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Physical Oceanography of the New Zealand Fiords

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ABSTRACT

A comparative physical oceanographic study of the New Zealand fiords was carried out in December 1977. Sounding runs showed typical fiord form with entrance sills of 30 m to 145 m depth and inner sills separating deep basins with maximum depths of 420 m.

Water structures, typical of fiord estuaries, with a relatively low salinity upper layer over a marked halocline at 5 to 10 m depth were found. Mean upper layer salinities from 26.8 to 33.3‰ were found and could be related to the freshwater inflow conditions in each inlet. Subsurface salinity maxima between 34.5‰ and 35.06‰ were found at about 100 m depth in the northern fiords and at the bottom in the southern ones. The relationship of these maxima to that usually found in the offshore waters, along with other oceanographic evidence, suggests that deep water renewal was occurring at the time of the survey. Temperature generally decreased with depth from between 12° and 17°c in the upper layer to about 11.5°c in the deep water. Dissolved oxygen values were generally high and no anoxic conditions were observed.

INTRODUCTION

The south-west coast of the South Island of New Zealand is indented by a group of fiord inlets extending from Preservation Inlet in the south to Milford Sound some 200 km to the north (Fig. 1). The inlets are the drowned lower reaches of valleys formerly occupied by glaciers during the last glaciation (Cotton 1956). They have typical fiord features, being narrow, steep-sided, and having one or more submarine sills separating their relatively deep basins from the open sea. The mountainous nature of the land in this region combined with its exposure to the prevailing westerly weather systems results in high rainfall and large freshwater runoff into the fiords.

The present paper reports the results of the FIORDS 77 cruise of R. V. *Tangaroa* in December 1977. The purpose of this cruise was to study the comparative physical oceanographic features of all the fiords. There are 14 inlets on the coast and a further eight arms or passages greater than 10 km in length inside the fiord system, along with numerous other small arms, bays

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Inset 1

and islands (Fig. 1). The Breaksea/Dusky Sound system and the Thompson/Doubtful Sound system both form complex interconnected inlets while the remaining fiords generally consist of a single inlet, in some cases branching into two arms near the head. Sutherland Sound, which has a very shallow entrance sill, was not visited on this cruise because of the unsuitable conditions for small boat operation which were experienced.

Previous hydrological work in the New Zealand fiords has been carried out in Milford Sound (Garner 1964, Stanton 1978), Caswell Sound (Stanton 1978), Nancy Sound (Stanton 1978), Doubtful Sound (Batham 1965), and Dusky Sound (Jillett and Mitchell 1973). Those New Zealand fiords which have been studied exhibit evidence of typical fiord circulation comprising a shallow low salinity surface layer travelling seaward with a deeper replacement inflow of coastal water below. The water in the deep basins is adequately ventilated and anoxic conditions have not been observed. Other fiord regions have generally received more comprehensive study, for example, British Columbia and Alaskan fiords (Pickard 1961, 1963, 1967); Chilean fiords (Pickard 1971) and Norwegian fiords (Saelen 1967). A recent study (Pickard and Stanton 1980) compares the oceanography of the Pacific fiords in British Columbia, Alaska, Chile and New Zealand.

Published bathymetric data for most of the New Zealand fiords are based on lead line soundings and these provide inadequate coverage for the determination of sill and basin profiles. All the fiords were surveyed in 1851 by H.M.S. *Acheron* and these soundings, along with some additions and corrections, are published in four Hydrographic Office Charts (NZ 7413, NZ 7522, NZ 7612, and NZ 7614). Recent comprehensive echo sounding surveys have been published for Milford Sound (Brodie 1963), Caswell Sound (Irwin 1973) and Nancy Sound (Irwin 1974). Similar surveys have been carried out in the Thompson/Doubtful Sound system (Irwin and Main in press) and Dagg Sound (Pickrill and Main 1980), the latter survey being one of the subsidiary projects on the FIORDS 77 cruise.

On the FIORDS 77 cruise the oceanographic survey of each fiord was preceded by a sounding run along the centre line of the inlet. On the return passage the oceanographic stations were worked and, during this or any subsequent ship manoeuvres, repeat soundings were taken to check the sill depths and any other bathymetric features of interest. All soundings were made with the 3.5 kHz and 12 kHz echo sounders installed on R. V. *Tangaroa*. The sounding lines are shown in Fig. 2(a-e) and the bathymetric profiles obtained are shown in Fig. 3(a-d). The recent topographic maps of the fiord region (N.Z. Map Series 1, scale 1:63,360) have been used as a base for Fig. 2 as the older hydrographic charts contain some errors in coastal outline. In the narrow and steep sided parts of the fiords false echos are frequently obtained. These have been eliminated as far as possible using the repeat soundings or by reference to the new bathymetric charts mentioned above. The maximum depth recorded in the various traverses across a given sill has been taken as the sill depth. However, the possibility remains that a deeper channel exists in some cases.

Oceanographic stations were worked at positions determined by the joint consideration of adequate sampling in the deep basins and obtaining a representative coverage of the fiords. The average station spacing was 6.5 km. Reversing bottle casts were made using standard techniques with the upper bottles closely spaced to define the surface layer. Bottle depths of 0, 2, 4, 6, 10, 15, 20, 30, and 50 m and then standard depths to near the bottom were generally used. In the outer reaches the near surface bottles were at depths of 0, 2, 5, and 10 m. Salinities were determined with an inductive salinometer. Additional temperature data were obtained with a 0-70 m bathythermograph cast at each station. Water samples for dissolved oxygen determination were taken at selected depths through the water column and these were analysed using the modified Winkler method.

The survey began at Milford Sound on 5 December and then proceeded to Preservation Inlet, the southernmost fiord. The inlets were then surveyed systematically working from south to north, finishing with a repeat survey of Milford Sound, 12 days after the first survey. Milford Sound provided a useful baseline for the fiord studies as routine meteorological and river runoff data are available there but not generally for the other fiords. Two recording current meters were moored (Stn I382) on the first visit and retrieved during the second survey. Off shore oceanographic conditions were sampled at four stations during the survey: the positions of these stations are shown in Fig. 1. Oceanographic station data for the FIORDS 77 cruise is given in Greig (in press).

GENERAL CHARACTERISTICS

Inlet Depth Profiles

The longitudinal depth profiles of the New Zealand fiords (Fig. 3) show that they all have a distinct entrance sill near the mouth with one or more relatively deep basins inside the fiord separated by inner sills. Where a branch inlet joins a major fiord a sill is

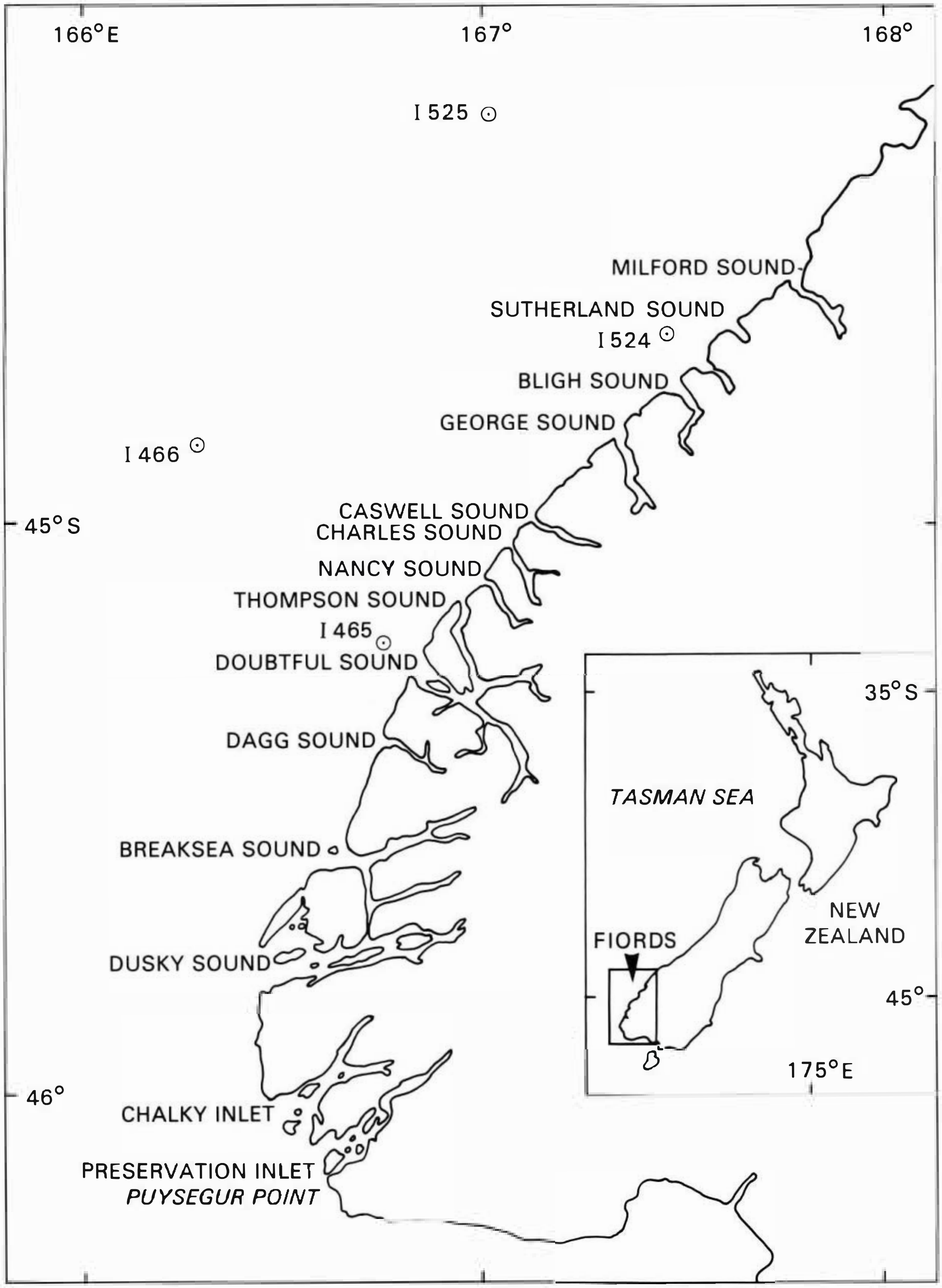

FIG. 1. The New Zealand fiord region showing the position of the four off-shore stations worked on the FIORDS 77 cruise, December 1977. Inset shows location of the fiords.

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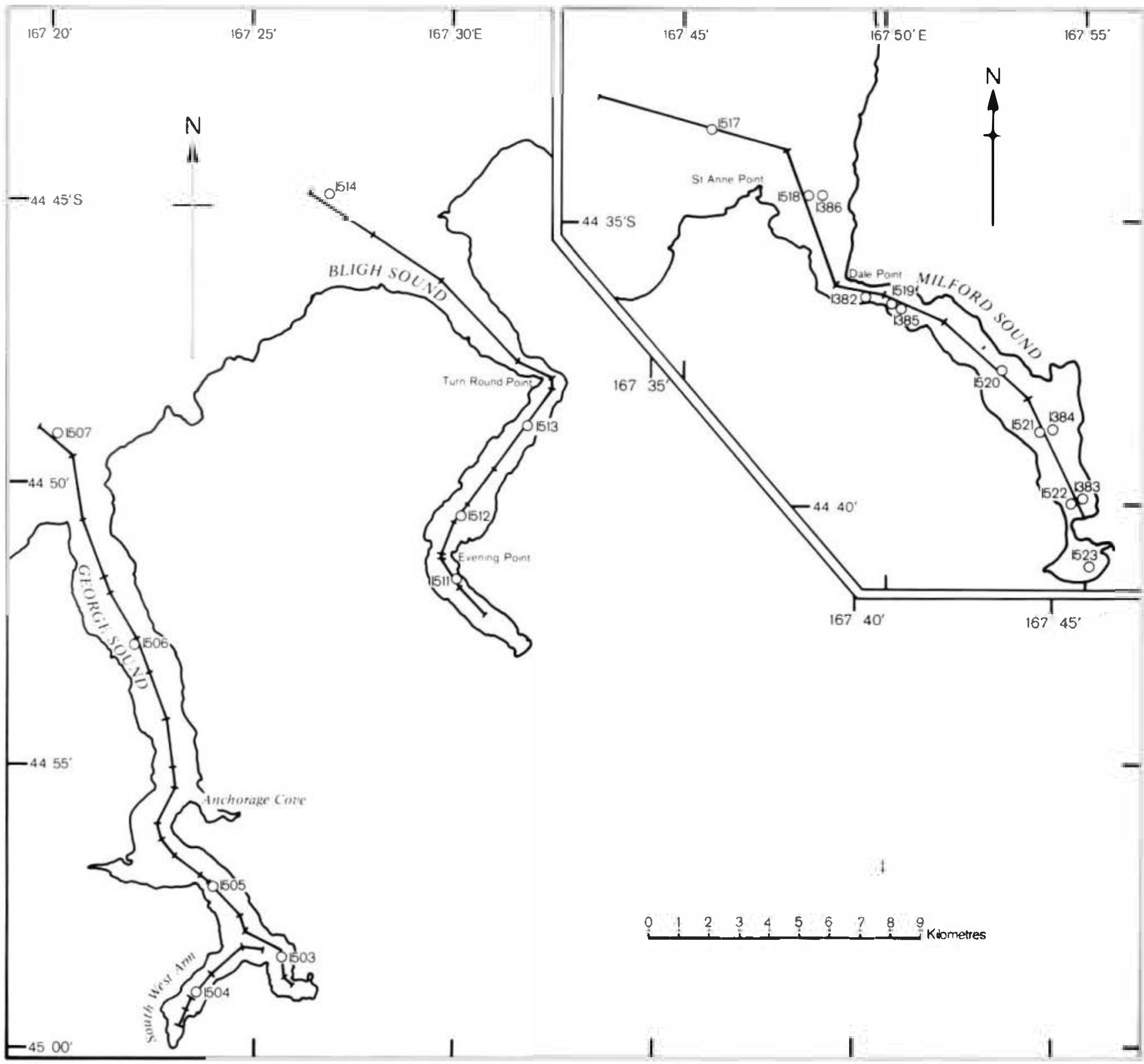

FIG. 2a. The position of the echo-sounding lines and oceanographic stations (open circles) worked in Bligh Sound, George Sound, and Milford Sound in December 1977. Ticks on the sounding lines mark course alterations.

generally found. The major dimensions of the fiords are given in Table 1. All sill and maximum depths in this table are best estimates from the FIORDS 77 sounding data, with the following exceptions.

(1) Milford Sound: Entrance sill depth taken as 35 fm from Brodie 1964, fig. 2. Note that this sill, at the seaward end of Entrance Basin, differs from the deeper sill at the landward end of Entrance Basin (near Dale Point) which Brodie (1964) called the "Entrance Sill". The maximum depth (147 fms) is taken from Brodie (1964).

(2) Caswell Sound: Irwin (1978) gives an entrance sill of 143 m but points out that shallower depths may occur seaward of his soundings. The sill at 66 m has been tentatively accepted based on the soundings of M. V. *Taranui* (Irwin 1978) and FIORDS 77 data. The maximum depth is from Irwin (1978).

(3) Nancy Sound: Sill and maximum depths are from Irwin (1978).

(4) Thompson/Doubtful Sound complex: All sills and maximum depths are taken from Irwin and Main (in press).

(5) Dagg Sound: Sill and maximum depth from Pickrill and Main (1980).

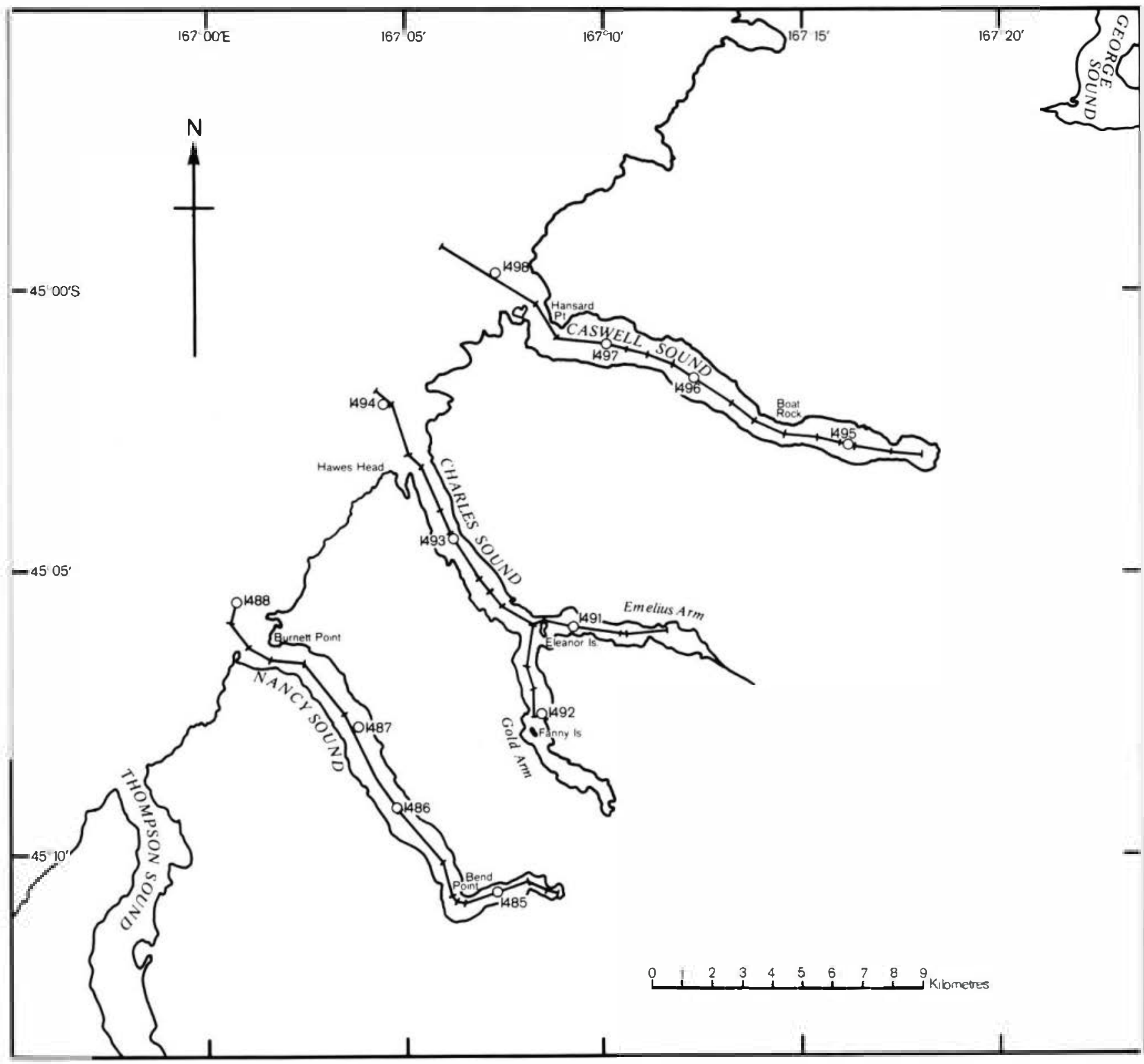

FIG. 2b. The position of the echo-sounding lines and oceanographic stations (open circles) worked in Caswell Sound, Charles Sound, and Nancy Sound in December 1977. Ticks on the sounding lines mark course alterations.

The fiord depth profiles (Fig. 3) were constructed from the FIORDS 77 sounding data except for some of the above fiords. Profiles for Milford, Caswell and Nancy Sounds were constructed from the published charts (Brodie 1963; Irwin 1973, 1974). Profiles in the Thompson/Doubtful Sound complex were partly redrawn, particularly over the sills, to more truly represent the maximum depth of water connections using the more comprehensive data of Irwin and Main (in press). Some inconsistencies consequently arise between the position of sounding lines (Fig. 2) and the profiles obtained (Fig. 3). The most important of these occurs in Pendulo Reach where the maximum water connection, as shown in Fig. 3, occurs to the east of Seymour Island, not along the original sounding line to the west of this island (Fig. 2).

Freshwater Inflow

The fiord region experiences an extremely high rainfall. Annual normal rainfall for the four stations in this region (N.Z. Meteorological Service 1973) are as follows:

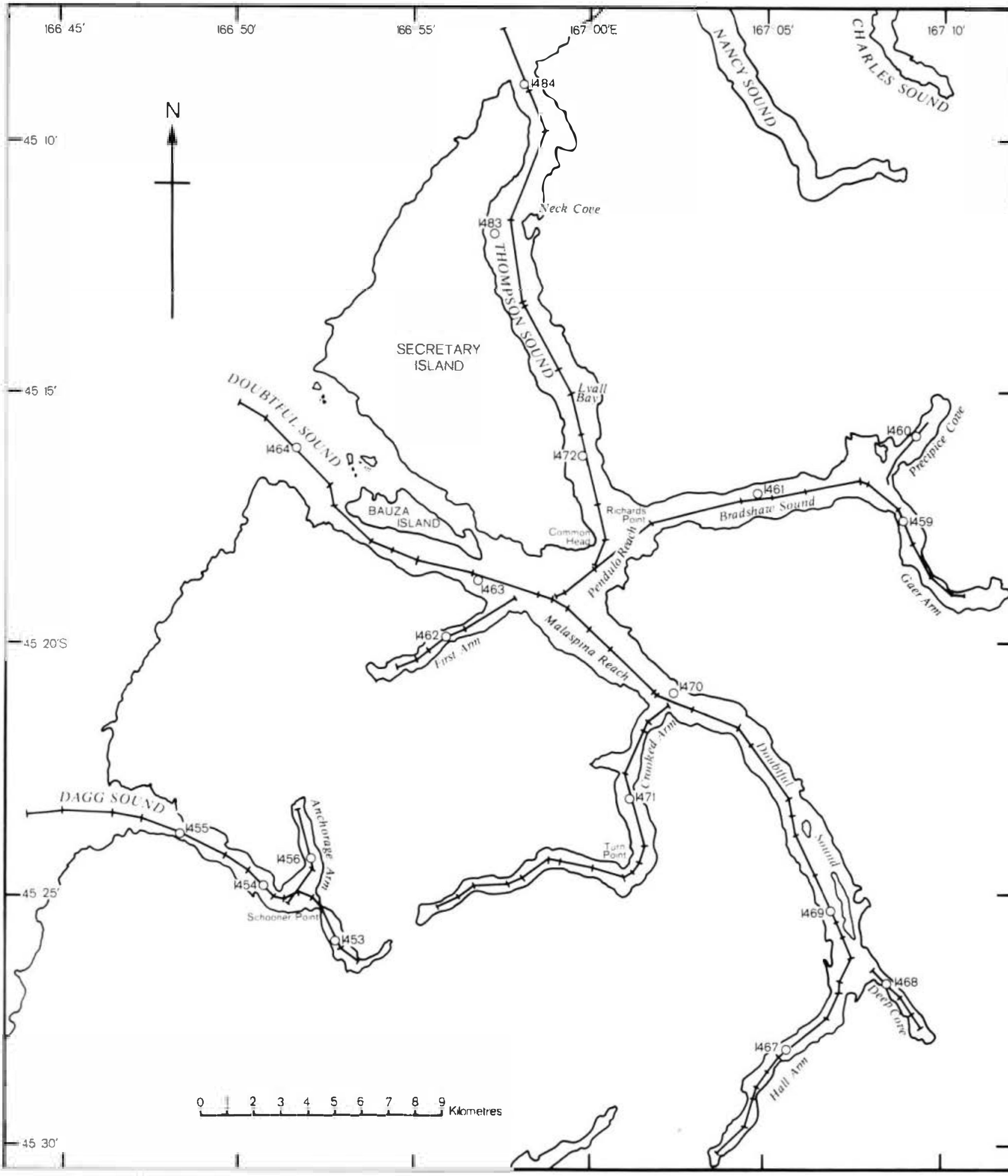

FIG. 2c. The position of the echo-sounding lines and oceanographic stations (open circles) worked in Dagg Sound and Doubtful Sound/Thompson Sound/Bradshaw Sound in December 1977. Ticks on the sounding lines mark course alterations.

FIG 2d (*opposite page*). The position of the echo-sounding lines and oceanographic stations (open circles) worked in Breaksea Sound and Dusky Sound in December 1977. Ticks on the sounding lines mark course alterations.


166°25′
166°30′
166°35′
166°40′E
166°45′
166°50′
166°55′
167°00′
45°30′
45°35′
45°40′ S
45°45′
N
1452
Breaksea Island
BREAKSEA SOUND
1451
Acheron Passage
1450
Chatham Point
Vancouver Arm
1441
1440
Broughton Arm
1443
1442
RESOUTION ISLAND
FIVE FINGERS PENINSULA
Oke Island
Wet Jacket Arm
1437
1438
1439
Supper Cove
1419
1418
Shark Cove
1421
COOPER ISLAND
Nine Fathoms Passage
Duck Cove
Bowen Channel
LONG ISLAND
1420
Cook Channel
ANCHOR ISLAND
Passage Islands
1422
DUSKY SOUND
1423
1424
South Point
0 1 2 3 4 5 6 7 8 9 Kilometres

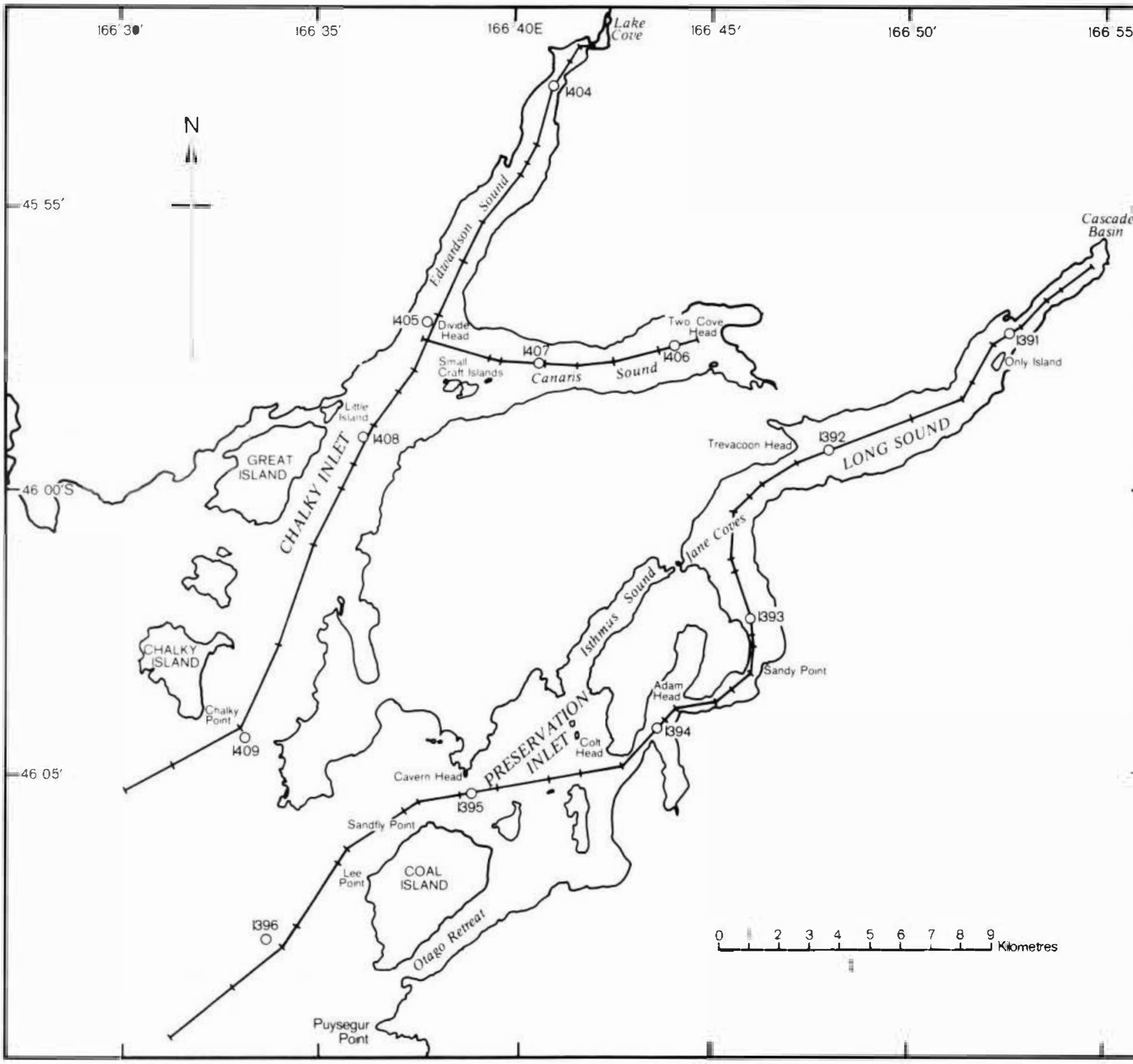

FIG 2e. The position of the echo-sounding lines and oceanographic stations (open circles) worked in Chalky Inlet/Edwardson Sound/Cunaris Sound and Preservation Inlet/Long Sound in December 1977. Ticks on the sounding lines mark course alterations.

Milford Sound	6236 mm
Deep Cove	5290 mm
Wilmot Pass	6747 mm
Puysegur Point	2355 mm

The variation between the Deep Cove and Wilmot Pass stations (in Doubtful Sound) which are some four kilometres apart demonstrates the high variability resulting from the extremely rugged terrain. The Puysegur Point rainfall recorded at the lighthouse is thought to be unrepresentative of the region as a whole (Maunder 1966). The Milford Sound station is the only long term climatological station in the region and hence data from this station are the most reliable.

Mean monthly rainfalls at all the stations exhibit a maximum in November with a second maximum in March (N.Z. Meteorological Service 1973). Minimum rainfall occurs in July with a secondary minimum in January. Rainfall, combined with the melting of winter snow, results in maximum freshwater inflow in the spring and summer period.

The fiord region is considered as one hydrological region (Toebes and Palmer 1969) and the Cleddau River catchment, at the head of Milford Sound, is taken as the representative basin for the region. The Cleddau River gaugings, obtained near its entry into the fiord, are the only routine gaugings of a natural catchment draining into the fiord region. Daily mean discharge rates for the Cleddau River and daily rainfall figures from Milford Sound over the period of the FIORDS 77 cruise are shown in Fig. 4. The close correspondence between peak rainfalls and peak river discharges demonstrates the rapid runoff exhibited by this region.

Nevins (1970) gives the average annual discharge of the Cleddau River at Milford as 23.8 $m^3.s^{-1}$. This river has been gauged since 1963 and using the most recent data, supplied by the National Water and Soil Conservation Organisation, the annual average discharge for 1963 to 1978 inclusive is 31.1 $m^3.s^{-1}$. Variability is high even in the annual flow rate as can be seen from the standard deviation of 10.7 $m^3.s^{-1}$ in the annual average discharge. Monthly mean discharge for the 1963 to 1978 period shows peaks of 53.5 $m^3.s^{-1}$ and 48.5 $m^3.s^{-1}$ in October and March respectively with a minimum of 16.2 $m^3.s^{-1}$ in July.

A considerable freshwater input to Doubtful Sound arises from the Manapouri hydro-electric power station outflow situated in Deep Cove. This 600 megawatt capacity station utilises the diversion of water from the lakes to the east of the main ranges and consequently the outflow at any given time is determined by electricity generating requirements. Outflow data for November and December 1977 have been supplied by the Electricity Division, Ministry of Energy.

Estimates of land runoff into the fiords must necessarily be based on the assumption of hydrological similarity between the Cleddau catchment and the catchment areas of the other fiords. Catchment areas of all the fiords were measured by planimeter from the relevant New Zealand Map Series 1 topographic maps (Table 2). The total catchment, the fiord area, and the upper catchments, being the catchment behind the head of each major arm, were measured. Derived from these the total catchment divided by the fiord area gives a measure of the relative effect of freshwater inflow on the salinity structure of each fiord in the case of a uniform rainfall distribution. From these figures (Table 2) it can be seen that the effect of freshwater inflow should be most marked in Milford Sound and least in Chalky Inlet. The five northern fiords have the largest values of this factor while the southern fiords generally have small values with the result that freshwater effects, on average, would be expected to decrease from north to south. The exception to this is the Doubtful/Thompson Sound complex, where the power station inflow artificially increases this factor in effect (Appendix 2). These considerations apply in a general way to the expected long term effects of freshwater inflow in the New Zealand fiords. Throughout the FIORDS 77 survey variations in rainfall, and hence runoff, resulted in somewhat different estimates of the freshwater effects in the fiords at the time of survey. This is discussed below in relation to the shallow salinity distribution.

Tides

The available tidal information for the fiords, derived from the tide tables (Marine Division, Ministry of Transport 1976) is given in Table 3. All data, except that for Deep Cove, are considered approximate, but they do suggest that only small variations in tidal range exist. The time differences are consistent with the propagation of the tidal wave southwards down the coast (Bye and Heath 1975). Tides in this region exhibit a marked declination with consecutive tides of different range, and consecutive fortnightly spring ranges which also differ. For this reason spring tides of up to 2.3 m were observed in Caswell and Nancy Sounds (Stanton 1978).

In Doubtful Sound, J. Irwin (pers. comm.) recorded tidal elevations at Utah Island, near the mouth of the fiord, over the period 14–18 April 1977. For an eight day period simultaneous recordings were made at Deep Cove, near the head of the fiord. The Utah Island records included one spring tide (range 1.78 m) and one neap tide (range 1.02 m).

At Deep Cove tidal ranges were 0.43 m lower on average, and high/low waters occurred generally one to two hours after those at Utah Island. These differences are larger than those observed elsewhere, but they may be local in origin in that the Deep Cove tide station was close to the outfall from the Manapouri Power Station, which discharges a considerable volume of fresh water (*see* Appendix 2). The tidal curves obtained at Deep Cove were markedly asymetrical around high and low water unlike those obtained at Utah Island. For comparison the greatest longitudinal differences observed in the British Columbian fiords (Pickard 1961) are a 10% reduction in elevation and a 10 minute lag in high/low water.

Stanton (1978) calculated a mean spring tidal current of around 3 $cm.s^{-1}$ through the entrance section of Caswell Sound. Similar values would be expected for the other fiords of similar size (Tables 1 and 2). Inward from the mouth the tidal current will decrease except where the flow is constricted by narrow or shallow passages. For the larger fiords more detailed bathymetry would be required to calculate tidal currents. For the Doubtful/Thompson Sound complex, where bathymetry is available, the multiple interconnections make a simple analysis impossible without additional information on tidal flows. The larger fiords tend to be rather broad at the mouth which would to some extent offset the effect of the larger tidal compartment in calculations of tidal velocity in these fiords.

Internal waves

Under calm conditions parallel bands of surface slicks were seen at various places within the fiords during the FIORDS 77 cruise. Such slicks can be the surface manifestation of internal waves travelling along

Inset 2

TABLE 1. Dimensions of the New Zealand fiords.

Name	Length (km)	Mean width (km)	Entrance sill depth (m)	Maximum depth (m)
Milford Sound ...	15.7	1.6	64	269
Bligh Sound ...	17.7	1.2	77	186
George Sound ...	21.2	1.4	47	224
Caswell Sound ...	15.7	1.1	66	416
Charles Sound ...	13.9	0.9	83	221
Nancy Sound ...	15.4	0.9	77	279
Thompson Sound ...	19.7	1.4	145	336
Bradshaw Sound ...	15.5	1.1	–	416
Doubtful Sound...	40.4	1.2	101	421
Crooked Arm ...	15.6	0.7	–	187
Dagg Sound ...	13.3	0.9	41	174
Breaksea Sound ...	33.3	1.3	93	365
Broughton Arm ...	10.6	0.7	–	169
Acheron Passage ...	14.5	1.4	–	364
Wet Jacket Arm ...	20.0	1.0	–	284
Dusky Sound ...	43.9	1.8	65	317
Chalky Inlet ...	27.7	2.3	45	374
Cunaris Sound ...	10.3	2.0	–	323
Preservation Inlet ...	36.5	1.8	30	371

TABLE 2. Catchment areas and surface areas of the New Zealand fiords.

Name	Total catchment (km^2)	Upper catchment (km^2)	Fiord area (km^2)	Total catchment / Fiord area
Milford Sound ...	542	387	25.3	21.4
Bligh Sound ...	206	79.5	21.1	9.8
George Sound ...	305	68.9	32.9	9.3
"East" Arm ...	–	61.8	–	–
Southwest Arm ...	–	7.1	–	–
Caswell Sound ...	273	174	17.5	15.6
Charles Sound ...	276	184	15.9	17.4
Emelius Arm ...	–	108	–	–
Gold Arm...	–	75.5	–	–
Nancy Sound ...	91.9	17.2	13.9	6.6
Doubtful/Thompson Complex ...	1069	315	133	8.0
Thompson Sound ...	152	–	28.4	–
Bradshaw Sound ...	290	185	20.9	–
Gaer Arm...	–	128	–	–
Precipice Cove ...	–	57.4	–	–
Doubtful Sound ...	627	129	83.7	
First Arm ...		17.7		
Deep Cove ...		69.8		
Hall Arm ...		33.8		
Crooked Arm ...		7.4		
Dagg Sound ...	111	33.6	14.7	7.6
Anchorage Arm ...		9.8		
"South" Arm ...		23.8		
Dusky/Breaksea Complex ...	1433	331	279	5.1
Breaksea Sound ...	337	25.4	61.5	
Vancouver Arm ...		12.1		
Broughton Arm ...		13.3		
Acheron Passage ...	63.4	–	19.6	
Wet Jacket Arm ...	176.8	33.1	19.1	
Dusky Sound ...	861	272	181	
Chalky Inlet...	515	224	110	4.7
Edwardson Sound ...		138		
Cunaris Sound ...		86.2		
Preservation Inlet ...	562	159	93	6.0

TABLE 3. Mean tidal ranges and time differences (relative to Milford) at New Zealand fiords.

Name	Spring (m)	Neap (m)	Time difference (h m)
Milford Sound	1.8	1.2	00 00
Bligh Sound	1.8	1.2	00 05
Deep Cove	1.6	1.2	00 17
Dusky Sound	1.8	1.3	00 25
Preservation Inlet	2.1	1.3	00 35

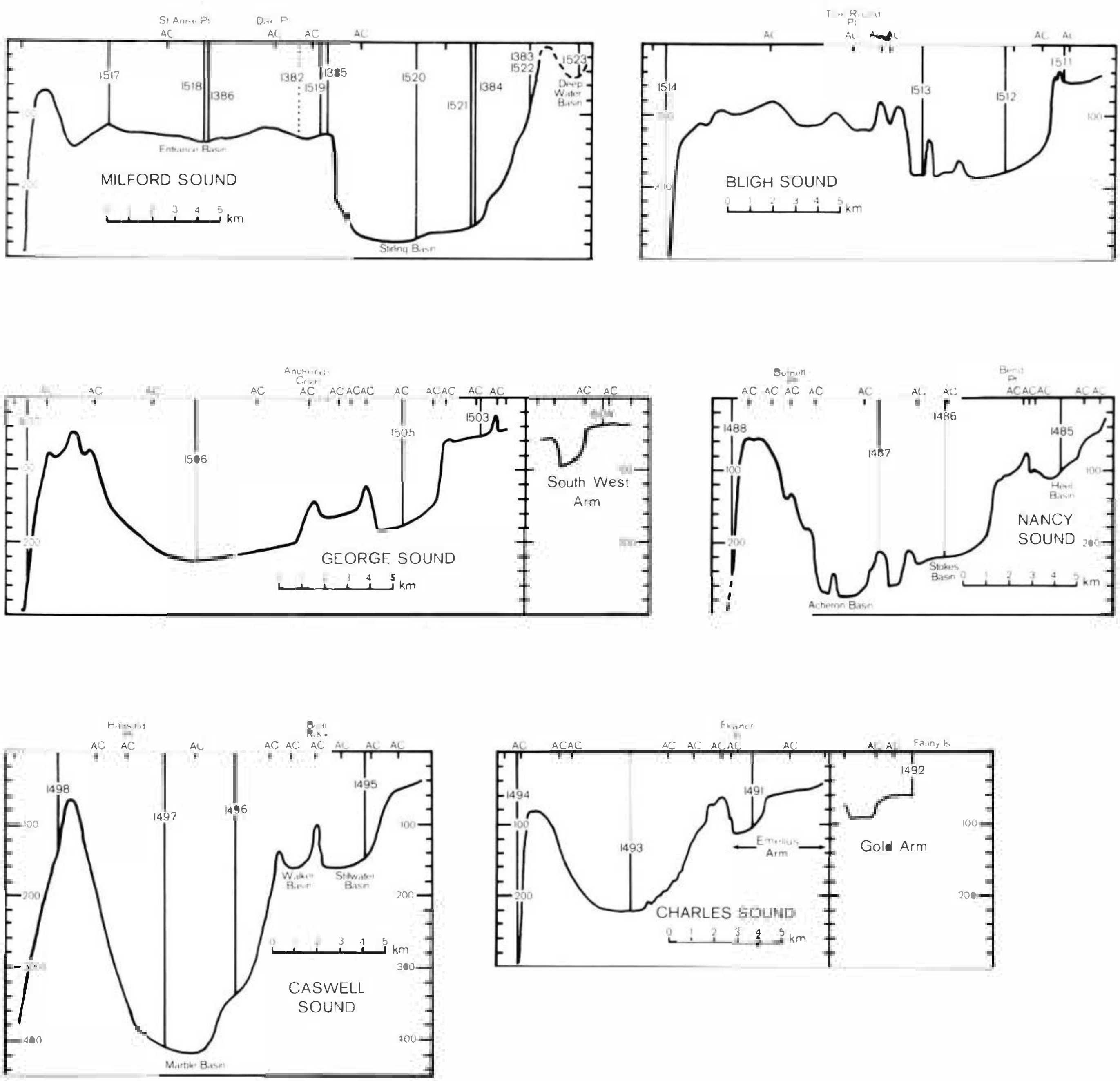

FIG. 3a. Longitudinal sections of Bligh Sound, Caswell Sound, Charles Sound, George Sound, Milford Sound, and Nancy Sound obtained along the sounding lines shown in Fig. 2a, b with station positions and alterations in course (AC) marked.

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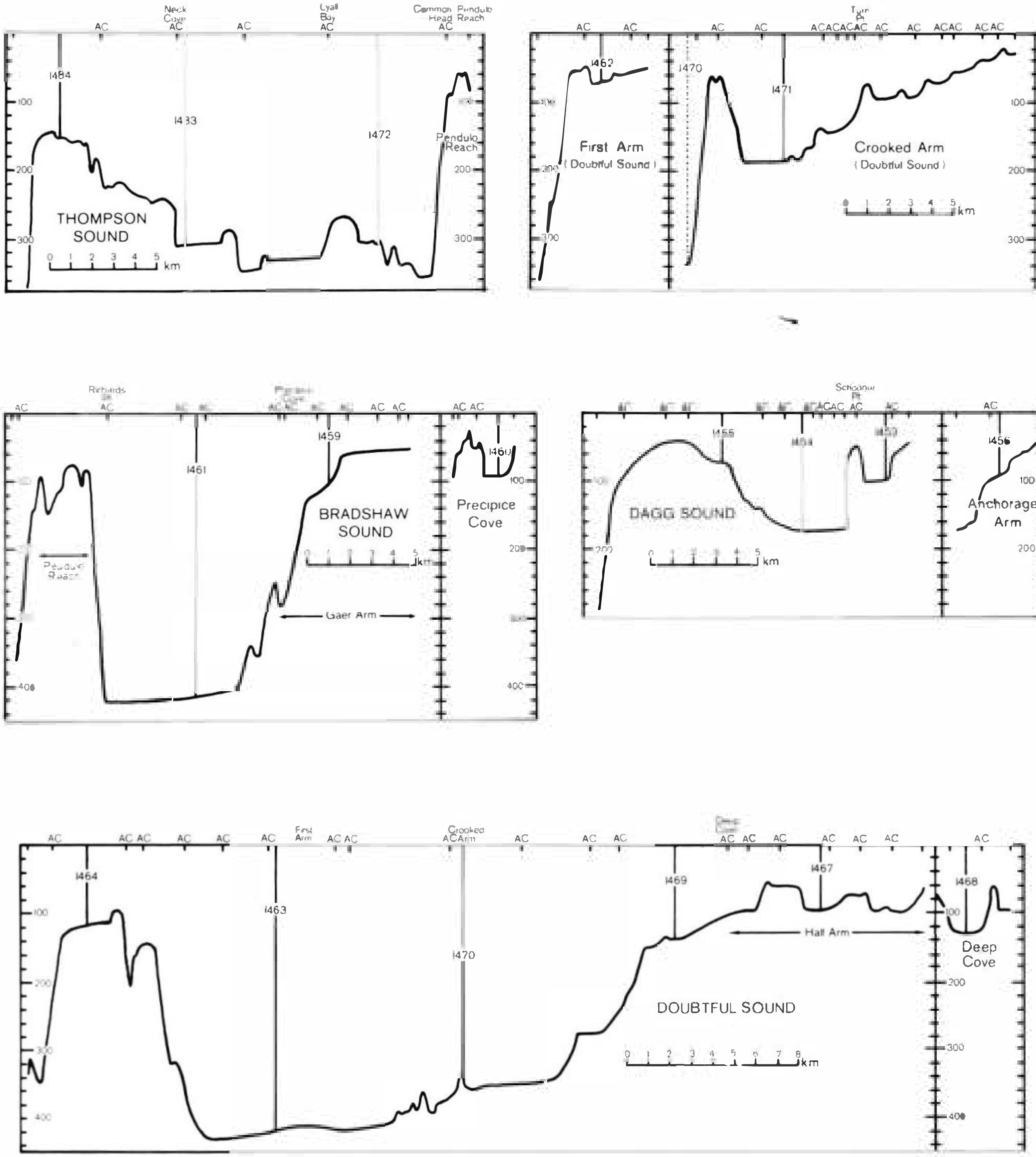

FIG. 3b. Longitudinal sections of Bradshaw Sound, Dagg Sound, Doubtful Sound, and Thompson Sound obtained along the sounding lines shown in Fig. 2c with station positions and alterations in course (AC) marked.

the pycnocline. In Dusky Sound, Jillett and Mitchell (1973) observed vertical displacement of the upper waters which may have been due to internal waves. Internal waves are known to be important in fiord inlets and have been frequently observed in other fiord systems (*see*, e.g., Pickard and Stanton 1980).

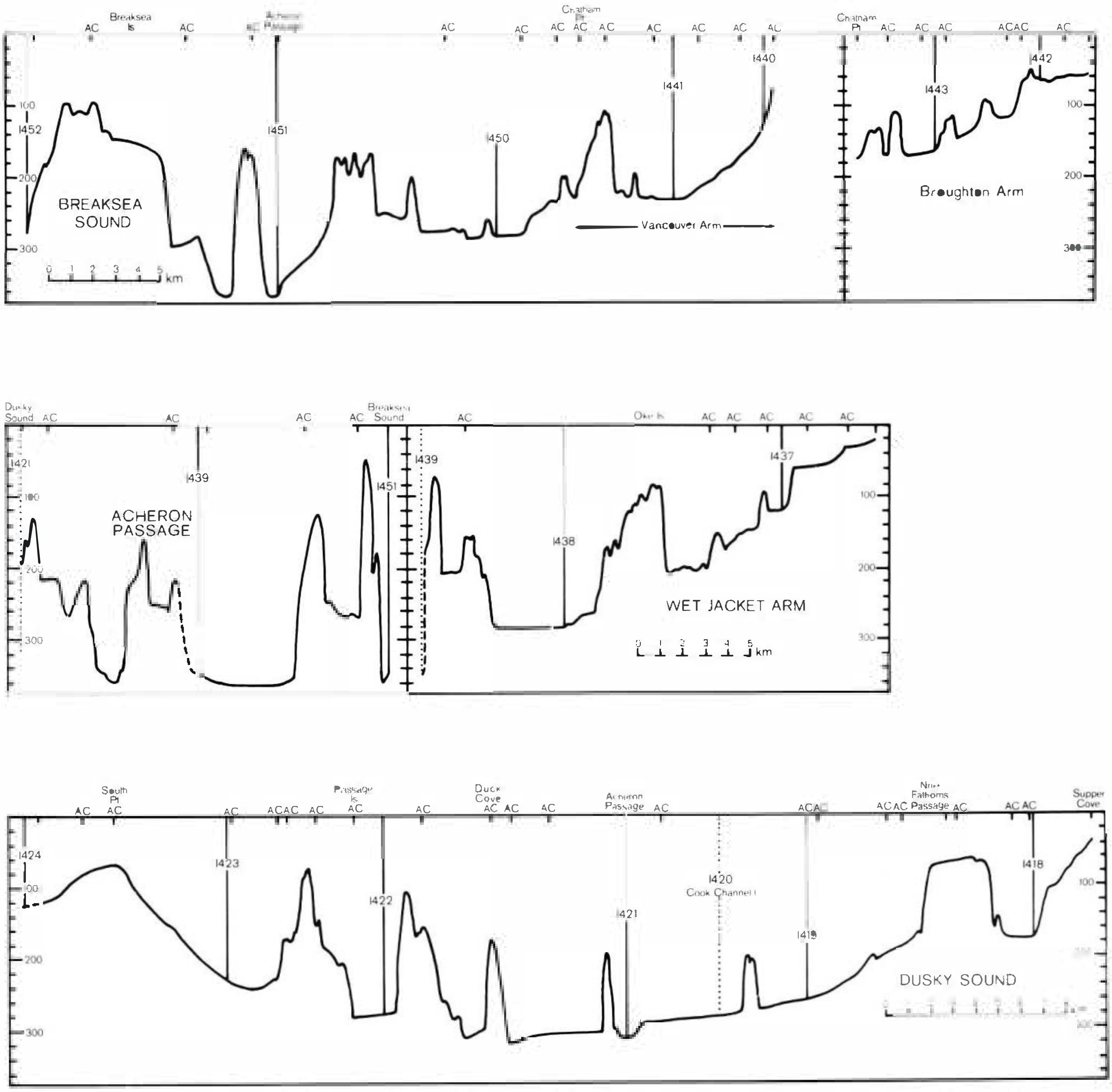

FIG. 3c. Longitudinal sections of Breaksea Sound, Acheron Passage, Wet Jacket Arm, and Dusky Sound obtained along the sounding lines shown in Fig. 2d with station positions and alterations of course (AC) marked.

OCEANOGRAPHIC OBSERVATIONS DURING THE FIORDS 77 SURVEY

The low salinity surface water with the strong halocline found below it are confined to an upper layer or shallow zone which in fiord oceanography, has, for convenience, been defined as the upper 20 m (Pickard 1961). In the present survey the salinity at 20 m was everywhere greater than 97% of the maximum value at

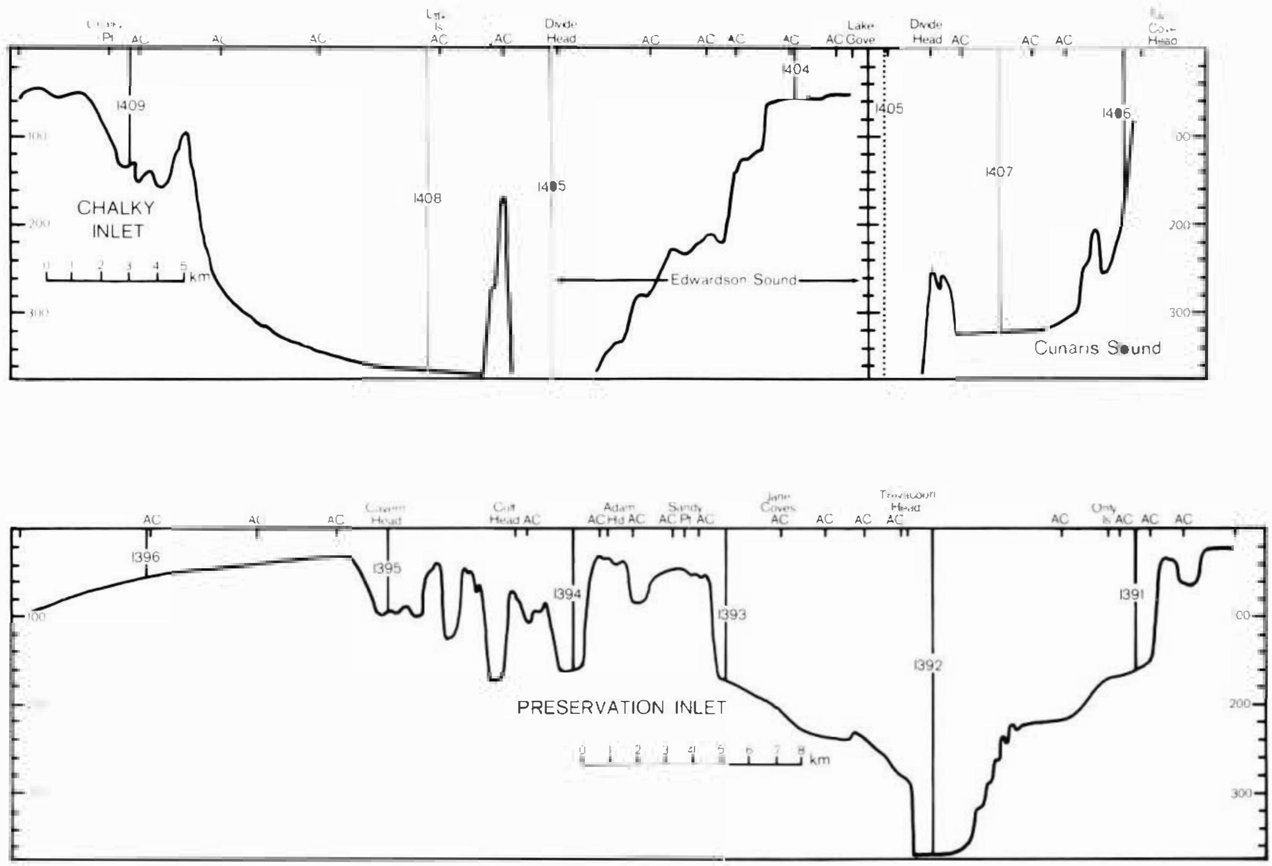

FIG. 3d. Longitudinal sections of Chalky Inlet/Edwardson Sound/Cunaris Sound and Preservation Inlet/Long Sound obtained along the sounding lines shown in Fig. 2e with station positions and alterations of course (AC) marked.

each station, i.e., greater than 34.0‰. The most marked temperature fluctuations were also found in the shallow zone, usually in the surface layers.

Salinity in the Shallow Zone

The low salinities found at the surface (Fig. 5) result from the inflow of fresh water which is itself a variable feature. The lowest surface salinities were found in Milford, Doubtful/Thompson and Dusky/Breaksea Sounds which implies that freshwater inflow was greatest in these fiords at the time of survey. Surface salinities were generally greater than 26‰ in the other fiords except near the head of some inlets where additional surface bucket samples showed lower salinities. The effect of freshwater inflow variations with time can be seen in the different surface salinity distribution observed in Milford Sound on each survey (Fig. 5a). These surveys were 12 days apart but from the nature of the Cleddau River discharge (Fig. 4) shorter term variations could be even more marked at times. Some evidence for this can be seen in Breaksea and Doubtful Sounds (Fig. 5d,e) where the mid-fiord salinity minima in each case occurred at a break in the sampling pattern. The minima occurred at the first station worked on the second day of sampling in these fiords where the up-fiord stations were worked on the previous day. In these two fiords and Thompson Sound sampling was interrupted, but in all other fiords stations were worked in a continuous sequence from head to mouth.

Another aspect of the variable freshwater inflow can be seen in the surface salinity distribution in Preservation Inlet (Fig. 5f) and the second survey of Milford Sound (Fig. 5a) where in both cases a mid-fiord salinity minimum was found. Assuming that the Cleddau River discharge (Fig. 4) can be used as a qualitative representation of the inflow into Preservation Inlet, by virtue of the hydrological similarity in the catchments, it can be seen that these mid-fiord minima were observed on the day following a peak in the discharge curve, i.e., Preservation Inlet was surveyed on 6 December following the peak discharge on 5 December and Milford Sound was surveyed on 17 December following the peak discharge on 16 December (Fig. 4). This suggests that the middle of each fiord retained a salinity structure reminiscent of that of a higher river inflow regime. This water was

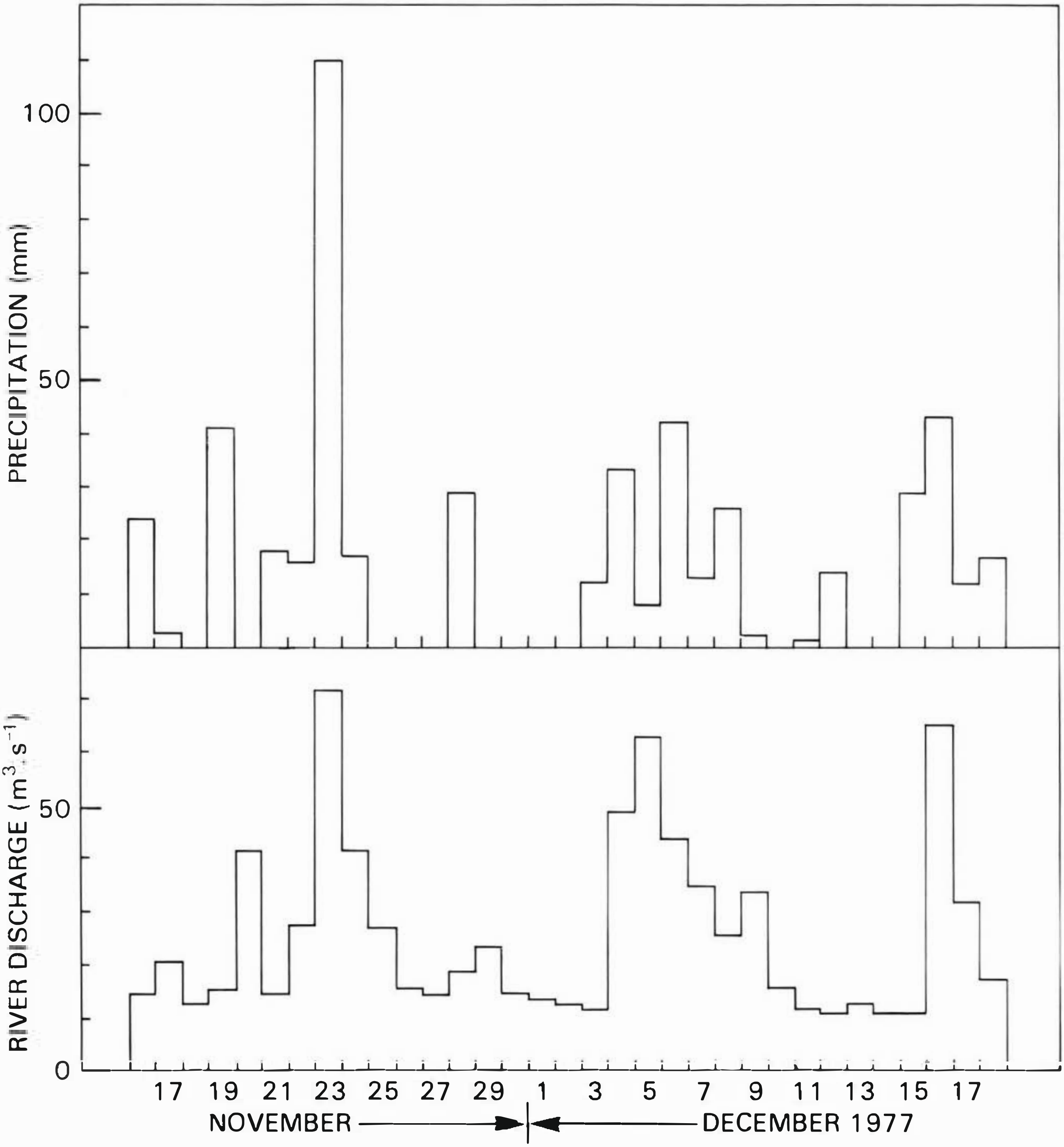

FIG. 4. Daily mean discharge of the Cleddau River and daily mean precipitation at Milford in November-December 1977.

found in mid-fiord because of the estuarine circulation pattern with its seaward-going near-surface current.

Under conditions of steady freshwater inflow at the head of a fiord the surface waters show a continuous rise in salinity towards the mouth as higher salinity water from below is entrained into the outflowing surface layer. Apart from the foregoing fiords the majority of the New Zealand fiords fitted this pattern (Fig. 5).

Surface salinity is not necessarily a good indication of

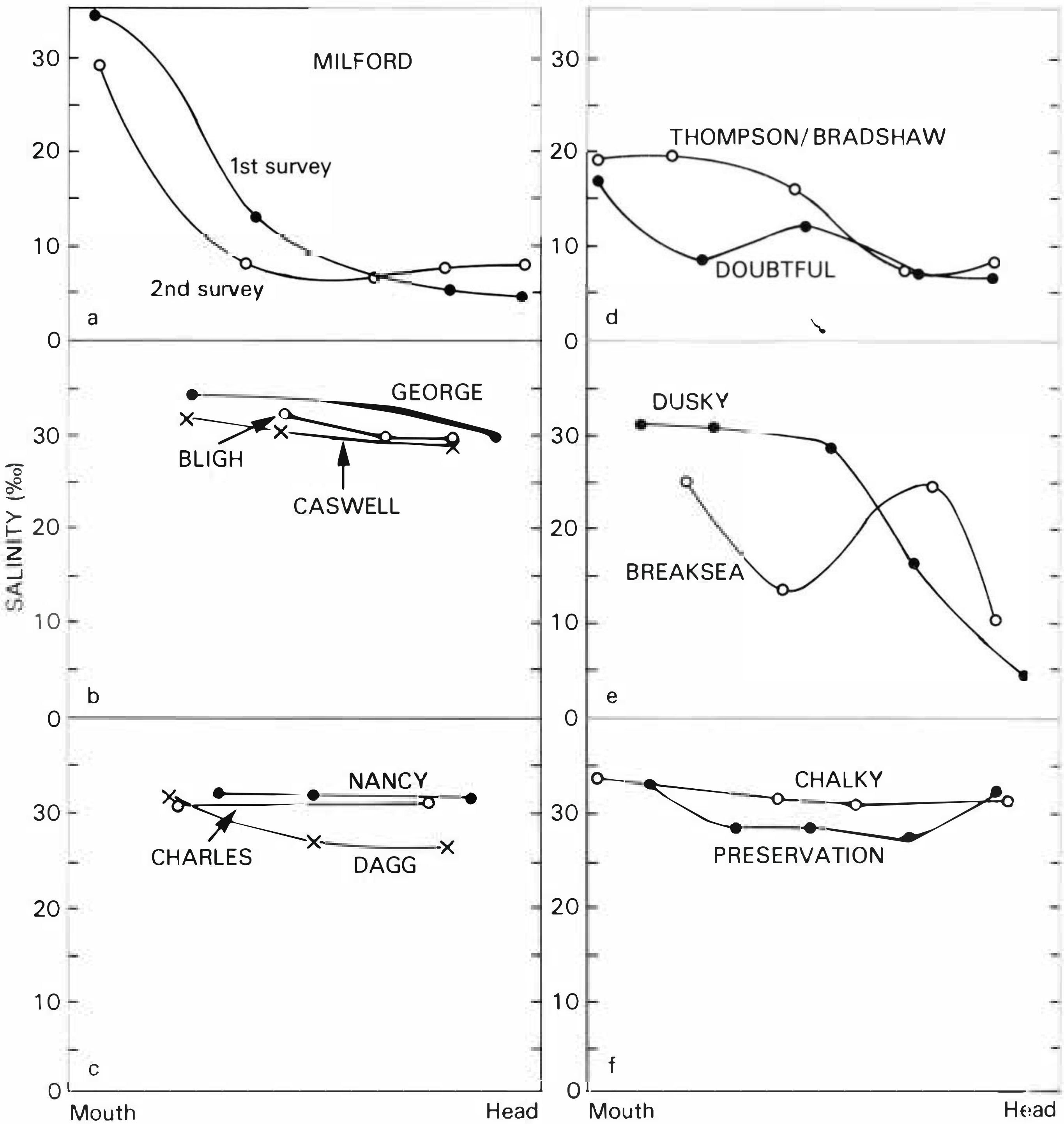

FIG. 5. Longitudinal surface salinity profiles observed in New Zealand fiords to December 1977. Fiord lengths have been scaled to unit length.

the amount of fresh water present at each station because of the variation in the salinity-depth profile which may occur. Pickard (1961) has classified the types of vertical salinity profile found in the shallow zone (Fig. 6). In the present survey the great majority of stations had no discernible homogeneous surface layer and salinity increased with depth from the surface (Pickard 1961 – type 2). Typical examples are shown in

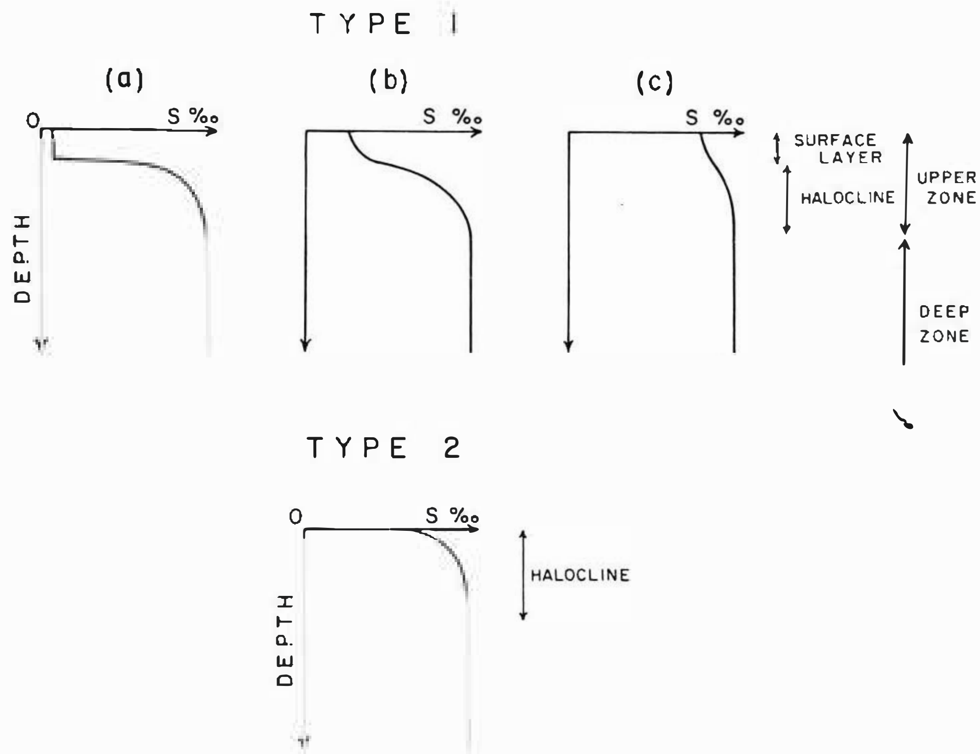

FIG. 6. Types of vertical salinity profile observed in the shallow zone of fiords (after Pickard 1967).

Fig. 7c and Fig. 7f. Any homogeneous layer, if present, must have been less than 2 m deep, the minimum spacing of reversing bottles used. At some stations salinity increased only slowly in the upper 2 m with a steeper halocline below (Pickard 1961 – type lb and lc). Such profiles were associated with either high freshwater inflow conditions or were found near the mouth of some fiords where the outflowing surface layer reaches its maximum thickness. These latter profiles had relatively high salinity in the upper layer. In the former class, associated with high inflow, were the stations at the head of Milford Sound (first survey, Fig. 7a), in the middle of Preservation Inlet (in the low salinity water previously described, Fig. 7i) and in Deep Cove in Doubtful Sound (Fig. 7d). A few other stations scattered seemingly randomly throughout the fiords also exhibited, generally weakly, type lb or lc salinity profiles.

Changes in the freshwater inflow produced changes in the salinity profiles as illustrated by the repeated station I384/I521 in Milford Sound. At the time of higher inflow during the first survey, the halocline was deeper (Fig. 7a) than on the second survey (Fig. 7b).

A qualitative assessment of the effect of freshwater inflow on near surface salinity can be made from the correlation between the two throughout the fiords (Table 4). The mean salinity in the upper 10 m was used to allow for the variation in vertical salinity profile, and a mean over all stations within each fiord was taken to give the mean near-surface salinity for the fiord. Freshwater inflow into each fiord was assessed using the discharge data from the Cleddau River (Fig. 4). This 155 km^2 catchment has been selected as the representative basin for the fiords (National Water and Soil Conservation Organisation 1970) and the inflow into the other fiords can be estimated using this data and the fiord catchment areas (Table 2). The 3-day mean flow, ending on the day of survey, was used, and, to remove relative size effects, a relative inflow was calculated by dividing the estimated inflow by the fiord area (Table 4). In the Doubtful/Thompson Sound system supplementary inflow at Deep Cove from the Manapouri Power Station has been included. At the time of survey the 3-day mean discharge from the power station was 459.8 $m^3. s^{-1}$, calculated from data supplied by the Electricity Division, Ministry of Energy. At the same time the natural inflow based on the Cleddau data was 113.5 $m^3. s^{-1}$. The rank difference correlation coefficient between near-surface salinity and relative inflow is -0.71. Since the depression of near-surface salinity in the fiords derives from the freshwater input, the high, negative correlation obtained suggests that this simple model holds despite the deficiencies in the data. The major uncertainties are contained in the representation of mean salinity from the somewhat non-uniform station distribution and the estimation of inflow from the representative basin data. However, these results suggest that this simple model

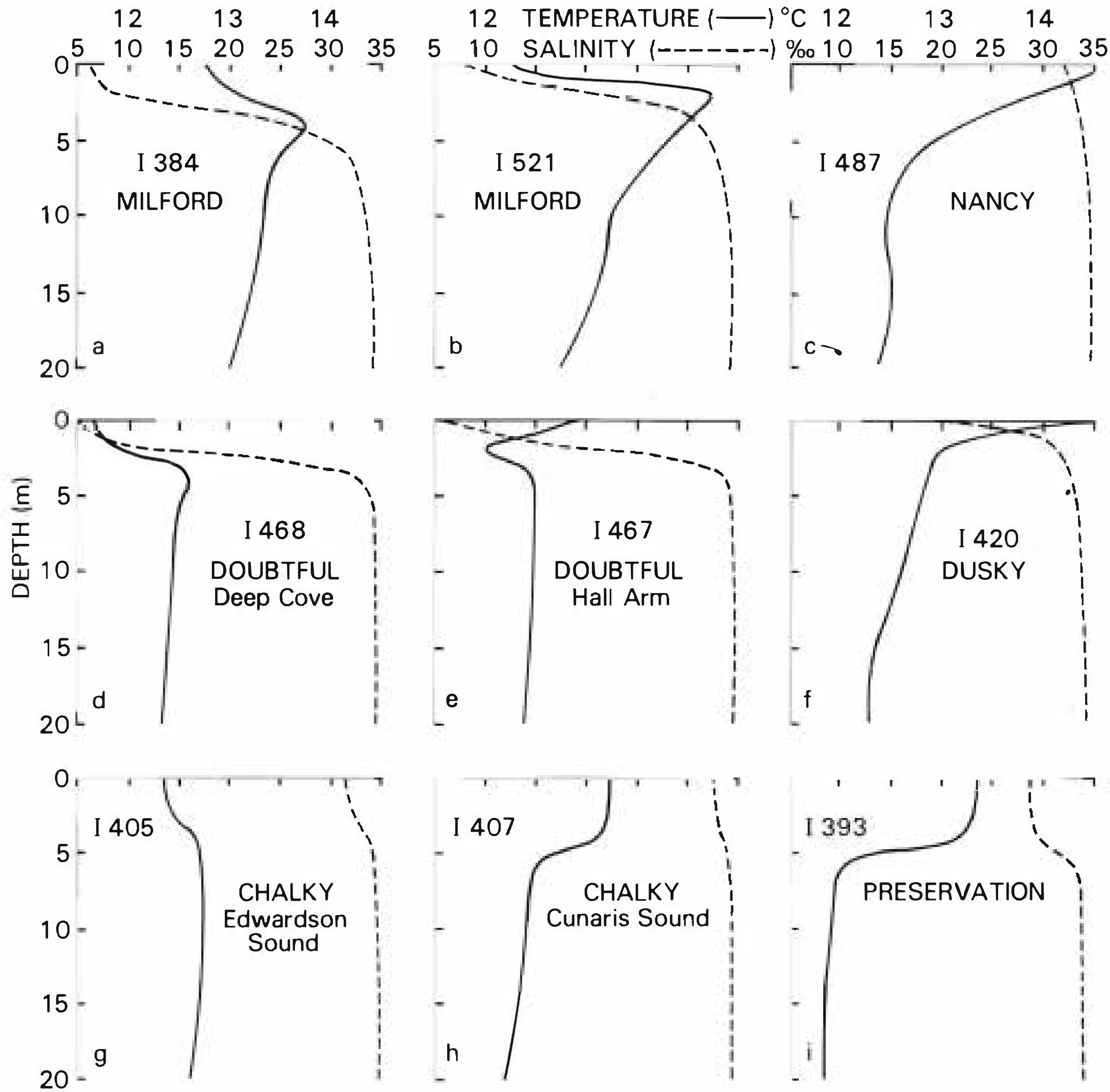

FIG. 7. Some vertical temperature and salinity profiles observed in the shallow zone of the New Zealand fiords in December 1977.

could be used to estimate the mean salinity conditions in any fiord given the relative Cleddau River discharge data, or even only the relevant rainfall data.

In the Doubtful/Thompson Sound system freshwater input from the Manapouri Power Station forms a large proportion of the total freshwater inflow for much of the time. Some typical conditions are discussed in Appendix 2.

The salinity/inflow relationship in fiords which divide into two arms can be analysed in a similar fashion to that done for the fiords as a whole in Table 4. Although the detailed analysis is not shown here, in all cases the lower salinities found in one arm were always attributable to a larger catchment area in that arm as in Table 2. In particular, salinities were lower in Vancouver Arm (Breaksea Sound) than in Broughton Arm and lower in Edwardson Sound (Chalky Inlet) than in Cunaris Sound (Fig. 7g and 7h). In the other branching fiords only one station was worked in each arm. Consequently, the salinity distributions were not well defined, but generally they followed a similar pattern with lower salinities in the arm with the biggest catchment area.

Temperature in the Shallow Zone

In most fiords the temperature profile was a mirror image of the salinity profile, i.e., the surface water was warm and below this a sharp thermocline, coinciding with the halocline, was found. Typical examples can be seen in Fig. 7c, f, and i. Below the thermocline temperatures continued to fall slowly with depth. The strength of the thermocline, measured for convenience by the difference in temperature, ΔT, between the surface and 10 m depth showed longitudinal variations, always decreasing to near zero at the mouth. The maximum thermocline development was associated with the lowest surface salinities, hence ΔT was generally a maximum at the head of the fiord. On average ΔT was 2.3°C at the head of these fiords with the extreme value of 4.3°C being found at the head of George Sound (where the maximum surface temperature of 16.8°C was recorded). In Preservation Inlet the maximum ΔT value (2.2°C) was found in mid-fiord coinciding with the minimum in surface salinity.

A few fiords had cooler surface water with a negative thermocline in the first few metres, i.e., temperature increased with depth to a subsurface maximum found between 2 and 5 m (Fig 7a, b, d, g). In many cases a normal thermocline was found below the temperature maximum with a marked decrease in gradient near 10 m depth (Fig. 7b). Cooler surface waters were found in parts of Milford Sound, Doubtful Sound, Breaksea Sound, and Chalky Inlet.

In Milford Sound the cooler surface layer was less than 2 m deep, based on the bathythermograph data from the second survey. Bathythermograph casts were not made on the first survey but the available reversing bottle temperature data suggests that conditions were similar on that survey. On the second survey, ΔT had a minimum value (-1.21°C) in mid-fiord, corresponding to the minimum in surface salinity. This contrasts with the maximum ΔT value found at the surface salinity minimum in Preservation Inlet. The mid-fiord salinity minimum found in these two fiords was associated with previous high inflow conditions in the salinity analysis above, consequently the different temperature structure must result from the relative amounts of inflow in these fiords (Table 4).

In the main reach of Doubtful Sound, excluding Thompson Sound, Bradshaw Sound, First Arm and Crooked Arm, cooler surface waters were found in the upper 4 m. A minimum ΔT value (-0.78°C) was found in Deep Cove corresponding to a surface temperature of 11.63°C, the lowest found anywhere in the fiords (Fig. 7d). The ΔT values increased seaward of Deep Cove suggesting that this temperature anomaly resulted from the high inflow of fresh water from the Manapouri Power Station. In Hall Arm (Fig. 7e) a unique temperature profile was observed with a surface warm layer less than 2 m thick, overlying a temperature minimum at 3 m. Below the minimum the temperature profile was similar to that in Deep Cove (Fig. 7d).

In Breaksea Sound, Wet Jacket Arm and the head of Dusky Sound (Stn I418) cooler near-surface water, to a depth of 2 m, was found. The temperature profile below the subsurface maximum was similar to the profiles found in Dusky Sound (Fig. 7f). The minimum ΔT value (-1.46°C) was found in the main reach of Breaksea Sound (Stn I451). However, some inconsistencies were found in the temperature data which could be attributed to the break in sampling, as found in the

TABLE 4. Mean salinity in upper 10 m and estimated freshwater inflow during FIORDS 77 cruise. Estimated inflow is based on Cleddau River discharge (Fig. 4) and fiord catchment areas (Table 2).

$$\text{Relative Inflow} = \frac{\text{Cleddau discharge}}{\text{Cleddau catchment}} \times \frac{\text{Fiord catchment}}{\text{Fiord area}}$$

Name	Survey date	Mean salinity (‰)	Estimated inflow ($m^3.s^{-1}$)	Relative inflow ($m.s.^{-1}$)
Milford Sound (1st survey)	5.12.77	26.80	142.9	5.64
Milford Sound (2nd survey)	17.12.77	28.68	125.1	4.94
Bligh Sound ...	16.12.77	33.03	38.1	1.80
George Sound	15.12.77	33.92	22.1	0.67
Caswell Sound	15.12.77	33.29	19.8	1.13
Charles Sound	14.12.77	33.51	19.8	1.25
Nancy Sound	14.12.77	33.80	6.6	0.47
Doubtful/Thompson Sound*	11-13.12.77	28.67	573.3	4.31
Dagg Sound ...	10.12.77	32.57	17.7	1.20
Dusky/Breaksea Sound	8-10.12.77	30.38	301.6	1.07
Chalky Inlet ...	7.12.77	33.60	154.4	1.40
Preservation Inlet	6.12.77	32.39	185.6	2.00

* Estimated inflow = 459.8 $m^3.s^{-1}$ from Manapouri Power Station at Deep Cove, plus 113.5 $m^3.s^{-1}$ natural inflow.

salinity analysis above. The areas of cooler surface water found in the Dusky/Breaksea Sound system correspond to the areas of lowest surface salinity.

In Chalky Inlet, Edwardson Sound exhibited cooler surface water with ΔT of $-0.3°C$ while Cunaris Sound had warmer surface water with ΔT of 0.8°C (Fig. 7g, h). The main reach of Chalky Inlet showed no temperature stratification. As Chalky Inlet experienced only moderate freshwater inflow (Table 4) similar to that of Bligh Sound or Charles Sound, which exhibited warmer surface waters, the explanation appears to lie in the exposure of Chalky Inlet to the prevailing south-westerly weather conditions. This fiord is the only one so exposed, and the temperature structure in the more exposed Edwardson Sound suggests surface cooling while in the more sheltered Cunaris Sound some surface warming occurred. Other water properties suggest this fiord is exceptionally exposed and this is discussed later.

In conclusion, the temperature profiles showed that relatively cool surface water was found under the highest freshwater runoff conditions, i.e., in Milford Sound, the main reach of Doubtful Sound, and the low surface salinity regions of the Dusky/Breaksea Sound system. Some cooling was evident in Chalky Inlet, but in general the near-surface waters were relatively warm in the fiords with low freshwater runoff. The warming of surface layers was generally evident where surface salinity was lowest because of the effect of salinity on density and hence stability of the water column. Where surface salinity was low and hence stability was high the vertical mixing was severely inhibited. Towards the mouth of a fiord where the salinity stratification weakens vertical mixing would be greater and hence the warmer surface temperature anomalies weakened. The unusual temperature profile observed in Hall Arm with warm water overlying a subsurface minimum suggests that the very large outflow from Deep Cove spreads up Hall Arm, and inhibits the surface circulation in this arm sufficiently to allow the surface layers to be warmed by solar or atmospheric heat transfer.

Salinity in the Deep Zone

On the basis of the deep zone salinity distribution (Table 5) the fiords could be divided into two groups. The northern group, from Milford Sound to Doubtful Sound, had a salinity maximum of 35.06 (±0.01)‰ at around 100 m (Fig. 8a).

In some fiords the salinity at the maximum remained constant along the fiord length while in other fiords it decreased towards the head (Table 5). Below the salinity maximum salinity decreased slowly with depth, tending towards 35.00‰ depending on the maximum depth sampled (Fig. 8a). In the southern group of fiords, Dagg Sound to Preservation Inlet, the salinity maximum was not present and the highest salinity water, found at the bottom, was always less saline than the maxima found in the northern group (Fig. 8b and c). Observed values of bottom salinity decreased from fiord to fiord toward the south with the exception of Chalky Inlet where the values of 34.9‰ do not fit this sequence (Table 5). In the southern group of fiords, Breaksea and Dusky Sounds had bottom salinities which increased towards the head while in Preservation Inlet a sequence with salinities decreasing towards the head was observed in the three basins sampled. Moving up-fiord (*see* Fig. 3) salinities of 34.51‰ (Stn I395), 34.41‰ (Stn I394) and 34.32‰ (Stn I392) were observed in these basins (Fig. 8c). Chalky Inlet and Dagg Sound, in the southern group, exhibited no longitudinal variation in bottom salinity.

When considering water properties in the shallow zone, each of the two large fiord complexes, Doubtful/Thompson Sounds and Dusky/Breaksea

TABLE 5: Maximum salinities observed in the New Zealand fiords, December 1977.

Name	Maximum salinity (‰)	Depth of maximum (m)	Longitudinal variation in salinity maximum up-fiord
Milford Sound	35.06	100	none
Bligh Sound	35.06	85	none
George Sound	35.07	85	decreases (35.07–35.04)
Caswell Sound	35.05	150	none
Charles Sound	35.05	110	none
Nancy Sound	35.05	100	decreases (35.05-35.03)
Thompson/Bradshaw Sound	35.06	100	decreases (35.06-35.02) (Precipice Cove 35.07)
Doubtful Sound	35.06	145	none (Crooked Arm 35.07)
Dagg Sound	35.02	bottom	none
Breaksea Sound	35.02	bottom	increases (34.99–35.02)
Wet Jacket Arm	34.98	bottom	decreases (34.99–34.98)
Dusky Sound	34.78	bottom	increases (34.71-34.78)
Chalky Inlet	34.90	bottom	none
Preservation Inlet	34.51	bottom	decreases (35.51, 35.41, 35.32)

Sounds has been treated as a freely connected whole. For the deep zone analysis (Table 5) the individual fiords have been treated separately. The maximum depth in Pendulo Reach connecting Thompson and Doubtful Sounds is 71 m (Irwin and Main in press) and the salinity data suggests this is sufficiently shallow to inhibit the free exchange of deep water between these fiords (Fig. 8a). In Thompson and Bradshaw Sounds, which form one continuous inlet, salinity at the maximum decreased smoothly from 35.06‰ near the mouth to 35.02‰ near the head, while in Doubtful Sound salinity at the maximum showed no particular longitudinal variation. In Bradshaw Sound, the bottom salinity of 35.07‰ in Precipice Cove contrasted with the salinity maximum in the main fiord of 35.02‰. The bathymetry and other water properties in Precipice Cove suggest it was somewhat isolated from the main fiord, a point which is discussed later. Similarly, in Doubtful Sound, a slightly higher bottom salinity of 35.07‰ was found in Crooked Arm.

In the Dusky/Breaksea Sound system soundings are inadequate to establish if a real physical barrier to the interchange of deep water exists. Considerable difficulties were experienced with side echos in the sounding of Acheron Passage (Fig. 2). However, the salinity data suggests the individual fiords should be treated separately. Bottom salinities in the range 34.98 to 35.02‰ were observed throughout Breaksea Sound, northern Acheron Passage and Wet Jacket Arm, while bottom salinities in Dusky Sound were in the range 34.71 to 34.78‰ (Fig. 8b). These data suggest that deep water in Wet Jacket Arm derives from Breaksea Sound.

Deep salinities in Milford Sound showed no variations in the 12 days between the two surveys. In comparison, considerable changes in near-surface salinity were observed over the same interval, as discussed earlier.

Temperature in the Deep Zone

Water temperature in the deep zone generally decreased with depth (Fig. 8). Below the main thermocline, associated with the main halocline, the rate of decrease in temperature was small. Typically temperature at 50 m was around 12.0°C and at 200 m around 11.6°C (Table 6). Some stations exhibited minor maxima or minima in the temperature profile but the relative temperature change was always small, less than 0.1°C. These stations were randomly distributed throughout the fiords and the anomalous temperature profiles appear to have little physical significance. The lowest temperatures were observed at the bottom of the deepest fiords, for example 11.31°C at 400 m in Bradshaw Sound.

In most fiords the temperatures at 50 m decreased slightly towards the head of the fiord. At greater depths longitudinal temperature variations weakened. The greatest longitudinal temperature variations were observed in Dusky Sound, where temperature at 50 m decreased by 0.32°C and temperature at 100 m increased by 0.33°C in the up-fiord direction.

Mean temperature at 50 m in Milford Sound fell by 0.22°C in the interval between the two surveys (Table 6), but this change was consistent with the observed changes in the salinity profile resulting from the changes in freshwater inflow (Fig. 7a, b).

Mean temperature differences of around 0.3°C observed between Thompson Sound and Doubtful Sound at depths greater than 100 m (Table 6 and Fig. 8a) support the conclusion drawn from the salinity data that deep-water exchange between these fiords was inhibited. In contrast, the differences in deep salinities observed between Breaksea Sound and Dusky Sound were not reflected in the deep zone temperatures (Fig. 8b).

In Dusky Sound, some differences were observed between the deep temperatures in Cook Channel (Stn

TABLE 6. Mean temperatures at selected depths in the New Zealand fiords, December 1977.

Name	Temperature at 50 m (°C)	Temperature at 100 m (°C)	Temperature at 200 m (°C)
Milford Sound (1st survey)	12.16	11.80	11.54
Milford Sound (2nd survey)	11.94	11.76	11.59
Bligh Sound	11.92	11.85	–
George Sound	11.84	11.70	11.52
Caswell Sound	11.85	11.78	11.61
Charles Sound	11.87	11.61	11.50
Nancy Sound	12.00	11.78	11.58
Thompson/Bradshaw Sound	12.18	11.76	11.40
Doubtful Sound	12.23	12.12	11.71
Dagg Sound	12.04	11.78	–
Breaksea Sound	12.33	11.88	11.62
Wet Jacket Arm	12.32	12.10	11.85
Dusky Sound	12.25	11.95	11.73
Chalky Inlet	12.13	11.87	11.63
Preservation Inlet	11.96	11.84	11.76

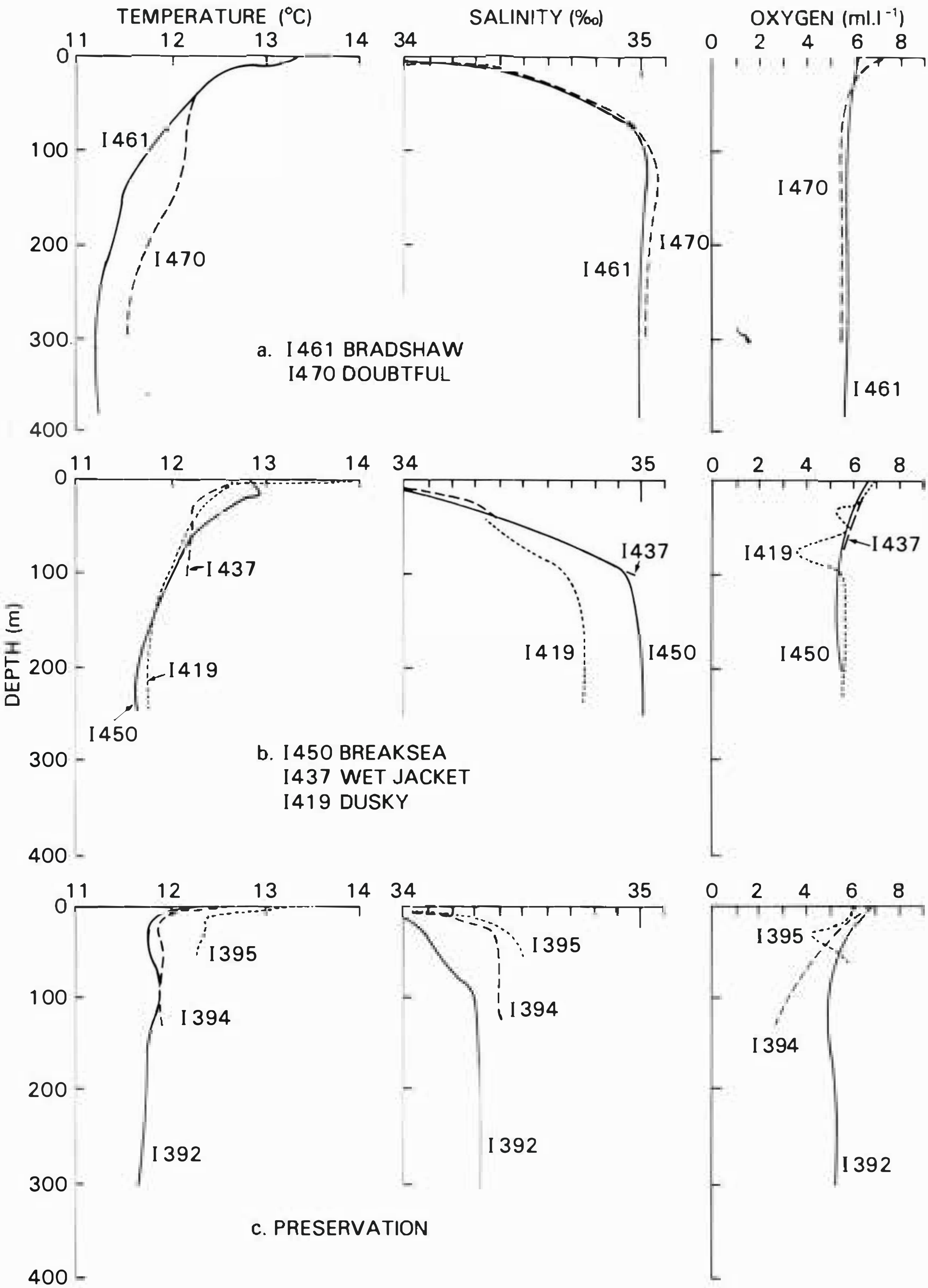

FIG. 8. Some vertical temperature, salinity, and dissolved oxygen profiles observed in the New Zealand fiords in December 1977.

I420) and those in the main reach (Stns I419 and I421). Below 150 m temperatures were around 0.4°C higher in Cook Channel at all depths. The temperature profile at Stn I420 was very similar to that at the head of Dusky Sound (Stn I418) down to 150 m, the limit of observations at that station. At both these stations temperature increased slightly with depth below 80 m. Insufficient bathymetric data is available in the interconnecting passages between Cook Channel and the main reach of Dusky Sound and, as the deep salinities showed no large differences, the reasons for these temperature differences remain obscure. The similar temperature profiles at Stations I418 and I420 suggest the possibility that deep-water exchange is easier through Nine Fathoms Passage than through Paget Passage.

Small temperature inversions near the bottom were observed at four stations: Emelius Arm, Charles Sound (Stn I491), Precipice Cove, Bradshaw Sound (Stn I460), Deep Cove and Crooked Arm, Doubtful Sound (Stns I468 and I471). Typically temperature increased around 0.1°C in the bottom 25 m at these stations. Although this change is small other factors discussed later suggest that these arms are partially cut off from the main fiords.

Temperature-Salinity Relationships

The temperature-salinity correlation curves (T-S curves) within a given fiord were generally quite similar suggesting a common mixing regime for the water types in those fiords. However, some longitudinal variations were observed in Thompson/Bradshaw Sound, Doubtful Sound, Chalky Inlet and Preservation Inlet. A succession of T-S curves trending towards higher salinity near the mouth were found in both Thompson/Bradshaw and Doubtful Sounds. In Chalky Inlet distinctive T-S curves were observed in Edwardson and Cunaris Sounds with the curves in the main reach being intermediate between these. In Preservation Inlet three distinct curves were observed; that found at Stations I391–I394, that found at Station I395, and that found at Station I396. In the salinity analysis deep-water salinities of 34.51, 34.41 and 34.32‰ were observed in the three basins sampled by stations I395, I394, and I392 respectively. However, the T-S curves in these basins showed the same water type in the two inner basins (Stns I394, I392) and a different T-S curve in the outer basin (Stn I395).

Over the fiord region, the T-S curves showed a general trend towards the association of lower temperature and salinity values as one moved towards the south (Fig. 9). The deep-water T–S characteristics were very similar from Milford to Dagg Sounds; to the south there was a marked trend towards lower salinities, with values in Chalky Inlet not fitting the general trend. At the high salinity end of the T-S diagram, curves generally fell between the extremes given by Stations I511 and I393 in Fig. 9. In the shallow zone (Fig. 9), while the general trend was still evident, larger variations also occur. The T-S curves for the two surveys of Milford Sound suggested that much of the variation found in the shallow zone curves for the other fiords is related to variations in freshwater inflow.

Transverse Temperature and Salinity Variations

A transverse section was worked, from a boat, across each of Thompson, Bradshaw, and Doubtful Sounds (Fig. 2). These sections comprised three stations equally spaced across the fiord with sampling limited to the upper 20 m. No consistent transverse variation in temperature or salinity was observed. Generally the variations were small and the maximum variations occurred near the surface. Maximum variations between adjacent surface values were around 0.8°C in temperature and 1.6‰ in salinity.

Off-shore Oceanographic Conditions

Four temperature–salinity stations were occupied off the coast (Fig. 1) to examine the oceanic conditions prevailing during the FIORDS 77 survey. The continental shelf is extremely narrow, even non-existent, in parts of this region and the continental slope drops steeply to around 4000 m in the Tasman Basin. Consequently, the near-shore circulation is well defined by geostrophic methods, which have shown the south-west flowing Southland Current as a persistent feature in the region (Heath 1973, 1975; Stanton 1976). Heath (1975) observed current velocities up to 0.64 $m.s.^{-1}$ in the Southland Current off George Sound. The present data showed somewhat lower geostrophic velocities with 0.08 $m.s.^{-1}$ off Sutherland Sound. Off Doubtful Sound the Southland Current, while still present, was even weaker.

Surface salinity at the off-shore stations was lowered by land runoff as is commonly found off this coast (Stanton 1976). Below the surface, salinity increased with depth to a maximum of between 35.00‰ and 35.13‰ at around 100 m. Below the maximum, salinity decreased to a minimum of 34.42‰ at 950 m, marking the core of the Antarctic Intermediate Water. The temperature profiles showed a generally well-mixed layer in the upper 25-50 m with a weak thermocline below this layer. Below 200 m depth temperatures off shore were cooler than those found at comparable depths inside the fiords.

Density

Density variations in the shallow zone are almost completely dependent on the salinity and consequently need not be discussed separately from the salinity distribution. In the deeper layers, particularly near and below the salinity maximum, where this occurred, changes of salinity with depth are small and hence

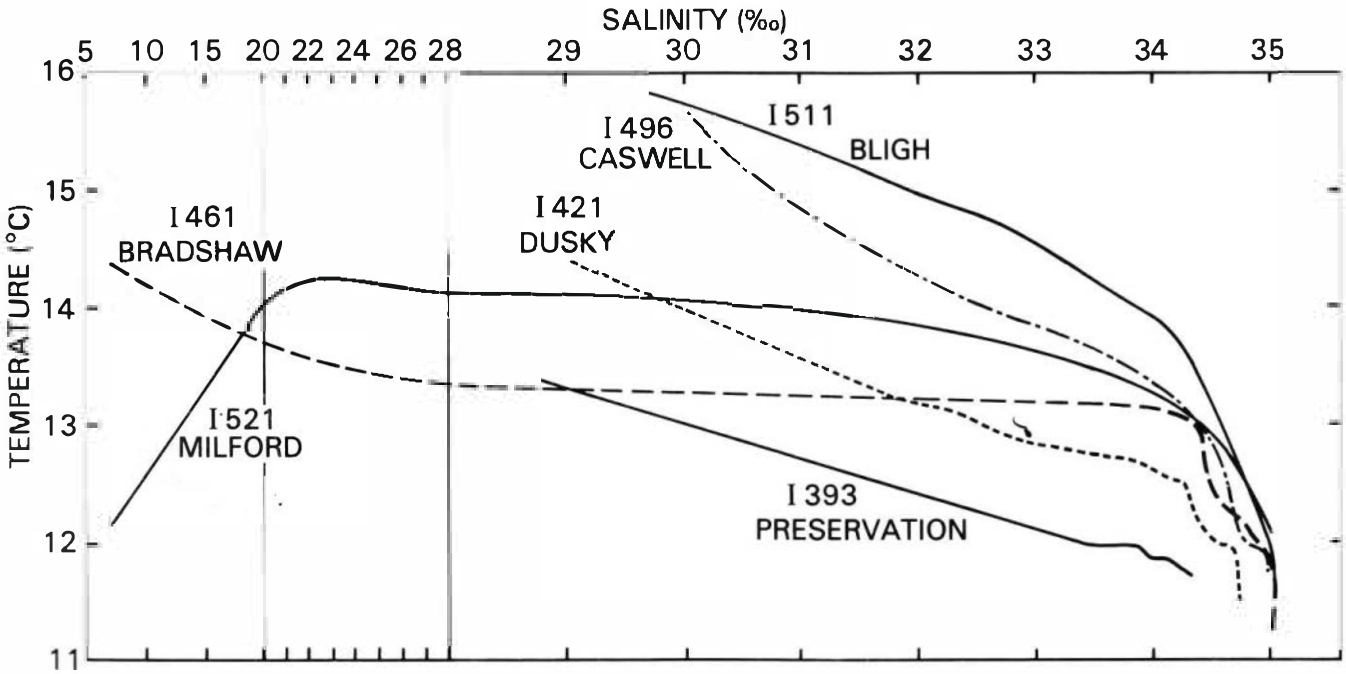

FIG. 9. Some temperature-salinity (T-S) curves observed in the New Zealand fiords in December 1977. Note that the salinity scale changes at 20‰ and 28‰.

temperature becomes important in the density distribution. Density near the sill depth and in the deep basins controls the interchange of deep water between the off-shore ocean and the fiords, and also between basins inside the fiords.

Density at 100 m depth was rather uniform (δ_T = 26.70 ∓ 0.03 kg m^{-3}) in the northern fiords, Milford Sound to Dagg Sound excluding Doubtful Sound. To the south density at 100 m decreased as follows: Doubtful Sound 26.6, Breaksea Sound 26.6, Wet Jacket Arm 26.5, Dusky Sound 26.4, Chalky Inlet 26.4, Preservation Inlet 26.1–26.2.

It can be seen that deep-water density follows the general trend of the temperature/salinity distribution with the northern fiords being rather similar and the southern fiords showing a general decrease towards the south with the largest change occurring between Chalky and Preservation Inlets.

Dissolved Oxygen

Dissolved oxygen values were at or above saturation at the surface and decreased with depth in the upper 20 to 50 m. At greater depths most stations had dissolved oxygen values in the range of 5–6 ml.l^{-1} representing water of greater than 80% saturation throughout the water column (Fig. 8). Generally the lowest oxygen value was found at the greatest depth sampled. However, exceptions to this were found in Milford Sound, with a minimum at 50 m, while parts of Doubtful Sound (Stn I470), Breaksea Sound (Stns I441, I443, I450), Dusky Sound (Stns I418–I422) and Preservation Inlet (Stn I392) exhibited minima at around 100 m depth. In only Dusky Sound and Preservation Inlet did the oxygen value at the minimum fall below 5 ml.l^{-1} (Fig. 8). All reversing bottles were not sampled for dissolved oxygen because of limited analytical facilities, and consequently the relative minima in the oxygen profiles were not well defined.

Extremely low dissolved oxygen values were found at only one location. In Deep Water Basin, a lagoon-like basin at the head of Milford Sound, dissolved oxygen values decreased to 0.76 ml.l^{-1} (13% saturation) at the bottom (40 m). Relatively low oxygen values, less than about 4.5 ml.l^{-1}, were found at a few stations, generally near the head of the longer fiords or in partially cut-off arms. In the Doubtful/Thompson Sound system near-bottom dissolved oxygen values of 3.02 ml.l^{-1} in Precipice Cove, 4.25 ml.l^{-1} in Hall Arm, 4.51 ml.l^{-1} in Deep Cove, and 4.76 ml.l^{-1} in Crooked Arm, were recorded. In Dusky Sound a minimum oxygen value of 3.41 ml.l^{-1} at 75 m was found at Station I419 (Fig. 8b). At the head of this fiord (Stn I418) a minimum oxygen value of 4.51 ml.l^{-1} was observed at 100 m depth. In Preservation Inlet the lowest oxygen value of 2.79ml.l^{-1} was observed at the bottom (125 m) at Station I394 (Fig. 8c) while at Station I393 there was a value of 3.80 ml.l^{-1} at the bottom (143 m). Unlike the other fiords these low values occurred in mid-fiord.

At the 50 m and 100 m level, where data was adequate, the dissolved oxygen values generally decreased slightly towards the head of the fiord, particularly in the longer fiords. The maximum longitudinal variation observed was a 1.54 $ml.l^{-1}$ decrease at 50 m depth between stations I463 and I467 in Doubtful Sound. Mean values of dissolved oxygen in the deep zone (Table 7) illustrate the generally well-ventilated nature of the New Zealand fiords. In the deep zone oxygen values in Chalky Inlet were noticeably higher than those in the other fiords, which supports the deduction from the temperature/salinity data that wind-mixing was probably greater in this fiord than in the other New Zealand fiords.

Dissolved oxygen values observed in the New Zealand fiords during FIORDS 77 were similar to those found off the coast by other workers (Klepikov 1961, Garner 1962, Japanese Fisheries Agency 1972). Typically dissolved oxygen values in the range of 5–6 $ml.l^{-1}$ have been found in the upper 500 m off the fiord coast. The limited data show no recognisable seasonal or geographic trends.

Deep-Water Exchange

Deep-water exchange between the fiords and the open sea or between inner deep basins is controlled by the density distribution, and where significant differences in dissolved oxygen content occur these can provide a useful indication of the residence time of water in deep basins. At most fiords a station was worked outside the entrance sill and data from these, along with that from the four off-shore stations worked, were used to assess the density at sill depth for comparison with the density at and below sill depth inside the fiords. In all the fiords except Charles Sound density was slightly higher at sill depth outside the fiord than that found at or below sill depth inside the fiord. In some of the deep inner basins density at the bottom was slightly higher than that found at sill depth outside the fiord but from density considerations alone flow over the sill was not inhibited at slightly shallower depths. Generally these density differences were small and this fact, along with the high oxygen values, similar to those outside the fiords, show that at the time of survey exchange of deep water over the entrance sills was possible. In Charles Sound, although density at sill depth (83 m) was 0.1 kg m^{-3} higher inside the entrance sill (Stn I493) than that found outside (Stn I494), other properties, particularly dissolved oxygen, showed nothing unusual about this fiord and it appears that deep-water exchange was not inhibited in this fiord. Entrance sill depths (Table 1) in comparison to those found elsewhere (Pickard 1961, Saelen 1967) are generally sufficiently deep not to inhibit deep-water exchange for long periods of time.

Deep-water exchange between the inner basins in some of the fiords appears to be inhibited to various degrees and these cases are best treated individually. Near anoxic conditions were observed only at 40 m depth in Deep Water Basin at the head of Milford Sound. Sill depth as shown on the hydrographic chart (NZ 7413) may be as shallow as 1 m (0.5 fms) while within the basin a maximum sounding of 53 m (29 fms) is shown. In this basin the surface water derived from the Cleddau River inflow was fresh, well oxygenated, and some 2.7°C cooler than surface water in the rest of the fiord. Temperature and alinity increased with depth to values of 12.52°C and 34.17‰ respectively at 40 m while dissolved oxygen fell to 0.76 $ml.l^{-1}$ (Fig. 10). This low oxygen value suggests this water had been isolated from the sea for some time, possibly several years.

Water in Precipice Cove below the 40 m deep sill separating the cove from Bradshaw Sound (Irwin and Main in press) differed from that found in the main reach of Bradshaw Sound (Fig. 10). At 85 m, the maximum depth sampled, the salinity (35.07‰) was higher than that at the salinity maximum in Bradshaw

TABLE 7. Mean dissolved oxygen ($ml. l^{-1}$) at selected depths in the New Zealand fiords, December 1977.

Name	50 m	100 m	200 m
Milford Sound (1st survey)	5.10	5.07	5.28
Milford Sound (2nd survey)	5.09	5.16	-
Bligh Sound	5.38	–	-
George Sound	5.52	5.44	5.31
Caswell Sound	5.56	5.58	5.54
Charles Sound	5.47	5.51	5.35
Nancy Sound	5.48	5.57	5.41
Thompson/Bradshaw Sound	5.43	5.59	5.62
Doubtful Sound	5.32	5.33	5.71
Dagg Sound	5.55	5.51	-
Breaksea Sound	6.16	5.51	5.59
West Jacket Arm	6.14	5.46	5.55
Dusky Sound	5.90	5.43	5.53
Chalky Inlet	6.18	6.45	5.75
Preservation Inlet	5.70	4.97	5.28

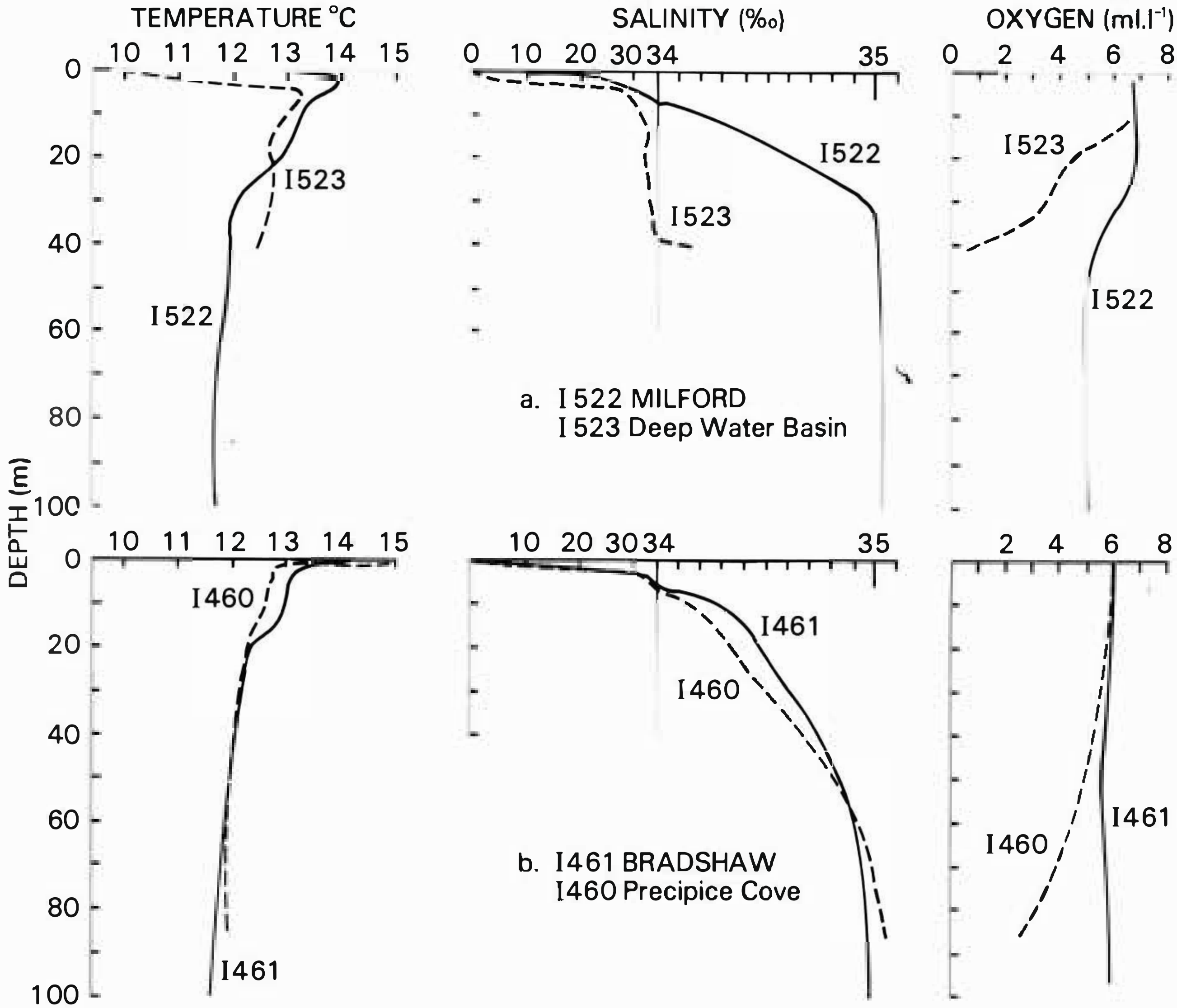

FIG. 10. Vertical temperature, salinity, and dissolved oxygen profiles in two inner basins and at adjacent fiord stations in December 1977. Note that the salinity scale changes at 34‰.

Sound (35.02‰). This water was also warmer than that at similar depth in Bradshaw Sound and the relatively low dissolved oxygen value of 3.02 $ml.l^{-1}$ (50% saturation) suggest that this water was a remnant of a previous exchange process at a time when salinity was higher in Bradshaw Sound. Density at and below sill depth in Precipice Cove was slightly higher than at equivalent depths in Bradshaw Sound (Stns I459, I461) and this difference of around 0.05 $kg.m^{-3}$ may have been sufficient to prevent deep-water exchange at the time of FIORDS 77. A similar interpretation applied to deep water in Hall Arm, Deep Cove, and Crooked Arm in Doubtful Sound where small differences in salinity, density and dissolved oxygen between these arms and the main reach of Doubtful Sound suggest that deep-water exchange was inhibited. Sills at depths of 54 m, 55 m and 61 m occur at the mouths of Hall Arm, Deep Cove, and Crooked Arm respectively (Irwin and Main in press). The greater depth of these sills compared to that in Precipice Cove probably accounts for the lower contrast in oceanographic properties found in the Doubtful Sound arms.

On a larger scale the shallow depths of Pendulo Reach separating Thompson/Bradshaw Sounds from Doubtful Sound prevented exchange of deep water and the distinct deep zone temperatures and salinities have been discussed previously. Similarly the deep salinities in the Dusky/Breaksea Sound system showed that deep-water exchange between Wet Jacket Arm and the sea occurred via Breaksea Sound. In this case however, no bathymetric obstruction in Acheron Passage was found which would prevent deep-water exchange with

Dusky Sound and the reason for the apparent preference for exchange to occur through the northern passage remains unclear. More accurate soundings in the Acheron Passage are required as a first step in resolving this question.

The stations near the head of Dusky Sound (Stns I418-I420) exhibited a weak dissolved oxygen minimum at 75 to 100 m depth. This minimum probably arose from weak circulation in the deep zone with correspondingly longer residence time of this water. Dusky Sound is the longest of the New Zealand fiords (Table 1) and had a relatively low inflow of fresh water (Table 4); consequently, a relatively weak estuarine circulation would be expected. The relatively slow flow of deep water up this long fiord would lead to more oxygen depletion, relative to the other fiords, of the water reaching the head of the fiord. Some small difference in deep temperature and salinity between the deep water in Cook Channel and that in the main reach suggest that deep-water exchange is slightly inhibited between these parts of Dusky Sound.

Preservation Inlet was unique among the New Zealand fiords in that deep-water exchange between the basins along the main reach was inhibited. On present data this would appear to arise from the series of sills between these basins which were shallower than those found in other fiords. The entrance sill at 30 m depth, along with a sill at 36 m between Stations I395 and I394 and a sill at 28 m between stations I394 and I393, were found (Fig. 3). The sequence of decreasing deep salinities found in the three basins sampled suggest that deep-water exchange occurred in a series of overspill events from one basin to the next. The exchange of water between the deep zone and the low salinity near-surface outflow would account for the decreasing salinities in the up-fiord direction. Relatively low dissolved oxygen values were found in the deep water in both of the upper basins (Stns I394, I393) and this suggests that the passage of deep water up the fiord may take some time. In the deep upper basin dissolved oxygen appeared to have a minimum at around 150 m from the available data at stations I392 and I393 (no oxygen data was available for Station I391).

COMPARISON OF FIORDS 77 DATA WITH PREVIOUS WORK

Milford Sound

This fiord has been visited by various oceanographic expeditions on five occasions prior to FIORDS 77. Data are available for January 1952, February 1955, January 1957 (all in Garner 1964), February 1971 (Stanton 1978) and April 1974 (Greig in press). While the coverage achieved on each of these expeditions varied greatly, a useful comparison of the oceanographic conditions recorded is given for typical stations worked in Stirling Basin (Table 8).

In all but one of the earlier stations (Garner 1964) wide sampling intervals were used and consequently the shallow zone was not well described. The exception, station Ga615 in January 1952 (Garner 1964), where one metre depth intervals were sampled, showed clearly a salinity profile of type 2 (Fig. 6). At the same station, temperature decreased smoothly with depth below a 3 m isothermal layer at the surface. At station H283 in February 1971 (Stanton 1978) the salinity profile was of type 1c while at station N204 and other stations worked in April 1974 (Greig in press) salinity profiles of type 2 were obtained. By comparison, the salinity profiles obtained during the two FIORDS 77 surveys varied from type 1b to type 2 as previously described.

Temperature in the shallow zone exhibited a shallow

TABLE 8. Temperature (T in °C) and salinity (S in ‰) at selected depths in Stirling Basin, Milford Sound. Stations Ga608, A96, A329 from Garner (1964); Station H283 from Stanton (1978) and Stations N204, I384, I520 from Greig (in press).

Station	Date	50 m		100 m		200 m	
		T	S	T	S	T	S
Ga608	18 Jan. 1952	12.25	34.87	11.69	35.05	11.58	35.04
A96	27 Feb. 1955	13.70	28.75	13.19	35.02	11.36	35.12
A329	28 Jan. 1957	12.40	34.78	11.60	35.10	11.10	35.12
H283	4 Feb. 1971	16.45	34.69	12.52	34.97	-	-
N204	25 April 1974	16.25	34.73	13.09	35.07	11.95	35.04
I384	5 Dec. 1977	11.98	35.01	11.82	35.06	11.54	35.03
I520	17 Dec. 1977	11.89	35.02	11.76	35.04	11.59	35.03

maximum on all occasions except those of January 1952 mentioned above (Stn Ga615) and possibly in the February 1955 survey (Stn A96) where data was insufficient to resolve the exact profile. Temperatures at the maximum varied widely from 20.2°C in February 1971 (Stn H283) down to 13.7°C during the FIORDS 77 survey. The wide variation in temperature and salinity values in the upper layers is reflected in the values obtained at 50 m depth (Table 8). All these data were collected between December and April so that even greater variations might be expected if winter data were available.

In the deep zone, a weak salinity maximum was found at 95 m in January 1952 (Garner 1964) and a more strongly developed maximum at 100 m in April 1974 (Greig in press). During FIORDS 77 a similar subsurface salinity maximum was observed on both surveys. The other surveys showed no maximum and salinity increased slowly to the bottom. At 200 m depth, variations in temperature and salinity were moderately small, with temperatures between 11.1°C and 12.0°C and salinities between 35.00‰ and 33.12‰ being recorded (Table 8).

An overall comparison of oceanographic conditions during FIORDS 77 with previous surveys of Milford Sound (Table 8) shows that generally temperatures were lower and salinities higher than on previous occasions. This would in part be due to the fact that all previous surveys have been later in the summer season when seasonal heating has been more advanced.

Dissolved oxygen data for some of the previously mentioned surveys are available but these show no general comparative trends. Dissolved oxygen values in excess of 4.7 $ml.l^{-1}$ have always been found (excluding Deep Water Basin) showing that the fiord is well oxygenated.

Caswell and Nancy Sounds

The FIORDS 77 data of December 1977 can be compared with the earlier survey of these fiords in January/February 1971 (Stanton 1978).

Throughout the water column salnities were higher and temperatures were lower on the 1977 survey than those found in 1971. In the shallow zone the salinity differences would result from the lower freshwater inflow on the later survey. Estimated freshwater inflows for both fiords in 1977 (Table 4) were around one third of those estimated for the 1971 survey (Stanton 1978). In Caswell Sound, surface salinities were markedly higher during the lower inflow period while in Nancy Sound they showed little difference between the two surveys. In Nancy Sound the different inflow conditions were reflected only in the different salinity profile obtained in the shallow zone. This response is probably related to the relatively low inflow this fiord experiences (Table 2).

Deep zone salinities were higher during the FIORDS 77 survey than those found in the 1971 survey. In Caswell Sound, the 1971 salinity profiles showed a curious flattening of the salinity gradient between 34.4‰ and 34.5‰. Below this a shallow salinity maximum at 75 m (34.9‰) and a deep maximum at 200 m (35.0‰) were observed in Marble Basin. In comparison, a salinity maximum at 150 m (35.05‰) was found in December 1977, and it is notable that this maximum was observed at somewhat greater depth in Caswell Sound than in other fiords in which a maximum was found (Table 5). No deep salinity maximum was observed in Nancy Sound during the 1971 survey. Sampling was limited to 144 m depth so it is possible that a deeper maximum was missed. In December 1977 a salinity maximum at 100 m was observed.

Temperatures were everywhere lower in the December 1977 survey than those observed in January/February 1971. In the upper layers this would arise because the FIORDS 77 data was collected at an early stage in the summer heating cycle. In both fiords temperatures decreased from a surface maximum during the 1977 survey, whereas during the 1971 survey a distinct temperature maximum was present at around 5 m depth. Maximum temperatures were 3°C to 5°C lower at the time of the FIORDS 77 survey compared to those observed on the earlier occasion. Significant temperature differences were also found in the deep water. For example, at 300 m in Marble Basin, Caswell Sound, temperatures were typically 11.4°C in December 1977 and 12.0°C in January 1971.

Dissolved oxygen values in Caswell Sound were similar on each of the two surveys. No dissolved oxygen data was collected in Nancy Sound during the earlier survey.

Stations worked outside the entrance sills of Caswell and Nancy Sounds on both surveys all exhibited the typical shallow salinity maximum found in this coastal region. Water of salinity greater than 35.10‰ was present outside these fiords. The generally lower salinities in the deep water inside these fiords on the earlier survey suggests that this water had a longer residence time, with consequently greater entrainment of low salinity water from the shallow zone, than was the case with the water sampled during the FIORDS 77 survey.

Doubtful Sound

Batham (1965) has published some limited oceanographic data taken in February 1960 and February 1963 during an ecological survey of Doubtful Sound. Most data are surface values although two salinity profiles through the upper 4 m were taken at the head of Hall Arm and near the junction of Crooked Arm with Malaspina Reach. Salinities were determined with hydrometers and consequently may have been in error, but relative readings were probably consistent.

The two salinity profiles in the shallow zone differed in that a type 2 profile (Fig. 6) was obtained in Hall Arm and a type 1b profile in Malaspina Reach. Surface salinities were low and of comparable magnitudes to those obtained during the FIORDS 77 survey. This might be a little unexpected in view of the fact that the earlier data was collected before the Manapouri Power Station was built. However, Batham (1965) found surface water close to the shore could be much less saline than water in the centre of the fiord, in contrast to the transverse stations worked in Doubtful Sound during FIORDS 77 which showed little significant transverse variation. The earlier results probably arise from local runoff effects and are confined to the immediate shore zone. From the information given (Batham 1965) it is not clear which stations were worked close to the shore and which in the centre of the fiord. Consequently, if these stations were worked close to shore, the surface salinities in the centre of the fiord may have been much higher. Surface temperatures were generally around 2°C higher during the 1960 and 1963 surveys than those found in December 1977.

Dusky Sound and Wet Jacket Arm

Jillet and Mitchell (1973) reported nine oceanographic stations worked in Dusky Sound and Wet Jacket Arm in February 1969. Two of the Dusky Sound stations were repeated at later times in the expedition.

Generally, a wide sample spacing was used in the shallow zone except at the two repeated stations. A salinity profile of type 1c (Fig. 6) was found near the mouth of the fiord (Station B) and a type 2 profile near the head (Station E). These profile types were similar to those found in December 1977. Temperature in the shallow zone in February 1969 decreased from a surface maximum similar to the situation prevailing during FIORDS 77. Surface salinity values were relatively high in February 1969 as data were collected during a period of low rainfall. At the repeated stations considerable depression of surface salinity was observed after a period of high rainfall. Surface temperatures were around 2°C higher during February 1969 than in December 1977.

Salinities in the deep zone of Dusky Sound were everywhere markedly lower on the FIORDS 77 survey than those found by Jillet and Mitchell (1973). Bottom salinities were less than 34.8‰ in December 1977 whereas in February 1969 they were around 35.0‰. In Wet Jacket Arm salinities in the deep zone on both surveys were of comparable value.

Temperatures in the deep zone were slightly warmer during the December 1977 survey than those for February 1969. This is opposite to the difference found in the shallow zone. However, the temperature differences were generally less striking than the salinity difference and in the near-bottom waters they tended towards the same values on each survey. The weak longitudinal gradients in deep-water temperature and salinity found during FIORDS 77 were not apparent in the earlier survey when deep-water properties were rather uniform.

Dissolved oxygen values, while fractionally higher on the FIORDS 77 cruise, generally showed similar profiles on both surveys. Dissolved oxygen values were supersaturated at the surface and decreased to values between 5 and 6 ml l^{-1} below 50 m depth. Lower values were observed near the head of Dusky Sound where dissolved oxygen values in the range of 3.4–4.5 ml l^{-1} were found at 50 to 100 m depths on both surveys. A similar low dissolved oxygen value was observed at the head of Wet Jacket Arm in February 1969 but was not observed on the FIORDS 77 survey.

DEEP-WATER RENEWAL IN THE NEW ZEALAND FIORDS

A shallow salinity maximum is generally found between 50 m and 150 m depth off the west coast of South Island. A systematic survey in April 1974 (Stanton 1976) showed that this feature was generally most pronounced near the coast and weakened off shore. Salinity values at the maximum decreased towards the south and on the most southern section, off Milford Sound, salinity at the maximum was 35.23‰. No systematic survey of the region south of this has been done but the limited data available suggest that salinity at the maximum continues to decrease towards the south. For example, Heath (1975) found salinity maxima of 35.12‰ off Milford, 35.02‰ off Doubtful Sound and 35.00‰ off the Chalky Inlet in February/March 1970. While the coastal stations (I465, I524) worked on FIORDS 77 showed salinity at the maximum decreasing from 35.11‰ off Sutherland Sound to 35.07‰ off Doubtful Sound, the off-shore stations showed a reverse trend. Other data in the area, notably Klepikov (1961), Garner (1962) and Japan Fisheries Agency (1972) show a similar trend, but numerically the values show quite large scatter suggesting that seasonal and year to year variations are important. Little is known about the seasonal changes in salinity off the fiord coast but Garner (1969) has shown that bottom temperatures over the shelf in winter can be about 1°C warmer than in summer, suggesting an important advective influence on the seasonal cycle.

While the general southward decrease of salinity at the subsurface maximum in the coastal waters was reflected in a general way by a similar trend in the maximum salinity values found within the fiords, much of the detail remains unexplained. In the northern group of fiords (Milford to Doubtful Sounds inclusive) a deep salinity maximum of 35.00‰ with relatively high density (δ_T = 26.7 kg.m^{-3}) was found. In the southern group (Dagg Sound southwards) maximum salinities were found at the bottom and, in the deep water, salinity and density values showed a general decrease towards the south with Chalky Inlet not falling exactly within this sequence. A possible reason for this is that the fiords may have been at different stages in their annual deep-water renewal cycles at the time of sampling.

Annual variations in the deep-water properties have been observed in most fiord areas (Saelen 1967, Anderson and Devol 1973, Pickard 1975, Helle 1978, Cannon and Laird 1978). In the deep water, density and dissolved oxygen slowly decrease for much of the year as a result of diffusion from above and, in the case of dissolved oxygen, biological oxygen demand. This period is followed by a renewal phase when the deep water is replaced by more dense water from outside the fiord. The renewal process occurs at different times in different fiords and in some cases small inflows can occur several times within a yearly cycle (Pickard 1975, Cannon and Laird 1978). Consequently, there is no reason to expect that deep-water renewal in the New Zealand fiords will occur simultaneously and, from what is known about the variations in the oceanographic parameters in the coastal waters, one might even expect suitable conditions for renewal to occur at different times.

At the time of the FIORDS 77 survey it is possible that the northern group of fiords had recently experienced a deep-water renewal event and consequently they exhibited similar salinity and density structure. The subsurface salinity maximum found in these fiords was probably a remnant of the similar maximum found in coastal waters. Presumably such a maximum would be eroded away by vertical diffusion if deep water remained in residence for any length of time, which explains why it has not always been observed in the previous data collected in the New Zealand fiords. In the southern group of fiords complete deep-water renewal had probably not occurred at the time of the FIORDS 77 survey but may have been underway in some cases. The low salinity and density in the deep waters of Dusky Sound compared with the higher values found in February 1969 (Jillett and Mitchell 1973) suggest that after a renewal event, higher salinity or higher density water could be expected in this fiord. Similarly, the differences in deep-water properties between Dusky Sound and Breaksea Sound (including Wet Jacket Arm) found on the FIORDS 77 survey when no apparent bathymetric obstruction to deep-water exchange was found in the Acheron Passage, suggests a similar conclusion. In contrast, deep water in Wet Jacket Arm and Dusky Sound was found to be similar on the February 1969 survey.

Further evidence that deep-water renewal had not occurred in at least the three southern-most fiords at the time of FIORDS 77 is found in the observed deep salinities. Deep-water salinities in Chalky Inlet did not follow the general trend of a decrease towards the south, found throughout the southern group of fiords. Assuming that deep-water salinities decrease by diffusion downwards from the lower salinity water above then this might be expected to occur more quickly in fiords with a relatively large amount of freshwater inflow. Such trends are evident in the data from the three southern fiords, where Chalky Inlet with the lowest relative inflow (Table 2) had the highest deep-water salinity (Table 6), followed in order by Dusky Sound and then Preservation Inlet.

The generally high dissolved oxygen values found in the deep water of the New Zealand fiords during both FIORDS 77 and previous surveys show that the main basins at least are adequately ventilated. Garner (1964) shows, using biological respiration estimates, that the deep water in Milford Sound must be renewed at least once a year. He concluded that renewal occurred at the time of coldest coastal temperatures, probably in August. Subsequent work however (Garner 1969), has shown that bottom water (100 m) over the shelf off the fiord coast was around 1°C warmer in winter than in summer. If these observations made in 1967 are typical, then this water of 12°C to 13°C is too warm to be the source of the fiord deep water where temperatures are typically 11.5°C during winter. This fact along with the FIORDS 77 observations of deep salinities suggest that renewal occurs later than August and may not have been complete by December when the FIORDS 77 survey was done. From the FIORDS 77 data it is possible that deep-water renewal was happening in sequence from north to south. Obviously this aspect of the fiord oceanography requires investigation of the annual cycle of oceanographic properties both within the fiords and over the shelf. Presently available data in the fiords is limited to the December to April period and the few suitable off shore data are also largely summer values.

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LITERATURE CITED

ANDERSON, J. J.; DEVOL, A. H. 1973: Deep water renewal in Saanich Inlet, an intermittently anoxic basin. *Estuarine and Coastal Marine Science 1 (1)*: 1–10.

BATHAM, E. J. 1965: Rocky shore ecology of a southern New Zealand fiord. *Transactions of the Royal Society of New Zealand, Zoology 6 (21)*: 215–27, 2 pls.

BRODIE, J. W. 1963: Milford Sound Bathymetry 1:32,750. *New Zealand Oceanographic Institute Chart, Miscellaneous Series 5.*

BRODIE, J. W. 1964: The Fiordland shelf and Milford Sound. Pp. 15–23 *in* Skerman T. M. (Ed.) "Studies of a Southern Fiord". *New Zealand Oceanographic Institute Memoir 17*: 101p.

BYE, J. A. T.; HEATH, R. A. 1975: The New Zealand semi-diurnal tide. *Journal of Marine Research 33 (3)*: 423-42.

CANNON, G. A.; LAIRD, N. P. 1978: Variability of currents and water properties from year-long observations in a fiord estuary. Pp. 515–35 *in* Nihoul J. C. J. (Ed.) "Hydrodynamics of Estuaries and Fjords". Proceedings of the 9th International Liege Colloquium on Ocean Hydrodynamics. Elsevier Oceanography Series 23. Elsevier Scientific Publishing Company, Amsterdam. xiv, 546p.

COTTON, C. A. 1956: Coastal history of southern Westland and northern Fiordland. *Transactions of the Royal Society of New Zealand 83 (3)*: 483-8.

GARNER, D. M. 1962: Analysis of hydrological observations in the New Zealand region, 1874–1955. *New Zealand Oceanographic Institute Memoir 9*: 45p.

GARNER, D. M. 1964: The hydrology of Milford Sound. Pp. 25–33 in Skerman T. M. (Ed.) "Studies of a Southern Fiord". *New Zealand Oceanographic Institute Memoir 17*: 101p.

GARNER, D. M. 1969: The seasonal range of sea temperature on the New Zealand shelf. *New Zealand Journal of Marine and Freshwater Research 3 (2)*: 201–8.

GREIG, M. J. N. (Comp.) in press: New Zealand Oceanographic Institute Hydrology Station Data 1978. *New Zealand Oceanographic Institute Hydrology Station Data 1978.*

HEATH, R. A. 1973: Direct measurements of coastal currents around southern New Zealand. *New Zealand Journal of Marine and Freshwater Research 7 (4)*: 331-67.

HEATH, R. A. 1975: Oceanic circulation and hydrology off the southern half of South Island, New Zealand. *New Zealand Oceanographic Institute Memoir 72*: 36p.

HELLE, H. B. 1978: Summer replacement of deep water in Byfjord, western Norway: Mass exchange across the sill induced by coastal upwelling. Pp. 441-64 *in* Nihoul, J. C. J. (Ed.) "Hydrodynamics of Estuaries and Fjords". Proceedings of the 9th International Liege Colloquium on Ocean Hydrodynamics. Elsevier Oceanography Series 23. Elsevier Scientific Publishing Company, Amsterdam. xiv, 546p.

HYDROGRAPHIC OFFICE, ROYAL NEW ZEALAND NAVY 1959: George, Bligh and Milford Sounds. *Chart N.Z. 7413.*

HYDROGRAPHIC OFFICE, ROYAL NEW ZEALAND NAVY 1959: Daggs Sound to Caswell Sound 1:72,000. *Chart NZ 7522.*

HYDROGRAPHIC OFFICE, ROYAL NEW ZEALAND NAVY 1959: Dusky and Breaksea Sounds. *Chart NZ 7612.*

HYDROGRAPHIC OFFICE, ROYAL NEW ZEALAND NAVY 1959: Preservation and Chalky Inlets. *Chart NZ 7614.*

IRWIN, J. 1973: Caswell Sound Bathymetry 1:15,840. *New Zealand Oceanographic Institute Chart, Miscellaneous Series* 23.

IRWIN, J. 1974: Nancy Sound Bathymetry 1:15,840. *New Zealand Oceanographic Institute Chart, Miscellaneous Series 24.*

IRWIN, J. 1978: Bathymetry of Caswell and Nancy Sounds. Pp. 11–18 *in* Glasby, G. P. (Ed.) "Fiord Studies: Caswell and Nancy Sounds, New Zealand". *New Zealand Oceanographic Institute Memoir 79*: 94p.

IRWIN, J.; MAIN, W. DEL. in press: Doubtful Sound Bathymetry 1:25,000 (4 sheets). *New Zealand Oceanographic Institute Chart, Miscellaneous Series 53.*

JAPANESE FISHERIES AGENCY 1972: Report of the voyage of the investigations of the *Kayo Maru* 1970 in New Zealand waters. Japanese Fisheries Agency, Tokyo. Text 292p., tables 290p. (In Japanese).

JILLETT, J. B.; MITCHELL, S. F. 1973: Hydrological and biological observations in Dusky Sound, south-western New Zealand. Pp. 419–27 *in* Fraser, R. (Comp.) "Oceanography of the South Pacific 1972". N.Z. National Commission for UNESCO, Wellington. 524p.

KLEPIKOV, V. V. (Ed.) 1961: Third marine expedition of D. E. V. *Ob* 1957–58. *Trudy Sovetskoi Antarktichieskoi Ekspeditsii 22*: 234p. (In Russian).

MARINE DIVISION, MINISTRY OF TRANSPORT 1976: New Zealand Nautical Almanac and Tide Tables for the year 1977.

MAUNDER, W. J. 1966: New Zealand in maps, 5. Average annual rainfall patterns. *New Zealand Geographer 22(2)*: 177–81.

NATIONAL WATER AND SOIL CONSERVATION ORGANISATION 1970: Representative basins of New Zealand 1970. *New Zealand Ministry of Works and Development, Water and Soil Division. Miscellaneous Hydrological Publication 7*: 291p.

NEVINS, T. H. F. 1970: River discharges: New Zealand's place in the world. *Journal of Hydrology (New Zealand) 9 (1)*: 43–46.

NEW ZEALAND METEOROLOGICAL SERVICE 1973: Rainfall normals for New Zealand 1941 to 1970. *New Zealand Meteorological Service. Miscellaneous Publication 145*: 34p.

PICKARD, G. L. 1961: Oceanographic features of inlets in the British Columbian mainland coast. *Journal of the Fisheries Research Board of Canada 18*: 907–99.

PICKARD, G. L. 1963: Oceanographic characteristics of inlets of Vancourver Island, British Columbia. *Journal of the Fisheries Research Board of Canada 20*: 1109–44.

PICKARD, G. L. 1967: Some oceanographic characteristics of the larger inlets of south-eastern Alaska. *Journal of the Fisheries Research Board of Canada 24*: 1475-506.

PICKARD, G. L. 1971: Some physical oceanographic features of inlets of Chile. *Journal of the Fisheries Research Board of Canada 28(8)*: 1077–106.

PICKARD, G. L. 1975: Annual and longer term variations of deepwater properties in the coastal waters of southern British Columbia. *Journal of the Fisheries Research Board of Canada 32(9)*: 1561–87.

PICKARD, G. L.; STANTON, B. R. 1980: Pacific fiords—a review of their water characteristics. Pp. 1–51 in Freeland, H. J.; Farmer, D. M.; Levings, C. D. (Eds) "Fiord Oceanography". Plenum Press, New York. xiv, 715p.

PICKRILL, R. A.; MAIN, W. DEL. 1980: Dagg Sound Bathymetry 1:16,000. *New Zealand Oceanographic Institute Chart, Miscellaneous Series 52.*

SAELEN, G. M. 1967: Some features of the hydrography of Norwegian fjords. Pp. 63–70 in Lauf, G. H. (Ed.) "Estuaries". *American Association for the Advancement of Science Publication 83*: 757p.

STANTON, B. R. 1976: Circulation and hydrology off the west coast of the South Island, New Zealand. *New Zealand Journal of Marine and Freshwater Research 10 (3)*: 445–67.

STANTON, B. R. 1978: Hydrology of Caswell and Nancy Sounds. Pp. 73–82 in Glasby, G. P. (Ed.) "Fiord Studies: Caswell and Nancy Sounds, New Zealand". *New Zealand Oceanographic Institute Memoir 79*: 94p.

TOEBES, C.; PALMER, B. R. 1969: Hydrological regions of New Zealand. *New Zealand Ministry of Works and Development, Water and Soil Division. Miscellaneous Hydrological Publication 4*: 45p.

APPENDIX 1: MEAN FRESHWATER INFLOW AT MILFORD SOUND

The Cleddau River has been gauged at Milford since 1963. Using the provisional data provided by the National Water and Soil Conservation Organisation, the ten year period 1967 to 1977, excluding 1974, was chosen for analysis. Data prior to 1966 was excluded because a different recording system was used, while data from 1974 was largely lost because of a major instrumental malfunction during that year. The monthly mean discharges along with the normal daily rainfall at Milford Sound (N.Z. Meteorological Service 1973) are given in Table A1. Rainfall exhibits a maximum in November with another slightly lower maximum occurring in March. Minimum rainfall occurs in July with a less marked secondary minimum in January. The Cleddau River discharge shows maxima and minima in the same months but, in contrast to the rainfall, the greatest values occur in the March maximum when the melting of winter snow supplements the rainfall.

TABLE A1: Monthly mean discharge ($m^3 s^{-1}$) of the Cleddau River at Milford for the period 1967–1977 (excluding 1974) and normal daily rainfall (mm) at Milford Sound for the period 1941–1970.

Month	Cleddau River mean discharge ($m^3.s^{-1}$)	Normal daily rainfall (mm)
January	29.8	17.1
February	30.0	20.1
March	42.6	20.3
April	39.3	17.5
May...	27.8	15.6
June	15.8	14.0
July ...	15.3	12.2
August	20.0	13.7
September	31.0	17.9
October	32.6	17.6
November	33.8	21.3
December	33.1	17.9
Annual	29.2	17.1

APPENDIX 2: FRESHWATER INFLOW TO DOUBTFUL/THOMPSON SOUNDS IN 1977

The Manapouri Power Station outfall at Deep Cove introduces considerable volumes of fresh water into Doubtful Sound. This 600 megawatt station utilises the diversion of water from Lake Manapouri to the east of the main range. The power station is designed to use the available inflow to Lake Manapouri and over 90% of the available inflow to the lake is utilised throughout the year. Consequently power station discharge depends primarily on the available water in the Lake Manapouri catchment. The relative volumes of introduced and natural freshwater inflow are examined using the 1977 data (Table A2). Power Station data has been supplied by the Electricity Division, Ministry of Energy. Natural inflow to the Doubtful/Thompson Sound system has been estimated from the Cleddau River flows scaled by the ratio of the catchment areas. The Cleddau River catchment is 155 km^2 while that of the Doubtful/Thompson Sound system is 1069 km^2. This calculation considers the Doubtful/Thompson Sound system as a whole and it should be noted that for smaller component parts such as Doubtful Sound alone or Deep Cove the natural inflow would be smaller (*see* Table 2). However, from Table A2 it can be seen that the power station inflow is generally greater than that of the natural inflow to the whole Doubtful/Thompson Sound system. The annual rates for 1977 (which for the Cleddau River was close to average—(*see* Appendix 1) show the power station inflow was double the estimated natural inflow. It should be noted also that power station discharge, being largely dependent on available water in the Lake Manapouri catchment, shows a broadly similar variation to the Cleddau flow rates with a minimum in the winter months.

TABLE A2: Monthly mean flow rates ($m^3.s^{-1}$) for 1977 of the Cleddau River at Milford Sound, the Manapouri Power Station at Deep Cove, Doubtful Sound and the estimated natural freshwater inflow to the Doubtful/Thompson Sound system. Estimated natural inflow = ratio of the catchment areas × Cleddau flow.

Month	Cleddau River mean flow	Estimated natural freshwater inflow	Manapouri Power Station mean flow
January	40.0	276	320
February	27.5	190	457
March	27.2	188	407
April	58.8	406	393
May	18.0	124	462
June	21.5	148	452
July	8.1	56	374
August	7.8	54	206
September	24.7	170	161
October	34.8	240	293
November	27.4	189	461
December	24.7	170	438
Year	26.7	184	368

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