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ECHO TRACES ASSOCIATED WITH THERMOCLINES[1, 2]

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ABSTRACT

Echoes received from the depth of the thermocline in Windermere, the North Sea, the Barents Sea and off Spitsbergen have been associated with aggregations of plankton organisms: zooplankton at a density of 25/litre in Windermere and phytoplankton at a density of 100,000 cells/litre (*Thalassiosira gravida* and *Chaetoceros* sp.) in the Barents Sea.

INTRODUCTION

With commercial sounders, signals have been recorded from sharp temperature discontinuities in the sea or from "scatterers" associated with them (Schubert, 1950 a, b; Schüler and Krefft, 1951 a, b; Krefft and Schüler, 1951; Tucker, 1951; Schüler, 1952; Trout, *et al.*, 1952; Herdman, 1953). Such traces are characterized by vertical thinness (about one pulse length) and horizontal extensiveness, thereby indicating that signals are being received from the axis of the sound beam only. It is unlikely, therefore, that such signals are received

[1] Since writing this paper, we have read "Visual detection of temperature-density discontinuities in water by diving" by Limbaugh and Rechnitzer (Science, *121*: 395; 1955). Our results differ from theirs in that our echo record is not diffuse; nor did Lt.-Cdr. Hodges see any aggregation of material at the thermocline. This suggests that the aggregation described in Limbaugh and Rechnitzer's paper was denser than ours; consequently it is possible that echoes were received from angles away from the axis, thus making a diffuse trace, which was presumably more extensive in depth than ours.

[2] Submitted for publication 3 September 1954.

from fish, since fish traces are fairly thick vertically and comparatively narrow horizontally, the signals being received from any part of the sound cone. They might be received from three possible sources: (a) the physical discontinuity itself; with oscillators fairly distant from the reflecting surface and with a discontinuity giving a temperature change from 16° to 10° C, within one wavelength, the relative impedance is 0.005% (speeds of sound in fresh water at 16° and 10° C are taken from Matthews, 1939); most discontinuities, however, are not flat surfaces of zero thickness but show a graded distribution of temperature and density with depth; (b) a layer of turbid sediment at the discontinuity; (c) plankton organisms at or near the discontinuity.

In July 1952, observations were made on a fairly sharp thermocline in Windermere in order to try to separate three possible sources all effective in producing echoes. Also, a thermocline obtained in the North Sea in July 1952 was examined, and discontinuities in the Barents Sea and off southern Greenland in the summers of 1951 and 1952 respectively have been considered.

I. OBSERVATIONS IN WINDERMERE

Method. The echo sounder was a special triple-frequency sounder (see Cushing and Richardson, 1955), of which only the 30 kc/s oscillator (pulse length 1 ms or millisecond) was used; the transmitter was activated by an 800v. inductive charger. The machine was mounted in the Freshwater Biological Association's vessel Mysis, with the oscillators lashed outboard on either side.

Temperature measurements were made with a thermistor and with a bathythermograph. Plankton and sediments were sampled at different depths with water bottles; the 5-litre Rodhe bottle attached to a wire was used to catch plankton animals; diatoms and sediments were sampled with an Ekman reversing bottle which, when lowered on its side on a wire to the required depth, was closed by a frogman, who also observed the visible nature of the thermocline.

Stations were made at four locations: at the Centre Buoy in the North Basin, off Slape Scar, at Rough Nab Buoy (RNB), and off Windermere Sewage outfall (WS).

Echo Records. An echo from the thermocline was certainly recorded on one day (RNB 1 and 2). Plate 1a, illustrating a trial run at RNB 1, shows a clear record of three echoes in order of depth: from the thermocline, from the depth marker at 10 m on the frogman's rope, and from the weight on the rope. The strong echo is from the frogman; he found the thermocline quickly, went beneath it, above it, returned to it, and then surfaced.

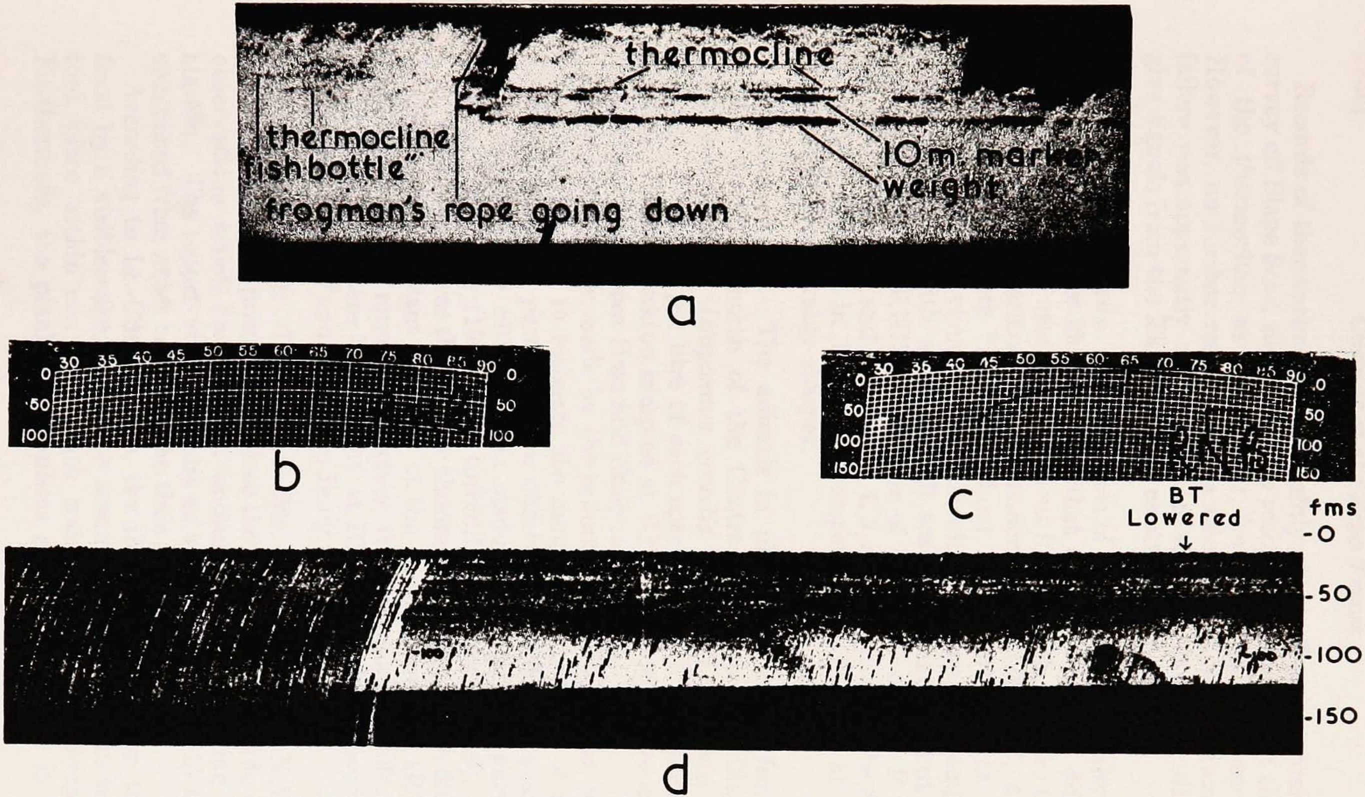

Plate I. **a.** An echo trace of the thermocline in Windermere. The large dark patch on the right is the echo from the frogman, his breathing set, and his air bubbles. The marker rope was suspended from the MYSIS and the fish bottle was hanging from the buoy to which MYSIS was moored. **b, c.** Bathythermograph records showing a sharp "knee" at RNB 4 (temp. corr. - 0.2°F) where no echo was recorded, and a less sharp one at RNB 2 (temp. corr. - 0.3°F) where an echo was recorded. **d.** Echo trace taken approaching St. 82, Cruise V, ERNEST HOLT, 1952 SW of Cape Farewell at 59° 31'N, 44° 29'W. The horizontal temperature profile in Fig 3(a) corresponds to the noisy part of the record when the ship was approaching the station. When the ship had stopped and was occupying the station, the record was clearer. The bathythermogram is shown in Fig. 3(b).

Records of thermoclines were possibly obtained on our preliminary survey off Slape Scar, since our echo records show marks at the depth of the thermocline as determined from thermistor observations. However, no further records of the thermocline were obtained, but failure was apparently not due to our sounder since it continued to give signals from the Ekman bottle as strongly as before.

Temperature Records. Examination of the individual bathythermograph records (Plate 1b, 1c) show that there are marked differences between them at or near 30 feet (about 9 m), which is where the frogman found the thermocline independently. At RNB 3, 4, 5 and WS there is a sharp "knee" at about 30 feet whereas at RNB 2 there is none. Obviously it is difficult to define the temperature gradient exactly with such a small scaled instrument, but a close approximation for RNB 2 would be of the order of 2.7° F in three feet (1½° C in 1 m) and for RNB 3, 4, 5, and WS it would be 6.6° F in three feet (3½° C in 1 m); the temperature difference at RNB 3 is probably considerably sharper.

Plankton Results. The animals in plankton samples from RNB 2, 3, 4 and WS, north of the Centre Buoy, and off Slape Scar were identified as *Diaptomus gracilis* Sars and *Daphnia hyalina* Leydig. Numbers per litre of each species at each level are given in Table I. Phytoplankton sampled at RNB 2, 3 and 4 were identified as *Asterionella formosa* Hass and *Staurastrum* sp.

Since counts were made by the sedimentation technique, it should have been possible to estimate the numbers of particles of detritus. However, since no particles were observed in sufficient quantity to merit counting, no estimate was made of numbers of particles as estimated by Jerlov (1953) or of turbidity by Joseph (1949).

In Table I it is clear that, at the thermocline, there are no differences of significance in plant numbers at the stations sampled (RNB 2, 3 and 4). In animal numbers, however, there *are* marked differences at the thermocline, there being many at RNB 2 and at Slape Scar, but few at RNB 3, 4, 5 and at Centre Buoy.

Frogman's Report. The late Lt.-Cdr. H. J. Hodges, R.N.V.(S) R., who was employed primarily to close the water bottles, made valuable observations which he described immediately on surfacing at each station. The report which appears as an Appendix (p. 12) has been condensed from notes taken at the time of interrogation.

According to Lt.-Cdr. Hodges, the thermocline appears to be defined by a visible edge, hence the assumption that the discontinuity took place within one wavelength was probably not unreasonable. Furthermore, the plankton organisms appeared to drift in a mass,

TABLE I. Estimation of Zooplankton and Phytoplankton (Numbers/litre) at Certain Depths

Station; Depth of Thermocline	*Depth Metres*	*Diaptomus gracilis*	*Daphnia hyalina*	*Asterionella formosa*	*Staurastrum* sp.
RNB 2	5	9	40	3,800	7,200
	11	135	5	13,900	6,700
11–13.7 m	13.7	—	—	3,800	6,100
	15	63	0	—	—
	18.3	—	—	18,000	3,800
RNB 3	5	3	0	2,800	16,200
	8	6	11	—	—
9 m	8.5	—	—	16,700	3,300
	9	5	3	7,500	24,400
	9.5	—	—	3,600	7,000
	10	8	3	21,400	15,800
	12	—	—	7,400	11,200
	15	27	0	—	—
RNB 4	5	2	28	—	—
	8	16	55	—	—
9 m	above	—	—	15,000	30,700
	9	5	5	6,700	14,300
	below	—	—	4,400	6,600
	10	18	2	—	—
	15	70	—	—	—
RNB 5	0	1	131		
	5	21	47		
8 m	12	2	31	No Samples	
	16	1	6		
	25	0	0		
Centre Buoy	8	10	3		
	11	2	0	No Samples	
11 m	14	31	0		
Slape Scar	8	6	0		
	12	88	0	No Samples	
12 m	15	63	0		

with individuals hopping randomly in any direction. The rate of drift of air bubbles from his diving apparatus was least at RNB 1 and greatest at RNB 2; this increase resulted from a southeast wind that sprang up in the afternoon of the first day of observations during the interval between RNB 1 and RNB 2. Assuming that large air bubbles rise at about 15 cm/sec, the midlayers were probably moving at about 1.3 cm/sec while the epilimnion was moving at 7 cm/sec. These velocities are not inconsistent with the theoretical estimates made by Mortimer (1952) for a three-layer model in Windermere.

II. OBSERVATIONS IN THE NORTH SEA.
CRUISE XIV 1952 SIR LANCELOT

In 1952, a thermocline was found off the northeast coast of England, and observations were made on the depth distribution of temperature, plants, detritus, and animals. The animals were sampled at 5-fathom depth intervals with a coarse net (60 meshes to the linear inch)

TABLE II. Numbers of Algae at Different Depths in Association with Echo Records

	Station 1 No echo layer			Station 2 Echo layer at 24.5 m			Station 4 Echo layer at 24 m		
Depth (m)	Dinoflagellates	Detritus	Green lumps	Dinoflagellates	Detritus	Green lumps	Dinoflagellates	Detritus	Green lumps
18	16	210	40	—	—	—	1	231	1
19	10	777	0	—	—	—	—	—	—
20	122	735	50	1	210	6	2	420	25
21	120	1470	73	0	315	75	—	—	—
22	—	—	—	9	0	40	4	189	25
23	80	735	125	6	105	15	—	—	—
24	9	525	100	10	1995	15	8	210	10
25	—	—	—	—	—	—	—	—	—
26	—	—	—	—	—	—	—	40	15
27	—	—	—	—	—	—	—	—	—
28	—	—	—	—	—	—	—	5	3

towed horizontally. A Nansen-Pettersson water bottle was used to obtain temperatures as well as plants and detritus, the latter two being estimated by the sedimentation technique. Counts were made of dinoflagellates, detritus and "green lumps" and the numbers are given in Table II; it is probable that the lumps were *Phaeocystis*, but after prolonged preservation *Phaeocystis* becomes difficult to identify. The term "detritus" includes any dark irregular particle that was not referrable to the above categories.

The zooplankton samples, taken at depths of 7 and 15 fathoms, were obviously too far apart in depth for our purpose. However, at night the numbers of plankton animals at these depths increased by four to six times, and at the same time the signals from the echo sounder increased by four to nine times. Signals were measured on a C.R.T. by matching them with known voltages from a signal injector. Although the evidence is by no means positive, we think it possible that the recorded echoes in the North Sea were associated with layers of plankton animals.

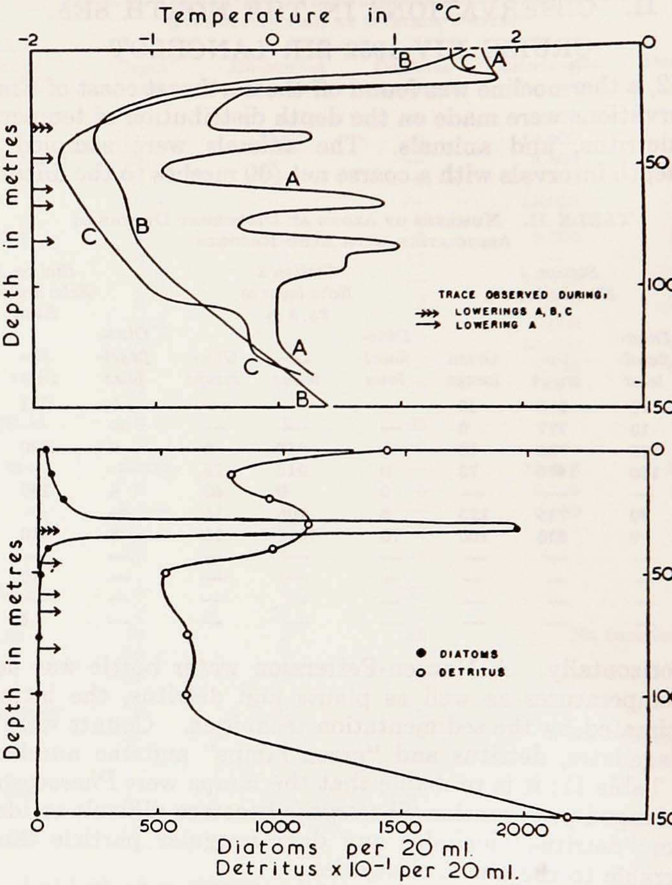

Figure 1. *a* (top), temperature gradients at St. 32, near Hope Island on 26 August 1951. A: BT lowering at 1335 hours. B: Water bottle lowering at 1408–1434 hours. C: BT lowering at 1440 hours. *b* (bottom), distribution of diatoms and detritus at the same station.

III. OBSERVATIONS IN THE BARENTS SEA AND OFF SPITSBERGEN

While investigating possible relationships of echo traces and sharp temperature discontinuities near Hope Island in the Barents Sea in August 1951, water samples were taken with Nansen reversing bottles at St. 32 in order to estimate the quantity of plants and detritus by the sedimentation technique. Discontinuity traces were observed on the 10 and 30 kc/s sounders, and a BT lowering was made at 1335 hours with the ship stopped. The resulting profile is shown in Fig. 1a together with depths at which traces were observed. No trace could be observed in the upper 18 m because of a strong echo produced by a trawl over the ship's side; however, at depths greater than that of the trawl a clear association between temperature discontinuities and traces was observed. The temperature profile obtained concurrently with the lowering of water bottles between 1408 and 1434 hours, together with a profile obtained by another BT lowering at 1440 hours, are also shown in Fig. 1a.

These latter profiles show only the uppermost of the discontinuities recorded by the first BT lowering; the ship probably did not move far off station in the interval since there was no wind. After the first BT lowering at 1335 hours the echo-sounder records often became masked by large echoes, but so far as we can tell all the discontinuity traces disappeared except that at 33 m, although that too became weaker than before. Only the two most shallow traces were recorded on the 30 kc/s sounder, and these had, in fact, disappeared on this sounder even before the first BT lowering was made.

The results of the plant and detritus counts are given in Fig. 1b. There was a pronounced maximum in the diatom distribution at 30 m, the main species being *Thalassiosira gravida* Cleve and *Chaetoceros* sp. There was also a less pronounced maximum in the detritus distribution at the same depth.

From these observations we conclude first that, whatever causes the echo, the structure considered as a whole changes its character rapidly, and second that the first and sharpest echo is associated with a layer of detritus and a pronounced layer of diatoms.

Data from a later observation indicate that these traces were not caused by the physical discontinuities themselves. On 11 September 1951 an echo was obtained at night on a 30 kc/s machine at St. 113 about 22 miles southwest of Sörkapp, Spitsbergen. The temperature profile from a BT lowering at 2305 hours is shown in Fig. 2. Since a strong signal was associated with the steep temperature gradient between 29 and 35 fathoms while no signal of similar strength was associated with the shallower and even steeper temperature gradient between 16 and 19 fathoms, it seems plausible to rule out temperature discontinuities themselves as the cause of echoes.

Both Sts. 32 and 113 were close to fronts where relatively warm Atlantic and cold Arctic water meet. Since eddies are common in these areas, the temperature profile obtained at St. 32 is probably due to vorticity; indeed it is difficult to understand how such a distribution arose in any other way if we assume that each echo was associated with a diatom layer. Herdman (1953) has noted that traces

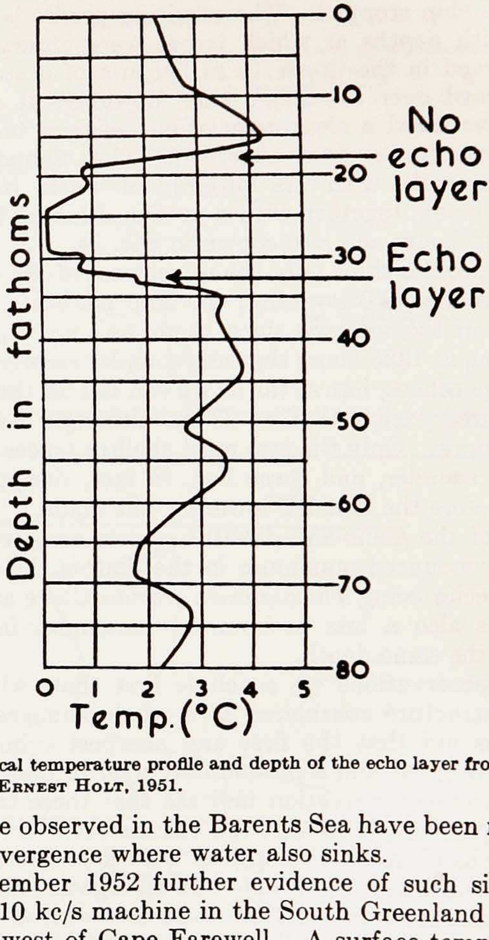

Figure 2. Vertical temperature profile and depth of the echo layer from a BT lowering at St. 113, Cruise V, Ernest Holt, 1951.

similar to those observed in the Barents Sea have been recorded at the Antarctic Convergence where water also sinks.

On 14 September 1952 further evidence of such sinking was obtained with a 10 kc/s machine in the South Greenland area at St. 82, 24 miles southwest of Cape Farewell. A surface temperature survey with a thermograph showed the presence of a clockwise eddy on the boundary between the warm Irminger and the cold East Greenland components of the West Greenland Current. The temperature profile obtained from a BT lowering near the end of the station is shown in Fig. 3b. Strong "discontinuity traces" observed on the echo sounder (Plate 1d) can be associated with the different gradients on the vertical temperature profile.

The surface temperature profile recorded by the thermograph when the station was approached is shown in Fig. 3a. Traces descended from the surface at the front between the two water masses:

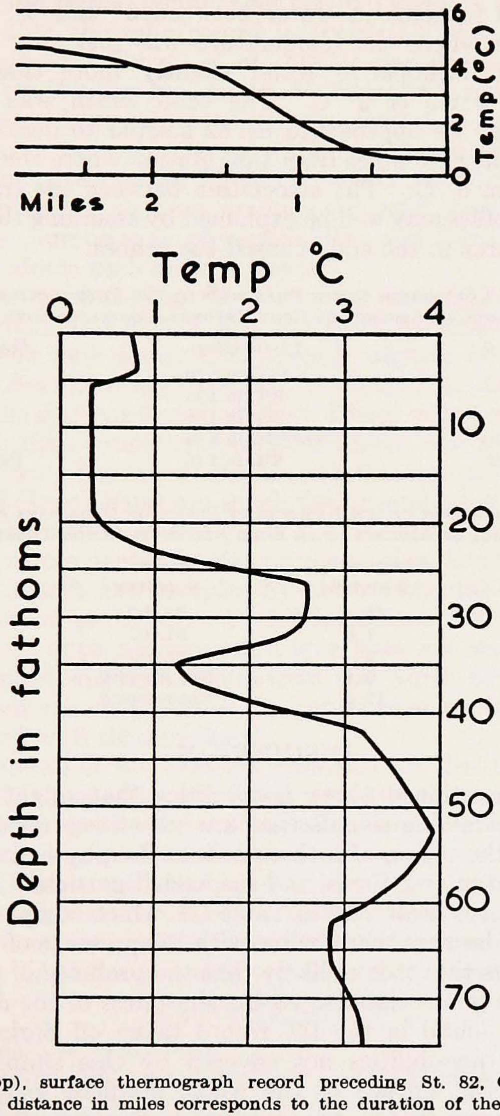

Figure 3. *a* (top), surface thermograph record preceding St. 82, Cruise V, ERNEST HOLT, 1952. The distance in miles corresponds to the duration of the noisy part of the record shown in Plate I *d*. *b* (bottom), bathythermogram at St. 82, Cruise V, ERNEST HOLT, 1952.

those below 50 fathoms in water between 3° and 4° C at St. 82 left the surface where the temperature was just over 4° C, whilst those above 50 fathoms in water slightly more than 2° C left the surface in water of 2° C. The echo which was at a depth of 100 fa. just as we approached St. 82 started to descend from the surface at a point nine miles from that station where the temperature fell sharply from 6° C. The association between the traces and the temperature profiles may well be explained by assuming that organisms carried downwards in the eddy caused the echoes.

TABLE III. Comparison of the Sharpness of the Thermocline with the Presence or Absence of Echo Records Associated with It

Station	*Thermocline*	*Echo record*
RNB 2	1½°C in 1 m	Yes
RNB 3	3°C in 1 m	No
RNB 4	3°C in 1 m	No
Centre Buoy	1–1½°C in 1 m	No
Slape Scar	2°C in 1 m	Possibly

TABLE IV. Comparison of the Numbers of Plankton Organisms per Litre with the Presence or Absence of an Echo Record from the Thermocline

Station	*Zooplankton organisms*	*Phytoplankton organisms*	*Echo record*
RNB 2	28	20,600	Yes
RNB 3	1.6	31,900	No
RNB 4	2	21,000	No
Centre Buoy	0.4	Not sampled	No
Slape Scar	17.6	Not sampled	Possibly

DISCUSSION

Earlier we mentioned three possibilities that might account for the rather considerable signals that are sometimes received by echo sounders from the region of a thermocline: the physical discontinuity itself, the plankton organisms, and suspended particles.

The first factor is dealt with in Table III, which compares the sharpness of the Windermere thermocline with the presence of echo records. This table shows that it is unlikely that the presence of an echo from the thermocline is associated with the sharpness of the discontinuity; confirmation is found in the BT record taken off Sörkapp (Fig. 2). There are two possibilities not covered by this simple treatment. First, perhaps the surface of the whole gradient and not just its sharpest boundary should be considered; hence one would expect signals extensive in time, which are not found. Second, small changes in the micro structure of the discontinuity might scatter sound back to the receiver, but this is unlikely to be of importance when the discontinuity is normal to the axis of the sound beam.

The effect of the second factor is set out in Table IV, from which it seems possible that the echo record is associated with the presence of plankton animals. Trout, *et al.* (1952) describe a thermocline echo obtained off Whitby by the M. V. Platessa, and it is worth noting here that this trace was distinctly patchy in its occurrence, being sometimes completely absent, whilst the thermocline persisted. The observations presented in Table IV do not constitute conclusive evidence that plankton animals produce the echo, but negative evidence from the numbers of phytoplankton and from temperature structure do reinforce such an hypothesis.

The evidence given in Fig. 1b shows an association between a marked echo trace and a thin but concentrated diatom layer. In Windermere there were about 25,000 cells/l, whereas off Hope Island in the Barents Sea there were 100,000, or about four times as many. Furthermore, the diatoms found off Hope Island were between 50 and 200 times larger than those found in Windermere, and the two species found in the Barents Sea layer form long chains; it is possible that the diatom layer off Hope Island was much thicker and more concentrated than that in Windermere.

The third possible factor is the presence of a layer of detritus. Counts of the North Sea samples by the sedimentation technique revealed numbers of particles up to 2,000,000/litre. At Windermere, however, numbers approaching such a level were not observed. This evidence, combined with the results from the North Sea, leads us to believe that sedimented particles do not always contribute to the echoes associated with thermoclines.

From examination of the evidence collected for the three possibilities, it seems that the echo associated with the thermocline was returned from a very definite layer of plankton organisms. Sometimes the layer may continue in the same form for many miles and sometimes, possibly in association with sinking vortices, layering becomes complex. It appears that both diatoms and animals, and in one case, detritus, if concentrated sufficiently at the thermocline, may scatter enough energy back to the receiver to record consistent signals.

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APPENDIX

Report of Observations by LT.-CDR. H. J. HODGES

RNB 1. Midday. Sun, white clouds and clear water (Trial dive). At a depth of 10 m I could see 19 feet in green water. The sun was constantly visible as a dull white area. I could distinguish between "hoppers" (zooplankton) and "sedimentation" (phytoplankton); as I looked upward, the plankton was brown against a pale green background, on looking horizontally it was white against a green background, and on looking down, nothing was seen. There was a general slow northerly drift of plankton in the upper layer (epilimnion); this was gauged by watching individuals moving across the field of view. Individual plankton animals made sudden hops in any direction and there appeared to be little difference in numbers either vertically or horizontally.

RNB 2. Afternoon. Heavy rain and dark clouds; wind from the SE. Visibility was reduced to the width of the boat. The thermocline was perceptible in a layer of approximately 8–10 inches thick; I found it easy to break the thermocline by forcing cold water up into the warm water and by forcing warm down into the cold. At RNB 1, by hanging onto my measured rope, I observed a positive drift of organisms to the north above the thermocline, but I noticed no such drift below it. At RNB 2, however, I did observe plankton organisms moving north beneath the thermocline, but those above it were moving much more rapidly.

RNB 3. Clouds with some sunshine. The thermocline was exactly at 9 m by my measured rope (suspended from the anchored ship). The boundary between warm and cold water appeared to lie within a 7 inch layer; it was possible to have three inches above the horizontal Ekman bottle, in warm water, and four inches below it, in cold water. At 9.5 m the water was much colder than at 9 m and it seemed that the boundary was actually limited to about 3 or 4 inches. The light, when I descended, changed from pale green above to a darker green across the boundary. When I looked horizontally below the boundary, visibility again increased markedly. Whether I was above or below, the boundary appeared as a line. The boundary is a visible line; from above it is rather like looking over the tops of clouds and from below it is rather like a cloud base. Above the thermocline, the plankton consisted of sedimentation (small brown or dark brown objects rather like cigarette ash) with a certain number of "hoppers" dispersed amongst it, the latter appearing black. Below the thermocline, only "hoppers" occurred. I estimated the drift in two ways: (a) by observing the plankton directly; all of them were moving in one direction, with the movement above the thermocline twice as fast as that below; (b) by using the air bubbles from my breathing set; below the boundary the air bubbles went up nearly vertically (5° from the vertical), but at the boundary they bent off sharply at an angle of 30° from the vertical.

RNB 4. Clouds with some sunshine. Above the boundary the bubbles went up at 25–30° from the vertical, below it at 5–10° from the vertical. I could now locate the thermocline by watching the rising bubbles alter course. Again there was a faster northward drift above the thermocline than below.

Hoppers (i.e., plankton animals) make no 'up and down' movement but usually make tight spiral or circular movements in any direction.