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THE PHYSICAL OCEANOGRAPHY OF THE BRAS D'OR LAKES: DATA ANALYSIS AND MODELLING

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ABSTRACT

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The Bras d'Or Lakes are a system of interconnecting basins open to the Sydney Bight near the mouth of the Gulf of St. Lawrence. Most of the Lake area is covered by ice during the winter with surface waters warming by more than 10°C over a period of from May to July. Temperature, salinity and current meter data collected in between 1972 and 1974 provide an indication of the conditions in the Lakes, particularly during the early summer when there is a period of maximum heating and a rapid decrease in fresh water input. These data have relatively low accuracy but it is possible to reconcile them enough to construct a simple budget model of the system consisting of 2 to 3 layers in 9 different regions. Data from comprehensive hydrographic surveys in May and June, 1974 were used to derive horizontal and vertical transports for the Lakes. Both horizontal and vertical transports (net transport + exchange) range over 3 orders of magnitude, from 5 to 2775 and from 1 to 2520 $m^3 s^{-1}$ respectively. The model transports compare reasonably well to estimates derived from available current meter data. The model's predicted temperatures and salinities for July had rms errors of about 1.5°C and 0.82, respectively. Dissolved oxygen concentrations in 4 isolated basins are similar to those calculated from the model, giving additional support to the derived circulation.

RESUME

Gurbutt, Paul A., Brian Petrie and Francis Jordan. 1993. The Physical Oceanography of the Bras d'Or Lakes: Data Analysis and Modelling. Can. Tech. Rep. Hydrogr. Ocean Sci. 147: vii + 61 pp.

Les lacs Bras d'Or sont constitués d'un ensemble de bassins reliés les uns aux autres qui débouche sur la baie de Sydney, à proximité de l'embouchure du golfe du Saint-Laurent. La majure partie de leur surface est recouverte par les glaces en hiver. Leurs eaux superficielles se réchauffent de plus de 10°C de mai à juillet. Des données sur la température, sur la salinité et sur les courants recueillies de 1972 à 1974 nous donnent une indication des conditions qui règnent dans ces lacs, en particulier au début de l'été, période où le réchauffementest à son plus fort et où l'apport d'eau douce diminue rapidement. Les données en question ne sont pas très exactes, mais il est possible de les rapprocher suffisamment pour obtenir une modélisation simple du régime de ces bassins, portant sur deux à trois couches dans neuf régions. On s'est servi de données tirées de levés hydrographiques exhaustifs réalisés en mai et en juin 1974 pour calculer les transports verticaux et horizontaux dans ces lacs. Tant les transports horizontaux que les transports verticaux (transport net + échange) s'échelonnent sur trois ordres de grandeur, allant de 5 à 2 775 m^3s^{-1} et de 1 à 2 520 m^3s^{-1} respectivement. Les transports indiqués par le modèle se comparent assez bien aux estimations dérivées des données fournies par les courantomètres. Les températures et les salinités prédites par le modèle pour juillet comportaient une erreur quadratique moyenne d'environ 1,5°C et 0,82 respectivement. Les concentrations d'oxygène dissous dans quatre bassins isolés sont comparables à celles du modèle, ce qui corrobore la circulation calculée d'après les données.

1. Introduction

The Bras d'Or Lakes are connected to the Atlantic Ocean by a long (30 km), narrow (1 km), shallow(20 m) passage, the Great Bras d'Or Channel (Figure 1). The Little Bras d'Or Channel, the only other permanently open connection to the ocean, is a more restrictive feature. A lock on St. Peter's Inlet (south of station 24, Fig. 1) allows summer traffic into the southern end of St. Peter's Basin. The Lakes consist of several basins and channels with maximum depths exceeding 250 m and with a total volume of 3.2×10^{10} m^3.

The combination of restricted access to the ocean and freshwater inflow keeps the salinity of the Lakes in the range of about 20 to 26 (Figure 2). The drainage areas are about 1500 and 2200 km^2 for the regions north and south of Barra Strait, respectively, with the open water areas included. The mean freshwater inflow of 140 $m^3 s^{-1}$ varies from a monthly average maximum of 300 $m^3 s^{-1}$ in May to 56 $m^3 s^{-1}$ in August, based on 6 to 57 years of gauged river flow and drainage areas (Krauel, 1975a).

The principal tidal component in the Sydney Bight, M_2 with an amplitude of 0.37 m, rapidly decreases to 0.17 m inside the mouth of the Great Bras d'Or Channel, and to 0.035 m at the south shore of Bras d'Or Lake (St. Peter's Basin). Though the tides are quite small, their movement through narrow straits can give rise to strong currents, a potential source of energy for mixing.

In August 1972, Krauel (1975b) began the most comprehensive hydrographic and current meter survey covering the Lakes. It continued until July, 1974, and was complemented with current meter moorings in the summers of 1973 (average record length 33 d) and 1974 (35 d). Krauel (1975a,b) presented the hydrographic observations as listings of temperature, salinity, sigma-t and depths, and the current meter data as histograms and time series plots of rate and direction and as progressive vector diagrams. There was a brief discussion of some aspects of the oceanography of the Lakes. Prior to this work, there were no investigations of the physical oceanography of the Bras d'Or Lakes. Since that time, there has been a study of a small basin, the Little Narrows Pond, (Birch, 1978) and a water chemistry survey, (Pagé, unpublished data, Université du Québec à Montréal, Montréal, Canada). We have concentrated more on the analysis and interpretation of the data from Krauel's program, and have attempted to present a picture of the circulation in the Lakes as a whole through a multiple box model.

Aquaculture is a growing industry in the Bras d'Or Lakes. In 1991, approximately 360 t of finfish and 155 t of shellfish, with a total value of Cdn$1.55 million were harvested (Turner, pers. comm., Dept. of Fisheries and Oceans, Halifax, Canada). Most of the activity has been north of the Barra Strait, but there is a growing demand for aquaculture licences for southern sites. Results from this technical report have already been applied to aquaculture assessments in the Lakes. Recent proposals to develop a regional landfill site in the Denys Basin area have raised concerns about the leakage of contaminants into the Lakes. Data from the Bras d'Or Lakes study have been used in this problem and in engineering considerations for the Barra Strait railway bridge replacement. The physiology and genetics of the indigenous cod stock in the

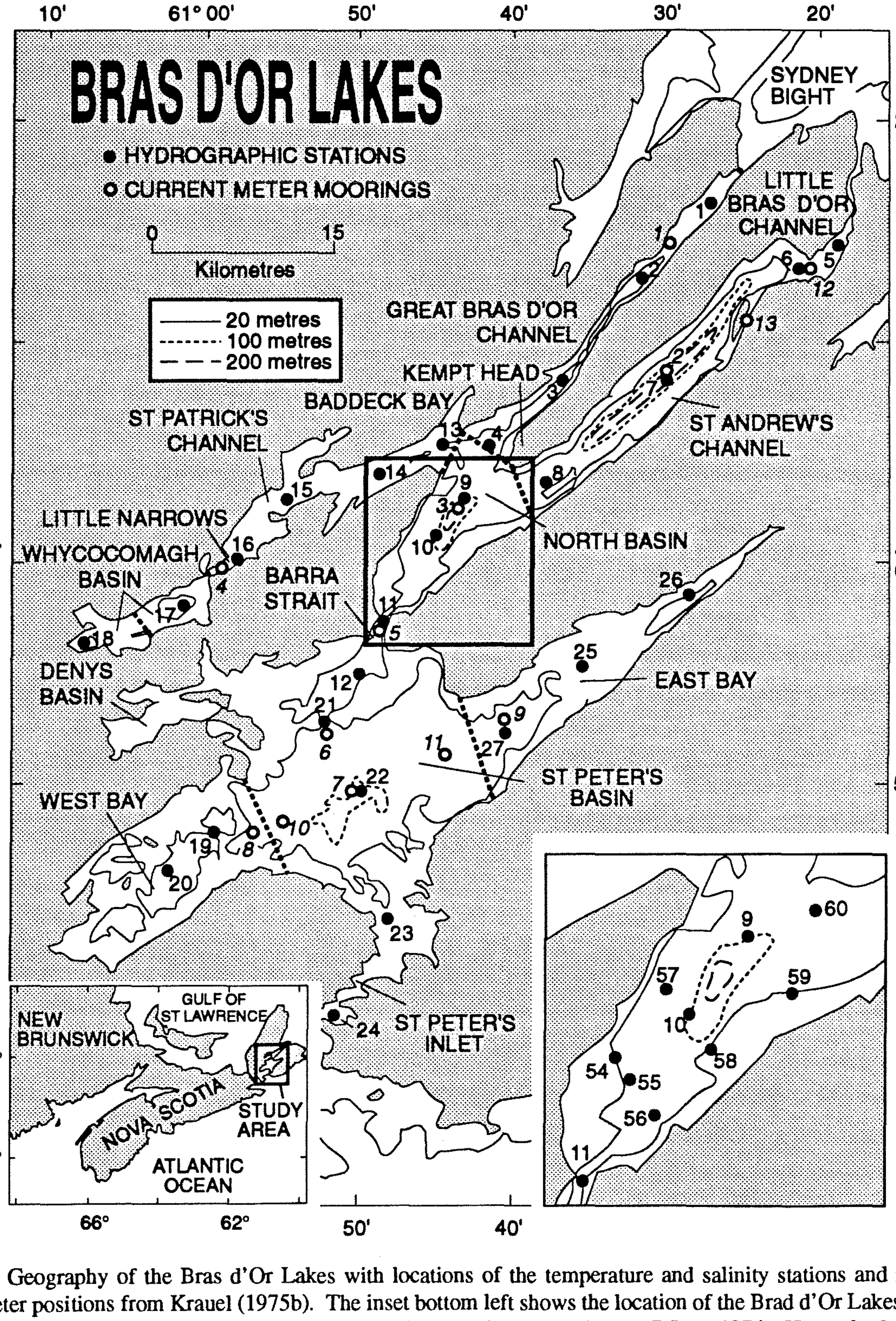
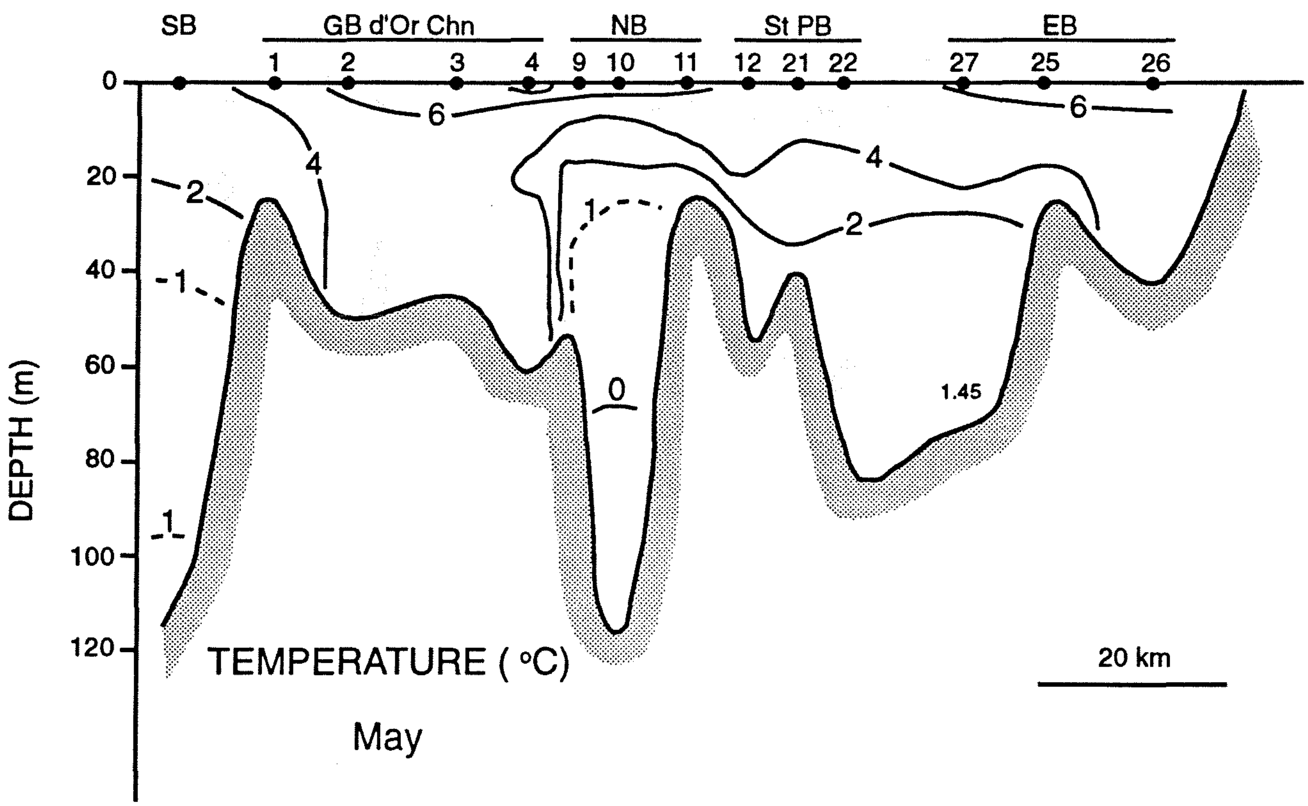


Figure 1. Geography of the Bras d'Or Lakes with locations of the temperature and salinity stations and moored current meter positions from Krauel (1975b). The inset bottom left shows the location of the Brad d'Or Lakes within Nova Scotia and the inset bottom right shows the station locations occupied on 7 June 1974. Heavy broken lines indicate the boundaries of the box model. Note the boundary slightly west of current meter site 4 in Little Narrows and just south of hydrographic station 11 in Barra Strait. Hydrographic stations 2-4 are used for Great Bras d'Or Channel averages.

A



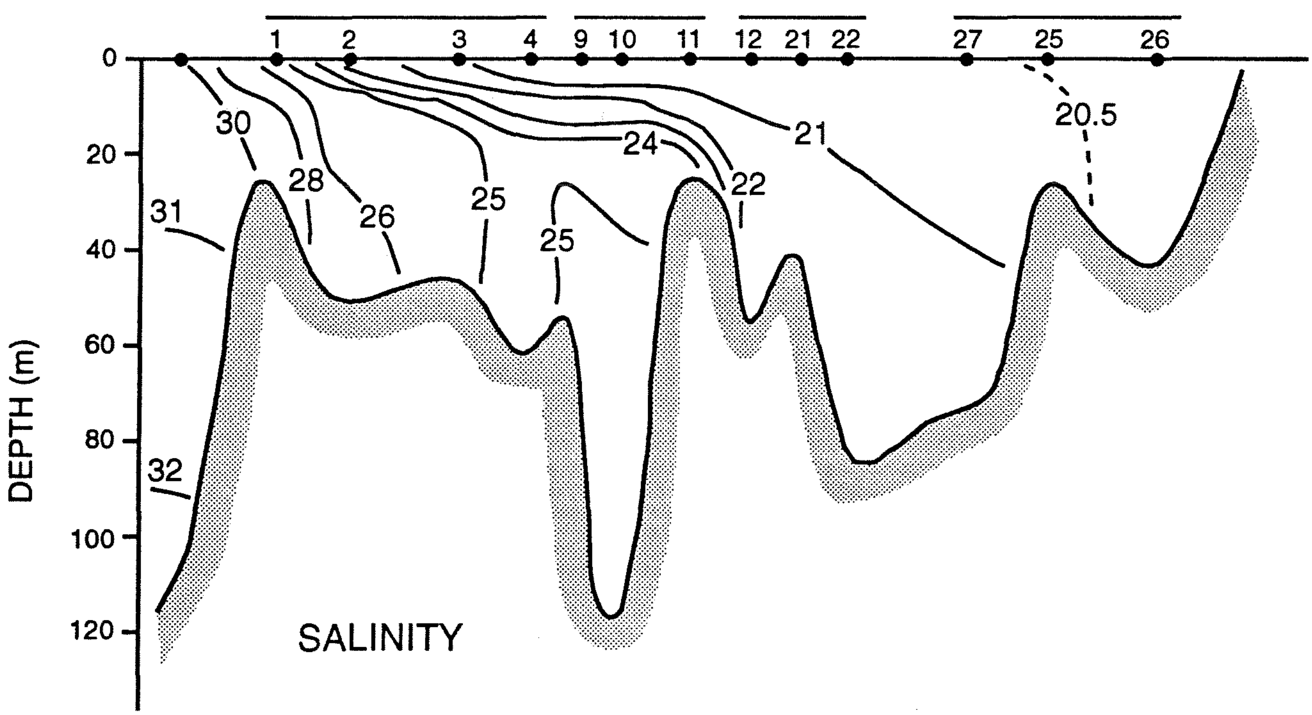


Figure 2a-d. Temperature and salinity sections for May 1974 from Sydney Bight (SB), through the Great Bras d'Or Channel (GB d'Or Chn), North Basin (NB), St. Peter's Basin (St PB) to a) East Bay (EB), b) West Bay (WB), c) St. Andrew's Channel (St A Chn), and d) St. Patrick's Channel (St P Chn) and Whycocomagh Basin (Why B). The profiles for Sydney Bight are the long-term mean for May from Drinkwater and Trites (1987).

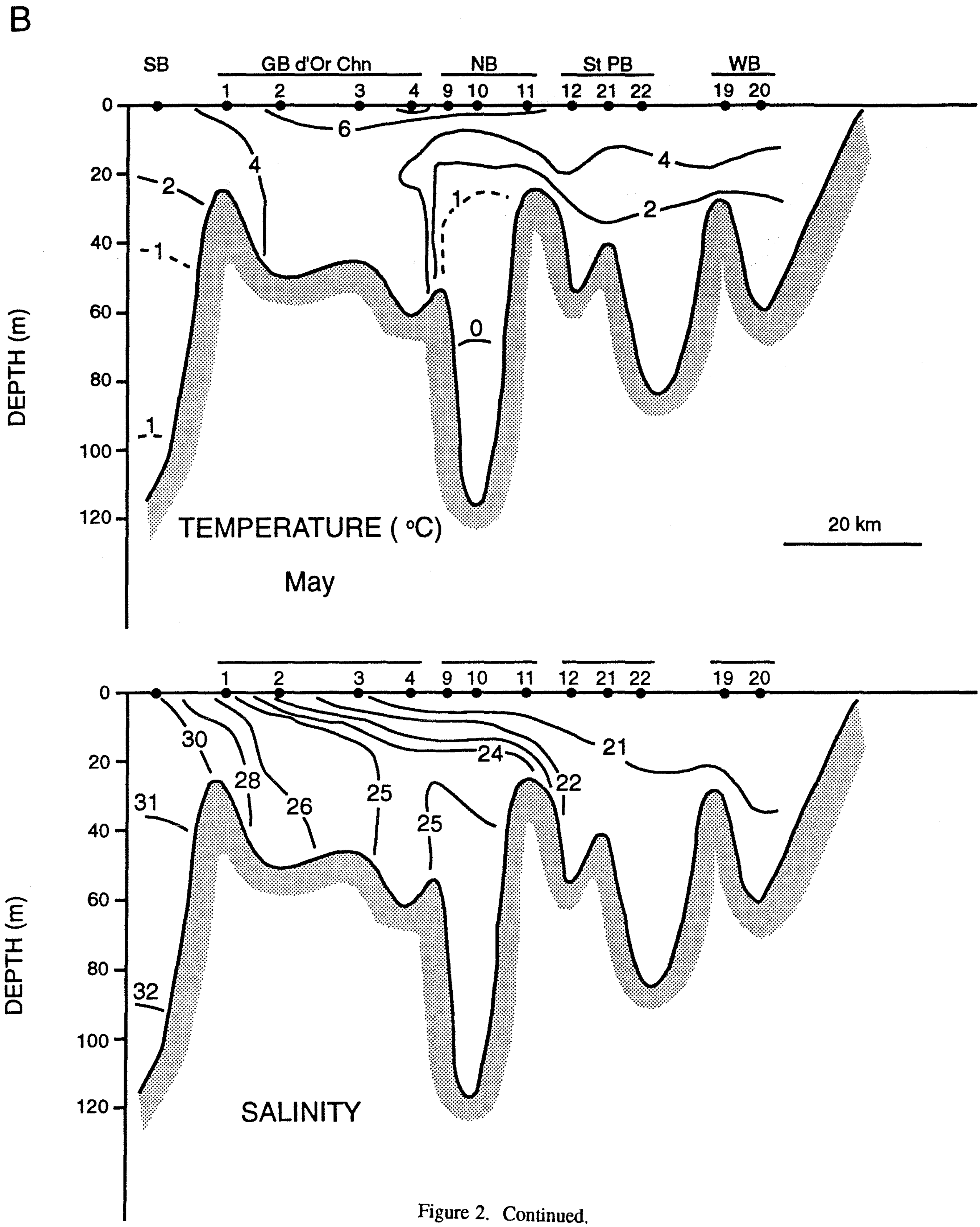


Figure 2. Continued.

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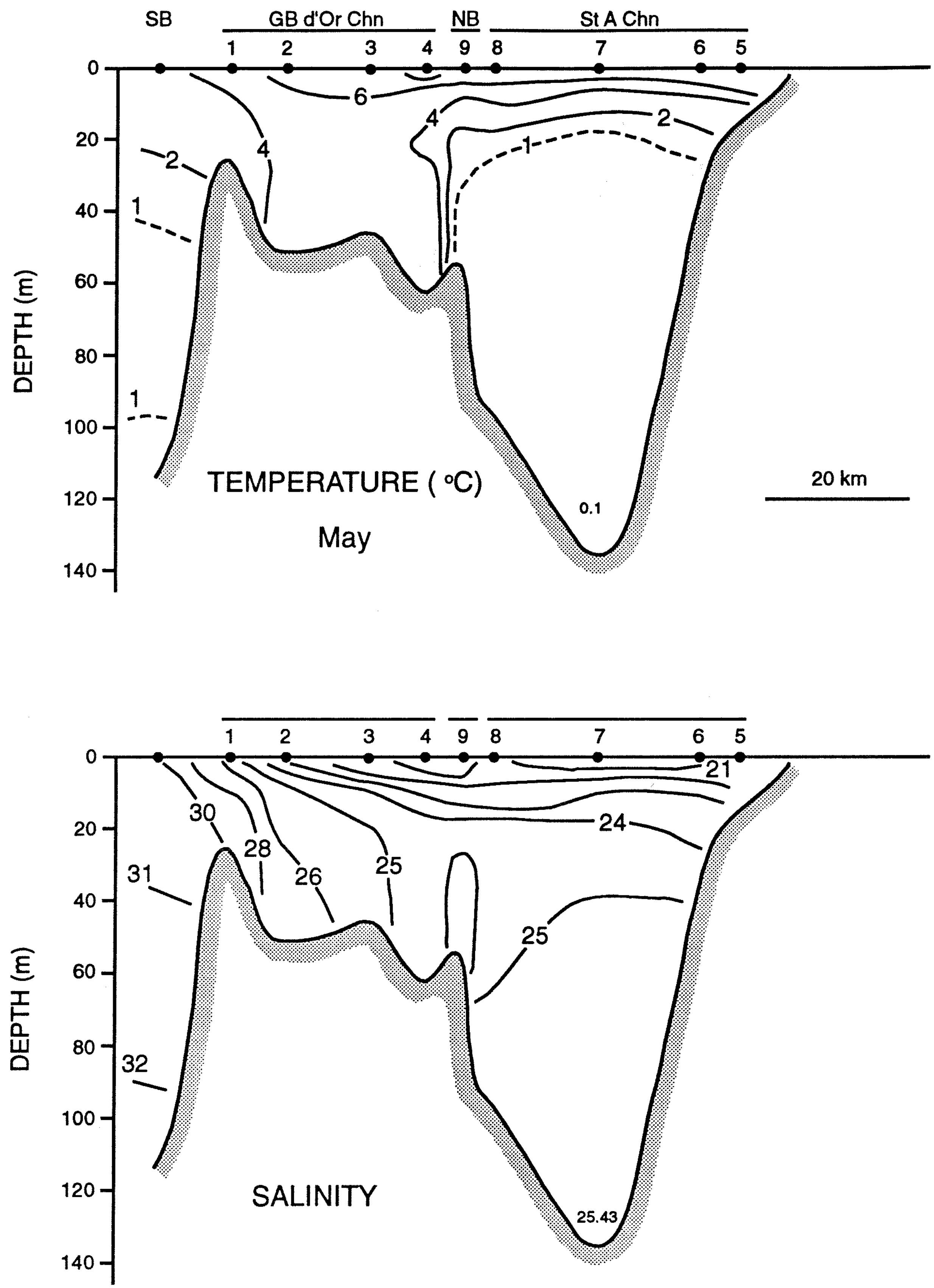

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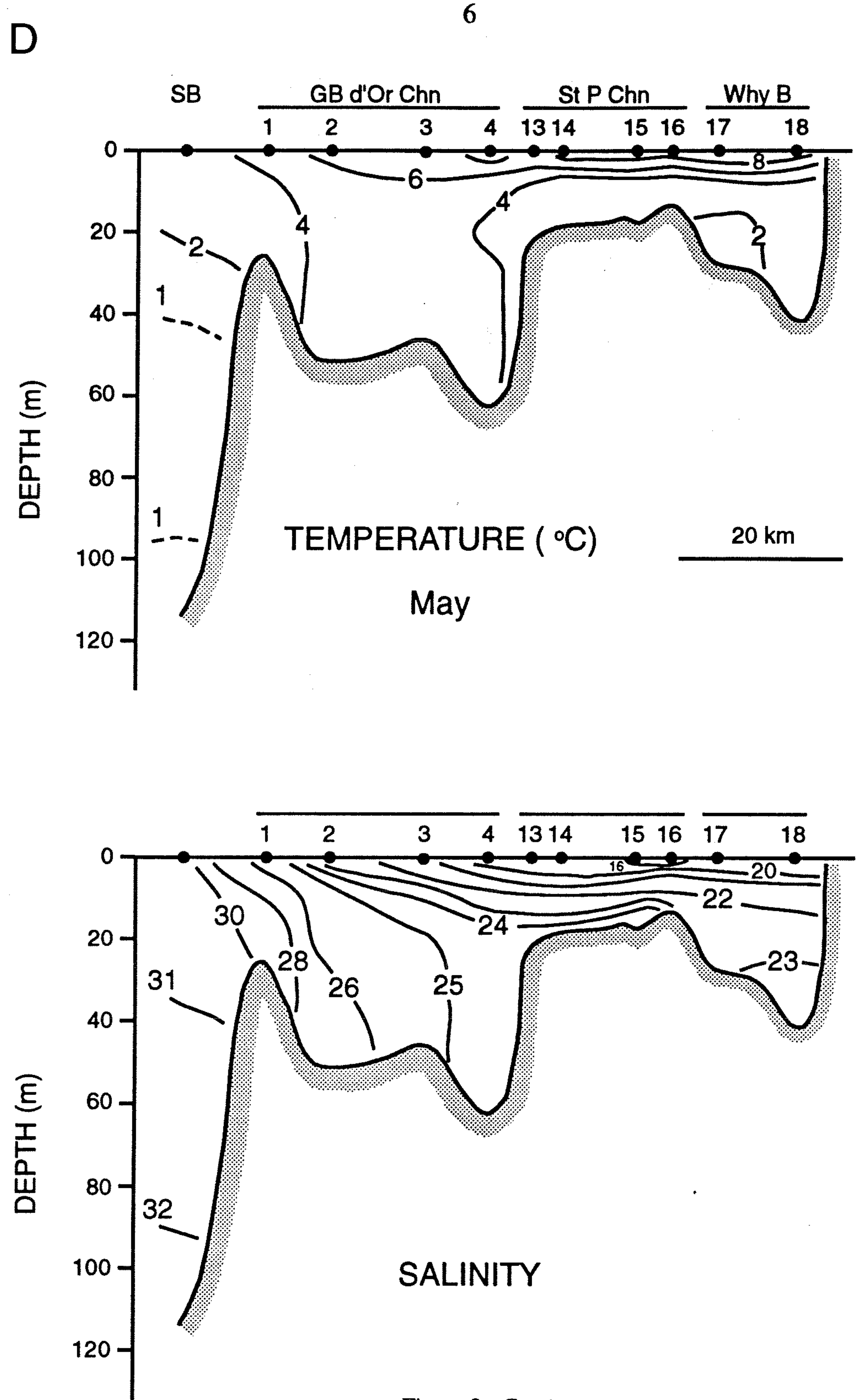


Figure 2. Continued.

Lakes are part of an ongoing intercomparison study with stocks in the Sydney Bight and the North Sea. In addition to raising site-specific questions, these issues demand an understanding of the general physical oceanography of the system. This has motivated us to use the temperature and salinity data (Krauel, 1975b) to develop a box model of the circulation, to compare the estimated transports with those determined from current meter records where possible, and to explore the processes that control mixing and exchange between basins.

2. Temperature and Salinity Data

2.1 Availability

Krauel (1975b) reports on three campaigns to measure temperature and salinity: the first between August 1972 and February 1973, the second between July 1973 and August 1973 and the third between May 1974 and July 1974. Figure 1 shows the location of the standard station positions, 1-27, used in these surveys and Table 1 provides an indication of the coverage of this grid.

Sampling of these temperature and salinity stations in 1972 was intermittent, with only one almost complete synoptic survey on 13 and 14 September. Only stations 11 (Barra Strait) and 16 (Little Narrows) were occupied at least once per month between August 1972 and February 1973. In July 1973, the coverage was better. In 1974, there were three synoptic surveys on 23-24 May, 17-19 June and 15-17 July, together with a more extensive survey of the North Basin and of part of St. Peter's Basin on 7 June, 1974. This report will concentrate on the 1974 observations, but their interpretation is supported by the other data.

2.2 Reliability

Instruments

The temperature and salinity data for the Bras d'Or Lakes were collected using instruments less accurate than their modern equivalents. The data are also spatially and temporally sparse. Both of these factors lead to errors in estimates of the mean temperatures in the different regions and different depths of the Bras d'Or Lakes.

Most of the temperature and salinity data were collected using a Beckman RS5, although some of the later data (July 1974) were collected using a Bissett-Berman 9060 STD. Krauel (1975b) states that the Beckman RS5 has a temperature sensor with an accuracy of 0.5°C and a salinity sensor with accuracy of 0.3 and claims that these could both be reduced to 0.1°C and 0.1, respectively, with calibration. However, it appears that no *in situ* water bottle samples or reversing thermometer measurements were made for the RS5 casts, although it is 'probable' that they were made for the Bissett-Berman STD casts (Lively, pers. comm., Dept. of Fisheries and Oceans, Dartmouth, Canada). These measurement inaccuracies probably account for some of the inversions seen in some of the profiles.

Table 1

Data coverage of the temperature and salinity surveys between 1972 and 1974

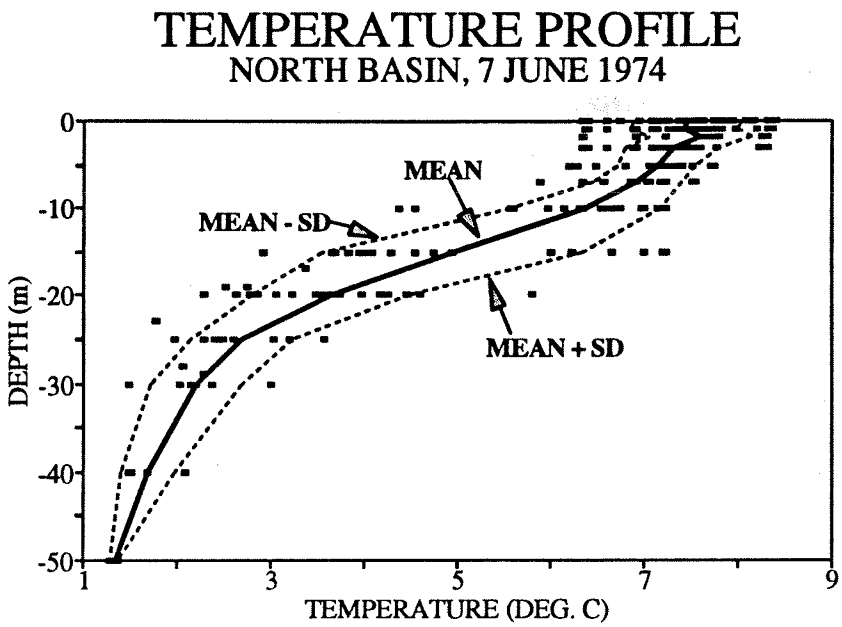
	Month	Time Span (days)	Number of Stations	Number of Sampling Days	Stations per Day	Percentage Coverage of Stations 1-27
1972	August	9	13	3	4.3	48
	September	21	31	8	3.9	74
	October	25	21	9	2.3	48
	November	20	22	7	3.1	70
	December	7	9	2	4.5	30
1973	January	1	2	1	2.0	7
	February	1	2	1	2.0	7
	July	15	46	7	6.6	45
	August	1	4	1	4.0	15
1974	May	2	27	2	13.5	100
	June	3	53	5	10.6	100
	July	4	26	5	5.2	93

Temporal-Spatial Aliasing

Data sparsity may present an even greater problem to our analysis. During 7 June 1974, a survey of the North Basin (Figure 1, inset) sampled station 11 nine times, stations 9 and 10 twice each and a number of other stations, which were not normally occupied, once each. This one day of data provides an ideal opportunity to examine some of the likely errors due to temporal and spatial variability.

Data

Figure 3 shows all the temperature and salinity data from 7 June, 1974 with an indication of the mean and standard deviation. Near the surface the temperature range is about 2°C increasing to about 4.5°C at 15m and then decreasing rapidly below 20m. Similarly, the salinity range decreases sharply below 20m from about 2 near the surface. Nine measurements made at station 11 over 5.25 hours showed significant variability that was particularly noticeable at depths of 15 and 20 m in both temperature (by as much as 3°C) and salinity (by 1.5). Some of this variation may be caused by the semi-diurnal tides (Figure 4).



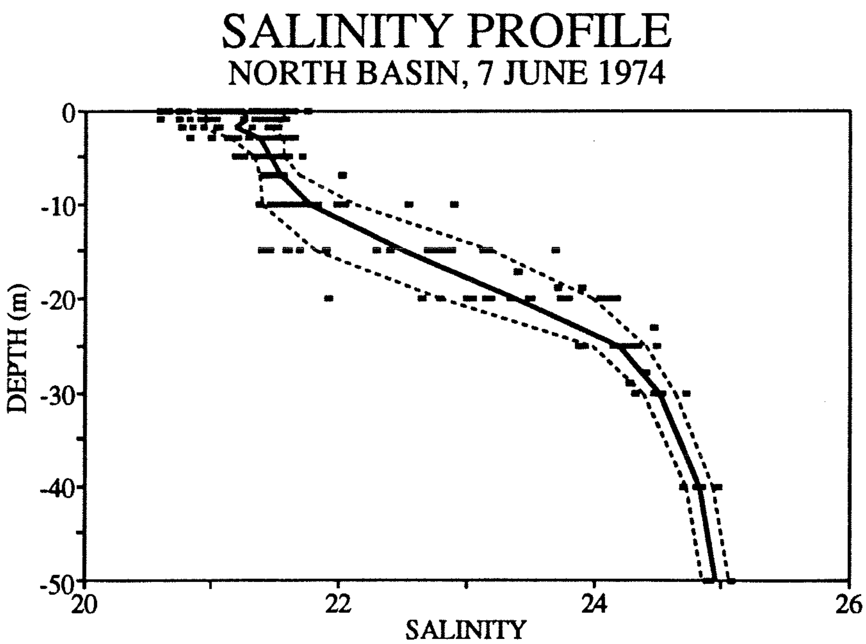


Figure 3. Plot of all the (a) temperature and (b) salinity data against depth for the North Basin, station 11 on 7 June 1974. Individual observations from the 9 profiles that were taken are shown as small rectangles, the mean (solid line) and mean ± 1 standard deviation (dashed lines) are drawn.

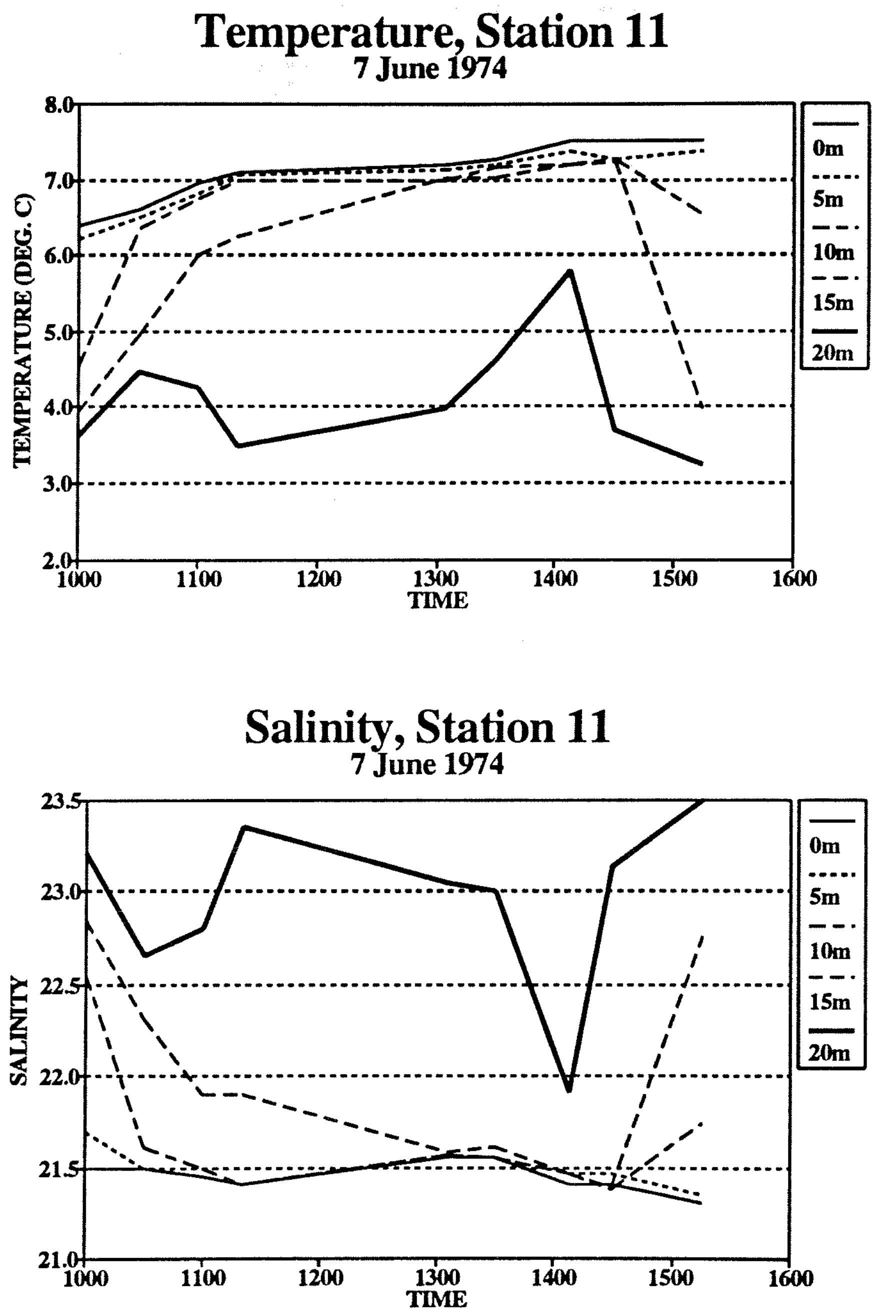


Figure 4. Plot of the time variation of the (a) temperature and (b) salinity at station 11 (Barra Strait) for 7 June 1974 at 5 depths.

To characterise the temperature and salinity in each basin for modelling purposes we formed the mean of the standard stations (Figure 1 and Table 2) within each basin for each of the synoptic surveys in 1974. In the North Basin, the stations were averaged in the depth bands 0-15m, 15-30m and >30m. The data from 7 June, 1974, allows us to obtain multiple estimates of the mean temperatures and salinities. Figures 5a,b(i) show the 36 estimates from using different combinations of standard stations 9, 10 and 11; Figures 5a,b(ii) show the estimates obtained from each station separately. The horizontal lines in the figures show the means of all the independent estimates. Clearly visible in Figures 5a,b(i) is some form of tidal variation from the 5.25 hours coverage of station 11. Figures 5a,b(ii) show that only stations 9 and 10 were sampled below 30 m and stations 54, 58 and 59 were not sampled below 15 m (Figure 1 inset). It is this under-sampling of the deeper levels that leads to the large variation seen in Figures 5a,b(ii) especially in level 2. This problem is important in the synoptic survey on 17 June 1974 when very few stations in the entire Bras d'Or Lakes were sampled below 50m. We see from Figures 5a,b(i) that tidal variations give an error of the order of 10% when the standard stations 9, 10 and 11 are used together. However, Figure 5a,b(ii) shows that under-sampling of the deeper levels and natural variability in the 15-30m depth band can result in errors of over 50% of the mean of all estimates. Where mean temperatures and salinities were not available for the third level for June, they were calculated by linear interpolation from the May and July values.

Table 2
The grouping of stations in basins for forming mean temperature and salinity profiles

Basin name	Standard Stations
Great Bras d'Or Channel	2,3,4
North Basin	9,10,11
St. Patrick's Channel	13,14,15,16
Whycocomagh Basin east	17
Whycocomagh Basin west	18
St. Andrew's Channel	5,6,7,8
St. Peter's Basin	12,21,22,23,24
East Bay	19,20
West Bay	25,26,27

In summary, instrument inaccuracies can give rise to temperature and salinity errors of approximately 0.5 °C and 0.3, respectively; spatial and temporal aliasing can also result in errors of as much as 1°C and 1, respectively.

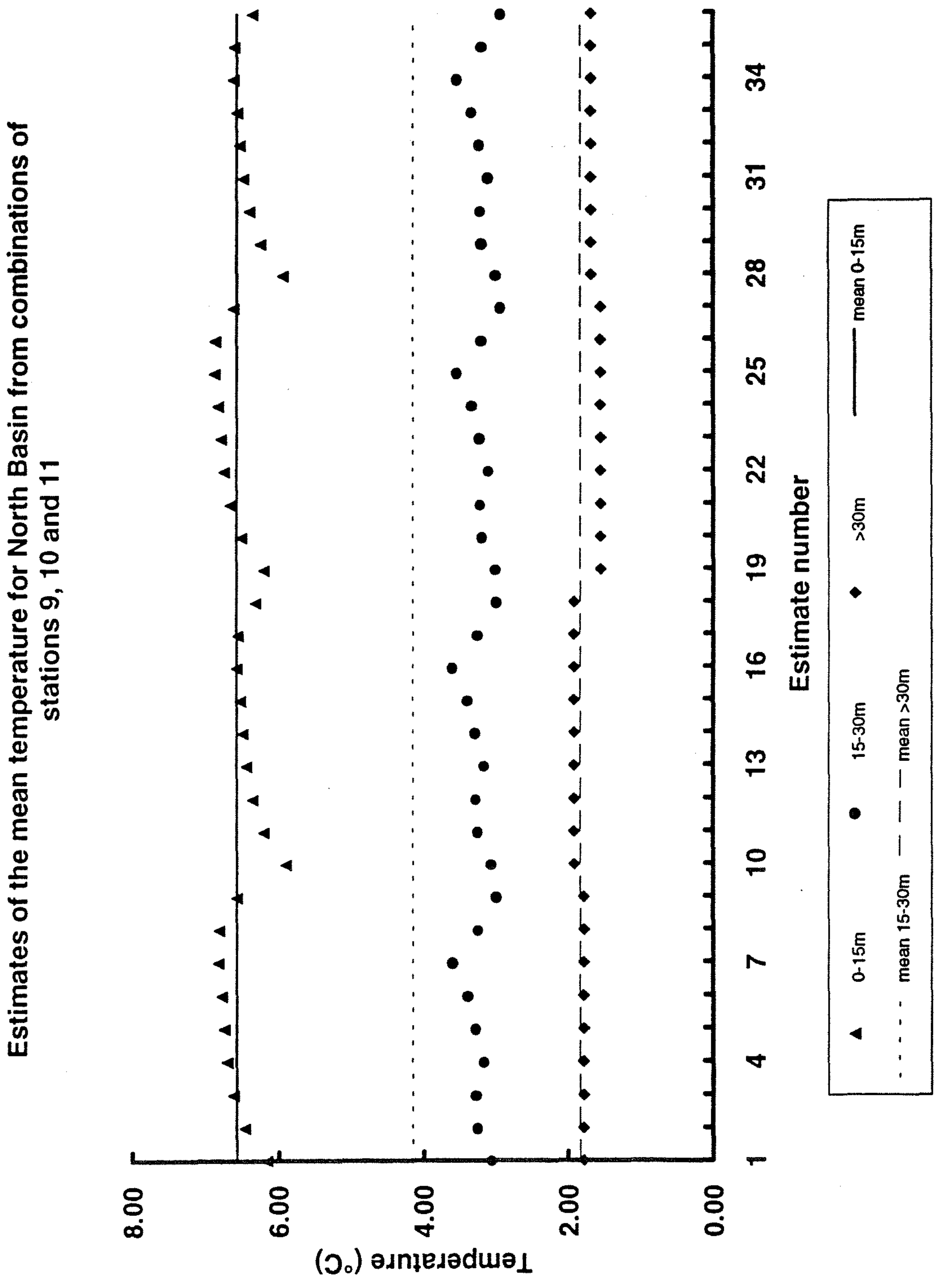


Figure 5(a)(i)

Figure 5. Plot of the estimates of the (a)(i) temperatures and (b)(i) salinities on 7 June 1974 in the North Basin for depth bands 0-15m, 15-30m and >30m. The 36 sets of points are estimates from all possible combinations of samples from stations 9 (2 profiles taken), 10 (2 profiles) and 11 (9 profiles). Figures (a)(ii) and (b)(ii) are estimates from single stations including those which are not normally sampled. Missing values in level 3 indicate no data in this depth range. The horizontal lines in the figures represent the averages of all single station estimates.

Estimates of the mean temperature in North Basin treating each station as a separate estimate

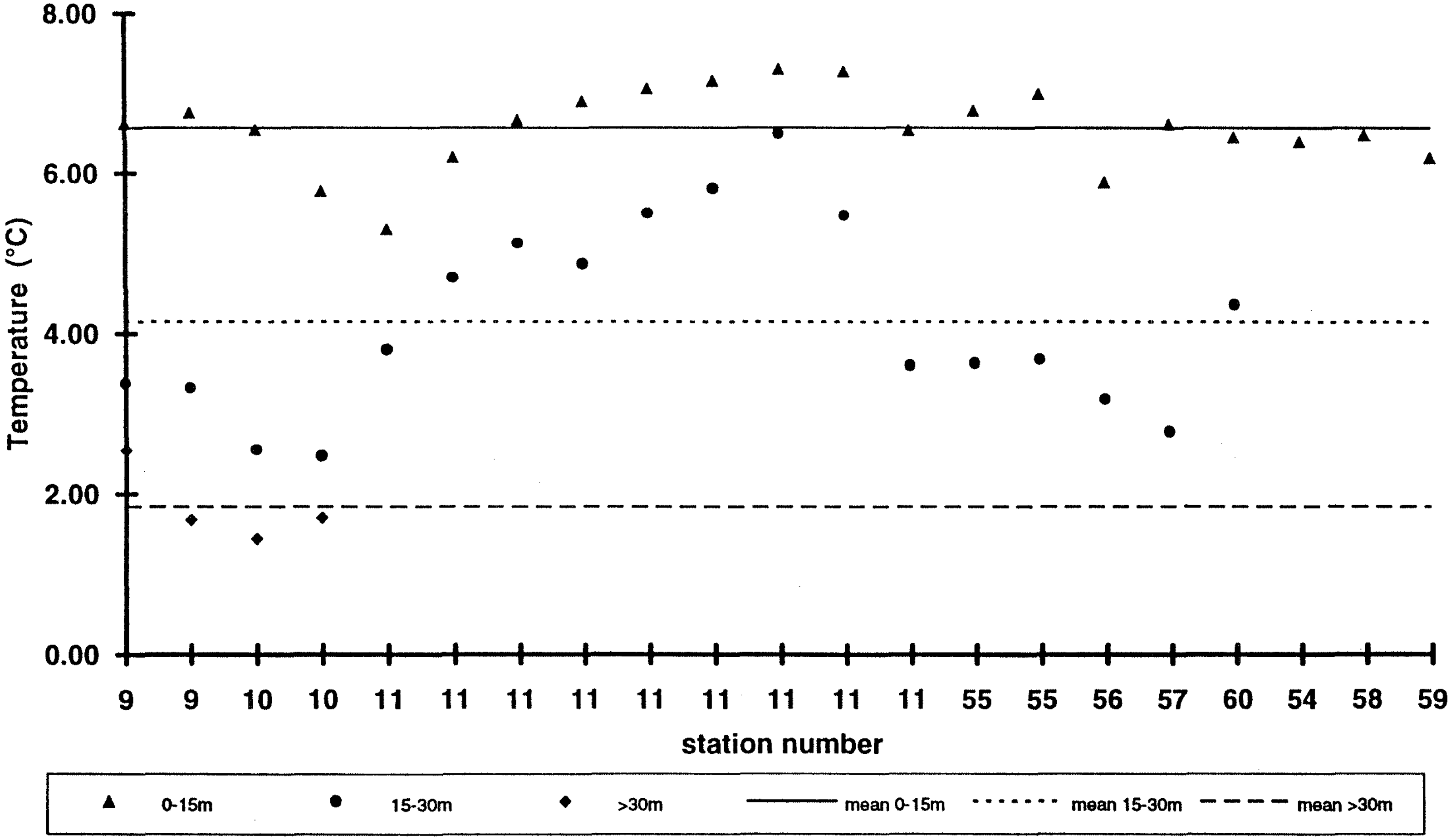
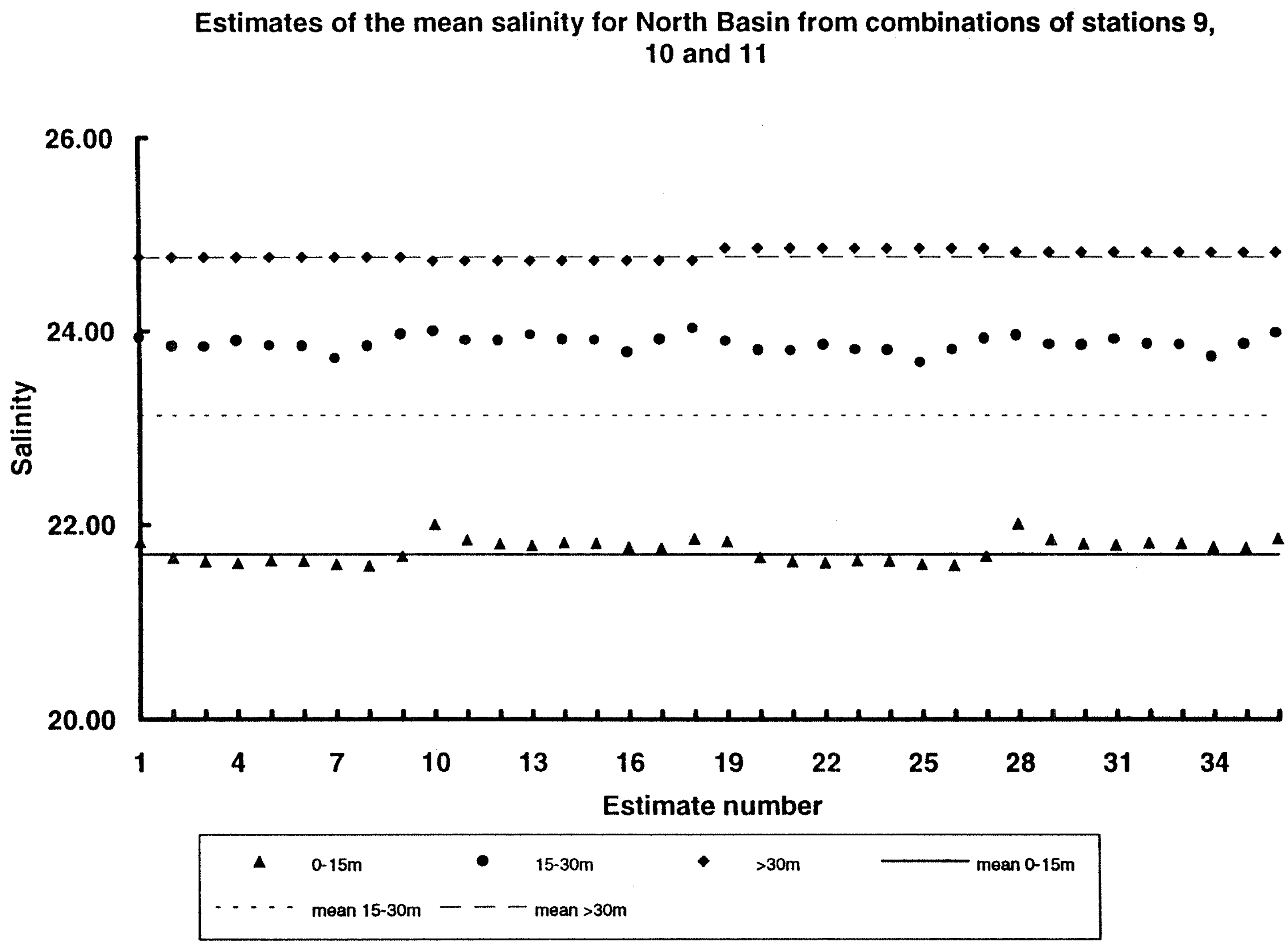


Figure 5(a)(ii)



Estimates of the mean salinity for North Basin from combinations of stations 9, 10 and 11
26.00
24.00
22.00
20.00
Salinity
1
4
7
10
13
16
19
22
25
28
31
34
Estimate number
0-15m
15-30m
>30m
mean 0-15m
mean 15-30m
mean >30m

Figure 5(b)(i)

Estimates of the mean salinity in North Basin treating each station as a separate estimate

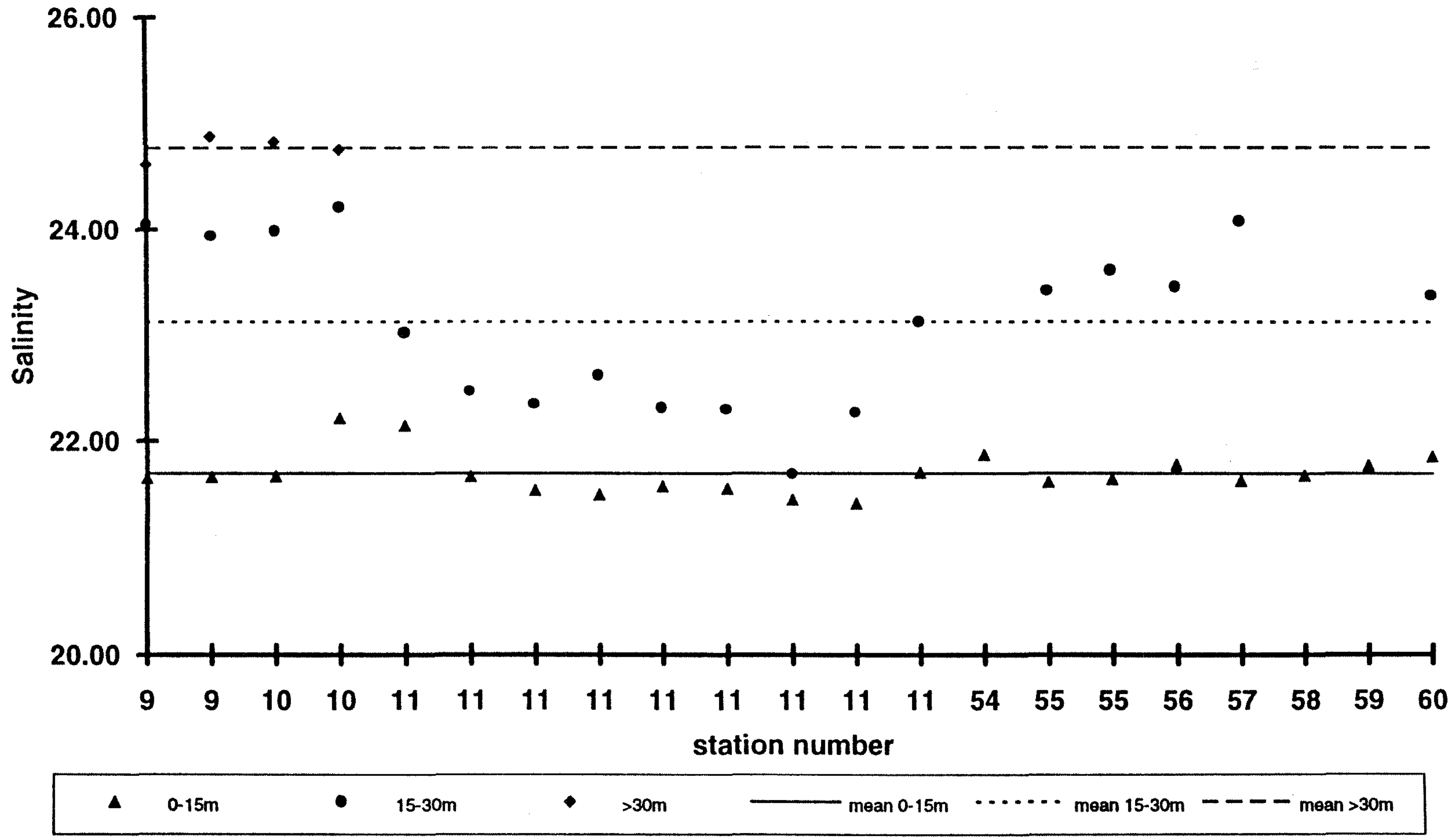


Figure 5(b)(ii)

2.3 Distributions

Figure 2 shows the sections from Sydney Bight into the Lakes for May 1974. The temperature generally increases from the Bight into the Lakes with the deep basins remaining less than 2°C. The salinities gradually decrease from between 30 and 31 in Sydney Bight to 20.3 in East Bay. Thermal stratification is stronger in St. Andrew's Channel with temperatures decreasing from about 7°C at the surface to 1°C at about 20 m. Temperature decreases to 0.1°C in the deeper parts of the Channel with salinities of 25-25.4. The strongest thermocline and halocline are found in St. Patrick's Channel and Whycocomagh Basin with surface temperatures and salinities of >8°C and 16, respectively, and near bottom values of <2°C and >23.

The temperature and salinity sections from Sydney Bight into the Lakes for June and July are shown in Figure 6. Near-surface temperatures in June warmed by about 6°C throughout the Lakes with the largest increases found in Whycocomagh Basin where surface temperatures in excess of 19°C were observed. There is evidence of an intrusion of higher salinity water into the Lakes. In the deeper Great Bras d'Or Channel and North Basin (Figure 6), salinity increased from 25-26 in May to as high as 28.5 in June. In addition, salinity generally increased by about 2 in St. Peter's Basin, East and West Bay, and by as much as 4 near bottom at station 12, near Barra Strait. The current meter data (to be discussed in Section 3) indicate that significant subsurface inflows occurred in the Great Bras d'Or Channel and at Barra Strait. Winds were generally weak before the June 1974 survey implying that this was not a conventional wind-driven flushing event (Klinck et al., 1980). At 20 m and greater in Whycocomagh Basin, temperature and salinity changed slightly, by 0.3°C and -0.2, respectively. There were no data from depths >50 m for June.

There was no evidence that the high salinity water persisted into July. Temperature had generally increased in the deeper basins although water slightly < 0°C was found at 90 m in the North Basin. In St. Peter's Basin and East and West Bays, while there was an overall decrease of salinity by 2 from June, the July observations represent a gradual warming and increase of salinity when compared to the May observations. The data from St. Andrew's Channel (>50 m) and Whycocomagh Basin (>20 m) indicate changes of about 0.1°C, -0.1 and -0.1°C, 0.1, respectively, in the deeper waters from May to July. These latter changes are less that the instrument accuracy.

Temperature-salinity plots (Figure 7) for May 1974 show a linear relationship through the Great Bras d'Or Channel indicating various degrees of mixing between seawater from Sydney Bight and fresh water input. In June in the Channel, there was a general warming but at station 4, 20-24m there was a remnant of water with May T-S characteristics. In July, general warming was again apparent but there was some cold water at station 4, which was sampled to 85m.

The May water temperatures in the North Basin were colder than those in the Great Bras d'Or Channel though the salinity range is smaller. The water with T=8°C, S=20 was common to both areas. Water at about 0°C was from station 10, beginning at 65m. The water had warmed and become more saline in June, a fact evident in the sections as well (Figures 2 and 6). No data

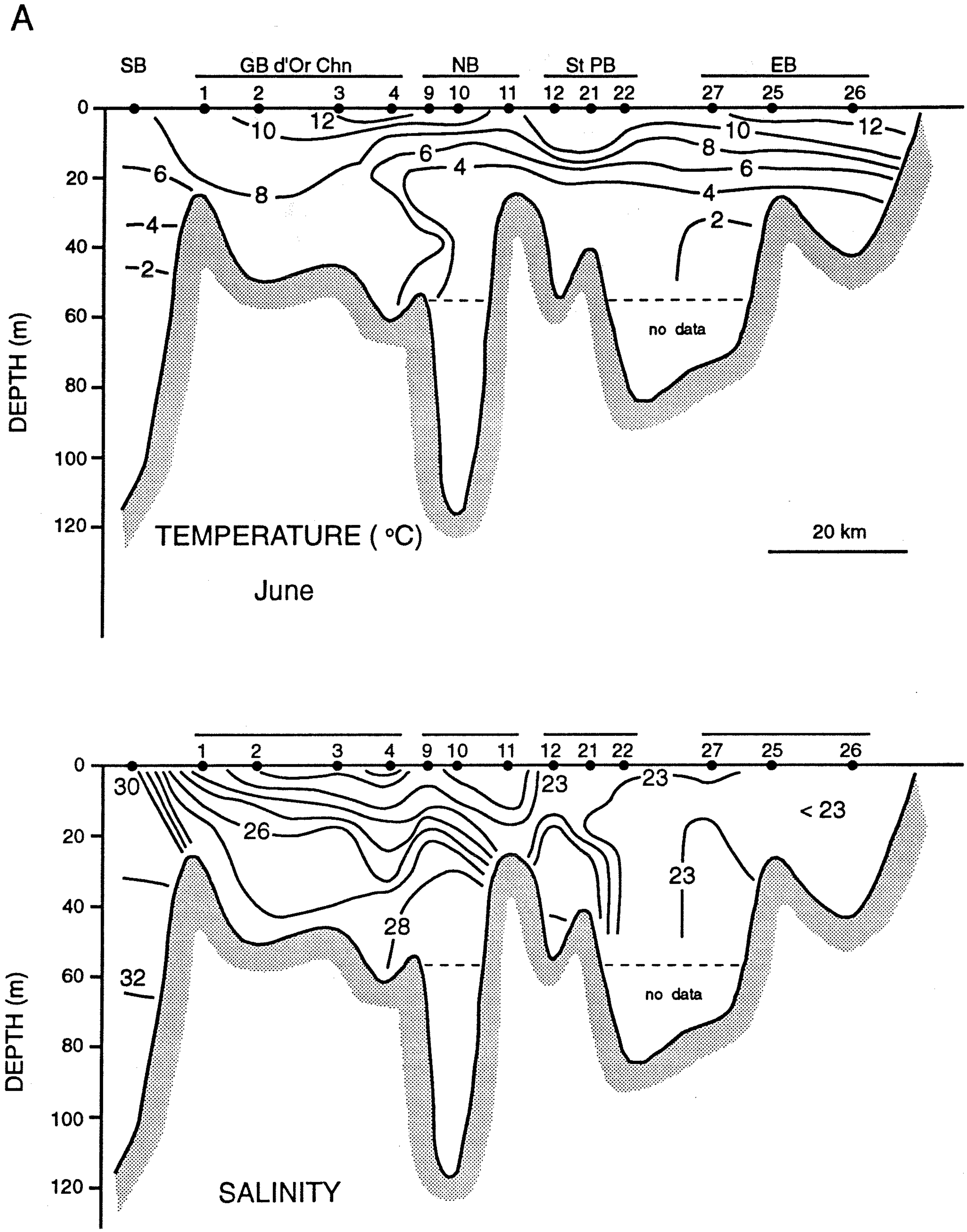


Figure 6. Temperature and salinity sections for June and July 1974 from Sydney Bight (SB), through the Great Bras d'Or Channel (GB d'Or Chn), North Basin (NB), St. Peter's Basin (St PB), East Bay (EB), West Bay (WB), St. Andrew's Channel (St A Chn), St. Patrick's Channel (St P Chn), and Whycocomagh Basin (WB). The profiles for Sydney Bight are the long-term means for June and July from Drinkwater and Trites (1987).

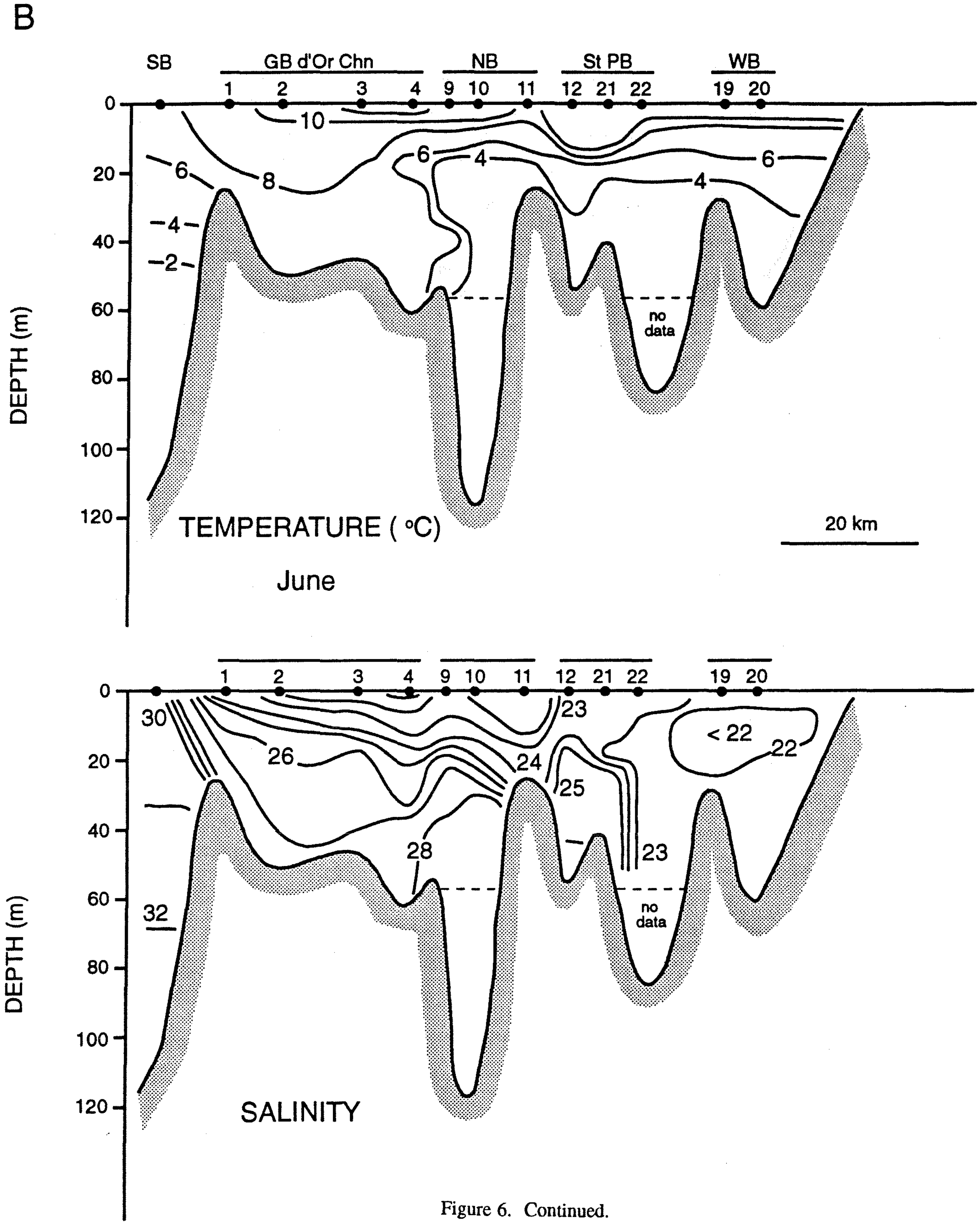
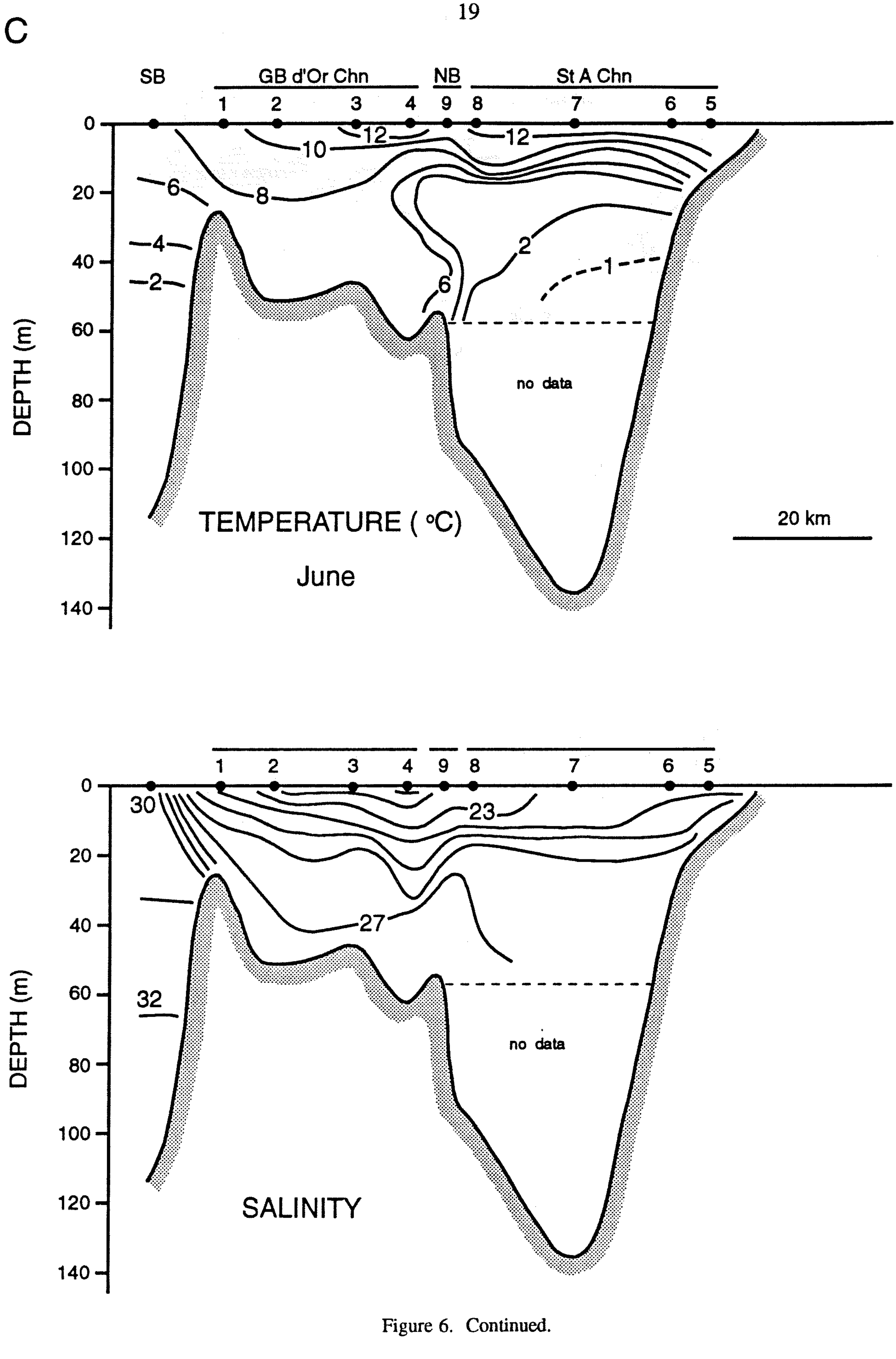


Figure 6. Continued.



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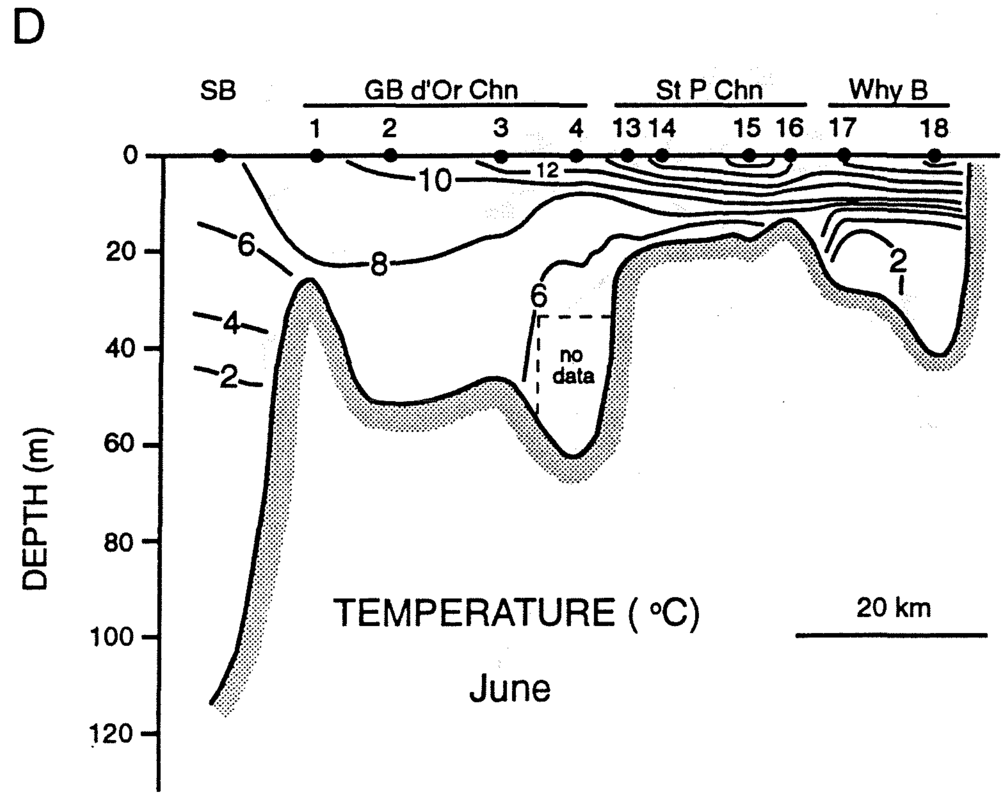

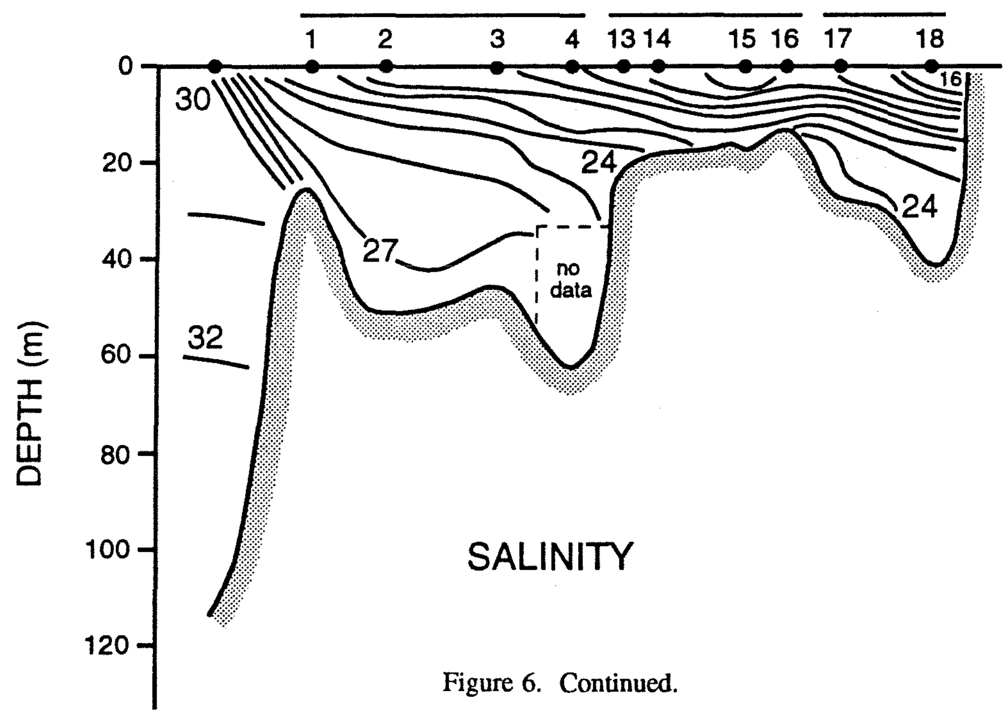

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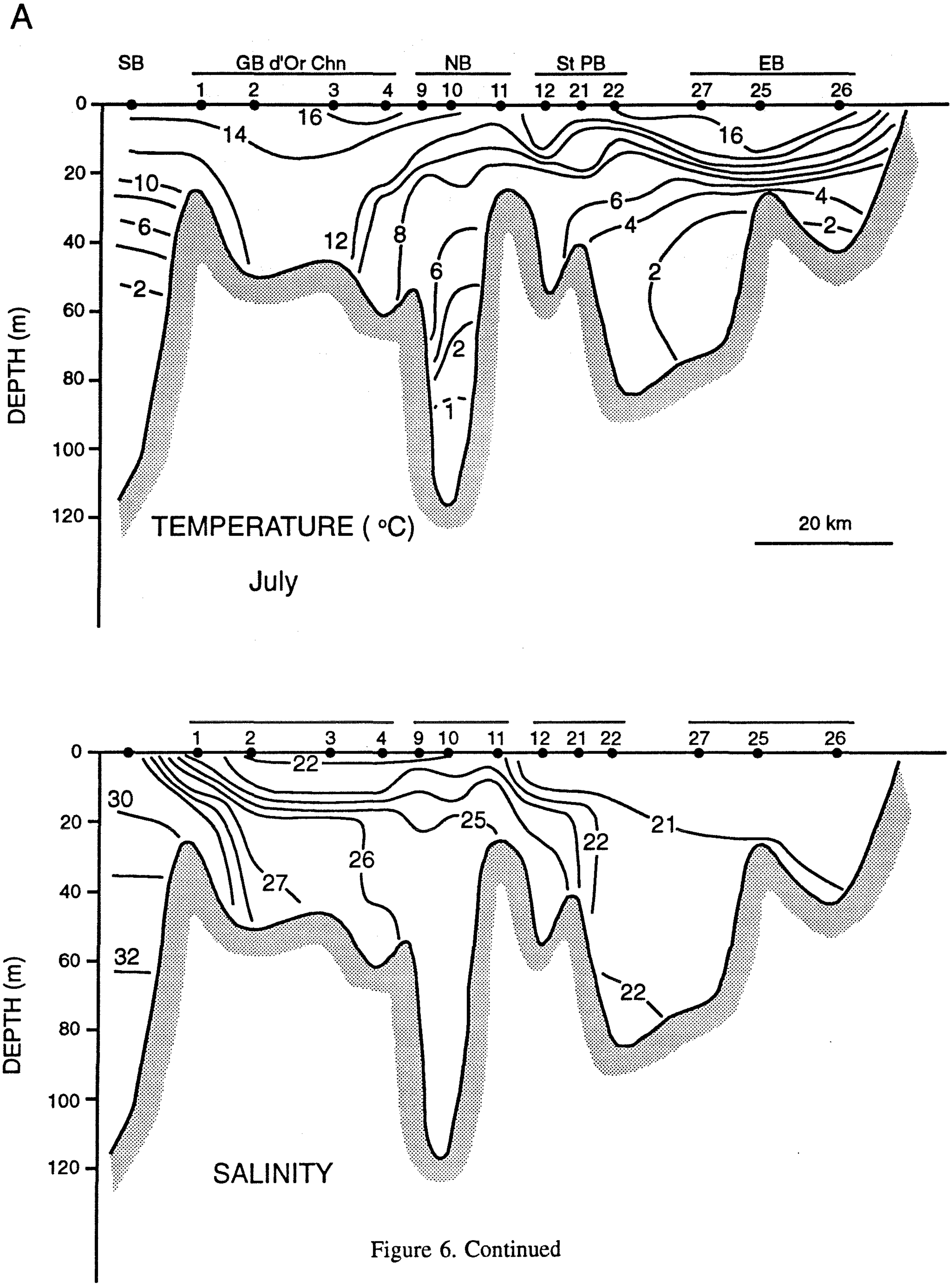

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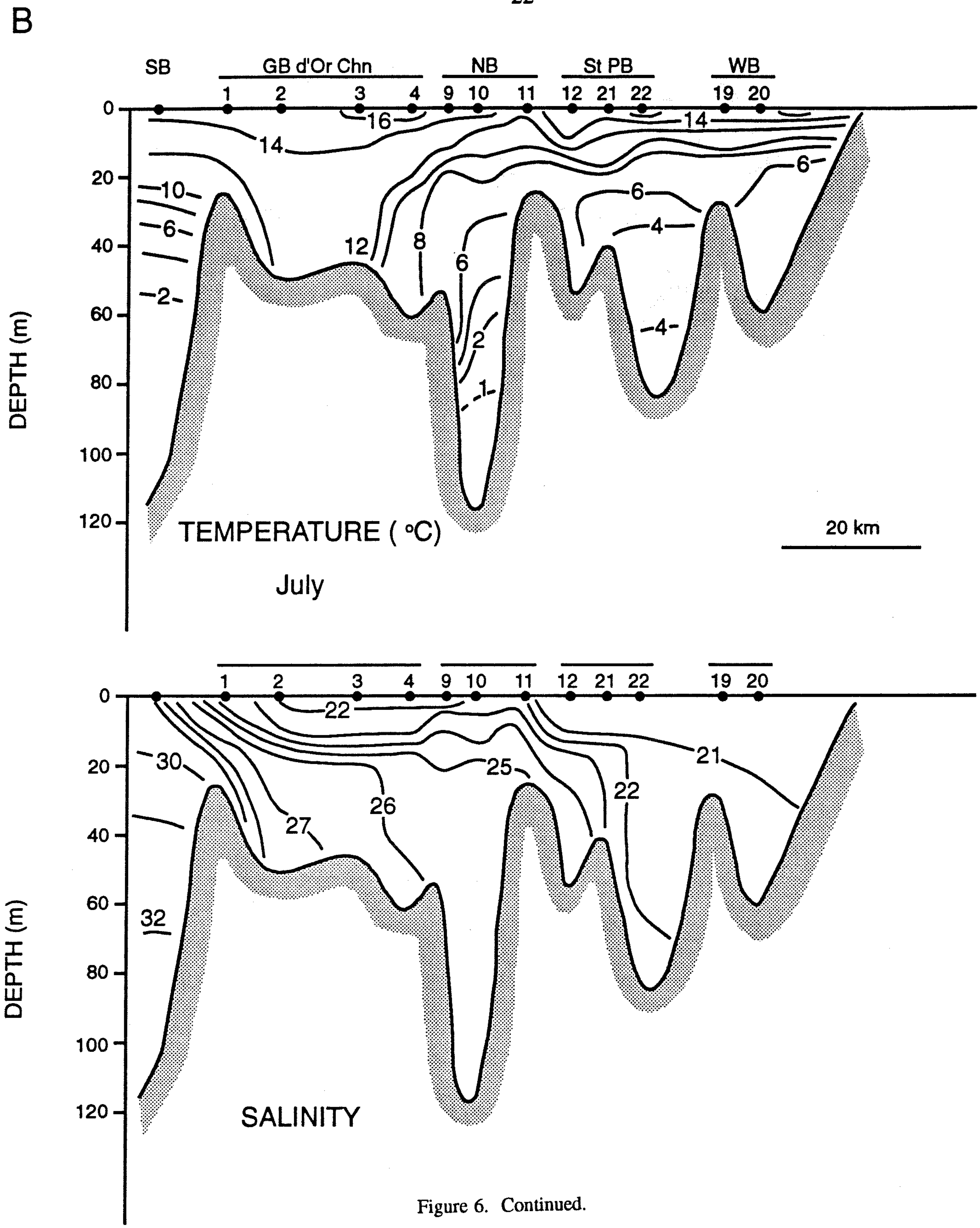

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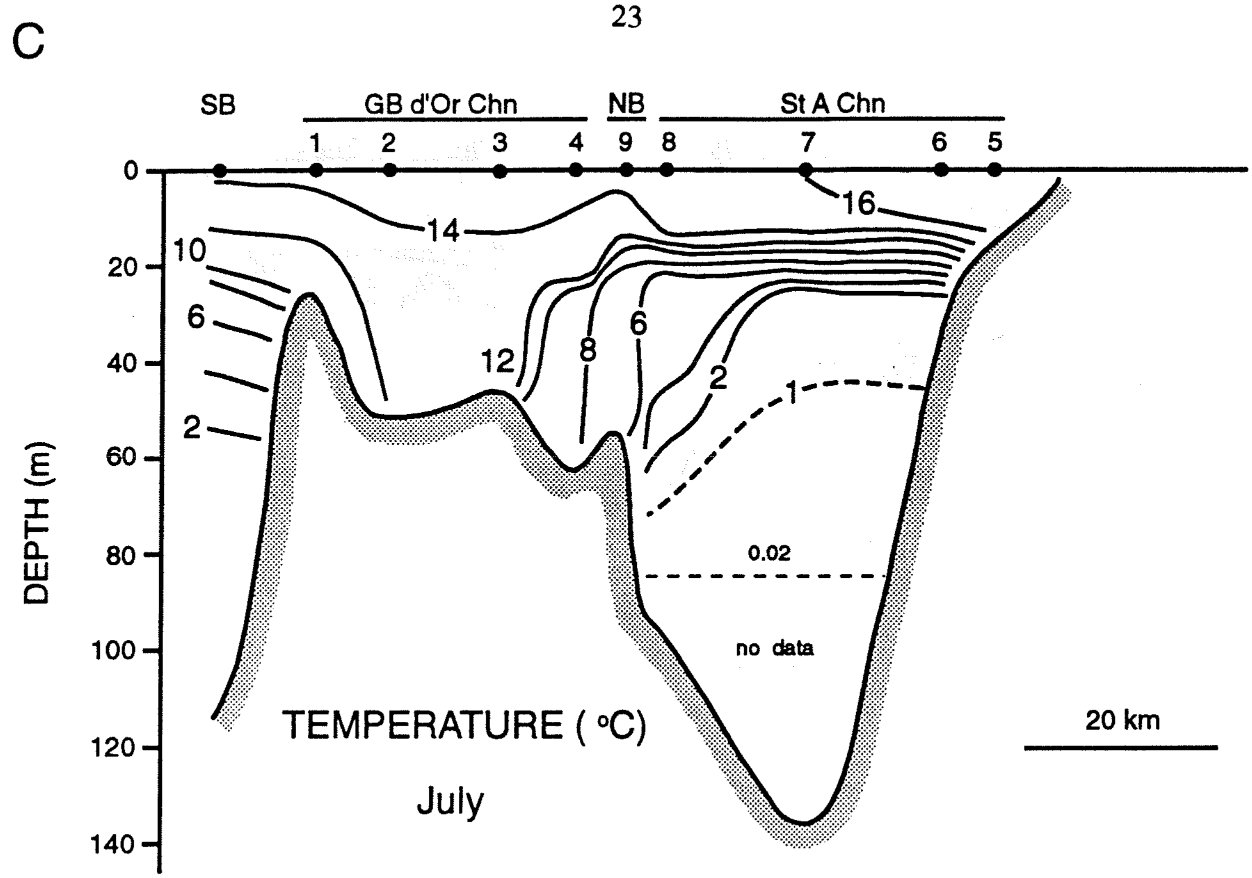

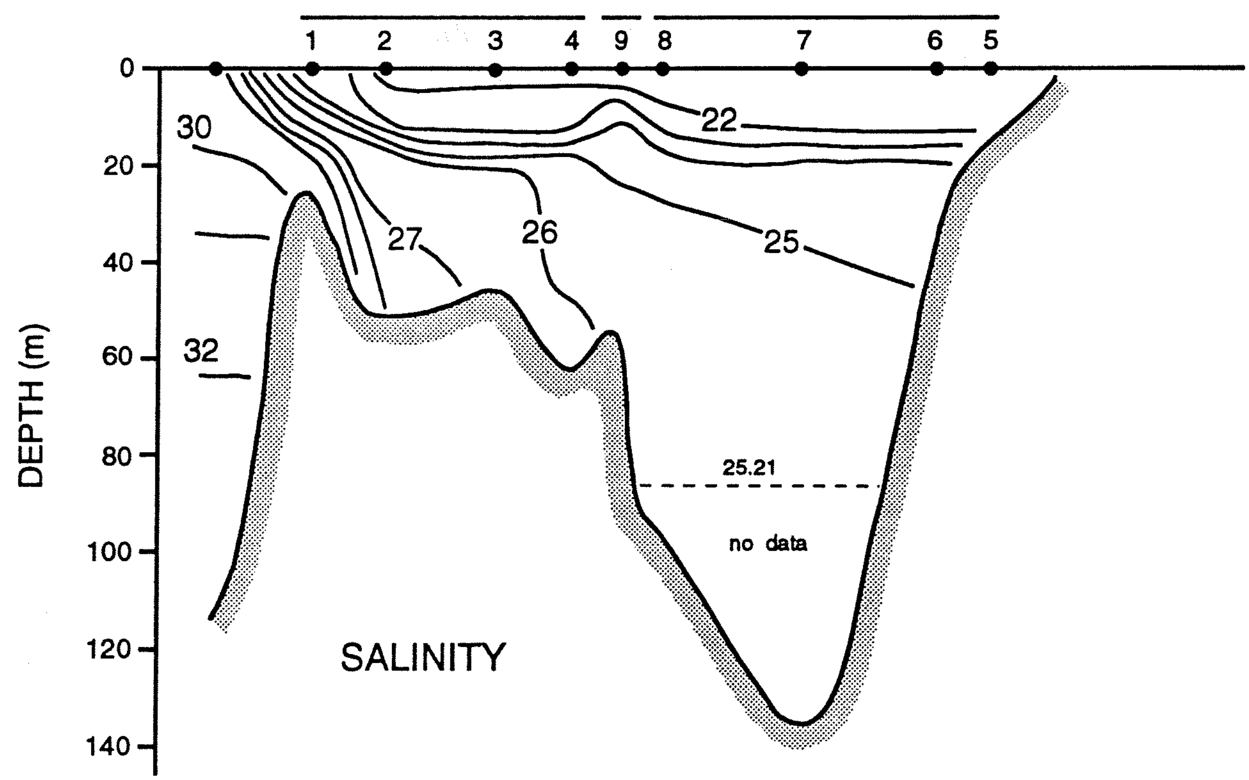

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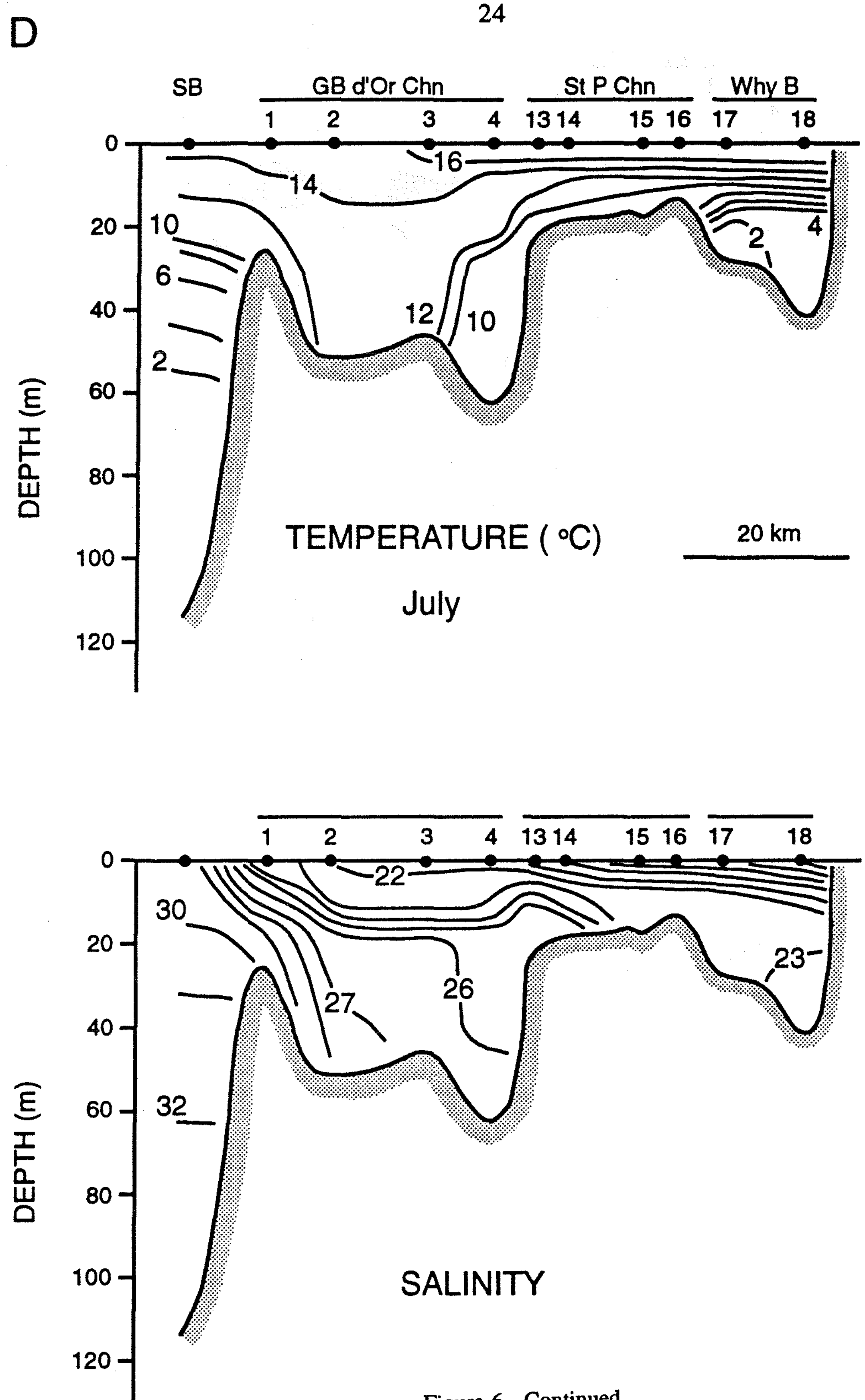


Figure 6. Continued.

were available from depths greater than 50m in June. In July, the higher salinity water was not found, however, 0°C water with a salinity of about 25.5, seen in May, was still present at station 10, 90m and deeper. This indicates a slow renewal rate for the deep waters of the North Basin.

The freshest waters in the Lakes were found at the western end of St. Patrick's Channel in the Whycocomagh Basin. The fresh water flow into this region is large, whereas, the water surface area is small and exchange is restricted by narrow channels. A considerable amount of scatter had developed in the T-S relationships from May to July. Some remnants of May water properties were found in July in the deeper sections of Whycocomagh Basin. In fact, the lowest temperatures occurred at station 17.

The temperature and salinity of the shallower waters of St. Andrew's Channel increased from May to July. In May the 0-1°C waters were found for depths ≥25m, while in July, they were found at depths ≥50m.

The T-S distribution of St. Peter's Basin waters had the most restricted salinity range. In May, two distinct water masses were present - one with salinity of about 21, the second with salinities of about 24. This second group arose solely from water at station 24 in St. Peter's Inlet. This station was at least 36m deep according to the bathymetric charts and was isolated from St. Peter's Basin by a 7m deep sill. This water was perhaps a remnant from the winter. Some of it, 5 of the 11 T-S points, was found at station 24 (at S=25) in June. The other T-S points in this group originated at station 12 (5 points) and station 21 (1 point), the closest stations to Barra Strait. Thus, they may represent water that entered from the North Basin. Station 24 was not sampled in July. The waters with salinities greater than 23 were again found at station 12 and 21, near Barra Strait.

In summary, the observations indicate that there was strong surface heating during the period of May to July 1974, with some indication of the influx of deep (25-50m), more saline water from the Sydney Bight. In the deeper isolated sections of the Lakes, there was only a limited exchange.

There are few data throughout the whole year. Station 11 near Barra Strait and station 16 near the Little Narrows have the best temporal coverage. Figure 8 shows the temperatures at station 11 for depths 1, 5, 10, 15 and 20m for the period from 1972 to 1974. During the autumn of 1972, the waters were vertically well mixed. There was a gradual decrease in temperature to below 0°C in February 1973. In the winter, the Lakes are covered by sea ice which melts in April and May. From May to July of 1973 and 1974, the waters were stratified and temperature rose rapidly. Similar variations occurred at station 16.

3. Current meter observations

There are two sets of current meter observations from the Bras d'Or Lakes from July 1973 and July 1974. The moorings were deployed both in narrow passages and in the centres of the basins

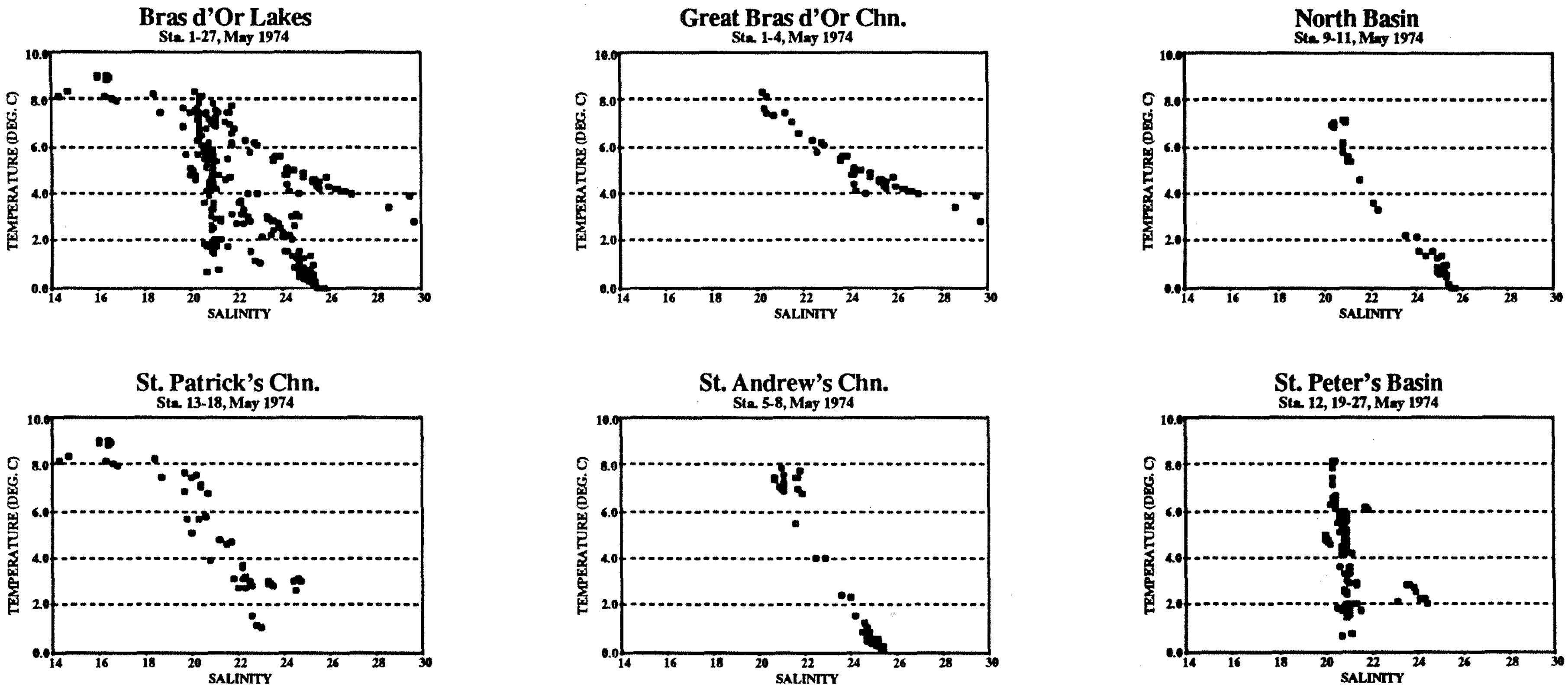


Figure 7. Temperature-salinity diagrams for May, June and July. In these figures, the Whycocomagh Basin stations have been included with the St. Patrick's Channel ones; similarly, the East and West Bay stations have been included with the St. Peter's Basin profiles. Note that stations 23 and 24, which are in the southern part of St. Peter's Basin, are included in these plots but were not part of the section plots (Figures 2 and 6).

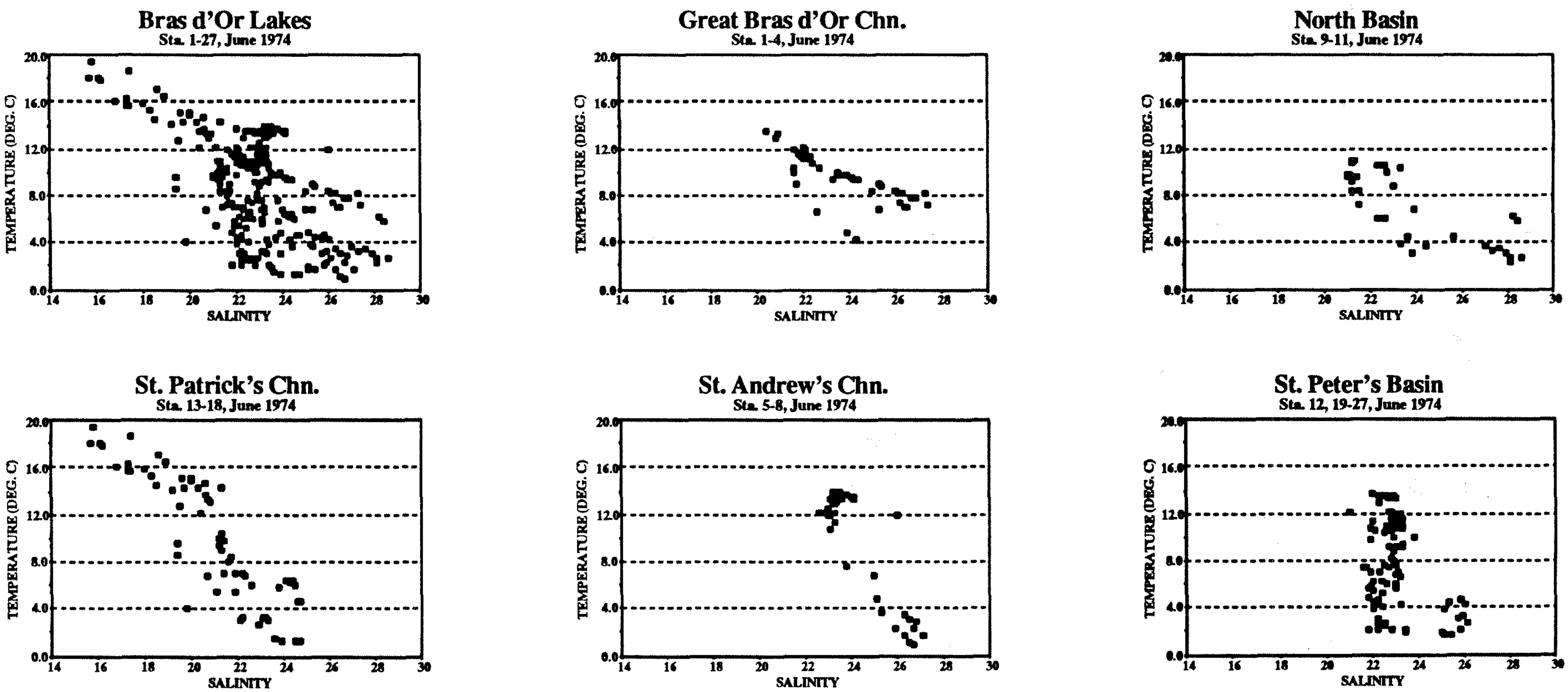
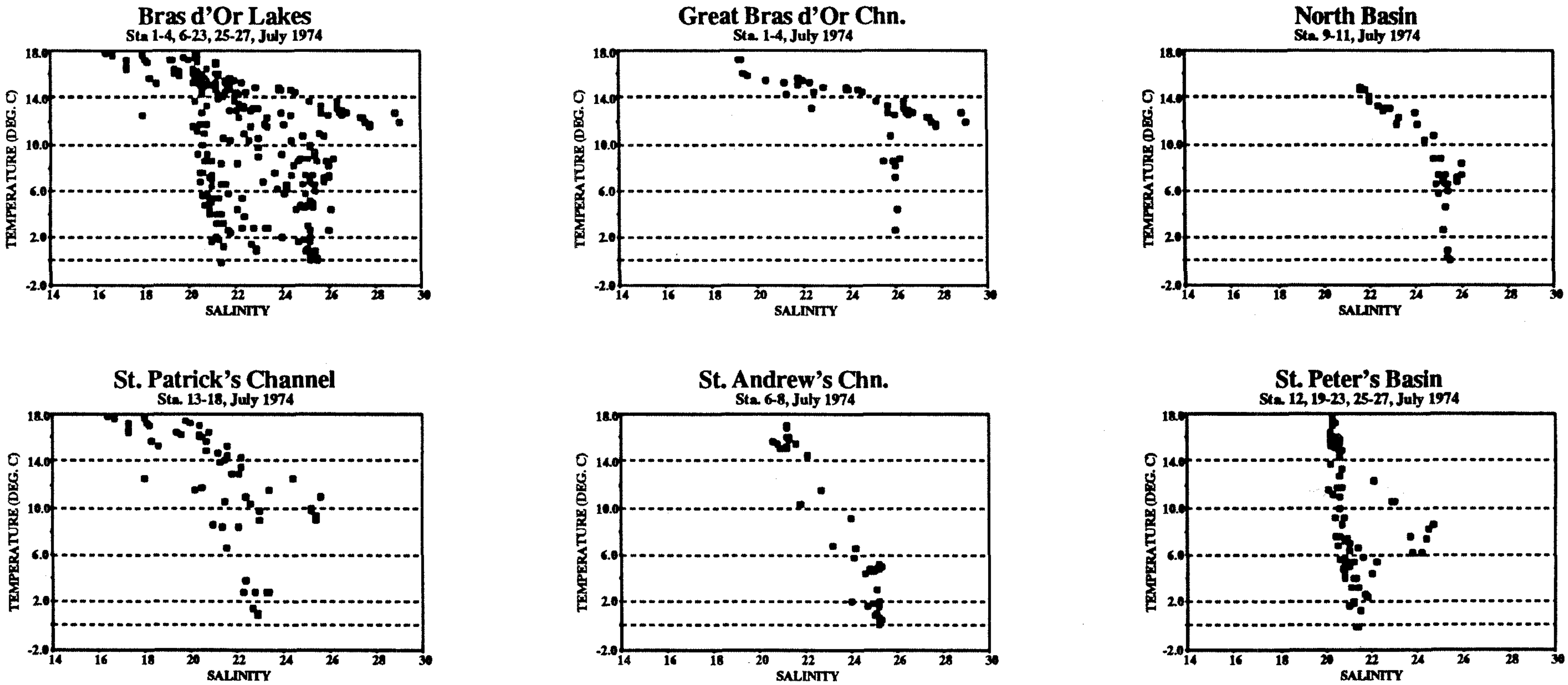


Figure 7. Continued.



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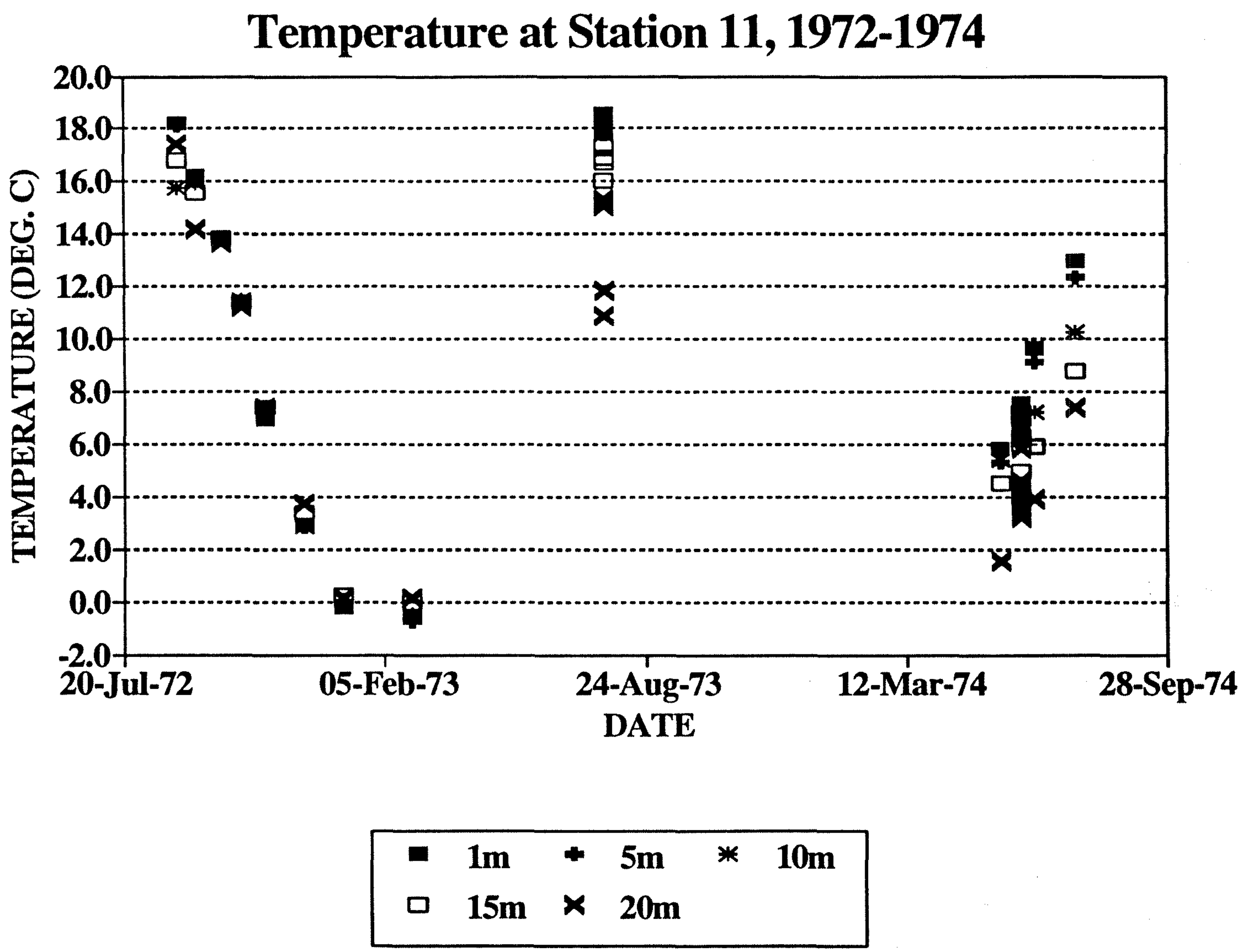

Figure 8. Annual variation in temperature at station 11 near the Barra Strait between 1972 and 1974.

(Figure 1). Either Braincon 381, or 316 instruments, both of which used a film recording system, or Plessey 21 current meters, which recorded on magnetic tape, were used in 1973. These have an accuracy of ±10° in direction and ±3 cm s^{-1} in speed (Krauel, 1975b). During 1974, Braincon 381 and Aanderaa RCM4 and RCM5s were used. The Aanderaa instruments have a much improved compass error of ±2° but the same speed error (Krauel, 1975b).

Not all instruments functioned correctly for the whole of each deployment. There was some fouling and some fishing damage. The records were edited to remove suspect data. The residuals are calculated by first taking hourly means and then applying a low pass Cartwright filter to remove the tides. Table 3 gives details of the moorings where useful data were collected.

Table 3
Current meter statistics from the Bras d'Or Lakes moorings
(B-Braincon; P-Plessey; A-Aanderaa)

Station	Meter	Start	Duration	Meter	Velocity	Velocity		
Number	Depth	Date	(days)	Type	u	v	Speed	Direction
	(m)				(cm/s)	(cm/s)	(cm/s)	
1	20	5/7/73	34.8	B381	-2.3	-1.8	2.9	232
1	10	5/7/73	34.8	B381	-0.8	1.8	2.0	336
1	43	5/7/73	34.8	B381	-5.7	-6.1	8.4	223
2	10	10/6/73	14	P	3.9	2.0	4.4	63
2	61	10/6/73	33	P	0.1	-0.1	0.1	225
2	122	10/6/73	33	P	0.1	0.1	0.1	45
2	183	10/6/73	32.9	P	0.4	0.1	0.4	76
2	20	11/7/73	30.5	B316	-0.1	-0.1	0.1	225
2	20	10/8/73	31	B316	-0.1	-0.1	0.1	225
2	123	10/7/73	31	B316	0.2	-0.3	0.4	214
2	10	10/7/73	31	B316	0.1	-1.4	1.4	184
3	20	4/7/73	35.5	B381	0.4	-0.2	0.5	243
3	100	4/7/73	35.7	B381	0	0	0	0
3	5	4/7/73	35.8	B381	-.8	2.6	2.7	343
4	5	4/7/73	40	B381	1.2	-1.7	2.1	215
4	13	4/7/73	40	B381	-.9	-2.0	2.2	204
5	22	10/7/73	30	B381	-17.5	-30.6	35.3	210
5	5	10/7/73	30	B381	9.6	18.2	20.6	28

6	5	5/7/73	38.5	B381	-6.5	-4.2	7.7	237
6	18	5/7/73	38.5	B381	-1.1	-0.4	1.2	250
6	38	5/7/73	38.5	B381	0.6	0.2	0.6	72
7	18	19/7/73	24.7	B381	0	0	0	0
7	38	19/7/73	24.7	B381	0.1	0	0.1	90
7	5	19/7/73	24.7	B381	0.3	0.1	0.3	72
8	18	7/7/73	36.8	B381	0.5	1.1	1.2	24
8	5	7/7/73	36.8	B381	-2.4	-0.2	2.4	265
9	5	5/7/73	36	B381	2.9	-2.3	3.7	232
9	18	5/7/73	38.7	B381	-1.3	-1.7	2.1	217
1	10	4/6/74	41.3	A	-13.5	-9.1	16.3	236
1	21	4/6/74	41.3	A	-7.1	-8.1	10.8	221
1	32	4/6/74	41	A	-9.2	-12.5	15.5	216
1	43	4/6/74	41.3	A	-0.4	-2.5	2.5	189
3	5	3/6/74	45.7	A	0.3	-0.6	0.7	207
4	4	4/6/74	42	A	1.4	0.9	1.7	57
4	12	4/6/74	41.9	A	-1.5	-3.6	3.9	203
5	5	4/6/74	44.7	A	9.2	16.1	18.5	30
5	10	4/6/74	44.7	A	2.9	-5.7	6.4	207
5	20	4/6/74	44.7	A	-22.5	-43.0	48.5	208
10	15	5/6/74	42.8	B381	0.9	-0.9	1.3	225
11	5	5/6/74	42.8	B381	-0.1	-2.0	2.0	183
12	5	3/6/74	41.9	A	1.9	-1.0	2.2	242
12	13	3/6/74	41.9	A	-6.7	-0.2	6.7	268

In the narrow passages (Great Bras d'Or Channel - station 1, Little Narrows - station 4 and Barra Strait - station 5) the mean flows were aligned close to the axis of the channel. Near-surface currents tended to move seaward, whereas, deeper currents flowed into the Lakes. The same is true for station 12 at the head of St Andrew's Channel.

We can use the data of Table 3 to estimate the transports through the passages. We take the current meter results to represent the flow half-way to the nearest current meter on the same mooring, or, if there is no current meter present, to the surface or bottom. The results for moorings 1, 4, 5 and 12 are given in Table 4.

Table 4
Estimates of transports in the passages of the Bras d'Or Lakes

Year	Mooring	Orientation of Local Bathymetry	Instrument Depth (m)	Transport in Direction of Local Bathymetry (m^3s^{-1})
1973	1	45	10	20
			20	-180
			43	-170
1974	1	45	10*	-420
			21	-690
			32	-240
			43	-80
1973	4	45	5	0
			13	-10
1974	4	45	4	35
			12	-22
1973	5	15	5	2420
			22	-2900
1974	5	15	5	1340
			10	-380
			20	-3450
1974	12	90	5	190
			13	-100

*represents 10 to 15.5m; note positive (negative) transport indicates flow out of (into) the Lakes.

At site 1 in the Great Bras d'Or Channel during July 1973, there was a weak, near-surface outflow which did not balance the stronger, deep inward transport of 350 m^3 s^{-1}. No outflow was evident in 1974. The total inflow of 1430 m^3 s^{-1} exceeded the 1973 value by a factor of 4.

Horizontal transports were weaker at site 4 near the mouth of Whycocomagh Basin with a net inflow of 10 m^3s^{-1} in 1973. In 1974, the near surface outflow of 35 m^3 s^{-1} was the same order as the deeper inflow of 22 m^3 s^{-1}.

The largest transports were found at Barra Strait (site 5) where in 1973 the outflow of 2420 m^3 s^{-1} was nearly matched by the deep inflow of 2900 m^3 s^{-1}. However, in 1974 the ingoing transport of 3830 m^3 s^{-1} exceeded the outgoing by almost 3 times.

At the eastern end of St Andrew's Channel, the current meter observations from site 12 indicate that there may be a significant outflow and exchange through the Little Bras d'Or Channel. The transports are of the order of 100 to 200 m^3 s^{-1}, about 8 to 14 times less than that through the Great Bras d'Or Channel. The latter is based on contemporaneous data from 1974. Although these exchanges may affect the temperature and salinity distributions in St. Andrew's Channel, there is little evidence of this from the temperature and salinity sections (Figures 2 and 6).

Between the May-June 1974 hydrographic surveys, there was a significant salinity increase in the North Basin and St. Andrew's Channel (Section 2c). If the 1430 m^3s^{-1} inflow estimated from the current meter data occurred during the 26 days between the surveys, then this would account for 30% of the total volume of water in the North Basin and St. Andrew's Channel. Thus, a considerable fraction of the water in these two areas could have been replaced and this inflow could account for the salinity increase. During the same period, salinity south of Barra Strait rose by about 2 (Figure 7). Taking the inflow as 3830 m^3s^{-1} for the 26 days between surveys and with a combined volume of $1.83x10^{10}m^3$ for St. Peter's Basin, East and West Bays, then 47% of the water could have been replaced. Again this is a very significant fraction of the total volume.

4. Inputs

4.1 Fresh water inputs

Flow records from gauged rivers were used to estimate the fresh water runoff into the Bras d'Or Lakes. For basins that were either partially gauged or not gauged at all, the fresh water input was estimated as the ratio of the ungauged drainage area to the drainage area of the nearest gauged river multiplied by the observed river flow. Thus fresh water inflow to all regions of the Lakes could be estimated. Results for the 5 year period 1970-1974, which includes the years of the hydrographic sampling, are shown in Figure 9 for the basins north and south of Barra Strait. The annual cycle is clearly visible. There is a sharp rise in the inputs in the autumn, fairly high inputs during the winter months, with a peak in March and April as the ice begins to melt and then a rapid decrease during June to August. St. Patrick's Channel receives a disproportionately large input for its surface area as it drains quite a large region. Interannual variability is especially evident when comparing the 1970 runoff with the other four years.

4.2 Heat inputs

In order to estimate the heat input into the Lakes during 1974, we have examined the heat budget for one region (Whycocomagh Basin) and compared the heat flux with those of other authors.

Table 3 reveals that the inflow into the Whycocomagh Basin in June 1974 at the deeper (12m) current meter is 3.9 cm s^{-1} and the outflow at 4m is 1.7 cm s^{-1}. Using the conservation of mass and a fresh water input into the Whycocomagh Basin for the period May to June 1974 of 26.9 m^3 s^{-1}, we estimate the inflow to be 12 m^3 s^{-1}, with the interface between the two flows at

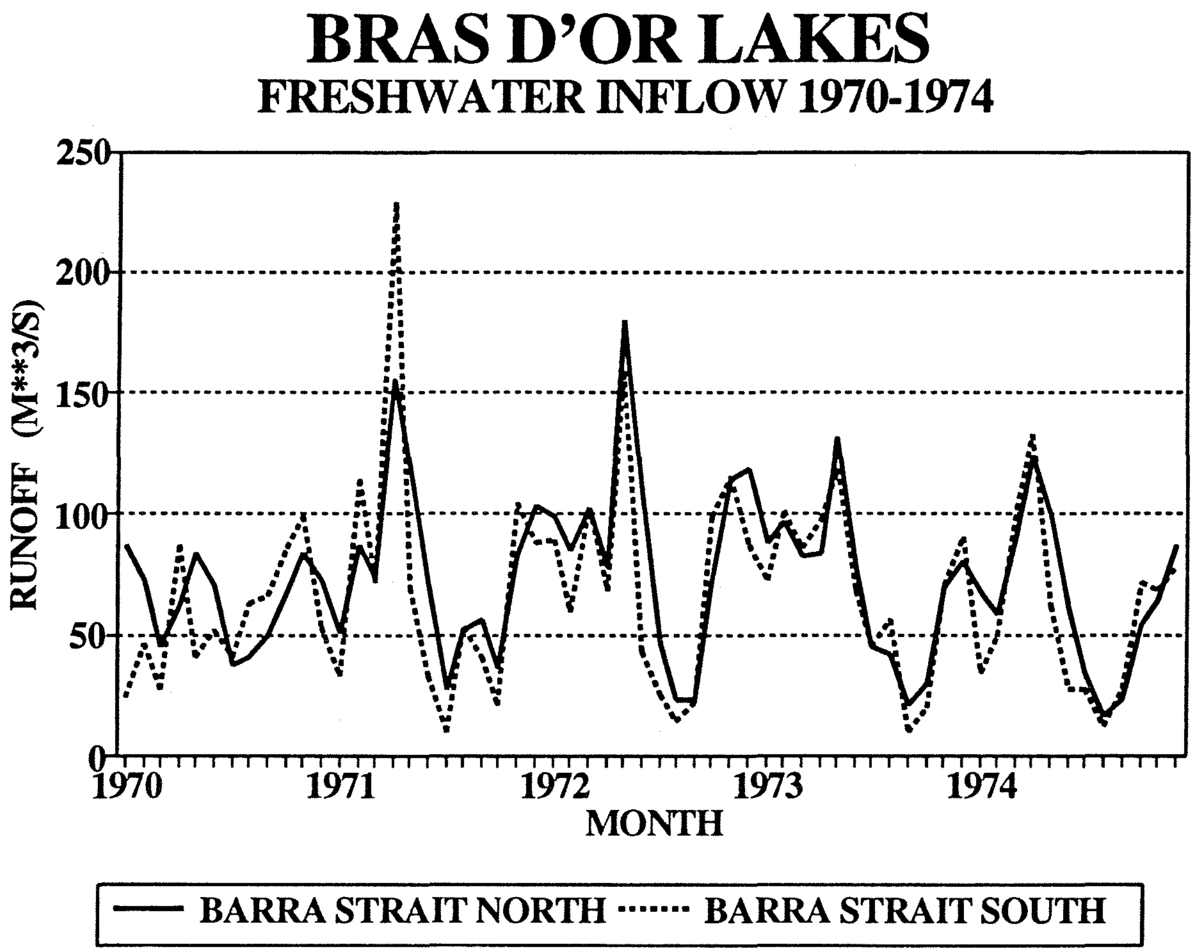

Figure 9. Estimates of the fresh water inputs (run-off and direct precipitation) into the Bras d'Or Lakes for the period 1970 to 1974.

approximately 10m. The conservation of heat, taking into account the net rise in mean temperature of the Whycocomagh Basin during this period of 4.4°C, implies that there must be a net heat flux into the surface of 130 W m^{-2}. This is approximately 70% of the long-term estimate by Bugden (1981) for the Magdalen Shallows in the southern Gulf of St Lawrence (the nearest part of his model to the Bras d'Or Lakes). This reduced heat influx for the Whycocomagh Basin is consistent with the daily air temperatures measured at Baddeck during 1974 (Figure 10). There is a clear rise in temperature between May and June but the observed mean temperature for May is 2.8°C less than the long-term mean and about 3.5°C less than the surface water temperature during the 23 May survey. The air temperature mean for June is only 0.1°C cooler, whereas, July is 2.2°C cooler than the long-term mean for the month. Surface water temperatures in Whycocomagh Basin ranged from 16.2 to 19.4 °C, 3 to 6°C above air temperature. The air-water temperature differences although only available for 2 days imply a reduced heat flux from the atmosphere to the ocean for this basin. However, surface temperatures for all other areas of the Lakes were lower than those in the Whycocomagh Basin implying greater heat fluxes from the atmosphere. In the modelling, we shall not attempt to account for interbasin differences of heat flux but shall use the long-term values of Bugden (1981) scaled by the daily air temperatures at Baddeck. Conservation of salt does not require any evaporative losses (within the limits of measurement error of the salinity). This is in agreement with estimates of evaporation for the area for May to July (Vowinckel and Orvig, 1977; Isemer and Hasse, 1985).

5. Mixing in the Lakes

The average flux over half a semi-diurnal tidal period through the Great Bras d'Or Channel to account for the 0.1m mean tidal range over the Lakes is approximately 4800 m^3 s^{-1}, about 3 times larger than the bottom steady inflow observed in 1974. Similarly, the tidal flux through the Barra Strait amounts to 3300 m^3 s^{-1}, comparable with the steady transports (Table 4). Given the magnitude of these fluxes and since the water advected into a basin during a flood tide may have different T-S properties than the water flowing out during the ebb, this process could contribute significantly to the horizontal mixing in the Lakes.

The vertical shear evident in the current meter data (Table 3) prompted us to examine the possibility of flow instabilities in the narrow passages. (This mechanism has been discussed by Bryden and Stommel (1984) for the Strait of Gibraltar. Their Froude number criterion is equivalent to a Richardson number, Ri, of 0.5 when the two layers are of equal thickness. For $Ri \leq 0.5$, instabilities should grow in the vertical plane, with subsequent collapse of the features and vertical mixing.) Hydrographic data are available during mooring periods for sites 1, 4 and 5 in 1973 and for 1, 5 and 12 in 1974. Values of Ri were calculated for all sites but approached 0.5 only for mooring 5 in Barra Strait. In 1973, four hydrographic stations taken at site 5, when combined with the current shear, give values of Ri from 1.2 to 4.0. In 1974, there were 3 occasions when water sampling occurred during the mooring period. Currents were available for 3 depths, 5, 10 and 20m. Between 5 and 10m, Ri varied from 0.2 to 6, while between 10 and 20m the values were 0.1, 5.4 and 800, the latter occurring when there was little vertical shear. There is an indication from the current meter data that the 10m instrument oscillated from being

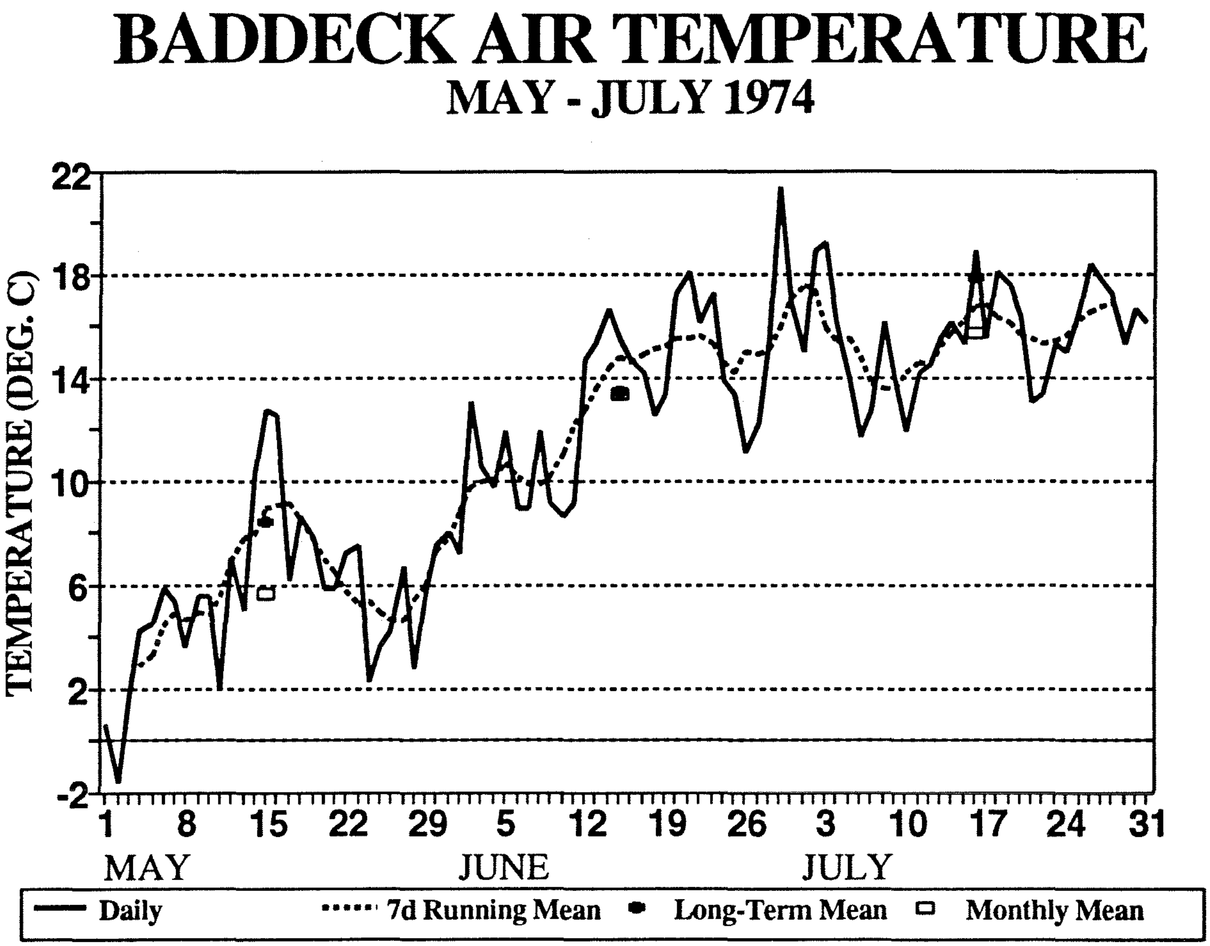

Figure 10. Observed daily air temperatures at Baddeck for May to July 1974. The dashed line is a 7 day running mean, the + symbol indicates the long-term monthly mean and the open square is the actual monthly means for 1974. (Courtesy of Environment Canada).

in the upper layer to being in the lower layer. Nevertheless, the results suggest that there is a potential for mixing between the two layers in Barra Strait due to flow instability.

6. Description of model

6.1 Model structure

The current measurements for July 1973 and July 1974 both indicate that there is flow into the Lakes from the Sydney Bight in the lower layers and outflow at the surface. This pattern is repeated through both the Barra Strait and the Little Narrows. This suggests that a budget (compartment or box) model of the Bras d'Or Lakes should have at least two levels with inflow from Sydney Bight in the lower level and outflow in the upper one.

An examination of the temperature and salinity data (Figures 2 and 6) reveals that there is a relatively well-mixed surface layer extending to approximately 10 to 15m, a region of a sharp thermocline and halocline and then a region of slowly varying properties below that. Thus we chose a two layer model with the interface somewhere in the region of the pycnocline. The thickness of the upper layer was generally taken to be 10m except where there was a significant horizontal gradient in a property across a region when it was set at 15m (e.g., the Great Bras d'Or Channel - see Figure 2). However, the North Basin between Barra Strait and Kempt Head reaches over 100m. It is separated by depths of less than 50m from St Andrew's Channel which reaches depths of over 250m. In these two basins we added a third layer to account for the deeper waters, with the bottom layer in each only connected to the layer above. A similar situation arises in the Whycocomagh Basin most of which is less than 15m deep. There are two deeper sections that have different properties. As a consequence, it was decided to divide the small Whycocomagh Basin into two regions (east and west) with a surface layer of depth 10m connected horizontally and separate lower levels only connected with the layer above in that region. The Whycocomagh east basin then connects through the Little Narrows to St. Patrick's Channel in the upper layer only.

Thus, the Bras d'Or Lakes have been divided into nine regions (Figure 1): Whycocomagh west basin (region 1); the Whycocomagh east basin (region 2); the West Bay (region 3); the East Bay (region 4); St. Andrew's Channel (region 5); St. Patrick's Channel (region 6); St. Peter's Basin (region 7); the North Basin (from Barra Strait to Kempt Head - region 8) and the Great Bras d'Or Channel (region 9). The box thicknesses are given in Table 5, as are the box volumes and surface areas.

So far we have described the gross features of the horizontal advective flow and the box configurations. For continuity, there must be upwelling, in either all or some regions. Also, as we saw above, we expect there to be horizontal and vertical mixing, especially in the narrow passages. Mixing can be represented as an equal and opposite exchange between adjacent boxes of the model. For example, if we assume that the mixing flux is proportional to the concentration gradient, then a vertical mixing rate of 10^{-4} m^2 s^{-1} across an interface area of $5x10^7$

m^2 gives an exchange of 250 m^3 s^{-1} when the gradients are evaluated over the typical box thickness of 20 m.

Table 5

Box depth ranges, volumes and surface areas by region (see Figure 1 and Table 2). Note Whycocomagh Basin west (Region 1), Whycocomagh Basin east (2), West Bay (3), East Bay (4), St. Andrew's Channel (5), St. Patrick's Channel (6), St. Peter's Basin (7), North Basin (8), Great Bras d'Or Channel (9).

Layer Depth Range (m)

Region	1	2	3	4	5	6	7	8	9
Level									
1	0-10	0-10	0-10	0-10	0-10	0-10	0-10	0-15	0-15
2	10-Btm	10-Btm	10-Btm	10-Btm	10-50	10-Btm	10-Btm	15-30	15-Btm
3					50-Btm			30-Btm	

Volumes ($10^6 m^3$)

Region	1	2	3	4	5	6	7	8	9
Level									
1	74.5	149.6	1287.3	887.3	1219.0	497.2	3931.4	1175.7	527.1
2	57.6	122.8	1934.4	1024.8	3001.6	175.7	9257.2	719.4	419.0
3					4313.2			1176.0	

Areas ($10^6 m^2$)

Region	1	2	3	4	5	6	7	8	9
Area	15.9	15.9	145.3	106.7	130.4	66.3	449.1	94.2	48.5

The structure of the model is summarised in Figure 11 by representing the exchanges, whose derivation will be presented shortly, as arrows whose magnitudes are related to the flow. All the exchanges are two-way except those between the Bras d'Or Channel and the Sydney Bight. Originally, this was done to insulate the model from possible incompatibility between the monthly means used to represent conditions in the Lakes and the long-term averages used for the Sydney Bight. However, the results presented in this section were calculated using the data from station 1 at the mouth of the Great Bras d'Or Channel instead of the long-term means. The flow is essentially in at the lower level into Great Bras d'Or Channel and then it splits into St. Patrick's Channel, St. Andrew's Channel and St. Peter's Basin through the North Basin. It then upwells in these regions, as well as any extensions of these basins before it returns in the surface layer to the Great Bras d'Or Channel and Sydney Bight.

In each of these regions, except Whycocomagh, there are at least 2 temperature and salinity stations occupied in each of the 3 synoptic surveys in the summer of 1974 so that estimates can be made of mean properties in each of the basins. As many of the temperature and salinity

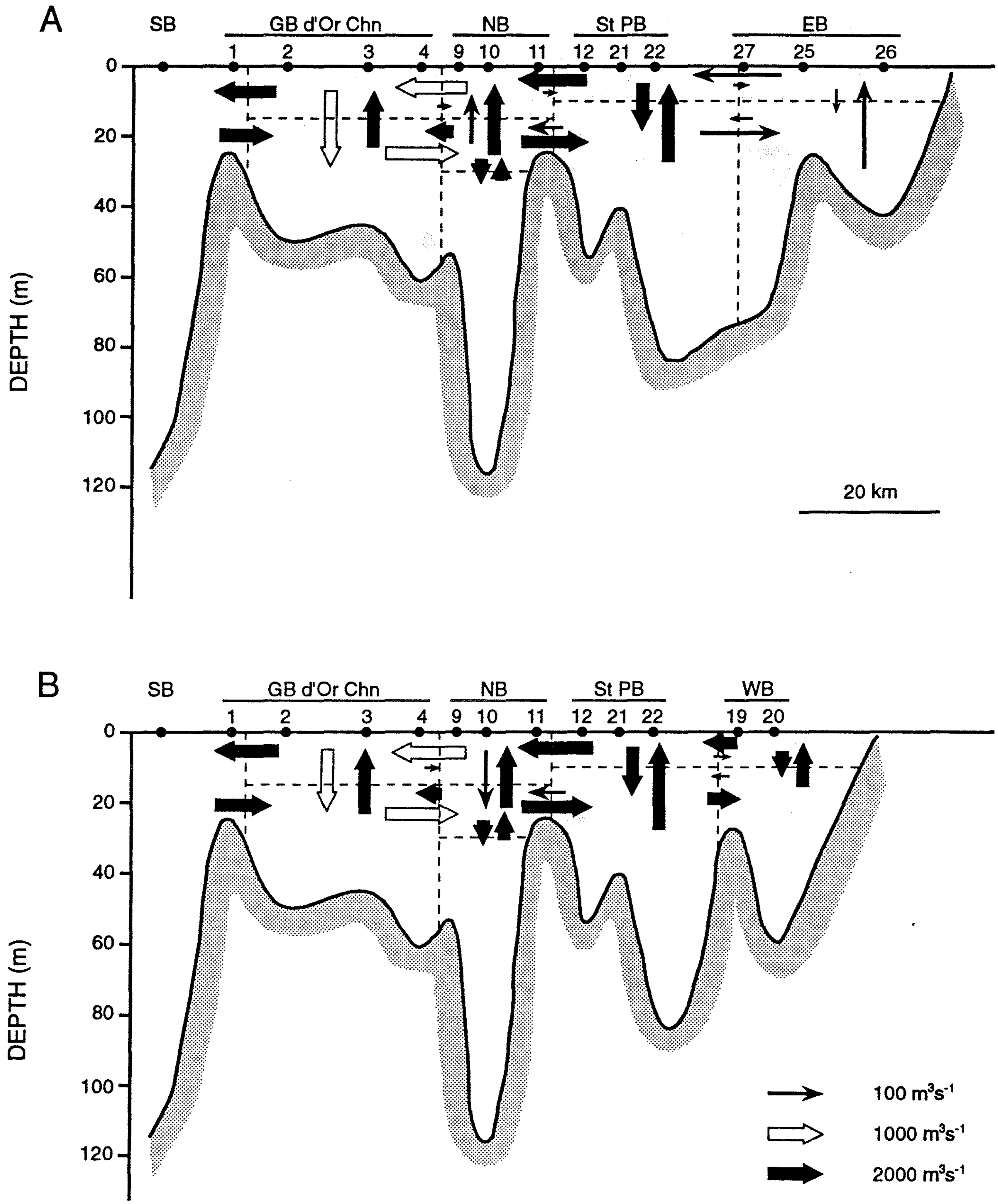

Figure 11. The box structure for the model overlaid on the topographic sections from Figure 2. The advection and mixing are shown as arrows representing the strength of the exchanges between the boxes. Some shallow regions between stations are not drawn. In panel D, the North Basin exchanges have been omitted to show the St. Patrick's Channel results more clearly.

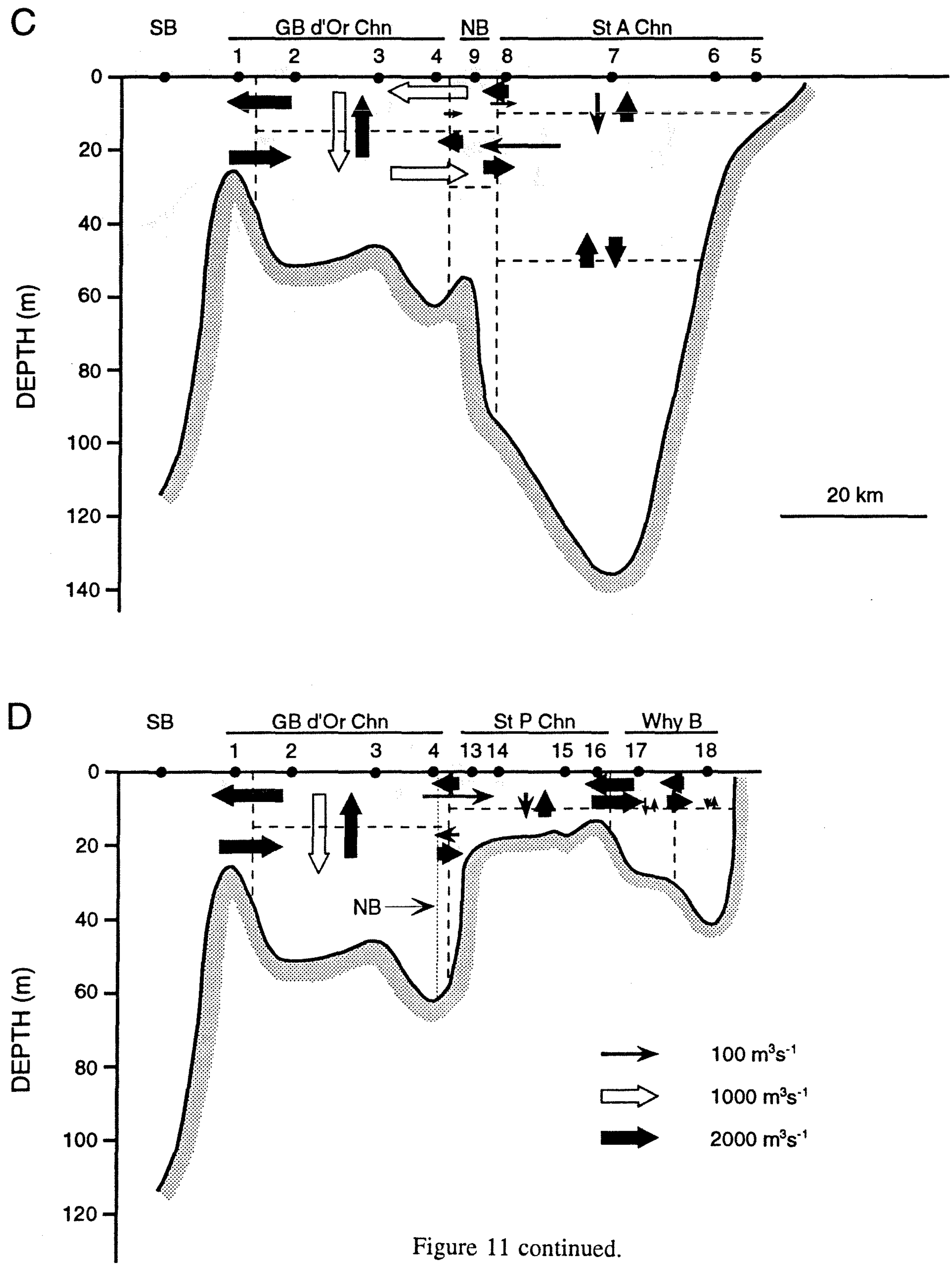

Figure 11 continued.

stations occupied in June 1974 were only relatively shallow, where there are no data then values have been interpolated between May and July, especially in the deeper layers. Table 6 shows the mean properties for these boxes in May, June and July 1974 from the 3 synoptic surveys.

Table 6

Mean temperatures and salinities in the boxes of the model for May, June and July, 1974. Where no deep data existed for June, values have been interpolated from the May and July observations. Note Whycocomagh Basin west (Region 1), Whycocomagh Basin east (2), West Bay (3), East Bay (4), St. Andrew's Channel (5), St. Patrick's Channel (6), St. Peter's Basin (7), North Basin (8), Great Bras d'Or Channel (9).

May 1974

	Temperature			Salinity		
Level	1	2	3	1	2	3
Region						
1	6.6	2.9		18.5	22.7	
2	5.6	1.5		19.5	22.6	
3	5.6	3.3		20.9	21.0	
4	6.0	4.1		20.6	20.6	
5	6.4	1.1	0.3	21.5	24.6	25.2
6	5.8	3.3		20.3	23.6	
7	5.4	2.9		20.9	21.9	
8	6.2	3.0	2.1	21.1	23.6	24.9
9	5.0	4.3		24.8	26.2	

June 1974

	Temperature			Salinity		
Level	1	2	3	1	2	3
Region						
1	12.5	3.3		18.3	22.6	
2	11.7	2.0		19.1	23.4	
3	9.6	5.0		22.6	22.0	
4	12.1	6.0		22.8	22.8	
5	12.6	3.0	0.7	23.4	26.0	25.2
6	12.5	6.2		20.2	23.7	

7	9.8	4.6		23.1	23.9	
8	8.5	3.9	3.7	22.2	25.1	28.0
9	10.2	7.9		23.3	26.1	

July 1974

	Temperature			Salinity		
Level	1	2	3	1	2	3
Region						
1	11.1	3.2		19.8	22.8	
2	13.4	3.1		19.5	22.6	
3	14.0	6.7		20.4	20.8	
4	16.7	6.3		20.4	20.9	
5	15.6	5.4	1.1	21.2	24.4	25.2
6	14.7	10.6		21.1	24.8	
7	14.6	6.8		20.5	22.0	
8	13.9	9.7	6.4	22.0	25.0	25.6
9	15.1	13.2		22.5	26.2	

6.2 The equations

In constructing our box model we assume: no strong gradients in the temperature, salinity and other properties within a region; anything entering a box is rapidly mixed throughout the box in a time short compared with the flushing time of the box; and, properties are conserved. In fact, examination of Figures 2 and 6 shows that there are strong property gradients within regions. However, despite our concerns with data accuracy and the existence of strong gradients, we have built this model in order to determine if a useful, general picture of the circulation in the Lakes can be derived from the data. Evaluation of the model will rest on whether reasonable predictions of water properties can be made for times of the year not used in the determination of transports, comparison with transports estimated from the current meter data, and comparison with dissolved oxygen distributions in the isolated, deeper basins.

The equations for the conservation of mass, heat and salt are set up to determine the transfers between the boxes. The conservation of mass can be re-written as the conservation of volume if one neglects the variations in density (about 0.5%) throughout the basins. However, the heat and salt budgets need a little more care.

The mean temperature of the Lakes rose from 3.3°C in May 1974 to 5.5°C in June and 7.6°C in July and thus the time derivative of temperature cannot be neglected in the conservation of heat equations. If only the atmospheric heat fluxes determined the temperature, then we would expect the rise in temperature, dT, to be

$$dT = Q*A*dt/(\rho*c_p*V)$$

where $Q=200\ W\ m^{-2}$ is the heat input, $A=1.07x10^9\ m^2$ is the surface area of the Lakes, $dt=30x86400$ s is the time interval, $\rho=1020kg\ m^{-3}$ is the water density, $c_p=4200\ J\ kg^{-1}\ °C^{-1}$ is the specific heat, and $V=3.2x10^{10}\ m^3$ is the volume of the Lakes. This gives expected changes of temperature of about 4°C for both May to June and June to July since for both these months the heat fluxes are nearly equal (Bugden, 1981). Thus, the expected change of 8°C exceeds the observed change of 4.3°C by a factor of 2 and implies that there must be a significant heat flux in the form of colder water from the Sydney Bight as well as redistribution within the Lakes.

The position is less clear for the conservation of salt. Mean salinity changed from 19.2 to 20.5 and down to 19.6 over the same period, but this may be attributed to measurement inaccuracies or to an 'event' (Sections 2c and 3 above).

Figure 12 is a schematic diagram of the exchanges for a three level region. x_1 and x_2 are the vertical exchanges between levels 1 and 2 and x_7 and x_8 are those between levels 2 and 3. x_3 and x_4 are horizontal exchanges between level 1 and level 1 in the seaward region and similarly, x_5 and x_6 are those for level 2. It should be noted that x_3, x_4, x_5 and x_6 from connecting regions further from the sea must be added in to the equations for the correct balances to be maintained. These are indicated in Figure 12 by the primed values on the left hand side of the diagram.

Using the exchanges labelled as in Figure 12 with superscripts to indicate the region, the equations are given below. T^i_j is the value of the mean temperature in region i at level j (and similarly for S). The first three equations are for the conservation of volume (mass). As was pointed out above, the net evaporative losses for the period May to July are negligible so the only input or loss of mass is that from fresh water, f_i, entering either from the rivers or directly as rain. The summation over k is meant to indicate all the inputs from more landward regions and the subscript j is meant to indicate the seaward region. The second three equations are for the heat balance. The term Φ_i is the total heat flux term including not only the solar heating but also the effects of ice melting, etc. (Bugden, 1981). The equations for the salt budget are similar to those for heat, except there is no equivalent of the total heat flux term because evaporation is negligible for this period. The time derivative terms were estimated by differencing the values in different months.

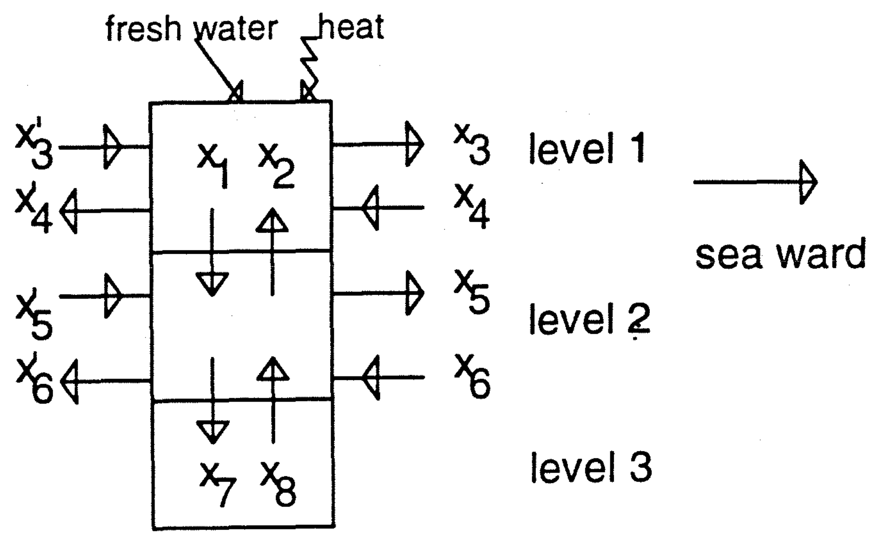

Figure 12. A schematic diagram of the exchanges for a three-level region. The same labelling system for two level regions applies with the appropriate exchanges removed. Primed values on the left of the diagram indicate exchanges from more landward regions.

$$f^i+\sum_k (x_3^k-x_4^k) - x_1^i + x_2^i - x_3^i + x_4^i = 0$$

$$\sum_k (x_5^k-x_6^k) + x_1^i - x_2^i - x_5^i + x_6^i - x_7^i + x_8^i = 0$$

$$x_7^i - x_8^i - 0$$

$$\Phi^i+\sum_k (x_3^k \cdot T_1^k - x_4^k \cdot T_1^i) - x_1^i \cdot T_1^i + x_2^i \cdot T_2^i - x_3^i \cdot T_1^i + x_4^i \cdot T_1^j = V_1^i \frac{dT_1^i}{dt}$$

$$\sum_k (x_5^k \cdot T_2^k - x_6^k \cdot T_2^i) + x_1^i \cdot T_1^i - x_2^i \cdot T_2^i - x_5^i \cdot T_2^i + x_6^i \cdot T_2^j - x_7^i \cdot T_2^i + x_8^i \cdot T_3^i = V_2^i \frac{dT_2^i}{dt}$$

$$x_7^i \cdot T_2^i - x_8^i \cdot T_3^i = V_3^i \frac{dT_3^i}{dt}$$

and similarly for S^i_j.

This is an over-determined system of equations for the non-negative exchanges (x_1 to x_8). The regions have been ordered so that an over-determined sub-system of equations for each region can be used sequentially to calculate the exchanges with a personal computer package (MATHCAD, 1987). This uses the Levenberg-Marquardt algorithm (Lawson and Hanson, 1974) which minimises the squared residuals of the equations. Using MATHCAD gave some insight into the inconsistencies between the equations that may not have been so evident if the system had been solved as a complete set using the same algorithm from the IMSL subroutine library (IMSL, 1989). For example, changes in heat flux within the estimated error or a slight relaxation of an equality could cause the solution for one region to change significantly from a horizontal advection solution to a vertical mixing solution, or vice versa. When the whole set of equations was solved using the IMSL routine, solutions from MATHCAD were used to scale the transfers to be between 0 and 1. Also, the squared residuals were scaled according to our confidence in the reliability of the data, e.g., 10 to indicate high confidence in mass conservation and 0.1 to indicate low confidence in the salinity data and hence salt conservation. Despite these scalings, many solutions were near to the MATHCAD estimates, it was decided to manually adjust some of these exchanges to improve the rms differences between the model predictions and observations for June and July. Such a set of exchanges is given in Table 7.

A comparison of Table 4 for 1974 and Table 7 shows some agreement between the model and the observations. In particular, the Great Bras d'Or Channel (station 1) shows an inflow of 1430 m^3 s^{-1} compared with the model's 1000 m^3 s^{-1}. The Little Narrows exchanges between Whycocomagh east basin and St Patrick' Channel (regions 2 and 6) are a net flow of 10 m^3 s^{-1} compared with the estimated net flow of 13 m^3 s^{-1} (see Table 4). The most problematic comparison is for the exchanges through the Barra Strait (station 5) between regions 7 and 8. Here, the observed fluxes are 1340 m^3 s^{-1} outflow and 3830 m^3 s^{-1} deep inflow (a mass imbalance of 2490 m^3 s^{-1}). This compares with the model net exchanges of 1195 m^3 s^{-1} and 1230 m^3 s^{-1}, respectively. Overall, there is reasonable quantitative agreement between model and observations, in spite of there not being enough instruments at stations 1 and 5 to resolve the flow adequately.

Table 7

Exchanges between boxes in the model. They are arranged in columns by region and in rows by the exchange number as indicated in Figure 11, i.e., x_1 is the exchange from level 1 to level 2. Exchanges are in units of m^3s^{-1}. Note Whycocomagh Basin west (Region 1), Whycocomagh Basin east (2), West Bay (3), East Bay (4), St. Andrew's Channel (5), St. Patrick's Channel (6), St. Peter's Basin (7), North Basin (8), Great Bras d'Or Channel (9).

Region	1	2	3	4	5	6	7	8	9
Trans-fers, x_1	1	2	265	15	70	35	715	95	2520
x_2	1	2	690	150	225	225	1350	1075	1000
x_3	355	690	440	145	195	360	1235	2620	1095
x_4	350	680	5	5	35	125	5	10	0
x_5	0	0	5	5	125	35	55	255	0
x_6	0	0	430	140	280	225	1250	2775	1000
x_7	0	0	0	0	490	0	0	305	0
x_8	0	0	0	0	490	0	0	305	0

6.3 Errors in the estimates of the transfers between boxes

The data report (Krauel, 1975b) quotes the accuracy of the Beckman RS5, which was used to collect most of the data, as 0.5°C for temperature and 0.3 for salinity. To gain insight into how this level of accuracy could affect the estimation of exchange coefficients, some simple numerical experiments were performed on regions 1 and 2, separate from the complete Lakes model. It is important to realize that reducing the root-mean-squared (rms) errors for the Lakes as a whole can give different answers for a specific area than if that area is considered by itself.

As there are only two levels in regions 1 and 2 (Whycocomagh basins), it is possible to calculate the exchange rates by the solution of simultaneous equations for mass and heat conservation. First, the basic data were used to calculate the exchanges. Then, a different random number in the range 0.5 (the observational accuracy of the Beckman RS5) was added to each of the temperatures and a new mean temperature calculated for both levels in regions 1 and 2. Finally, these values, together with the heat and fresh water input from the original calculations, were used to calculate new exchanges within region 1 and between region 1 and 2. Estimates from 1000 such calculations were used to construct Table 8.

It is difficult to draw firm conclusions from this table, except to emphasise that there is considerable variability possible in the small vertical exchanges (of more than 100%) and a smaller variation in the horizontal exchanges (of about 25%). Thus any sensitivity study of this model should take these into account.

Table 8
Estimates of the vertical and horizontal exchanges for the Whycocomagh west basin calculated from the conservation of mass and heat. Column 1 gives the values derived from the data as reported. Column 2 gives the maximum values and column 3, the percentage change relative to column 1 from 1000 different calculations of the exchanges with random numbers being added to the temperatures to simulate observational errors.

Exchanges (m^3s^{-1})	Estimate from Reported Data	Maximum Estimate	Maximum Percentage Change
Level 1 to 2	11.4	24.2	113
Level 2 to 1	11.4	24.4	113
Level 1, Region 1 to Level 1, Region 2	108.8	133.8	23
Level 1, Region 2 to Level 1, Region 1	102.8	127.7	24

6.4 Model predictions

Once the exchanges have been obtained then the heat and salt balance equations above can be used to study the time evolution of the temperature and salinity in the Lakes. The equations were time-stepped using the method of Gear (1971) for 'stiff equations' with the implementation taken from the IMSL subroutine library (IMSL, 1989). A number of simulations were done for this period and the output compared with observations. The exchanges were adjusted by hand in a manner that would improve the fit of the solution (i.e., reduce the rms errors) to the observations for temperatures in June and still maintain mass conservation. In general, this meant reducing the vertical exchanges between levels 1 and 2 (x_1 and x_2) and increasing some of the horizontal mixing (i.e. the minimum of pairs of horizontal exchanges). The exchanges given in Table 7 are the result of such adjustments, after the resulting exchanges have been used as an initial estimate for the Levenberg-Marquardt routine and after they have been rounded to the nearest integer.

Figure 13 shows the model predictions compared with the observations. It should be noted that June predictions should be better than July predictions because they were used in the estimation of the exchanges between the compartments. However, some July temperatures and salinities

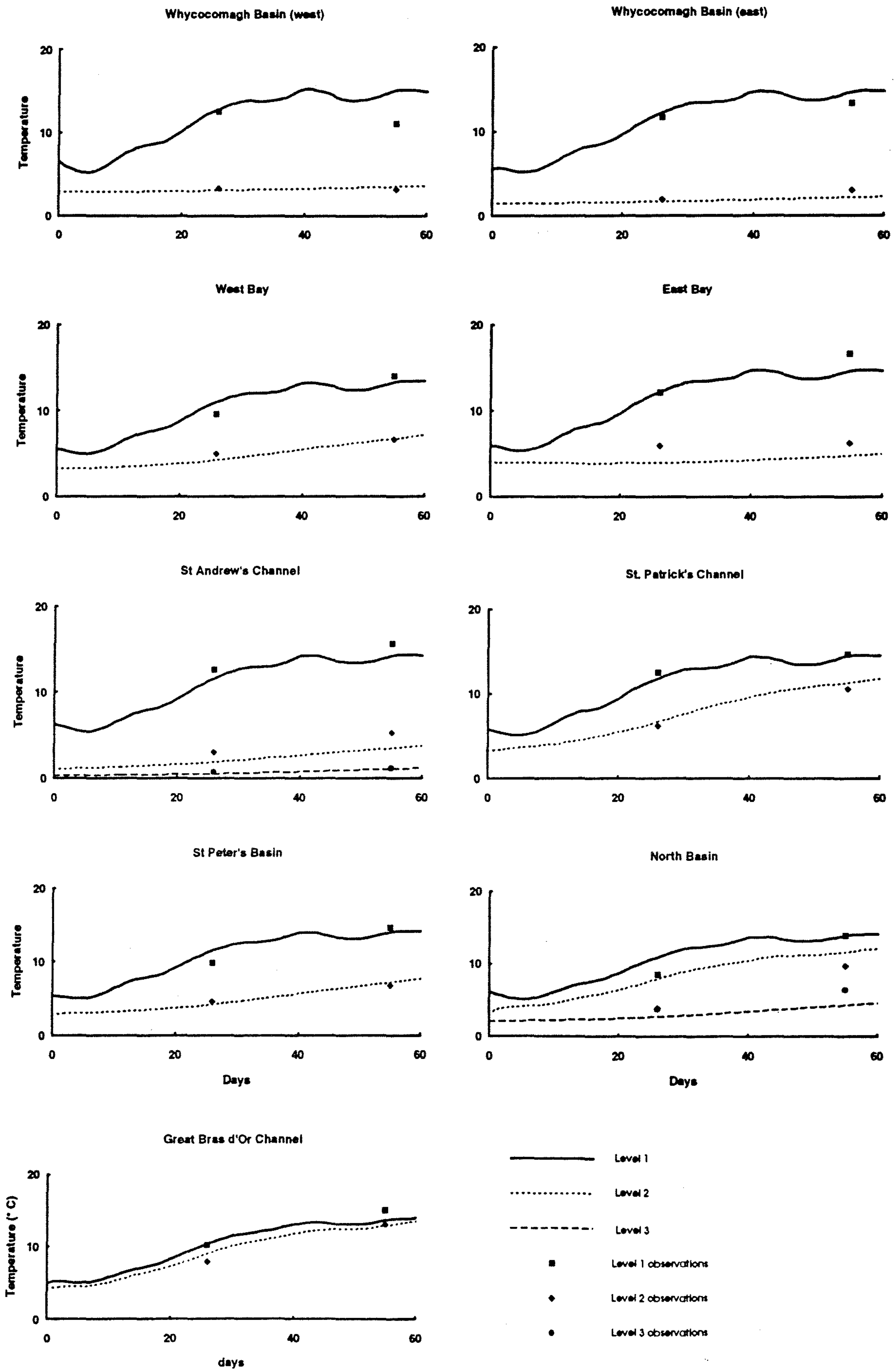

Figure 13. Model predictions of temperature and salinity for 60 days from 23 May 1974. The observations are marked for 17 June and 16 July.

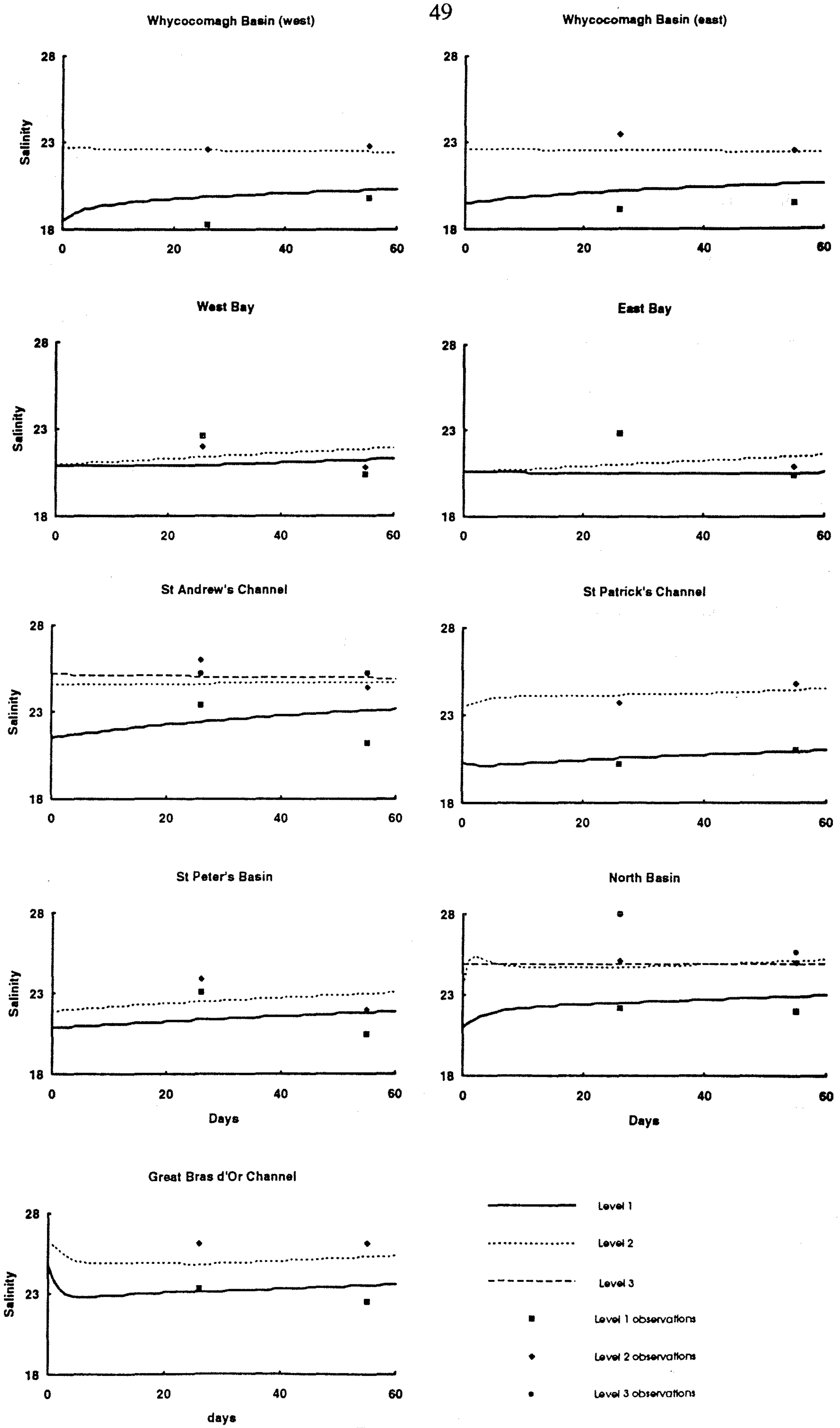

Figure 13. Continued.

were used for interpolating the June values where there was a lack of deep data (see section 2). The temperature predictions are closer to the observations than those for salinity. The non-constant temperature increases in the upper levels of the model over the 60 day period are a result of scaling the variations in heat input by the air temperatures at Baddeck. The deeper levels are generally less affected by this variation, except in St. Patrick's Channel, North Basin and the Great Bras d'Or channel, where vertical mixing is comparatively strong. The poor prediction in the Whycocomagh west basin in July may result from a sampling and aliasing problem. Temperatures and salinities here (station 18) showed the strongest and most variable thermoclines and haloclines. The smaller variability in the deeper levels resulted in a better match of predictions with observations, except in the North Basin. Here, the level 2 temperatures (15-30m) were consistently overpredicted by more that 2°C and the deeper temperatures underpredicted. Some of the difficulty here may be related to the great variability seen in the temperatures in the thermocline region and the use of interpolated data for depths greater than 50m in June.

The increase of salinity in the deeper parts of the Lakes in June is not predicted. Instead, the model shows a steady, if small, rise in salinity over the whole period in most regions. In the Great Bras d'Or Channel, the initial fall of salinity results from the adjustment of the observed data from 1974 to the forcing by the long-term mean data from the Sydney Bight.

Despite these discrepancies, the rms differences between the model predictions and the observations were the minimum found. The differences were of a similar order to the errors that could result from instrument inaccuracies and aliasing.

6.5 Sensitivity analysis

The exchanges between the boxes given in Table 7 have been tuned to reduce the rms differences between the model predictions and the observations. Separate runs of the minimisation procedure with different weights on the equations all seemed to indicate that the inflow from the Sydney Bight should be reduced from the results of the initial minimisation calculations. The exchanges produced had to be adjusted to ensure mass conservation in many of these cases. Table 9 shows the rms differences for several of these changes. The initial exchanges derived from MATHCAD are given in run 1. The runs 2 to 9 are variations of these obtained by reducing the inflow from the Sydney Bight and the exchanges for run 8 are given in Table 7. There is little to choose between runs 6 and 8 (inflows of 1200 $m^3 s^{-1}$ and 1000 $m^3 s^{-1}$, respectively). The salinity differences are close to that expected from sampling error. The temperature differences are due in a large part to the errors in regions 1 and 8 (Whycocomagh west basin and North Basin) where the model may not adequately represent the gradients observed.

We have seen from the above discussion of the observations that there is temporal variability in the Bras d'Or Lakes, occurring on relatively short time scales in addition to the errors inherent in the measurements themselves. Both of these lead to an uncertainty in the transfers used in the model and as a consequence to errors in the predictions. One way in which examine the variability, is to perform a sensitivity test on the model.

Table 9
The rms differences between model predictions and data for a number of different exchanges between the boxes in the model.

Run	Temperature 17 June	Temperature 16 July	Salinity 17 June	Salinity 16 July
1	1.39	1.59	1.36	1.61
2	1.37	1.59	1.40	1.71
3	1.38	1.57	1.36	1.18
4	1.28	1.50	1.41	1.23
5	1.36	1.57	1.39	1.30
6	1.37	1.54	1.37	0.97
7	1.37	1.45	1.35	0.82
8	1.38	1.42	1.37	0.92
9	1.39	1.49	1.45	0.76
10	1.65	1.95	1.34	1.09
11	1.56	1.81	1.38	0.77
12	1.32	1.70	1.65	1.10
13	1.45	1.59	1.29	1.10
14	1.14	1.35	1.67	1.18
15	1.54	2.86	1.50	1.54
16	1.50	2.80	1.56	1.31
17	1.46	2.73	1.91	1.55

Descriptions

1 as obtained from optimisation
2 as 1 except two-way exchanges allowed with Sydney Bight
3 as 1 except inflow from Sydney Bight reduced to 1400 m^3s^{-1}
4 as 3 but greater variation in mixing allowed
5 as 4 except two-way exchanges allowed with Sydney Bight
6 as 3 except inflow reduced to 1200 m^3s^{-1}
7 as 6 except inflow \reduced to 1000 m^3s^{-1}
8 as 7 except reduced flow forced in regions south of Barra Strait
9 as 8 except inflow reduced to 800 m^3s^{-1}
10 as 8 except vertical mixing (vm) times 0.1 and horizontal mixing (hm) times 0.1
11 as 8 except vm x 0.1 and hm x 1
12 as 8 except vm x 0.1 and hm x 10
13 as 8 except vm x 1 and hm x 0.1
14 as 8 except vm x 1 and hm x 10
15 as 8 except vm x 10 and hm x 0.1
16 as 8 except vm x 10 and hm x 1
17 as 8 except vm x 10 and hm x 10

We saw that there is mixing caused by both tidal exchanges through narrow passages and shear instabilities. This mixing is represented in the model by two-way exchanges between the compartments as the passages cannot be resolved. To obtain an appreciation of the effect of changing the mixing the model was run with both a ten-fold increase and a ten-fold decrease in mixing, both horizontally and vertically. That is the equal and opposite fraction of a pair of exchanges was increased or decreased by the appropriate factor. The results are shown in Table 9 as rms differences for runs 10 to 17. All these runs had higher variances confirming the choice of levels of mixing applied between boxes.

7. Discussion of results

7.1 Flushing times

Estimates of the flushing times of the different regions of the Bras d'Or Lakes can be made from the model by following the dispersion of an initial release and measuring the rate of decay of the concentration. The results of these calculations are given in Table 10. Most of the times lie within the range of 1 week to three months. The upper levels of all regions and the second layers of regions 8 and 9 flush in about one week. The deepest level of region 8 (>30m) takes 150 days, while the bottom of St Andrew's Channel, which reaches over 250m, takes 284 days. Flushing times of about 2 years for the deepest parts of the Whycocomagh Basin may account for the observed oxygen depletion below about 20m there.

Table 10

Estimates of the flushing time in days for each compartment in the model calculated by measuring the rate of decay of an initial concentration in the region. Note Whycocomagh Basin west (Region 1), Whycocomagh Basin east (2), West Bay (3), East Bay (4), St. Andrew's Channel (5), St. Patrick's Channel (6), St. Peter's Basin (7), North Basin (8), Great Bras d'Or Channel (9).

Region	1	2	3	4	5	6	7	8	9
Level 1	5	6	8	6	7	7	7	8	8
Level 2	672	717	48	91	99	12	65	9	8
Level 3					284			150	

7.2 Application of the model to dissolved oxygen distributions

Four of the model compartments, namely the deepest layers in both Whycocomagh basins, St. Andrew's Channel and the North Basin, can only have their oceanographic characteristics modified by vertical exchange. From 15-19 July, 1974, dissolved oxygen was measured at discrete depths for stations 1-27 (except for station 24) throughout the Lakes. The percentage saturation values found at these stations are shown in Figure 14 as a function of depth. In Great Bras d'Or Channel, St. Patrick's Channel, and south of Barra Strait, 55 of the 58 observations had saturations of 91% or greater. Saturations of 81% and 83% were found at Station 26, 55m in East Bay and at station 4, 90m on the border between Great Bras d'Or Channel and the North

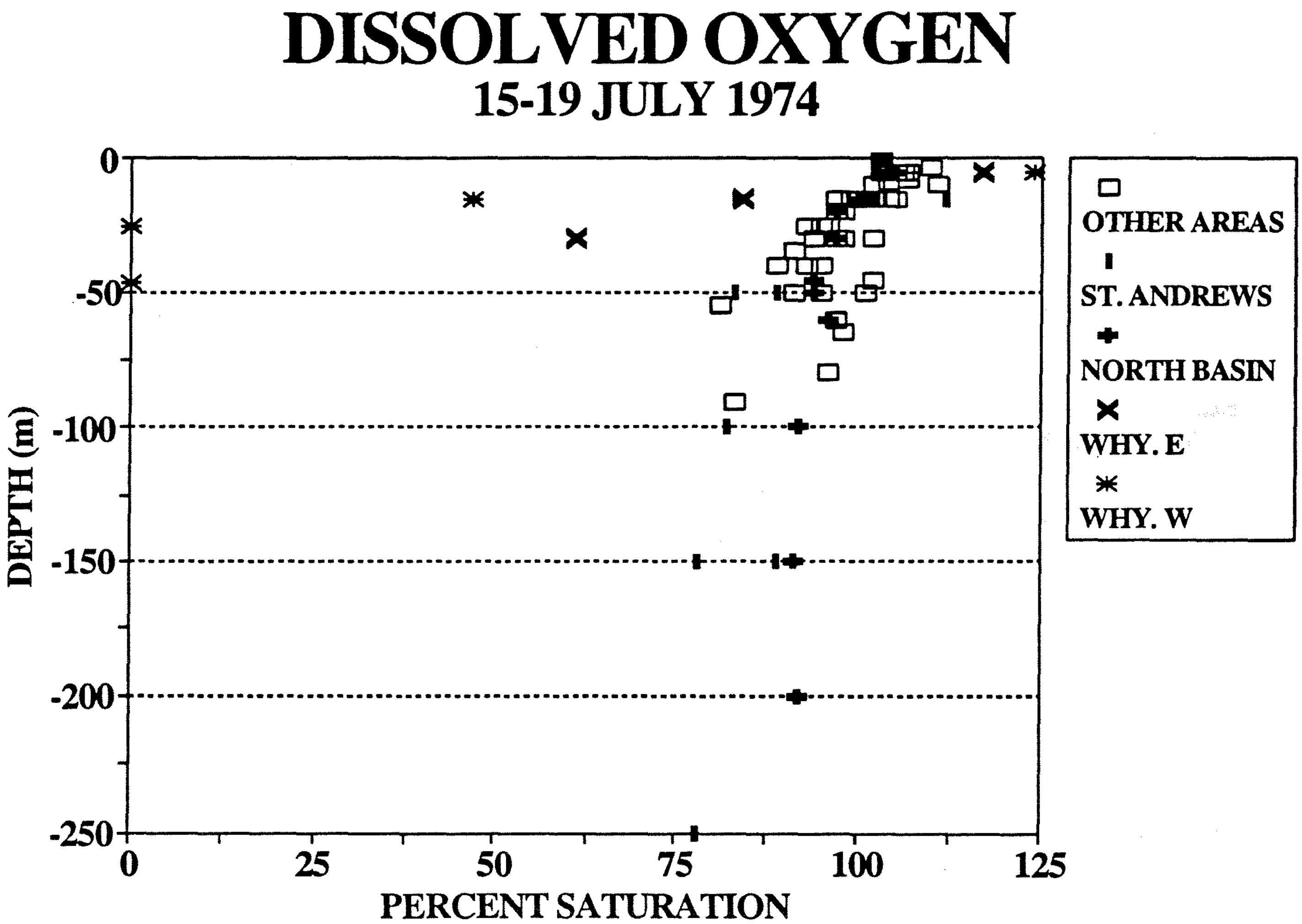

Figure 14. Percentage saturation of dissolved oxygen against depth for measurements made between 15 and 17 July 1974.

Basin, respectively. The lowest oxygen values were found in the Whycocomagh Basins, with anoxic conditions at 25m and deeper, station 18 (western basin) and 61% saturation at 30m, station 17. Reduced levels of 78-83% were also observed in the deeper part (50-250m) of St. Andrew's Channel; whereas, in similar depths (50-200m) in the North Basin values of 91-96% were recorded. We shall now investigate a simple model of oxygen utilisation to determine if the model can account for the observed distribution. Consider the following balance between oxygen supply, export and utilisation:

$$x_7 C_U + x_8 C_L + S_{WC} + S_B + S_R = 0$$

where x_7 and x_8 are the transports into and out of the bottom layer and are taken from the model. For regions with only 2 layers, e.g. Whycocomagh Basin, x_7 and x_8 should be replaced by x_1 and x_2, respectively;

C_U and C_L represent the oxygen concentrations in the layer above the bottom layer and the bottom layer;

S_{WC}, S_B and S_R represent the oxygen sinks due to utilisation in the water column, benthic uptake and fish respiration.

Examination of some fish respiration data for Bras d'Or Lakes cod (Nelson, pers. comm., Dept. of Biology, Dalhousie University, Halifax, Canada) indicated that this sink was negligible.

The results are given in Table 11, where, in the absence of measurements from the Bras d'Or Lakes, we have used a benthic oxygen consumption rate of 26.1 mg $m^{-2}h^{-1}$ from Grant et al. (1991) which is based on measurements for fine sediments from nearby St. Georges Bay, Nova Scotia. Water column utilisation rates are from Williams (1984) for the Northwest Atlantic coastal, shelf and slope areas. We have selected two values from the range that was given: 50 μg O_2 dm^{-3} d^{-1} represents an average rate for the near-surface layer, 10 μg O_2 dm^{-3} d^{-1} corresponds to a subsurface rate for the depth range 100-500m, and is perhaps the more applicable for our situation. The oxygen transport represents the flux into the bottom layer. We solve for the oxygen concentration, C_L, in the lower layer and given in the above equation.

The model predicts anoxic conditions for both Whycocomagh basins with either water column utilisation rate. In fact, anoxic conditions are found at 25 and 40m in the western basin, and substantial reductions, by up to 39%, in the eastern basin. Reasonable agreement is obtained for St. Andrew's and the North Basin if the lower water column utilisation rate is used. The model predicts oxygen percentage saturation reductions of 16 and 6% for St. Andrew's and North Basin, respectively, while values of 17-22% are observed in the deep layer for the former, and 4-9% for the latter. Overall agreement of the model and observed dissolved oxygen concentrations is good, lending support to the derived circulation.

Table 11a
Physical parameters, dissolved oxygen concentrations and exchanges of isolated basins.

BASIN	VOLUME ($10^6 m^3$)	AREA ($10^6 m^2$)	O_2 CONC. UPPER (ml l^{-1})	O_2 CONC. LOWER (ml l^{-1})	EXCHANGE ($m^3 s^{-1}$)
Whycocomagh West	57.6	1.3	8.6	3.8@15m 0@25,40m	1
Whycocomagh East	122.8	10.3	8.0	6.8@15m 5.2@30m	2
St. Andrew's	4313	48	7.8	6.7	490
North Basin	661	15	6.9	6.8	305

Table 11b
Derived dissolved oxygen levels in isolated, deep basins.

BASIN	O_2 Transport (mg s^{-1})	Benthic Loss (mg s^{-1})	Water Column Loss (mg s^{-1})@50m	Water Column Loss (mg s^{-1})@10m	Percent Reduction Model	Percent Reduction Data
Whycoco-magh West	$1.2x10^4$	$9.4x10^2$	$3.3x10^4$	$6.7x10^3$	100,100	53,100
Whycoco-magh East	$2.3x10^4$	$7.5x10^4$	$7.1x10^4$	$1.4x10^4$	100,100	16,39
St. Andrew's	$5.5x10^6$	$3.5x10^5$	$2.5x10^6$	$5.0x10^5$	52,16	17,22
North Basin	$3.0x10^6$	$1.1x10^5$	$3.8x10^5$	$7.6x10^4$	16,6	4,9

An alternative way to consider the observations is to assume that the net oxygen flux into the bottom layer completely oxidizes the carbon flux from the productive upper layer. In this way we can obtain an estimate (likely an upper bound) of the suspended particulate concentration in the upper layer. We have

$$a\ b\ X\ O_2 = w\ A\ C$$

where

a=106/276 is the ratio of the average number of carbon atoms to be oxidized by oxygen atoms in organic matter;
b=12/16, the ratio of the atomic weights of carbon and oxygen;
X is the exchange from Table 11a;
O_2 is the difference in oxygen concentration in the upper and bottom layer;
w is the net particle sinking velocity;
A is the basin area, Table 11a; and,
C is the carbon concentration.

If we take the suspended particulate concentration as twice the carbon concentration then we obtain values of 0.9, 2, 0.5 and 0.04 mg l^{-1} for St. Andrew's Channel, North Basin, Whycocomagh West and East, respectively. With the exception of the east basin of Whycocomagh, these estimates are quite similar to the concentrations of 1.0-1.4 and 1.2-1.4 mg l^{-1} for Nova Scotia inlets reported by Kranck (1980) and Petrie and Yeats (1990).

In summary, the model appears to give good overall agreement with the observed oxygen distributions as well as reasonable estimates of the suspended particulate concentrations.

7.3 Circulation during other periods of the year

This model has been established for the early summer period of May to July. Krauel (1975b) reports very little data for the remainder of the year. As can be seen from Table 1, there are data between August 1972 and February 1973. Figure 15 shows the temperature at station 11. Here, we see that the vertical gradient in temperature disappears in early October 1972 and only begins to re-establish in early December, but in the reversed sense with the lowest temperature near the surface. This pattern is repeated in other regions. Figure 16 shows the data from station 18 (Whycocomagh west basin) for 1972. Again the vertical gradient disappeared in the upper layers at the end of October, but the temperature at 30m appears to be little changed, confirming the low vertical exchanges in the model. An examination of the weather reports from this period shows that there was a period of heavy rainfall and strong winds. For example, on 29 October 1972, winds exceeded 40 mph (64 kph) and there was 1.55 inches (39.4 mm) of rain reported at Sydney, to the east of the Lakes.

We tried to simulate the autumn period using the model and making simple changes to the heat, salt and fresh water inputs based upon annual mean data. We used the monthly heat inputs given by Bugden (1981) for the Magdalen Shallows and the annual mean data from Sydney Bight for the inputs from the Atlantic Ocean (Drinkwater and Trites, 1987). Fresh water inputs were allowed to grow uniformly across the Lakes following the pattern of increase given in Figure 9. This increase in fresh water was advected out of the model in the surface layer. By starting from the July 1974 data, the model predicted that the temperature in the surface layers continued to increase through August and into September. Thereafter there was a steady decrease in surface layer temperature. Throughout the whole period, the lower layer temperatures increased slowly and steadily until around late October and early November when the water column in all regions was predicted to be no longer thermally stratified. The model then went on to predict an unstable density gradient. This occurs at a time when there are strong winds and heavy rainfall. Throughout this period the salinity changed slowly and uniformly, becoming fresher in the surface layers, reflecting what is seen in the data.

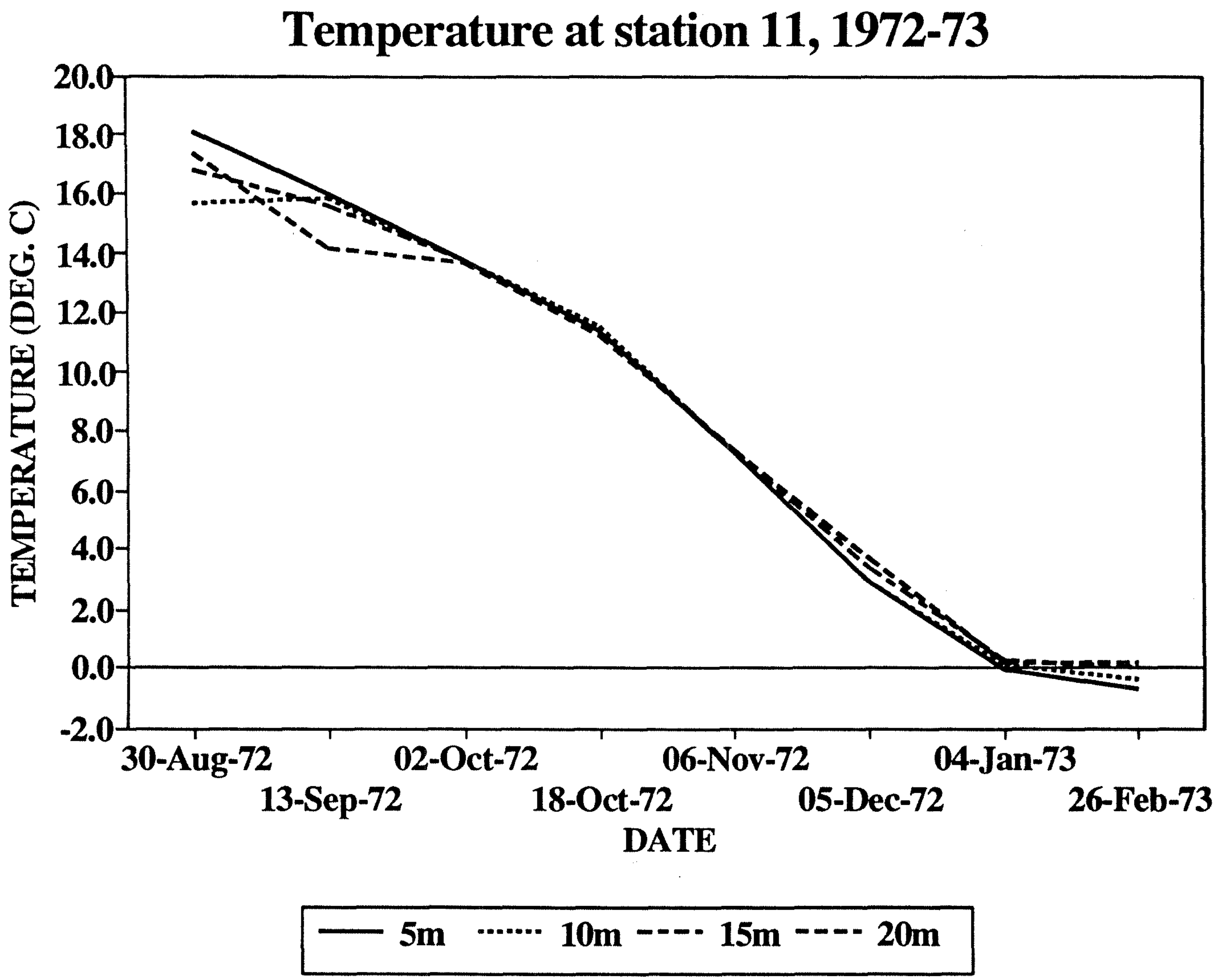

Figure 15. Temperature data for station 11, Barra Strait during the autumn and winter of 1972/73.

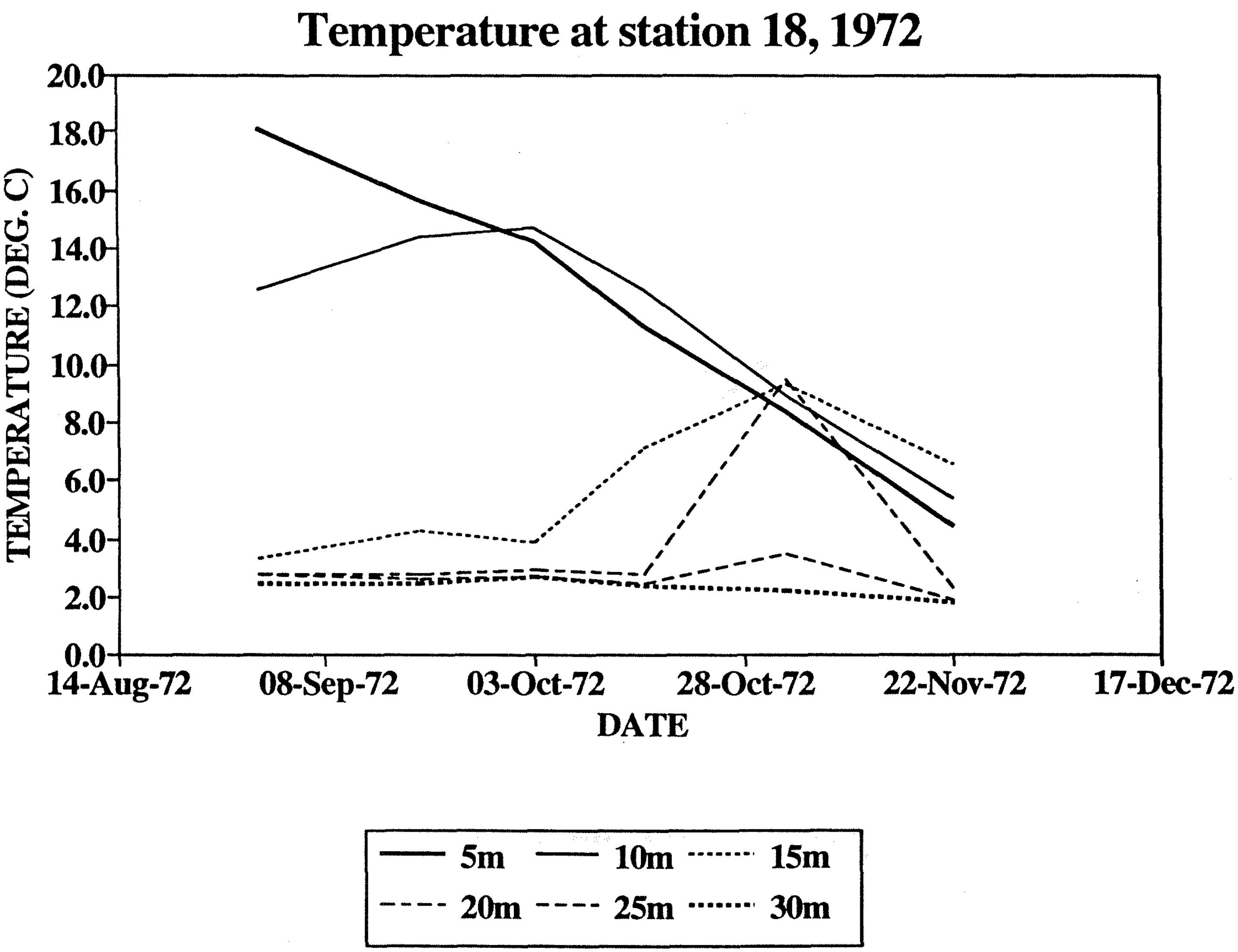

Figure 16. Temperature data for Whycocomagh Basin (west, station 18) during the autumn and winter of 1972/73.

8. Summary

The Bras d'Or Lakes are a complex system of inter-connecting basins of widely different depths that exchange with the Sydney Bight by two narrow channels. Hydrographic surveys were conducted from 1972 to 1974 but suffer from significant temporal and spatial aliasing as well as sensor inaccuracies. Despite this, the application of box modelling techniques has put together a coherent picture of the summer circulation within the Lakes, consisting of a deep inflow from the Sydney Bight through the Great Bras d'Or Channel, upwelling within the Lakes and a surface outflow which is warmed by solar heating and freshened by precipitation. This work has given us the needed large-scale picture that will serve as a basis for site-specific problems that may arise from the pressure for increased aquaculture within the Lakes and from pollution concerns from industrial and urban developments. All this demonstrates that archived, less than state-of-the-art data can be put to good use for answering management questions.

The picture for the summer circulation is supported by the limited set of current meter data, the oxygen data and the prediction of the onset of the autumnal overturning within the Lakes. We have identified that in the narrow passages there is considerable potential for mixing that does not exist in the centre of the basins during the summer where mean (typical amplitude is 0.3 cm s^{-1}) and variable (typical rms amplitude for $z \geq 15$m, tides included is 3.9 cm s^{-1}) currents are low.

Comparison of the Bras d'Or Lakes with other inlets on the Nova Scotian coast reveals that the ratio of the outflow at the mouth to the fresh water inflow is 12 compared with a mean value of 21 from the Gulf of St. Lawrence (El-Sabh, 1977; Drinkwater et al., 1979; Bugden, 1981; Koutitonsky and Bugden, 1991), 40 for Halifax Harbour (Petrie and Yeats, 1990) and 300 for St Margaret's Bay (Heath, 1973). Apart from this there is little information in the literature about the Nova Scotia inlets. In comparison, the Baltic Sea has a ratio of 2 (Falkenmark, 1986; Pocklington, 1986). This suggests that the Bras d'Or Lakes are more like an enclosed sea than a fjord.

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