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*On the Oceanography of
Jones Sound, N.W.T.*

F.G. Barber and A. Huyer

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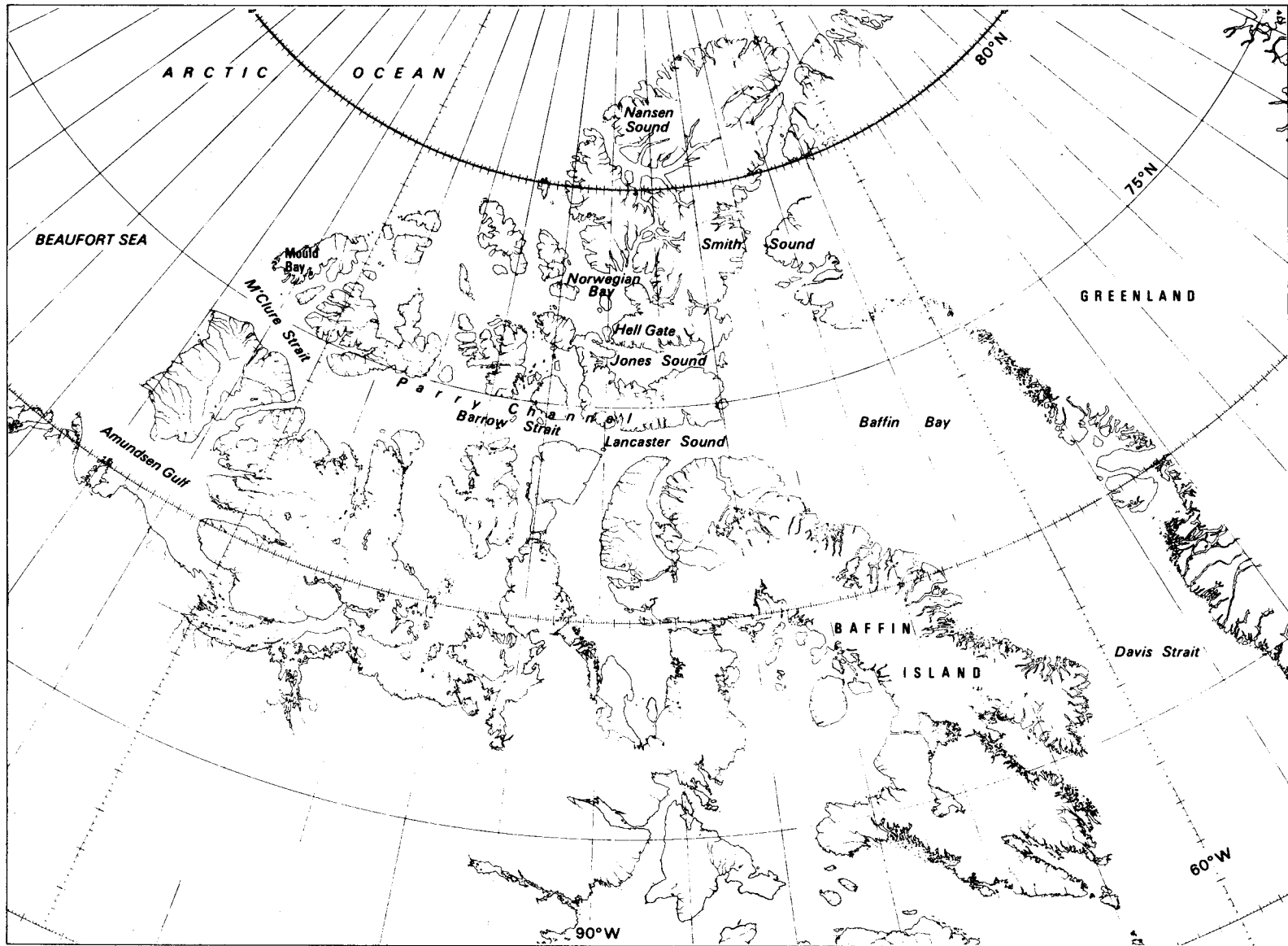
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Frontispiece. Location of Jones Sound, N.W.T., Canada.



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1. ABSTRACT

Distributions of salinity, temperature and dissolved oxygen in Jones Sound indicate the movement of a surface water from the central archipelago and a deeper water from Baffin Bay. The extent that the region becomes ice-free each year can be reflected in surface distributions and a particular area of open water, the North Water, likely contributes to an annual variation observed at depths below the surface layer.

RÉSUMÉ

Nous décrivons les distributions de la salinité, la température et l'oxygène dissous dans le "Jones Sound" et prévoyons l'importance d'un mouvement superficiel de l'archipel central et d'un mouvement plus profond de la baie de Baffin. Les distributions à la couche de surface sont fortement influencées chaque saison par l'étendue de la surface libre et la région de "North Water" bien connue de nous contribue peut être à la variation annuelle observée.

2. INTRODUCTION

Oceanographic data were obtained in 1963 in Jones Sound (frontispiece) in CCGS "Labrador" while the vessel was engaged in routine patrol in arctic waters. The material is the most extensive obtained in the sound to 1963 (Table 1) and as well, appears to be of high quality. The purpose here is to provide a pictorial presentation and a description of the data with a review of earlier observations. Twenty-five positions (Figure 1) were occupied during the period September 24 to September 28 at each of which a bathythermogram and serial data for salinity, temperature and dissolved oxygen were obtained. The work was undertaken as a general programme of study of the water of the arctic archipelago begun in 1960, which was to include the application of budget techniques to data obtained up to 1962 and the presentation of the data in atlas form. The 1961 and 1962 observations have been combined in one such atlas (Barber and Huyer, 1971) and aspects of heat and volume budgets also have been reported (Huyer and Barber, 1970; 1971); an atlas of the 1960 observations is in preparation.

Table 1. A listing of oceanographic data observed in Jones Sound from shipboard up to and including the 1963 season, indicating the year, the ship, the CRN number and one appropriate reference. Dunbar (1951 p. 19) noted that USS "Edisto" visited Jones Sound in 1947.

<u>Year</u>	<u>Ship</u>	<u>CRN</u>	<u>Reference</u>
1928	"Godthaab"	2601-28-001	Riis-Carstensen, 1936
1952	"Edisto"	368	*Anonymous, 1954
1954	"Labrador"	219	Bailey, 1955
1962	"John A. MacDonald"	359	Anonymous, 1966
1962	"Labrador"	362	Anonymous, 1967a
1963	"Labrador"	10-63-005	Anonymous, 1967b

*Classified

Although most of the observations of 1960-1962 were made during the months of September and October, they suggested considerable variability, mainly in temperature, which it was thought might reflect changes of annual period, either in a pattern of circulation or of the character of the water in the circulation. During the preparation of the data report for the 1963 data (Anon., 1967b) it was considered that relatively less variation occurred in that portion of the data for Jones Sound (e.g. Figure 4 here) particularly within the surface layer. It seemed that this could be due in part to the relatively restricted connections to the western archipelago, i.e. Hell Gate and Cardigan Strait, through which a movement of a surface water into Jones Sound was likely. In addition, the horizontal temperature gradient in the deeper water was considerably less than observed in eastern Lancaster Sound and northern Baffin Bay where an obvious influence was a warmer element, apparently from west of Greenland and the Labrador Sea. However, in neither Lancaster Sound nor Jones Sound was it clear where the colder element of the

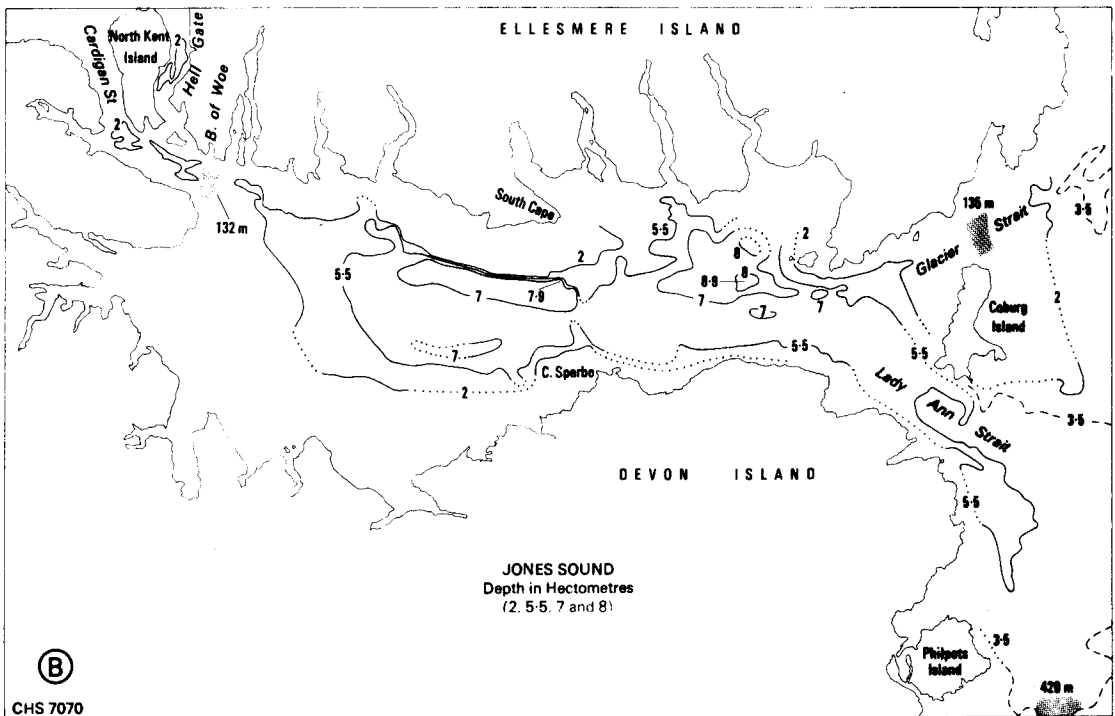
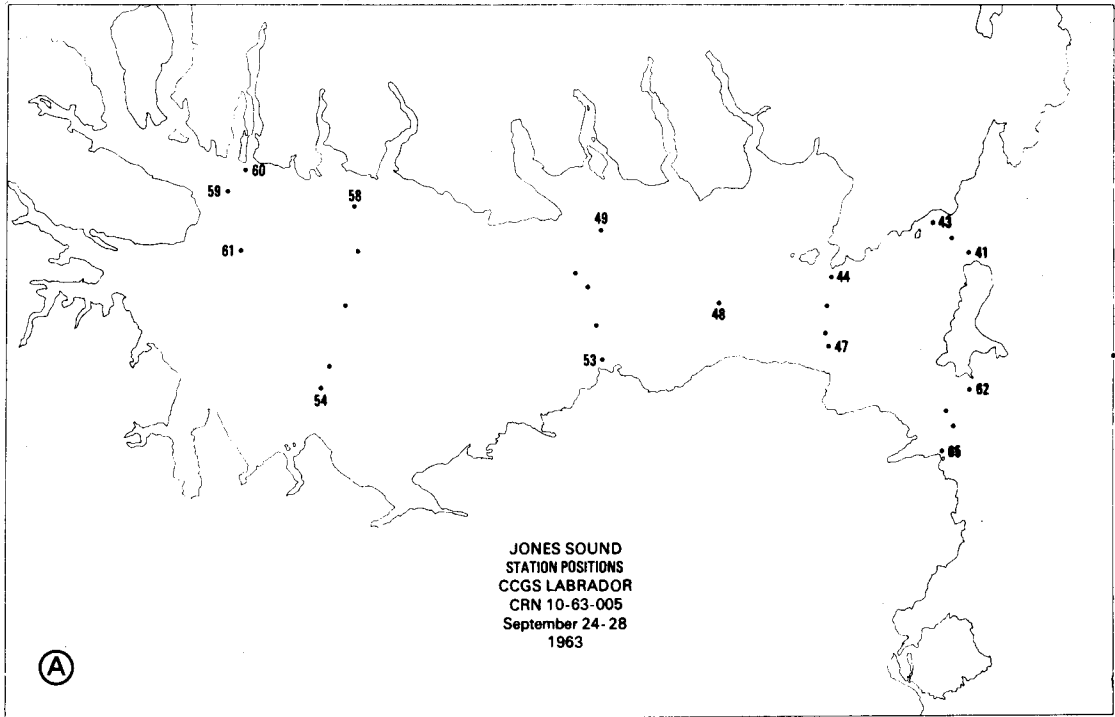


Fig. 1. General information. (a) Approximate position and number of the stations occupied in Jones Sound in CCGS "Labrador" in 1963 (Anon., 1967b). (b) Place names and bathymetry from Canadian Hydrographic Service charts 7070 and 7950. Probable areas of threshold depth are shaded.

gradient originated; it seemed certain not from the west and it was considered that perhaps it entered from the Arctic Ocean through Nares Strait or perhaps it was formed locally, i.e. in northern Baffin Bay. The latter possibility had been a particularly engrossing one, for the formation of such a cold water could be expected if a feature such as North Water (Dunbar, 1973a) were significant. As well, the curious structure of the deep and bottom water of Baffin Bay seemed to require further elaboration which might possibly include local processes, perhaps those occurring at the surface and perhaps in association with mixing and exchange processes originating with the tide. Subsequently, Muench (1971) has discussed the oceanography of Lancaster Sound, as well as possible modes of formation of both North Water and the deep and bottom water of Baffin Bay and he provided a tabulation of some of the available oceanographic data with a detailed description of them. More recently, Sadler (1976a,b) in a description of data observed in Nares Strait, provided estimates of the transports there and described the formation of a Baffin Bay Bottom Water.

3. DESCRIPTIVE

A useful reference for general information is the work of Dunbar and Greenaway (1956), while somewhat more detail concerning Jones Sound is available in the Pilot of Arctic Canada (Anon., 1968a) including climatic information and a climatological table for Craig Harbour. The latter table indicates an extraordinary frequency of calms which it notes, may be due to the location of the weather observing site. The following two paragraphs are from the Pilot (p. 393):

Almost the whole of Jones Sound is surrounded by steeply rising shores, backed by mountainous terrain. On the north-eastern side of the sound, a highland zone of ancient Precambrian rocks, forming the southeastern part of Ellesmere Island, extends northward and rises to an elevation of about 4,500 feet (1,371 m 6); westward of this, the rocks are overlain by increasingly thicker strata of later sedimentaries which extend inland beyond the heads of the numerous fiords indenting the north side of the sound. Elevations decrease westward, to about 1,500 or 2,000 feet (457 m 2 or 609 m 6) near Hell Gate. Sverdrup has aptly described the northern side of Jones Sound as "one perpendicular headland after another, with high bluffs and precipices falling straight down to the narrow strip of shore.

The southeastern shore of Jones Sound is mainly formed of cliffs which, though steep, are not precipitous, and in many places there is a rough, narrow foreshore. Inland, the country is high and rugged, and the whole of this part of the coast is dominated by the great east Devon Island ice field which rises to over 6,000 feet (1,828 m 8) about 20 miles inland. From this high land a number of large glaciers extend down to tidewater. Westward of Cape Sparbo (Lat. 75°50'N, Long. 84°03'W) the southwestern side of Jones Sound is essentially one of screebanked, sedimentary cliffs marking the northern margin of the sedimentary plateau which forms the western part

of Devon Island. Along this sector the inland plateau has elevations of about 1,000 to 1,800 feet (304 m 8 to 548 m 6), and it is broken along the coast by the outlets of numerous flat-floored, outwash-filled valleys. At the western end of Jones Sound, the rugged and snow covered COLIN ARCHER PENINSULA rises steeply to about 1,800 feet (548 m 6).

The main features of the bathymetry (Figure 1) appear to have been established, although survey of the region is not yet complete. The deepest depth in the sound appears to be 890 m and the deepest threshold 420 m. The latter occurs in Baffin Bay just south and east of Philpots Island. The deepest depth in the Glacier Strait approach appears to be 135 m, while that in the western approach is close to 132 m. It is possible that the deep portion of the sound consists of two regions, one to 890 m and the other to 800 m, connected through a depth of about 650 m. Pelletier (1966) in a description of the development of the submarine topography also provided an interpretation of bathymetric data.

Information on the tide is meagre but it seems that it would be described as "mainly semidiurnal". A prediction of time and height is given for an area just southwest of Cape Sparbo (Anon., 1967c p. 18) where the range of large tides may exceed 4 m (Barr, 1971 p. 256 reported a range of 3.28 m based on data from S. Apollonio). The range is reported (Anon., 1968a) to be 3 m at Craig Harbour (p. 400) and Grise Fiord (p. 402). Strong tidal currents are reported for the Craig Harbour area (p. 400) and for Hell Gate and Cardigan Strait (p. 410-1). Dohler (1964, his figure 17) provided data on the progression and range of tide in the northwest Atlantic and eastern arctic. From this, it would seem that the range of 4 m occurring within the sound is several times larger than in the archipelago west of Barrow Strait and Hell Gate, although an equally large range occurs in Smith Sound. It was Dohler's interpretation that the range in northern Baffin Bay is at least 1.8 m. Godin (1966 p. 135) attributed the observed increase in the M_2 component to reflection at the head of Baffin Bay of an impulse travelling from the North Atlantic through Davis Strait and concluded (p. 30) that "appreciable semidiurnal currents" are to be expected there. It seems likely that in this region and in Jones Sound in particular, a significant influence on the distributions would result from mixing due to the turbulence associated with these tidal motions and from an exchange due to an asymmetry in the flood and ebb patterns of tidal movement.

3.1 Runoff

An estimate of the amount of runoff which may enter the sound during any time interval does not appear to be available. In 1962 Apollonio (1962 p. 320) measured* runoff "from July 14 to August 11, during the main melt period" and noted that much higher ablation was recorded in 1962 than in 1961. How much higher is not indicated, but it seems possible that the dual influences of glacier storage and wide variation in summer heat budgets could lead to relatively large differences in annual runoff. Over the long-term it could be expected that the average annual runoff would not exceed

*Apparently these observations are the same as those referred to by Koerner (1963 p. 74-5).

the average annual excess of precipitation over evaporation which is estimated to be 10 cm/year, i.e. precipitation is estimated at 16 cm/year (Anon. 1967d) and evaporation 6 cm/year. The area of Jones Sound is about equivalent to that of the land drainage into the sound so that the average amount added to the sound each year is about one-fifth of a meter. This is at least an order of magnitude less than the amount of freshwater (see section 3.3) in the sound, even in winter, and following a recent argument (Huyer and Barber, 1971) would suggest the influence of a persistent movement from the west of the relatively low-salinity water there.

3.2 Ice Conditions in 1963

The ice in Jones Sound begins to form in the second half of September, but remains in motion till late winter, leads opening and closing with change of tide and wind. About March, coverage reaches a point where most of the leads disappear, only a few narrow ones remaining in Lady Ann Strait and at the head of the sound.

In Cardigan Strait and Hell Gate, strong currents keep the water open all winter In Hell Gate, the channel usually contains little more than a good deal of brash ice, but just to the east of Calf Island, the ice cover is generally complete.

During July, the ice in Jones Sound loosens considerably, and with westerly winds, much of it moves out into Baffin Bay. In late August and September, the ice cover has reached a minimum, but frequent easterly winds may keep it as high as about 5/10^{ths} all summer. Some icebergs enter from the east through Glacier Strait and are sometimes found as far west as the head of the sound.

Water landings in inlets of Jones Sound would be practical for a short time in late August in most years. (from Dunbar and Greenaway, 1956, p. 427-8).

Ice conditions in Jones Sound in 1963 were surveyed on a number of occasions between the end of March and the end of November. The observations (Anon., 1964) indicated that by the beginning of May, an area of 1 to 3 tenths ice occurred in the eastern sound, the remainder being 10 tenths. By May 23, the amount of open water in the eastern sound had increased and two small areas of open water existed in the western approach; the remainder was 10 tenths. On June 19-24 the cover in and eastward of Hell Gate was 10 tenths. By July 24 (Figure 2) little change had occurred except in the approaches; in Baffin Bay considerable open water was observed and in the west a significant area of 1 to 3 tenths existed. By August 5, considerable open water occurred and by August 23 the sound was very nearly entirely open water. Observations on August 29 indicated little open water in the western approach. On September 17, ice of 1 to 3 tenths occurred in mid-sound and by the beginning of October, ice was observed in all areas of the sound in concentrations varying from 1 to 9 tenths.

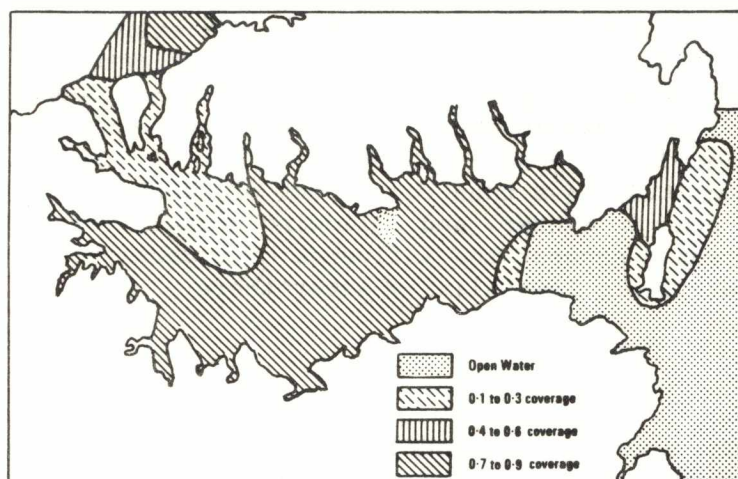


Fig. 2. Ice conditions in Jones Sound July 24, 1963 (from Anon., 1964).

Other descriptions of the general* condition in 1963 are available (Black, 1963; Markham, 1963; Dunbar, 1964; Hill, Cooper and Markham, 1965) and from these, it is evident that conditions in the eastern Arctic during the navigation season were considerably later than normal. In Jones Sound conditions appear to have been later than in 1962 (Anon., 1963) a year of an unusually early breakup and Hill et al. (1965, their figure 10) suggested that the breakup in Jones Sound in 1963 was late. Lindsay (1968) provided further detail on the breakup and freeze-up patterns as well as a quantitative expression of the decrease of the ice cover with time for 1962, 1964 and 1966; years which he described as "good", "bad" and "average" respectively. From this it would seem that the situation in Jones Sound on July 24, 1963 (Fig. 2) was one of more extensive ice than in any of the years examined by Lindsay.

The ice condition during the winter months is not well known, but in the winter of 1961-62, "The coastal waters of Jones Sound froze solidly in early November..." (Apollonio, 1962 p. 318) and, "...the main body of Jones Sound did not freeze over until early January" (Koerner, 1963 p. 59). It is not known whether such a late date of freeze over is typical of Jones Sound, but it seems unlikely (Lindsay, 1968 p. 32). Later in the spring, the development of open water in the eastern approach based on satellite imagery has been observed (Dunbar, 1969 p. 439) such that by early April, a continuity with North Water was indicated (p. 440). (See also Dunbar, 1973a p. 280)

*It was known that the surface ice condition through Nares Strait in 1963 would likely be anomalous (Nutt and Coachman, 1963).

3.3 Data of 1963

The serial data observed in 1963 in Jones Sound (Anon., 1967b) are presented as horizontal distributions in the atlas portion of this work (Fig. 13), while distributions with depth and a temperature-salinity diagram are shown in Figures 3 and 4. The distributions of salinity, temperature and oxygen with depth (Figure 3) suggest that a surface mixed layer, a halocline and a relatively isohaline deep layer may be distinguished. The surface layer is not a particularly well-defined feature of the salinity structure but the halocline is. Generally the salinity increased from 31.5 ‰ within the upper 50 m to near 33.8 ‰ at about 200 m and increased to more than 34.3 ‰ in the deeper water. The temperature generally increased with depth, so that the colder water was at the surface, although as may be seen in the bathythermograms (Anon., 1967b p. 198-200) some small temperature structures occurred frequently above 100 m. Within the depth range of the halocline the water was nearly isothermal at about -0.8°C . The dissolved oxygen decreased with depth from 8.8 ml/l at the surface to about 5.6 ml/l in the deeper water*.

The temperature-salinity relation of the 1963 data in the sound was plotted by computer using an expanded temperature scale (Figure 4). It indicates that the salinity ranged from 31 to 34.5 ‰ and the temperature from -1.68 to 0.09°C ; the temperature range was largest for salinities less than about 32.7 ‰. Between this salinity and 34.0 ‰ the temperature increased slightly from about -0.95° to about -0.75°C . In this range there are four temperatures significantly lower than the bulk of the data; all of these were observed in the eastern approaches at stations 41, 46, 62, and 63. Two of the warmer points in this range were observed in the western approach at station 60. Between 34.0 ‰ and 34.392 ‰ the temperature increased more strongly with salinity from about -0.75 to -0.10°C . It appears that in the 1963 data, the temperature range between 33.0 and 34.0 ‰ is relatively small for it will be shown in the following section that such small range has not always been observed.

The salinity distributions (Fig. 13) to 200 m are dominated by an apparent accumulation of low salinity water in the eastern part, i.e. at stations 43, 47 and 48, and to a lesser extent close to shore. This accumulation is demonstrated in Figure 5 which shows the amount of freshwater in meters using 33.8 ‰ as the base salinity. The accumulation was associated with a relatively warm water, to 0.0°C , at 50 and 75 m (Fig. 13e,f).

The salinity distributions to 100 m depth in the eastern sections are such as to imply a strong movement into the sound through Glacier Strait and another out through Lady Ann Strait and with considerable continuity in the total movement. In that portion of the sound west of Cape Sparbo, the distributions of salinity suggest a counterclockwise circulation about a mid-central region of relatively high salinity. At some depths, 75 and 100 m, the salinity at the western-most stations was the highest so that a continuity is implied with water in and west of Hell Gate. But this is weak relative to that occurring in the eastern approach so that in the depth above

*Two values in Figure 3 may be the result of blunders. One occurred at 442 m at consec number 26, the other at 85 m at consec number 59. It is noted that in 1962 at some depths, relatively low values were observed (Anon., 1966 p. 73) such that a value of 4.16 ml/l occurred in the deeper water.

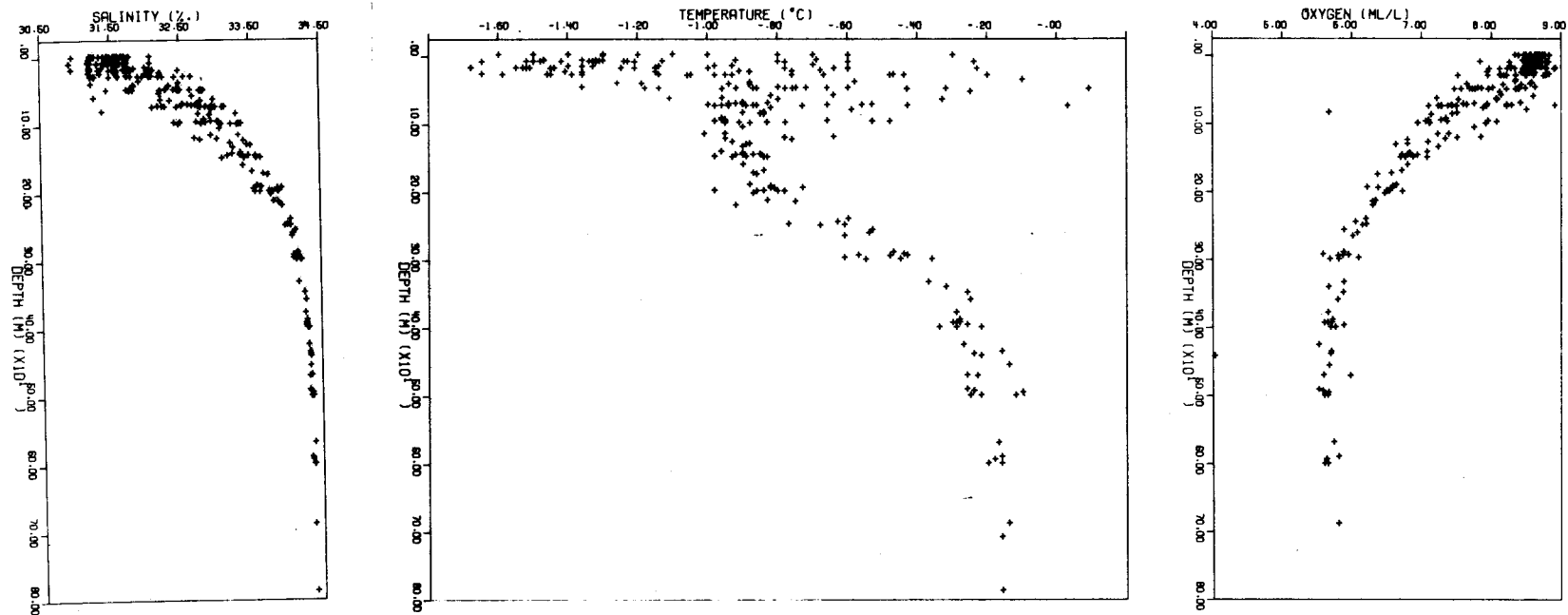


Fig. 3. Distributions with depth at stations 41-65 in Jones Sound in 1963, plotted by computer. (a) Salinity (‰); (b) Temperature (°C); and (c) Dissolved oxygen (ml/l).

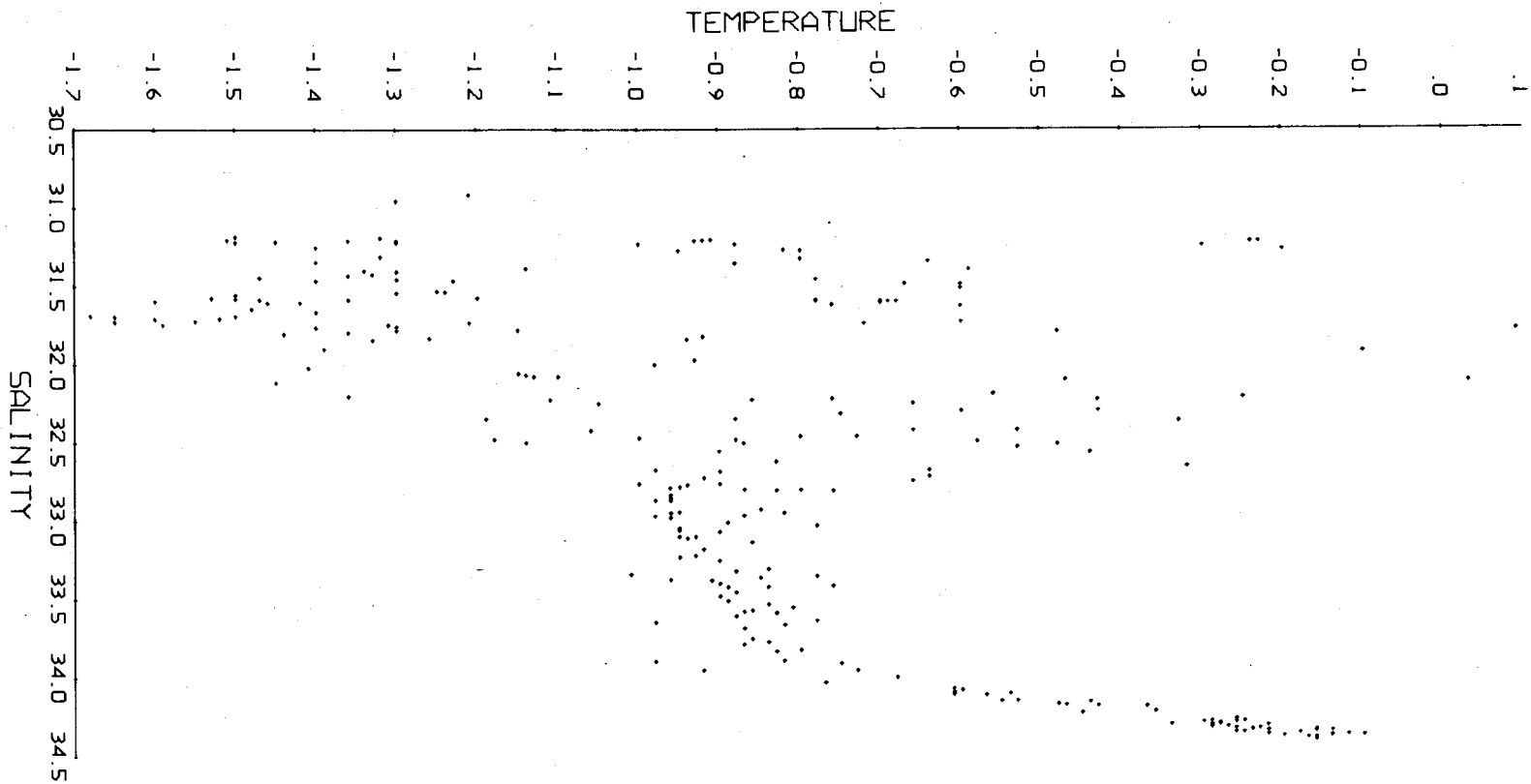


Fig. 4. A computer generated temperature-salinity relation (Wilson, 1967) of the serial data in the range of 30 to 35 ‰ observed in Jones Sound in 1963 (Anon., 1967b).

100 m a circulation pattern as shown in the schematic (Figure 6) is visualized for the 5 day period of the observations.

At the deepest depth sampled, 787 m at station 48, the observed salinity, 34.392 ‰, was a maximum for the sound; the temperature at this depth was -0.16°C . The highest temperature in the deeper water, -0.10°C , was observed at 496 m at station 62 with a salinity value of 34.361 ‰. Water of similar T-S can occur in northern Baffin Bay (Figure 7) appropriately close to the sill off Philpots Island.

The implication is that the deeper water of the sound is continuous with that in Baffin Bay and probably originates there, but the data on this are few. In the western approach the data in this regard are somewhat ambiguous in that in Norwegian Bay a salinity of 34.0 ‰ has been observed at 140 m, i.e. close to sill depth, and on a different occasion at 190 m (Figure 8). Other data observed on these two occasions were utilized (Huyer and Barber, 1970, their figure 3) to show that the depth and temperature of the 33.8 ‰ surface was shallower (100 m) and warmer (-0.8°C) in Norwegian Bay than elsewhere in the archipelago (but not including Kennedy Channel). Later here it will be suggested that a slightly warmer water (-0.6°C at 33.8 ‰) can occur in Jones Sound under the ice cover during the winter.

3.4 Review

A further examination of the data observed in Jones Sound before 1963 (Table 1) showed that they exhibit considerable variability. An example is the generally colder water at depth observed in "Godthaab" in 1928 (Figure 9). Bailey (1957 p. 765) drew attention to the difference of temperature which existed at depth between the 1928 and 1954 data from the three sounds, Smith, Jones and Lancaster, and suggested an influence of a change of climate. On the other hand, Muench (1971 p. 30) concluded that no net changes had occurred between 1928 and the 1960's. He also noted (p. 41) that, "Seasonal temperature and salinity variations in Jones and Lancaster Sounds have not been documented", presumably because the matter had not yet been examined. A discussion of similar differences in data for eastern Lancaster Sound (Barber, in preparation) led to the suggestion that the variability there may in part be due to a change with a period not greater than a year. The temperature-salinity relations for the data of 1928, 1954 and 1962 (Figure 10), apart from the systematically* lower temperatures observed by "Godthaab", suggest that the largest variation of temperature with time occurs at salinities between 33.5 and 34.0 ‰. At these salinities the 1963 data (Fig. 4) generally have temperatures between -0.9 and -0.8°C with some data at about -1.0°C . The "Godthaab" observations in 1928 (Figure 10a) were taken in eastern Jones Sound; the highest temperature observed at salinities between 33.5 and 34.0 ‰ was -1.08°C , the lowest temperature, -1.45°C , was observed at 33.8 ‰. The 1954 observations from "Labrador" (Figure 10b) were also in and near the eastern approaches to the sound. Again the water between 33.5 ‰ and 34.0 ‰ was colder than observed in 1963; the lowest

*There exists a probability that a larger than usual systematic error occurred in a portion of the "Godthaab" data as the reversing thermometers were not calibrated to less than 0°C (Riis-Carstensen, 1936 p. 15).

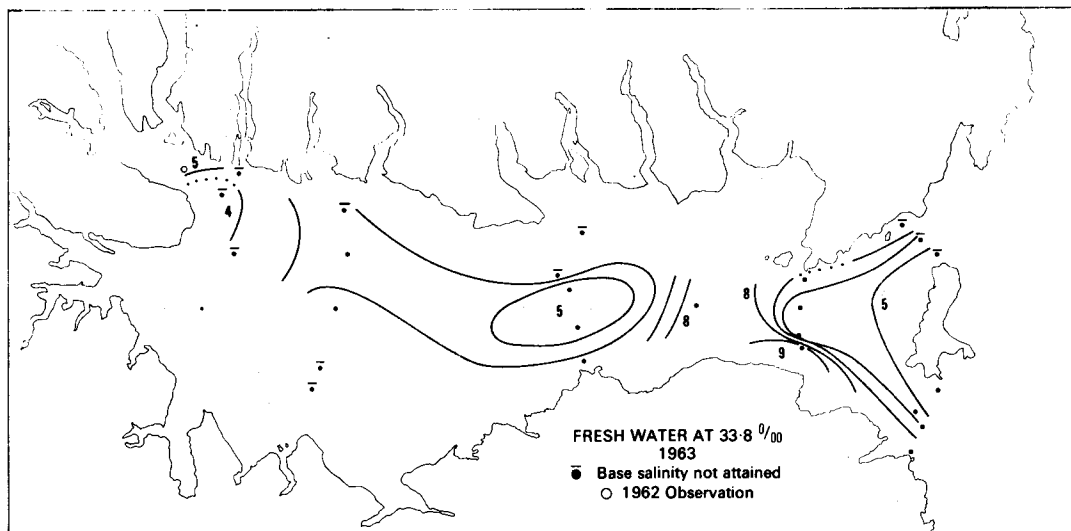


Fig. 5. The distribution of the amount of freshwater to the 33.8 ‰ surface from the 1963 observations. Also included are 1962 data observed at CCGS "John A. MacDonald" station 29 (Anon., 1966).

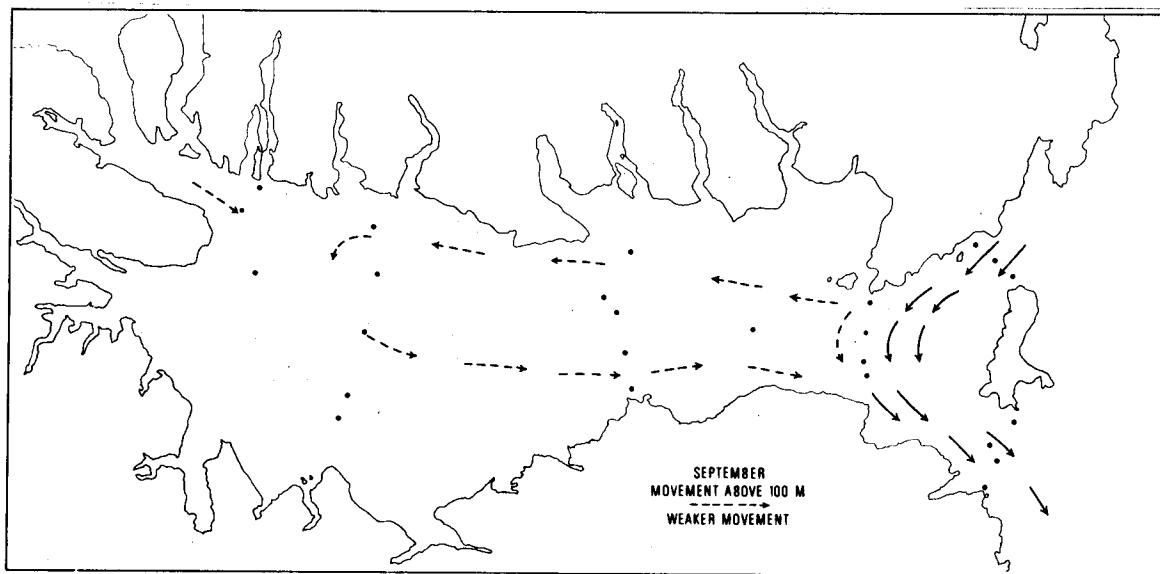


Fig. 6. The inferred movement of water to 100 m depth during the period of the 1963 survey.

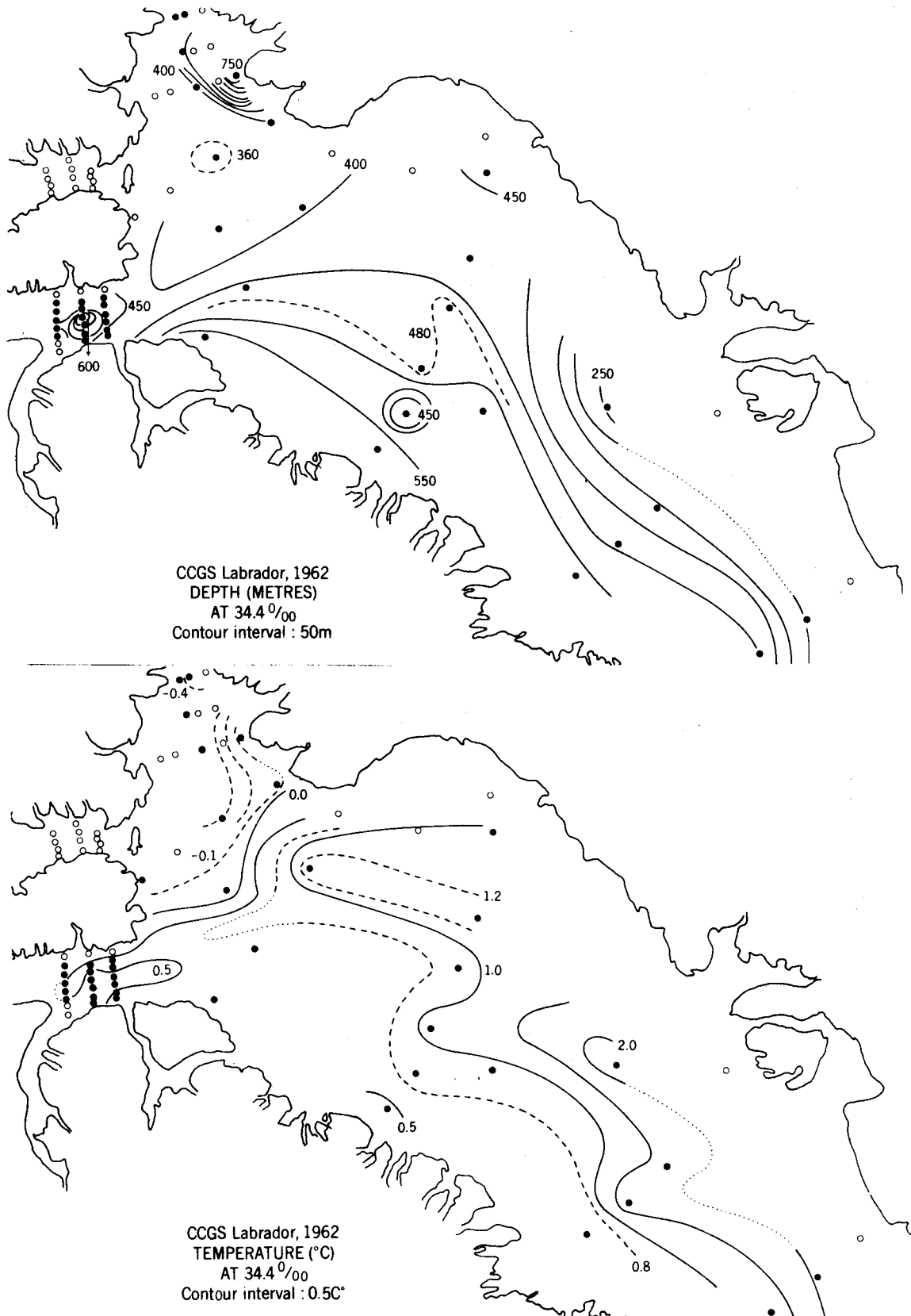


Fig. 7. An interpretation of the distribution of depth and temperature at 34.4 ‰ from data obtained in CCGS "Labrador" in 1962 (from Barber and Huyer, 1971).

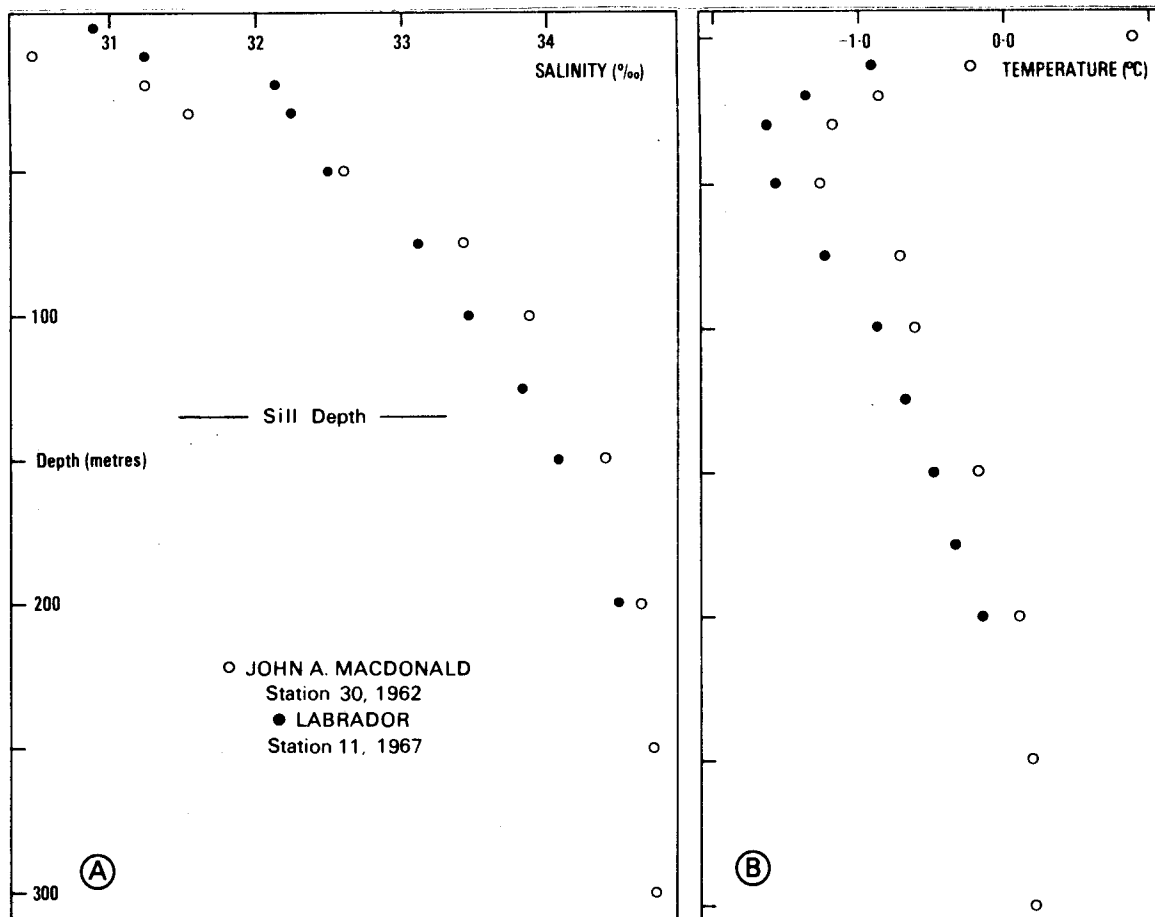
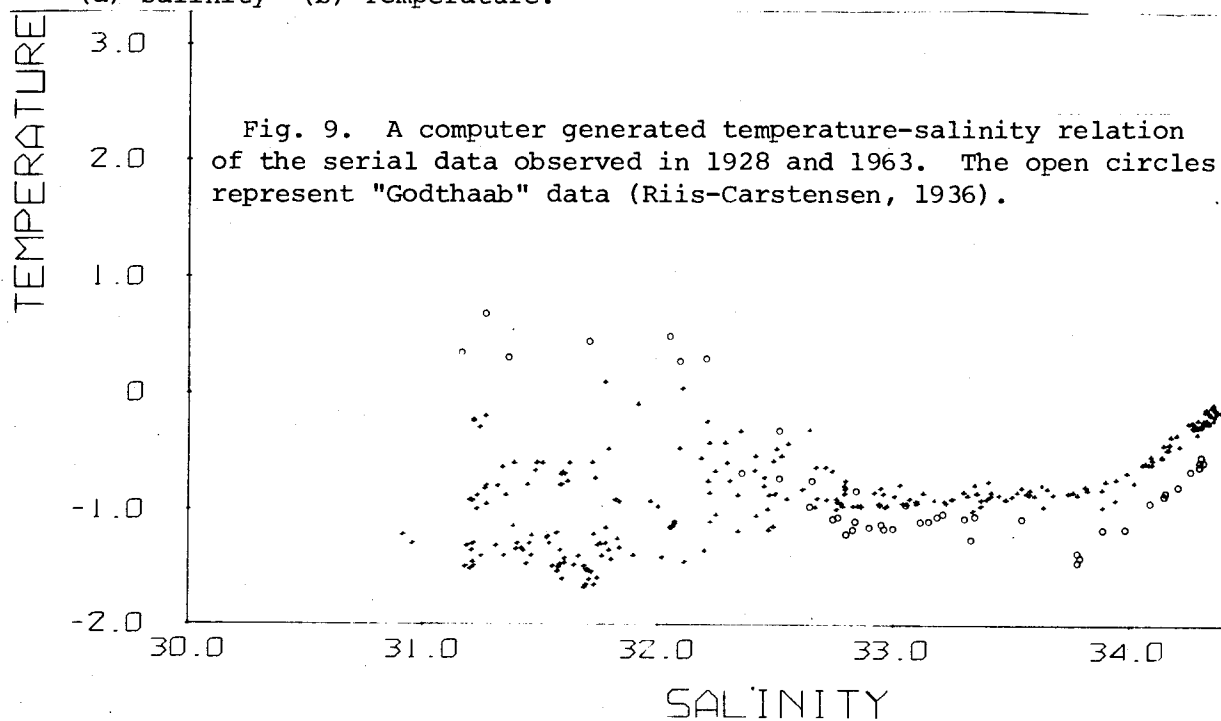


Fig. 8. A presentation of data obtained in the western approach to Jones Sound at $77^{\circ}05'N$, $89^{\circ}38'W$ by CCGS "John A. MacDonald" (Anon., 1966) and at $77^{\circ}00'N$, $89^{\circ}46'W$ by CCGS "Labrador" (Anon., 1968b).
(a) Salinity (b) Temperature.



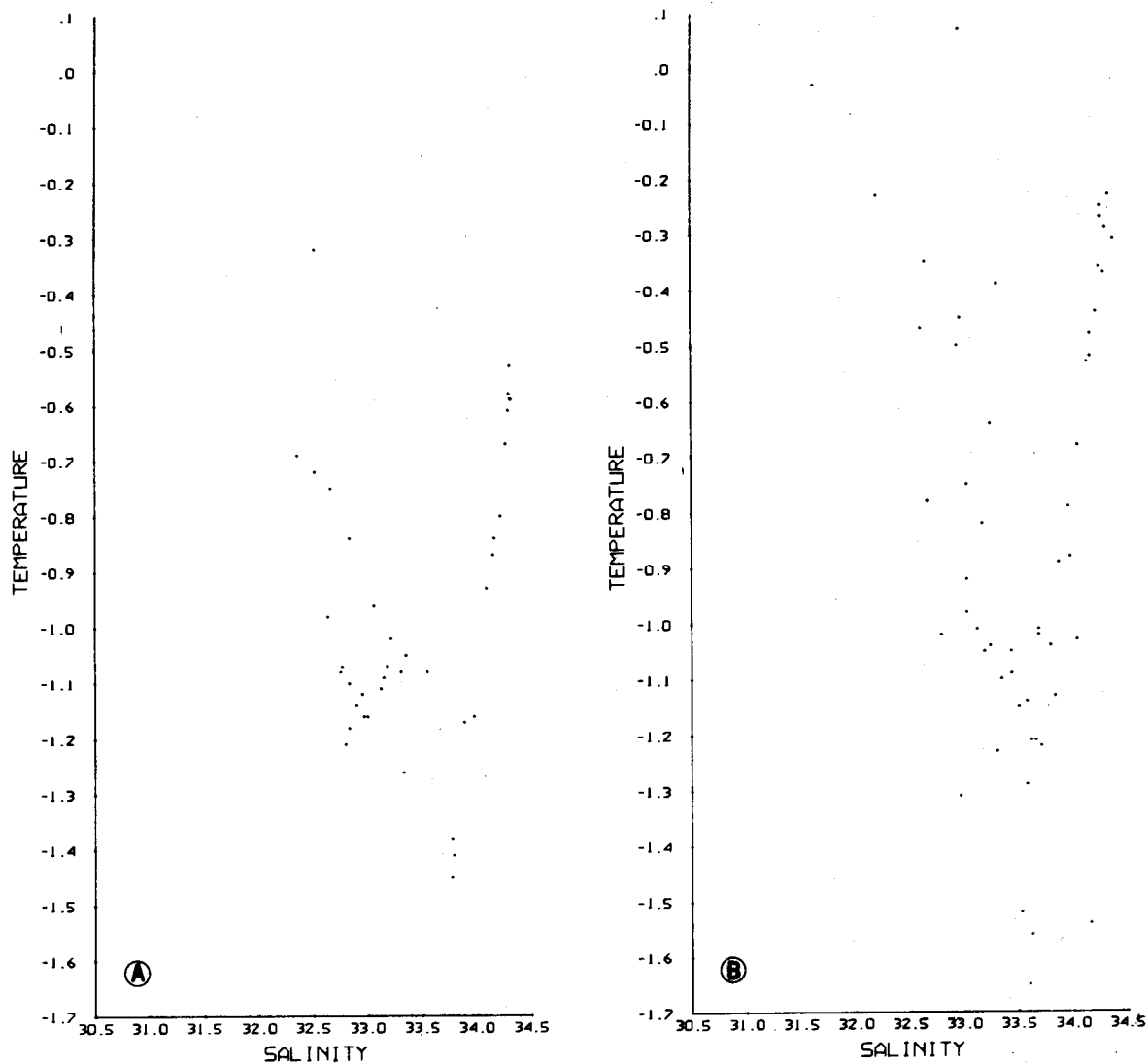


Fig. 10. Temperature-salinity relations of the serial data observed in Jones Sound. (a) 17 and 18 August, 1928. (b) 5 and 6 August, 1954. (c) 14 and 15 August, 1962. (d) 28 and 29 September, 1962.

temperature in this salinity range* was -1.65°C at 33.6 ‰ . In 1962 observations were made in both August and September in eastern Jones Sound where the minimum temperature was -1.45°C at 33.64 ‰ . Some of the data observed in late September 1962 (Figure 10d) were in the eastern half of the sound where temperatures in the range 33.5 to 34.0 ‰ were about the same as in 1963. The observed temperature minimum in this range was -0.96°C ; it occurred at 33.8 ‰ (the 1963 observations were also made in late September). From Figures 4 and 10 and the above, a pattern emerges: a distinct temperature minimum in the salinity range 33.5 and 34.0 ‰ is apparent in eastern Jones Sound in early August. Additional support for this is believed in those data of Palfrey (1968 p. 115) wherein temperatures to -1.69°C at the appropriate salinity were observed on August 2 and 3, 1966. As the feature appears to be limited to the eastern part of the sound, it seems likely that it is related to the movement through Glacier and Lady Ann Straits (Figure 6) and reflects either a change in the pattern of advection or a change in the temperature of the advected water. Bailey (1957 p. 747) described the movement as inferred from the 1954 data:

In the region at the entrance to Jones Sound a general westward movement through Glacier Strait and a southward movement through Lady Ann Strait are indicated. In Jones Sound the water movements appeared to be more complex with an eastward flow taking place in the surface layer across the section. The cold water layer, however, moved westward on the north side and eastward on the south side. Movements in the deep waters, although slight, were generally eastward.

Muench (1971 p. 46) considered that in the eastern approach to Jones Sound the circulation could be anticipated to have an association with the cyclonic circulation known to exist (see also Avis and Coachman, 1971) in northern Baffin Bay, specifically with the "cyclonic gyre in the region between Jones and Lancaster Sounds and Cape York" (p. 79). From this it seems that the circulation pattern in eastern Jones Sound is similar to that suggested in Figure 6 and it may be inferred that the temperature variation described above is indeed due to a variation in the temperature of the advected water. It is believed that the variation will prove to be of annual period and to be related to certain surface processes which occur in northern Baffin Bay in association with open water in winter, i.e. North Water, with particular movement of surface and deeper waters and with relatively intense mixing from all sources including the tide.

As expected, in a region where there is an annual rather than a perennial ice cover the surface water may exhibit changes associated with the annual variation of the ice cover. The winter condition is relatively constant from year to year so that little change is expected in the winter distributions. The ice cover is quite variable for the earlier part of the summer and the temperature and salinity distributions at the surface depend to some extent on the amount and the duration of the open water. In 1962,

*There is also one very low temperature observation, -1.54°C at 34.16 ‰ ; it seems possible that the value is an error. However, Bailey (1957 p. 742) appeared to consider it valid as he included it in a vertical temperature section of Lady Ann Strait.

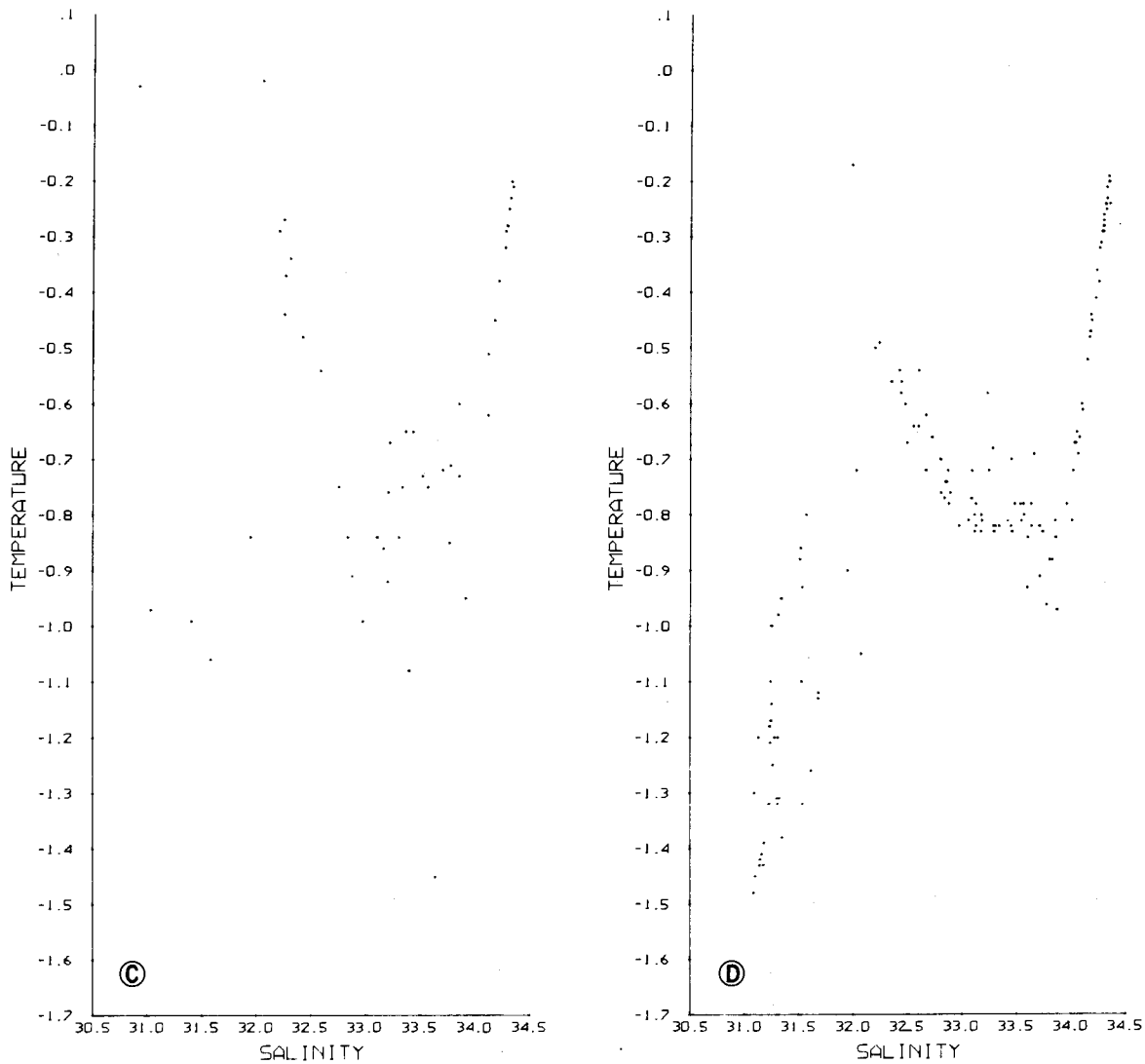


Fig. 10. Temperature-salinity relations of the serial data observed in Jones Sound. (a) 17 and 18 August, 1928. (b) 5 and 6 August, 1954. (c) 14 and 15 August, 1962. (d) 28 and 29 September, 1962.

which was unusually open, surface temperatures were as high as 4°C in mid-August and salinities were as low as 28 ‰ (Figure 11). By the end of September, salinities were generally in excess of 31 ‰ and temperatures were less than -1.0°C . The highest surface temperature observed in mid-August in 1928 was 1.1°C , while in early August 1954, the highest temperature observed was 1.6°C . It is likely that similar variations in the summer surface temperature distributions occur in northern Baffin Bay. Because of the mixing there, the year to year variations at the surface will also be apparent at deeper depths and may be reflected in the temperature of the water at $33.6 - 33.8 \text{ ‰}$ advected through the eastern part of Jones Sound.

Variations also seem to occur in the volume transport through Jones Sound, Kiilerich (1939) estimated from the "Godthaab" data that a volume transport of $0.29 \times 10^6 \text{ m}^3 \text{ sec}^{-1}$ was occurring into Baffin Bay through Jones Sound on August 17, 1928 and Bailey (1957) estimated from the "Labrador" data of August 6, 1954 a transport of $0.39 \times 10^6 \text{ m}^3 \text{ sec}^{-1}$, but in the opposite direction. A similar difference in direction of the transport calculated by the same authors occurred for Smith Sound, the existence of the difference there being supported by observations on the movement of an ice island (Nutt, 1966). Kiilerich (1939) and Riis-Carstensen (1936) were concerned that tidal effects in Jones Sound were strongly reflected in the "Godthaab" section (stations 116-121) and the rather meagre information on tides there suggests that such could be the case. Palfrey (1968) described data which were observed in two occupations of stations across Glacier and Lady Ann Straits to provide information on the "magnitude of tidal influence on the water exchange" (p. 9) and concluded (p. 16) that a qualitative relationship could be shown. Strong tidal currents are experienced in each of the straits of the approaches and in Hell Gate maximum strength is in the range $1\frac{1}{2}$ to $3\frac{1}{2}$ knots (75 to 175 cm sec^{-1}), which likely reflects the permanent southerly set which exists there (Anon., 1959 p. 380; 1968a p. 410). Collin and Dunbar (1964 p. 72) remarked, "Collin's more recent work includes a revision of the volume transport calculations through Jones Sound based on current observations in Eureka Sound and oceanographic observations in the channels of the northwest archipelago" and, "the total eastward transport was estimated...through Jones Sound at 0.27 million m^3/s ". This would require a net current of 0.18 m sec^{-1} eastward through the section Cape Hawes to Bay of Woe (width $15,000 \text{ m}$, depth 100 m). More recently, Palfrey (1968 p. 24) estimated net transports to the eastward of from $0.20 \times 10^6 \text{ m}^3 \text{ sec}^{-1}$ to $0.42 \times 10^6 \text{ m}^3 \text{ sec}^{-1}$ and Muench (1971 p. 91) inferred a "net westward baroclinic flow" from the 1962 data and an eastward flow from the 1963 data.

Apollonio (1961; 1962) indicated that the oceanographic data being obtained in Jones Sound by the Devon Island Expedition of the Arctic Institute of North America included tidal observations (1961 p. 254) and runoff measurements as well as temperature and salinity measurements. In a later report Apollonio (1963 p. 65) described the temperature and oxygen at a station* on the ice which was occupied during the winter of 1961-62 as follows:

*It was located at approximately $75^{\circ}45'\text{N}$, $84^{\circ}32'\text{W}$, 2 miles from shore off Cape Sparbo where the depth was about 80 m . These data were made available by the Arctic Institute of North America and were subsequently forwarded to the Canadian Oceanographic Data Centre (CRN 473).

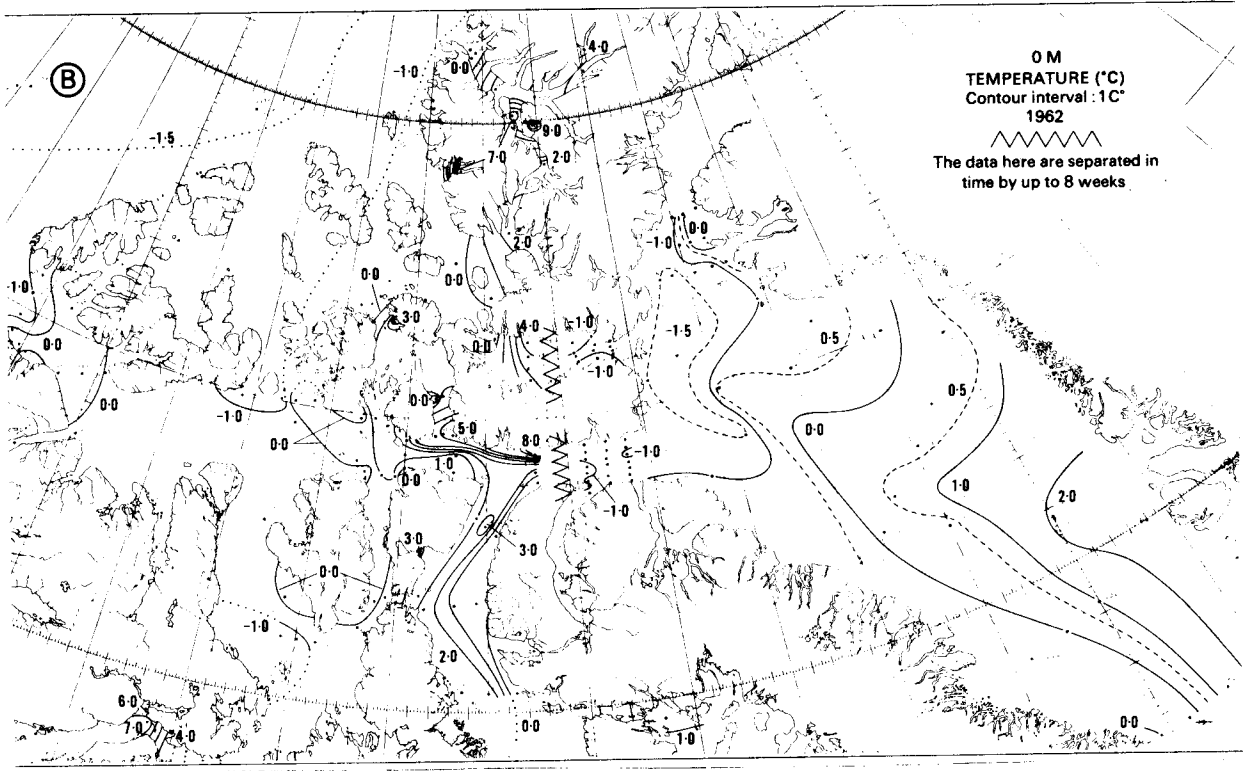
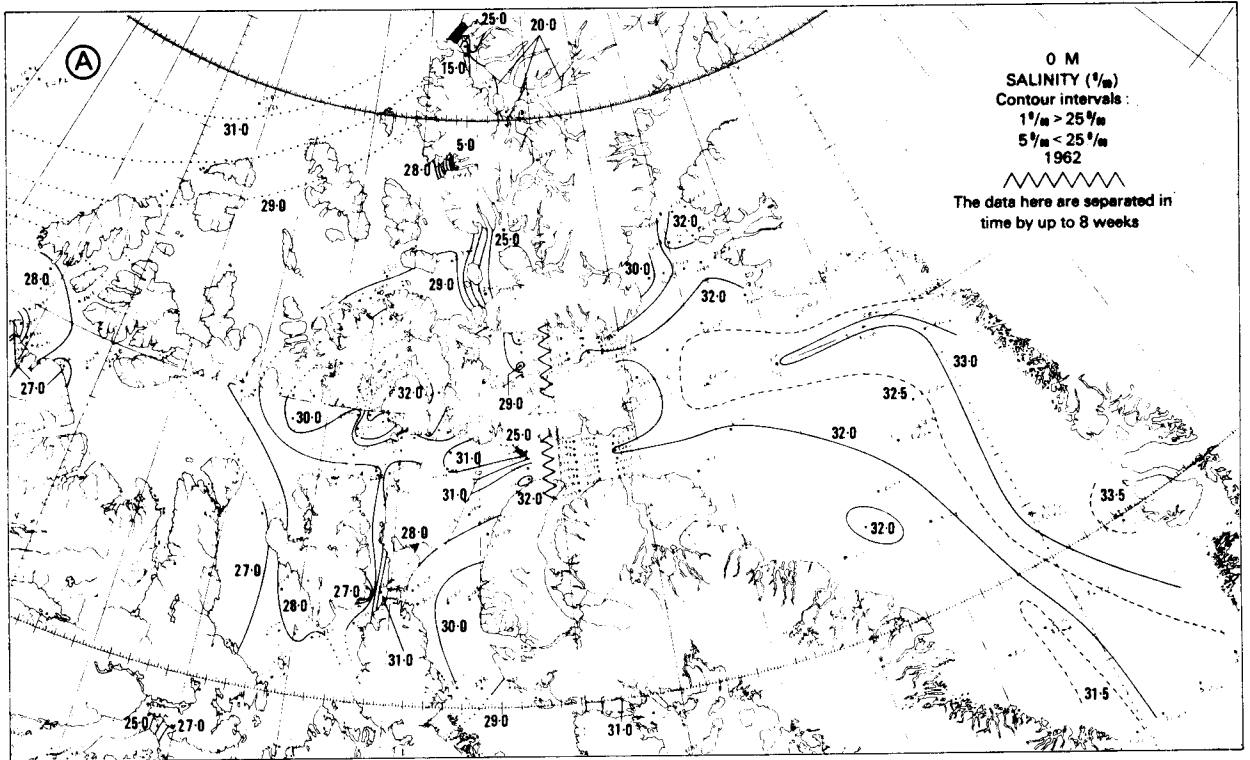


Fig. 11. Surface observations in 1962 in the area about the end of September (from Barber and Huyer, 1971) (a) salinity (b) temperature.

Temperature - The data show gradual cooling through the winter with the deepest water at 80 m being affected only in December. The water column from 0-50 m cooled from about -1.74°C to -1.80°C , but there was a considerable lag at 80 m. It was only by mid-February that the temperatures became nearly uniform at about -1.80°C through the column. There was very little change thereafter.

Oxygen - The data for each date show a consistent decline in dissolved oxygen toward the bottom. The decrease is rather small from the surface to 50 m but until January, the rate of decline increased from 50 to 80 m. This type of distribution suggests an oxidation-reduction reaction with the bottom sediments that reached an equilibrium in January. An alternative explanation may be simply that the annual variations are limited to water above 80 m.

The oxygen content at 80 m appears to be approximately constant through the winter but there was a general decline in oxygen between 0 m and 50 m from November until April. About 0.8 ml/l was lost. The main loss occurred in January, followed by a smaller and more variable rate of loss.

By April (1962) the water was nearly isohaline at 33.2 ‰ and isothermal at -1.8°C to 80 m depth and by the end of June, an increase of temperature and decrease in salinity was apparent at all depths observed.

Apollonio (private communication) also made available data observed in May, 1969 in Jones Sound and in two fiords on the south coast of Ellesmere Island during a field investigation of the relation between glaciers and nutrients in arctic seas (Apollonio, 1973). These indicate that in a surface layer to 50 m depth the water was isothermal at about -1.65°C to -1.51°C and isohaline at close to 33.1 ‰. In the deeper water, at 200 m for example, his data indicate a water warmer by about 0.3°C and somewhat more saline than is indicated in the 1963 data (Figure 13i). If these be representative of the winter condition in Jones Sound generally, then it seems that a quite recognizable seasonal variation occurs there. A determination which may be associated with that in the eastern sound of the amount of freshwater in these data (3 m at his station 9) as for Figure 5 here, suggests that the increase in the salinity of the surface layer could be due largely to the removal of freshwater through ice formation assuming that about 2 m of ice forms annually (Bilello and Bates, 1971). These data of Apollonio are significant in that they indicate that a change of annual period in a surface layer does occur, that a halocline structure exists throughout the year and that the late winter surface salinity could have been predicted using serial data obtained in late summer combined with ice thickness data and a not unreasonable assumption about maximum winter ice thickness at the location.

4. DISCUSSION

An attempt is made here to provide a model of the oceanography of Jones Sound which will include most of the features described above, namely the annual ice cover, the surface layer, the halocline, the relatively isohaline deeper layer and the seasonal temperature variation at about 33.7 ‰ in the eastern part of the sound. It is believed that this temperature variation is the result of processes occurring in northern Baffin Bay. It is not known whether the relatively strong flow through Glacier and Lady Ann Straits is a permanent feature or whether it is seasonal in nature. It is believed that it does not exert much influence on the main circulation through Jones Sound and it is therefore neglected in the following except as an indication of processes occurring in Baffin Bay.

Barber and Huyer (1971) in a presentation of data observed in 1961 and 1962 in the archipelago and Baffin Bay, showed the general relation of the distributions in Jones Sound to those in the west and east. They recognized the importance of the advection at the surface of low salinity water from the west to both Jones and Lancaster Sounds, the existence in each of shallower sill depths in their western approaches and the consequent greater significance of a water from Baffin Bay at depth.

In another report they (1970) suggested that mixing within the archipelago led to an increase of temperature at some salinity values and utilized the temperature distribution at 33.8 ‰ in demonstration. They argued that no significant gains or losses at the surface occurred and that a gradual modification of the temperature of the water occurred as it moved through the archipelago, in whatever direction. However, they recognized that were significant areas of open water to exist during the cooling period of each year a deficit could occur which, through mixing processes, would lead to lower temperatures at depths below the surface layer. As mentioned here in the "Introduction" this aspect was of particular interest even though in Jones Sound, it did not appear that unusual ice conditions occurred. That is, the existence of a complete ice cover for much of the year suggests that the exchange of heat at the surface is small and, on an annual basis, close to zero and likely a loss to the water*. The export or import of ice could be significant, but these are not generally known. Lindsay (1968) attempted an assessment for the season of 1966 (p. 40) and suggested the manner by which appropriate data might be obtained. His work indicated that the sum of export and import is on the average close to zero and it will be assumed that in 1963 in Jones Sound neither export nor import were significant. The data for 1963 described earlier suggest that the assumption is not unreasonable, but it is to be noted that marked differences in ice distribution from year to year can be expected due to the influence of surface wind (Dunbar and Greenaway, 1956 p. 428). It will also be assumed that the observed halocline structure exists throughout the remainder of the year as well as in the autumn and late winter. The consideration is that in the presence of an ice cover, a net movement of surface water from the west occurs (Figure 12). As it is relatively low salinity, i.e. about 33 ‰ or

*If the late freeze over of Jones Sound (in January) reported by Koerner (1963) is usual then the annual heat loss at the surface is probably not negligible and could lead to some subsurface cooling through the mixing processes described here.

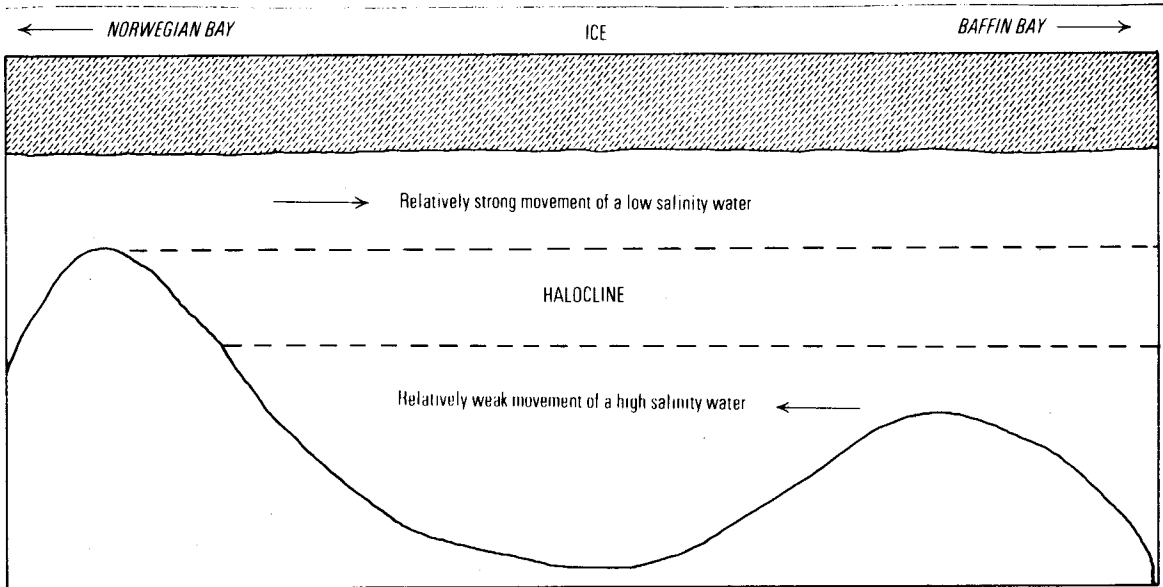


Fig. 12. A schematic of the pattern of water movement under the ice cover in Jones Sound.

less, the halocline structure would be preserved. If the structure does persist and if the exchange of heat at the surface is small, as suggested above, then it would seem that at no time is a sub-surface water formed due directly to surface processes within the sound. It follows that the observed T-S relationship below the surface layer is mainly advected, the deeper relationship from Baffin Bay, the shallower probably from the west. The word "advected" may not be altogether appropriate with regard to the deeper water as the movement is likely very much less than in the near-surface. Mixing arising from these movements, as well as from tidal movements, probably occurs throughout the sound over the total depth. It would lead to an exchange which would tend to remove vertical gradients such as the halocline. As we saw, the halocline is likely a persistent feature but it persists because of advection. Our simple model then for Jones Sound (Figure 12) comprises a mixing between advected water masses of somewhat different character. One, from the west, is of low salinity and generally close to the freezing point; its residence time in Jones Sound is likely of the order of one month. The other, from Baffin Bay, is of relatively high salinity and somewhat warmer, i.e. warmer than -1.0°C ; its residence time is likely of the order of a year. Mixing is visualized as occurring over the total depth to the same degree, except within the halocline where it may be enhanced by the shear associated with relative movement of the two main water masses. An important consideration here is that mixing across the halocline likely occurs but it is not preferential, i.e. an equal exchange takes place across it. As the residence time of the surface water is short, no particular change in it is observed. However, as the residence time of the deeper water is longer and as the exchange is generally with a colder (surface) water, the deeper water becomes colder. It is visualized that the distributions in the deeper water represent a balance between this mixing within the sound and a tidal exchange mechanism which couples the water of Jones Sound to that of Baffin Bay. Thus, the mixing within the sound is one whereby the influence of a surface process, in this case heat loss, can become recognizable at depth at locations where a density gradient exists, i.e. where there is considerable stability in the column.

In northern Baffin Bay, the tidal range and currents are comparable to those in Jones Sound, so that the mixing processes due to the tides are similar to those in Jones Sound. The halocline there is a much weaker feature than in Jones Sound and as a result, the mixing is more effective and seasonal cooling and heating are apparent at relatively deep levels. Thus, the deeper water of northern Baffin Bay may be expected to reflect the influence of surface processes to greater degree than Jones Sound. If this is so, then we may consider the possible formation of a deeper water within northern Baffin Bay, but not necessarily of a water at a freezing point. The formation may occur through modification of water advected into the region, an advection which seems to include varying amounts from the north and from the south. This modified water appears to form the bulk of the deeper waters of Baffin Bay and in some circumstances, may be responsible for the formation of the deepest elements there.

It is possible that the results of a similar mixing process were detected by Giletti and Kulp (1959) through measurements of tritium. The tritium content of the atmosphere was increased by the 1954 atomic tests in the Pacific Ocean; the surface water was contaminated from the atmosphere. The authors observed a higher tritium content at 400 m in the Arctic Ocean

(north of Nansen Sound) than at 80 m. They concluded that the low value at 80 m is "evidence of the strong near-surface stratification which prevents rapid vertical mixing to 80 m". Regarding the high tritium content at 400 m they wrote:

It is suggested, therefore, that this water resulted from conditions in the sounds of the Canadian archipelago similar to those in the Weddell...and Chuckchi Seas...(that is, surface water freezes, adds salt to the water immediately below which becomes more dense and sinks). In this case the amount of water is small and affects only the bottom 100 m. This sinking water mixes with the normal Atlantic-derived water but, being surface water, has a much higher tritium content. If the sample (0.9 0.1 TU) were largely arctic surface water, it could not have flowed down earlier than 1953 and still retain a tritium content of 0.9 TU. A similar age limitation would apply to the sample if it were Atlantic-derived, requiring improbably rapid subsurface flow rates in the Arctic Sea of about 10 cm/sec (if a path length of 3,500 miles and 2 years' travel time are assumed). It is suggested that the water represented by this sample moved down along the continental shelf during 1953-55.

We agree with Barnes and Coachman (1959) that there are valid objections to the interpretation. Conditions in the archipelago are not similar to those in the Weddell Sea, as there is always a degree of density stratification and therefore, convective mixing, associated with cooling and freezing, tends to be limited to the surface layer. However, it seems that mixing processes in a coastal region can mix surface water with deeper water, even in the presence of some density stratification. It is suggested that such mixing occurs within the archipelago as well as in Jones Sound and northern Baffin Bay, so that the bottom waters of the channels there would contain some surface water, and hence, a higher tritium content.

Because the precipitation at high latitudes is low in deuterium, freshwater derived from melting sea ice contains more deuterium than freshwater from precipitation, runoff or glacial ice there, according to Redfield and Friedman (1969). These authors examined, "the relation of deuterium concentration in the subsurface waters of the polar seas" and found interesting but not altogether clear-cut relationships including a quantitative estimate of the increase of salinity of deeper waters due to ice formation at the surface. Muench (1971) considered that this result supported the view that Baffin Bay bottom water was formed locally (Sverdrup, Johnson and Fleming, 1942), even though Redfield and Friedman (1969 p. 211) were careful not to so interpret the result. Nevertheless, the data seem to demand an interpretation in terms of present knowledge of the amount of ice formation and such features as North Water. For example, if Redfield and Friedman (1969 p. 214) are correct in that ordinary ice formation could lead to the required quantity of salt (brine) it would seem that the required heat loss at areas of open water like North Water is met by loss of sensible heat rather than latent heat, i.e. no extraordinary* amount of ice is formed there.

*We note here the consideration (Dunbar and Dunbar, 1972 p. 240) that North Water is an "active and important ice factory".

This is of course, a very useful if only tentative result, for it leads to an examination of the possible ways in which the required sensible heat could occur at the surface within the area of North Water. The recent review and study of Muench (1971) was directed to this problem and while he was not able to determine the mode of formation* of the feature, he concluded (p. 123) that (underline is ours):

"All data suggest that the North Water is maintained primarily by mechanical removal of ice by winds and currents. Transfer of heat to the surface from the Atlantic Water via thermohaline convection is impossible, while diffusion and upwelling are insufficient as mechanisms of upward heat transfer for prevention of ice formation. Oceanographic data suggest that insufficient heat is present in the area to maintain open water, and that insufficient heat is transported northward into the area by currents."

It would seem therefore, that it is his conclusion that the necessary heat loss is met by loss of latent heat, i.e. by ice formation. It is considered that there is at least one element of error in this interpretation. It seems to derive from the evaluation of the required sensible heat loss at the surface and the consequent need for a sizeable heat transport from the south into the area, a transport which he deemed insufficient. It is the view here that the transport may be sufficient, for there is evidence that in winter a water close to 1.0°C occurs as far north as the Cary Islands (for example, see Muench p. 68 and 69). If so, then it is possible that a large portion of the necessary heat loss at the surface of North Water (about $50 \times 10^3 \text{ g cal cm}^{-2}$ according to Muench p. 115) could be met out of the sensible heat in such a water. The mixing process by which the heat would reach the surface is visualized as being similar to that described for Jones Sound, but perhaps more effective because of the existence of open water. This is not to suggest that the mixing is the cause of the open water: the argument is that should an area of open water be formed and maintained, then the necessary heat loss could occur through loss of sensible heat.

It is the hypothesis that the sensible heat loss at open water in ice is the same dimension as the latent heat associated with ice export. In the following, the hypothesis is examined for Baffin Bay, but as there exist a number of uncertainties, the result is itself uncertain.

Smith (1931 p. 49) said that not more than half the sea ice "which drifts out of Baffin Bay" is formed there, while Vowinckel and Orvig (1962) determined that $491 \text{ km}^3 \text{ yr}^{-1}$ flowed out at the border at Davis Strait. Dunbar (1973b) considered that $75 \text{ km}^3 \text{ yr}^{-1}$ moved south through Nares Strait and that a total of $225 \text{ km}^3 \text{ yr}^{-1}$ moved through the various channels, including Fury and Hecla Strait (Sadler, 1976a estimated that $110 \text{ km}^3 \text{ yr}^{-1}$ moved through Nares Strait into Baffin Bay). With Dunbar's value and with that of $3.9484 \times 10^{19} \text{ cal yr}^{-1}$ for the heat associated with the ice export at Davis Strait (Vowinckel and Orvig*, 1962), we accept that the heat associated with

*Dunbar and Dunbar (1972) reviewed the likely causes of the North Water.

While it is not certain, it does seem that some of the values calculated by Vowinckel and Orvig (p. 211 and Table 3) are an order of magnitude too low. For example in Table 3 (p. 220) the value of $-2,541 \times 10^{15} \text{ cal}$ is based on a volume of $36,000 \text{ km}^3$ at an unstated temperature (perhaps unstated because it is a net value), but which is calculated to be -0.07°C . Similarly, the value of 1576×10^{15} (p. 211) is based on values of $10^6 \text{ m}^3 \text{ sec}^{-1}$ ($31,536 \text{ km}^3 \text{ year}^{-1}$) and a temperature of 0.5°C , so it should be $1576.8 \times 10^{16} \text{ cal}$. Apparently the value of 0.5°C for the temperature of the West Greenland Current is based on data for the current in the Labrador Sea from Smith et al. (1937 p. 173). Similarly a value of $-3784.2 \times 10^{16} \text{ cal}$, rather than 10^{15} , results using a volume of $2.10^6 \text{ m}^3 \text{ sec}^{-1}$ at a temperature of -0.6°C for the Baffin Current.

the net of export over import of ice is about 2×10^{19} cal yr⁻¹, which is then the sensible heat loss at polynyas and leads (Table 2).

Table 2. A heat budget for Baffin Bay, reference temperature -1.8°C , $E - P = 0$ and runoff assumed = 0.

<u>Source</u>	<u>Volume</u> Sv	<u>Temp.</u> ($^{\circ}\text{C}$)	<u>Above Base</u> ($^{\circ}\text{C}$)	<u>Heat</u> (10^{12} cal sec ⁻¹) (10^{19} cal yr ⁻¹)	
Trans-archipelago	2	-1.6	0.2	0.4	1.4
West Greenland Current	1	1.0	2.8	2.8	8.8
Baffin Current	-3	-1.2	0.6	-1.8	-5.7
Total inflow	3			3.2	10.2
Total outflow	-3			-1.8	-5.7
Exchange	0			1.4	4.5
Loss thru ice cover					-1.4
Loss at polynyas and leads					-2.0
Remainder (loss at surface southeast Baffin Bay)					-1.1

At open water, a large loss would occur at the North Water which at a rate of 65×10^3 cal cm⁻² each winter (Muench, 1971, Table 8) at an effective area of 10^{14} cm² in March (Aber and Vowinckel, 1972) indicates a total loss of 0.65×10^{19} cal yr⁻¹. This, and heat associated with ice export, suggests a total such area of 3×10^4 km², or about 4% of the total area.

This does not include the area of open water which exists each winter in south eastern Baffin Bay, north of Davis Strait, due to heat mainly from the West Greenland Current (e.g. Dunbar, 1972), nor does it include the deficit which occurs at the surface of the ice cover. The latter is likely about $2,000$ cal cm⁻² yr⁻¹, but a value for the annual deficit at open water between Davis Strait and Disko Island was not found.

There is growing evidence that the trans-archipelago transport is close to 2 Sv (e.g. Coachman and Aagaard, 1975 p. 53, 54) so that if the West Greenland Current at Davis Strait is 1 Sv (Smith et al., 1937) then the Baffin Current there is 3 Sv. As well, the trans-archipelago transport is not entirely at the freezing point, so that it constitutes a gain to Baffin Bay, but the average temperature of this transport is not at all evident, except that as it would mainly comprise a surface water it would be close to the freezing point. We have arbitrarily selected -1.6°C as this temperature, which at a transport of 2 Sv would be balanced by a heat loss through the ice cover in winter, i.e. at a rate of $2,000$ cal cm⁻² yr⁻¹. The West Greenland Current also constitutes a gain of heat which at 1°C (Smith et al., 1937) would be 8.8×10^{19} cal yr⁻¹. The average temperature of the Baffin Current

seems colder than the -0.6°C of (Smith et al., 1937); we have chosen -1.2°C . A balance is achieved by a loss of 1.1×10^{19} cal yr^{-1} out of the West Greenland Current in southeast Baffin Bay, which gives a net exchange due to advection in Baffin Bay of 4.5×10^{19} cal yr^{-1} or a gain of about $6,000$ cal cm^{-2} yr^{-1} .

We would note that the latter value is close to that determined for the Polar Ocean out of which there also is a relatively large export of ice, and that it is much bigger than that calculated for Hudson Bay where the net of ice export over import is believed small, close to zero.

The significance for the work here is that a large portion of the sensible heat carried in by the West Greenland Current may be given off at the surface of open water during the period that the ice is usually being formed. The result emphasizes the likely existence of considerable convective activity in the water at such locations, an activity reinforced by motions due to surface wind and tides. In the area of North Water, it is believed possible that this is sufficient to couple the surface and deeper waters so as to maintain the necessary supply of heat. Presumably the process would be enhanced by the general increase of surface salinity due to ordinary ice production there and in adjacent areas, and it is possible that the winter surface salinity at North Water is near 33.7 ‰ (Sadler 1976a p. 53). This, as is visualized, would occur in a homogeneous surface layer rather deeper than exists in late summer and autumn, i.e. the surface layer would extend to a depth of about 150 m with a temperature of -1.6°C . Observations from aircraft, specifically from fixed-wing aircraft using air-dropped XBT's (e.g. Kielhorn et al., 1971; Sessions et al., 1976), might provide useful data on the structure. It is foreseen, however, that the most useful information at this early stage in our understanding of North Water would be knowledge of the distribution of surface salinity during the period prior to ice formation each year through to breakup. Indeed, it may be possible to apply usefully remote sensing techniques of the kind described by Dippleman et al. (1970), as a horizontal gradient in the surface temperature at open water is likely small.

5. ACKNOWLEDGEMENTS

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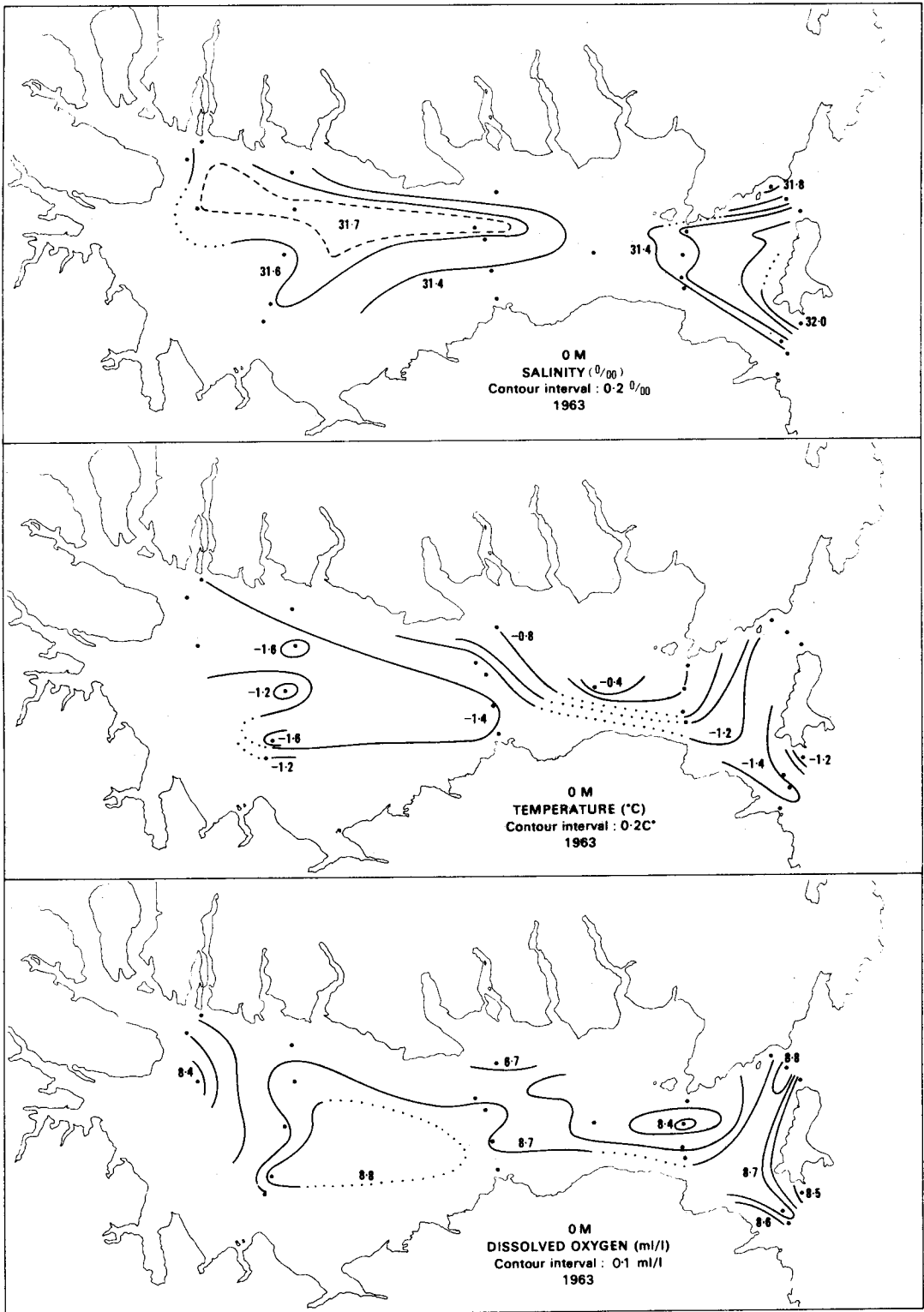
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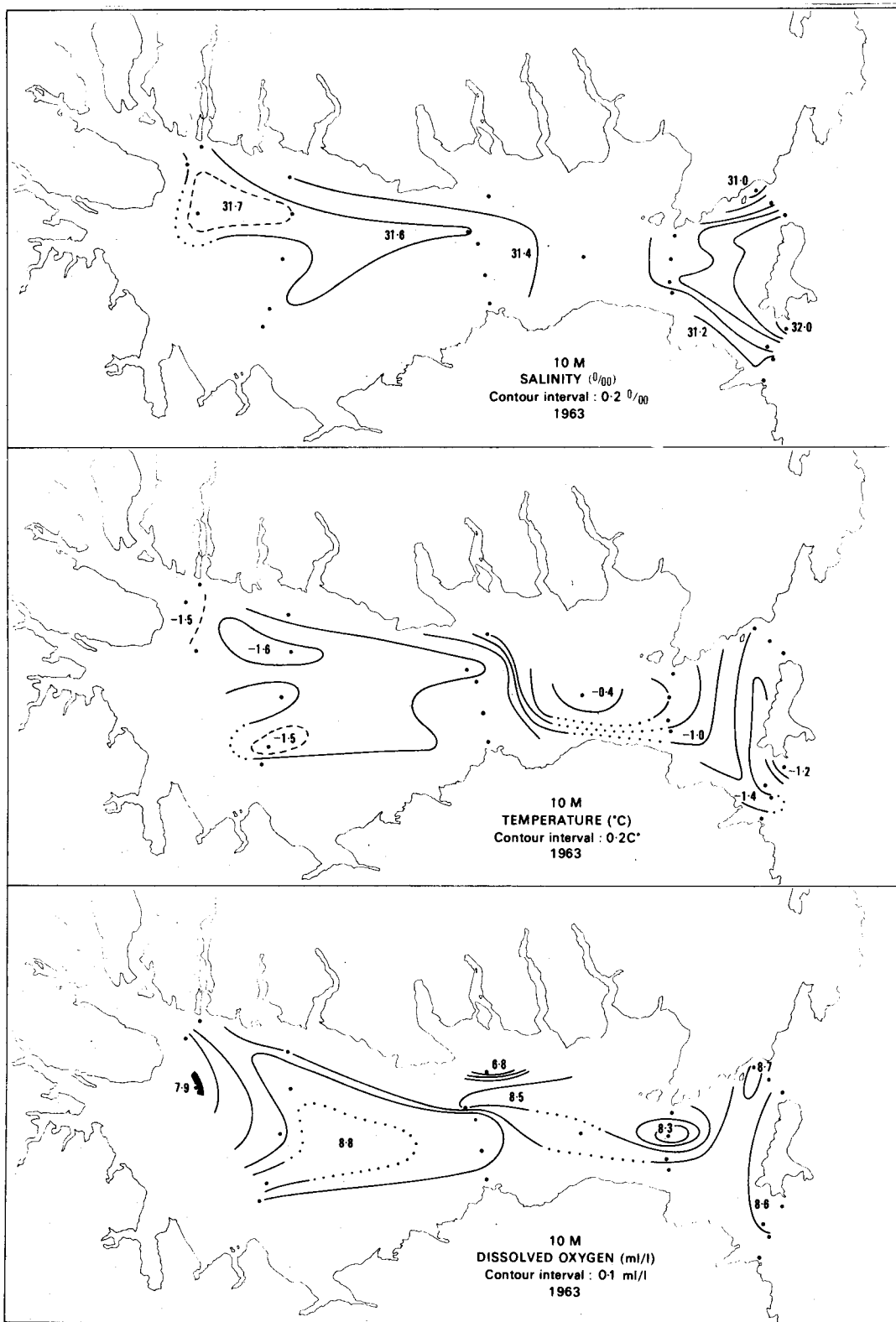
7. APPENDIX: AN ATLAS OF THE DATA FOR 1963

The data presented here in Figure 13 are those observed in 1963 in Jones Sound in the "Labrador" in a programme which began in Kennedy Channel in mid-September and comprised relatively detailed observations there and in Smith and Jones Sounds. The observations in Smith Sound were utilized (Collin, 1965) in an assessment of the volume transport there, while Muench (1971) used some of the material in his treatment of the physical oceanography of northern Baffin Bay.

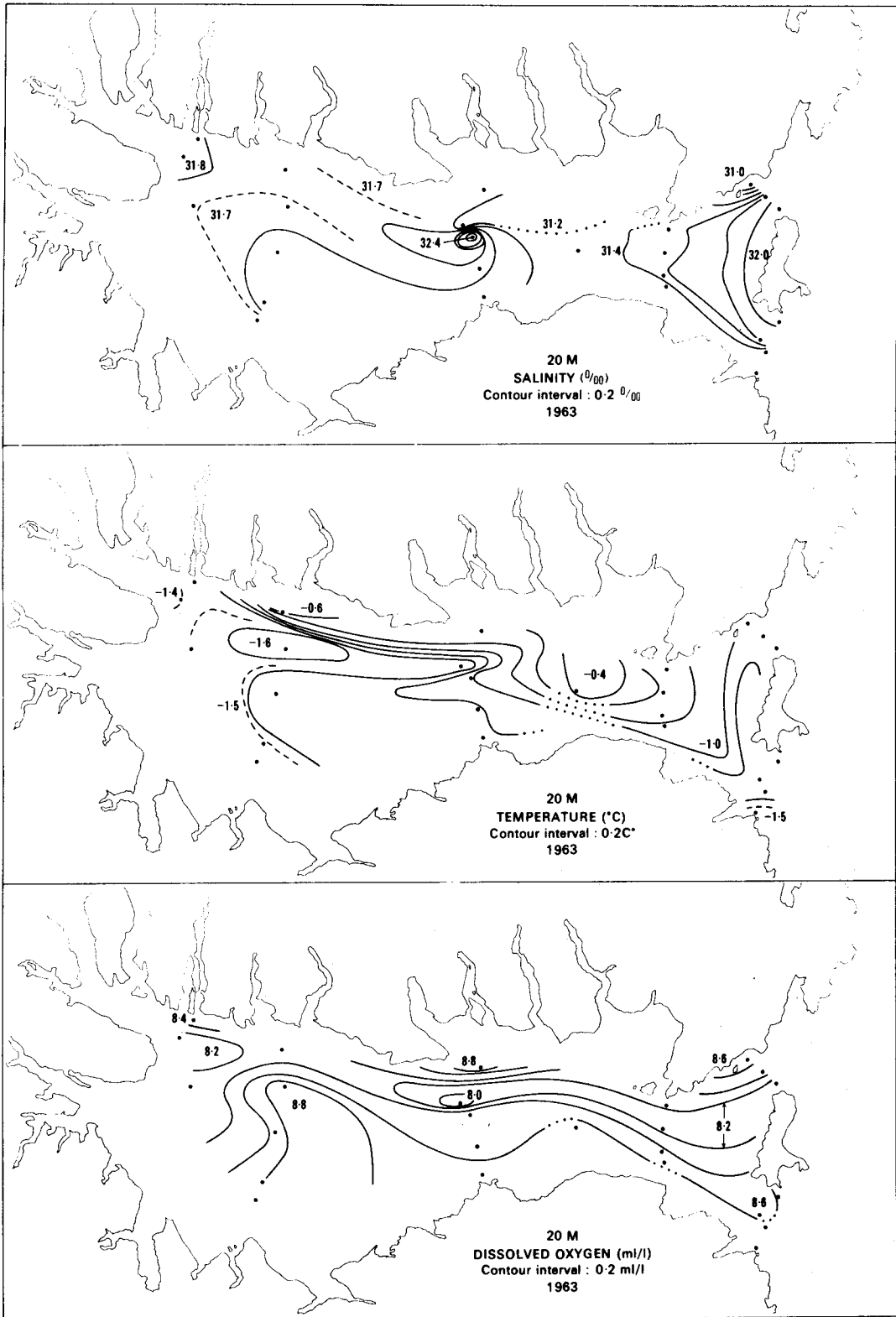
Fig. 13. The presentation at standard depths to 500 m of the distribution of salinity, temperature and dissolved oxygen as determined from an assessment of the individual representation of the observed value at the observed depth and position. The contour interval is indicated in each presentation; a dashed contour indicates an additional interval and a dotted contour indicates a doubtful interpretation. Also presented are the distribution of depth, temperature and dissolved oxygen on the 33.8 ‰ surface. (a) surface (b) 10 m (c) 20 m (d) 30 m (e) 50 m (f) 75 m (g) 100 m (h) 150 m (i) 200 m (j) 300 m (k) 400 m (l) 500 m (m) the 33.8 ‰ surface.



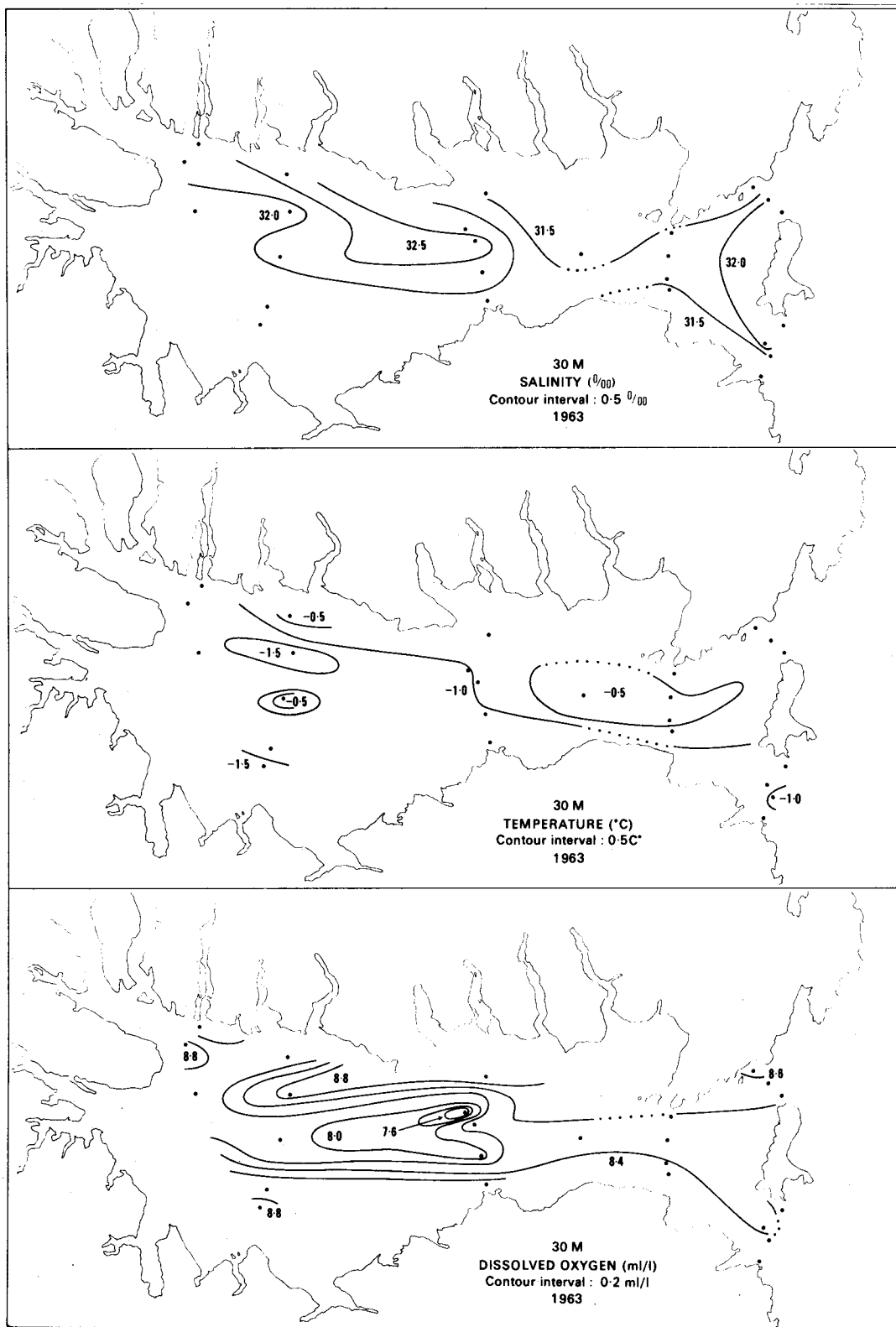
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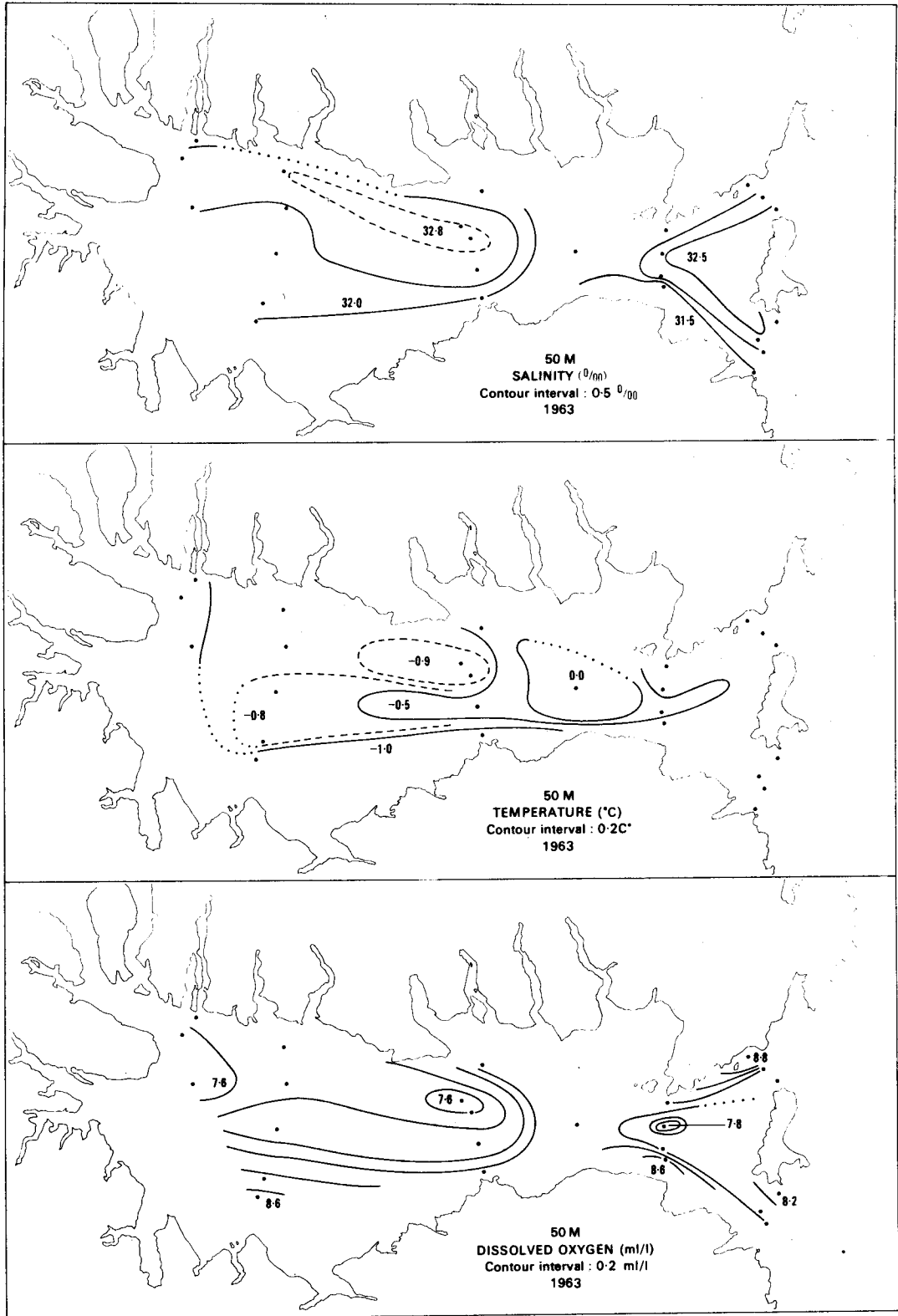
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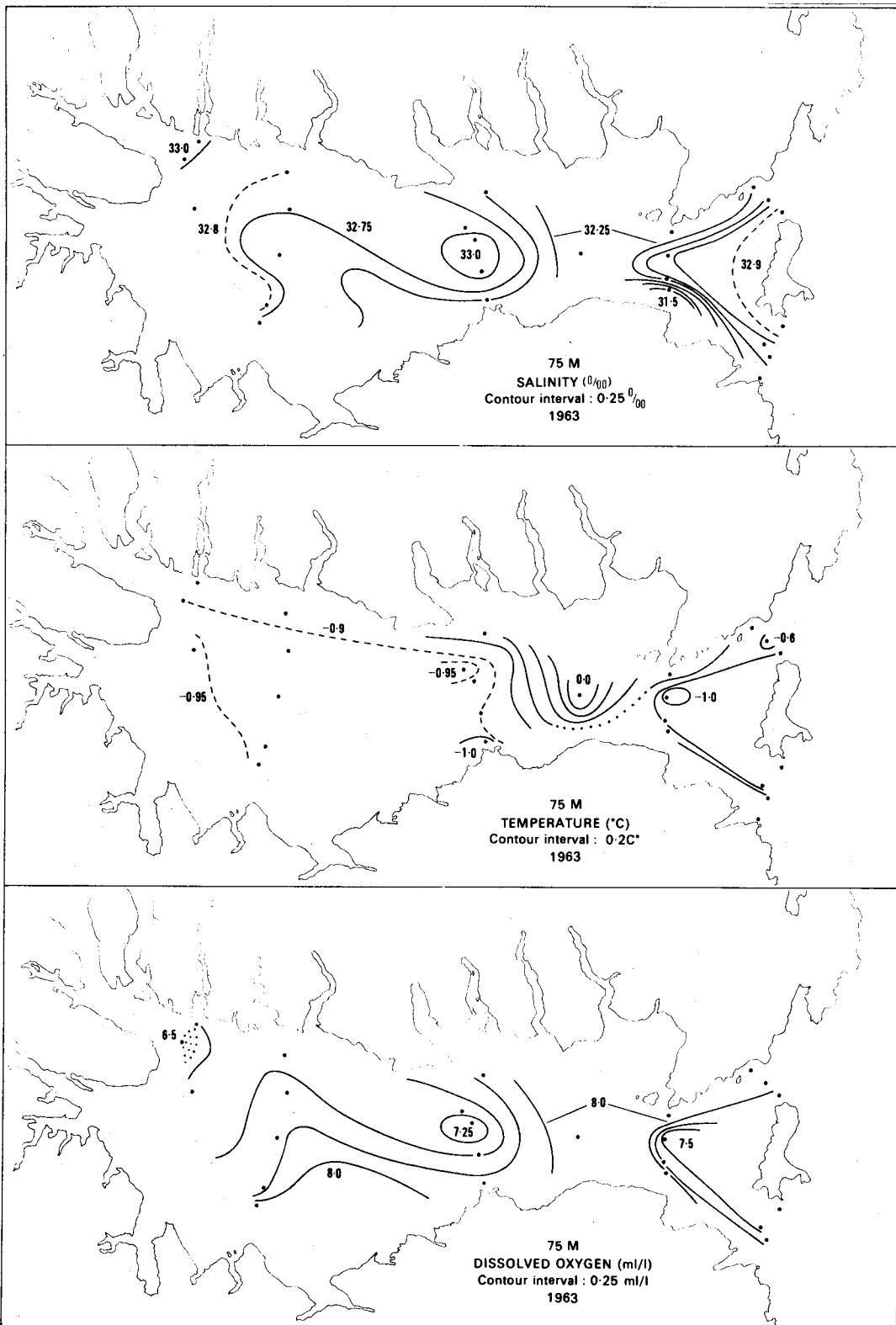
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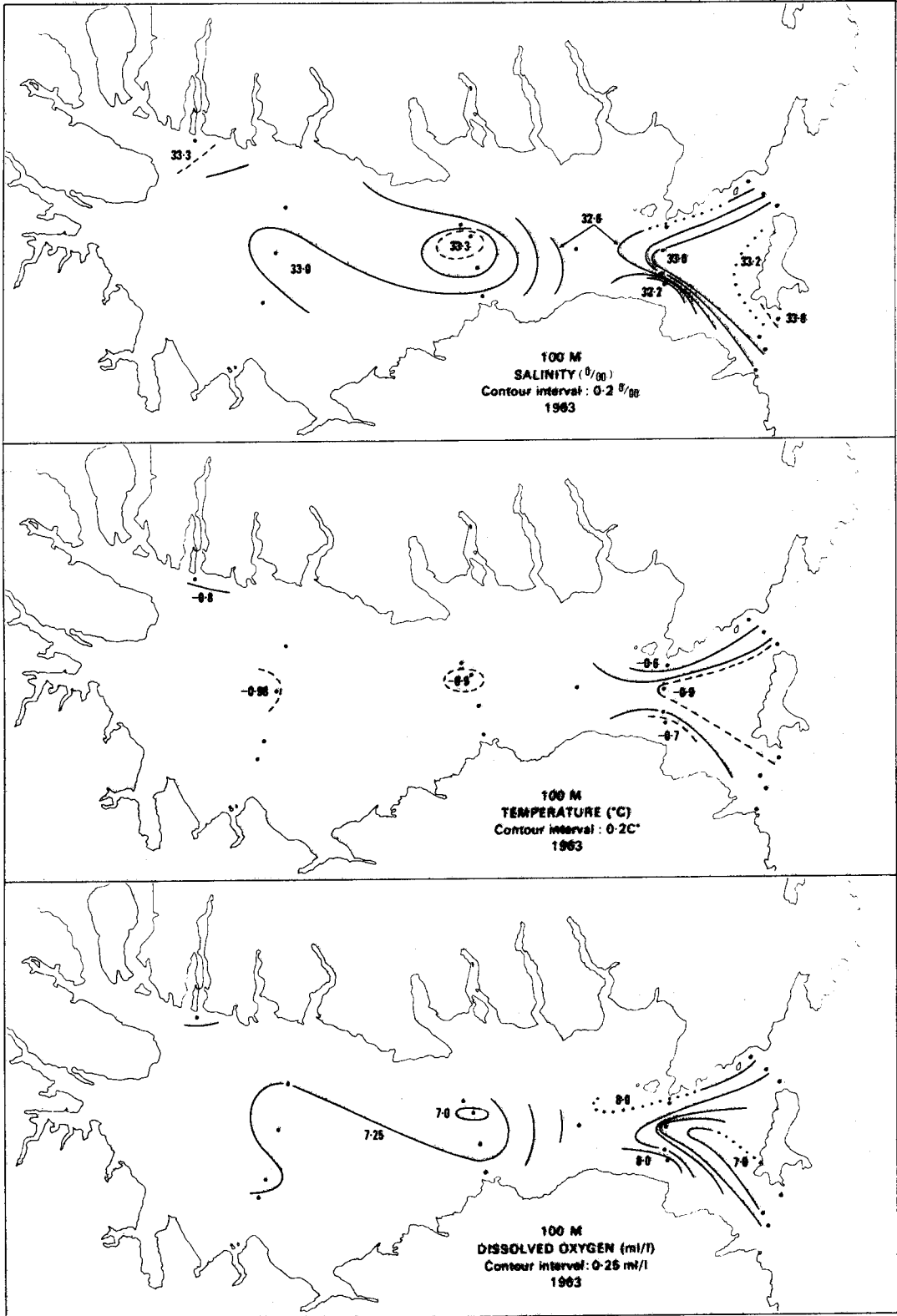
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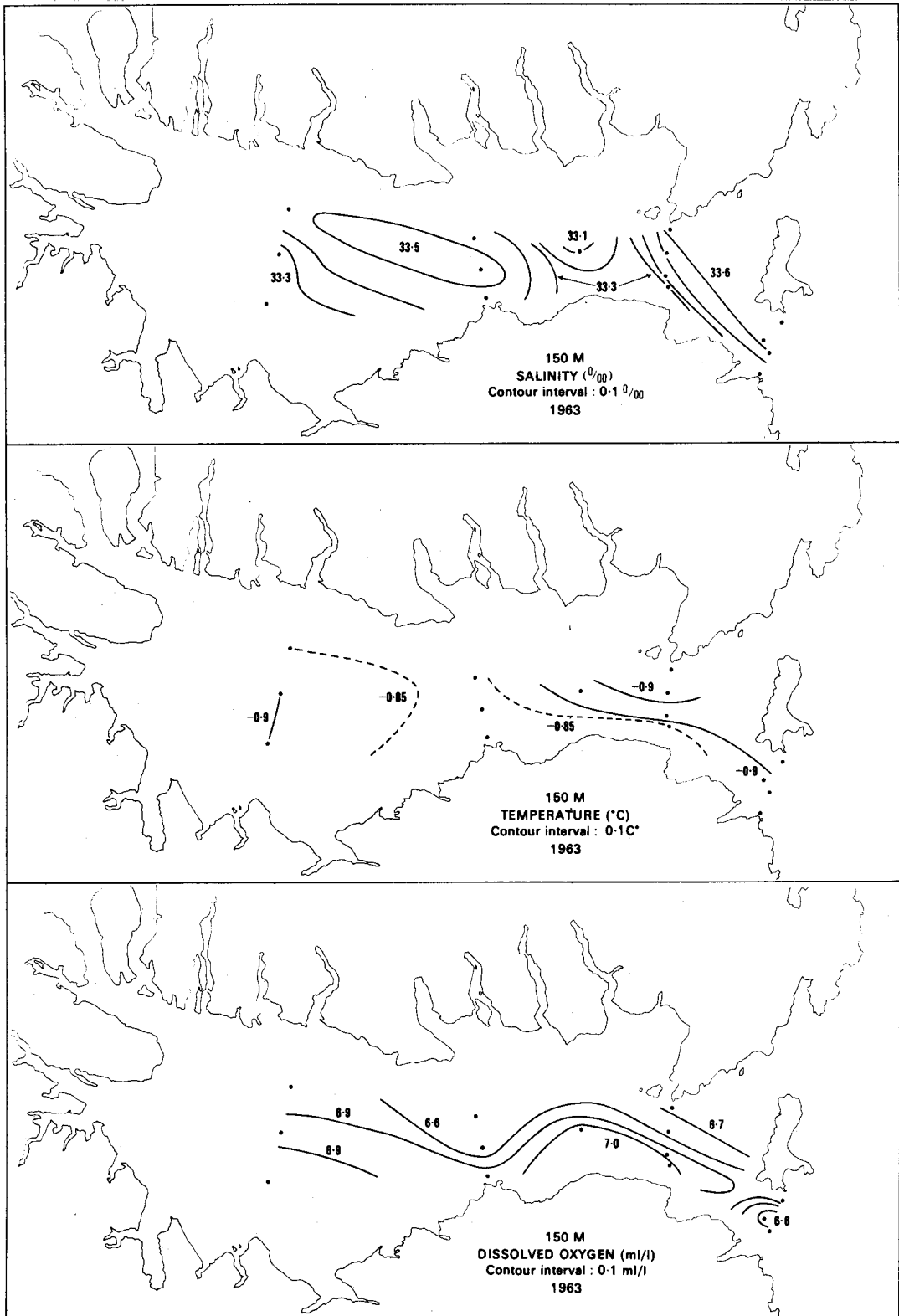
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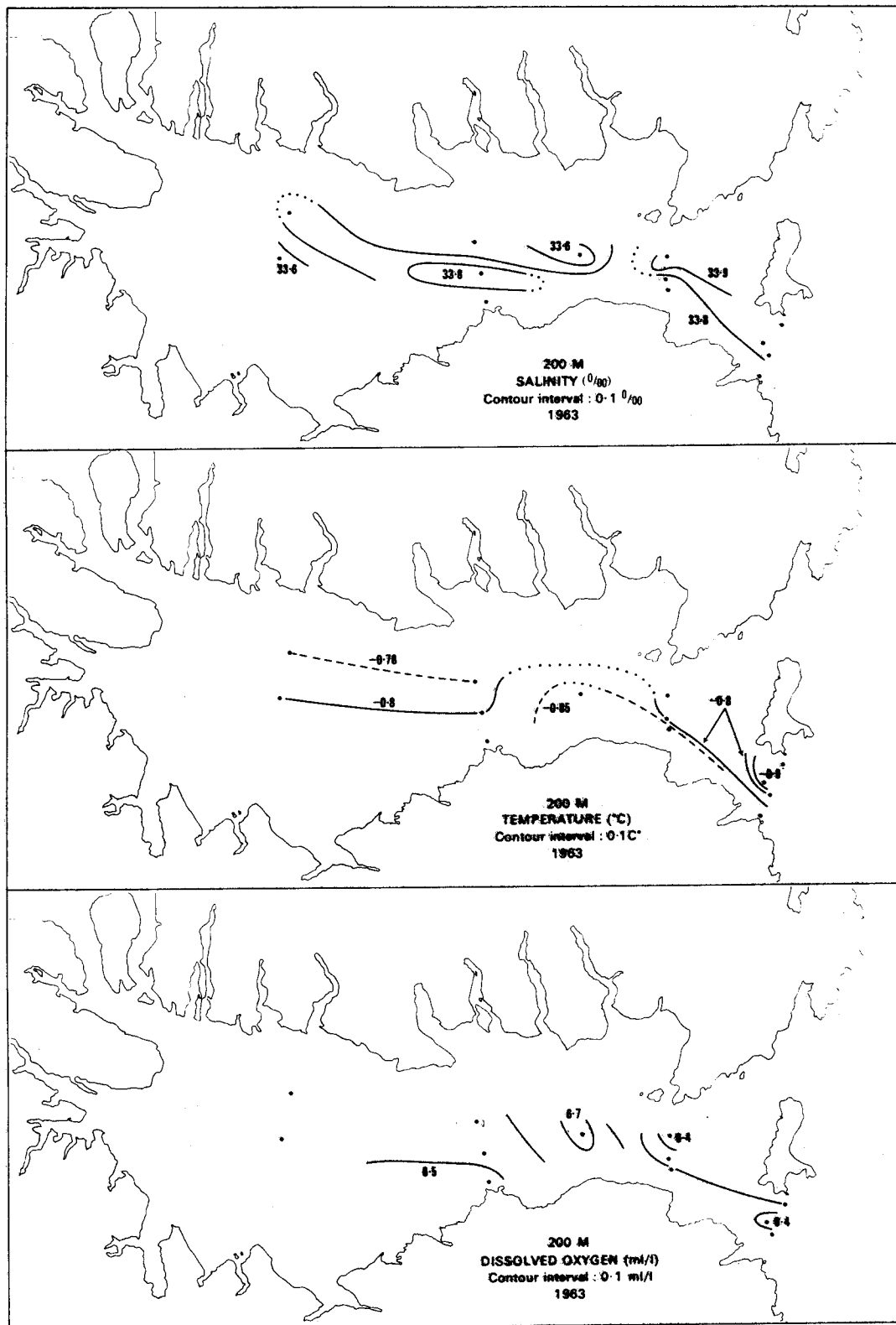
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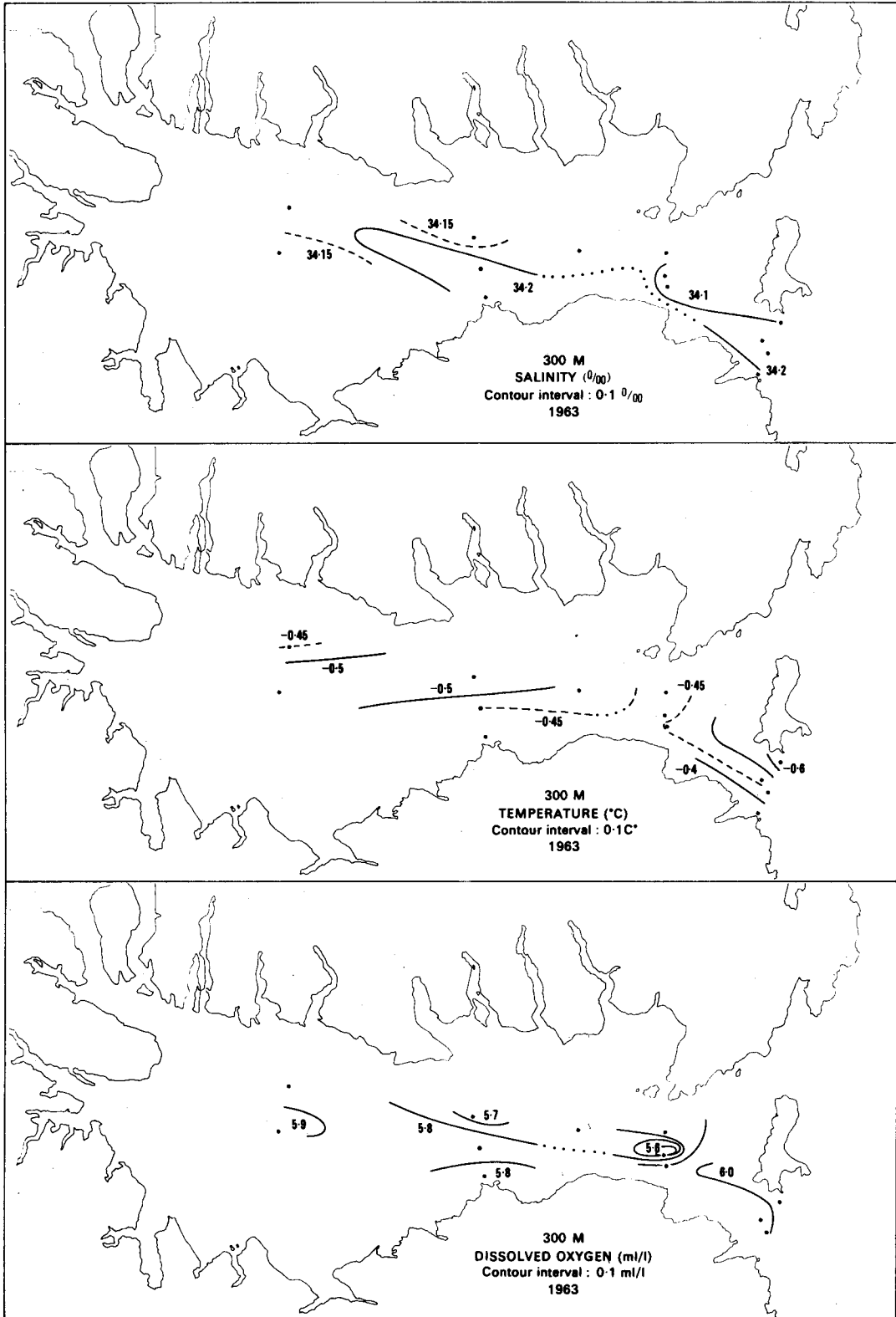
(g)



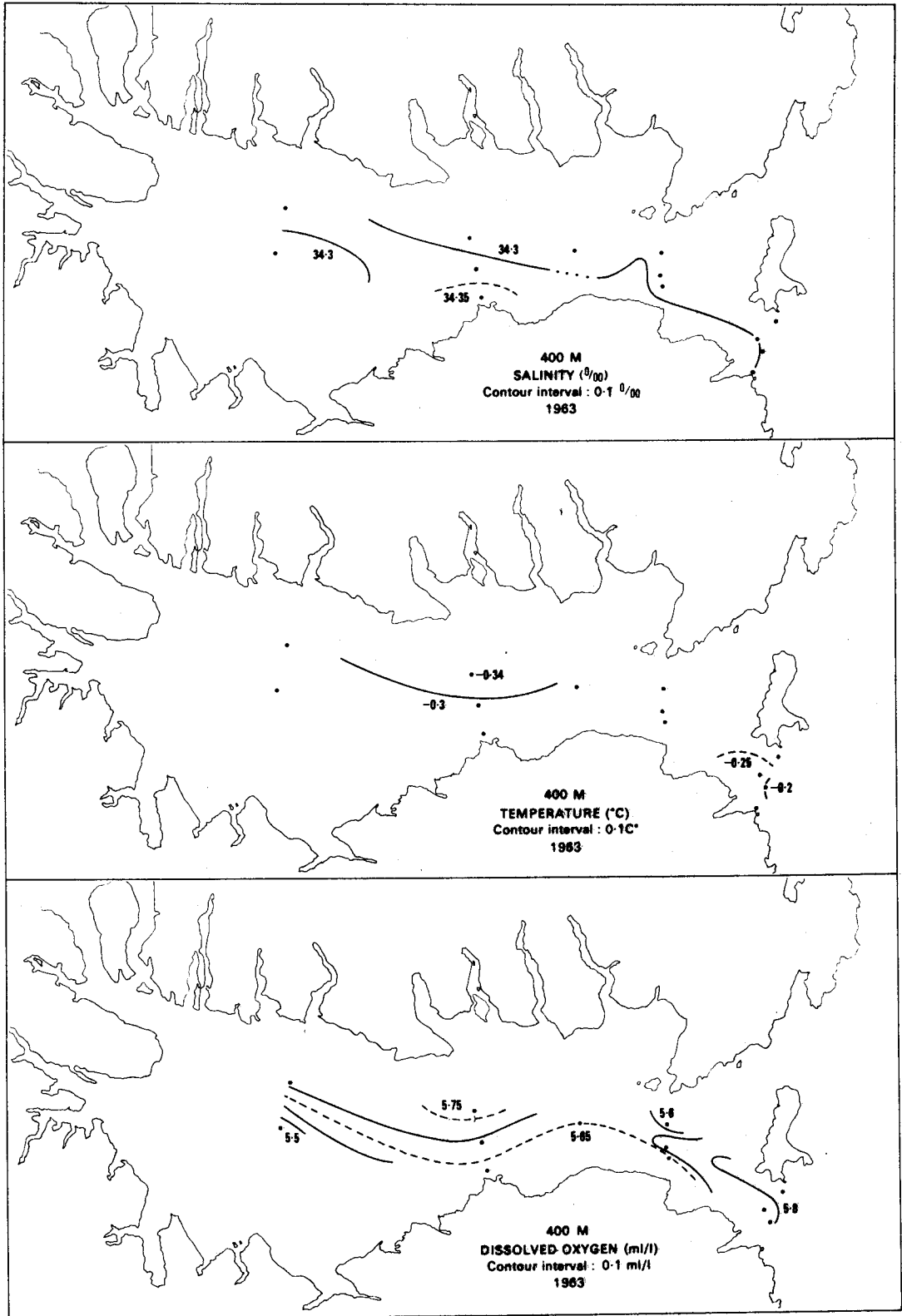
(h)



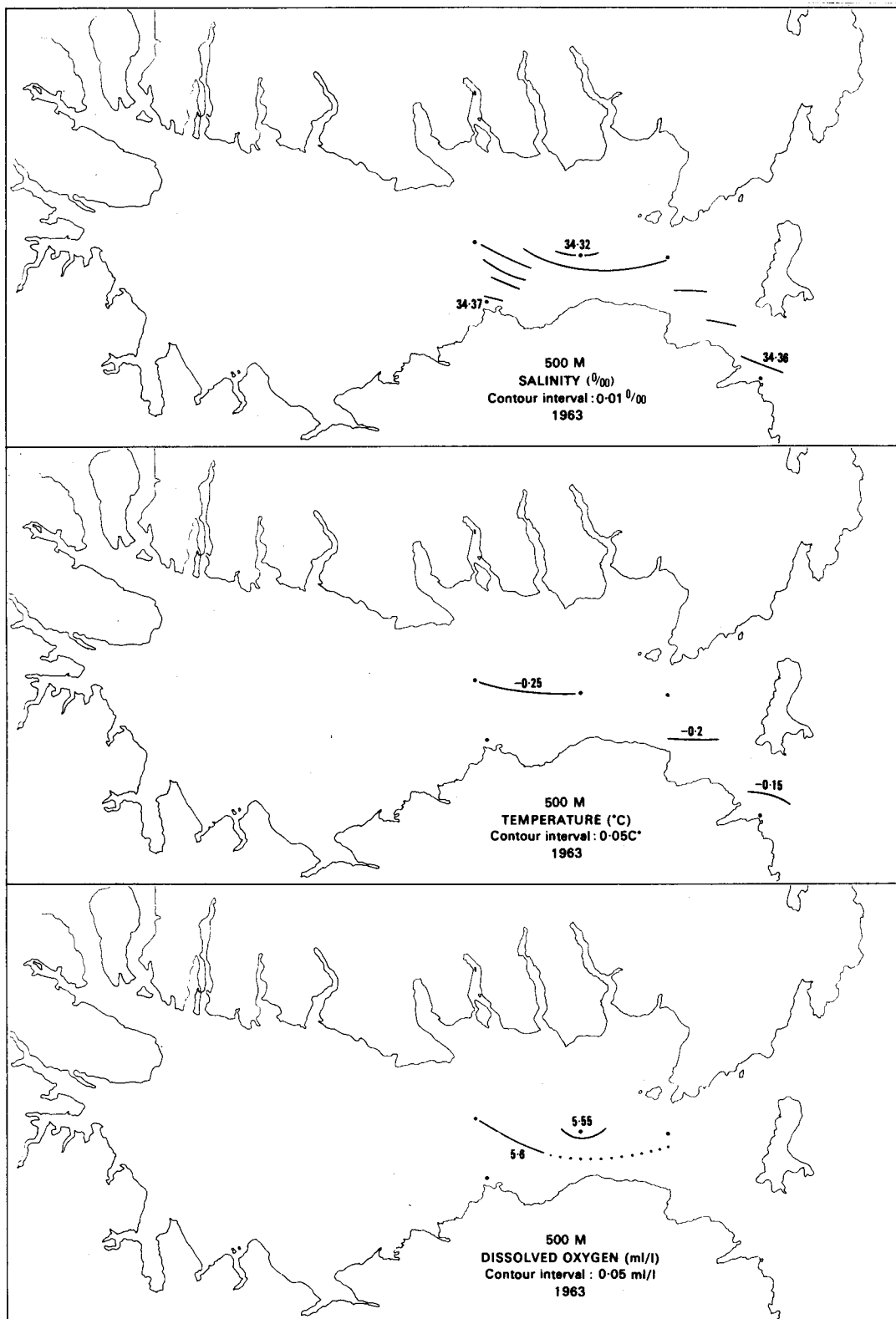
(i)

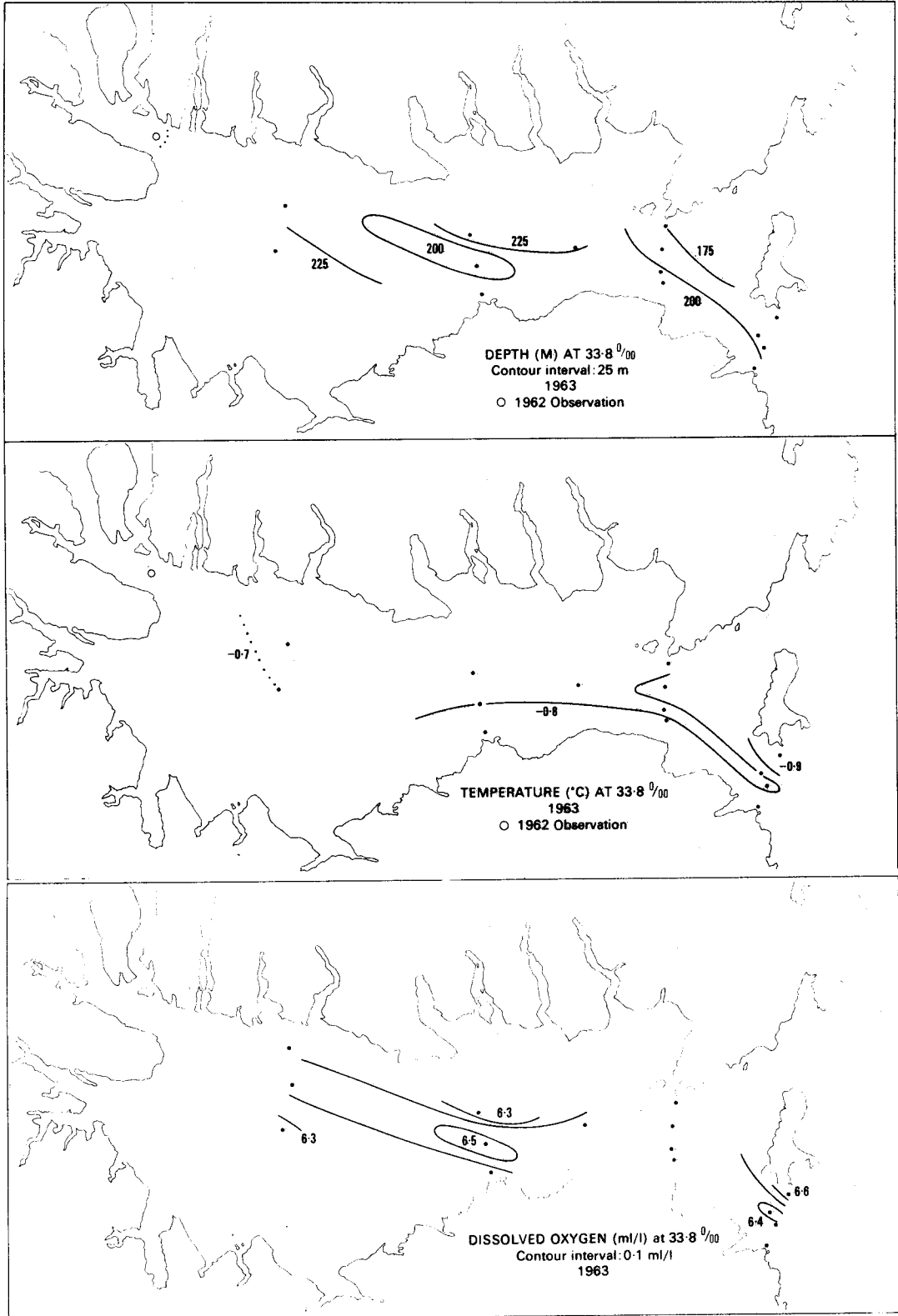


(j)



(k)





(m)