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Subsurface temperature and salinity conditions at Ocean Weather Stations ALFA, INDIA and JULIETT in 1964

by

D. J. Ellett

Fisheries Laboratory, Lowestoft

Introduction

In 1961 British Ocean Weather Ships began a programme of weekly serial water-bottle observations during their periods of duty at Ocean Weather Stations ALFA, INDIA, JULIETT and KILO. Winches and sampling gear were installed by the Admiralty aboard the four ships operated by the Meteorological Office, and the observations have been made by the ships' officers. Instruction of the crews of two of the ships at sea was carried out by the Fisheries Laboratory, Lowestoft, and in 1964 this laboratory became responsible for processing the data collected and for the general standards of thermometry and salinometry. Accuracy of the data in the earliest years of the scheme was somewhat reduced by a shortage of thermometers and by a number of salinity sampling and determination difficulties. By the early months of 1964 these troubles had been eliminated and the accuracy of the observations since may be regarded as approximating closely to research vessel standards.

The number of serial stations worked during each month of 1964 at ALFA, INDIA and JULIETT is shown in Table 1. In this year station KILO was occupied for one month only by a British weather ship, and the sets of data obtained will be considered at a later date with others taken at the same station in subsequent years. In general, the water-bottles were aimed to sample at depths of 10 and 250 metres and at standard depths from 300 metres downwards. Complementary temperature data in the upper layers have been obtained by means of twice-daily bathythermograph observations, which are not considered here. The water-bottle data have been processed with the aid of a computer program which produces temperature and salinity values interpolated to the depths given above by the method of Rattray (1962). These values have been meaned over the year for each level at each of the three weather stations. Table 2 sets out the number of observations available at each level, the means and their standard deviations, and these two latter are plotted as temperature and salinity profiles against depth in Figure 1. Because of the relatively low sampling frequencies and irregular sampling within the year the 10 metre means must be regarded as a very rough approximation only to the true mean annual characteristics of the highly variable surface layer. As both salinity and temperature values are likely to be non-normally distributed about the means their standard deviations must be used to determine confidence limits with some caution, but it is felt that the figures give a useful measure of the greatly differing degrees of variability encountered at the three stations. Figure 2 shows the mean values plotted in the form of temperature-salinity diagrams, and the comparison between these enables us to make a number of useful deductions about the circulation of the north-east Atlantic.

Table 1 Number of sets of observations per month at Ocean Weather Stations ALFA, INDIA and JULIETT in 1964

Month	Number of observations		
	ALFA	INDIA	JULIETT
January	4	4	-
February	-	4	4
March	3	4	4
April	5	5	-
May	-	2	3
June	1	-	5
July	3	6	2
August	-	4	6
September	-	6	10
October	-	6	6
November	-	3	4
December	-	6	5
Total	16	50	49

Ocean Weather Station ALFA (62°N, 33°W)

Sixteen sets of observations were obtained at this station between January and July 1964. Twelve of these sets were taken within 20 nautical miles radius of the nominal station position and the remaining four at distances of from 23 to 35 nautical miles from the central position. Figure 1 and Table 2 show that the variation in temperatures at the standard depths was generally a little less than at INDIA and much less than at JULIETT, and that salinity variations were notably less than at both the other stations. At 2000 and 2500 metres the standard deviation of the salinity

Table 2 1964 mean temperatures and salinities at standard depths and their standard deviations at Ocean Weather Stations ALFA, INDIA and JULIETT

Depth	ALFA (62°00'N, 33°00'W)						INDIA (59°00'N, 19°00'W)						JULIETT (52°30'N, 20°00'W)					
	n	$\bar{t}$°	S.D.	n	$\bar{S}$°/oo	S.D.	n	$\bar{t}$°	S.D.	n	$\bar{S}$°/oo	S.D.	n	$\bar{t}$°	S.D.	n	$\bar{S}$°/oo	S.D.
10	16	6.74	1.267	16	34.998	0.0334	45	10.52	1.114	43	35.277	0.0502	56	13.02	2.007	57	35.298	0.0624
250	12	5.66	0.378	12	34.979	0.0238	44	9.64	0.425	43	35.293	0.0466	48	10.16	0.450	48	35.317	0.0767
300	16	5.66	0.423	15	34.989	0.0302	49	9.55	0.418	49	35.293	0.0469	43	9.75	0.587	49	35.277	0.0829
400	16	5.38	0.439	16	34.984	0.0292	49	9.29	0.402	49	35.283	0.0502	41	8.57	1.624	42	35.178	0.0983
500	15	5.11	0.326	15	34.977	0.0183	49	8.90	0.368	49	35.259	0.0497	42	7.80	0.972	42	35.111	0.0991
600	15	4.79	0.369	15	34.961	0.0191	50	8.52	0.415	48	35.254	0.0548	41	6.98	0.775	41	35.105	0.0734
800	15	4.19	0.278	15	34.940	0.0194	50	7.17	0.537	50	35.179	0.0592	41	5.85	0.594	40	35.104	0.0656
1000	15	3.82	0.159	15	34.921	0.0194	48	5.83	0.460	47	35.097	0.0511	41	4.72	0.356	40	35.012	0.0404
1200	15	3.67	0.065	15	34.918	0.0159	44	4.75	0.296	44	35.014	0.0353	39	4.10	0.180	38	34.958	0.0264
1500	15	3.67	0.038	15	34.943	0.0148	12	3.89	0.113	12	34.946	0.0133	37	3.73	0.067	36	34.933	0.0135
2000	11	3.46	0.048	11	34.964	0.0033	-	-	-	-	-	-	33	3.44	0.065	31	34.944	0.0114
2500	4	3.10	0.051	3	34.964	0.0042	-	-	-	-	-	-	8	3.07	0.104	7	34.948	0.0096

values is equal to that of the inductive method of determination, which reflects favourably upon the accuracy of the original observations.

The characteristics of the water column at station ALFA have been measured by the very complete serial observations made by Norwegian vessels at this station over the course of a number of years (Mosby 1965) and have recently been the subject of detailed study by Blindheim (1968). Our t-s diagram for the January to July 1964 observations (Figure 2) illustrates the general features clearly. The upper waters of the eastern Irminger Sea are formed by the mixing of Atlantic water with colder and fresher surface waters from the south and west. The means of 116 observations taken at 100 metres depth at station ALFA by Norwegian weather ships between 1954 and 1965 provide us with a general value for this Irminger Atlantic Water of 6.42^{o} and 35.002^{o}/oo, but Blindheim (loc. cit.) has shown that year to year salinity variations are large at station ALFA and appear to increase with the predominance of north-easterly wind conditions at the station. Our mean t-s diagram has higher salinity values at temperatures above 4^{o}C than the mean t-s curves for July-December 1954 and July 1956 to January 1957 given by Blindheim, but has lower salinities than those for the other three periods of Norwegian observations, June to December 1958, June to December 1960 and November to April 1963. In Figure 2, apart from an artefact produced between 250 and 300 metres by the differing numbers of observations, the t-s curve descends directly to a salinity minimum at 1200 metres, with values close to those of Labrador Sea Water characterized by Worthington and Metcalf (1961) as having a potential temperature of 3.4^{o}C and a salinity of 34.89^{o}/oo. Subsequently the salinity increases and the points at 1500 and 2000 metres indicate mixing between Labrador Sea Water and North-east Atlantic Deep Water, the product of the overflow of Norwegian Sea Water across the Iceland-Scotland ridges assigned the general characteristics of potential temperature 2.6^{o}C and salinity 35.03^{o}/oo by Lee and Ellett (1967). Only four sets of observations extended to 2500 metres, but these show mixing with a markedly colder water mass, possibly the product of the Iceland-Greenland overflow. Both the deep salinity maximum and the minimum have more extreme values at ALFA than at JULIETT.

Ocean Weather Station INDIA (59^{o}N, 19^{o}W)

Fifty sets of data were taken during 1964 at this station, and June was the only month in which samples were not obtained. Thirty-two observations were made within 10 nautical miles of the centre of the station grid, and only seven sets were made at distances of more than 20 miles from it. This is the shallowest of the three stations, with a bottom which rises sharply to the eastward, and observations are limited to depths of 1500 to 1900 metres. Figure 1 shows the greater variability of temperature and salinity at this station in 1964 compared with that found at ALFA, and examination of Table 2 shows that this is greatest at the 800 metre standard depth. In contrast to station JULIETT, the mean temperature gradient at INDIA is much less steep, and Figure 2 brings out the remarkable point that depth for depth below about 320 metres temperatures at the more northern station were the higher by amounts of up to 1.5°C.

The t-s curve for station INDIA in Figure 2 descends between 250 and 600 metres depth across the envelope ascribed by Sverdrup, Johnson and Fleming (1942) to North Atlantic Central Water, but below this shows a higher salinity content than the Central Water. This, allied with the greater variability of conditions at depths of 600 to 1000 metres, shows conclusively that this part of the water column contains a proportion of water of Mediterranean origin, named by Cooper (1952) Gulf of Gibraltar Water. The presence of this water mass at intermediate depths has previously been demonstrated as far north as latitude 50°N, in the area to the south-west of Porcupine Bank by Cooper, Jones and Lee (1962), where closely spaced samples enabled salinity maxima to be delineated at depths of 850 to 1000 metres. Such maxima could not be shown by the standard depth samples of our observations, but it is possible that close-interval sampling might encounter them. In the Bay of Biscay and off the Portuguese coast large and rapid changes have been observed in the Gibraltar Water layer (Ellett 1965), and these could be the cause of the greater variability in conditions at INDIA in the 600 to 1000 metre depth range. An alternative explanation might be that the water approaches the station by differing routes.

Below 1000 metres the t-s curve descends towards the Labrador Sea salinity minimum. A few observations made between 1800 and 1900 metres depth show that salinity values began to increase again below 1500 metres.

Ocean Weather Station JULIETT (52°30'N, 20°W)

Forty-nine sets of observations to depths of 250 metres and over were made in 1964 at this station, no data being available for the months of January and April. Thirty-three serial stations were taken within 10 nautical miles radius of the centre of the station grid, and only four were made at distances of over 20 nautical miles from it. Figure 1 and Table 2 show the great variability of conditions at JULIETT in 1964, temperatures varying most at the 400 metres standard depth, and salinities at 500 metres. Between

500 and 800 metres the mean salinity values changed little, but individual salinity-depth profiles had greatly varying gradients between these depths. Below 800 metres both temperature and salinity variations were somewhat less than at the same depths at station INDIA.

Figure 2 shows the mean t-s curve for the station. The upper points fall within the envelope of North Atlantic Central Water characteristics. Mixing is not taking place towards the point marking Labrador Sea Water, but apparently towards values characteristic of what we have called Irminger Atlantic Water in our discussion of station ALFA. However, I am grateful to Mr A. J. Lee for pointing out that the observations obtained during the three 1963 NORWESTLANT surveys (Lee, in press) preclude the possibility that water from the vicinity of station ALFA could have reached JULIETT. Cold, low-salinity water was found to be extending eastwards in the upper few hundred metres of the water column from the area to the south and south-west of Cape Farewell, forming an effective barrier to such a movement. It may be inferred from the NORWESTLANT data that this sub-arctic water adjoined the Atlantic Current at about 50°N latitude, the situation being similar to that shown by Dietrich and Stefánsson (1963), who, in April-May 1961, observed a low-salinity tongue running eastwards to 30°W between latitudes 52 and 55°N, the oceanic Polar Front being situated between 50 and 51°N.

Dietrich (1964) has shown that, during IGY observations taken in spring and autumn 1958, the front was distinguishable at 200 metres depth as far east as 20 to 25°W, and it would appear that in 1964 the frontal zone lay frequently in the vicinity of station JULIETT. Probably at its eastern extremity the front meanders and forms weak secondary fronts which could have been responsible for the large variations at JULIETT. Howe and Tait (1967) have described a large detached eddy observed by them near JULIETT in July 1965 which had temperature and salinity characteristics frequently reproduced by individual t-s diagrams of the 1964 data, and the rapid passage of small "parcels" of cold water through JULIETT was observed in September 1962 with the aid of a temperature-depth recorder (Lumby and Ellett 1965). In fact, only a small number of the individual 1964 t-s curves, chiefly those for February and March, had a vertical section between 500 and 800 metres like that which, in Figure 2, leads the mean t-s curve to values which we have deduced at INDIA to be those of North Atlantic Central Water with a Gibraltar Water admixture. More often, and most especially during the last quarter of the year, a sharp discontinuity of salinity was encountered between the mixed sub-arctic water and the Central Water, producing at times near-horizontal (i.e. isothermal) portions of the t-s curves, and on a few occasions slight temperature inversions. Examples of such observations are shown in Figure 3. The salinity inversions occurred sometimes in the 500-600 metre depth range, as on 21 and 26 October, sometimes in the 600-800 metre depth range, as on 17 December, and as often spanned both ranges, according to the respective magnitudes of the salinity minimum above the boundary and the salinity maximum below it. As mentioned previously, standard depth observations can give only approximate information about the form and depth of any interface between water masses. The inset of Figure 3 shows observations taken at JULIETT in September 1962 with water-bottles spaced at 25 metre intervals, and suggests that our 1964 observations at standard depths will have frequently missed sampling the extreme values of the maximum and minimum salinities.

Figure 4a is an isopleth diagram of salinity against depth and time centred upon October 1964. If we bear in mind the aliasing effect of the standard depth observations, the figure usefully shows the beginning and development of a salinity inversion at depths between 450 and 850 metres. Figure 4b shows an instance in December when both maximum and minimum showed strong development over the same period. Examination of the complete data for the year confirms that the development of a maximum was no bar to the development of a minimum and vice versa, indicating that their relative strengths cannot be related solely to spatial changes, but rather that both water masses were subject to internal variations.

Returning to our discussion of the mean t-s diagram for JULIETT of Figure 2, we find that from 800 metres to 1500 metres the relationship followed the same path as that for station INDIA, though with notably lower temperature and salinity values at the same standard depths. The salinity minimum caused by the presence of Labrador Sea Water occurred in the vicinity of 1500 metres, and below this higher salinity means show the influence of North-east Atlantic Deep Water.

Discussion

Our examination of the water column at these three ocean weather stations has shown a number of features of the general structure of the north-east Atlantic. We have, for instance, been able to confirm that Labrador Sea Water underlay the more saline Atlantic waters of the area at depths which increase towards the east, and that North-east Atlantic Deep Water was present beneath this at the two deeper stations. More notably we are led to a number of conclusions about the oceanic circulation responsible for the features of the intermediate depths of the water columns.

Firstly, it appears that station JULIETT lay close to the oceanic Polar Front in 1964. This being so, the greater bulk of the sub-surface water approaching the British Isles from the south and south-west must have passed across the 200 miles of deep water between JULIETT and Porcupine Bank.

Secondly, water which was warmer and slightly more saline to a depth of at least 1500 metres reached INDIA, and hence must have passed northwards to the eastward of JULIETT. Station INDIA is situated on the northwestern corner of the deep-water banks to the west of Rockall and consideration of the sill-depths of the channels to the east of the station make it probable that water from between JULIETT and Ireland reaches INDIA by skirting the southern and western edges of the banks lying between JULIETT and INDIA.

Thirdly, at intermediate depths the water columns at both INDIA and JULIETT had a significant Gibraltar Water content. It is not possible to tell from the standard depth observations whether this existed as a layer with sharp boundaries above and below it, or whether mixing had produced a modified Central Water.

All these points accord well with the streamlines of the North-east Atlantic sub-surface circulation drawn by Helland-Hansen and Nansen (1926), which are shown in Figure 5. These approach the position of JULIETT from the south-south-west, curve around the station, suggesting the proximity of the Polar Front, and then head north-westwards. The NORWESTLANT results (Lee, in press) indicate that the outer streamline continues westwards into the Irminger Sea. The inner streamline, containing one would imagine water of higher temperature and salinity depth for depth than its companion, travels from the deep water between JULIETT and Porcupine Bank to station INDIA. Helland-Hansen and Nansen deduced an active contribution to the northern branch of the Atlantic Current by water containing Mediterranean outflow, and the topography of the 1000 metre surface relative to 2000 metres drawn by them (not reproduced here) indicates a flow from the Iberian continental shelf by way of the deep water immediately to the west of Porcupine Bank and thence to the vicinity of station INDIA.

Helland-Hansen and Nansen had no data for the southern Rockall Channel and their scheme of circulation shows no details in this area. High-salinity water from the western Biscay region appears along the edge of the Irish continental shelf on mean charts drawn from the 20 years of surface observations made by weather ships on passage to and from stations INDIA and JULIETT, and it seems possible that the sub-surface waters flowing into this channel may come from a southerly direction after undergoing modification in the eastern North Atlantic Basin, rather than approaching it directly from the North Atlantic Current.

Conclusion

The correspondence between the deductions drawn from our data and those of Helland-Hansen and Nansen inspire some confidence in this model of the circulation of the northern branches of the North Atlantic Current, simplified though it may be in many respects, and suggests that the areas between Ireland and JULIETT and between Iceland, INDIA and Scotland are worthy of detailed research. Work at the ocean weather stations has continued in the years since 1964 and the results are likely to yield interesting data about changes in the water column with time.

Summary

Mean curves of data obtained by weekly sampling through the water column from 250 metres downwards at Ocean Weather Stations ALFA, INDIA and JULIETT during 1964 have allowed the following conclusions to be drawn:

1. Variations of temperature and salinity were greatest at JULIETT at depths down to 800 metres. At INDIA the variation was generally less, but it had a maximum (below 250 metres) at 800 metres depth. At ALFA, where samples were available for January to July only, temperature and salinity variations were the least of these for the three stations.
2. Below 320 metres, to the lowest observations at 1500 metres, temperatures and salinities were higher by up to 1.5°C and 0.15‰ at INDIA than at the same depths at JULIETT, 400 miles further south. This implies that a main branch of the Atlantic Current passes to the east of JULIETT and reaches INDIA.
3. The upper part of the intermediate depths at JULIETT were frequently occupied by water with a low salinity, suggesting that secondary fronts, or cut-off cold eddies passed through the station, which must have been close to the oceanic Polar Front.
4. The lower intermediate waters at both JULIETT and INDIA contained a marked component of Gulf of Gibraltar Water.
5. Conclusions made from these points about the oceanic circulation in the area between JULIETT and INDIA fit well with the streamlines of the northern branches of the Atlantic Current drawn by Helland-Hansen and Nansen (1926).

Acknowledgements

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References

BLINDHEIM, J., 1968. Hydrographic investigations in the Irminger Sea in the years 1954-1964. FiskDir. Skr. Ser. Havunders., 14, 72-97.

COOPER, L. H. N., 1952. The physical and chemical oceanography of the waters bathing the continental slope of the Celtic Sea. J. mar. biol. Ass. U.K., 30, 465-510.

COOPER, L. H. N., JONES, P. G. W. and LEE, A. J., 1962. Hydrographical conditions along the 14°W meridian south-west of Ireland, July 1960. Annls biol., Copenh., 17, 75-6.

DIETRICH, G., 1964. Oceanic Polar Front survey in the North Atlantic. Research in Geophysics, 2, 291-308. (Ed. H. Odishaw). The M.I.T. Press, Cambridge, Mass., 608 pp.

DIETRICH, G. and STEFÁNSSON, U., 1963. Hydrographic conditions in the northern North Atlantic in April/May 1961. Annls biol., Copenh., 18, 18-23.

ELLETT, D. J., 1965. Hydrographic observations off the Iberian Coast, June-July 1963. Annls biol., Copenh., 20, 73-82.

HELLAND-HANSEN, B. and NANSEN, F., 1926. The eastern North Atlantic. Geophys. Publ., 4(2). 76 pp.

HOWE, M. R. and TAIT, R. I., 1967. A subsurface cold-core cyclonic eddy. Deep-Sea Res., 14, 373-8.

LEE, A. J. (in press). Section on Physical oceanography. Spec. Publ. int. Commn NW. Atlant. Fish., (7).

LEE, A. J. and ELLETT, D. J., 1967. On the water masses of the Northwest Atlantic Ocean. Deep-Sea Res., 14, 183-90.

LUMBY, J. R. and ELLETT, D. J., 1965. Some considerations on oceanographic observations. J. Cons. perm. int. Explor. Mer, 29, 237-48.

MOSBY, H., 1965. Oceanographic tables from Weather Ship Station A, (62°N, 33°W), 1954-65. Univ. Bergen, Geophys. Inst., Bergen.

RATTRAY, M., Jr., 1962. Interpolation errors and oceanographic sampling. Deep-Sea Res., 9, 25-37.

SVERDRUP, H. U., JOHNSON, M. W. and FLEMING, R. H., 1942. The oceans: their physics, chemistry and general biology. New York, Prentice-Hall, Inc. 1087 pp.

WORTHINGTON, L. V. and METCALF, W. G., 1961. The relationship between potential temperature and salinity in deep Atlantic water. Rapp. Cons. Explor. Mer, 149, 122-8.

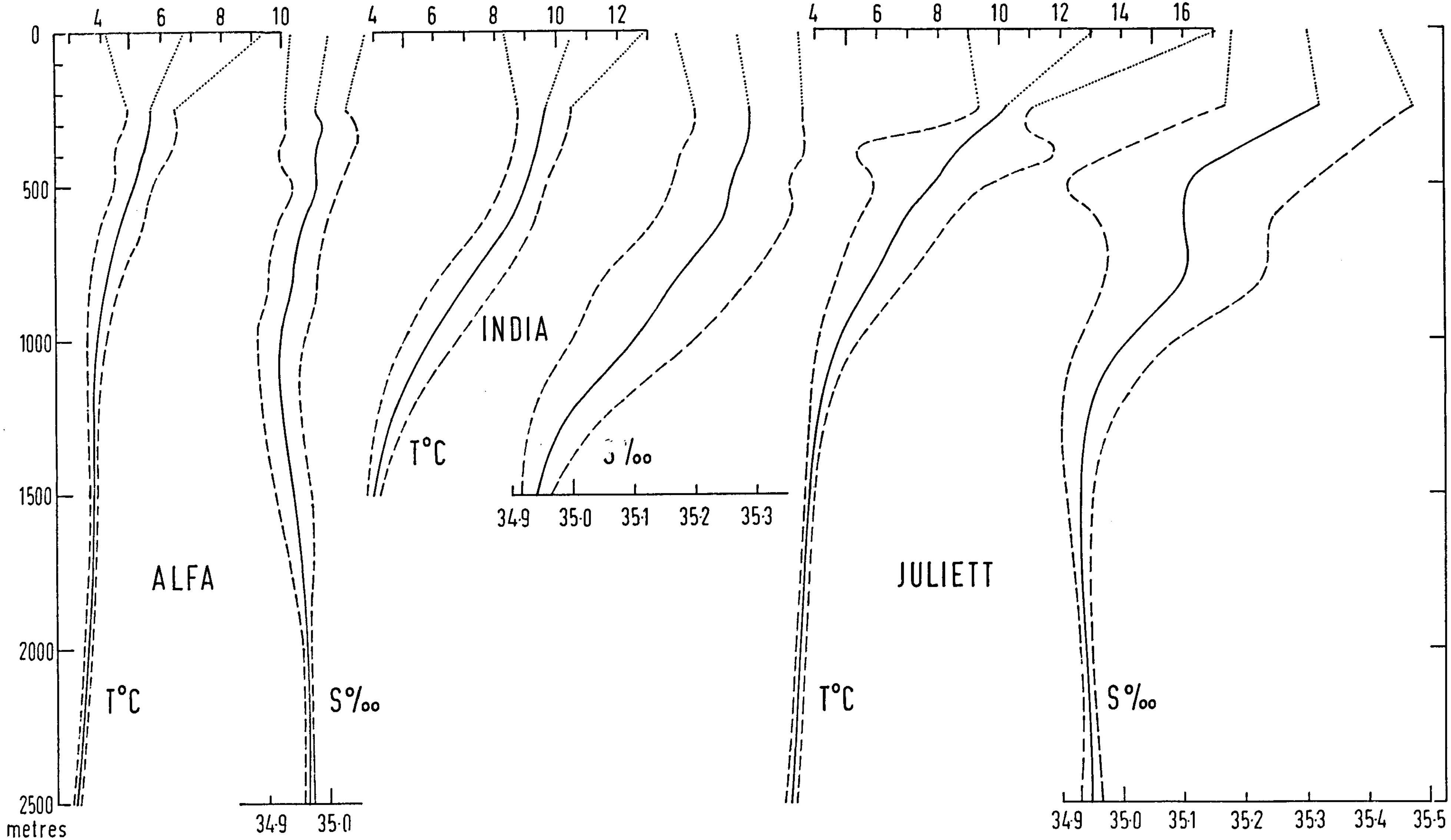

Figure 1 Mean temperature and salinity profiles, Ocean Weather Stations ALFA, INDIA and JULIETT, 1964. (Mean values shown by continuous lines. Broken lines represent limits of two standard deviations above and below means).

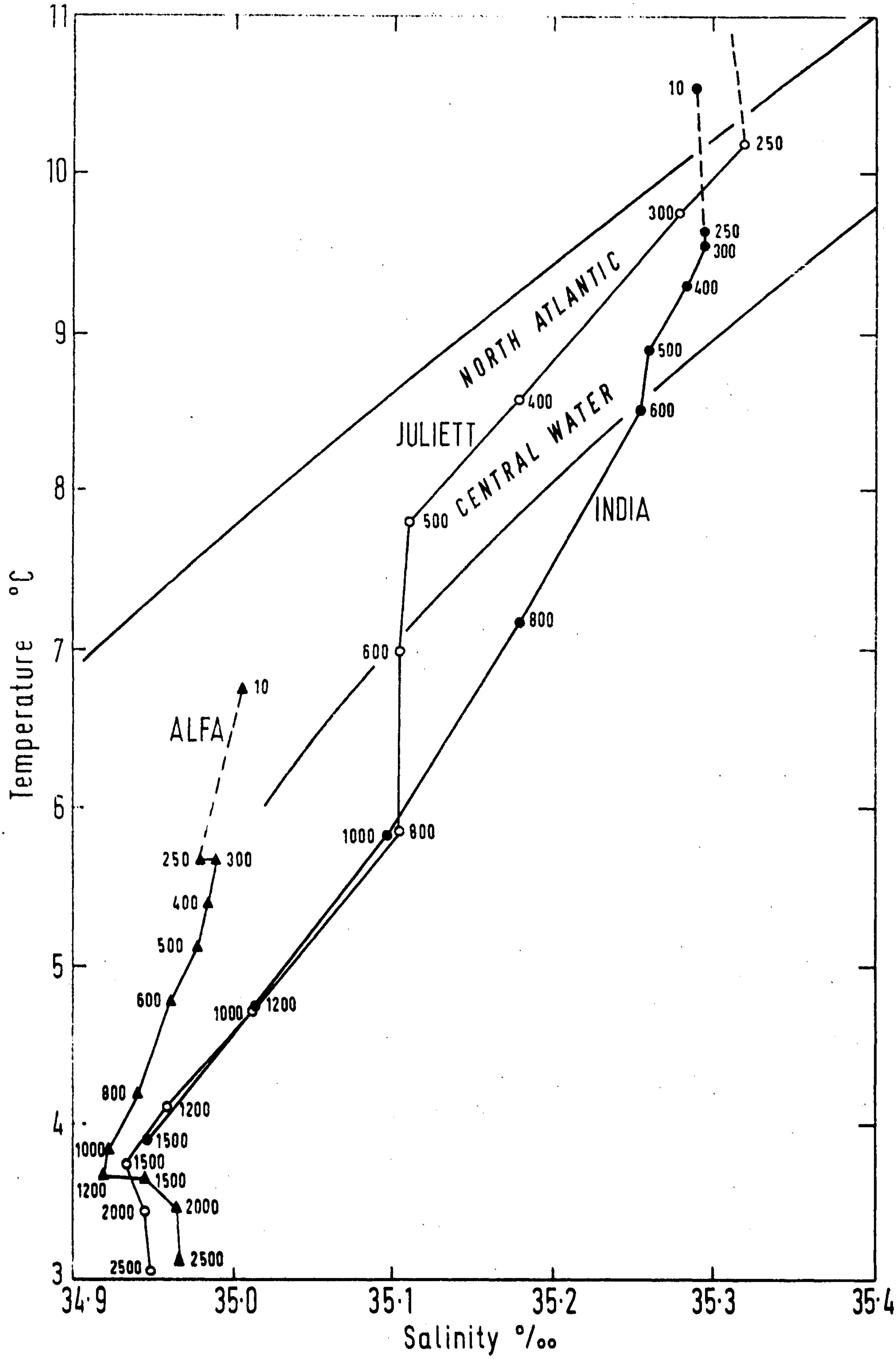

Figure 2 Temperature-salinity diagrams for the 1964 mean values at Ocean Weather Stations ALFA, INDIA and JULIETT.

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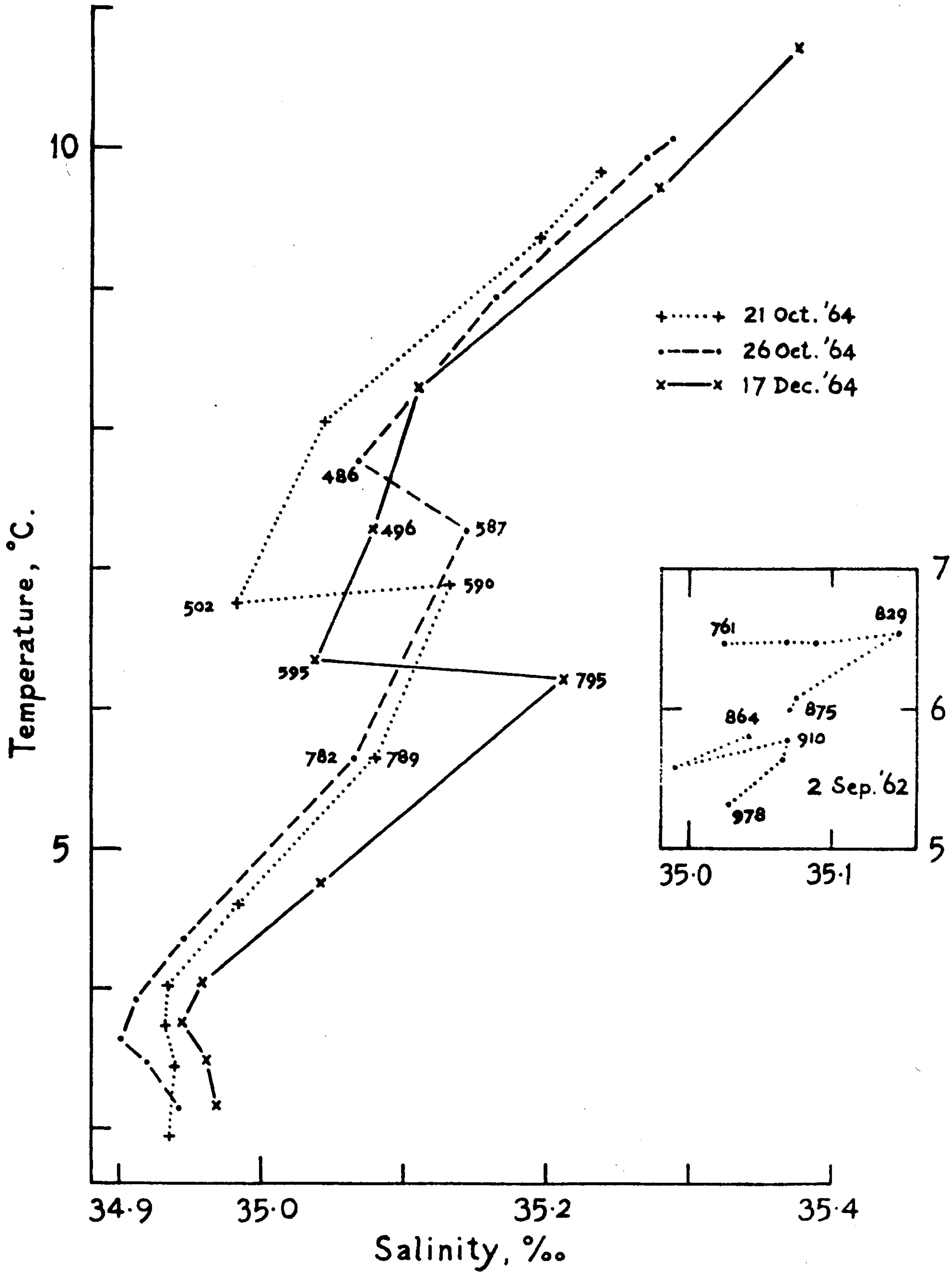

Figure 3 Examples of temperature-salinity diagrams at station JULIETT.

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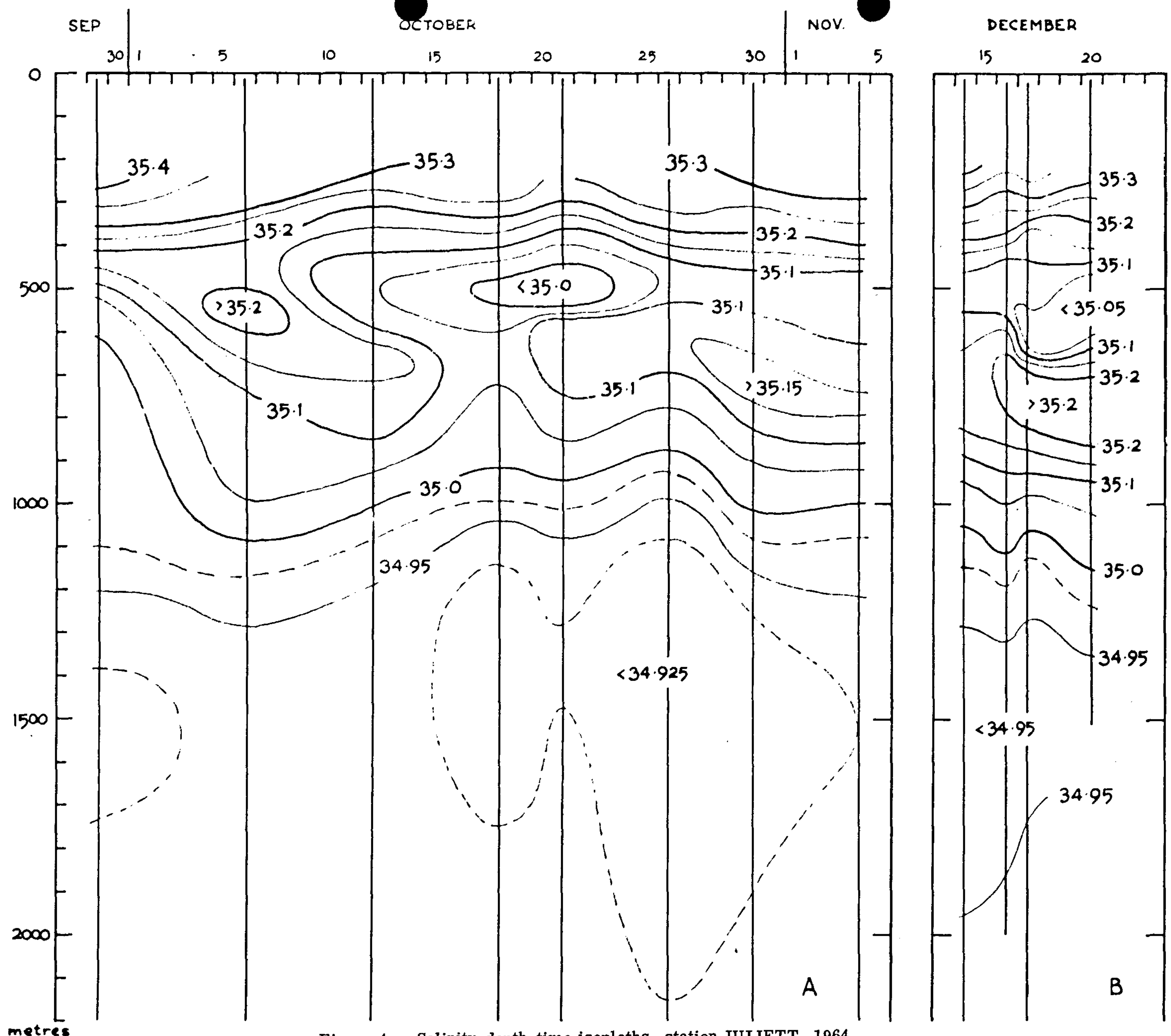

Figure 4 Salinity-depth-time isopleths, station JULIETT, 1964
a. 29 September-4 November b. 14-20 December.

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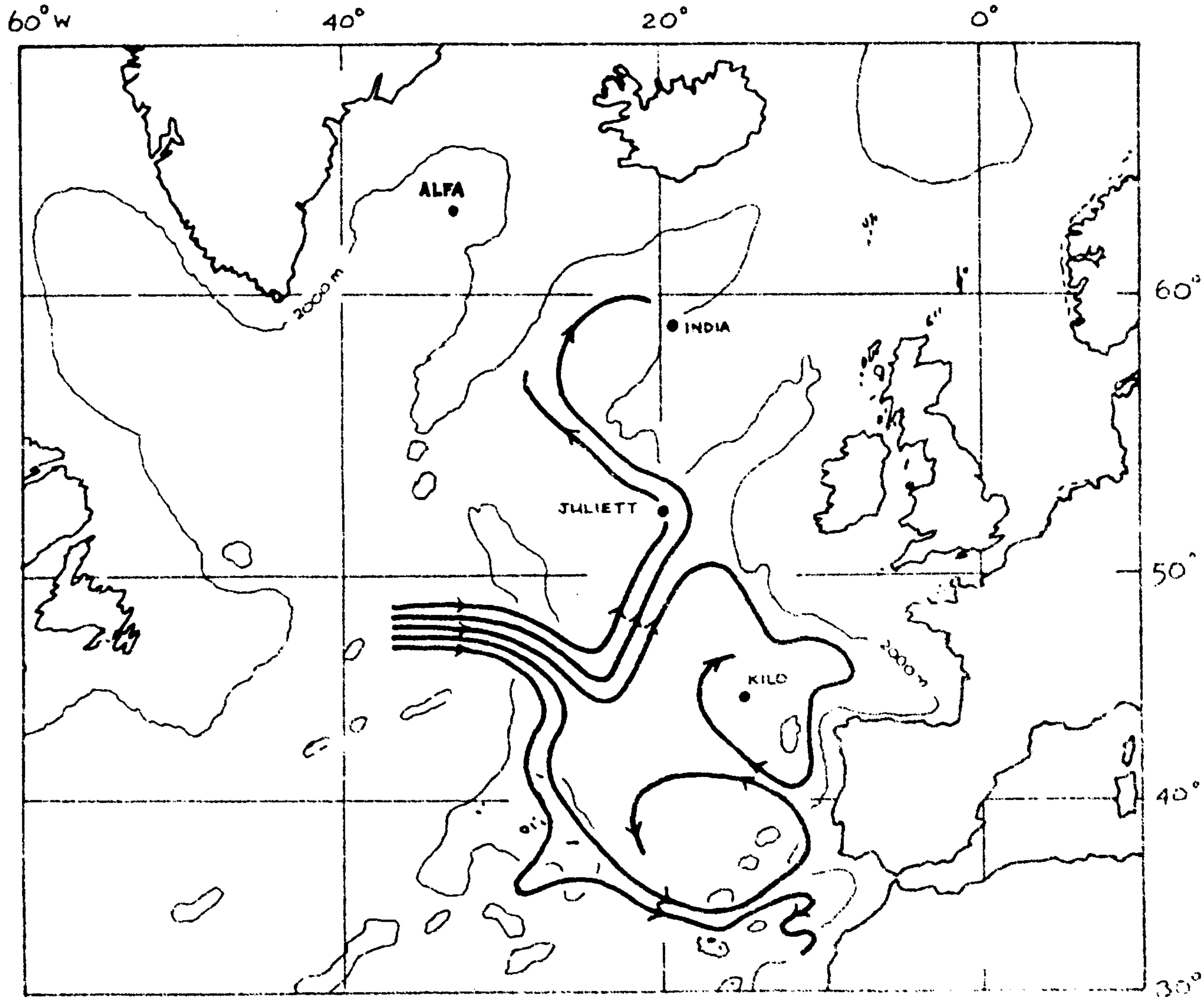

Figure 5 The sub-surface circulation of the eastern North Atlantic, according to Helland-Hansen and Nansen.

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