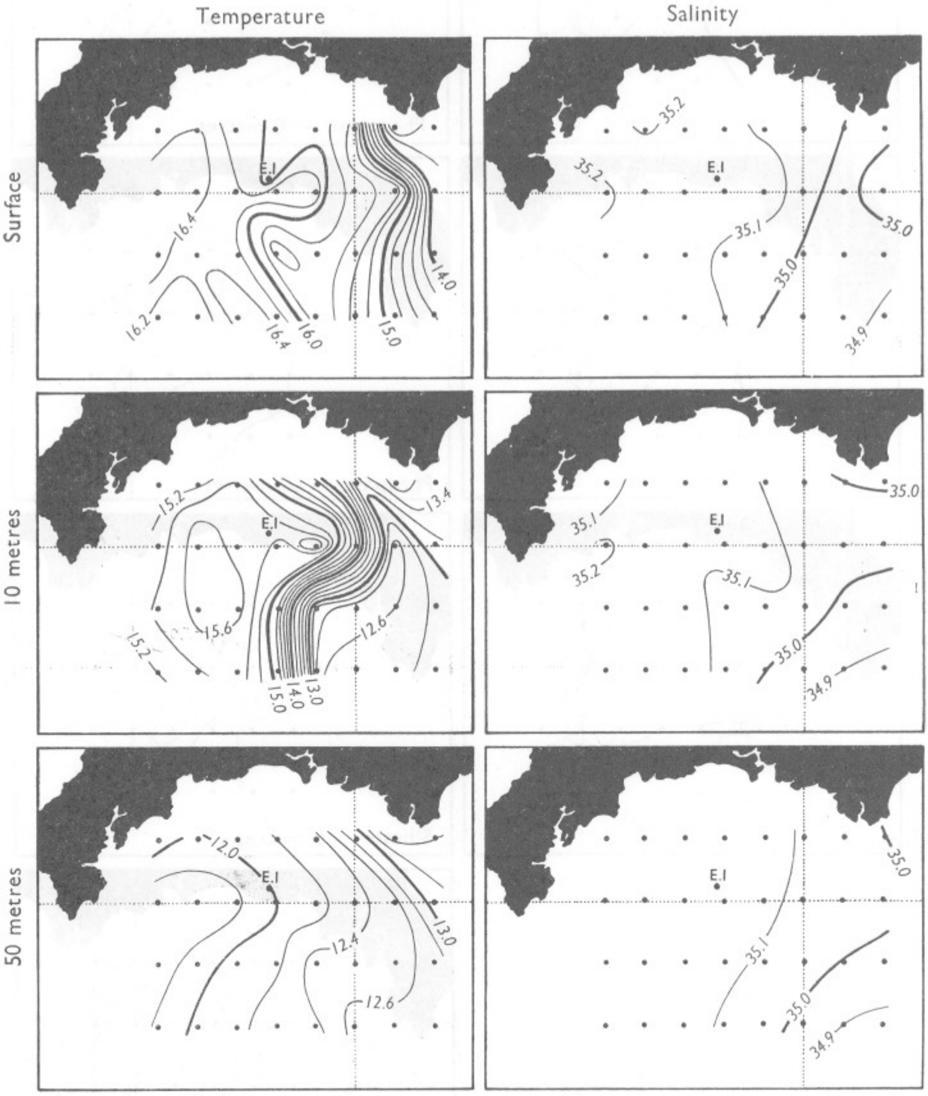

Fig. 4. Temperature (° C) and salinity (‰), June 1959.

it is difficult to judge whether from the south-west., as is suggested by the 0 and 10 m diagrams, or from the south-east as by the 50 m one. The distribution of densities suggests a movement towards the south-east. As would be expected from the irregular temperature contours, particularly at 10 m, the depth of the thermocline was very irregular, which suggests some vigorous mixing process. It was somewhat deeper to the west of the area.

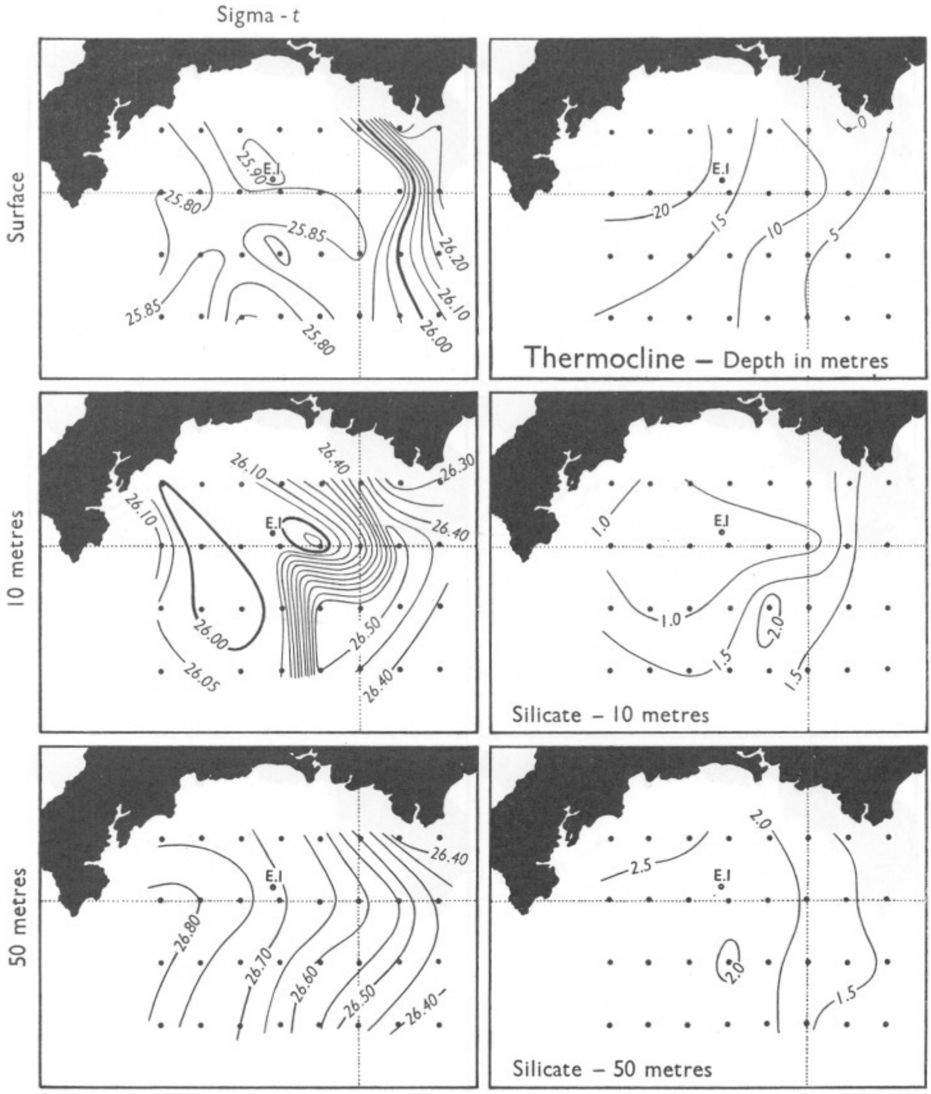

Fig. 5. Density (σ_t), depth of thermocline (m) and silicate (μgatom Si/l.), June 1959.

Phosphate values were quite low (from 0·08 to 0·22 μg-atom P/l.) in the upper layers.

July 1960 (Figs. 7, 10)

Temperatures were highest to the west, at 0 and 10 m, and to the east at 50 m. Salinities are slightly lower than in May, and there is an intruded band of water of salinity reaching in a north-westerly direction from the

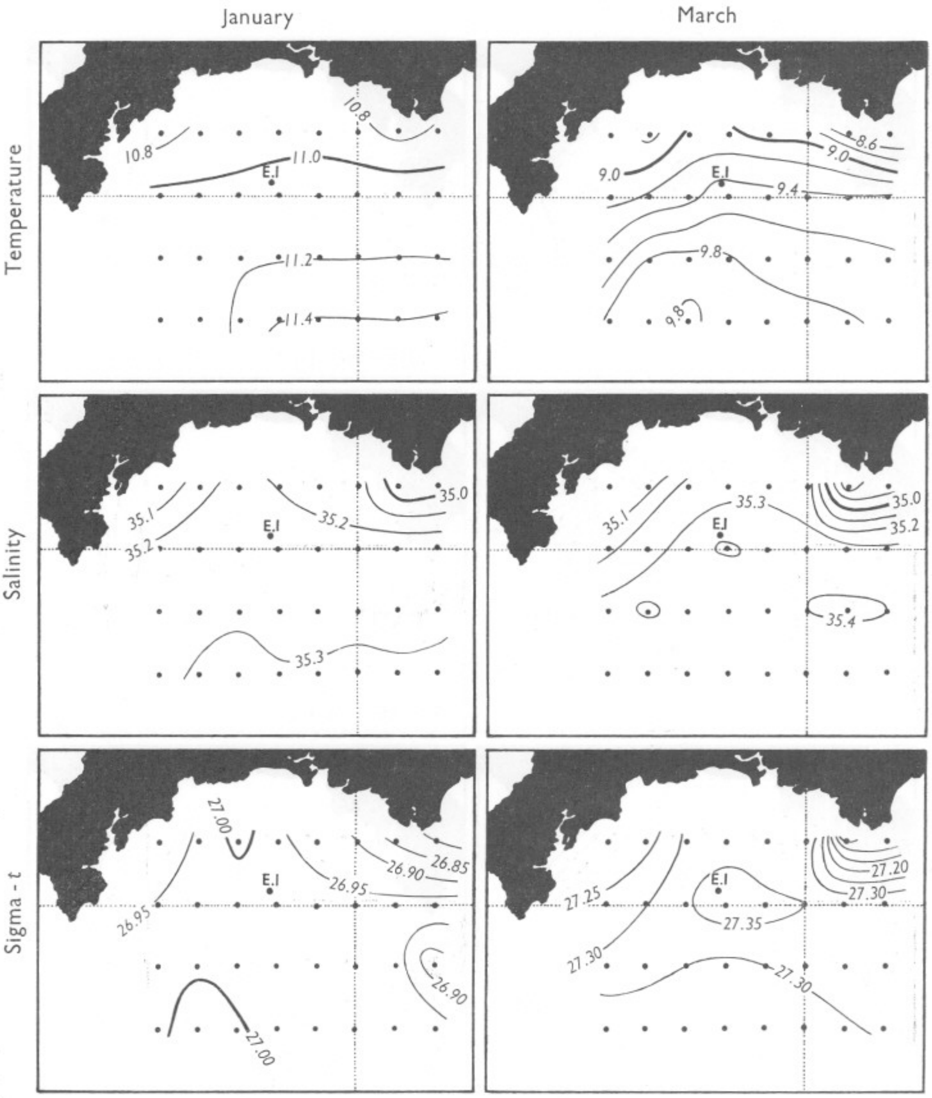

Fig. 6. Temperature, salinity and density at 10 m, January and March 1960.

south-eastern corner where values of less than 34·7‰ were found. The depth of the thermocline was about 20 m over the whole area except the north-eastern corner near Start Point. Nutrient levels were low over the whole area.

October 1960 (Figs. 8, 11)

Vertical mixing had occurred over the whole area and the 10 m values are typical of all depths. The lowest temperatures were found offshore. Low-

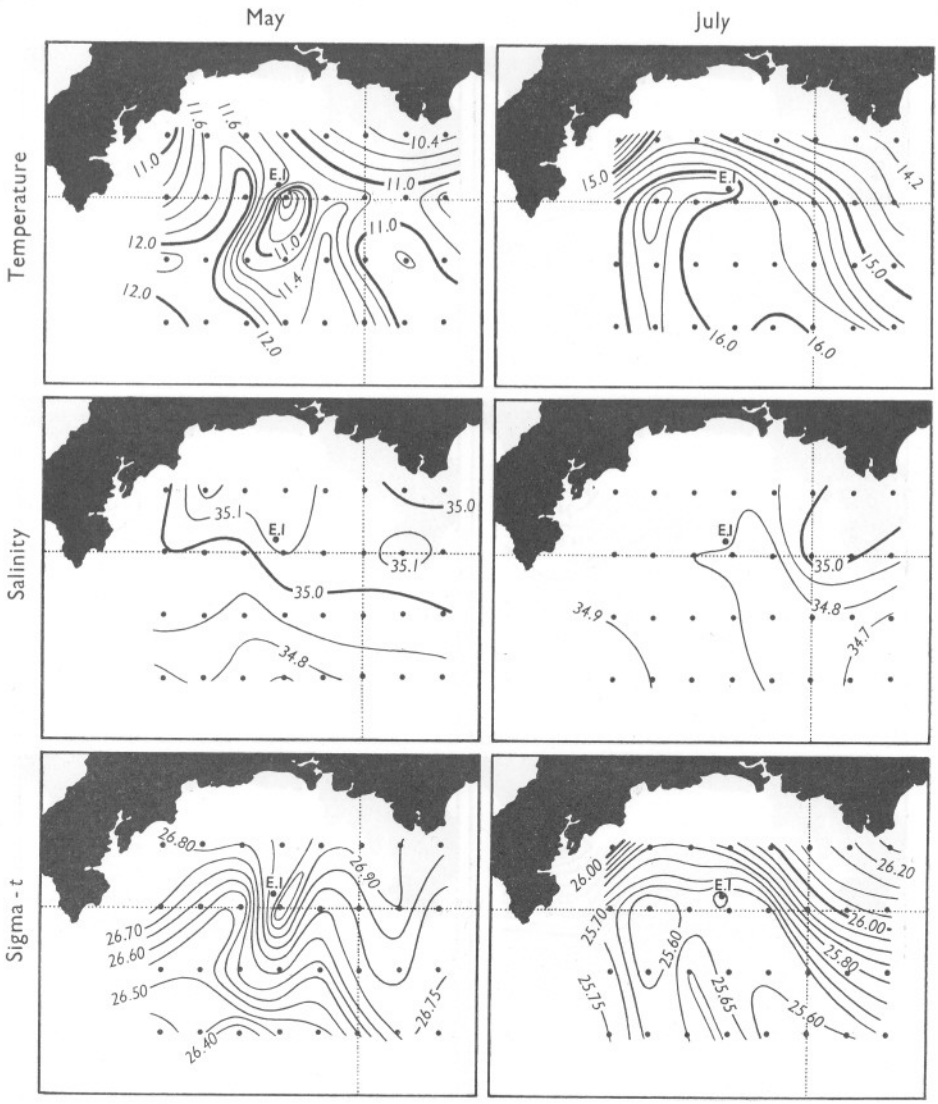

Fig. 7. Temperature, salinity and density at 10 m, May and July 1960.

salinity water is found near the coast, but farther offshore the low-salinity water had been replaced by other of much higher salinity which appeared to enter from the south-west. The density gradients indicate a flow in to the east.

December 1960 (Figs. 8, 11)

Temperatures have fallen considerably and are now highest offshore, where again, the highest salinities are found. As a result maximum density

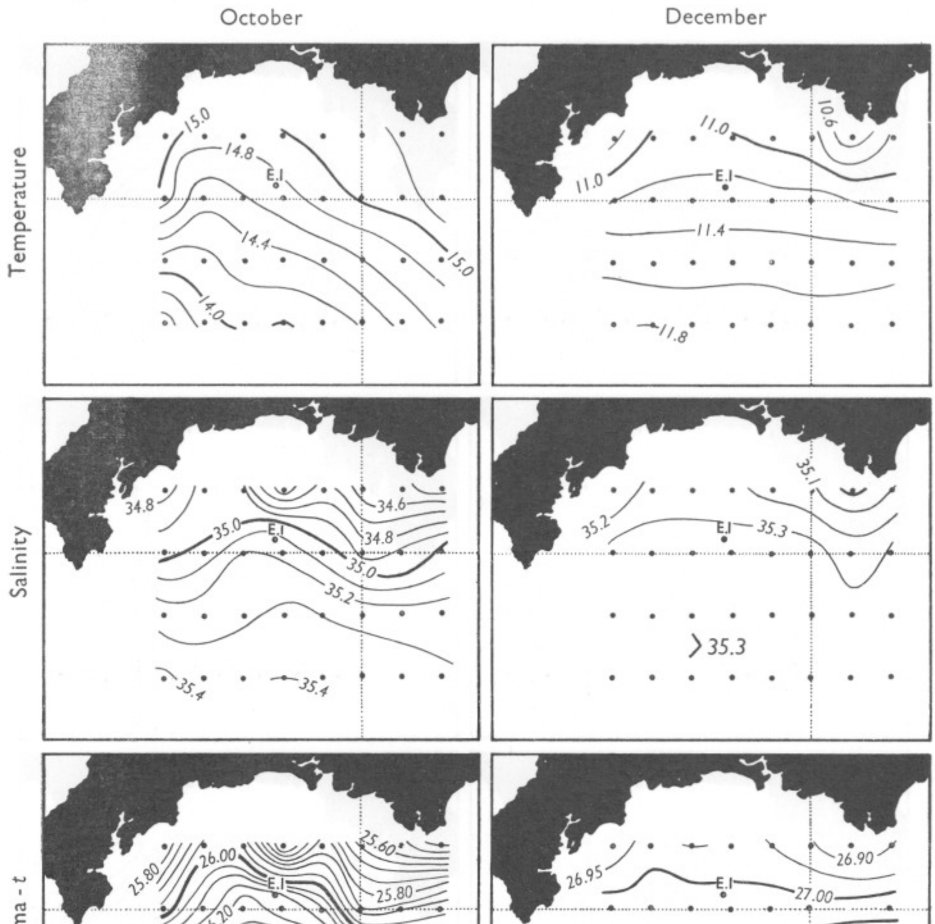

Fig. 8. Temperature, salinity and density at 10 m, October and December 1960.

occurs in a band offshore, lying east and west. Currents would therefore be expected to run westward near the west and eastward along the southern part of the area.

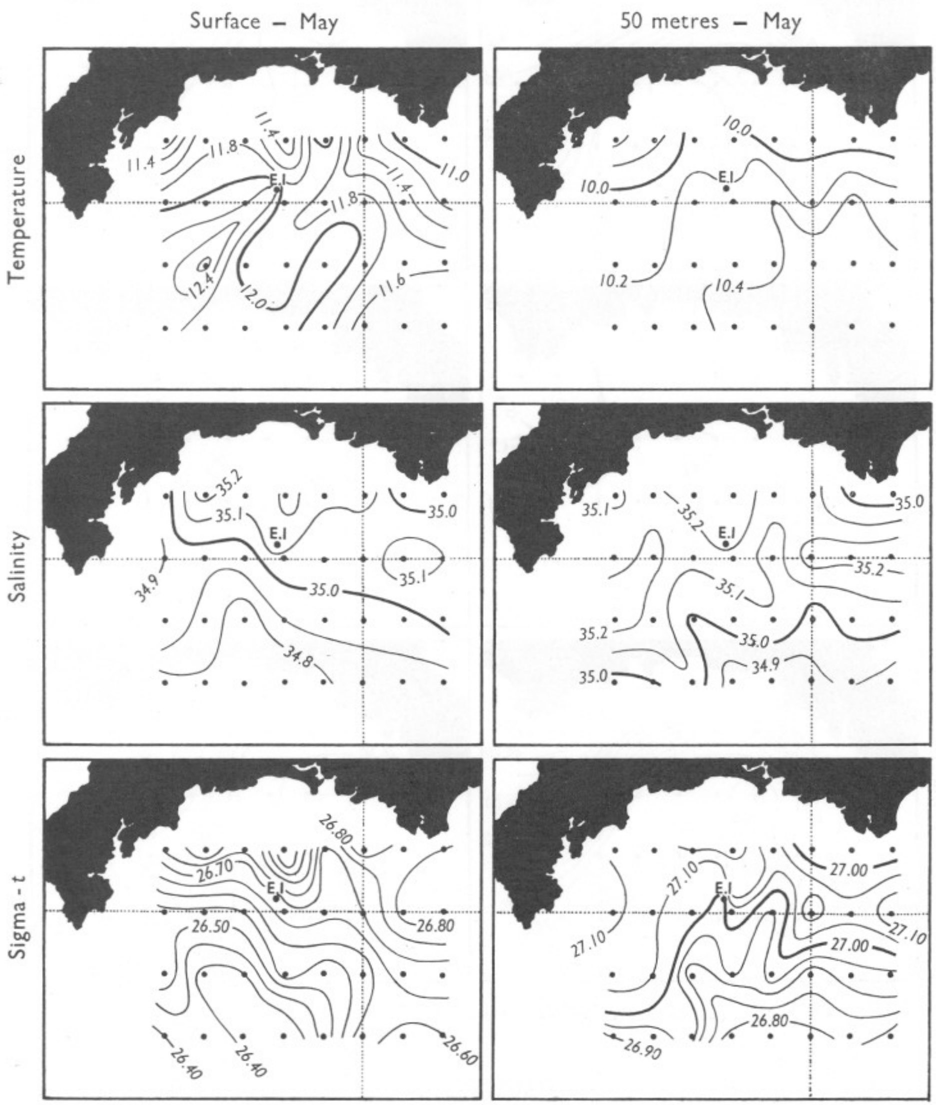

Fig. 9. Temperature, salinity and density at 0 and 50 m, May 1960.

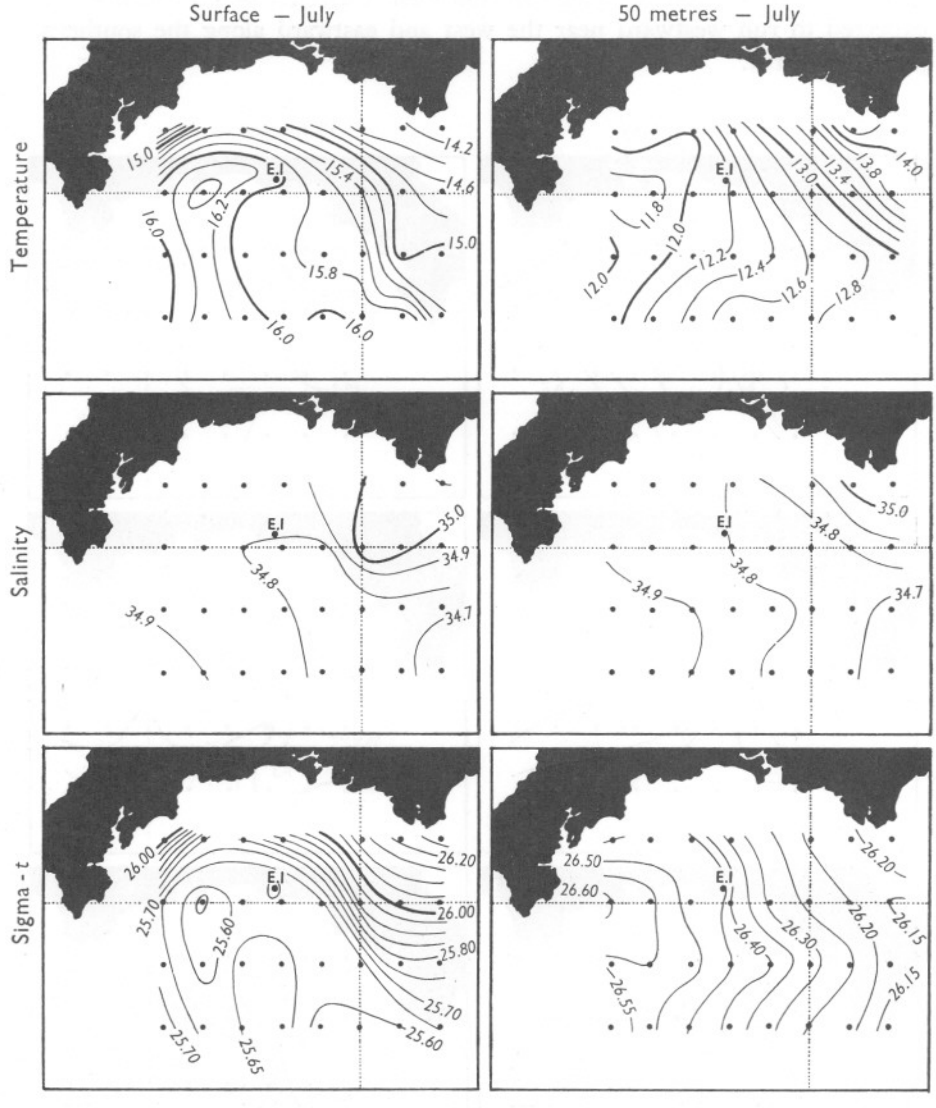

Fig. 10. Temperature, salinity and density at 0 and 50 m, July 1960.

DISCUSSION

It is at once apparent that even in so small an area as this there are quite large differences from place to place, and that surveys at intervals of 2 months are too infrequent to allow one to trace water movements. It is obvious that station E1 is often surrounded by water of rapidly changing characteristics

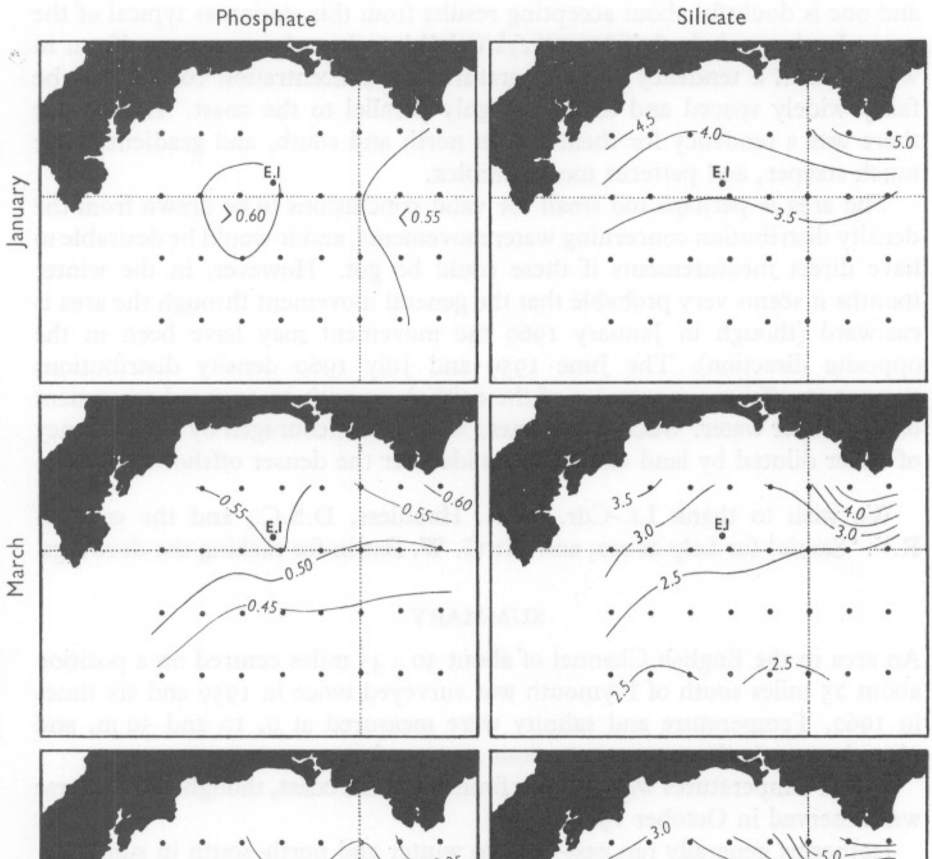

Fig. 11. Phosphate and silicate at 10 m, January, March, October and December 1960.

and one is doubtful about accepting results from this station as typical of the area. In the period of these surveys conditions have been more uniform in winter, with a tendency for temperature and concentration contours to be fairly widely spaced and to run roughly parallel to the coast. In summer there was a tendency for them to run north and south, and gradients were much steeper, and patterns more complex.

The area is perhaps too small for valid conclusions to be drawn from the density distribution concerning water movements, and it would be desirable to have direct measurements if these could be got. However, in the winter months it seems very probable that the general movement through the area is eastward (though in January 1960 the movement may have been in the opposite direction). The June 1959 and July 1960 density distributions suggest an offshore movement of the epithalassa with an opposed movement of the deeper water. Such a movement would be encouraged by the tendency of water diluted by land drainage to slide over the denser offshore water.

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SUMMARY

An area in the English Channel of about 30 × 45 miles centred on a position about 25 miles south of Plymouth was surveyed twice in 1959 and six times in 1960. Temperature and salinity were measured at 0, 10 and 50 m, and phosphate and silicate concentrations at 10 and 50 m.

Lower temperatures were usually found near the coast, though the converse was observed in October 1960.

Isotherms generally ran east–west in winter and north–south in summer.

Salinity was usually lower near the coast, but not in the summer.

Density contours generally resembled those of temperature, and suggested an eastward water movement in winter. In summer they suggested an offshore movement at the surface and an onshore movement of the deeper water.

In winter the distribution of phosphate and silicate resembled that of salinity, high values of nutrients corresponding to low salinities.

In summer the depth of thermocline was greater to the west.

The properties of the water were so variable from place to place, and changes in them so rapid, that it is difficult to accept results from station E1, or any other single station in the area, as typical of the whole.

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