

NEW ZEALAND  
DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH

BULLETIN 143

# HYDROLOGY OF CIRCUMPOLAR WATERS SOUTH OF NEW ZEALAND

by

R. W. BURLING

New Zealand Oceanographic Institute  
Wellington

New Zealand Oceanographic Institute  
Memoir No. 10

1961



HMNZS *Hawea* in the Southern Ocean, December 1956.

*Photograph by T. Lloyd*

*Frontispiece*

NEW ZEALAND  
DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH

BULLETIN 143

**HYDROLOGY OF CIRCUMPOLAR  
WATERS SOUTH OF  
NEW ZEALAND**

by

R. W. BURLING

New Zealand Oceanographic Institute

Wellington

**New Zealand Oceanographic Institute  
Memoir No. 10**

1961

## FOREWORD

IN December 1956 and January 1957, the N.Z. Oceanographic Institute carried out oceanographic observations in Antarctic and Subantarctic waters from the frigates HMNZS *Pukaki* and *Haweā*. This undertaking initiated a series of cruises to southern waters during the International Geophysical Year. During the voyage the principal objectives were hydrological observations, particularly in the region of the Antarctic Convergence and, on the return to New Zealand waters, in the region of the Subtropical Convergence. The sampling also included surface plankton tows and sediment and core sampling.

Some of the hydrological results ( $^{14}\text{C}$  activities of bulk water samples from depth) have been interpreted and published elsewhere. Preliminary analysis of the results reported here has guided subsequent work by the Institute carried out in the Southern Ocean.

Preliminary editing has been carried out by Dr D. E. Hurley and Mrs P. M. Cullen. The material has been finally edited for publication by Mr M. O'Connor, Information Bureau, D.S.I.R.

J. W. BRODIE, Director,  
New Zealand Oceanographic Institute.

# CONTENTS

	<i>Page No.</i>
INTRODUCTION	9
RESULTS OF THE <i>Pukaki-Hawea</i> CRUISES IN SOUTHERN WATERS	
Collection of Data	10
Surface Characteristics	10
Ambiguities in the Construction of Isolines	10
Bathythermograph Sections	11
Station Data	11
REVIEW OF PREVIOUS WORK ON WATER MASSES AND THEIR BOUNDARIES SOUTH OF NEW ZEALAND	14
HYDROLOGICAL FEATURES IN THE ANTARCTIC AND SUBANTARCTIC REGIONS	
Subsurface Waters	15
The Antarctic Convergence	16
Antarctic Surface Water	19
Australasian Subantarctic Water and Circumpolar Subantarctic Water	20
Warm Saline Water South of New Zealand	23
Australasian Subantarctic Front	24
General Water Movements Over the Campbell Plateau	34
THE SUBTROPICAL CONVERGENCE REGION	
Introduction	25
Atlantic and Western Indian Oceans	26
East Indian Ocean and South of Australia	27
East of New Zealand	28
West of New Zealand	30
South of New Zealand	33
Extent of the Subtropical Convergence Region	36
THE SOUTHLAND FRONT	
General Description	37
Water Movements near the Southland Front	38
A MIXING PROCESS AT THE SUBTROPICAL CONVERGENCE	42
EDDIES, DIVERGENCE, AND STREAMS	
An Eddy in Antarctic Waters	44
Divergence and the Antarctic Convergence	46
A Free Stream Current in Subantarctic Waters	49
CURRENTS IN SUBTROPICAL AND SUBANTARCTIC WATERS	
Tasman Current	51
Southland Current and Canterbury Current	51
East Cape Current	52
The Circumpolar Current	52
Drift Currents	52
A Constricted Current	53
Bounty-Campbell Gyral	54
Free Stream Current	54
Origin of the Southland Front	54
SUMMARY	
The Subtropical Convergence Region	56
Subantarctic Water	56
The Southland Current and Southland Front	56
Constricted Current	56
Australasian Subantarctic Front	57
Free Stream Current	57
BountyCampbell Gyral	57
Eddies	57
Divergence	57
Antarctic Intermediate Current	57
Mixing Processes	57
ACKNOWLEDGMENTS	58
REFERENCES	59
APPENDIX A STATION DATA	
<i>Pukaki</i> Stations	62
<i>Hawea</i> Stations	64
INDEX	66

## FIGURES

<i>Fig. No.</i>	<i>Page No.</i>
1. Tracks of <i>Pukaki</i> and <i>Hawea</i> , bathymetry, and station positions	12
2. Surface isotherms and isohalines	13
3. Temperature sections from bathythermograph observations north of Lat. 56°S	17
4. Temperature sections from bathythermograph observations south of Lat. 56°S	21
5. Temperature sections from bathythermograph observations between Lat. 65°S and Lat. 63°S	25
6. Temperature sections from bathythermograph observations between the Chatham Islands and Dunedin	27
7. Vertical section of salinity and density distributions between NZOI Stations C 10 and C 29	29
8. Vertical section of temperature distribution between NZOI Stations B 28 and B 36	31
9. Vertical section of salinity distribution between NZOI Stations B 28 and B 36	31
10. Vertical section of density between NZOI Stations B 28 and B 36	33
11. Vertical section of temperature and salinity between Macquarie and Auckland Islands	35
12. Water characteristics at constant depths across the Subtropical Convergence	35
13. Observed positions of the Subtropical Convergence Region	37
14. T-S characteristics, NZOI Stations C 10 to C 29	39
15. T-S characteristics, <i>Discovery II</i> Stations. South of Atlantic and Western Indian Ocean, and <i>Ob</i> Stations south of Central Indian Ocean	41
16. T-S characteristics of <i>Discovery II</i> and <i>Ob</i> Stations. South of the Eastern Indian Ocean and Tasmania	43
17. T-S characteristics of <i>Discovery II</i> , <i>Ob</i> , and <i>Derwent Hunter</i> Stations in and south of the Tasman Sea and South of New Zealand	45
18. T-S characteristics of <i>Pukaki</i> and <i>Discovery II</i> Stations in and south of the Tasman Sea and south of New Zealand	47
19. Comparison of the observed range of Subtropical Convergence Region with mean monthly isotherms for February and August	49

## PLATES

	<i>Facing page</i>
Frontispiece. HMNZS <i>Hawea</i> in the Southern Ocean, December 1956	2
1. Bathythermograph observations from HMNZS <i>Pukaki</i>	18
2. Reading reversing thermometers on board HMNZS <i>Pukaki</i>	18
3. Bergs south of the Antarctic Convergence	34
4. Lowering the <sup>14</sup> C Sampler, Station B 28	34

## CHARTS

1. (in folder) Currents in the Southern New Zealand Region.

# HYDROLOGY OF CIRCUMPOLAR WATERS SOUTH OF NEW ZEALAND

## INTRODUCTION

This paper provides a description and interpretation of hydrological data obtained by the New Zealand Oceanographic Institute during cruises on the RNZN frigates *Pukaki* and *Hawea* into Antarctic waters during December 1956 and January 1957. These cruises formed part of the Institute's contribution to the International Geophysical Year programme. Some results of this investigation suggested the more detailed study of waters in and close to the northern Subantarctic region, using also data from the RRS *Discovery II*, the Russian RV *Ob*, and the Australian FRV *Derwent Hunter*. Hypotheses are then offered concerning the nature of currents in the Southern Ocean, south of New Zealand.

Hydrological observations carried out from *Pukaki* and *Hawea* were designed to sample surface temperature and salinity over the regions traversed and temperatures to 250 m by bathythermograph. During the return voyages serial temperatures and salinity observations to greater depths were made through the Antarctic and Subtropical Convergences and over the Campbell Plateau.

J. W. Brodie, H. M. Pantin, and R. W. Burling conducted the oceanographic work from *Pukaki* and R. P. Willis, that from *Hawea*.

## RESULTS OF THE "PUKAKI"-“HAWEA” CRUISES IN SOUTHERN WATERS

From 17 to 19 December 1956 the frigates HMNZS *Pukaki* and HMNZS *Hawea* escorted the Royal Yacht *Britannia*, with H.R.H. the Duke of Edinburgh on board, from Lyttelton to Waitangi, Chatham Islands. The frigates left Waitangi on the evening of 19 December and proceeded to Dunedin. They then accompanied HMNZS *Endeavour* between 22 and 27 December from near Stewart

Island to the pack-ice, near Scott Island. *Endeavour* continued her southward voyage to McMurdo Sound, while the two frigates returned to New Zealand along the meridians 169° E (*Pukaki*) and 180° (*Hawea*) (fig. 1) *Hawea* returned to Wellington on 3 January 1957 and *Pukaki* to Lyttelton on 4 January.

## COLLECTION OF DATA

The temperature of sea water entering the engine-room intakes at a depth of 4 m, was continuously recorded by thermograph throughout the voyages on both frigates. The surface thermograph readings on *Pukaki* were calibrated from reversing thermometer readings at nine stations. The average *Hawea* temperatures were then corrected to agree with average *Pukaki* temperatures, measured while the ships were stationed less than 5 miles apart (see fig. 1). Surface isotherms are shown in fig. 2, the data being supplemented south of Scott Island by a thermograph recording from *Endeavour* during the southward journey.

Hourly samples for salinity analysis were also taken on both frigates. Those on *Pukaki* proved to be unsatisfactory because of a periodic recirculation occurring in the cooling system, and were discarded. The thermograph element was nearer the intake entrance and this recirculation had no measurable effect on the recorded temperatures. Surface isohalines, drawn from the *Hawea* data and from surface salinities measured at nine stations worked on *Pukaki*, are also shown in fig. 2.

Bathythermograph observations were taken from both frigates (fig. 3, 4, 5, and 6). Surface temperatures have been corrected from the thermograph readings, and an additional check on the bathythermograph used on *Pukaki* is given by nine hydrological stations worked during the return journey. Comparisons with reversing thermometer temperatures show that observations may be corrected to within 0.25°C.

Water samples for salinity analysis were collected at four depths from *Hawea* at each of the Stations C 1 to C 29 (fig. 1; table 2). Salinity and  $\sigma_t$  isolines for the northern section of this line of stations are shown in fig. 7. Surface samples at these stations were collected by bucket; salinities of this extreme surface water averaged about 0.03 ( $\pm 0.04$ )‰ and 0.02 ( $\pm 0.02$ )‰ above those at 4 m at the 10 southern and 19 northern stations respectively. These surface samples were not collected on the hour as were those from 4 m below the surface via the engine-room intake; thus the above differences may be due to differences in the time of sampling and to the measurement errors in each sample.

All salinity values reported in this paper have been obtained using a conductivity meter (Hamon, 1956) as a transfer instrument checked against a sub-standard sample which was in turn checked against a Copenhagen standard. The accuracy of

this instrument is given by Hamon as  $\pm 0.04$ ‰, but the observed consistency of the measurements on the sub-standard suggests that they are correct to  $\pm 0.03$ ‰.

Nine serial stations were worked on *Pukaki* at N.Z.O.I. Stations B 28 to B 36 (fig. 1). Observed temperatures and salinities and computed values of  $\sigma_t$  are given in table 1.

Two water samples for  $^{14}\text{C}$  analysis were collected from *Pukaki*. These have been reported previously (Brodie and Burling, 1958; Rafter and Fergusson, 1958), and the relation of the  $^{14}\text{C}$  activity in these samples to the general distribution of observed  $^{14}\text{C}$  activities between 9° S and 67° S near New Zealand has been discussed elsewhere (Burling and Garner, 1959).

## SURFACE CHARACTERISTICS

Surface characteristics of the waters between New Zealand and Scott Island, as found by *Pukaki* and *Hawea*, are shown in fig. 2. Surface isohalines are drawn from samples obtained hourly along *Hawea's* tracks and from surface values at *Pukaki* hydrological stations (fig. 1). Dashed lines for *Pukaki* isohalines (fig. 2) indicate the relative uncertainty of their positions. Isotherms are based on corrected thermograph recordings. During the return journeys, significant warming was observed where the ships crossed their earlier tracks. Observations from HMNZS *Pukaki* indicated no noticeable change where the tracks crossed between Stations B 35 and B 36 (12 days later) but indicate warming of about 0.5°C where the tracks cross off Dunedin and Banks Peninsula (14 and 18 days later). No account was taken of the latter difference in drawing the isotherms, but the 13°C closed isotherm was possibly absent on the earlier occasion, with the 12°C isotherm extending farther north.

On the *Hawea* tracks near the Chatham Islands at about 44° S, 180° E the warming was slightly less than 1°C (13 and 15 days later). On the northward course a temperature of 14°C was observed at the southern crossing of tracks. This warming may cause the isotherms as drawn, except those for 14°C and 15°C, to be bent southward along the eastern and western tracks, and the 16°, 17°, and 18°C isotherms to be displaced southward. However, the bending will be small south of 60° S where fewer than five days separate the observations, and is probably significant only north of 55° S along the 180° meridian (10–13°C). The remaining isotherms shown along

the northward track are based on observed temperatures.

#### AMBIGUITIES IN THE CONSTRUCTION OF ISOLINES

There are ambiguities in the manner in which any isotherm may be drawn when it is intersected more than once along one or more tracks. Most difficulties in the present instance appear in the southern region where the isotherms for 9°C and 7°C represent two ways in which the isolines may be drawn for similar distributions of the observed surface temperatures. Nearly all isohalines for salinities less than 34.40/00 and all isotherms except those for 4°, 5°, and 10°C are topologically ambiguous in a similar manner, and unless there is a definite reason for choosing a particular description of a feature, the choice of shape of particular isolines must often be made arbitrarily. Here it may be noted that certain features can be interpreted: (a) as limited pockets (perhaps eddies) of water; (b) as tongues, which may have either of two orientations near a given line; (c) as enlarged or extended pockets or tongues intersected by two ships' tracks but apparently not extending to the third (compare the 9°C and 34.20/00 isolines); (d) as still more extended strip features (perhaps streams) intersected by all three tracks (illustrated by the 33.90/00 isohaline); or (e) as combinations of the above features.

#### BATHYTHERMOGRAPH SECTIONS

Vertical temperature sections along the three tracks are shown in fig. 3, 4, 5, and 6. For comparison they are plotted according to latitude. Where there was a change of course longitudes are indicated at the foot of each diagram.

Fig. 3b and 4b were drawn from *Hawea* observations and fig. 3c and 4c from *Pukaki* observations 5 miles to the west when both ships were following their parallel southward courses. The surface reading on each bathythermograph was corrected from the thermograph reading on the same ship, the mean of all thermograph readings from each ship having first been standardised. No further effort was made to standardise temperatures in the sections, nor to standardise the relative positions. Thus, these sets of diagrams illustrate differences between the two sets of ob-

servations arising: (a) from instrumental errors ( $\pm 0.5^\circ\text{C}$ ); (b) from navigational uncertainty ( $\pm 0.15^\circ$  of latitude); (c) from real differences in the east-west temperature distribution; and (d) from sampling at different times (the observations were made at alternate hours from the two ships north of  $61^\circ\text{S}$ ) or different time intervals (hourly on *Pukaki*, two-hourly on *Hawea*, south of  $61^\circ\text{S}$ ).

The two sections are similar. At only one or two points does the difference reach  $1^\circ\text{C}$ , e.g., near  $48^\circ\text{S}$  between 100 and 220 m and between  $63^\circ\text{S}$  at 50–150 m. This is not obviously due to the effects of instrumental or position errors and particularly not to different sampling times. The position near  $48^\circ\text{S}$  is on a "front", or sharp horizontal gradient, in the subsurface temperature distribution. At  $62^\circ\text{S}$  there is an unusual cold tongue, possibly associated with considerable east-west temperature variation. The smaller scale vertical fluctuations revealed by halving the sampling interval are particularly noticeable.

#### STATION DATA

Salinity and  $\sigma_t$  sections between Stations C 10 and C 29 (fig. 7) have been constructed from analyses of samples obtained at a few depths only at each station. The  $\sigma_t$  values were computed from bathythermograph temperatures at the sampling depths and are intended to show the trend of the isolines; there will be greater errors than in  $\sigma_t$  values computed from standard station procedure. This figure illustrates in more detail a region shown in fig. 3a; in fig. 7 the horizontal scale has been doubled.

Fig. 8, 9, and 10 are drawn from data obtained at reversing bottle Stations B 28 to B 36. Between Stations B 31 and B 32 the isolines are dashed since there is good evidence for the temperature structure only in the upper 270 m. Lines are dashed also near Stations B 34 and B 36 where the slopes are unknown. Isolines of  $\sigma_t$  in fig. 10 conform with temperature and salinity values in fig. 8 and 9.

Temperature and salinity (T-S) characteristics at Stations C 10 to C 29 are plotted in fig. 12 and 14 and those of Stations B 32 to B 36 in fig. 18.



Fig. 1: Chart showing *Hawea* and *Pukaki* tracks, N.Z.O.I. Station positions and contours of bottom relief (depths in fathoms from U.S. Chart H.O. 2562). The frigates *Pukaki* and *Hawea* steamed in company from Christchurch to Dunedin; *Hawea* was 5 miles east of *Pukaki* along track marked by double line; *Hawea* returned to New Zealand via the 180° meridian and *Pukaki* via the western track.

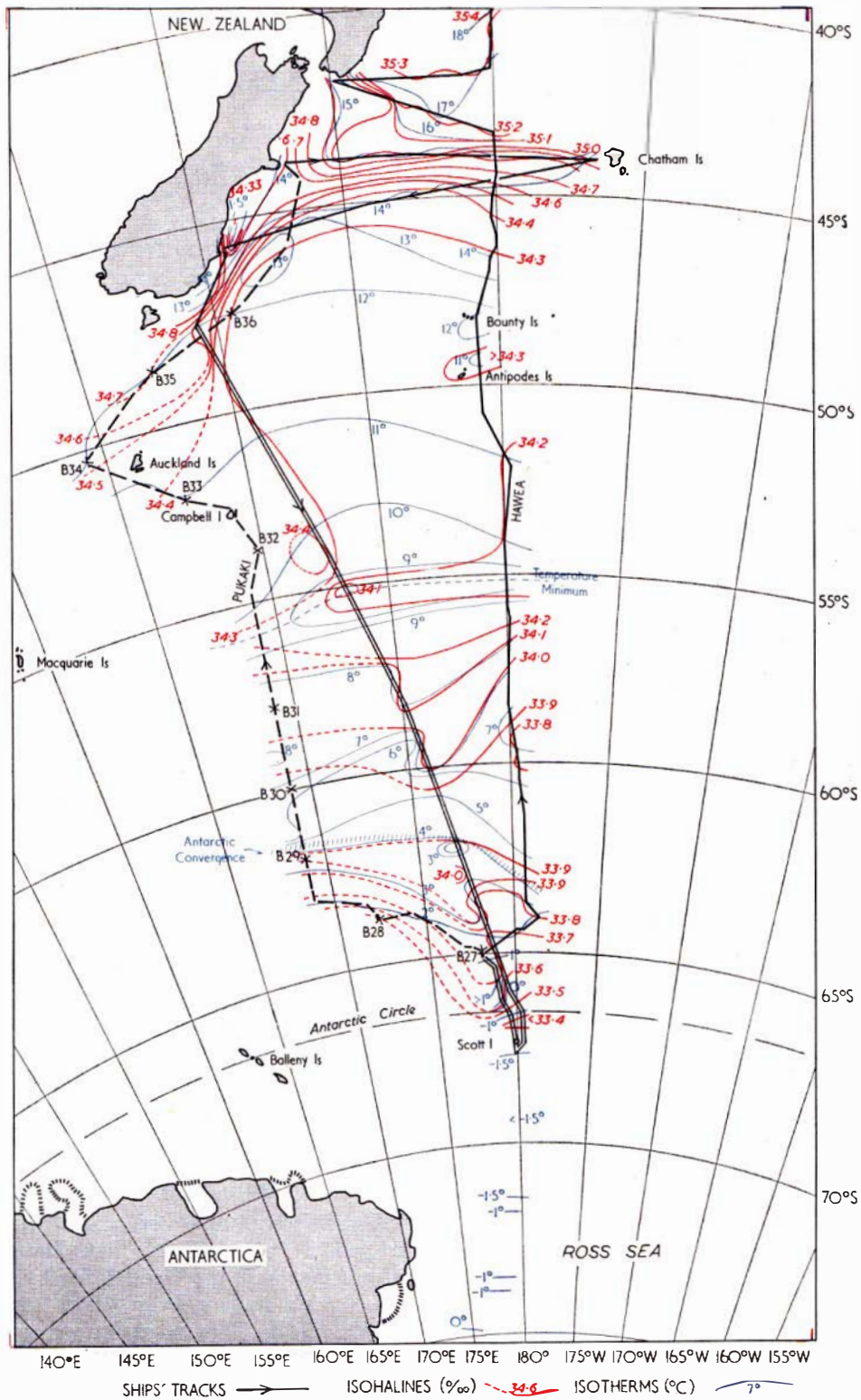


Fig. 2: Surface distributions of:

Isotherms (blue lines); from continuous thermograph recordings.  
 Isohalines (red lines); hourly samples from engine room intake along solid line ships' tracks and from station positions (marked X) along Pukaki's track (dashed line).

## REVIEW OF PREVIOUS WORK ON WATER MASSES AND THEIR BOUNDARIES SOUTH OF NEW ZEALAND

The hydrology of the Southern Oceans has been discussed by various authors (e.g., Deacon, 1937; Middtun and Natvig, 1957; Sverdrup, 1933). The following description is based on that of Deacon (1937);

The region between the Antarctic Continent and about 65° S latitude lies in the easterly wind zone; the region to the north lies in the westerly wind belt of the "forties" and "fifties". The temperature of surface waters in the Pacific Ocean is lowest near the edge of the ice-pack surrounding the Antarctic Continent and is only slightly warmer immediately to the north; a sudden sharp temperature increase is however met somewhere between about 54° S and 62° S. The position of this increase is known as the Antarctic Convergence. To the south lies Antarctic Water. To the north, the warmer Subantarctic Region extends to where its surface waters moving to the north and east meet even warmer Subtropical Water. This occurs in a sometimes well defined, but often indistinct, region known as the Subtropical Convergence, between 35° S and 47° S.

The main movement of the whole water mass in the westerly wind system is towards the north-east. Northward or southward motions, characteristics of certain water masses which may be identified by such properties as temperature and salinity, are superimposed on the general north-eastward motion.

In the easterly wind zone there is a component of motion towards the west at the surface, often extending to depths of several hundred metres.

There is ample evidence (e.g., Deacon, 1937; Sverdrup *et al.*, 1942), that the whole main body of flow is deflected to the north on approaching a ridge from the west, but to the south when the depth increases.

South of the Antarctic Convergence, three main water masses can be distinguished—Antarctic Surface Water, Deep, and Bottom Waters. North of the Antarctic Convergence there is a further water mass, the Antarctic Intermediate Water, which sinks near the Antarctic Convergence.

In winter almost the whole of the Antarctic Surface Water forms a homogeneous surface layer with temperatures near freezing point ( $-1.8^{\circ}$  to  $-1.9^{\circ}\text{C}$ ) and salinities of 34.0–34.5‰

in southerly regions. The temperature of this layer increases northward from the edge of the pack-ice. During spring and summer, the surface of this layer is warmed and the salinity is lowered to less than 34.0‰ by the addition of fresh water from melting pack-ice and precipitation. In winter the surface water is cooled, and mixed downward through convection and wind action. Far south, ice formation leads to an increase in salinity and the consequently increased surface density further encourages mixing.

Below Antarctic Surface Waters lies Deep Water with higher temperature and salinity than winter Surface Water above, or the Bottom Water below. This Deep Water originates mainly in the North Atlantic Ocean, where highly saline surface water cools and sinks. It moves southward as the North Atlantic Deep Current and mixes on the way with high salinity Mediterranean water. Near 40°–50° S most of this Deep Water moves eastward after mixing with water of slightly lower temperature and salinity which has come through Drake Passage from the Pacific Ocean. Still further east it mixes with Indian Ocean Deep Water which is partly derived from high salinity Red Sea Water.

The Deep Water has two distinct layers. South of the Antarctic Convergence the lower layer is characterised by a salinity maximum and salinities greater than 34.66‰, and rises steeply towards the surface near the convergence. The upper layer may be recognised by a temperature maximum and has a salinity (34.50‰ approximately) greater than that in the Surface Water, but less than that in the lower Deep layer (34.66‰). North of the convergence the upper layer does not usually have a temperature maximum in the Indian and Pacific Oceans, except near the Antarctic Convergence.

Antarctic Bottom Water, characterised by lower temperature and salinity than Deep Water, is formed mainly in the Weddell Sea by winter cooling of high salinity Deep Water over the continental shelf. This water moves partly northward into the Atlantic Ocean and partly eastward in the Circumpolar Current. Some Bottom Water is also formed south of the Indian Ocean (Sverdrup, *et al.*, 1942) and perhaps in the Ross Sea (Deacon, 1937). Water from the Ross Sea does not appear to contribute towards Bottom Water

in the Pacific Sector, but merely to maintain low average temperatures in this region. These temperatures are, however, not as low as those of Bottom Water found in the Indian and Atlantic sectors of the Antarctic.

In the Subantarctic Region a vertical salinity profile often shows a low surface salinity ( $34.0-34.40/_{00}$ ), with a maximum below, and a minimum at still greater depth. The minimum is a characteristic of Antarctic Intermediate Water, which is formed by the sinking of a mixture of poorly saline Antarctic and Subantarctic surface waters near the Antarctic Convergence. This Antarctic Intermediate Water sinks and spreads northward in its general eastward motion along the surfaces of density of approximately  $\sigma_t = 27.2-27.3$ . As it moves northward, temperature and salinity increase through mixing with water above and below.

Water above the Antarctic Intermediate Water is called Subantarctic Water. This is warmer than Antarctic surface water, and its temperature increases steadily northward. In it two layers may

often be seen. Usually there is a nearly homogeneous layer between the surface and 50 or 80 m, and beneath it a layer with a salinity maximum which is sometimes very weak. This salinity maximum is quite shallow near the Subtropical Convergence and it is often continuous through the convergence, at a depth of about 75 m on the north side, increasing rapidly to about 200 m in the Subantarctic Region and about 300-500 m further south. Less than 200 miles north of the Antarctic Convergence this feature tends to weaken and may even disappear. Deacon (1937) suggests that this lower layer of Subantarctic Water must move southward since it maintains its higher salinities in spite of mixing with the poorly saline Intermediate Water moving to the north below. The surface water moves to the north in the Ekman layer (wind-mixed) driven by the westerly winds. Sverdrup (1934) argues that, in order to maintain the sharp horizontal temperature gradient observed at the Antarctic Convergence, the Subantarctic Water in both layers must move to the south, and the salinity difference must be maintained by precipitation.

## HYDROLOGICAL FEATURES

### IN THE ANTARCTIC AND SUBANTARCTIC REGIONS

#### SUBSURFACE WATERS

In general the distribution of subsurface water properties south of New Zealand, as found by the present *Pukaki-Hawea* investigations (fig. 8, 9, and 10), is in accordance with those described by previous authors (e.g., Deacon, 1937).

At Station B 28 the water at 2,000 m has a temperature of  $0.26^{\circ}\text{C}$ , indicating a mixture of Bottom Water with some Deep Water. The lower stratum of Deep Water has salinity values greater than  $34.70/_{00}$  (fig. 9) and the upper stratum has salinities between approximately  $34.4$  and  $34.60/_{00}$  in the Subantarctic Region (indicated in fig. 8 by the southward pointing tongue of warm water in the Antarctic zone). The Intermediate Water is represented (fig. 9) by a typical downward and northward pointing tongue of low salinity water between  $55^{\circ}\text{S}$  and  $60^{\circ}\text{S}$ ; salinity minima at Stations B 34 and B 36 on the western and north-eastern slopes of the Campbell Plateau show its extension to these regions.

Water characteristics at the one latitude differ considerably with longitude and with time. South of New Zealand the effect on the eastward-flowing currents of the Macquarie-Balleny Ridge, the channel between the Macquarie Islands and the Campbell Plateau, and other topographic features (fig. 1) gives rise to differences of salinity in an east-west direction. *Discovery* Stations 2768-2771 (Anon., 1957) show that at  $175^{\circ}\text{E}$ , in November 1950, the upper layer of Deep Water which had a temperature greater than  $2^{\circ}\text{C}$  penetrated southward beyond  $63^{\circ}\text{S}$  between 400 and 1,000 m. In the present section ( $169^{\circ}\text{E}$ , fig. 8) and another near  $163^{\circ}\text{E}$ . (*Discovery* Stations 2201 and 2213, January-February 1938) this water was not present south of  $62^{\circ}\text{S}$ . This trend of isotherms to the south-east, supports a general trend suggested by Deacon (1937, fig. 22) and also based on rather meagre data.

Changes of water characteristics with time are well illustrated by the difference in maximum

salinities in two sections through Deep Water between the Macquarie and Auckland Islands. One is Section 14 of Deacon (1937) drawn from *Discovery* data observed in June–July 1932; the second is drawn from measurements from the Research Ship *Ob* during April, 1956 (*Ob* Stations 56–77, Anon, 1958). Part of the *Ob* section is reproduced in fig. 11. In the *Discovery* section the maximum salinities were about 34.740/00; in the *Ob* section maximum salinity was 34.820/00. These differences support the suggestion (Deacon, 1937, p. 102) that higher salinities in Deep Water to the east of New Zealand may have been due to fluctuations in the salinity of Deep Water passing to the south of Australia from the Indian Ocean. Wüst (1929) did not consider this possibility in attempting to explain salinities which were higher to the north of New Zealand than farther south and found it necessary to postulate that high salinity water should sink from a surface source somewhere in the Pacific Ocean. The present author considers Wüst's hypothesis is unnecessary.

The high salinities to the north may support Stommel's theory (1958) that east of New Zealand, water below 2,000 m flows northward, as part of a circulation system which is required by continuity to balance an upward transfer of mass throughout most of the oceans.

There is a sharp horizontal salinity gradient between 52° 06' S and 52° 36' S along the *Ob* section between the Macquarie and Auckland Islands near longitude 162° 40' E (fig. 11). Surface salinity rises from 34.04 to 34.420/00 a short distance to the north-east, and further increases to 34.530/00 with another 0.6° decrease in latitude. The downward sloping tongue of low salinity is such that isohalines for 34.1–34.40/00 extend to depths of about 220, 330, 560, and 1,080 m respectively. It is possible that the isohalines in the *Pukaki* section (fig. 9) follow a similar distribution and that a steep surface salinity gradient occurs near 55° S–56° S.

A steep gradient of surface salinity was also observed in the N.Z.O.I. investigations near 55° S and 173° E (fig. 2) but was not observed on the *Pukaki* return voyage farther west where samples were taken only at stations. By constructing isohalines with a steep front near this position, (corresponding to that of the temperature tongue (fig. 8)), it is possible to minimise the vertical density tongue (fig. 10). The general impression given by such amended versions of fig. 9 and 10 remains the same: the intensity of the disturbance

in the  $\sigma_t$  section is only slightly reduced and the 34.1, 34.2, and 34.30/00 isohalines still lie close together through the cold tongue, with maximum depths near 400, 600, and 800 m respectively.

#### THE ANTARCTIC CONVERGENCE

A "convergence" at the sea surface may be defined as a point or line towards which there is mean motion of surrounding surface water and at which sinking occurs. In the major oceans "convergences" are regions in which sinking of surface water may occur and in which converging water may be transferred by accelerated surface currents. The Antarctic Convergence usually extends through one or more degrees of latitude with surface water moving towards it on the south side, and sinking may occur throughout a zone extending from slightly to the south to somewhat north of the convergence region; the meridional motion of surface waters on the north side, however, is still in dispute. The Antarctic Convergence is often marked by a steep meridional gradient of surface temperature but not of salinity.

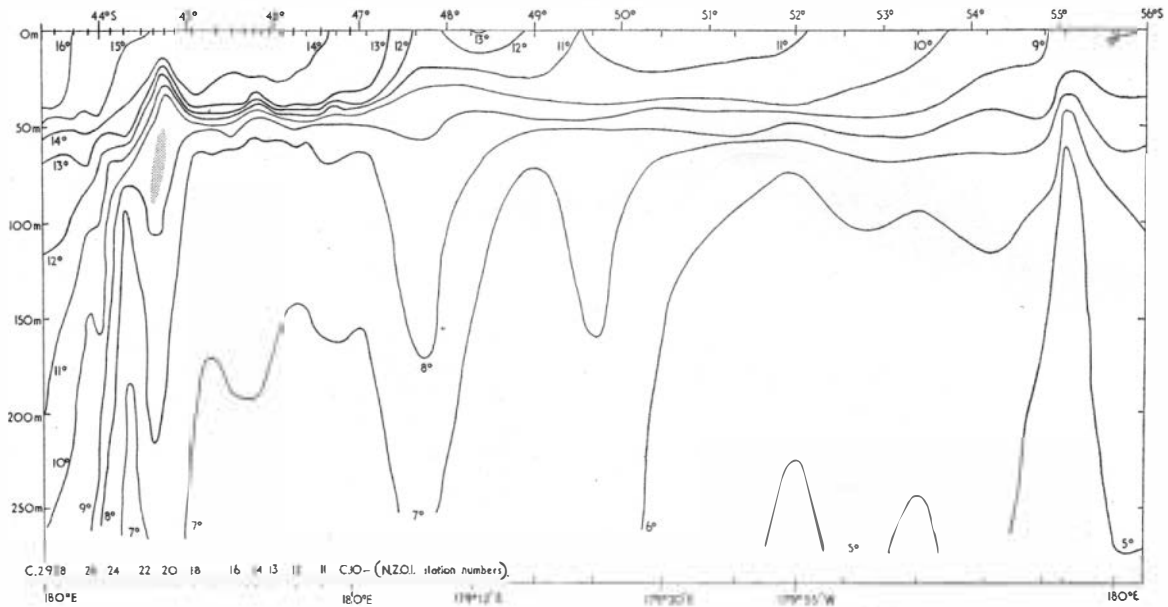
The Antarctic Convergence is usually located by determining the centre of the zone where the north-south surface temperature gradient is at a maximum. For the present data this lies close to the 4°C isotherm (fig. 2), and agrees with the mean mid-temperature for December–January found by Mackintosh (1946). However the observed position lies south of the mean positions plotted by Mackintosh (about 59° S near 170° E, and 60° S near 180° E) which are based on observations east and west of the present area and one observation within the area. From data published by Lyman (1958), the mid point of the convergence in this region is near 52° 40' S in the December to February period, or about 30 nautical miles south of the mean of the three positions shown.

Mackintosh (1946) gives an alternative definition for the location of the convergence—that position at which the temperature minimum sinks below 200 m. However, the present and earlier data indicate that the position of the subsurface temperature minimum may fluctuate between positions 1°–2° of latitude south of the surface feature and up to 4° north of it (fig. 4a).

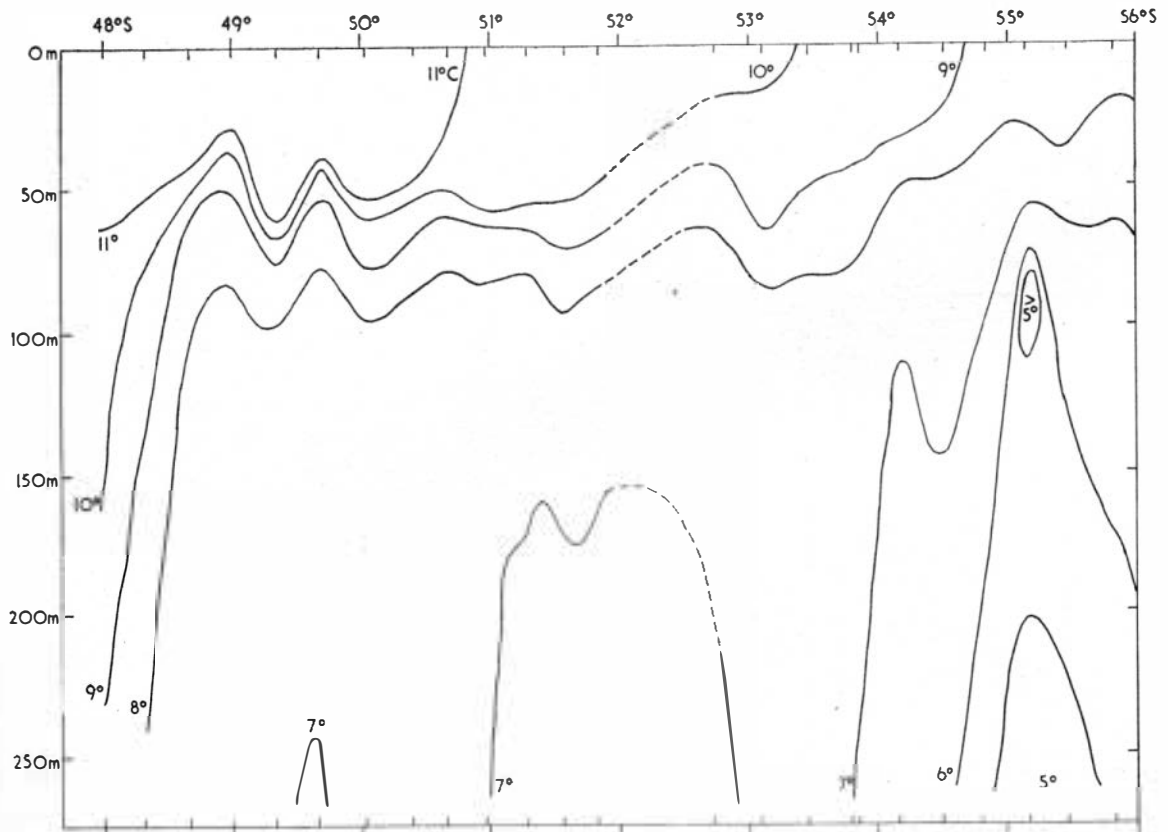
From Deacon (1937) it would appear that winter water just south of the convergence has a temperature of about 1°C. In the present data, the 1°C isotherms (fig. 4a and 4d) slope rapidly downward towards the north from about 100 m

Fig. 3: Distributions of temperatures ( $^{\circ}\text{C}$ ) from bathythermograph observations, in sections (depth against latitude) along *Hawea* and *Pukaki's* tracks (fig. 1) north of latitude  $56^{\circ}\text{S}$ .

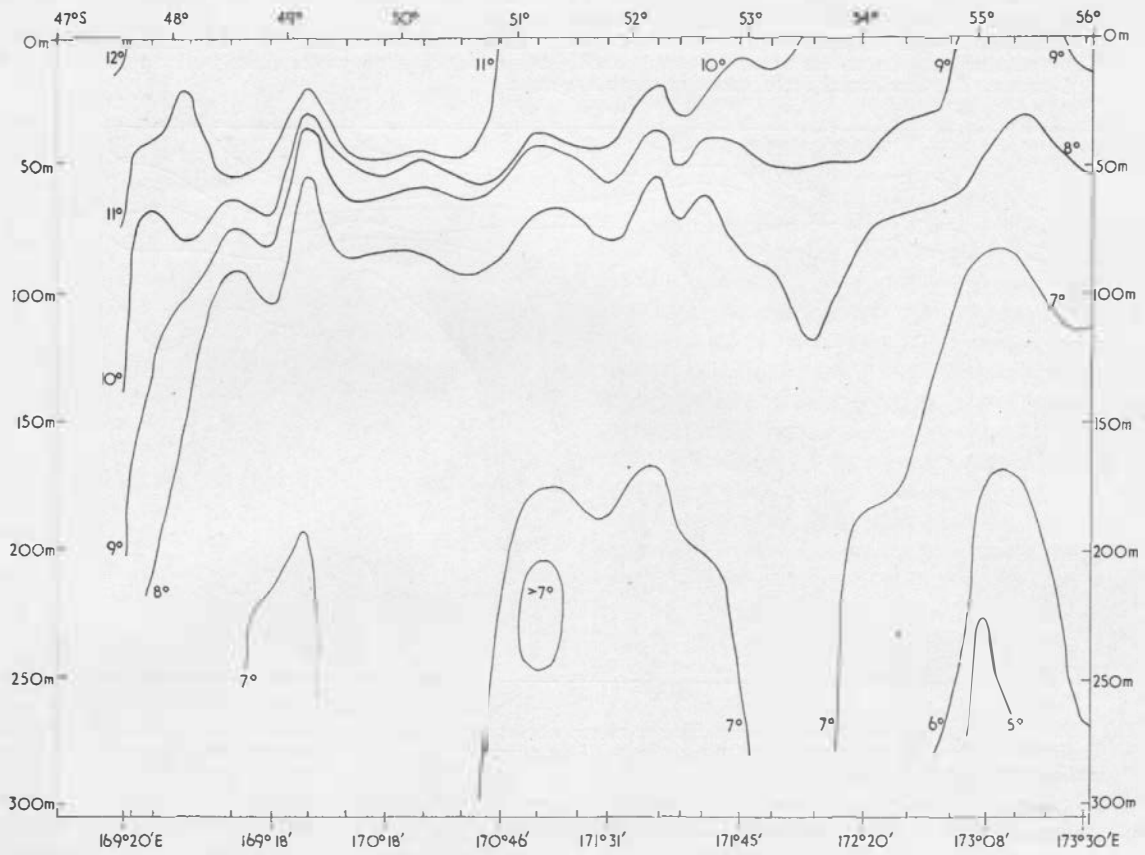
The latitude of each observation is marked at the top of each diagram; the longitudes may be linearly interpolated between values entered beneath each diagram which show where there were appreciable changes of course. The horizontal scale varies in these diagrams.



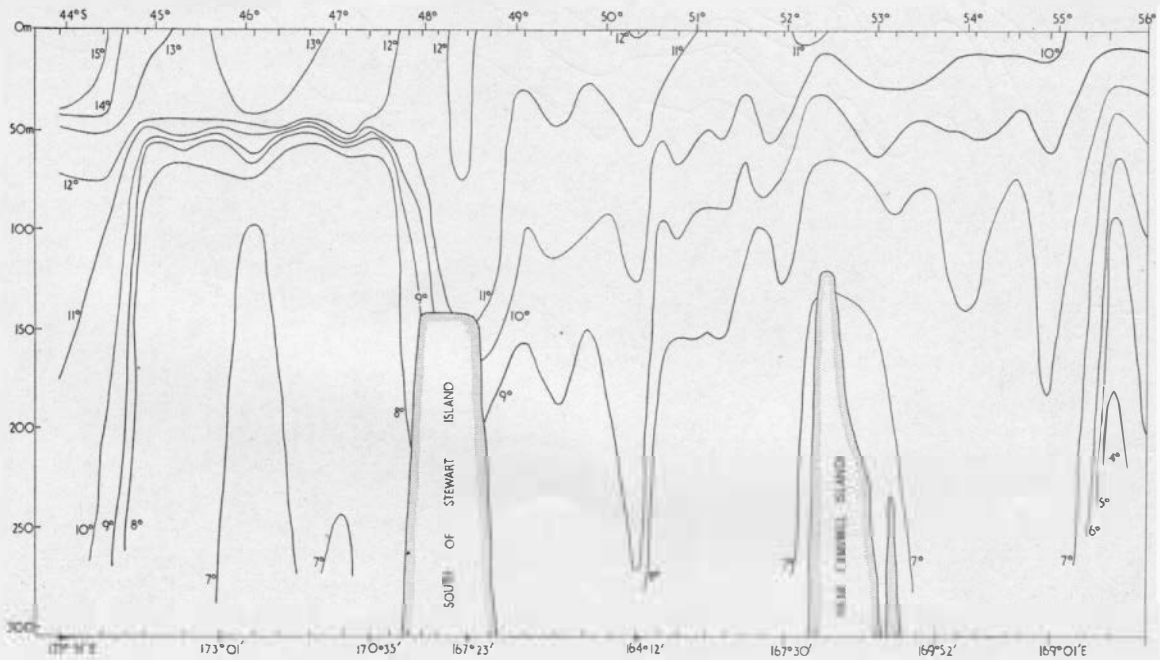
(a) Bathythermograph observations from *Hawea* along northward track. The positions of shallow stations are indicated at the top and bottom of the diagram. The stippled area shows the position of a pocket of high salinity water.



(b) Bathythermograph observations from *Hawea* along southward track (5 miles to east of *Pukaki*).



(c) Bathythermograph observations from *Pukaki* along southward track (5 miles to west of *Hawea*).



(d) Bathythermograph observations from *Pukaki* along the northward track.



*Plate 1. Bathythermograph observations from HMNZS Pukaki*



*Plate 2. Reading reversing thermometers on board HMNZS Pukaki*

*facing p. 18*

but turn back southward at about 250 m beneath the tongue of cold winter water; the most northerly position of this 1°C tongue is close to the convergence. Bathythermograph sections from other observations in this region (e.g., three sections in Garner (1959), four sections in Lyman (1958)) during November to March, show a similar pattern with the 1°C isotherm varying in greatest depth from 180 m to more than 270 m.

The maximum northward reach of the continuous 1°C isotherm lies no more than 2° of latitude north of the maximum surface temperature gradient. Even where an anomalous situation apparently occurs, such as near the cold tongue at 62° S (fig. 4b and c) which is the deepest observed penetration of water colder than 1°C, or where a detached mass colder than 1°C appears to the north (fig. 4d), this is still true for the data inspected. No other detail of the temperature structure appears to agree so consistently with the position of the surface feature. It is therefore suggested that where the surface gradient is not well defined, or is obscured, and bathythermograph observations are available, the northward extension of the continuous 1°C isotherm can be used to locate the convergence between November and March in this region. This question has not been pursued further for other regions nor for winter conditions; however, Midttun and Natvig (1957), indicate from *Brategg* data that the 1°C isotherm and the steepest surface temperature gradient lie within 1° of latitude in the Pacific Ocean near 90°, 120°, and 150° W in December and January. This is supported by one section at 148° E in Lyman (1958).

#### ANTARCTIC SURFACE WATER

The coldest Antarctic Surface Water was found within the pack-ice belt just south of Scott Island (fig. 2). Both north and south of the belt the open water is warmed by solar radiation.

Both surface salinities and temperatures (apart from some minor fluctuations) decrease with distance southward to the point just south of Scott Island at which the two frigates left *Endeavour* (fig. 1). This was about 6 miles inside loose mushy pack at the edge of the main pack-ice belt. Near the convergence, the surface is warmed at the start of summer and the effect of precipitation and melting and the northward motion of the Ekman layer is reflected in low salinity. Further south in early summer, the salinity decreases since insolation first melts the winter pack-ice,

(which here extends to about 63° S) and summer warming of the water begins later

Salinity values show a minimum ( $<33.90/_{00}$ ), on tracks north of the convergence (fig. 2). A maximum shows up somewhat south of the convergence on the two central tracks and appears to be present just north of the convergence on the eastern track and just south of it on the western track. Because of the minimum to its north, the salinity maximum cannot be due to a southward movement of Subantarctic Surface Water. Deacon points out that the salinity maximum to the south is due to upward movement of highly saline Deep Water from beneath. These salinity maxima and minima are most distinct during summer and late autumn. This may be explained by the addition of seasonal melt-water which is carried northward in the Ekman layer to the position of the minimum. It should be noted that the present data do not conform with the usual summer distributions observed elsewhere, in that the salinity maximum lies much less than 4° of latitude south of the convergence and even slightly north of it in the east of the sector (fig. 2), and minimum surface salinities lie to the north instead of being either at the convergence or between it and the maximum. This anomaly may be due to the meridional position, to prolonged abnormal weather conditions, or possibly to disturbances in the general water motion of a more temporary nature.

North of Scott Island there is clearly a southward displacement of surface isohalines and probably of isotherms. From less detailed observations, Mackintosh (1946), has drawn monthly surface isotherms which also indicate a southward bulge, but it is much less pronounced than the shape of the tongue shown here.

Frequently there is a complete summer clearance of pack-ice along the 180° meridian, while to the east and west the pack-ice remains quite thick. This ice clearance and the surface distributions shown in fig. 2 suggest that there may be a divergence of surface waters along this longitude, perhaps due to the bottom topography near Scott I. At this latitude the prevailing winds are easterly and surface waters and pack-ice will drift westward. This drift has been observed farther west (Wordie, 1921). If this motion extended to a depth of a few hundred metres, it would be deflected southward on moving onto the shallower region near Scott Island. Deflections of this nature would produce the southward extensions of the surface contours found by

*Pukaki* and *Hawea* near Scott Island, and the forced upwelling would cause a clearance of pack-ice.

In general, *Pukaki* and *Hawea* bathythermograph sections (fig. 4) show the presence of winter water near the temperature minimum as far north as 62° S overlying warmer Deep Water and having summer-warmed water above. The depth of the minimum temperature increases in all sections, from the south towards the Antarctic Convergence, except where influenced by fluctuations due to internal waves and/or other disturbances. Features illustrating northward motion and sinking of winter water and of the surface layers are somewhat obscured by mixing; but the nature and extent of these motions and of summer warming is indicated by water colder than 2°C (shaded areas, fig. 4 and 5), and water less than 0°C (darker shading).

The southernmost observation was made about 6 miles inside loose mushy pack-ice. The coldest water at this position was only 10–15 m from the surface and only very slight warming of winter water had taken place. It is usual, according to earlier investigators (Deacon, 1937; Lyman, 1958), to observe almost isothermal water (–1.5°C) beneath true pack-ice—which lies only a few miles farther south of 68° S—to a depth of at least 50 m and more often to 100–200 m. The unusually shallow depth of the minimum at 66° 30' S found by *Pukaki* and *Hawea* (fig. 4c) supports the suggestion, put forward to explain the summer clearance of ice-pack south of Scott Island and the associated southward extension of isohalines (fig. 2), that upwelling occurs near the 180° meridian.

North of the pack-ice, in summer, the surface is warmed and the temperature decreases downward through the upper layer to nearly freezing point (–1.8 to –1.9°C) at the temperature minimum. The minimum increases northward to about 1°C near the convergence. Observed temperature minima in all *Pukaki* and *Hawea* sections conform with mean values given by Deacon (1937).

From observations during the *Bratigg* Expedition east of 175° W, and from *Discovery* stations to the west, Midttun and Natvig (1957), show that in the Antarctic Region the depth to the Upper Deep Water is greatest (>200 m) at the convergence. (The depth to Antarctic Upper Deep Water is defined as the depth to the greatest vertical temperature gradient between the temperature minimum and the warmer Deep Water beneath). To the south this depth decreases to

between about 100 m and 150 m but it then increases again still farther south. Midttun and Natvig's observed least depths of the minimum were about 80 m near 66° S, at 165° W to 175° W. The corresponding *Pukaki* and *Hawea* depth was about 100 m near latitudes 64° S–66° S. This is where the maximum rate of Deep Water upwelling occurs.

The presence of internal waves is indicated by a wave-like structure through the winter water; the structure is evident to some extent in the bathythermograph sections south of 56° S, more especially where the sampling interval is least (fig. 4, 5).

#### AUSTRALASIAN SUBANTARCTIC WATER AND CIRCUMPOLAR SUBANTARCTIC WATER

Between the Subtropical Convergence Region and the Antarctic Convergence is the Subantarctic Region. Here, distinct types of Subantarctic Surface Water are present above 600 m. Subantarctic Water south of the Atlantic and Western Indian Oceans and the east of New Zealand is mostly less saline than 34.50/00. In these regions, salinities between 34.5 and 34.80/00 occupy only a narrow zone in the upper 200 or 300 m. This zone is usually not more than about 2° of latitude wide and lies just south of the Subtropical Convergence. However, just south of the convergence between 100° E and 167° E in the Australasian Region, water of this higher salinity, >34.50/00, is present to depths of 400–600 m. or more (fig. 16, 17, and 18), and water with salinities in excess of 34.50/00 extends as much as 7°–8° of latitude further south. Some observed positions of the boundary between the more saline and less saline types of Subantarctic Water are shown in fig. 13; Chart 1 shows its positions between 157° E and 180° E deduced from observations on *Pukaki* during summer (early January 1957) and from *Ob* in autumn (April 1956). It is proposed that Subantarctic Water north of the boundary be called "*Australasian Subantarctic Water*" since it exists mainly south of the Australasian Region; and that the Subantarctic Water to the south be called "*Circumpolar Subantarctic Water*".

The southern boundary of Australasian Subantarctic Water is here called the Australasian Subantarctic Front. The eastern boundary crosses the Campbell Plateau between Campbell and Auckland Islands and continues northward towards New Zealand to meet the southern bound-

ary of the Subtropical Convergence Region. This boundary is described later as the Southland Front.

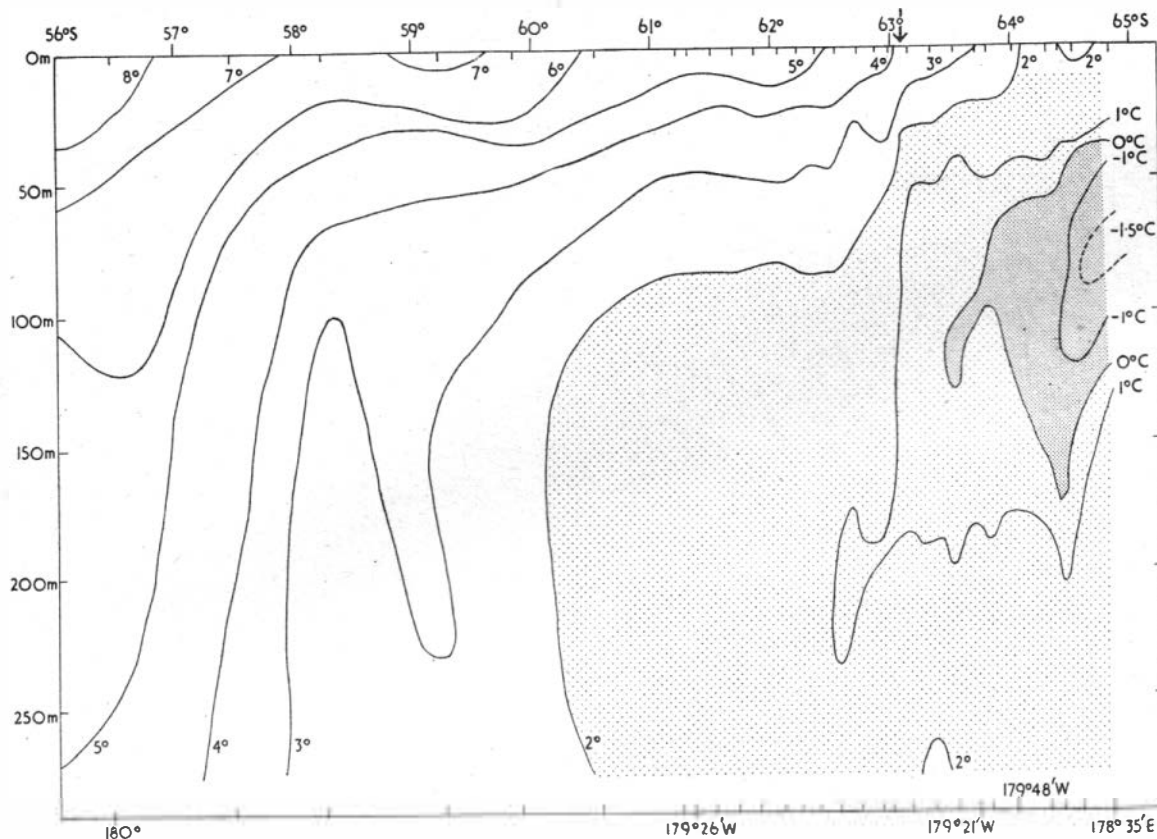
The Australasian Subantarctic Water thus includes Garner's Campbell Plateau Water (Garner, in press): it originates, as Garner suggested, through a relatively greater southward transfer of higher salinity water across the Subtropical Convergence south of the Eastern Indian Ocean and the Tasman Sea than elsewhere. Australasian Subantarctic Water is usually colder than 8°C below 400–600 m or more, but warmer above, whereas Circumpolar Subantarctic Water is colder than 8°C below 200 m except for a very narrow zone near the Subtropical Convergence (fig. 3a, 8 and 11, and 13 to 18).

Over the Campbell Plateau the position of the 34.30/00 isohaline shows that there is a marked south-eastward surface extension of Australasian Subantarctic Water. Isotherms drawn by Garner (1959) from surface temperatures, observed in

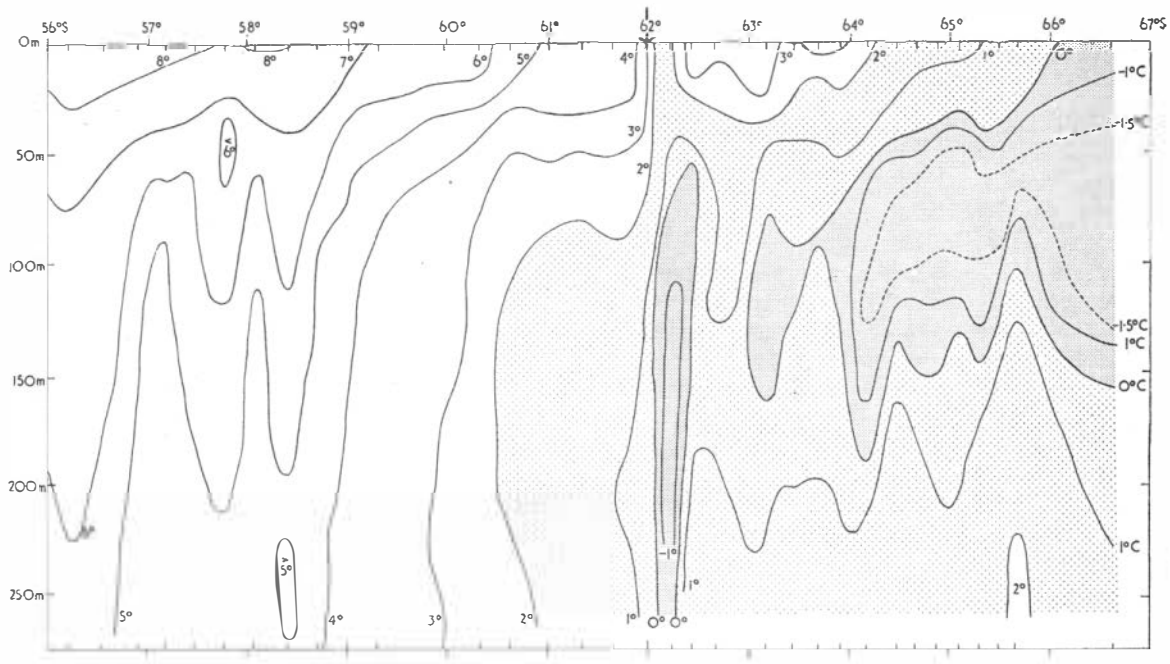
April 1951 along a triangular course between Dunedin, Campbell Island and a point near 50° S, 175° E, are similar to the *Pukaki-Hawea* isohalines. (Positions of the 10°C and 11°C isotherms may have been affected in the interval between observations by warming of water along the eastern *Hawea* track; if this effect were allowed for, these isotherms would then resemble more closely the shape of the isohalines for 34.3 and 34.40/00.)

Particularly noticeable in the bathythermograph sections (fig. 4) is the variability of the temperature structure over some six degrees of latitude north of the Antarctic Convergence. This is shown by fluctuations in the relative depths and positions of the 4°, 5°, and 6°C isotherms. Together with the relative constancy of the 1°C isotherm farther south (and to some extent of those for 2°C and 3°C), this suggests that much mixing takes place here down to greater depths than were reached by the bathythermographs.

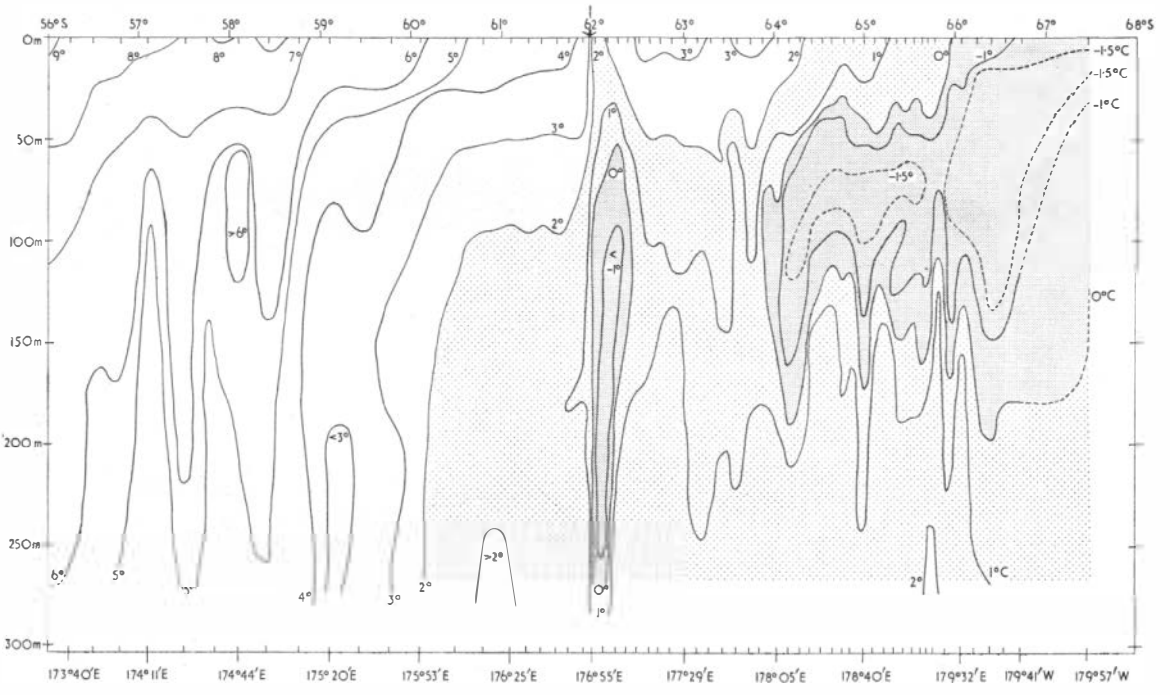
Fig. 4: Distributions of temperature (°C) from bathythermograph observations in sections along *Hawea* and *Pukaki* tracks south of latitude 56° S (Legend as in fig. 3). The light stipple indicates the northwards penetration of Antarctic Water and the darker stipple the main core of Winter Water.



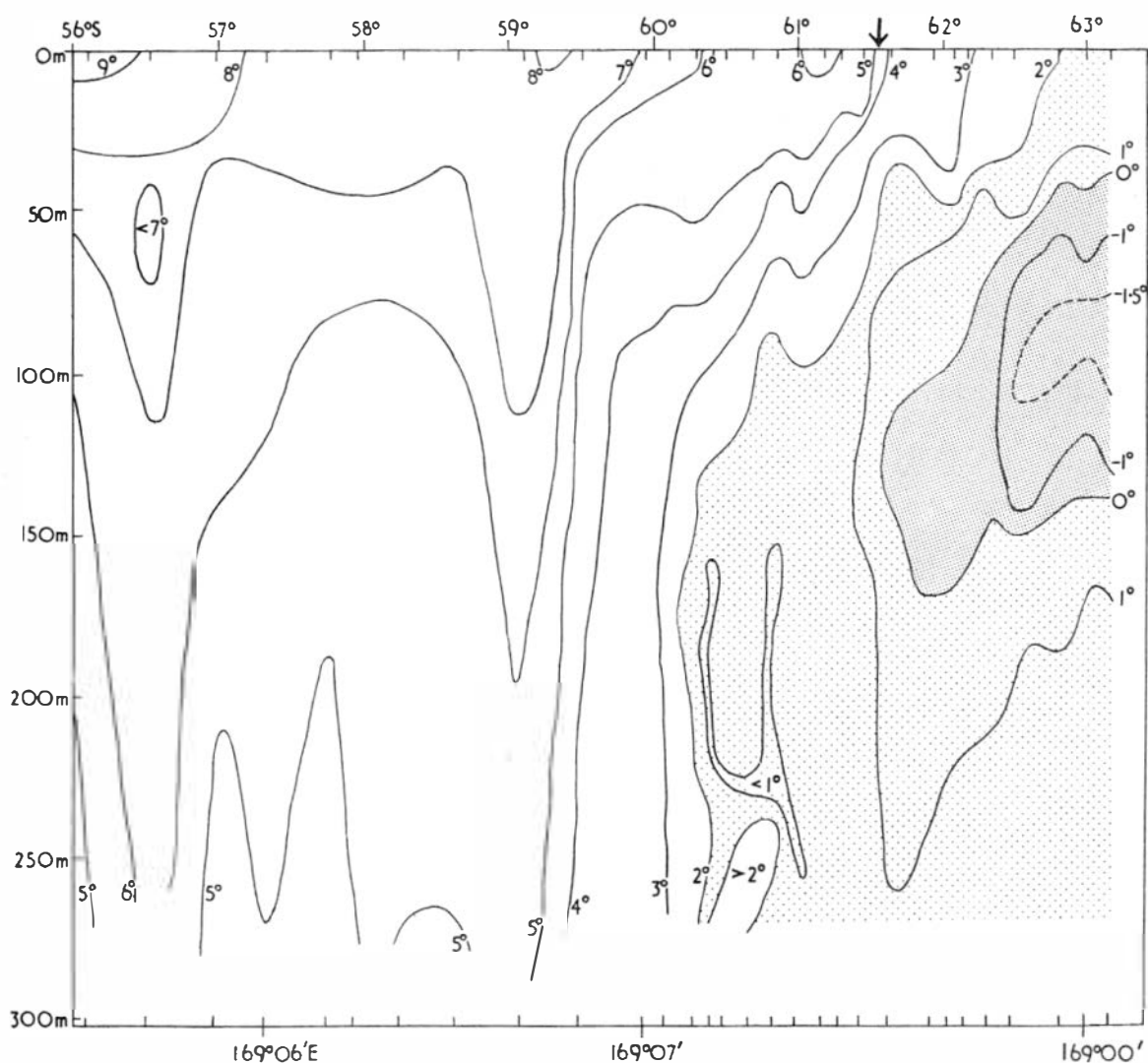
(a) Observations from *Hawea* (northward voyage).



(b) Observations from *Hawea* (southward voyage—5 miles east of *Pukaki*).



(c) Observations from *Pukaki* (southward voyage—5 miles west of *Hawea*).



(d) Observations from *Pukaki* (northward voyage).

This agrees with the idea that the Antarctic Intermediate Current originates near the Antarctic Convergence through the sinking of mixed Subantarctic and Antarctic Surface Waters (Deacon, 1937). The rapid increase in salinity northward of the salinity minimum in Antarctic Intermediate Water is due to mixing which probably occurs quite near the surface. The cold tongue between 55° S and 56° S which appears in each *Pukaki* and *Hawea* section (fig. 3) may be associated with this mixing process, but it is more likely that it represents a stream of cold water.

#### WARM SALINE WATER SOUTH OF NEW ZEALAND

The general configuration of isolines just south of New Zealand (fig. 2) suggests an intrusion,

from the west around the south of the South Island, of water which is warmer and more saline than Subantarctic Water to the east and south. A similar intrusion was described by Bary (1956) and Garner (1959). The present observations show that this is most intense inshore and extends some distance up the east coast. Near Dunedin, it is cut off from Subtropical Water farther north in the warm saline tongue indicated by the 15°C and 35.0‰ isolines, by cold, poorly saline water which has upwelled from shallow depths. The presence of the warm saline water cannot therefore be explained by an extension to the south of Subtropical Water from north-east of Banks Peninsula; it must arrive from the Tasman Sea west of New Zealand.

Predominantly Subantarctic Water with temperatures less than 8°C is present at depths greater than 100 m over the southern and eastern portion of the Campbell Plateau (fig. 3b, 3c, and 3d; south of 50° 30' S). Along the 180° meridian, Subantarctic Water extends much further northward to the Subtropical Convergence in 44°–45° S. The convergence is clearly shown by the closeness of the 8°C to 11°C isotherms and by a steep surface gradient of the isohalines (fig. 2).

A north-eastward trend in subsurface isotherms over the plateau may be seen by comparing the western bathythermograph section (fig. 3d) with those further east (fig. 3b and 3c). The 8°C isotherm for example appears over the plateau at 250 m in the western section south of 50° S, while on the eastern side, this isotherm is near 48° S; it apparently turns more sharply northward in the distance (5 miles) between the two eastern sections. The great vertical spacing of the isotherms between 49° S and 52° S (fig. 3d) appears to indicate intense vertical mixing.

The *Ob* section (Moroshkin, 1958; Anon. 1958) between Macquarie Island and the Auckland Islands (fig. 11) shows a temperature increase from 7.9° to 9.5°C at a steep salinity gradient, while the 8°C isotherm slopes downward to meet the shelf at about 300 m.

A tongue of high salinity water extends outwards and upwards from the steep slopes just south-west of the Auckland Islands. Water with salinity values greater than 34.60/00 lies between 200 m and 400 m at the slope, and at 100 m near 52° 12' S at the tip of the tongue. This is about 100 miles south of *Pukaki* Station B 34 at which highly saline warm water is present between 75 m and 250 m (fig. 8 and 9). This water contributes to the formation of the Campbell Plateau Water of Garner (in press).

A remnant of this tongue is indicated by higher salinity values at Station B 32 much further east and south, between 25 m and 235 m (table 1). Both the *Ob* and *Pukaki* observations show that Circumpolar Subantarctic Water, with temperatures below 8°C and salinities less than 34.50/00, was present on each occasion over most of the Plateau roughly east of the 34.50/00 isohaline shown in fig. 2. At *Ob* Station 76, mid-way between Auckland and Stewart Islands, salinities less than 34.40/00 occurred at all depths above 400 m. Water of much higher salinity was observed both to the north and in the tongue south of this position.

#### AUSTRALASIAN SUBANTARCTIC FRONT

A sharp "front" existed in April, 1956 between *Ob* Stations 71, and 72 and 73 (fig. 11, 17): that is, at the boundary of the two Subantarctic Water Masses. This feature is defined by the close spacing of the 34.3–34.60/00 isohalines and the 7°C and 8°C isotherms. A similar front was present between *Ob* Stations 98 and 99 (fig. 16) and between the pairs of *Discovery* Stations 2144 and 2145, 899 and 900. It is well developed in sections including *Ob* Stations 70 to 77 and 92 to 100 (Moroshkin, 1958); it is less clearly developed in sections drawn from *Discovery* data (*Discovery* Stations 869 to 926, Sections 9–13, Deacon 1937). It is probable that this front also exists west of 165° E near the southern boundary of Australasian Subantarctic Water, and that there is a steep south-north horizontal gradient of characteristics across it—roughly between salinities of 34.4–34.50/00 between 150 and 400 m, while temperature increases 1°C or more (e.g., from less than 7°C at *Ob* Station 99, to more than 9°C at *Ob* Station 98) between 150 m and 200 m.

Observations from December to May in any year indicate that Australasian Subantarctic Water and its associated Front may extend much further south of the Subtropical Convergence in the Tasman Sea in early summer and late autumn than in mid winter. The seasonal spread of the observations is too limited to make any positive assertions regarding seasonal trends, but Australasian Subantarctic Water may exist through a narrower zone of latitude during winter. This implies either a decrease in the transfer of warmer, more saline water to the south during late autumn and winter, or an increased transfer of Circumpolar Subantarctic Water to the north at this time; this latter transfer could be associated with an increasing movement of Antarctic Surface Water to the north and an increasing tendency for water just north of the Antarctic Convergence to sink as Intermediate Water with the approach of winter. The Australasian Subantarctic Front reaches to 1,000 m or more (fig. 11, 16, and 17).

#### GENERAL WATER MOVEMENTS OVER THE CAMPBELL PLATEAU

Australasian Subantarctic Water intrudes southward along the western edge of the plateau as far as the Auckland Islands. This rapidly mixes with colder, less saline water as it moves eastward so that the characteristics at Stations B 32 and B 33 near Campbell Island are predominantly typical of Circumpolar Subantarctic Water fur-

ther south or east of New Zealand. However, the salinity is greater than at *Ob* Station 76 midway between Auckland and Stewart Islands or at Station B 36 farther north. These observations (particularly at *Ob* Station 76 and *Pukaki* Station B 36) imply,

- (a) north-westward flow of Subantarctic Water deeper than 100m over the south-east of the Plateau, or
- (b) south-westward flow from the east of the South Island, or
- (c) eastward flow of poorly saline water from west of Station B 34 above the higher salinity tongue.

The presence of such poorly saline water in June 1932, north-west of Station B 34 is shown by *Discovery* Station 923, but to account for the observed distribution during January 1957, such low salinity water would have had to flow above the water in the high salinity tongue (compare Station B 34) as a restricted stream between stations during observations north of latitude 51° S from both the *Pukaki* and the *Ob*. Since the presence of such a stream is most improbable some other explanation must be sought. It is therefore postulated that an anticlockwise flow occurs in a gyral extending over the Bounty Trough and the north-eastern area of the Campbell Plateau. This feature is here named the *Bounty-Campbell Gyral*.

The tongue of water of relatively high surface salinity projecting south-east of Campbell Island (fig. 2) must be due to mixing of Subantarctic Surface Water from both the south-west and north-east with water in the high salinity subsurface tongue extending around the edge of the Plateau.

Water in this tongue moves eastward on the southern side of low salinity gyral water. Water in the subsurface, higher salinity tongue is derived from Australasian Subantarctic Water farther west. The much more saline water found at Station B 35 south of Stewart Island is typical of water observed within, or very close to, the Subtropical Convergence Zone.

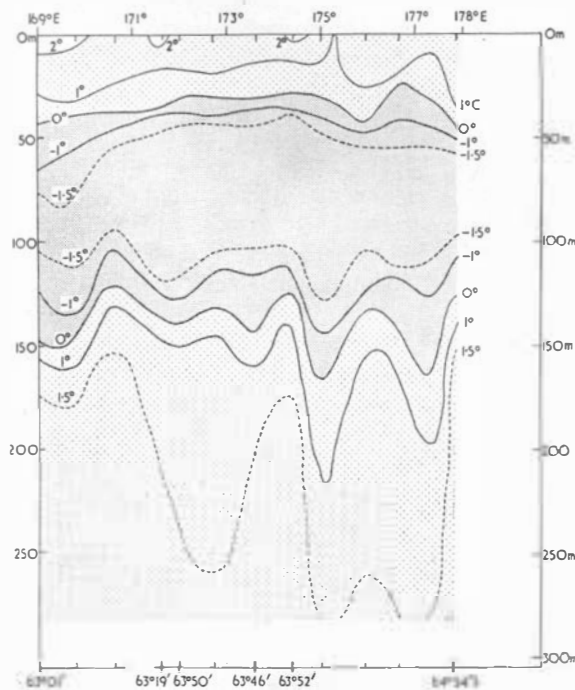


Fig 5: Distribution of temperature (°C) from bathythermograph observations from *Pukaki* between 65° S, 178° E, and 63° S, 169° E. Stippled areas may be compared with those in fig. 4.

## THE SUBTROPICAL CONVERGENCE REGION

### INTRODUCTION

This section describes the Subtropical Convergence and northern Subantarctic Water south of the Atlantic, Indian, and western Pacific Oceans with special reference to the Australian and New Zealand regions. *Discovery II*, *Ob*, *Derwent Hunter*, and *Pukaki-Haweia* data have been used but it has not been practicable to discuss data from other sources. A complete discussion using all available data (e.g., from *Meteor*, *Gauss*, *Deutschland*, *Galathea*, *Dana*) could well yield much further information.

The Subtropical Convergence extends through a region. Subtropical Surface Water is present to the north, and, according to Deacon (1937), Subantarctic Surface Water approaches it from the south. There is usually a general sinking throughout the region, particularly in winter.

The Subtropical Convergence is usually marked by a steep salinity gradient and a much less pronounced temperature gradient. Where it is subject to coastal influences it may not exhibit the usual convergent motions of surface waters. It is

therefore regarded here simply as a boundary region separating different water masses

East of New Zealand the Subtropical Convergence occupies a narrow band of latitude and separates Subantarctic and Subtropical Water. The upper and lower surface salinity values are roughly 35.0 and 34.50/00. West of New Zealand waters with surface salinities between these values extend from about 41° S–51° S. The position of the convergence, as described by previous authors, depends on the arbitrary surface temperature and salinity values chosen to define its central characteristics.

Deacon (1937) concluded that surface water north of the 14.5°C isotherm in summer and the 11.5°C isotherm in winter belongs to the Subtropical Water mass moving towards the south, and is not mixed with any Subantarctic Water. Using this criterion Deacon constructed a mean annual position of the Subtropical Convergence from monthly temperature charts and some *Discovery II* observations. The position of the convergence in the Australian and New Zealand sectors as determined by Deacon, is shown in fig. 13 and 19.

#### ATLANTIC AND WESTERN INDIAN OCEANS

The T–S characteristics at five groups of stations in the Atlantic Ocean extending across the convergence and two groups near 40° E and 70° E in the South-western and Central Indian Ocean (fig. 15) show clearly the general distinction between Subantarctic Water and Subtropical Water. Lines for salinities 34.7–34.00/00 and for  $\sigma_t = 26.8$  allow comparison with convergence features in other regions. The boundaries of the characteristics for Sverdrup's South Atlantic Central Water (S.A.C.) and Western South Pacific Water (W.S.P.C.) (Sverdrup *et al.*, 1942) may be compared. These boundaries roughly define the characteristics below 100 m of Subtropical stations to the north of those considered here. (The upper boundary of Sverdrup's Indian Ocean Central Water for salinities 34.6 and 35.60/00 lies 0.35° and 0.8°C below that for W.S.P.C. Water and the lower boundary is 0.3°C below that for W.S.A.C. Water for salinities in this range.

From both Deacon's surface temperature criterion (taking into account the season of observation), and from the general appearance of the curves (fig. 15), it is not difficult to identify the water mass at each station except at *Ob* Station

125. Those stations with salinities greater than 34.80/00 at 200 m are clearly in Subtropical Water; Stations 847 and 1807 are evidently very close to the convergence region but their distinct differences from stations to the south show that they are predominantly Subtropical. *Ob* Station 125 is evidently within the convergence region. At the northern stations, the  $\sigma_t$  values at 250 m are below 26.8 while at Subantarctic stations to the south they are greater than 26.8. A normal Subtropical salinity maximum occurs at Station 673. At Stations 847 and 1772 there is a salinity maximum at greater depths; this is probably connected with downward transfer processes near the convergence.

The Subantarctic Water salinity maximum is present at each Subantarctic station although poorly developed at Station 1808. In the Atlantic sector, less than 2° south of the convergence as deduced from these observations, the depth of the salinity maximum is at 150 m (Station 671). South-east of South Africa the salinity maximum is at 50 m.

Poorly saline water, with salinities below 34.50/00, is present at all depths above the Antarctic Intermediate Current at Stations 848 (salinity <34.30/00), 671, 1774, and 1808. These are within 4° of latitude of the convergence in the Atlantic sector. Subantarctic Water, more saline than 34.50/00, was observed only at Stations 1773, 2026 (in Atlantic Ocean), and 1613 (in south-western Indian Ocean), within about 2° of the convergence, and in the high salinity tongue at Station 2025 (about 4° of latitude south of the convergence in the Central Indian Ocean, Subantarctic Water salinities are much less than 34.50/00.

The mid positions of the convergence, found by interpolation from observed characteristics and station positions, are given in fig. 15. These differ by less than 2° of latitude from the positions indicated by Deacon (1937). The characteristics of some *Discovery* stations (part of Section 7, Deacon, 1937) have not been plotted since they show an unusual intrusion of Subtropical Water into the Subantarctic Region, and the convergence is not clearly defined. Fig. 15 indicates that the convergence position does not usually vary by more than one or two degrees of latitude, but there may be larger variations when there are unusual extensions of one water mass into another.

Where a summer thermocline exists in Subantarctic Waters, (e.g., at *Discovery* Station 2026), it always lies above the salinity maximum. North of the convergence, the maximum lies

within the thermocline (as at Station 673), but the situation is confused near the convergence at Stations 847 and 1772.

#### EAST INDIAN OCEAN AND SOUTH OF AUSTRALIA

Subantarctic Water in the sector of the Indian Ocean between 100° E and 147° E (fig. 16; Station positions, fig. 13) is rather different from Subantarctic Waters in the sectors south of the Atlantic Ocean, the western and central Indian Ocean, and to the east of New Zealand.

At *Discovery* Stations 893 and 2144, *Discovery* stations to the south of those in fig. 13, and at *Ob* Stations 99 and 100, the salinities of Subantarctic Water at all depths are less than 34.5‰. Subantarctic Water with salinities greater than this occurs roughly north of a line 6°–8° of latitude south of the convergence (dotted line, fig. 13). A short distance further north again, except at Station 894, salinities of 34.6‰ or more occur. From the relatively great displace-

ments between the characteristic curves at adjacent stations north and south of latitude 47° S (e.g., between *Ob* Stations 98 and 99), it is clear that a steep north-south horizontal salinity gradient occurs about 7° south of the Subtropical Convergence. A similar steep gradient is apparent at a number of positions between 100° E and 165° E. It appears in a section including *Ob* stations 92 to 100 (Moroshkin, 1958) and in *Discovery* sections 9, 10, 11, 12, and 13 (constructed from *Discovery* Stations 868 to 926 by Deacon 1937); and in the *Ob* Macquarie - Auckland Islands section (fig. 11). This gradient is best represented in the *Ob* data, where observations are most frequent.

The high salinity layer in Subantarctic Water is very prominent in the Indian Ocean - Australian sector between 100° E and 147° E (fig. 16); the maximum usually occurs between 150 m and 400 m and occasionally near 100 m. Here, the  $\sigma_t$  value at the salinity maximum almost always appears to be

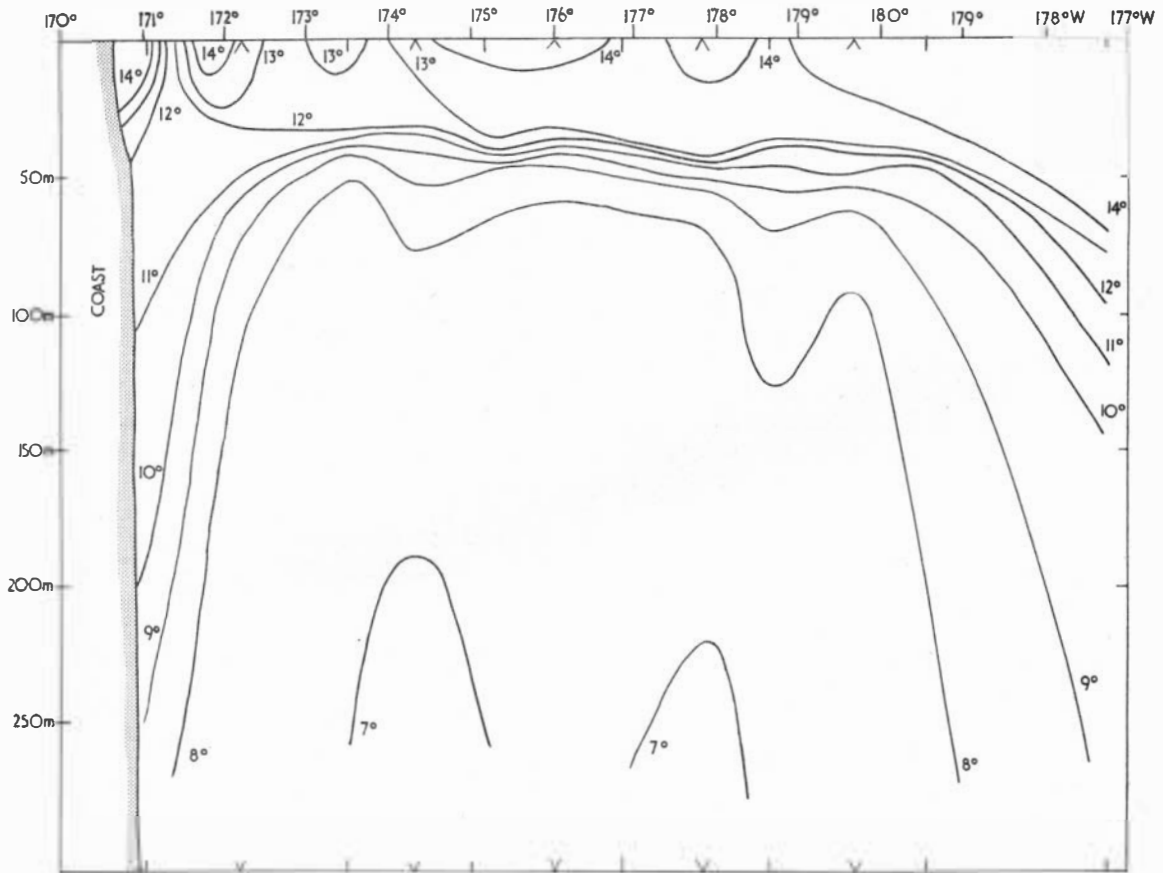


Fig. 6: Distribution of temperature (°C) between Chatham Islands and Dunedin, from bathythermograph observations taken alternatively from *Pukaki* (positions marked by short line at top and bottom of diagram) and from *Hawea* (positions marked by Vs).

between 26.8 and 26.9, except at stations obviously within the Subtropical Convergence Region; at these the maximum salinity occurs mainly at shallower depths, and at lower  $\sigma_t$  values. In the Atlantic and Western Indian Oceans (fig. 15) the salinity maximum apparently does not occur consistently near a given  $\sigma_t$  surface except very close to the convergence. However, its constancy in the Australian sector may apply only north of about  $7^\circ$  south of the convergence where the salinity at the maximum exceeds  $34.5\text{‰}$ ; in the Atlantic and Western Indian Ocean sectors, this region is quite narrow (less than  $4^\circ$  of latitude) and the number of stations available – three within  $2^\circ$  of the convergence – may not be sufficient to illustrate the feature (fig. 15).

The position of the Subtropical Convergence Region in the Australian sector is not always as sharply defined by station characteristics (fig. 16) as it is by the *Discovery* data from the Atlantic and Western Indian Oceans (fig. 15). On some of the ships' tracks (e.g., *Discovery* Stations 1688 and 1689, fig. 13) the region clearly lies between adjacent stations. Where a typical Subtropical salinity maximum occurs at depths less than 100 m there is also little doubt of its position. This occurs, for example, at Station 2147, but at Station 2146 the upper 300 m are well mixed and the characteristics are predominantly Subantarctic; this station must lie close to the southern limits of the Subtropical Convergence Region. The general appearance of the high salinity tongue in T-S curves (fig. 16) suggests that Subantarctic Water has salinities as high as  $34.8\text{‰}$ . At all stations in Subantarctic Water where the salinity maximum is equal to or less than  $34.8\text{‰}$  (except for *Discovery* Station 881 where there is an anomaly at 200 m), the  $\sigma_t$  value at 200 m is greater than 26.8. At all stations which are clearly in Subtropical Water, the  $\sigma_t$  value at 200 m is less than 26.8. Doubtful stations are *Discovery* Stations 895, 879, 871, 2154 and *Ob* Stations 94 and 95.

*Discovery* Stations 879 and 895 are obviously predominantly Subantarctic. Station 871 shows a Subtropical influence above 120 m with higher density waters beneath, and Station 2154 is indeterminate. At *Ob* Station 94, there is a Subtropical influence between 80 and 100 m and the low surface salinity could perhaps be explained by high rainfall, but Station 95 is quite abnormal. It displays the anomalies which can occur in this region of sharp water property and density discontinuities, particularly at 100 m

The convergence region indicated by the above

considerations is shown in fig. 13 by the shaded regions alongside the ship's tracks. This figure illustrates how the convergence region may be situated with respect to Deacon's Convergence "line", which is defined from a surface temperature south of Subtropical Water. There is good agreement west of Tasmania, except near  $145^\circ$  E.

#### EAST OF NEW ZEALAND

The water masses separated by the Subtropical Convergence are clearly distinguished east of New Zealand (fig. 2). Subtropical Water, with surface salinities greater than  $35.0\text{‰}$  and temperatures above  $16^\circ\text{C}$ , moves southward off the east coast of the North Island and is quite distinct from Subantarctic Water farther south which has surface salinities of less than  $34.4\text{‰}$  and temperatures below  $13^\circ\text{C}$ .

Deacon (1937) places the mid temperatures and salinity of the Subtropical Convergence at about  $11.5^\circ\text{C}$  in winter and  $14.5^\circ\text{C}$  in summer, and at a salinity always about  $34.9\text{‰}$ . On the  $180^\circ$  meridian the Subtropical Convergence east of New Zealand is plainly shown by a sharp salinity gradient at the surface between  $34.4$  and  $35.2\text{‰}$  (fig. 2). The temperature and salinity mid values are near  $14.5^\circ\text{C}$  and  $34.7\text{‰}$ . Thus, the convergence is recognised on an east-west line between the Chatham Islands and a point about 100 miles east of Banks Peninsula. Previous writers have agreed about the orientation and situation of this part of the convergence region. It may be displaced slightly northward in winter, and it may be more or less irregular.

Garner (1957 and 1959) has noted the tendency of cold, poorly saline water ( $34.4\text{--}34.6\text{‰}$ ) to extend northward, and to separate Subtropical Water in the southward directed tongue near New Zealand (represented by  $34.7\text{--}35.0\text{‰}$  isohalines off Banks Peninsula) from that near the Chatham Islands. This northward extension of water with salinity from  $34.4\text{--}34.6\text{‰}$  sometimes occurs between  $175^\circ$  and  $180^\circ$  E. It was not present during the *Pukaki-Hawea* observations.

Garner (1954) has suggested that the convergence, which he defined as the boundary between Subantarctic and Subtropical surface waters, swings northward towards New Zealand, following the  $34.8\text{‰}$  isohaline (fig. 2), and meets the coast near Cook Strait or slightly farther north. The origin of colder, less saline water on the inshore side of this northward trend is not clear; however, it appears to be mainly due to

upwelling from quite shallow depths and it may be partly due to run-off. On the evidence of *Pukaki-Hawea* data, it is unlikely to be surface water of Subantarctic origin.

Since the water in the Ekman layer tends to move to the left of the wind direction, upwelling could be caused by prevailing north-easterly winds north-east of Christchurch and north-westerlies between Christchurch and Dunedin. A band of cold water off Dunedin, previously noted by Bary (1956), is a north-westward extension of Subantarctic Water at 30–50 m. This moves shoreward and upwells to the surface on the inshore side of warmer water of higher salinity. The upwelled water mixes with warmer water and moves northward along the coast. Upwelling fluctuates considerably with changes of wind and local weather. The various distributions found by

Garner (1953, 1954, 1959, and 1960) show this variability.

Rochford (1957) has suggested that there is a considerable flow of water to the north-west through Cook Strait, while Deacon (1937) postulated that Subantarctic Water from the west coast of New Zealand flows through to the east. These inferences were based on insufficient data. More recently Garner (1959) has indicated that the west coast surface water is of Subtropical origin, having moved eastward from the East Australian Current. A small amount of this flows to the east coast through Cook Strait (Garner, 1960). The configuration of the 35.00/00 isohaline (fig. 2) suggests that this was so during the present observations.

By interpolating salinities (fig. 7) and using bathythermograph temperatures for the depths

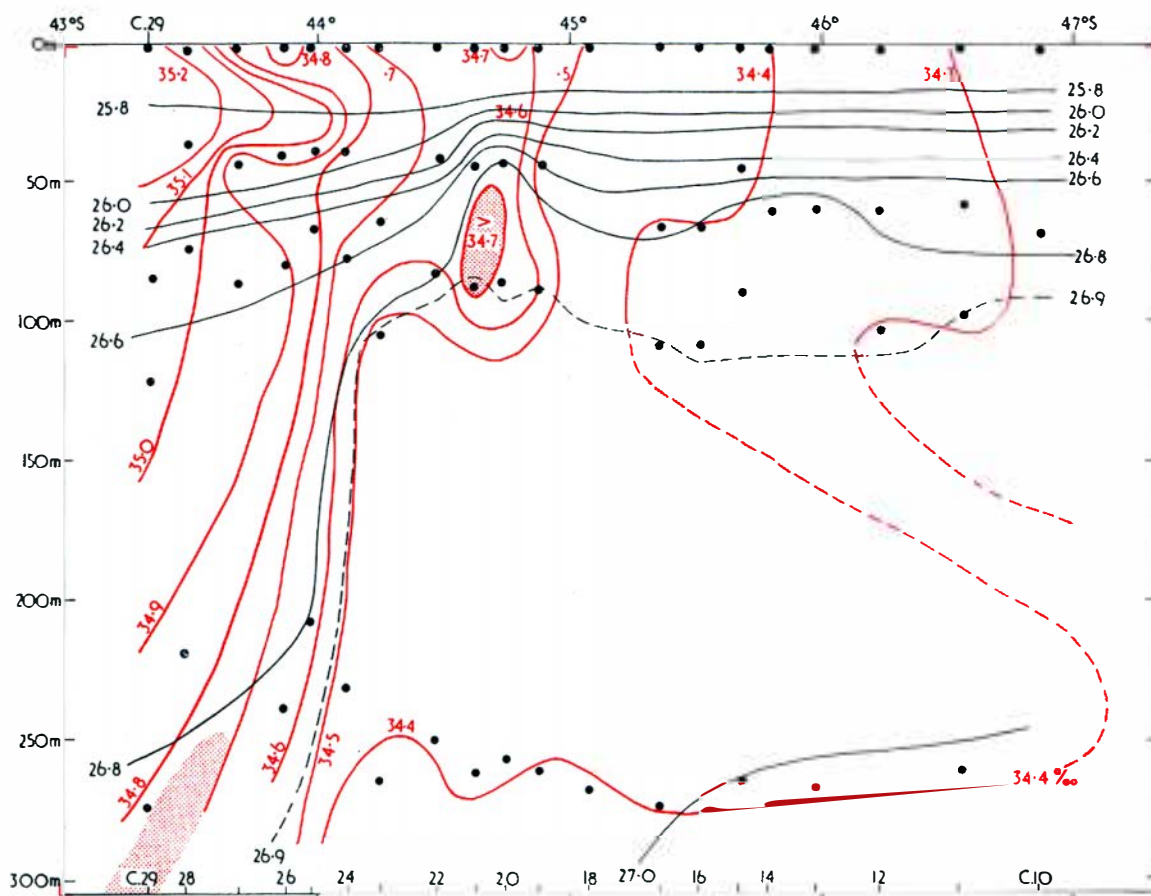


Fig 7: Distributions of salinity (red) and density (black) in the *Hawea* section between N.Z.O.I. Stations C 10 and C 29. Sampling positions are marked with a dot. Stipple indicates the position of a high-salinity pocket and the region from which the water within it had been transferred (assuming that major trends of features are fairly homogeneous transverse to the section). Abscissa represents latitude and the horizontal scale varies according to the direction of the ship's track.

shown in the T-S diagram the characteristics of the water masses along 180° to a depth of 250 m can be demonstrated (fig. 14). The curve for each station passes through the sample values given in table 2. The closeness of the stations permits a very detailed salinity section; hence characteristics through the convergence are well illustrated.

From *Hawea* sections (fig. 3a, 7), it is evident that Stations C 10 to C 23 lie within the Subantarctic Region, although above 100 m the characteristic curves at Stations C 19 to C 23 are disturbed by mixing. This disturbance is illustrated by a tongue between 50 and 100 m near 9°C and 34.7‰/00 (fig. 14). Stations C 10 to C 17 have salinity maxima between 150 and 250 m which do not appear on the diagram but occur within the region including the 250 m characteristics; at greater depths lower salinities and temperatures may be expected (fig. 14). The characteristics at Stations C 28 and C 29 typify Subtropical Water just north of the convergence, and show a Subtropical salinity maximum near 25 m. This maximum is prominent in the *Hawea* section (fig. 7) and apparently extends south over the steeply sloping subsurface front between Stations C 23 and C 27. We may assume these two stations to be at the limits of the convergence region.

As the station latitude decreases the characteristics between 100 and 250 m progressively approach those of Sverdrup's Western South Pacific Central water mass (fig. 14). Generally, in this Subtropical Convergence Region the salinity above 100 m is between 34.7 and 35.0‰/00 and the temperature is higher than that at the upper limit of the W.S.P.C. water mass.

At Station C 25 (Lat. 43° 58' S) the density at 200 m is approximately  $\sigma_t = 26.8$ . At this level the density increases to the south but decreases to the north. Similar properties hold for stations near the convergence elsewhere.

Water with salinity of less than 34.5‰/00 lies only 60 miles south of the convergence (fig. 7), above 100 m, and is present at the edge of the convergence region at greater depths.

The extension of the shallow (25-40 m) Subtropical salinity maximum over the deeper convergence features (shown by the tongue, Stations C 24 to C 29), is apparently a local feature which has not been observed elsewhere and may be transient.

Water in the upper 50 m just south of the convergence to the east of New Zealand, may have

been warmed 1-2°C more than is usual during early summer; a distinct summer thermocline is present (fig. 3, 6), resulting in long straight line portions of the curves above 100 m for Stations C 10 to C 19 (fig. 14), and also for Station B 36 (fig. 18).

The salinity maximum south of the convergence lies beneath the thermocline (fig. 3a and 7), which is represented by the relatively great vertical distance on the curves for Stations C 10 to C 19 between 25 m and 50 m (fig. 14).

The salinity of Subantarctic Water at N.Z.O.I. Stations B 32, B 33, and B 36; at *Discovery* Stations 900 and 1681 (fig. 18); at *Ob* Stations 70, 71 and 76 (fig. 17); and N.Z.O.I. Stations C 10 to C 17 (fig. 14), is less than 34.48‰/00. Characteristics at *Discovery* Stations 2209 to 2216 which are not plotted in any figure, but for which positions are shown (fig. 13) are similar to those for Stations B 33 and B 36 (fig. 18). The region south of the boundary between Australasian and Circumpolar Subantarctic Water (fig. 13) and east of 168° E is thus occupied by Subantarctic Water with salinities at all depths lower than 34.5‰/00 although the boundary may fluctuate.

#### WEST OF NEW ZEALAND

"West of South Island the water more than 100 miles off-shore has the temperature and salinity of Subtropical Water and is no doubt derived from the East Australian Current and from the easterly movement south of Australia". (Deacon, 1937, p. 62) and "The movements of Subantarctic Water in the neighbourhood of New Zealand show on the whole a close resemblance to those east and west of South America. As the West Wind Drift approaches the west coast of South Island, it divides into two branches just as it does off the west coast of Chile. Off each coast the division takes place in about 44° S and one branch flows northwards, whilst the other turns to the south. In each region also, the southward current flows towards the east round the southern extremity of the land, and, joined by more water from the main easterly drift, turns northwards along the east coast" (Deacon, 1937, p. 54).

Garner (1959) has discussed in detail the known surface features of the Subtropical Convergence near New Zealand and the various suggestions and explanations offered by previous authors for distributions of temperature, salinity, and fauna observed to the west and south of New Zealand. This region, has been variously

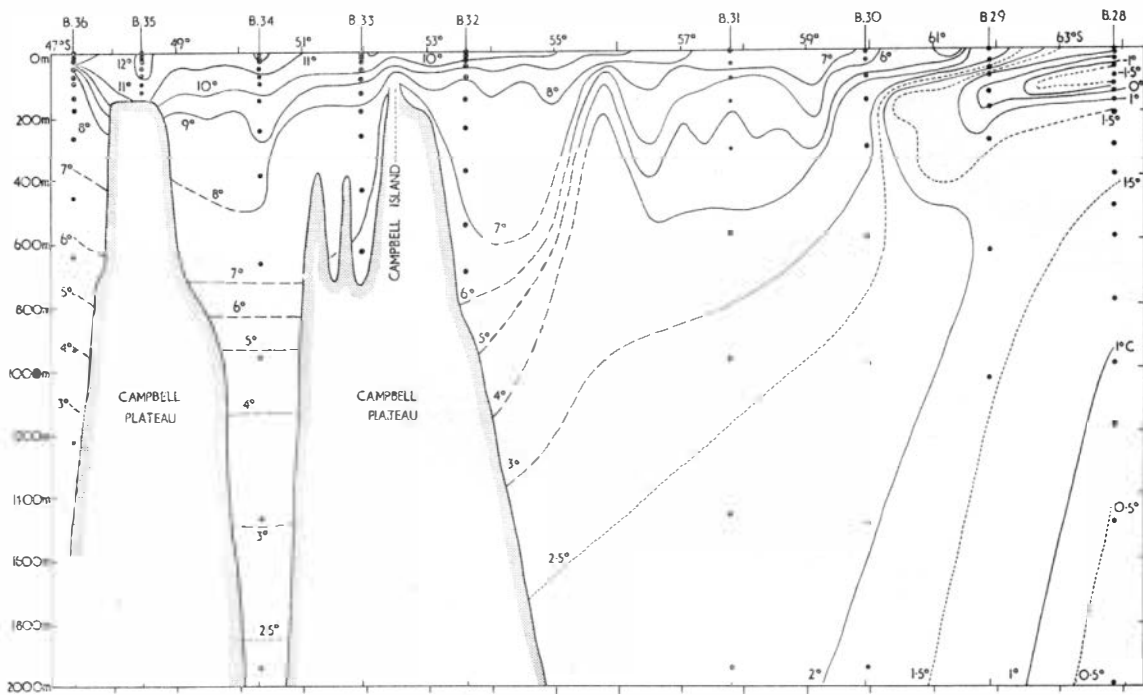
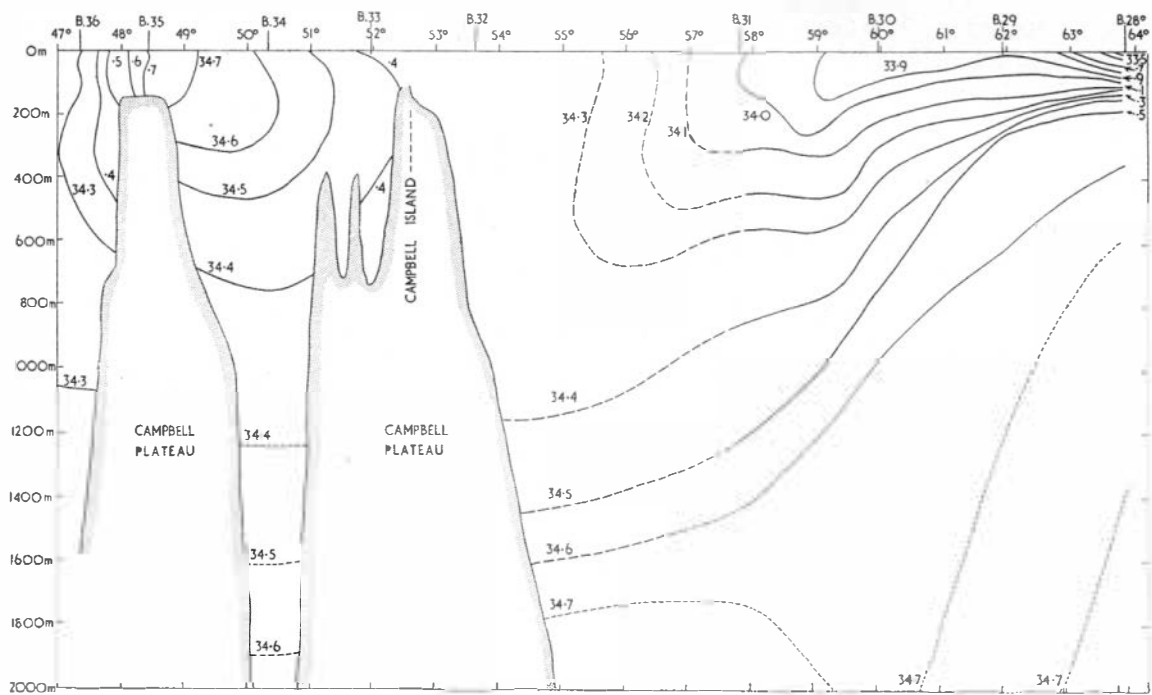


Fig. 8: Distribution of temperatures ( $^{\circ}\text{C}$ ) in the section along the *Pukaki* northward track. Sampling positions at N.Z.O.I. Stations B 28 to B 36 are shown (dots); at depths less than 250 m the isotherms are constructed from bathythermograph data. Some lines are broken where the position or orientation of isolines is ambiguous. Abscissa represents latitude and the horizontal scale varies according to the direction of the ship's track.



described as predominantly Subantarctic Water (Deacon, 1937, 1945), Subtropical Water (Turnbull, 1875; Garner, 1954, 1959; Bary 1956), and as waters of mixed origin (Fleming 1944, 1952).

Garner (1959) interpreted the *Discovery* data of June–July 1932 from the Tasman Sea differently from Deacon (1937). By choosing the 10°C and 34.7‰ isolines at the surface to define its position during the *Discovery* observations in June 1932 (fig. 12), he portrayed the Subtropical Convergence much farther south than Deacon placed it. He suggested it lay between latitudes 46° S–47° S across the Tasman and touched New Zealand in the extreme south near Stewart Island. This position agrees with more recent surface temperature, salinity, and bathythermograph observations (Garner, 1959).

Rochford (1959) studied the seasonal distribution of surface temperature and chlorinity in the Tasman and Coral seas. Taking typical surface values for August and February in the South Equatorial, West Central South Pacific, and Subantarctic Water masses, he computed the percentage contributed by these masses to the surface waters of the Tasman and Coral Seas. From his results he inferred the probable main direction of movement during or just before the two seasons. It was assumed explicitly that evaporation and precipitation changes were much less important than advection and implicitly that heat transfer across the sea surface and its variation with latitude and vertical transfers of mass and properties to greater depths were also negligible.

According to Sverdrup (1942), the Central Water masses are formed north of the Subtropical Convergence; near-surface waters are modified in winter and sink as deep as 700 m. Climatic influence on surface waters moving into new latitudes is known to be considerable (Jacobs, 1951; Privett, 1958). Surface waters in the southward-moving East Australian Current, for example, carry heat into higher latitudes and their temperature drops. If this surface water takes about two months to move from 15° S–35° S, then a winter drop in temperature of 3°C in the upper 50 m during this time is a conservative estimate (i.e., an average loss of 300 g. cal/sq. cm. per day). Rochford's mixing diagrams indicate that this is equivalent to a mixture containing about 20 per cent of Subantarctic Water. If part of the surface water turns eastward then a further short period at a similar rate of cooling would ensure that the surface water in the central Tasman Sea would apparently contain more than 25–30% of Sub-

antarctic Water. Rochford estimates that Tasman Sea surface waters in August are 100% Subantarctic Water in the south and 50–75% in the north, but it would seem from the foregoing that his discounting of cooling effects on Subtropical Water may not be justified.

Confusion in the terminology used to describe the water masses west and south of New Zealand has arisen through sparseness of data and also from the use, by most authors, of extreme surface properties only. In this paper subsurface properties are used to define the convergence region, and it will be seen that local climatic influences may affect determinations of positions based on surface data only.

North of the convergence, a Subtropical salinity maximum is common. Where this is present, it is normally shallower than 150 m and the maximum salinity is higher than that in the Subantarctic maximum which is usually deeper than 150–200 m not far south of the convergence (Deacon, 1937). This deeper Subantarctic maximum is a consequence of the dynamic properties of the Subantarctic Water mass, which, according to Deacon, moves towards the convergence in the upper layers, mixes with higher salinity waters near the convergence, and sinks and moves away from the region near the level of the salinity maximum. Where there is a summer thermocline in Subantarctic Water (fig. 3a,b,c,d), it is normally at much shallower depths than the salinity maximum. In Subtropical Waters the development of the thermocline is associated with that of the Subtropical salinity maximum (Sverdrup *et al.*, 1942), the latter lying near or slightly above the thermocline. These properties, and the general T–S characteristics near the convergence may be used to differentiate water with definite Subantarctic characteristics from those with Subtropical characteristics.

It does not seem possible to define one given characteristic, which will separate predominantly Subtropical from predominantly Subantarctic Water. However, we may define an area on the T–S diagram, which separates dominating characteristics in each of the two distinct water masses. This area on the T–S diagram corresponds to a geographical region which will be called the "Subtropical Convergence Region"; within it, the waters are intermediate in character or display features typical of either or both the more northern and more southern water masses at different depths—perhaps due to the state of mixing.

The positions of data observed between 100° E and 180° are shown in fig. 13. T-S characteristics at the closely spaced Stations C 10 to C 29 on the 180° meridian (fig. 14) illustrate a general pattern of detailed changes across the convergence. T-S characteristics in the Atlantic Ocean and south of Australia (fig. 15 and 16) show that the Subtropical Convergence may be located there by comparing water properties in the upper few hundreds of metres. The characteristics of water south of the Tasman Sea and south of New Zealand are illustrated in fig. 17 and 18; comparison with fig. 14-16 indicates the relation of station positions in fig. 13 to the Subtropical Convergence at the times of observation.

#### SOUTH OF NEW ZEALAND

T-S characteristics east of 148° E are plotted in fig. 17 and 18. Data from *Discovery* Stations 2209 to 2216 have not been used but the characteristics of Stations 2212 to 2216 resemble those of *Ob* Station 76 (fig. 17) and *Pukaki* Stations B 32, B 33, and B 36 (fig. 18). At Station 2209 the salinity is between 34.4 and 34.5‰ above 700 m with a maximum of 34.5‰ and the temperature is 7.5°C between 150 and 200 m.

South of the boundary between the two types of Subantarctic Water (fig. 13) salinities are less than 34.5‰; north of the boundary salinities are higher than 34.5‰ at some depth in Subantarctic Water. South of Australia this boundary corresponds with a sharp horizontal salinity gradient. Over the Campbell Plateau to the south of New Zealand, and further west, the region may fluctuate and a corresponding steep horizontal gradient in salinity values does not always exist. For example, there is no steep gradient along the *Discovery* track shown by Stations 921, 922, and 923 (fig. 17); the salinity at the southern station (921) barely reached a maximum of 34.5‰ between 300 and 500 m and the most northern stations showed only slightly higher values at these depths, but there is a steep salinity gradient between Stations 923 and 924 above 400 m. Comparison of these *Discovery* Stations with *Pukaki* Station B 34, *Ob* Stations 72 to 74, and *Discovery* Station 1682 (February 1936) suggests that colder and more poorly saline water was present between 100 and 400 m south-west of New Zealand in June 1932 than on other occasions. The maximum salinity value (34.5‰) at *Discovery* Station 2209 (T-S characteristics not plotted) suggests that the more saline Austra-

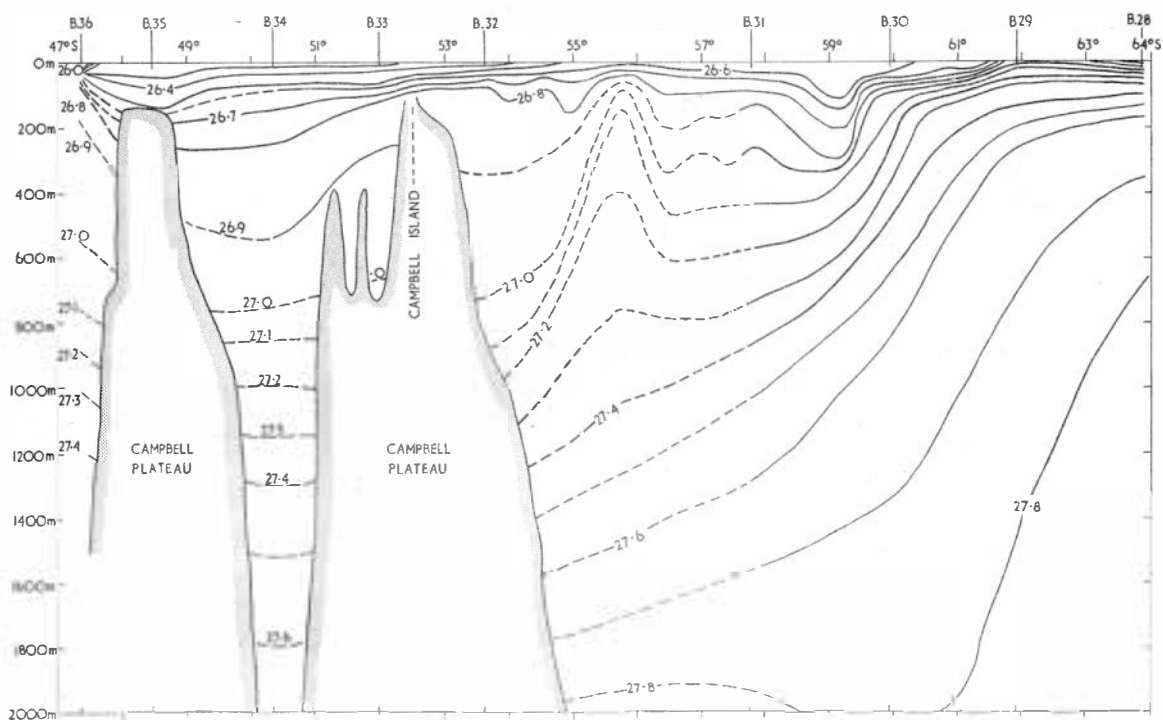
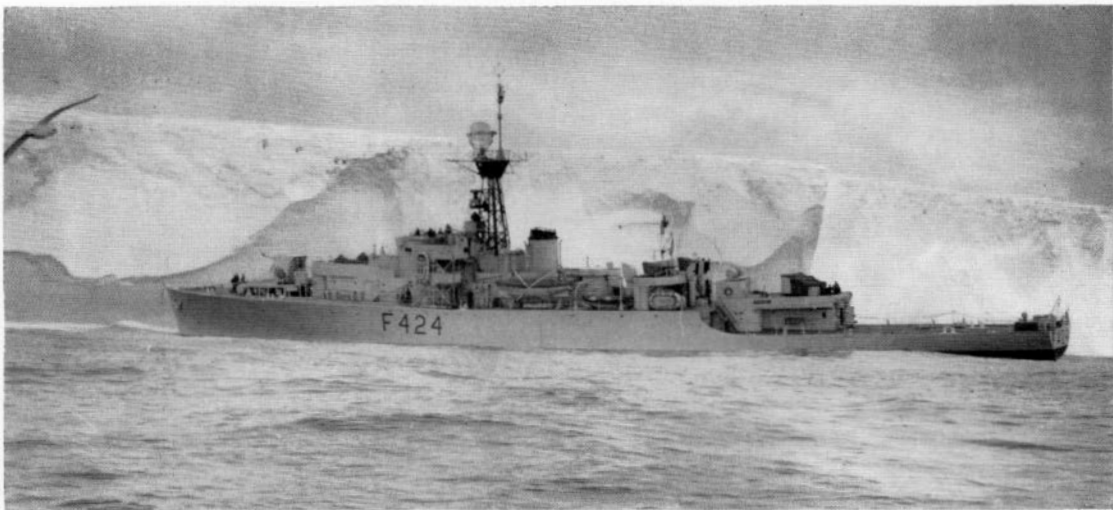


Fig. 10: Distribution of density ( $\sigma_t$ ) in the *Pukaki* section between N.Z.O.I. Stations B 28 and B 36. Abscissa represents latitude and the horizontal scale varies according to the direction of the ship's track.



*Plate 3. Bergs south of the Antarctic Convergence*



*Plate 4. Lowering the <sup>14</sup>C Sampler, Station B 28*

*facing p. 34*

surface salinities were observed. There are at least two possible explanations of this salinity maximum.

A salinity maximum would be produced if Subantarctic Surface Water shallower than about 50 m were to move northward and mix with much more highly saline Subtropical Water from greater depths. The surface layers would be heated at the more northerly positions. Alternatively a low salinity surface layer could be produced in Subtropical Water and maintained by land run-off and excess precipitation. On available data it is not possible to decide between these two possibilities but the following points are of inter-

est. The Eastern Tasman Sea south of 38° S lies always within the westerly wind zone, with wind velocities tending to increase to the south (e.g., McClintock, 1959). Since the surface water layer tends to move to the left of the wind direction it will have a northward tendency through the Subtropical Convergence Region. On the west coast of New Zealand rainfall is high and increases to the south (reaching over 200 in. per year in the south-west), but it is not known how far off shore this high orographic rainfall extends. While the westerly winds in most sectors of the Southern Ocean extend a few degrees to the north of the convergence region, the orographic effect on the rainfall is a local phenomenon. Because of low in-shore surface salinity, rainfall and land run-off are the more likely causes of a salinity maximum. It is possible that a combination of these, and other, factors may operate. The possibility of movements to the north-east through Cook Strait should not be overlooked, although current measurements (Olsson, 1955) and drift card observations (Brodie, 1960) showed mean currents and surface drifts in the opposite direction.

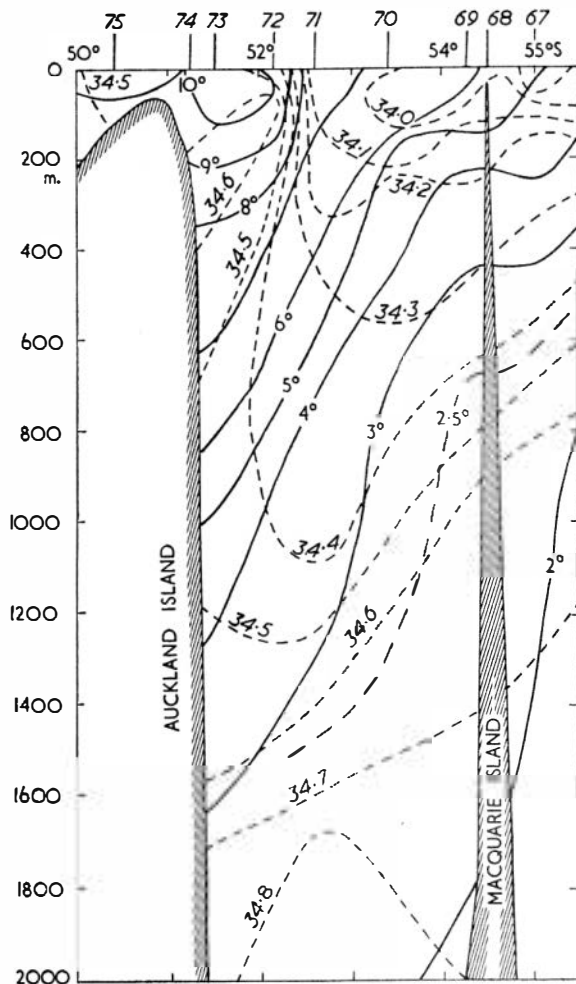


Fig. 11: Distribution of temperature ( $^{\circ}\text{C}$  full lines) and salinity ( $\text{‰}$ , broken lines) in a section between Macquarie and Auckland Islands, constructed from observations from the Russian ship *Ob* (Moroshkin, 1958); station positions are shown in fig. 13.

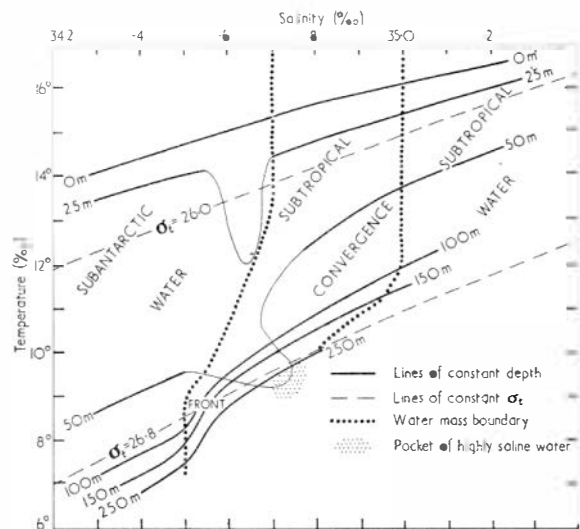


Fig. 12: Schematic diagram showing water characteristics at constant depths in a section along the 180° meridian across the Subtropical Convergence (fig. 3a and 7). The thick continuous lines show the smoothed main trends in characteristics, at constant depths neglecting minor fluctuations. The stippled region represents water within the high-salinity pocket, and the thin portions of the isobaths for 25 m and 50 m show distortions from the general trends in characteristics at these depths near the high-salinity pocket. (This figure is derived from the T-S diagram, fig. 14.)

Whatever the reason for the formation of the Subtropical salinity maximum it is reasonable to use water properties deeper than about 150 m to define the position of the convergence. In the Australian (fig. 16) and east New Zealand (fig. 14) sectors  $\sigma_t$  at 200 m is greater than 26.8 in Subantarctic Water and less than 26.8 in Subtropical Water, and with only a few exceptions, this property conforms with other properties used to define these water masses, which are separated by a region of water of salinity 34.7–35.0‰, at depths less than 200 m. In the Subantarctic Region, the depth of the salinity maximum nearly always exceeds 150 m and is greater than the depth of the summer thermocline. Using these criteria, stations in the Tasman Sea and south of New Zealand which fall within the convergence region or were not obviously in Subtropical or Subantarctic Water, are: *Derwent Hunter* Stations 56/55 and 53/56; *Discovery* Station 924; *Ob* Station 77 (fig. 17); and *Discovery* Stations 1684 and 2820 (fig. 18).

There are slight anomalies at some other stations. For example, at Station B 34 in Subantarctic Water the density is low at 200 m (fig. 18). This may be due to a Tasman Sea influence on the northern higher salinity Subantarctic Water, while the characteristics of Station B 35 show that it must be very near the southern edge of the convergence region.

Even if Subantarctic Surface Water does move northward in the Eastern Tasman Sea and is modified by heating and mixing, the water north of latitude 42° S has Subtropical characteristics: (low density at 200 m, maximum salinity above 35.0‰, and a salinity maximum coinciding with the thermocline) except at the anomalous *Derwent Hunter* Station 6/54 and at shallow water stations close in shore. Surface temperatures at *Derwent Hunter* and *Ob* Stations in the eastern Tasman are all above 15°C which agrees with Deacon's criterion that Subtropical Water exceeds 14.5°C in summer. *Discovery* Stations 2819, 2821 (fig. 18), and 925 (fig. 17) have Subtropical characteristics although they must be quite near the convergence region.

*Discovery* Stations 921 to 926 (June 1932) may indicate that the convergence region is farther north in June than in other months. Compare, for example, *Discovery* Station 924 with Stations 2820 and 2821 (May 1951) and Stations 925 and 926 with *Derwent Hunter* Stations 4/57 to 9/57 (January 1957).

#### EXTENT OF THE SUBTROPICAL CONVERGENCE REGION

The Subtropical Convergence Region determined from the above criteria is illustrated in fig. 13 by the shaded region—neglecting possible seasonal influences. East of New Zealand it corresponds with convergence positions from *Pukaki-Hawea* data and its northern limit east of Cook Strait corresponds with that determined by Garner (1954). West of New Zealand the region will be narrower at any one time.

The Subtropical Convergence Region and the convergence determined by Deacon (1937) have been compared (fig. 19) with mean summer and winter isotherms, constructed from sea surface temperatures observed on British ships from 1855 to 1939 (Meteorological Office, 1949). In some areas the data is inadequate and the positions of the isotherms are uncertain; particularly in the eastern Tasman Sea between 41° S and 46° S. However, the monthly isotherms in the published charts, except for January are similar to those for February and August (fig. 19). The January isotherms differ from the general pattern in the eastern Tasman Sea—the 58°F, 60°F, and 62°F (14.4°C, 15.6°C, and 16.7°C) isolines trend northward towards New Zealand east of longitude 162° E instead of southward, as in February. East of New Zealand the January isotherms have a southward-pointing tongue with the axis about 100 miles off shore.

In general, the trends of the northern and southern limits of the convergence region are similar to the trend of the isotherms. West of Tasmania, Deacon's convergence positions are in good agreement with the convergence region defined above. The latter corresponds to surface temperatures of about 55°–60°F (12.8°–15.6°C) February, and 50°–53°F (10.0°–11.7°C) in August.

South of Tasmania (longitude 151° E) and south of New Zealand, the cold, poorly saline limit of the convergence region is associated with surface temperatures about 1°C less than those south of Australia. East of New Zealand the region appears to be associated with temperatures about 1°C lower in winter and about 0.5°C warmer in summer than south of Australia. West of New Zealand, where the positions of both the isotherms and the convergence are most uncertain, the temperature ranges of the convergence region apparently agree to within 0.5°C of those observed south of Australia.

These limits require confirmation but the observed ranges agree qualitatively with Deacon's

criterion that north of the 14.5°C isotherm in summer and the 11.5°C isotherm in winter the water is entirely Subtropical and is not mixed with Subantarctic Water. It is possible, as previously noted, that the convergence region has different mean positions in summer and winter.

At any given season it will occupy a less extensive region than that represented by the shaded regions (fig. 13 and 19). Water within the convergence region has characteristics intermediate between those of Subtropical and Subantarctic Water masses.

## THE SOUTHLAND FRONT

### GENERAL DESCRIPTION

East of New Zealand is a distinctive front (Chart 1) associated with the southern edge of the Subtropical Convergence. It is also the Southern limit of the narrow zone of Subantarctic Water (salinity > 34.50/00) in this region, and is thus the northern limit of Circumpolar Subantarctic Water. Within the front, the 8°–9°C isotherms, the 34.5–34.6‰ isohalines and the constant density surfaces ( $\sigma_t$ , approximately 26.8–26.9) slope steeply down to the north from below the summer thermocline in Subantarctic Water from a depth of about 70 m. Because of its association with the Southland Current, (Garner, 1960), it is proposed to name this the “*Southland Front*”. There are however, no observations west of 164° E sufficiently concentrated to indicate its existence or position east of the Auckland Islands.

Since the temperature and salinity ranges correspond closely with those at the warm northern edge of the Australasian Subantarctic Front it might be conjectured that the two fronts are continuous. For reasons given later, it is believed that they are not dynamically associated, and that the Southland Front originates above 200 m not far west of the Auckland Islands. Except where it originates it may conveniently be associated with the southern limit of the Subtropical Convergence Region, from near the Auckland Islands to approximately 175° E off Banks Peninsula.

The position of the steep horizontal gradient of surface salinities marking the Subtropical Convergence Region on the 180° meridian coincides with a steep downward slope of isotherms towards the north (fig. 2, 3a). This is sharply defined at

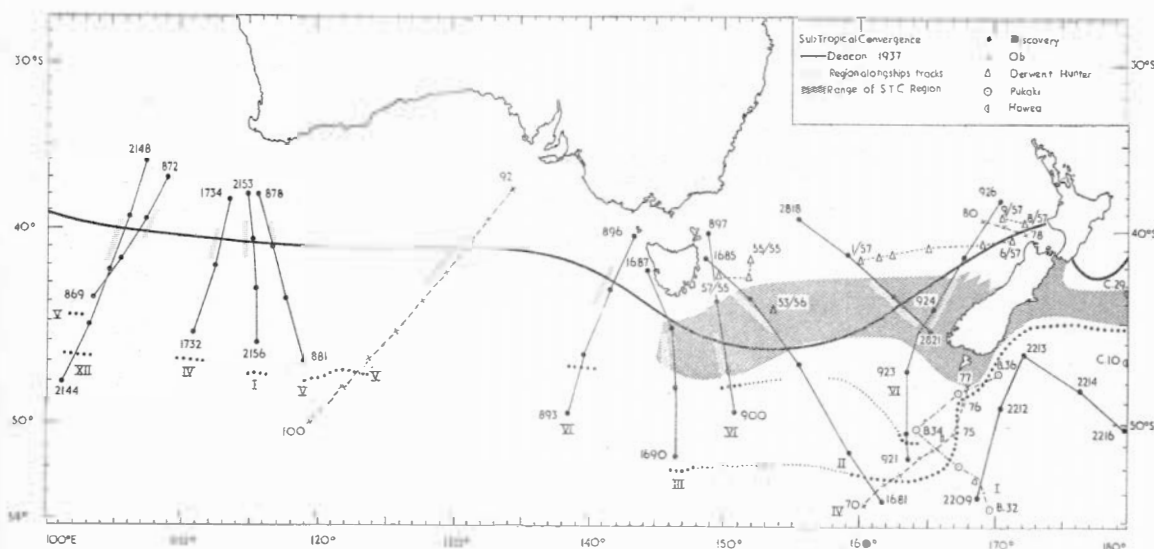


Fig. 13: Observed positions of the Subtropical Convergence Region and positions of Stations. Roman numerals show the month of observation. Short dotted lines indicate the observed southern boundary of Subantarctic Water with salinity greater than 34.50/00; finer dotted lines show a possible seasonal variation of this boundary. For T–S characteristics at all stations on this diagram except *Discovery II* Stations 2209 to 2216 see fig. 14, 16, 17, and 18.

depths greater than about 50 m and is roughly bounded on the cold water side by the 8°C isotherm. Below 50 m a sharp horizontal temperature gradient also exists but it is absent at the surface. Where the summer thermocline is well developed south of the convergence, the 8°C isotherm lies near its deeper limit (fig. 3).

Similar features are present in other bathythermograph sections (fig. 3, 6).

- (a) Near 44° 40' S, 173° 20' E (fig. 3d) the steep slope lies south of the surface features of the Subtropical Convergence where some of these trend towards Cook Strait. Here, the 8°C isotherm slopes steeply from its near-horizontal disposition beneath the thermocline, at a position close to the 34.6‰ surface isohaline (fig. 2).
- (b) In the east-west section from Chatham Island to Dunedin (fig. 6) the 8°C isotherm is similarly related to the summer thermocline, and its steep slope again nearly coincides with the 34.6‰ surface isohaline (fig. 2). Moreover, from the relation of this east-west section to the surface isohalines, it appears that the steep slope at the eastern end passes through that in the section along 180° (fig. 3a). Since the western isotherms between 44° 30' S and 48° S are obviously connected (fig. 3d), it is suggested that the region of steep slope is continuous. This is supported by the position of the 8°C isotherm in other meridional temperature sections (fig. 3b, 3c, and 3d; near 50° 30' S), and by the relation of the steep isothermal slopes to the 34.6‰ isohaline (fig. 2).
- (c) The isohalines and lines of equal  $\sigma_t$  values also slope downward near the same position on the 180° meridian (fig. 7), and the section shows that water beneath 8°C and 9°C is associated with salinities between 34.5 and 34.6‰ and  $\sigma_t$  values between 26.85 and 26.95. Distributions of temperature, salinity, and  $\sigma_t$  (fig. 1, 8, 9, and 10), especially from Station B 36 on the cold-water side of this feature, suggest that the steeply sloping isotherms near 48° S and east of Stewart Island (fig. 3d), are associated with similar salinities and densities. Water properties near Station B 34 and at 50° 30' S in the *Pukaki* western temperature section (fig. 3d) similarly agree.
- (d) The downward slope usually commences near a depth of 70 m and the isotherms be-

tween 48° S and 50° S in the western section (fig. 3d) suggest that *Pukaki's* track between Stations B 34 and B 35 was only a few miles to the north of the feature.

- (e) *Ob* Stations 76 and 77 in April 1956 (Moroshkin, 1958; Anon, 1958) near Stewart Island show the same feature in the same position (Station positions, fig. 13; T-S curves, fig. 17).

Thus south and east of New Zealand a continuous region of water with steeply sloping isolines of physical characteristics existed in December 1956 and January 1957. Bathythermograph data show that where the isopleths commence to slope steeply downward from about 70 m beneath warmer and more saline water, surface salinities are slightly greater than 34.6‰ near the 180° meridian and between 34.55 and 34.60‰ elsewhere. This demarcates a boundary on the cold water side of the region, deeper than 70 m, separating Subantarctic Water with temperature below 8°C and salinity below 34.5‰ (Circumpolar Subantarctic Water) from warmer, more saline water.

East of Banks Peninsula this feature coincides with the southern limit of the Subtropical Convergence, as defined by observed surface characteristics. The northern limit of the convergence trends to the north towards Cook Strait. The subsurface feature trends to the south-west south of New Zealand, to near Auckland Island. Between the front and the New Zealand coast warm water, arriving from the west, is not Subtropical Water, which has a higher salinity than 35.0‰. Near the coast it is typically Subtropical Convergence Water and elsewhere Australasian Subantarctic Water.

The subsurface feature has everywhere steeply sloping temperature, salinity and density isolines, and associated sharp horizontal gradients at depths greater than about 70 m. Since this feature separates two water masses with different characteristics, it is proposed that it be called a "front".

#### WATER MOVEMENTS NEAR THE SOUTHLAND FRONT

We may discuss the motion near the subsurface feature using Margules equation for a simple two-layer system, separated by a surface of discontinuity (e.g., Proudman (1953) p. 59). If  $\rho$  and  $\rho'$  ( $\rho' > \rho$ ) are densities and  $v$  and  $v'$  are components of horizontal velocity parallel to the surface of separation in the upper and lower layers respectively, and if  $g$  ( $\text{cm}/\text{sec}^2$ ) is the acceleration due to gravity,  $\varphi$  the latitude,  $\Omega$  the

earth's angular velocity, and  $\delta$  the angle of slope of the surface from the horizontal. then

$$\tan \delta = \frac{2 \Omega \sin \varphi}{g} \frac{\rho V - \rho' V'}{\rho' - \rho}$$

For continuous density and velocity distribution, this becomes

$$\tan \delta = - \frac{2 \Omega \sin \varphi}{g} \frac{\delta (\rho V)}{\delta \rho}$$

The convention of signs is such that in the southern hemisphere ( $\varphi < 0$ ), if  $\frac{\delta (\rho V)}{\delta \rho}$  decreases

(increases),  $\delta$  is measured downward from a level surface to the left (right) of the current direction.

Thus, in the *Hawea* section (fig. 7) between Stations C 10 and C 29, if the Subtropical Current is easterly, the current in the heavier Subantarctic Water has a smaller east-going velocity, is less easterly and may even flow towards the west. If the lighter warmer water flows towards the west then the colder, less saline water flows more rapidly westward.

It has been shown that the  $8^\circ$  and  $9^\circ\text{C}$  isotherms and the isohalines for 34.5 and 34.6‰ slope steeply downwards beneath warmer water near the 34.6‰ surface isohaline (fig. 2) with

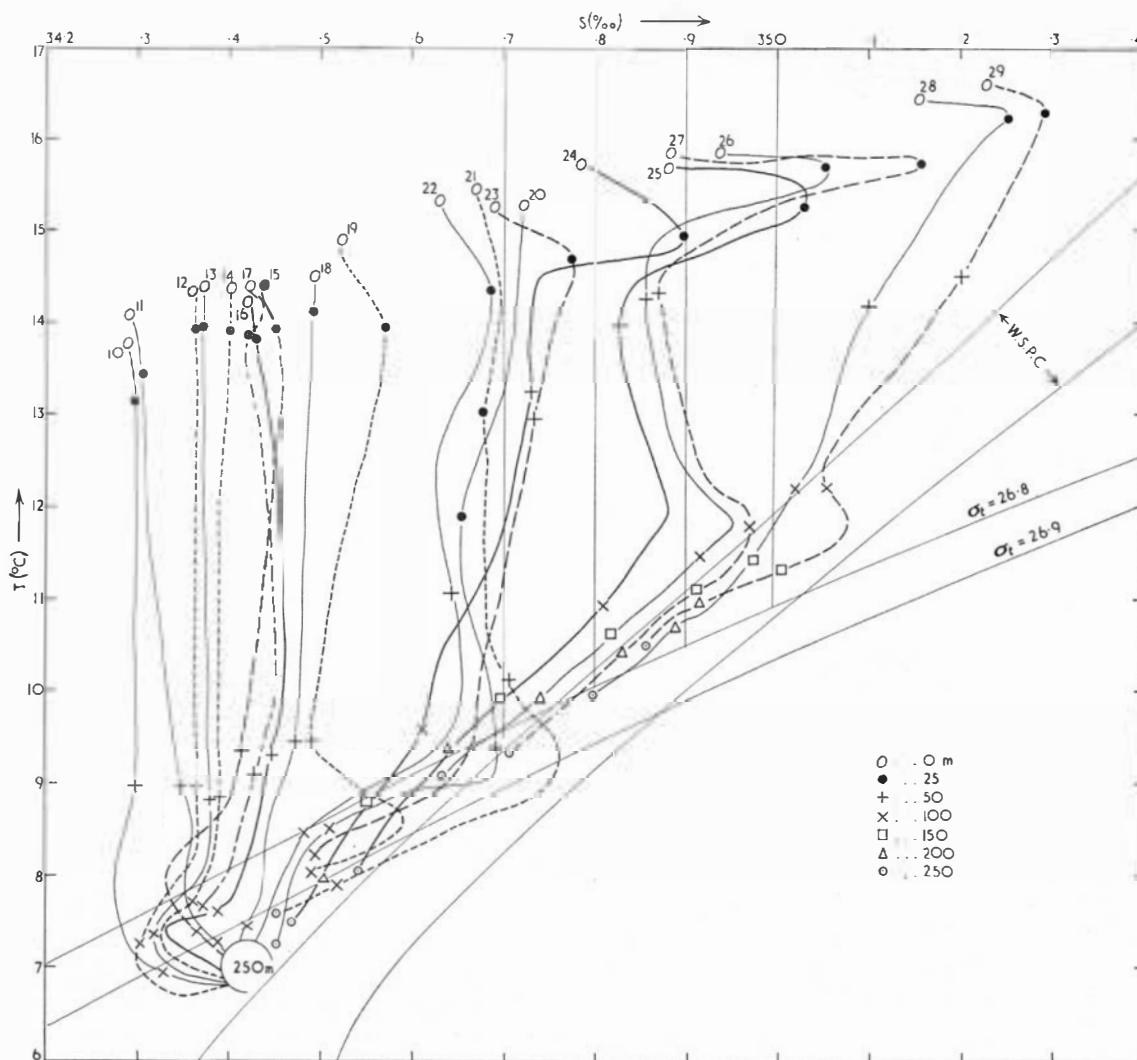


Fig. 14: T-S characteristics at N.Z.O.I. Stations C 10 to C 29. The region characteristic of Sverdrup's Western South Pacific Central Water is bounded by the smooth curves denoted W.S.P.C. and lines of constant density (for  $\sigma_t = 26.8$  and  $26.9$ ) are shown.

a corresponding steep slope in the  $\sigma_t$  surfaces. The temperatures, salinities, and densities in various relevant sections (fig. 7 and 3a; fig. 3d, 8, 9, and 10) suggest that the subsurface feature is represented by  $\sigma_t$  values between 26.85 and 26.95.

As an approximation it is assumed that the isoline of density ( $\sigma_t$ ) 26.9 in the *Hawea* section (fig. 7) represents the intersection with a surface separating two homogeneous layers. The slope of this surface downwards to the north below 100 m is about 7 m per km. From Margules equation we find for ( $\varphi = -45^\circ$ ,  $g = 980 \text{ cm/sec}^2$ ,  $\Omega = 7.3 \times 10^{-5}/\text{sec}$ )

$$\rho' v' - \rho v \approx 67 (\sigma_t' - \sigma_t)$$

Since  $\rho'$  and  $\rho$  are each approximately unity, if we take  $\sigma_t$  values of 26.95 and 26.65 for the lower and upper layers, we may write:

$$v' - v \approx 20 \text{ cm/sec}$$

This velocity of upper warmer water relative to Subantarctic Water is eastward. Since Margules equation is subject to the same assumptions used in deriving the gradient equations leading to Helland-Hansen's formula (Proudman, 1953, p. 63), these relations do not indicate absolute velocities.

Subantarctic Water approaches the Campbell Plateau from the west, and is diverted to the south near the Macquarie Islands by the bottom topography between the Macquarie Islands and the Plateau. Because of the effect of changes of depth on currents (Sverdrup *et al.*, 1942; Proudman, 1953, p. 64) this southward trend will be assisted as Subantarctic Water carried in the Circumpolar Current moves eastward into a deeper region across the ridge near the Macquarie Islands. Likewise, water approaching the Plateau will tend to turn north as it flows into shallower water. Thus, there will be a tendency to override the Plateau. The Subantarctic Water will, therefore, have a northern limit determined either by the southern New Zealand coast or by a northern water mass, with possibly an eastern limit imposed by the topography of the Plateau or by eastern water masses. As previously described, relatively warm, saline Subantarctic Water similar to part of the Campbell Plateau Water (Garner, *in press*) was present south of New Zealand but north of Circumpolar Subantarctic Water during early January 1957. *Ob* data show that it was also present in March 1956.

Subantarctic Water moving towards the Plateau is part of the West Wind Drift system; any eastward component of motion must be consistent with the dynamic processes. Except in so far as

it may be modified by mixing processes. It is deduced from Margules equation, and the general downward slope of isolines in the Front beneath the warmer northern water, that the overlying, lighter water north of the 34.6‰ surface isohaline (fig. 2) must move north-eastward along the isolines faster than the Subantarctic Water to the south.

Since cold, poorly saline Circumpolar Subantarctic Water moves westward in the Bounty-Campbell Gyral onto the Campbell Plateau, then warmer, more saline Australasian Subantarctic Water from the south Tasman Sea will move from the region between New Zealand and the Auckland Islands, to the north-east, as a relatively strong current roughly parallel to the 34.5 and 34.6‰ isohalines (fig. 2). This water which continues northwards between the eastern coast of the South Island and the Southland Front has been described from near-shore observations by Garner (1961) and named the Southland Current.

According to the *New Zealand Pilot* (1946), currents are directed eastward past the Auckland and Campbell Islands, the current off the south-west of the South Island sets almost constantly to the south, and off the east coast of the South Island the current usually sets to the north. In this last instance a southerly set may follow strong southerly winds; this must be due to the development of an upward inclination of the surface towards the north. That a persistent northerly current off the east coast of the South Island does normally exist is supported by drift card and drift bottle observations. Of 400 drift cards in plastic envelopes dropped near the south-west coast, only eight were recovered; these were found between Foveaux Strait and Banks Peninsula. Many more cards were released off the south-eastern coast up to 50 miles off shore; approximately 5% were recovered. All had moved to the north, some through several hundreds of miles. Of several hundred cards released further off shore only one was recovered; this had moved from 170 miles east of the coast to the Chatham Islands (Brodie, 1960).

Surface isopleths (fig. 2) show that this northward near-shore flow is complicated by cold, less-saline water of 11.5°C and 34.33‰ salinity, lying between the Southland Front and the coast near Dunedin, which separates warmer, more-saline water to the north-east and the south-east. Water with these properties is present further south at Station B 36, in Subantarctic Water, at depths of 30 and 40 m. Water of 11.5°C occurs about 35 m

deep east of the cold, poorly saline pocket (fig. 6), and generally between 30 and 50 m on the cold-water side of the Southland Front (fig. 3a, 3d, and 6). In the Dunedin - Chatham Islands section (fig. 6), isotherms above 50 m are drawn to agree with thermograph data. These also indicate that water at 40 m with a temperature of 11.5°C is continuous with that at the surface of the cold pocket and lies above the steep slope of the Front. This isotherms distribution and the low salinity within the pocket (34.33‰) strongly suggest an upwelling from depths of 30-50 m over the steep slope of the isotherms beneath.

Since the  $\sigma_t$  value at the surface of the pocket is about 26.4, while that to the east and west is only about 26.0 there is no possibility that the cold, poorly saline water is derived from river outflow.

The Southland Front swings north-east from near Station B 34 and apparently lies over a bottom shallower than 1,000 m (fig. 1), following the 34.5 and 34.6‰ isohalines east of New Zealand (fig. 2). Over most of the Campbell Plateau, bottom depths beneath the Front are about 500-700 m. From the Dunedin - Chatham Islands section (fig. 6), in which the depth at the most

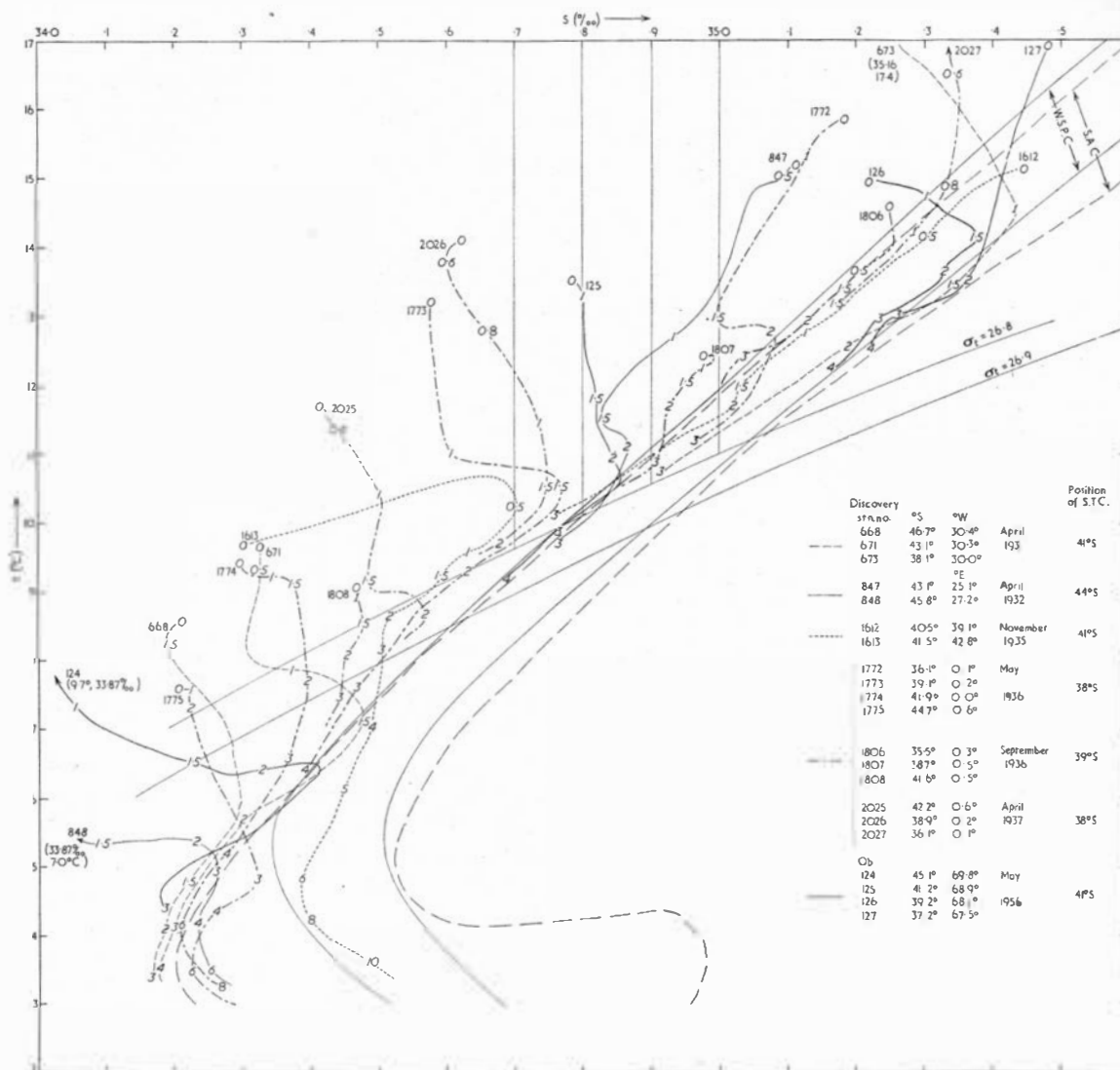


Fig. 15: T-S characteristics at Discovery II stations south of the Atlantic and Western Indian Ocean and at Ob stations south of the Central Indian Ocean. Regions characteristic of Sverdrup's Western South Pacific Central Water (W.S.P.C.) and South Atlantic Central Water (S.A.C.) are shown for comparison. Figures on the station curves indicate depth in units of 100 metres.

western bathythermograph station is 610 m, it can be seen that the warmer water deeper than 70 m lies along the outer edge of the steep continental slope. Margules equation applied to these circumstances shows that this warm water will continue to move to the north and later to the east around the Front faster than Subantarctic Water, parallel with the contours of the sloping bottom (fig. 1, 2, and 4d). East of Banks Peninsula it merges with warmer water from the north, which also swings eastward near this position. Since the warm, northward current is restricted to the narrow region between the Southland Front and the sloping bottom, it may have a quite high velocity.

It has been shown that near Dunedin, Subantarctic Water moved in shore at depths between 30 and 50 m and has formed a pocket of upwelled colder, less-saline water. Warmer, saline water on the shore side of this pocket originates from

the Tasman Sea after moving round the southern coast. Similar warm surface water to the east of the pocket (fig. 2 and 6) must have the same origin, since southward movement of the more northern Subtropical Water contradicts the implications of drift observations and deductions from Margules equation. Thus, the surface water from the Tasman Sea has on this occasion split to take two paths near Dunedin. The in-shore portion produces high salinities off Dunedin and presumably mixes to the north with the colder upwelled water. This mixture may contribute to the low salinity cold water inside the southward-pointing tongue north-east of Banks Peninsula (fig. 2). The off-shore portion of this current must move to the north above and on the shore side of the subsurface Southland Front, swinging to the east between 44° S and 45° S and merging with the south-eastward moving Subtropical Water of the East Cape Current (Fleming, 1950) which also swings to the east.

## A MIXING PROCESS AT THE SUBTROPICAL CONVERGENCE

Water properties in the *Hawea* section along the 180° meridian (fig. 7 and 12) illustrate a process by which the high salinity stratum frequently observed in Subantarctic Water may be formed. Deacon (1937) and Sverdrup (1934) have suggested alternative processes leading to the formation of this stratum. The present discussion is stimulated by the presence of a high salinity "pocket" near Station C 21.\*

Between about 40 and 90 m, salinities at Stations C 20 and C 21 (table 2) are higher than those to the north and south at Stations C 19 and C 22. (This maximum is shown in fig. 7 by the stippled region of salinities greater than 34.7‰, and in the temperature section, fig. 3a.) This high-salinity

pocket is associated with a pronounced distortion of isotherms and of lines of constant density on the southern side of the Southland Front. At Station C 23, between the pocket and the front, the isotherms (e.g., the 7°C isotherm, fig. 3a) and isohalines deeper than 80 m protrude upwards to shallower depths than at adjacent stations; this feature is interpreted as an eddy. It is assumed that the general trend of characteristics in the section is representative of those in other north-south sections, to the east and west, but that fluctuations such as the eddy and the high-salinity pockets are more localised.

It has been shown (Montgomery, 1938) that surfaces of equal density,  $\sigma_t$ , are those surfaces along which the energy required to cause interchange of water pockets or mixing is least. Hence, from the distribution of lines of constant  $\sigma_t$  in the *Hawea* section (fig. 7), it follows that in the Subantarctic Water of salinity less than 34.5‰, mixing occurs most readily horizontally. But if there is mixing across the front—which is represented by the steep isohaline slopes 34.5 and 34.6‰, and isolines of constant  $\sigma_t$  of values of 26.8–26.9—then Subantarctic Water from a given depth mixes with water from greater depths on the north side of the Front. If this type of mixing

\*At Stations C 1 to C 29 sampling bottles without thermometers were attached at known intervals along the bathythermograph wire and sampling depths calculated by proportional methods based on the greatest depth reached by the bathythermograph. The error in the estimated greatest depth (about 250 m) is about  $\pm$  20 m. The temperature at each sampling depth was read from the bathythermograph trace and where the vertical temperature gradient is great (fig. 3a) the errors may be large. However, the general configuration of isolines in fig. 7 must be approximately correct. This applies in particular, to the steep isohaline slopes near 44° S, to the shapes of the salinity tongues, and to the density distribution in the cold water tongue near Station C 20.

is to occur, Subantarctic Water 40–50 m deep must mix with water near 100 m deep north of the Front. But Subantarctic Water deeper than about 80 m—below the thermocline—mixes most readily with water of the same density from depths greater than about 250 m.

It is suggested that the high-salinity water within the pocket has been transferred to its position at Stations C 20 and C 21 along surfaces of constant  $\sigma_t$ , by motions associated with the eddy. If the transfer has occurred with little or no modification of the water in the pocket then this water must have come from depths of 250 m at Station C 27 or from greater depths farther north (stippled in fig. 7).

This process is illustrated in another manner in fig. 12, which is derived from a T–S diagram along the 180° meridian (fig. 14). This shows salinity and temperature properties along lines of constant depth (heavy lines), assuming that the effects of the eddy and other more minor fluctuations are absent. The lines conform roughly with the observed characteristics between Stations C 10 (left-hand extremities of equidepth lines) and C 29 (right-hand extremities). In the region representing Subantarctic Water the equidepth lines are nearly parallel to the constant density lines; but equidepth lines are inclined to the constant  $\sigma_t$  lines in the region of the Subtropical Convergence (at depths greater than about 30 m). This

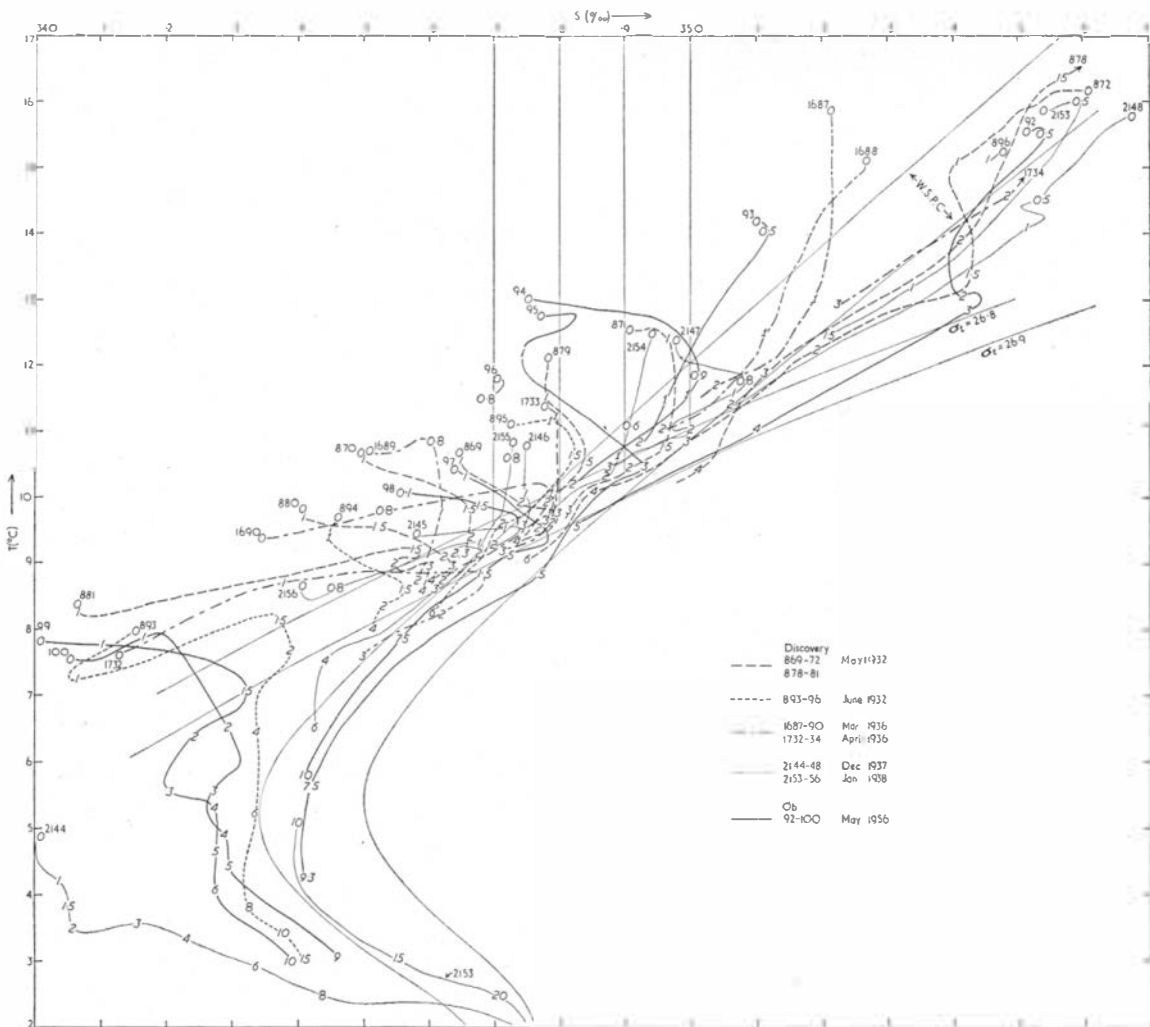


Fig. 16: T–S characteristics at *Discovery II* and *Ob* stations between longitudes 100° E (south of Eastern Indian Ocean) and 147° E (south of Tasmania). Station positions are shown in fig. 13.

Regions characteristic of Sverdrup's Western South Pacific Central Water (W.S.P.C.) and South Atlantic Central Water (S.A.C.) are shown for comparison. Figures on the station curves indicate depth in units of 100 metres.

inclination is greatest in the Southland Front region and small in the Subtropical Water Region. Water masses which may exchange and mix most readily are represented along the constant  $\sigma_t$  lines. The depths of waters which mix most readily across the Front are given by extrapolating the straight line portion of constant depth lines in Subantarctic Water to meet equidepth lines in the Subtropical Region (or vice versa). The high salinity pocket water is shown dotted and the curved sections for 25 and 50 m lines show the distortions produced by transfer of this water. It is clear that the characteristics of water within the pocket between 50 and 80 m are not those of Subantarctic Water. Nor could this water have been produced by any process in which Subantarctic Water mixed with nearby water masses unless there was a contribution of much more saline water, typical of Subtropical Water from depths greater than 250 m.\*

The same type of mixing may have occurred at depths of less than 30 m in the *Hawea* section across the Subtropical Convergence, as illustrated by the southward-pointing high-salinity tongue

\*Such mixing would be represented by a straight line connecting the characteristics of two mixing water masses and passing through the region, or by a network of lines connecting contributing water masses and containing the stippled region.

near Stations C 23 to C 29 (fig. 7). This water may mix with shallow Subantarctic Water of nearly the same density. The mixture would tend to sink slightly, but since it would be formed above the thermocline it would be prevented from sinking immediately by the sharp density gradient beneath. This shallow water, warmer than 14°C, could not have contributed to the high salinity tongue (fig. 12), unless it had been greatly modified by surface cooling in a very small area just above the tongue. This is very unlikely.

This high salinity pocket and its existence as a stage in mixing is of considerable importance. Fofonoff (1956) has suggested that vertical instability may arise through mixing of water of different temperature and salinity but similar  $\sigma_t$  values. This comes about through the non-linear dependence of  $\sigma_t$  on the S-T characteristics. In the present instance, water with a  $\sigma_t$  value between 26.8 and 26.9 has been transferred to where its surroundings have nearly the same density but markedly different salinity and temperature. A mixture of these adjacent waters has a greater density than that of the water it replaces and will tend to sink.

Near such a boundary waters of widely different character but similar densities may mix, and sinking becomes physically possible.

## EDDIES, DIVERGENCE, AND STREAMS

### AN EDDY IN ANTARCTIC WATERS

A striking feature of the distribution of temperature southward through the Antarctic Convergence near longitude 176° E in the *Pukaki* and *Hawea* Sections (fig. 4b, 4c) is a pronounced core of cold water near latitude 62° S at the southern edge of the Antarctic Convergence. The cold water within this structure extends deeper than similar cold water in the cold layer of winter water farther south. Its absence in the east and west sections (fig. 4a and 4d), indicates that it is limited in these directions. At the surface, it is represented by a limited area of low temperatures near 62° S, 177° E (fig. 2).

In general, the temperature at the southern limit of the Antarctic Convergence in summer increases with depth from a minimum value of about 1°C at 200 m to a maximum value of about 2°C in the upper Deep Water (see also fig. 8).

Thus the cold core cannot be due to upwelling. The coldest water near the convergence is usually about 1°C (Deacon, 1937) and water colder than 0°C is not usually present so close to the convergence. Explanations of the associated temperature structure (fig. 2, 4) offer some interesting possibilities. Wexler (1959) has offered an alternative explanation to the one given below; this is considered later.

Fuglister and Worthington (1951) showed that the Gulf Stream in the Atlantic Ocean is not a smoothly flowing current, but that it meanders. One of these meanders was observed to become very distorted and to break off into a cyclonic eddy on the warm water, lower latitude side of the Stream

It is possible that a similar phenomenon has led to the formation of the Antarctic cold core. Antarctic Water may be considered as a layer of

cold, poorly saline water overlying the warmer, more saline upper layer of Deep Water. The depth of this surface layer (from the surface to the sharp temperature gradient between the coldest Winter Water and the warmer Deep Water beneath) varies from about 100 m at the Antarctic Divergence to about 200 m near the Antarctic Convergence a few degrees of latitude farther north. At this depth, as well as the sharp temperature discontinuity, there is a vertical density gradient which slopes steeply downward to the north beneath the convergence. Strongest geostrophic currents are expected, and have been observed (Sverdrup *et al.*, 1942 p. 614), in the re-

gion of greatest horizontal density changes which lie beneath the Antarctic Convergence.

If the eastward flow of higher stream velocities is subject to meandering, the Antarctic Convergence will also meander. That this may be so is indicated here; however, more observations are required to show that the southward deviation of the convergence observed to the east is not a permanent local feature. (The position of the convergence is known to vary with time.)

It may be shown that, if a homogeneous water layer overlies denser water beneath and if friction is negligible, the vorticity  $\zeta$  (which is twice the angular momentum) of a vertical column of very

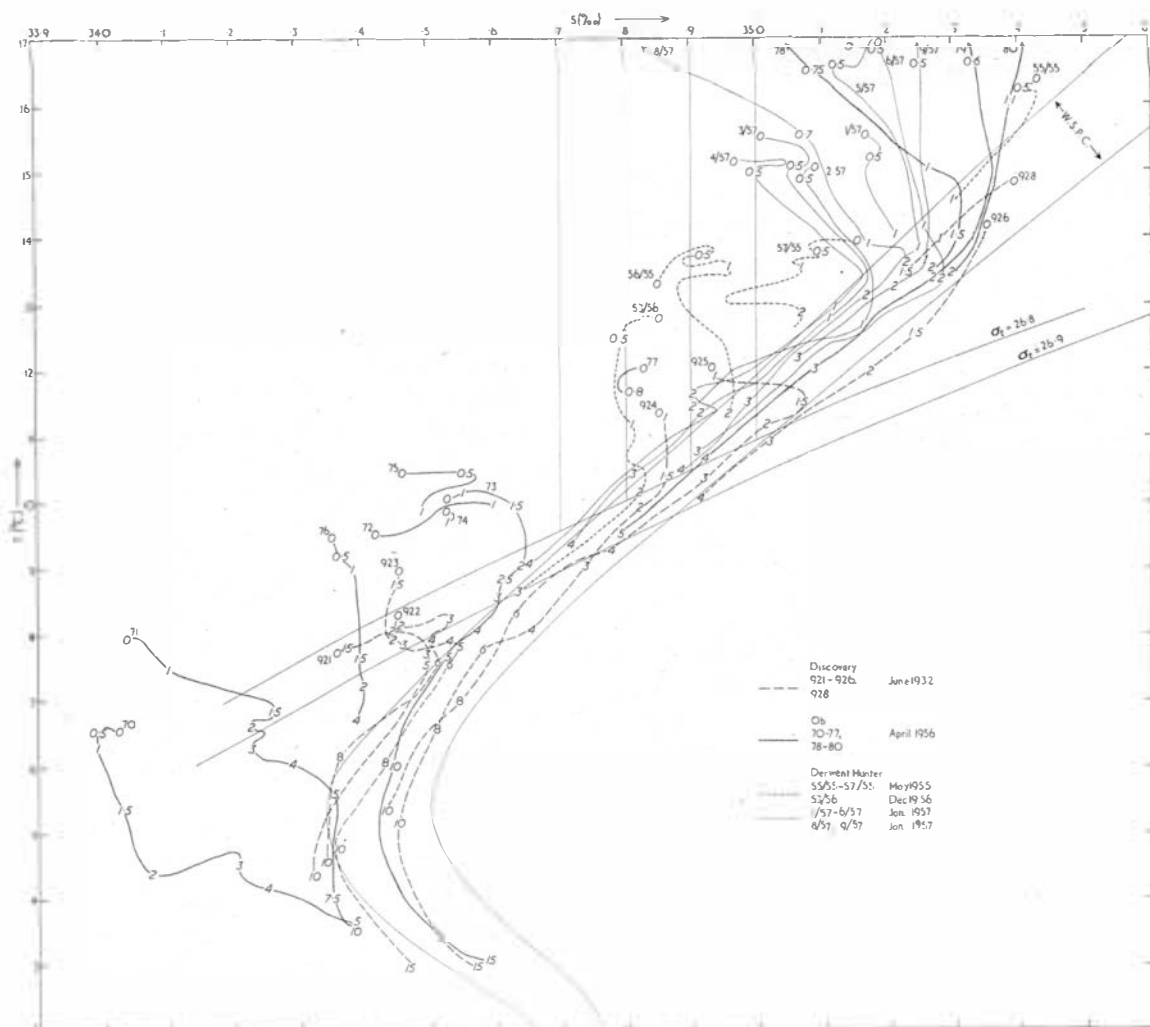


Fig. 17: T-S characteristics at *Discovery II*, *Ob*, and *Derwent Hunter* stations in and south of the Tasman Sea and south of New Zealand. Station positions are shown in fig. 13.

Regions characteristic of Sverdrup's Western South Pacific Central Water (W.S.P.C.) and South Atlantic Central Water (S.A.C.) are shown for comparison. Figures on the station curves indicate depth in units of 100 metres.

small extent throughout the depth  $D$  of the layer, is given by the equation (for example see Rossby, 1938).

$$\frac{d}{dt} \left( \frac{f + \zeta}{D} \right) = 0$$

where  $\frac{d}{dt}$  is the total derivative following the

motion of the column and  $f = 2\Omega \sin \varphi$  is the Coriolis parameter;  $\Omega$  is the Earth's angular velocity and  $\varphi$  the latitude. The convention for the Southern Hemisphere is that  $\varphi$  and  $f$  are negative, and that  $\zeta$  is positive for anticlockwise or anticyclonic rotation and negative for cyclonic circulation. This equation, expressing the constancy of the potential vorticity, may be written:

$$\frac{D\zeta}{dt} = \left( - \frac{df}{dt} \right) + \frac{f + \zeta}{D} \frac{dD}{dt}$$

The vorticity becomes more cyclonic (or less anticyclonic) if  $\frac{d\zeta}{dt}$  is negative. Thus there is a

cyclonic tendency if the column of water moves northwards ( $\varphi$  and  $f$  increasing) or if  $f + \zeta$  is negative and the depth increases. Hence, if water near the shallowest region of the Antarctic Surface Waters (near  $65^\circ$  S, depth 100 m, say, temperatures less than  $-1^\circ$  C) moves to near  $62^\circ$  S in a meandering motion, or by other means, the vorticity will be decreased; that is, there is a cyclonic tendency because of northward displacement.

The observed eddy occurred near the southern edge of the convergence, but is apparently separated from and extends deeper than water of similar low temperatures farther south. Suppose a northward meander has become distorted and cut off. This cut-off water would experience a cyclonic tendency also, if it moved to the new position without any change in depth of the constituent water. It would be surrounded by water of lower density at certain levels; and vertical extension must occur downward to maintain equilibrium. Alternatively, suppose that an eddy has formed in Antarctic Water by an unexplained process (perhaps under frictional or wind influence at the surface) and has been forced nearer the convergence where Antarctic Surface Water is deeper, the same effect would result. Either interpretation suggests the tendency to vorticity within the cold tongue at  $62^\circ$  S will be strongly cyclonic compared with that further south.

The first explanation, that the core is caused by meanders in eastward flow, is preferable if the

more northward extension to  $63^\circ$  S of cold winter water in the *Hawea* section (fig. 4b), is interpreted as the remnant of a northward deviation of the current system. Such a meander would be reflected in the surface contours which would differ from those between latitudes  $60^\circ$  S and  $65^\circ$  S (fig. 2). The  $4^\circ$  C and  $3^\circ$  C isotherms, for example, would bend to the south from the observed positions on the *Pukaki* western track, then to the north around the cold pocket. It is unlikely that the  $2^\circ$  C isotherm would be distorted so far north because of its observed positions near the east-west parts of the tracks. Thus the phenomenon would be represented by a sharp, almost northward-pointing, tongue of cold water ( $3^\circ$  and  $4^\circ$  C isotherms) enclosing a cold pocket of less than  $2^\circ$  C at its northern tip. The Antarctic Convergence would bend northward here and a pocket of warmer  $3^\circ$  C water would occur one degree of latitude south of the convergence.

Near longitude  $180^\circ$  and latitude  $44^\circ$  S, south of the Subtropical Convergence, there is another unusual temperature structure (fig. 3a, 6, and 7) in which the isotherms are deflected upward near the thermocline. This anomaly is probably associated with the mixing process at the convergence previously described. Here attention is drawn merely to its closeness to a steeply sloping density surface, normal to which there is a sharp density gradient and where high geostrophic currents may occur. These two phenomena, near the Antarctic and Subtropical Convergences, could possibly both originate from vorticity introduced in regions of high velocity shear, from current meanders, from fluctuations on the surfaces of sharp density changes, or from external processes acting at the surface. The first two are the most likely initial causes; but, whatever the origins of the phenomena, it is suggested that their highly developed state—particularly at  $62^\circ$  S—is made possible by the large changes of effective depth which become possible when lighter water overlies a steeply sloping surface of sharp density change.

#### DIVERGENCE AND THE ANTARCTIC CONVERGENCE

Wexler (1959) has postulated that the region known as the Antarctic Convergence is in fact a region of divergence. He argues that the cold tongue at  $62^\circ$  S (fig. 4b and 4c) and two similar but much less pronounced features occurring in two bathythermograph sections observed 42 days and 12 days earlier (near  $60^\circ 30' S$ ,  $172^\circ E$ , and  $61^\circ 30' S$ ,  $175^\circ E$  respectively), "can only be explained by upwelling induced by horizontal

divergence of the surface layer." The source of these cold cores "must have been horizontal motion northward from the cold subsurface Antarctic water . . . a breaking-off of this water mass from its source region, and a strong vertical stretching of the water column to produce cooling both in the surface layer and at depths below 600 ft." With this last statement the present author agrees. However, Wexler also argues that the detailed temperature sections, "seem definitely to point in the direction of a narrow band of horizontal divergence encircling Antarctica, at a position very close to that given by Mackintosh for the Antarctic 'Convergence' ". This could account for a surface temperature minimum just

south of the position of the "conventional" convergence and for a temperature maximum farther south (fig. 2; *Pukaki-Hawea* central tracks). Similar minima show up to some extent on six of the 15 "*Discovery*" sections in Deacon (1937).

Thermograph recordings on both *Hawea* and *Pukaki*, from the points where they turned due north on their return journeys, showed a steady increase in temperature as far as the convergence region. (This was apart from minor fluctuations, of  $\pm 0.5^{\circ}\text{C}$ , normally associated with detailed oceanic summer observations). Only one of four bathythermograph sections across the Antarctic Convergence published by Garner (1958) indicated

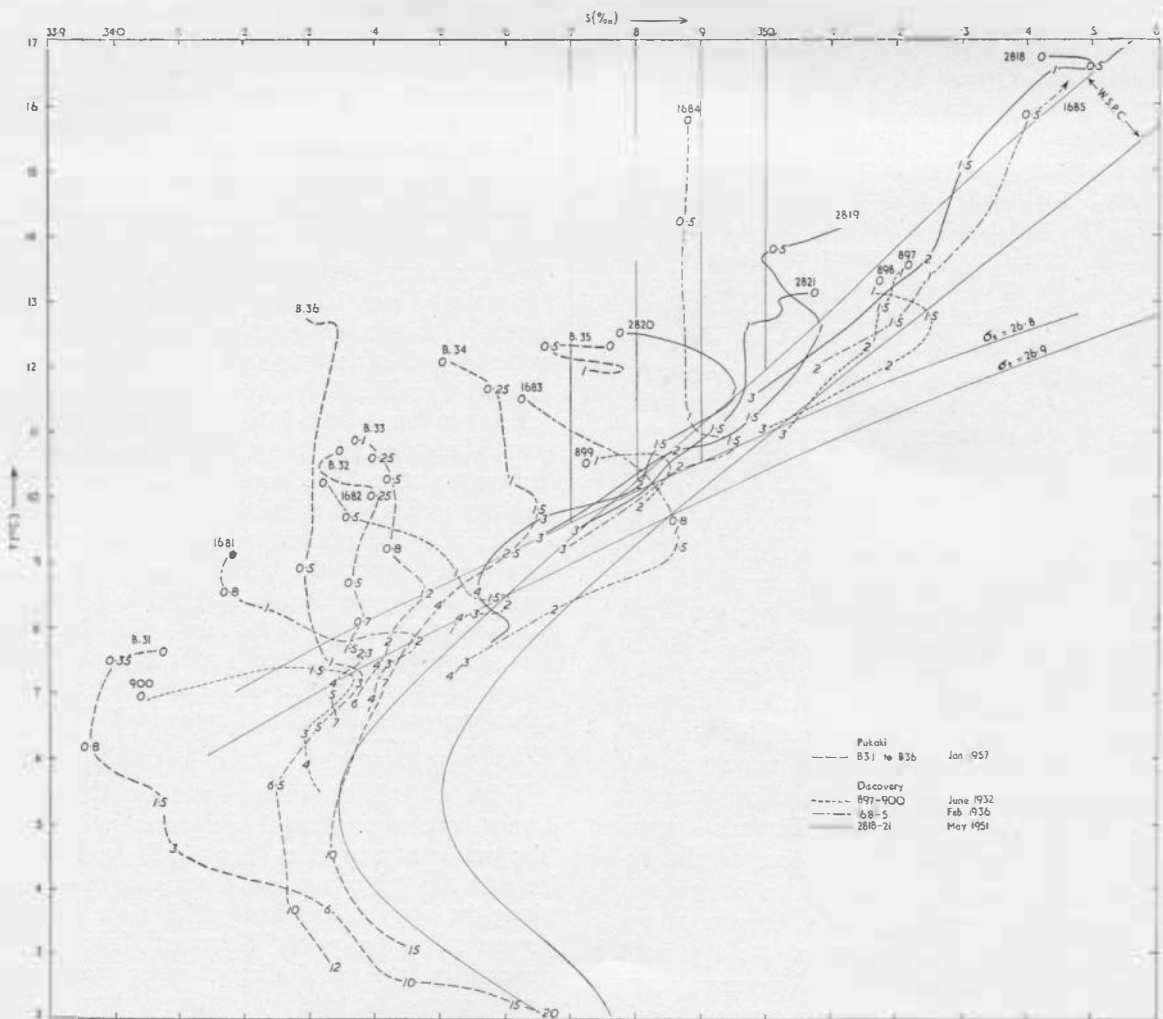


Fig. 18: T-S characteristics at *Pukaki* and *Discovery II* stations in and south of the Tasman Sea and south of New Zealand. Station positions are shown in fig. 13.

Regions characteristic of Sverdrup's Western South Pacific Central Water (W.S.P.C.) and South Atlantic Central Water (S.A.C.) are shown for comparison. Figures on the station curves indicate depth in units of 100 metres.

the presence of a surface temperature minimum. Temperature minima exist at the surface in 11 bathythermograph sections south of the Pacific Ocean and in the Scotia Sea, listed by Wexler, but in only three sections is there a well-pronounced cold core. One of these three is the *Pukaki* southward section of 62° S and 177° E (fig. 4c); the other two, at 60° 30' S, 172° E, and 61° 30' S, 175° E are from observations sufficiently near in place and time to have observed this phenomenon. It is suggested here that the deep cold core is not directly connected with Wexler's mean divergence; a more probable interpretation of the core is that already given. However, the frequent occurrence along a meridian of a surface temperature minimum in the upper 50 m south of the sharp southward decrease in temperature, is probably associated with the "Ekman divergence" in this region, suggested by Wexler.

Wexler has computed the latitudes of the maximum westerly winds around the Antarctic Continent from the mean meridional pressure gradients—between the longitudes 170° E and 177° E, the wind maximum lies between latitudes 52° S and 57° S—and remarks that the wind stress distribution "leads to a divergence south of the latitude of the maximum winds and a convergence to the north". This follows from a computation of horizontal divergence, based on wind stress relations (Koopmann, 1953; see equation below). This shows that convergence should occur only north of the maximum mean westerly winds, which are far north of the position normally regarded as the "Antarctic Convergence". He examines several possibilities "to explain the existence of such a narrow circumpolar zone" of upwelling coinciding with the temperature minimum. This is described as similar to phenomena observed in regions of coastal upwelling off Southern California and the west coast of South America, about 100 miles from the coast; in the present instance the boundary is the edge of the ice-pack in winter and the position of the convergence is maintained in summer by inertia. No attempt is made in this paper to explain Wexler's narrow zone of upwelling near the position usually described as the Antarctic Convergence but the following argument explains a general region of upwelling or "divergence" south of the Antarctic Convergence and the fact that sinking must occur to form Intermediate Water in the region of horizontal divergence in the Ekman layer.

Stommel (1958A) shows that horizontal divergence in the Ekman layer is given by the

formula

$$f \operatorname{div}_H \bar{M} = f \rho W_D = \beta M_y + \operatorname{curl} \bar{\tau}$$

where  $\bar{M}$  is the vertically integrated momentum of the layer and  $M_y$  the northerly component,  $D$  the depth of the layer,  $W_D$  the vertical component of velocity (positive upwards) at depth  $D$ ,  $f$  the Coriolis parameter,  $\beta = \frac{\delta f}{\delta y}$  ( $y$  positive northwards) and  $\bar{\tau}$  the wind stress acting at the surface. The divergence is zero where

$$\beta M_y = - \frac{\delta \tau_x}{\delta y}$$

in the Southern Ocean westerly wind zone, in which  $M_y$  (to the left of the wind direction) and  $\beta$  are positive; this position is north of the region of maximum westerlies. The westerly wind component decreases southward from a maximum in the Subantarctic to a minimum in the zone of easterly winds near the Antarctic Continent. Thus, this whole region south of the maximum westerlies is potentially one of divergence. The maximum divergence occurs roughly where the meridional gradient of the zonal wind velocity is greatest, and it is reasonable to assume that here the depth of the Ekman layer and of the upper layers of Antarctic Water is least. Observations indicate that the maximum divergence occurs between westerly and easterly wind zones. In discussing Antarctic surface features, a number of sections were mentioned in which a salinity maximum occurs between 3.5° and 4.5° of latitude south of the convergence. The density distributions in these sections indicate that this salinity maximum coincides with the greatest density of summer surface waters, with the nearest approach to the surface of a given density surface, and also with the closest approach to the surface of the top of the warm tongue in the upper layer of Deep Water. This is strong evidence that the maximum upwelling occurs here, and agrees with Deacon's hypothesis (1937).

North of this maximum upwelling the surface layers have a northward component of motion. The water at any given depth will tend to sink beneath the lighter water to the north and to move along the isopycnal surfaces which slope gradually downward to the north. However, there will not necessarily be a net sinking of water even farther north where the density surfaces slope steeply downward, since there must be a balance between the dynamic process tending to cause upwelling of deeper water, the tendency of denser water to sink, and the rate of modification of the waters

by climatic influences and by mixing. The first two processes, acting in opposition, must do much to stimulate this mixing.

The argument suggests that, between the point of maximum divergence and the region where the  $\sigma_t$  surfaces commence to slope steeply downwards, the net vertical motion is upwards, and that the water in the northward moving Ekman layer is further modified by warming and the density changes so that it does not sink; the small decrease in density values, as Surface Water moves northward, must be maintained at a given level by mixing downwards to the bottom of the layer.

North-south sections of  $\sigma_t$  values (or of specific volume anomalies) through the Subantarctic Region sometimes show (fig. 10; also fig. 162 in Sverdrup *et al.*, 1942) that above 500 m the isolines slope steeply downward to the north from near the Antarctic Convergence as far north as 55° S, the northern limit of the downward and northward pointing low salinity tongue (fig. 9 and 11). This limit coincides with the northern limit of the region of intense mixing on the north side of the convergence indicated by fluctuations in the isotherms above 250 m (fig. 4). From these facts we infer that sinking of Antarctic Intermediate Water occurs beneath a wide zone of intense mixing on the north side of the Antarctic Convergence. (This is rather different from Deacon's (1937) analogy of water pouring down the steep slopes as if over a waterfall.) Mixing may be enhanced by near equality in the mean balance between the tendency to sink due to buoyancy and the tendency to upwell due to wind distribution. At a given time different tendencies will predominate in different parts of the mixing re-

gion and exchanges along the sloping surfaces of constant density,  $\sigma_t$ , will be induced. However the average vertical component of motion taken over a very long time at one place, will be zero. The northern limit of the mixing region appears to be quite near the maximum westerly winds (near latitude 55° S), and south of both the line separating Circumpolar and Australasian Subantarctic Water (fig. 13) and the stream described below. North of latitude 55° S the isotherms in the bathythermograph sections (fig. 3) are much smoother. North of the maximum westerlies, the northward increase of convergence in the Ekman layer will impose a downward motion at the bottom of the Ekman layer, in agreement with Deacon's hypothesis of the vertical circulation in the Subantarctic Region. The northward increase of convergence possibly also influences the position of the Subtropical Convergence.

#### A FREE STREAM CURRENT IN SUBANTARCTIC WATERS

An interesting phenomenon is the tongue of cold temperatures between latitudes 55° S and 56° S in each *Pukaki-Hawea* bathythermograph section (fig. 3). Coinciding with this cold tongue there is a temperature minimum on each surface thermograph record (fig. 2). There were insufficient data (stations only) along *Pukaki's* western track to determine the detailed surface salinity structure, but there was a salinity minimum (fig. 2) on the central *Pukaki-Hawea* track, and also on the *Hawea* eastern track on the 180° meridian. It is suggested that the surface temperature and salinity minima and the subsurface cold-water tongue are continuous from east to west and that

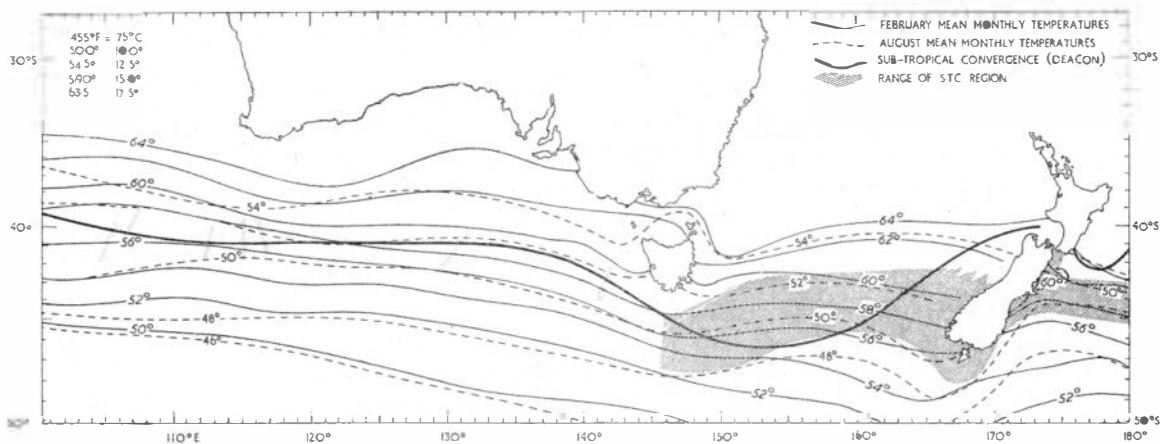


Fig. 19: Comparison of the observed range of the Subtropical Convergence Region with mean monthly sea surface isotherms for February and August. Isotherms from M.O. 516—see References.

they define a continuous zone of cold water flanked by warmer water, north and south.

The absence of sufficient subsurface salinity data through the *Pukaki-Hawea* sections prohibits a full description of this feature, although the general temperature, salinity, and density distributions (fig. 8, 9, and 10) suggest that steep gradients in the surfaces of constant density extend down to at least 700 m north of the cold water zone, but to somewhat lesser depths to the south. If the deeper water beneath the zone is assumed to have an eastward component of velocity, then pressure gradients, transverse to the axis of the zone and consistent with the density distribution, imply that the eastward current velocity along the north side of the zone increases as the depth decreases. Thus a strong eastward flow may be expected along the northern side of the zone. The density distribution, south of the zone implies that the eastward component of motion decreases with decreasing depth, and that the gradient current may possibly be westward at the surface. If there is a strong narrow eastward current along the northern side, a much smaller eastward current, or a weak shallow western countercurrent, will be present along the southern side. The resultant current system is thus one of relatively high shear.

The northern side of the cold temperature zone may constitute a continuation of the Australasian Subantarctic Front.

Fofonoff (1954) concluded that, in a free steady circulation in which the vertical component of absolute vorticity (i.e., vorticity of earth's rotation plus that relative to the earth) is constant along a streamline, eastward currents in an enclosed homogeneous ocean of constant depth must occur as narrow streams of high velocity and high relative vorticity. There cannot be slow, broad, eastward currents in such a system.

Stommel (1957) has suggested that the Circumpolar Current behaves largely as a closed circulation, in which the eastern and western boundaries are both near longitudes of the western South Atlantic where the average ocean depths, transverse to the main current, are quite shallow; the southern and northern boundaries are the Antarctic Continent and the Subtropical Convergence. Thus, within the Circumpolar Current, where friction is negligible (i.e., there is free flow), it is possible that Fofonoff's conclusions may apply.

However, it is not necessary to postulate that flow takes place in an enclosed ocean in order

to explain strong narrow streams. Since the absolute vorticity,  $f + \zeta$ , (where  $f$  is the Coriolis parameter and  $\zeta$  the vorticity relative to the earth) is conserved in a frictionless current of constant depth, then the absolute vorticity is changed whenever the current has a meridional component. For example, a change in latitude from  $48^\circ 30' S$  to  $55^\circ S$  causes a change (anticyclonic) in the relative vorticity of  $+ 10^{-5} \text{ sec}^{-1}$ : for a straight non-curving current  $\zeta$  equals the rate of change of the current transverse to its direction (for anticyclonic vorticity the current increases towards the poles in an eastwards current). Thus if  $\zeta = 0$  at  $48^\circ 30' S$  (i.e., no transverse velocity gradient) and a frictionless current is deflected to  $55^\circ S$ , then the velocity in an eastwards current near  $55^\circ S$  would increase towards the south by about 1.1 m/sec (2.2 knots) per degree of latitude.

It is evident that a deflection of the generally eastwards Circumpolar Current through about  $7^\circ$  of latitude would tend to produce a current with a high velocity shear, and consequently high velocities are possible. In an enclosed ocean, horizontal circulations must have a meridional component at some places because of continuity, and narrow streams of high velocity and high relative vorticity are impressed by the earth's rotation on a system of frictionless flow.

In the Circumpolar Current near New Zealand the current is forced to acquire a high velocity by constriction as it is forced (by continuity) to flow southwards past Auckland Islands. It is probable that mixing is large along the constricted current and that friction will tend to reduce the velocity gradients across this current. However, the anticyclonic tendency in the forced southwards motion will tend to maintain the velocity gradient. As the stream passes the southern boundary of the Campbell Plateau the restrictions to the left of the constricted current are removed and the current is free to resume its eastwards course. The frictional forces imposed by the restrictions will be much reduced and a free stream will flow eastwards.

It is therefore suggested that the zone of minimum surface temperatures and salinities near  $55^\circ S$ , and the extended zone of cold temperatures beneath (fig. 3 and 8) are observed manifestations of an eastwards free stream (of low friction) with high transverse shear and high velocities. This stream flows in geostrophic balance with the density distribution on the north side of the zone. The density distribution on the south side of the zone will be associated with the return to much

lower eastwards velocities to the south of the strong stream; if there is a weak shallow westwards countercurrent in this region it could be explained as a flow associated with a narrow high velocity jet stream (Rossby, 1936).

The above hypotheses can well be tested in

this region of great eastward mass transport in the Southern Ocean. Here there are high horizontal gradients of water properties and strong currents in a limited geographical region. Concentrated observations on the complicated dynamical nature of ocean current flow are possible and should be made.

## CURRENTS IN SUBTROPICAL AND SUBANTARCTIC WATERS

The Tasman, Southland, Canterbury, and East Cape Currents have been described by previous authors (Halligan, 1921; Fleming, 1952, Brodie, 1960; Garner, 1961). New ideas are offered below on each of these currents.

Movements of Subtropical Water (northern part of Tasman Current, East Cape Current) and of typical Convergence Region water (Southland and Canterbury Currents and southern part of Tasman Current) are shown in chart 1 (solid arrows). Probably both surface and subsurface currents flow in the same direction north of the southern limit of the Subtropical Convergence. Hence these arrows represent currents both at and below the surface except, possibly, for the Canterbury Current which is probably confined to the surface only. The width of the arrows indicates an assessment of their strength based on the steepness of slopes of constant density surfaces but not of their depth and may bear little relation to total transport.

### TASMAN CURRENT

The Tasman Current (Halligan, 1921) is derived from the East Australian Current as it turns eastward towards the Central Tasman Sea. The main body of the current lies in the Subtropical Region and extends farther north than latitude  $41^{\circ}$  S; it contains Subtropical Water but not the deeper Antarctic Intermediate Water. The deeper water may move more to the north in the eastern Tasman Sea, judging from the observed density distributions at *Discovery* Stations 1820 and 1821 (fig. 13 and 18). The extreme southern part of the Current consists of water within the Subtropical Convergence Region to depths of only about 200 m; the colder, less saline water beneath is part of the Circumpolar Current system. The precise geographical southern limit of the Tasman Current is not known, and may vary seasonally.

Most of the water in the southern part of the Tasman Current must be forced to the south as it approaches New Zealand; typical Subtropical Convergence Region water will flow to the east, south of New Zealand. This accounts for the surface salinities found south of Stewart Island by *Pukaki* and *Hawea* and at N.Z.O.I. Station B 35 and *Ob* Station 77; (fig. 13, 17, and 18).

### SOUTHLAND CURRENT AND CANTERBURY CURRENT

The Southland Current has been described by Garner (1961) as a surface current, containing water from the Tasman Sea, which flows along the southern coast of New Zealand and turns north-east past Dunedin. East of the South Island, the Southland Current contains both Subtropical Convergence water and an admixture of Australasian Subantarctic Water which moves north-east along the northern edge of the Southland Front in the upper 200 m. The dynamic conditions along this front indicate that the Southland Current reaches to the bottom at a depth of several hundreds of metres and is confined to a narrow region between the Front and the steep slopes of the continental shelf.

Near its northern limits, water carried by the Southland Current deeper than 70 m—the minimum depth of the front—will turn east to join Subtropical Water transported southward in the East Cape Current. Both of these currents will be influenced by the bottom topography but their eastward deflection will be reinforced by their confluence.

It has been shown that the pocket of poorly saline, cold surface water observed off Dunedin (fig. 2) implies that the Southland Current splits at the surface. The pocket is believed to have been caused by upwelling of water which had moved shorewards from just above the thermo-

cline in Subantarctic Water (fig. 6). This upwelled water must have crossed the Southland Front, which dips downward from about 70 m in the thermocline and would have divided the shallow waters of the Current. These shallow waters continue onwards into the Canterbury Current (Garner, 1961) farther north. It is not certain that all of this water continues northward; part may turn east with the deeper subsurface current, but probably similar shoreward transfers of upwelled Subantarctic Water often contribute cold, poorly saline water to the Canterbury Current.

The inshore current flowing northward near Cook Strait is a continuation of the Canterbury Current with a contribution derived from a mean south-eastward flow through Cook Strait (Brodie, 1960).

All of the above nearshore currents around New Zealand are stable; that is, they may persist if all forces are removed other than those due to restraints imposed by the sloping configuration of the bottom and the Coriolis mass acceleration. In the Southern Hemisphere, Coriolis accelerations tend to cause a moving particle to turn left of the direction of motion; thus when wind stresses and pressure gradients are absent, nearshore currents are unstable unless the leftwards tendency is prevented by a land mass.

#### EAST CAPE CURRENT

The East Cape Current (Fleming, 1952) transports Subtropical Water lying above Antarctic Intermediate Water as far south as the Subtropical Convergence. The present author interprets this current as a westward intensification (Stommel, 1957) of part of a complicated, anticyclonic (anticlockwise) circulation system, north of the Subtropical Convergence which extends an unknown distance eastward into the Pacific Ocean. Since the Tasman and Coral Sea circulations are fed largely by the South Equatorial Current (Rochford, 1957), these circulations, including the East Australian Current which is also a westward intensification, the Tasman Current and the East Cape Current, may all form part of the same general circulation system which includes Sverdrup's Western South Pacific Central Water Mass. Sverdrup's water mass extends eastward to about 160° W and north to approximately 10° S. It is the present author's conception that the East Australian and East Cape currents are dynamically similar to the Gulf Stream, the Kuro Siwo and the Agulhas Current on the western shores of the other major oceans.

#### THE CIRCUMPOLAR CURRENT

In the New Zealand sector of the Southern Ocean the author believes that the Circumpolar Current (Deacon, 1937) is comprised of a series of subsidiary currents, each of different dynamical nature, the features of which depend principally on the local topography. These subsidiary currents are:

- (a) *the Ekman, wind-driven current* in the wind-mixed surface layers;
- (b) *a constricted, highly frictional current* in which most of the flow is forced to the south as Subantarctic Water in the Circumpolar Current approaches the Campbell Plateau;
- (c) *the Bounty - Campbell Gyral*, postulated as an anticyclonic rotation north of the main current south-east of New Zealand;
- (d) *an eastward free stream current* of high anticyclonic vorticity which develops where the eddy-friction stresses become unimportant as the constricted current clears the steep western slopes of the Campbell Plateau.

In the Subantarctic Region, the Circumpolar Current consists of Subantarctic Water, Antarctic Intermediate Water, Deep Water, and Bottom Water (Deacon, 1937); as the depth decreases the lower water masses are excluded. The open broken arrows in Chart 1 represent a concept of the mean motion of the Circumpolar Current, between the bottom of the Ekman layer and the ocean bottom. The relative widths of the arrows indicate the apparent strength of each current at depths where it is most significant and do not necessarily indicate total transport. The current strengths are roughly those indicated by horizontal density differences observed at successive stations.

#### DRIFT CURRENTS

Double-headed arrows in Chart 1 represent the mean northward motion of Subantarctic Surface Water to the left of the Westerly Winds. This is in the upper wind-mixed layer which extends to the summer thermocline if the latter is present. Movement in this layer has two components; the northward Ekman current due to wind action, and a more or less eastward component consistent with gradient currents just beneath the wind-mixed layer.\* The mean motion in this layer is thus directed roughly between north and east but the precise directions are not important here and the Ekman currents are represented as

a north-eastward current. In most areas the direction of maximum velocity in the West Wind Drift at the extreme surface will be less than  $45^\circ$  to the left of the wind. Westerly winds decrease north and south of a maximum and similar changes are found in the Ekman component of Subantarctic Surface Water. These changes are important to the production of vertical motions just beneath the Ekman layer. They are implied by the relative lengths of the continuous arrows (Chart 1)

#### A CONSTRICTED CURRENT

The Circumpolar Current approaches the New Zealand Sector of the Southern Ocean from the west. Near  $159^\circ$  E it will be at its most northerly position after being deflected to the north as it approaches the Macquarie - Balleny Ridge. East of  $159^\circ$  E it turns south as it moves into deeper water to the east of Macquarie Island; this southward deflection, however, is mainly enforced by the constriction imposed on the flow by the steep western slopes of the Campbell Plateau. This has least effect on the southern part of the current, but the northern part is forced to flow to the south-east in a relatively narrow stream, as a *constricted current*.

Near  $157^\circ$  E, the eastward currents in Subantarctic Water are not uniform at all latitudes but must be stronger along the northern sides of the Antarctic Convergence and Australasian Subantarctic Front than elsewhere. The Australasian Subantarctic Front is near  $52^\circ$  S, thus at  $160^\circ$  E water above 500 m in the strong constricted current flowing along the slopes of the Campbell Plateau must be derived mainly from Australasian Subantarctic Water. To maintain the pressure gradient which is in balance with this current the Australasian Subantarctic Front must also turn south-east along the current's southern edge.

Since the observed southern limit of Australasian Subantarctic Water (dotted line, fig. 13) turns to the north near the Auckland Islands and apparently crosses the strongest part of the current, there must be much mixing along the front between the two different Subantarctic Water masses, beginning where the constriction first takes effect near  $160^\circ$  E. There must also be mixing on the

\*At the bottom of the surface layer, where the Ekman Current velocities are very small, eddy friction is considered to be negligible. The present author maintains that the persistent action of frictional forces just beneath the layer, even though small, must impart the mean motion of the gradient currents to the wind-mixed Ekman layer

northern side of the constricted current since Australasian Subantarctic Water had not penetrated to the position of N.Z.O.I. Station B 33 about 50 miles south-east of Auckland Island in January, 1957. Moreover, the very low salinity at *Ob* Station 76, 100 miles south of Stewart Island and 100 miles north-east of Auckland Island suggests that Subantarctic Water must approach this position from the east. This eastward motion may be part of a gyral.

Since the depth of water between Campbell and Auckland Islands is about 500 m it might have been expected that the Australasian Subantarctic Water would extend to the east between these islands. If, however some Australasian Subantarctic Water flows from just south of Auckland Island to just north of Campbell Island, extremely rapid mixing of this higher salinity Subantarctic Water with a greater quantity of lower salinity water must take place (compare for example fig. 2 and fig. 13 and 18—N.Z.O.I. Stations B 32, B 33, and B 34); but a south-eastward pointing tongue near Campbell Island in the  $34.30/00$  surface isohaline indicates that the highest salinity water in the current was south of Campbell Island. Less saline water from south of the tongue could not have crossed the current to reach the Island. Thus, even at shallow depths, Australasian Subantarctic Water must flow south-east in the constricted current parallel with the edge of the Campbell Plateau in approximately the same direction as water beneath. It is therefore expected that Australasian Subantarctic Water will extend an unknown distance along the constricted current, and that the boundary between Australasian and Circumpolar Waters will bend towards the south-east along each side of this current. The present indeterminate position of this boundary is indicated by the parts of the boundary extending along each side of the constricted current in chart 1. Mixing with poorly saline Circumpolar Subantarctic Water will occur along the boundaries of the current and eventually its "Australasian" characteristics will be lost. A maximum of salinity ( $34.500/00$ ) at 150 m at *Discovery* Station 2209, south of Campbell Island, partly supports the above hypothesis. Such an extension of the highly saline water will be markedly sensitive to any fluctuations in the Circumpolar Current system.

Data used to define the Australasian Subantarctic Front indicate that it reaches a depth of at least 1,000 m; that is, deep into the Antarctic Intermediate Current. The southward deflection of the current near  $160^\circ$  E must extend to Deep

Water below 2,000 m and the dynamic balance requires a steep horizontal density gradient at these great depths; hence the front along the southern side of the constricted current will extend to similar depths. *Ob* Stations 71 to 73 show that constant density surfaces slope down to the north at all depths greater than 100 m. If the level of the zero horizontal pressure gradient is beneath the front, or if the front extends to the bottom, then both the pressure gradient across the front and the gradient current velocity in the constricted current will increase as the depth decreases. Hence the flow must take place along the front at all depths greater than 100 m.

An eastward extension of quite shallow Australasian Subantarctic Water onto the Campbell Plateau in a direct eastward flow could be prevented by the presence of much less saline water east and north-east of the Auckland Islands; this less saline water must then persist against the inertia of the water masses impinging from the west. However, if a "frontal steering" explanation for the shallower parts of the constricted current be correct, this would allow the *persistence* of less saline water east of the Auckland Islands; "Steering" is caused by extension to the surface of the strong deep pressure gradient on the southern side of the constricted current.

#### BOUNTY - CAMPBELL GYRAL

The Bounty - Campbell Gyrals, postulated earlier, explains the *presence* of poorly saline water not far to the east and north-east of the Auckland Islands, and east of Stewart Island.

Circumpolar Subantarctic Water east and south of Stewart Island may move south-westward along the Front from east of 180° with an anticlockwise rotation over the Bounty Trough and most of the north-eastern part of the Campbell Plateau. It has been shown that warm water moves eastward on the northern side of the Southland Front; the difference in velocity across the front would balance the pressure distribution. Without more information the existence of the anticyclonic Bounty-Campbell Gyrals remains hypothetical, but this direction of rotation is consistent with the maintenance of the Southland Front near the east coast of the South Island and south of Stewart Island; it also agrees with observed distributions of salinity, and in particular, with the eastern limit of Australasian Subantarctic Water.

Since the mixed surface layer of Subantarctic Surface Water has a northward component of

motion and deeper Subantarctic Water has a southward component in the high salinity tongue after sinking south of the Subtropical Convergence, Subantarctic Water within the gyral may exchange and mix with that in the main Circumpolar Current to the south. This exchange could take place at the depth of the salinity maximum along the southern edge of the gyral between Campbell and Bounty Islands.

#### FREE STREAM CURRENT

The zone of low temperatures between 169° E and 180° near 55° 30' S, has earlier been interpreted as associated with a strong but narrow eastward current along the north of the zone, and a relatively small flow in the same direction or a weak shallow countercurrent along the south side. The strong eastward *free stream current* is the type of eastward flow, which must exist on a rotating earth, where friction is small and the water has been transported from other latitudes.

It has been remarked that the southern slopes of the Campbell Plateau east of 169° E must exert some control on the eastward flowing currents. This implies that not all of the Subantarctic Water in the Constricted Current is led into the Free Stream Current system, but that some is diverted north of the Free Stream Current along the steep slopes between Campbell Island and the Antipodes Islands. This current need not be subject to the Fofonoff restriction since friction may not be sufficiently small.

Confinement of the eastward Circumpolar Current flow into strong narrow streams, may occur wherever frictional forces are sufficiently small and the water mass has been deflected north or south. Eddy frictional stresses are probably important in the mixed water region (Deacon, 1937), which extends through several degrees of latitude north of the Antarctic Convergence. Here, roughly between 168° E and 180° and south of 56° S, extended free streams will not develop. However, free stream currents may occur in most other parts of the Circumpolar Current where topographical features deflect the main flow. This possibility is neglected in chart 1 (especially near longitude 157° E), except for the Free Stream Current which has been described and except where frictional forces are important.

#### ORIGIN OF THE SOUTHLAND FRONT

The Southland Front may be simply explained as a front which is developed in Subantarctic Water near the Auckland Islands between branches

of different currents. As Australasian Subantarctic Water approaches the Auckland Islands, from the west, denser Circumpolar Subantarctic Water lies to the east. In a gradient current, the density distribution is such that in the Southern Hemisphere lighter water lies to the left of the direction of the current. To maintain dynamic balance, Australasian Subantarctic Water which is not as deep as the bottom over the northern Campbell Plateau, must turn eastward before it reaches a point where the denser Circumpolar Subantarctic Water lies to its left. A pressure gradient is required to balance the eastward flow in the Australasian Subantarctic Water relative to the motion of the Circumpolar Subantarctic Water. This is provided by the development of a front near the Auckland Islands. The eastward flowing Australasian Subantarctic Water above 200 m is shown in Chart 1 by the broken arrow sweeping round the southern edge of the Subtropical Convergence Region. The Circumpolar Current at depths of more than 200 m must continue to the south and contribute to the Constricted Current. Where the Southland Front is developed between Stewart and the Auckland Islands, it is not sharp and it appears to come to the surface (fig. 4d); farther north it is a subsurface feature with steep gradients occurring only at depths greater than 70 m.

The presence of poorly saline Circumpolar Subantarctic Water about 100 miles south-east of the Auckland Islands has already been explained as a westward movement along the Front east of New Zealand. Its persistence is attributed to its being steered in the upper layers by deeper water in the Constricted Current south of the Auckland Islands through vertical continuity of the pressure gradients which are associated with the Front to the south. The Southland Front must then develop near the Auckland Islands to the north-east, in such a way that a dynamic equilibrium is maintained between the water masses of different

densities which merge there. The motions and characteristics of these water masses will depend on factors operating in widely different locations. Australasian Subantarctic Water arriving near the Campbell Plateau is influenced by the climates of all the oceans to the west, particularly the Eastern Indian Ocean and Tasman Sea. The Circumpolar Subantarctic Water east of New Zealand is partly influenced by conditions near the Subtropical Convergence for an unknown distance to the east in the Pacific Ocean, and partly by the general circulation of Circumpolar Subantarctic Water in higher southern latitudes. Thus, the general equilibrium near the Campbell Plateau is subject to variations in oceanic and meteorological conditions a great distance away. This suggests that some features may have large seasonal and longer term variations. For example, there will be fluctuations in the eastern limits of Australasian Subantarctic Water; in characteristics, particularly salinity, within the Constricted Current, over the western Campbell Plateau, and in the currents and water masses associated with the Southland Front south of Stewart Island.

East of New Zealand, the continuation of the Southland Front is closely associated with the Subtropical Convergence, and its dynamic equilibrium depends more directly on influences within the Western South Pacific (e.g., a balance between water in the East Cape Current and the Circumpolar Subantarctic Water). Its geographical position should be more static; it is probably most sensitive to seasonal changes in the subtropical currents. However, just south of New Zealand, near Stewart Island, salinities and temperatures at a given locality could vary between those of Circumpolar Subantarctic Water and those of Subtropical Water with regular seasonal variations superimposed on any significant non-seasonal fluctuations.

## SUMMARY

The author's generalised interpretation of water masses, currents, fronts, and regions separating water masses in the southern New Zealand Region is shown in Chart 1. The positions of the fronts, east of 165° E, are derived mainly from the *Pukaki* data December 1956 to January 1957, and the *Ob* data April 1956. The fronts west of 165° E and the Subtropical Convergence Region are deduced from pre-1958 data (fig. 13). The arrows are a schematic representation of the most probable system of current circulations which may determine, or be determined by, the water characteristics; the main currents and their boundaries obviously also depend on the bottom topography. In general the features illustrated will be more complicated at any one time than depicted and there may also be seasonal variations.

### THE SUBTROPICAL CONVERGENCE REGION

The Subtropical Convergence Region is located by water properties at depths less than 200 m. At these depths the salinity ranges from 34.7–35.00/00 and the density ( $\sigma_t$ ) is less than 26.8. Subtropical Water is usually warmer and more saline at these depths, and less dense at 200 m. The density ( $\sigma_t$ ) at 200 m in Subantarctic Water is greater than 26.8. The Subtropical Convergence Region probably extends farther to the north in summer than winter; and its width may also vary. It is broad near the west of New Zealand where the currents are greatly influenced by the land mass, but narrower and better defined offshore to the east of New Zealand. Surface water west of New Zealand, north of 42° S, is warmer than that typical of the Subtropical Convergence Region, and is often poorly saline, although, deeper than 50 m its salinities are greater than 35.00/00. These low surface salinities are probably caused by freshwater runoff from the land, although surface northward movement may possibly take in the Eastern Tasman Sea.

### SUBANTARCTIC WATER

Two distinct types of Subantarctic Water occur south of the Eastern Indian Ocean, the Australasian Continent, and the Tasman Sea. Southern *Circumpolar Subantarctic Water*, of salinity below 34.50/00, is present through most Circumpolar Regions. Warmer, more saline *Australasian Subantarctic Water*, with salinities sometimes >34.50/00, occupies a broad zone between the Convergence Region and Circumpolar Subant-

arctic Water, between 100° E and 167° E; elsewhere, water of similar properties occurs only in a narrow zone, 2°–4° of latitude wide, south of the Subtropical Convergence. Australasian Subantarctic Water probably originates mainly south of the Central and Eastern Indian Oceans.

### THE SOUTHLAND CURRENT AND SOUTHLAND FRONT

*The Southland Current* is shown to extend several hundred metres deep between the *Southland Front* and the Continental slope of southeastern New Zealand. The front develops near the Auckland Islands where the pressure gradient across it maintains dynamic equilibrium between the two types of Subantarctic Water which approach this region from opposite directions. The Southland Current originates south-west of Stewart Island north of the Front and is mainly water from the Subtropical Convergence Region with some Australasian Subantarctic Water. East and north-east of Stewart Island the Southland Front is a subsurface feature in which surfaces of constant temperature (8°–9°C); salinity (34.5–34.60/00), and density ( $\sigma_t$ ) (26.8–26.9) slope steeply downward from the base of the Subantarctic Water thermocline, at 70 m, beneath the warmer and more saline Southland Current. The Southland Current is joined by Circumpolar Subantarctic Water which moves shorewards 30–50 m above the subsurface Southland Front and upwells off Dunedin. Below 70 m this current follows along the front as it turns eastward south of Banks Peninsula. Shallower water above 70 m continuous mainly northward along the coast as the Canterbury Current.

### CONSTRICTED CURRENT

A *Constricted Current* flows south along the steep western slopes of the Campbell Plateau where the Circumpolar Current impinges from the west. It includes water masses at all depths below the upper wind-mixed layer to the bottom and its existence is deduced from salinity distribution. Subantarctic Water above 600 m is believed to be "steered" along the current and prevented from flowing over the Plateau by pressure gradients built up at deeper levels. Strong mixing occurs each side of the current where the Australasian Subantarctic Water loses its identity, and friction must be an important process. However, highly saline water may be carried far around the southern edge of the Plateau in the narrow constricted and free stream currents.

## AUSTRALASIAN SUBANTARCTIC FRONT

A laterally continuous steep gradient of properties, the *Australasian Subantarctic Front* exists near the southern boundary of Australasian Subantarctic Water and extends to depths of at least 1,000 m. This front swings southward along the southern edge of the constricted current west of the Auckland Islands and here probably reaches the bottom; surfaces of constant water properties slope steeply downwards to the north. The Australasian Subantarctic Front must be distinct from the Southland Front to allow continuity of flow in the Constricted Current.

## FREE STREAM CURRENT

A *Free Stream Current* moves as a strong narrow eastward flow of strong shear along the northern side of a zone of low temperature water south of the Campbell Plateau near 56° S. Either a weak eastward flow or a countercurrent exists along the southern side. The Free Stream is developed where frictional and boundary constraints acting on the Constricted Current are removed.

## BOUNTY - CAMPBELL GYRAL

The observed salinity distribution requires a westward flow of Circumpolar Subantarctic Water over some part of the Campbell Plateau north of Campbell Island. The circulation which is dynamically most consistent with the salinity distribution is an anticyclonic rotation, the *Bounty - Campbell Gyral*, extending over the Bounty Trough and northern Campbell Plateau.

Circumpolar Subantarctic Water in the Bounty - Campbell Gyral must be influenced by factors operating chiefly in the Western Pacific Ocean east of New Zealand but the properties of Australasian Subantarctic Water depend on processes occurring to the west of New Zealand, mainly in the Eastern Indian Ocean. Thus the balance between these water masses south of New Zealand and consequently the position of their boundaries depends on factors operating in widely separated areas.

## EDDIES

Eddies were observed near 62° S, 176° E and 45° S, 180° E just south of the Antarctic and Subtropical Convergences, respectively; their high cyclonic vorticity is an effect either of high-velocity shear or current meanders.

## DIVERGENCE

In the Southern Ocean there is a balance between the upwards tendency of water motion at the bottom of the wind-mixed Ekman layer and the downward tendency of cold Antarctic Surface Water moving north in the Ekman layer to sink beneath warmer, lighter water to the north. It is postulated that there is divergence (associated with a mean upwards motion) south of the Antarctic Convergence and a small degree of convergence to the north where the two tendencies are nearly equal. The region of small convergence extends northward through several degrees of latitude in mixed waters (Deacon, 1933).

## ANTARCTIC INTERMEDIATE CURRENT

Mixed water sinks as Antarctic Intermediate Water throughout the whole of the region of mean convergence. This contrasts with the previous conception that the Antarctic Intermediate Water sinks from the immediate vicinity of the Antarctic Convergence. The "balance" concept has some points in common with Wexler's hypothesis (1959) that divergence occurs at the Antarctic Convergence.

## MIXING PROCESSES

An unusual pocket of high salinity water was observed between 50-90 m in Subantarctic Water near the Subtropical Convergence. A cold-water tongue (interpreted as an eddy) was found between the pocket and a steep subsurface front along the southern edge of the convergence. The pocket is interpreted as water which has moved along a constant density surface from a deeper level north of the subsurface front. This transfer leads to the exchange of waters with markedly different characteristics and because of the non-linear dependence of density on temperature and salinity the mixture of the exchanged waters will sink to greater density levels. Similar transfers along surfaces of constant (potential) density occurring near any frontal region or near boundaries between water masses, will provide a mechanism inducing downwards transfers across surfaces of constant density. Near the Subtropical Convergence the process may contribute to the formation of the highly saline layer beneath the Subantarctic Surface Water.

## ACKNOWLEDGMENTS

The author's thanks are expressed to the New Zealand Naval Board for their generous cooperation in providing facilities to carry out oceanographic work during the Antarctic cruises of HMNZS *Pukaki* and *Hawea*.

The successful completion of the planned operations was materially due to the active assistance given by Captain R. T. Hale (HMNZS *Pukaki*), Lieutenant Commander W. G. Brown (HMNZS *Hawea*), and their ships' companies.

Thanks are also due to Professor V. Kort (In-

stitute of Oceanology, Moscow) for access prior to publication to the data from the *Ob* cruise between Antarctica and New Zealand and to Dr Harry Wexler (U.S. Weather Bureau) for access to the manuscript of his paper prior to publication; to Mr C. T. Webb (Chief Cartographer, N.Z. Geological Survey, D.S.I.R.) and his staff for preparation of figures for publication; to Miss B. Krebs for assistance with references, and to Mr D. M. Garner, Mr J. W. Brodie, and Mr N. M. Ridgway for helpful criticism and suggestions.

## REFERENCES

- ANON. 1932: *Discovery Investigations Station List 1929-1931. Sta. 300-700. Discovery Rep. 4:* 1-65.
- 1941: *Discovery Investigations Station List 1931-1933. Sta. 701-1184. Ibid. 21:* 1-226.
- 1942: *Discovery Investigations Station List 1933-1935. Sta. 1185-1589. Ibid. 22:* 1-196.
- 1945: *Discovery Investigations Station List 1935-1937. Sta. 1590-2072. Ibid. 23:* 1-196.
- 1947: *Discovery Investigations Station List 1937-1939. Sta. 2073-2652. Ibid. 24:* 198-422.
- 1957: *Discovery Investigations Station List 1950-1951. Sta. 2653-2911. Ibid. 28:* 300-98
- 1958: Rezul'taty Nabljudenii. In: *Trudy Komp. Antarkt Eksp. Akad. Nauk. SSSR. Gidrol. gidrokh. geol. i biol. issled; dizel' elektrokhode 'Ob' 1955-56.* 23-145.
- BARY, B. M. 1956: Notes on Ecology, Systematics and Development of some Mysidacea and Euphausiacea (Crustacea) from New Zealand. *Pacif. Sci. 10 (4):* 431.
- BRODIE, J. W. 1960: Coastal Surface Currents Around New Zealand. *N.Z. J. Geol. Geophys. 3 (2):* 235-52.
- BURLING, R. W. 1958: Age Determinations of Southern Ocean Waters. *Nature, Lond. 181:* 107-8.
- BURLING, R. W.; GARNER, D. M. 1959: A Section of  $^{14}\text{C}$  Activities of Sea Water Between  $9^{\circ}\text{S}$  and  $66^{\circ}\text{S}$  in the South-west Pacific Ocean. *N.Z. J. Geol. Geophys. 2 (4):* 799-824.
- C.S.I.R.O. AUST. 1957: Onshore and Oceanic Hydrological Investigations in Eastern and South-western Australia, 1955. *C.S.I.R.O. Aust. Div. of Fish. and Ocean. Oceanogr. Sta. List. 27:* 82.
- 1959: Hydrological Investigations from *FRV. Derwent Hunter, 1957. Ibid. 37:* 3-10.
- DEACON, G. E. R. 1933: A General Account of the Hydrology of the South Atlantic Ocean. *Discovery Rep. 7:* 171-238.
- 1937: The Hydrology of the Southern Ocean: *Ibid. 15:* 1-123.
- 1945: Water Circulation and Surface Boundaries in the Oceans. *Quart. J. roy. met. Soc. 71:* 11-25.
- FERGUSON, G. J. 1958: Reduction of Atmospheric Radio-carbon Concentration by Fossil Fuel Carbon Dioxide and the Mean Life of Carbon Dioxide in the Atmosphere. *Proc. roy. Soc. A, 243:* 561-74.
- FLEMING, C. A. 1944: Molluscan Evidence of Pliocene Climatic Change in New Zealand. *Trans. roy. Soc. N.Z. 74:* 207-20.
- 1950: Some South Pacific Sea-birds Logs. *The Emu 49 (3):* 169-88.
- 1952: The Seas Between, in "The Antarctic Today", Ed. F. A. Simpson, pp. 102-26. N.Z. Antarctic Society and A. H. and A. W. Reed, Wellington.
- FONONOFF, N. P. 1954: Steady Flow in a Frictionless Homogeneous Ocean. *J. mar. Res. 13:* 254-62.
- 1956: Some Properties of Sea Water Influencing the Formation of Antarctic Bottom Water. *Deep-Sea Res. 4:* 32-5.
- FUGLISTER, F. C.; WORTHINGTON, L. V. 1951: Some Results of a Multiple Ship Survey of the Gulf Stream. *Tellus, 3:* 1-14.
- GARNER, D. M. 1953: Physical Characteristics of Inshore Surface Waters between Cook Strait and Banks Peninsula, New Zealand. *N.Z. J. Sci. Tech. B. 35:* 239-46.
- 1954: Sea Surface Temperature in the South-west Pacific Ocean from 1949 to 1952. *Ibid. B. 36:* 285-303.
- 1957: Hydrology of Chatham Rise, in "General Account of the Chatham Islands 1954 Expedition", by G. A. Knox. *N.Z. Dep. sci. industr. Res. Bull. 122 (N.Z. Oceanogr. Inst. Mem. 2):* 18-27.
- 1958: The Antarctic Convergence South of New Zealand. *N.Z. J. Geol. Geophys. 1:* 577-94.
- 1959: The Subtropical Convergence in New Zealand Surface Waters. *Ibid. 315-37.*
- 1961: Hydrology of New Zealand Coastal Waters 1955. *N.Z. Dept. Sci. Industr. Res. Bull. 138 (N.Z. Oceanogr. Inst. Mem. 8).*

- (in press): Analysis of Hydrological Observations in the New Zealand Region 1874–1955. *N.Z. Dept. sci. industr. Res. Bull. (N.Z. Oceanogr. Inst. Mem. 9)*.
- HALLIGAN, G. H. 1921: The Ocean Currents Around Australia. *J. roy. Soc. N.S.W.* 55: 188.
- HAMON, B. V. 1956: A Portable Temperature-Chlorinity Bridge for Sea Water Analysis. *J. sci. Instrum.* 33: 329.
- JACOBS, W. C. 1951: The Energy Exchange between Sea and Atmosphere and Some of its Consequences. *Bull. Scripps Instn. Oceanogr., La Jolla.* 6: 27–122.
- KOOPMANN, G. 1953: Entstehung und Verbreitung von Divergenzen in der Oberflächennahen Wasserbewegung der Antarktischen Gewässer. *Deut. Hydrogr. Zeitschrift Ezzgänzungsheft 2, Deut. Hydrogr. Inst., Hamburg.*
- LYMAN, J. 1958: The U.S. Navy International Geophysical Year, Antarctic Program in Oceanography. *The Intern. hydrogr. Rev.* 35 (2): 111–26.
- MACKINTOSH, N. A. 1946: The Antarctic Convergence and the Distribution of Surface Temperatures in Antarctic Waters. *Discovery Rep.* 23: 179–212.
- McLINTOCK, A. H. (Ed), 1959: "A Descriptive Atlas of New Zealand." Government Printer, Wellington, New Zealand.
- MARINE BRANCH METEOROLOGICAL OFFICE, 1949: "Monthly Sea Surface Temperatures of Australian and New Zealand Waters. *M.O. 516.*" H.M.S.O. London.
- MIDTTUN, L.; NATVIG, J. 1957: Pacific Antarctic Waters, Scientific Results of the *Brategg* Expedition, 47–48. No. 3. (*Publ. Christensens Hvalfangstmus, No. 20.*)
- MONTGOMERY, R. B. 1938: Circulation in Upper Layers of Southern North Atlantic Deduced with Use of Isentropic Analysis. *Pap. Phys. Oceanogr. and Meteor., M.I.T. and W.H.O.I.* 6 (2): 1–55.
- MOROSHKIN, K. V. 1958: Gidrologicheskie Nabludeniya. *Trudy. Komp. Antarkt. Eksp. Akad. Nauk. SSSR. Opisanie Eksp. na dizel' elektrokhode 'Ob' 1955–56.* 52–68.
- NEW ZEALAND MARINE DEP. 1946: *N.Z. Pilot.* Wellington.
- OLSSON, B. H. 1955: The Electrical Effects of Tidal Streams in Cook Strait, New Zealand. *Deep-Sea Res.* 2 (3): 204–12.
- PRIVETT, D. W. 1958: The Exchange of Heat Across the Sea Surface. *Marine Observer,* 28: 23–8.
- PROUDMAN, J. 1953: "Dynamical Oceanography." Methuen, London.
- RAFTER, T. A.; FERGUSON, G. J. 1958: Atmospheric Radiocarbon as a Tracer in Geophysical Circulation Problems; Paper read at Second United Nations International Conference on the Peaceful Uses of Atomic Energy. 15/P/2128.
- ROCHFORD, D. J. 1957: The Identification and Nomenclature of the Surface Water Masses in the Tasman Sea (Data to the end of 1954). *Aust. J. Mar. & Freshwater Res.* 8: 369–413.
- 1959: The Primary External Water Masses of the Tasman and Coral Seas. *C.S.I.R.O., Aust. Div. of Fish. and Oceanogr., Tech. Pap. No. 7.*
- ROSSBY, C. G. 1936: Dynamics of Steady Ocean Currents in the Light of Experimental Fluid Mechanics. *Pap. Phys. Oceanogr. Meteor., Mass. Inst. Tech. & Woods Hole. Oceanogr. Instn.* 5 (1): 1–43.
- 1938: On the Mutual Adjustment of Pressure and Velocity Distributions in Certain Simple Current Systems, II. *J. mar. Res.* 1: 239–63.
- 1951: On the Vertical and Horizontal Concentration of Momentum in Air and Ocean Currents. *Tellus,* 3: 15–27.
- STOMMEL, H. 1957: A Survey of Ocean Current Theory. *Deep-Sea Res.* 4 (3): 149–84.
- 1958a: "The Gulf Stream." University of California Press, Berkeley.
- 1958b: The Abyssal Circulation. *Deep-Sea Res.* 5 (1): 80–2.
- Suess, H. E. 1953: Natural Radiocarbon and the Rate of Exchange of Carbon Dioxide between the Atmosphere and the Sea: *Nuclear Processes in Geologic Settings:* National Research Council, Washington.
- 1955: Radiocarbon Concentration in Modern Wood. *Science,* 122: 415–6.
- SVERDRUP, H. U. 1933: On Vertical Circulation in the Ocean due to the Action of Wind with Application to Conditions within the Antarctic Circumpolar Current. *Discovery Rep.* 7: 139–70.
- 1934: Wie Entsteht die Antarktische Konvergenz? *Ann. Hydrogr. Mar. Meteorol.* 8: 315–7.

- JOHNSON, M. W.; FLEMING, R. H. 1942: "The Oceans." Prentice Hall, New York.
- TURNBULL, T. 1875: The Haast Wreck and Ocean Currents. *Trans. Proc. N.Z. Inst.* 8: 446-50.
- UNITED STATES NAVY HYDROGRAPHIC OFFICE, 1956: Report on Operation Deep Freeze I. *U.S.N.H.O. Tech. Rep. TR-33*. (Formerly H.O. 16331-1).
- 1957: Operation Deep Freeze II, 1956-7. *Ibid. TR-29*
- WEXLER, H. 1959: Atmosphere and the Sea in Motion. *In* Bolin, B. (Ed.) "Scientific Contributions to the Rossby Memorial volume. New York. Rockefeller Inst. Press. in assoc. with Oxford Univ. Press: pp. 107-20.
- WORDIE, J. M. 1921: The Ross Sea drift of the *Aurora* in 1915-16. *Geogr. J.* 58: 219-24.
- WÜST, G. 1929: Schichtung und Tiefenzirkulation des Pazifischen Ozeans. *Veröffentl. Inst. Meereskunde, Berlin*, pp. 1-64.

**APPENDIX A**  
**STATION DATA**

(1) PUKAKI STATIONS

NZOI Station No.	Date	Time	Latitude	Longitude	Depth (m)	Temp. (°C)	Salinity (‰)	$\sigma_t$ g/ml
B 28	Dec. 1956 29	0745-1200 h	63° 50' S	172° 00' E	0	1.61	33.46	26.78
					10	1.20	33.48	26.83
					30	-0.68	33.64	27.08
					55	-1.63	33.73	27.18
					80	-1.67	33.87	27.29
					105	-1.61	34.04	27.43
					130		34.36	
					160	1.23	(34.56)*	(27.70)
					200	1.49	34.51	27.64
					300	1.58	34.54	27.66
					395	1.57	34.63	27.73
					490	1.40	(34.38)	(27.55)
					590	1.39	34.70	27.79
					790	1.24	34.74	27.84
					990	0.96	(34.67)	(27.80)
					1,190	0.93	(34.56)	(27.72)
					B 29	30	0230-0430 h	61° 56' S
32	3.22	34.04	27.12					
55	1.01	33.98	27.25					
80	0.56	34.04	27.32					
130	-0.22	34.05	27.38					
180	0.16	34.18	27.46					
280	1.77	34.51	27.62					
630	1.92	34.60	27.68					
1,030	1.65	34.69	27.76					
B 30	30	1600-1700 h	59° 58' S	169° 07' E				
					25	6.72	33.82	26.55
					75	3.75	33.87	26.93
					150	3.28	34.00	27.09
					295	3.11	34.18	27.74
					585	2.68	34.40	27.46
					985	2.27	34.60	27.66
					1,490	2.07	34.65	27.71
					1,950	1.75	34.69	27.77
B 31	31	0400-0600 h	57° 47' S	169° 06' E	0	7.61	34.07	26.63
					35	7.51	34.00	26.59
					80	6.16	33.96	26.73
					155	5.33	34.07	26.92
					305	4.69	34.09	27.02
					575	3.72	34.31	27.29
					970	2.61	34.42	27.48
					1,460	2.30	34.61	27.66
					1,945	2.05	34.76	27.80
					B 32	Jan 1957 1	0500-0800 h	53° 38' S
10	10.41	34.31	26.36					
25	10.05	34.40	26.50					
50	8.65	34.36	26.70					
75	8.10	34.38	26.80					
145	7.66	34.36	26.84					
235	7.61	34.38	26.87					
375	7.15	34.34	26.91					
545	6.92	34.33	26.93					
690	6.55	34.34	26.98					

## (1) PUKAKI STATIONS—continued

NZOI Station No.	Date	Time	Latitude	Longitude	Depth (m)	Temp. (°C)	Salinity (‰)	$\sigma_t$ g/ml
B 33	Jan. 1957 1-2	2300-0215 h	52° 00' S	167° 30' E	0	9.91	34.05	(26.40)
					10	10.82	34.38	26.35
					25	10.64	34.40	26.40
					50	10.32	34.42	26.47
					80	9.18	34.42	26.66
					123	8.52	34.47	26.80
					180	7.80	34.42	26.87
					260	7.63	34.42	26.90
					435	7.34	34.40	26.93
					625	6.75	34.36	26.97
					B 34	2	1240-1615 h	50° 20' S
10	11.95	34.54	29.27					
25	11.66	34.58	26.35					
50	11.33	(34.38)	(26.26)					
75	10.35	34.60	26.60					
100	10.28	34.61	26.62					
150	9.84	34.65	26.73					
245	9.14	34.60	26.80					
390	8.42	34.51	26.85					
670	7.24	34.42	26.96					
965	4.79	34.33	27.19					
1,450	3.03	34.45	27.47					
1,950	2.38	34.61	27.65					
2,450	2.00	34.69	27.75					
B 35	3	0400-0600 h	48° 28' S	167° 23' E	0	12.32	34.76	26.37
					10	12.32	34.69	26.32
					20	12.30	-	-
					30	12.30	34.69	26.32
					50	12.35	34.67	26.29
					75	11.99	34.78	26.45
					100	11.94	34.72	26.40
					130	11.98	34.78	26.45
					B 36	3	1630-1900 h	47° 23' S
12	12.65	34.31	25.95					
25	12.68	34.34	25.97					
50	8.90	34.29	26.60					
75	7.56	(34.40)	(26.89)					
95	7.41	34.33	26.86					
140	7.30	34.33	26.88					
180	7.37	34.36	26.90					
270	7.30	34.38	26.92					
460	6.61	34.34	26.98					
650	5.60	34.25	27.03					
940	3.86	34.27	26.24					
1,230	2.64	34.34	26.42					

\*Salinity values in brackets are anomalous and have been neglected in the present consideration.

## (2) HAWEA STATIONS

NZOI Station No.	Date	Time	Latitude	Longitude	Depth (m)	Temp. (°C)	Salinity (‰)	$\sigma_t$ g/ml
C 1	Dec. 1956 28	2145	63° 42' S	179° 21' W	0	3.0	33.91	27.04
					44	1.1	34.05	27.30
					88	0.1	33.96	27.29
C 2	29	0240	62° 53' S	179° 22' W	0	4.8	33.91	26.85
					43	2.4	33.95	27.13
					85	1.3	33.98	27.23
					256	1.5	34.23	27.42
C 3	29	0400	62° 43' S	179° 22' W	0	4.7	33.91	26.86
					44	2.5	33.96	27.12
					91	1.7	33.98	27.20
					272	1.2	34.25	27.45
C 4	29	0515	62° 32' S	179° 22' W	0	4.9	33.87	26.81
					46	3.0	33.95	27.07
					91	1.9	33.96	27.17
					274	1.3	34.22	27.42
C 5	29	0625	62° 22' S	179° 23' W	0	5.3	33.89	26.78
					45	3.1	33.91	27.03
					90	1.9	34.02	27.22
					268	1.3	34.22	27.42
C 6	29	0740	62° 13' S	179° 23' W	0	5.3	33.87	26.76
					45	3.2	33.91	27.02
					89	1.9	33.95	27.16
					268	1.3	34.16	27.37
C 7	29	0855	62° 03' S	179° 23' W	0	5.2	33.91	26.81
					44	3.1	33.98	27.09
					88	1.9	33.95	27.16
					262	1.3	34.13	27.35
C 8	29	1010	61° 52' S	179° 23' W	0	5.5	33.89	26.76
					44	3.2	33.91	27.02
					88	2.0	33.93	27.14
					262	1.4	34.14	27.35
C 9	29	1330	61° 12' S	179° 29' W	0	5.6	33.89	26.75
					42	3.2	33.91	27.02
					83	2.0	33.95	27.16
					250	1.6	34.11	27.31
C 10	Jan. 1957 1	1815	46° 52' S	179° 50' E	0	13.8	34.29	25.70
					68	8.0	34.27	26.73
C 11	1	2030	46° 33' S	180° 00' E	0	14.1	34.29	25.64
					57	8.5	34.36	26.72
					98	7.3	34.38	26.92
					262	6.7	34.43	27.04
C 12	1	2230	46° 14' S	180° 00' E	0	14.4	34.36	25.63
					60	8.0	34.34	26.78
					103	7.1	34.29	26.88
C 13	2	0030	45° 57' S	179° 58' W	0	14.4	34.36	25.63
					59	8.0	34.38	26.81
					268	6.7	34.42	27.04
C 14	2	0230	45° 47' S	179° 53' W	0	14.4	34.40	25.66
					60	7.9	34.36	26.81
					274	6.7	34.40	27.02
C 15	2	0330	45° 40' S	179° 49' W	0	14.4	34.43	25.68
					44	10.0	34.45	26.54
					89	7.7	34.36	26.84
					266	6.8	34.42	27.02

(2) HAWEA STATIONS—*continued*

NZOI Station No.	Date	Time	Latitude	Longitude	Depth (m)	Temp. (°C)	Salinity (‰)	$\sigma_t$ g/ml
C 16	Jan. 1957 2	0430	45° 31' S	179° 51' W	0	14.4	34.42	25.68
					66	7.7	34.40	26.87
					108	7.5	34.33	26.86
					274	6.8	34.40	27.01
C 17	2	0530	45° 21' S	179° 54' W	0	14.4	34.42	25.68
					66	8.0	34.33	26.70
					108	7.3	34.38	26.92
					274	6.9	34.40	26.98
C 18	2	0700	45° 04' S	179° 56' W	0 268	14.5 6.9	34.49 34.38	25.71 26.97
C 19	2	0830	44° 52' S	179° 59' W	0	14.9	34.52	25.64
					44	9.9	34.49	26.60
					88	8.5	34.60	26.90
					262	7.1	34.38	26.94
C 20	2	0945	44° 44' S	180° 00' E	0	15.3	34.72	25.70
					43	9.6	34.69	26.80
					85	9.1	34.69	26.88
					91	9.0	34.61	26.83
					256	7.3	34.45	26.98
C 21	2	1110	44° 37' S	179° 59' E	0	15.5	34.67	25.62
					44	10.6	34.69	26.63
					88	9.1	34.76	26.94
					262	7.6	34.45	26.93
C 22	2	1235	44° 28' S	179° 58' E	0	15.3	34.63	25.64
					41	12.8	34.63	26.16
					83	9.1	34.58	26.79
					250	7.3	34.40	26.94
C 23	2	1350	44° 12' S	179° 59' E	0	15.3	34.69	25.68
					63	11.3	34.70	26.51
					104	7.2	34.42	26.96
					266	6.9	34.36	26.96
C 24	2	1510	44° 05' S	180° 00' E	0	15.8	34.79	25.67
					39	14.6	34.74	25.88
					77	10.5	34.63	26.60
					232	7.4	34.47	26.98
C 25	2	1625	43° 58' S	180° 00' E	0	15.8	34.88	25.72
					34	15.3	35.03	25.94
					69	12.0	34.88	26.52
					208	9.3	34.63	26.80
C 26	2	1740	43° 52' S	180° 00' E	0	15.9	34.94	25.74
					40	15.2	34.92	25.88
					79	12.0	34.96	26.59
					238	9.1	34.63	26.83
C 27	2	1850	43° 41' S	180° 00' E	0	15.8	34.88	25.72
					43	15.1	34.87	25.87
					86	12.3	34.92	26.50
C 28	2	2000	43° 29' S	180° 00' E	0	16.5	35.16	25.77
					37	16.1	35.23	25.92
					73	12.7	35.05	26.54
					220	10.5	34.88	26.79
C 29	2	2100	43° 20' S	179° 57' E	0	16.7	35.23	25.78
					84	12.5	35.05	26.56
					122	11.9	35.08	26.70
					274	9.9	34.79	26.82

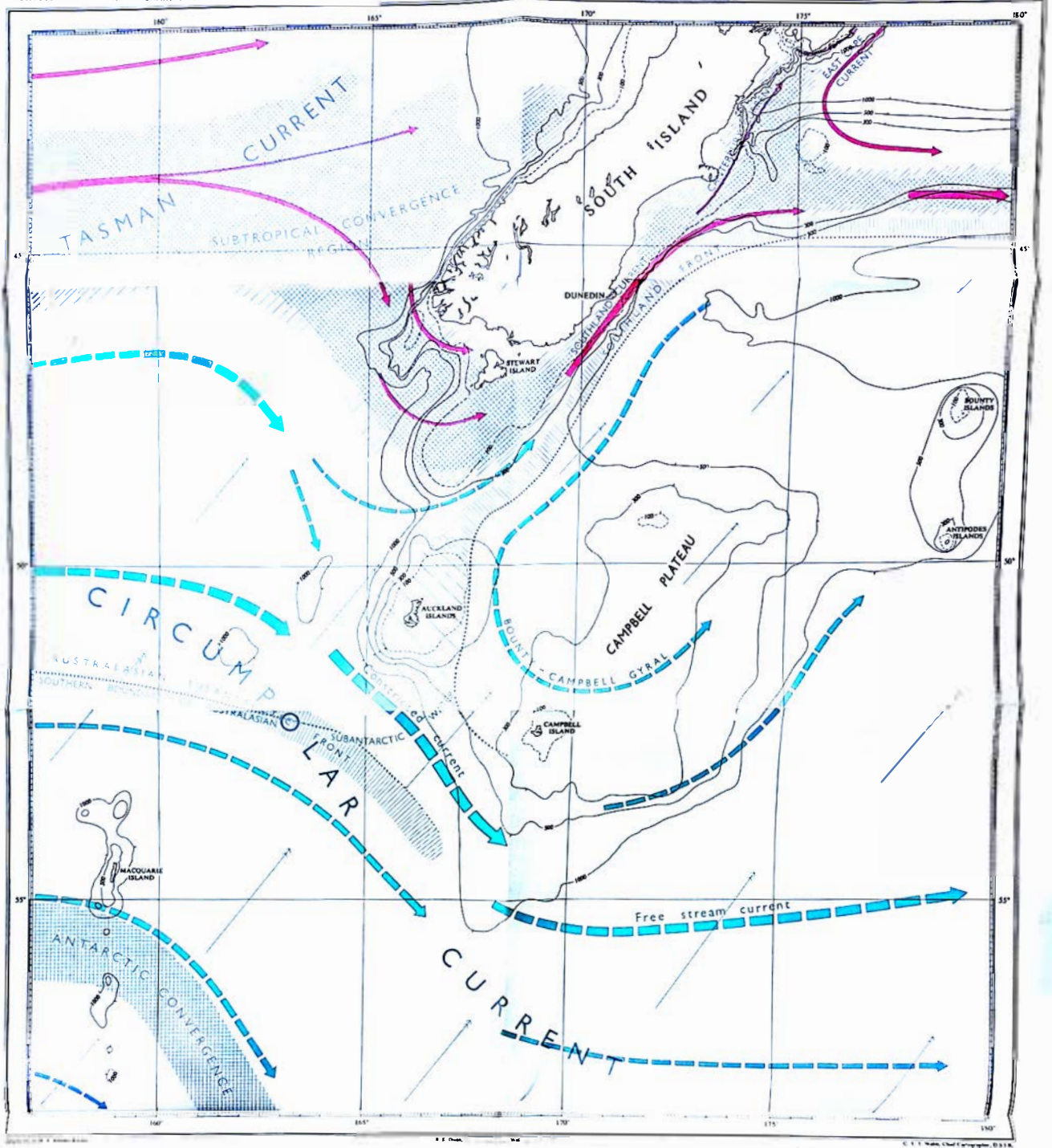
## INDEX

- Agulhas Current, 52  
 Antarctic Bottom Water, 14, 15, 42  
 Antarctic Continent, 14, 48, 50  
 Antarctic Convergence, 9, 14, 15, 16, 21, 23, 24, 44, 45, 46, 47, 48, 49, 53, 54, 57  
 Antarctic Intermediate Current, 23, 26, 53  
 Antarctic Intermediate Water, 14, 15, 24, 48, 49, 51, 52, 57  
 Antarctic Region, 20  
 Antarctic Surface Water, 14, 15, 17, 21, 24, 44, 46, 48, 57  
 Antarctic Upper Deep Water, 20  
 Antipodes Islands, 54  
 Atlantic Ocean, 14, 20, 25, 26, 27, 28, 33, 44, 50  
 Auckland Islands, 16, 20, 24, 25, 27, 34, 37, 38, 50, 53, 54, 55, 56  
 Australasian Region, 20  
 Australasian Subantarctic Front, 20, 24, 37, 50, 53, 57  
 Australasian Subantarctic Water, 20, 21, 24, 25, 30, 34, 38, 49, 51, 53, 54, 55, 56  
 Australia, 16, 27, 30, 34, 36  
  
 Banks Peninsula, 10, 23, 28, 37, 38, 40, 42, 56  
 Bounty-Campbell Gyral, 25, 40, 52, 54, 57  
 Bounty Trough, 25, 54, 57  
*Brategg*, 17, 20  
*Brittania*, RY, 9  
 Brown, Lieutenant Commander, W. G., 58  
  
<sup>14</sup>C activities, 10  
 Campbell Island, 20, 21, 24, 25, 53, 54  
 Campbell Plateau, 9, 15, 20, 21, 24, 25, 33, 40, 41, 50, 52, 53, 54, 55, 56, 57  
 Campbell Plateau Water, 20, 24, 40  
 Canterbury Current, 51, 52, 56  
 Chatham Islands, 10, 28, 38, 40, 41  
 Chile, 30  
 Christchurch, 29  
 Circumpolar Current, 14, 40, 50, 51, 52, 53, 54, 55, 56  
 Circumpolar Subantarctic Water, 20, 21, 24, 30, 34, 37, 38, 40, 49, 54, 55, 56, 57  
 Constricted Current, 52, 53, 54, 55, 56, 57  
 Convergence, defined, 16  
 Cook Strait, 28, 35, 36, 38, 52  
 Coral Sea, 32, 52  
 Coriolis Parameter, 46, 48, 50, 52  
  
*Dana*, R. V., 25  
 Deep Water, 14, 15, 16, 17, 20, 44, 45, 48, 52, 53  
*Derwent Hunter*, FRV, 9  
*Deutschland*, 25  
*Discovery II*, RRS, 9  
 Divergence, 17, 48, 57  
 Drake Passage, 14  
 Drift Currents, 52  
 Dunedin, 9, 10, 21, 23, 29, 38, 40, 41, 42, 51, 56  
  
 East Australian Current, 29, 30, 51, 52  
 East Cape Current, 51, 52, 55  
 Eddies, 11, 46, 57  
 Ekman layer, 15, 17, 29, 48, 52, 53, 57  
*Endeavour*, HMNZS, 9, 10, 17  
  
 Free Stream Current, 49, 52, 54, 57  
  
*Galathea*, H.D.M.S., 25  
*Gauss*, RV, 25  
 Gulf Stream, 44, 52  
  
 Hale, Captain R. T., 58  
*Haweia*, RNZN, 9  
  
 Indian Ocean, 14, 16, 20, 21, 25, 26, 27, 28, 34, 55, 56, 57  
 Indian Ocean Central Water, 26  
 Indian Ocean Deep Water, 14  
 International Geophysical Year, 9  
  
 Kort, Professor V., 58  
 Kuro Siwo current, 52  
  
 Lyttelton, 9  
  
 Macquarie-Balleny Ridge, 15, 53  
 Macquarie Island, 15, 16, 24, 27, 40, 53  
 Margules Equation, 38, 40  
 McMurdo Sound, 9  
 Mediterranean Water, 14  
*Meteor*, 25  
  
 North Atlantic Deep Current, 14  
 North Island, 28  
 New Zealand Naval Board, 58  
  
 ●b, RV, 9  
  
 Pacific Ocean, 14, 16, 17, 48, 52, 55, 57  
*Pukaki*, RNZN, 9  
  
 Red Sea Water, 14  
 Ross Sea, 14  
  
 Scotia Sea, 48  
 Scott Island, 9, 10, 17, 20  
 South Africa, 26  
 South America, 30, 48  
 South Atlantic Central Water, 26  
 South Equatorial Current, 52  
 South Equatorial Water Mass, 32  
 South Island, 23, 25, 30, 40, 51, 54  
 Southern California, 48  
 Southern Ocean, 9, 35, 48, 50, 52, 53, 57  
 Southland Current, 40, 51, 56  
 Southland Front, 21, 37, 40, 41, 42, 44, 51, 52, 54, 55, 56  
 Stewart Island, 9, 24, 25, 32, 38, 51, 53, 54, 55, 56  
 Subantarctic Region, 14, 15, 20, 30, 49  
 Subantarctic Surface Water, 15, passim  
 Subtropical Convergence, 9, 14, 15, 21, 24, 25, 26, 28, 30, 32, 33, 37, 38, 43, 46, 50, 51, 52, 54, 55, 57  
 Subtropical Convergence Region, 20, 21, 25, 28, 30, 32, 34, 35, 36, 37, 55, 56  
 Subtropical Current, 39  
 Subtropical Region, 51  
 Subtropical Surface Water, 14, 23, 25, 26, 28, 30, 32, 35, 36, 37, 42, 51, 52, 55  
  
 Tasman Current, 51, 52  
 Tasman Sea, 21, 23, 24, 32, 33, 34, 35, 36, 42, 51, 52, 55, 56  
 Tasmania, 28, 34, 36  
  
 Waitangi, 9  
 Weddell Sea, 14  
 Wellington, 9  
 West Wind Drift, 30, 40, 53  
 Westerly Winds, 52  
 Western South Pacific Central Water, 26, 30, 32, 52  
 Wexler, Dr Harry, 58

# CURRENTS IN THE SOUTHERN NEW ZEALAND REGION

TO ACCOMPANY N.Z. OCEANOGRAPHIC INSTITUTE MEMOIR No. 10 CHART No. 1

MISCELLANEOUS SERIES 1



## REFERENCES

**CURRENTS**

North of Subtropical Convergence Region  
 East Co. Current and southern part of Tasman Current (above Antarctic Subantarctic Convergence)  
 Southern part of Tasman Current (about 200 m)  
 Southern Current (surface to bottom)  
 Coastal Current

Subantarctic Region  
 Range of 100 m gradient (correct wind - induced surface layer)  
 Circumpolar Current (below Ekman layer to bottom)  
 Boundary - Campbell Gyral

**CONVERGENCES**

Range of Subtropical Convergence Region  
 (a) at 26° E at 200 m; (b) at 34° E to 35° E (a, b < 200 m)

Antarctic Convergence



**NEW ZEALAND OCEANOGRAPHIC INSTITUTE WELLINGTON**  
 Scale 1:125,000 at Lat. 35°  
 Soundings in Fathoms  
 Projection: Mercator

Compilation and interpretation by R. W. Burling, New Zealand Oceanographic Institute.  
 Uses maps and generalised bathymetry from U. S. Hydrographic Office Chart No. 210 (First Edition) and New Zealand Oceanographic Institute data.  
 © N.Z. Dept. of Scientific and Industrial Research, 1960

## REFERENCES

**FRONTS** (isopycnals in surface of density) and characteristics

Subtropical Front  
 26° to 27° C: 34.5 to 34.6  $\sigma_t$ ; at 26 E to 26 S

Antarctic-Subantarctic Front

**WATER MASS BOUNDARY**

Antarctic-Subantarctic water  
 (depth > 34.5  $\sigma_t$ ) on northern side west of 147° E.

Circumpolar Subantarctic water  
 (depth < 34.5  $\sigma_t$ ) on southern side.

**ISOBATHS**

Pressure	Depth
100	100
200	150
500	510
1000	1030