HYDROLOGY OF
SOUTH-EAST AUSTRALIAN WATERS

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Hydrology of South-East Australian Waters: Bass Strait and New South Wales Tuna Fishing Area

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HYDROLOGY OF SOUTH-EAST AUSTRALIAN WATERS: BASS STRAIT AND NEW SOUTH WALES TUNA FISHING AREA

By B. S. Newell*

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Summary

This paper examines the hydrological data collected in south-east Australian waters over a number of years, and presents the annual cycle of the surface circulation.

Part A includes a discussion on seasonal changes in the current systems of Bass Strait shown from recoveries of drift bottles released at four points in the region, brief reference to the winter-summer rhythm in prevailing meteorological conditions on the southern seaboard, and a summary of chlorinity and water temperature data collected in the area during 1938–59. From this evidence it is concluded that there is a seasonal rhythm in the circulation of the surface waters in Bass Strait.

In Part B the surface circulation off the southern coast of New South Wales is shown to undergo an annual cycle. During summer, movement of the East Australian Current shorewards brings high-chlorinity water to the continental shelf. During March, South Equatorial components bring lower-chlorinity water, but in April and May these disappear and the shelf is flooded with high-chlorinity water from the Trade Drift. In winter the East Australian Current moves offshore and low-chlorinity subsurface water is found on the continental shelf. Upwelling occurs on the shelf throughout the year, but it is more pronounced in winter. In late winter, water produced by mixing in eastern Bass Strait appears off Eden and makes its way northwards along the coast.

A. BASS STRAIT

I. INTRODUCTION

The water masses of Bass Strait have been identified and named by Rochford (1957). The observations, on which these identifications were made, were taken only in March, November, and December 1954. Since that date many additional observations have been taken and some of these are used in this paper.

II. DATA AND METHODS

Chlorinity data collected by this Laboratory from Bass Strait and its environs (the region between 140–152°E. longitude and 37–43°S. latitude) during the years 1952–59 (Table 1) were averaged in half-degree squares of latitude and longitude. A total of 998 chlorinity values recorded during winter and 968 recorded during summer were plotted and averaged.

Water temperatures from 1938 to 1959 (Table 1) were similarly treated and 700 values for winter and 570 for summer were plotted and averaged. For this investigation the period May to September has been designated as winter,

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TABLE 1
SOURCES OF DATA

Year	Vessel or Area	Ref.: C.S.I.R.O. Aust.
1938–40	F.R.V. *Warreen*	(1951*a*)
1940–42	F.R.V. *Warreen*	(1951*b*)
1947–50	F.R.V. *Warreen*	(1951*c*)
1951	R.R.S. *Discovery*	(1953*b*)
1952	*F.R.V. Derwent Hunter*	(1953*b*)
	Maria I., St. Helens, Cape Pillar	(1953*b*)
	Albatross I., Port Phillip Heads	
1953	F.R.V. *Derwent Hunter*	(1954)
	Port Phillip Heads, Port Fairy Wide	(1954)
	Low Head, St. Helens, Maria I.	
	Albatross I., Cape Pillar	
1954	F.R.V. *Derwent Hunter Cruises* DH 9/54	(1956)
	13/54	
	T.S.S. *Taroona*	(1956)
	Maria I., St. Helens	(1956)
1955	F.R.V. *Derwent Hunter Cruises* DH 16/55	(1957*a*)
	18/55	
	T.S.S. *Taroona*	(1957*b*)
	Maria I., St. Helens, Cape Sorell	(1957*a*)
1956	F.R.V. *Derwent Hunter Cruise* DH 4/56	(1957*c*)
	St. Helens, Maria I.	(1957*c*)
	T.S.S. *Taroona*	(1957*d*)
	M.V. *Claire Crouch*	(1957*d*)
1957	F.R.V. *Derwent Hunter Cruise* DH 4/57	(1959*b*)
	T.S.S. *Taroona*	(1959*c*)
	M.V. *Claire Crouch*	(1959*c*)
	M.V. *Denman*	(1959*c*)
	M.V. *Century*	(1959*c*)
	M.V. *Jillian Crouch*	(1959*c*)
	Stanley	(1958)
1958	M.V. *Jillian Crouch*	(1960*a*)
	S.S. *Talune*	(1960*a*)
	M.V. *Century*	(1960*a*)
1959	M.V. *Pateena*	(1960*b*)
	M.V. *Lorinna*	(1960*b*)
	S.S. *Talune*	(1960*b*)
	M.V. *Risdon*	(1960*b*)
	M.V. *Century*	(1960*b*)

and November to March as summer. Certain data collected in April and October appeared to belong either with the winter or summer observations and where this relation was clear the transfer was made.

Temperature-chlorinity diagrams, Figure 1(*a*) for the winter and Figure 1(*b*) for the summer, have been prepared from the half-degree square averages. A few single observations from the region immediately north-east of the area under examination have also been shown in Figures 1(*a*) and 1(*b*). These were included to indicate fairly typical East Australian Current water.

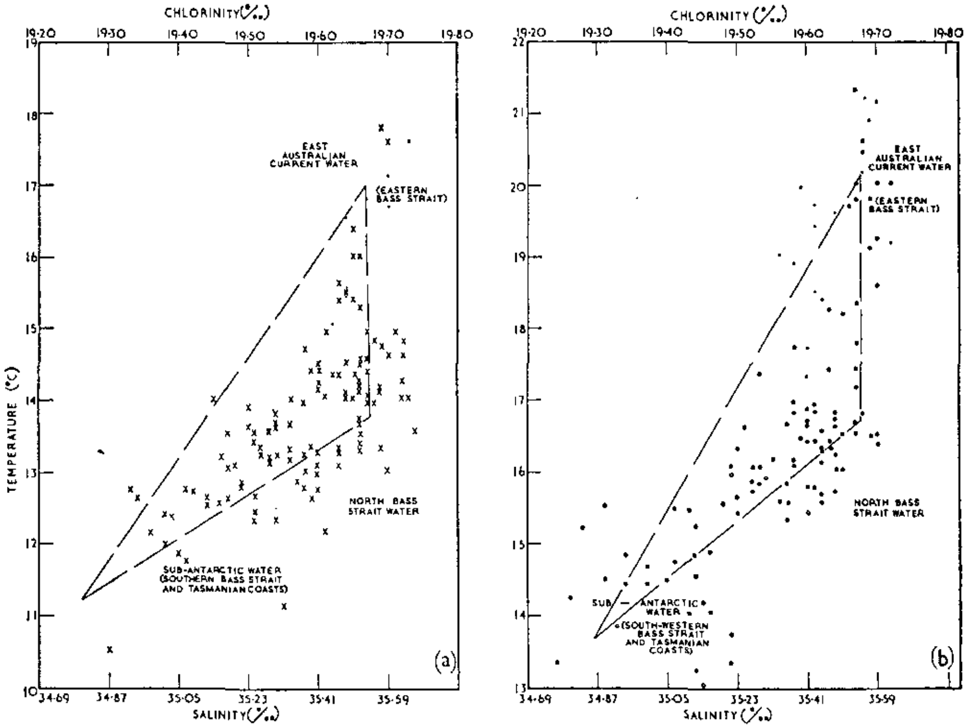

Fig. 1.—Temperature-chlorinity diagram for Bass Strait (*a*) winter and (*b*) summer. ● Samples from the East Australian Current.

III. Distribution of Chlorinity and Temperature in Winter and Summer

Assuming that the mean value of chlorinity or temperature obtained from each half-degree square is representative of conditions at the mid point of that square for each season, isohalines and isotherms were drawn. Figure 2(*a*) shows the winter and Figure 2(*b*) the summer distribution of chlorinity. Figure 3(*a*) shows the winter and Figure 3(*b*) the summer distribution of temperature.

IV. Evidence from Drift Bottles

The tracks of drift bottles released since September 1958 off Cape Northumberland in South Australia, Cape Otway in Victoria, and West Point and Mount Heemskirk in Tasmania (C.S.I.R.O. Aust., unpublished data), are shown

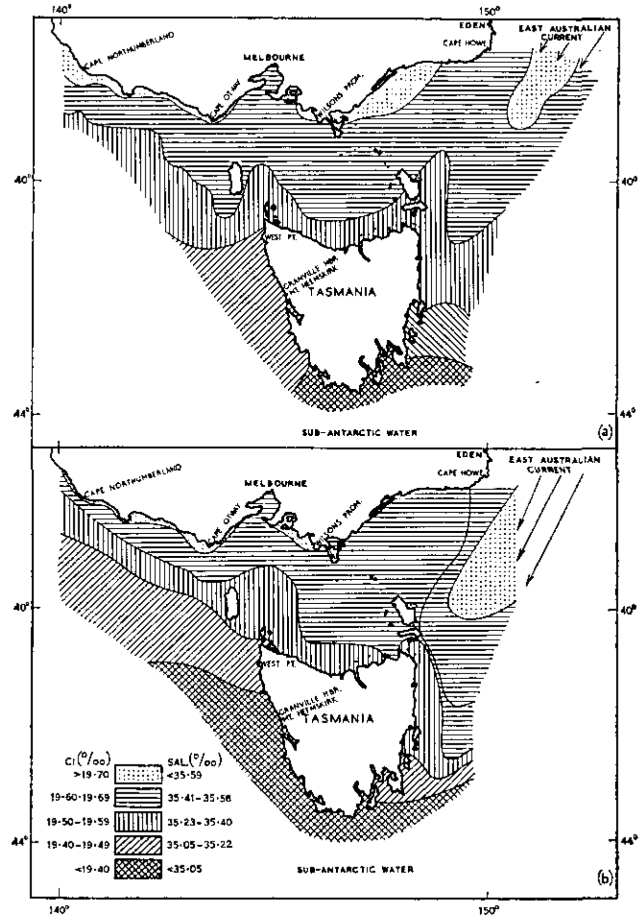

Fig. 2.—Distribution of chlorinity at the surface in Bass Strait: (*a*) winter and (*b*) summer.

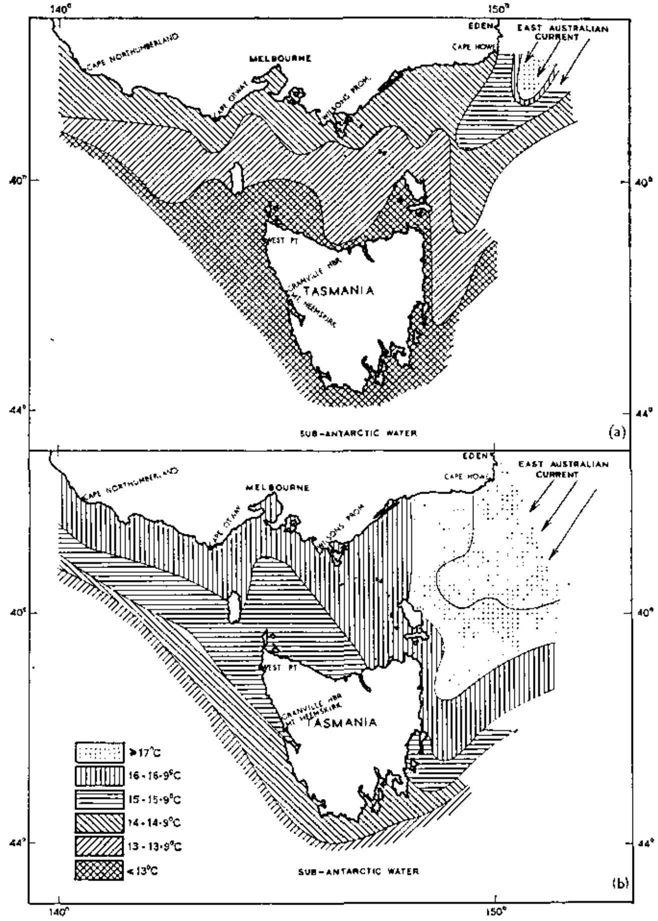

Fig. 3.—Distribution of temperature at the surface in Bass Strait: (*a*) winter and (*b*) summer.

in Figures 4(*a*) and 4(*b*). Using data supplied by the Royal Australian Air Force (1944) the direction of prevailing wind in winter and summer has been indicated in these figures. The recoveries from these releases indicate a winter-summer reversal in current patterns in this region.

V. Water Masses in the Region

Three primary water masses contribute to the waters in Bass Strait (Figs. 1(*a*), 1(*b*)). These are the complex of the East Australian Current, the sub-Antarctic, and the high-chlorinity water along the Victorian coast. The origin of this latter water is as yet undetermined. Schott (1935, Plate XXVII) and Sverdrup, Johnson, and Fleming (1942, Chart VI) show an extension of the high-chlorinity (19·65–19·93 ‰) zone of the south-eastern Indian Ocean to the east

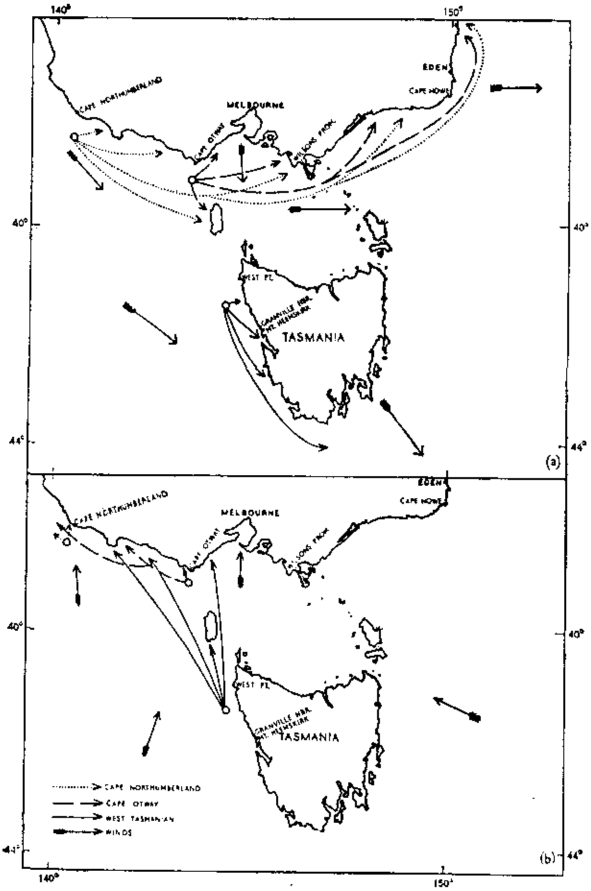

Fig. 4.—Movement of drift bottles released off Cape Northumberland, Cape Otway, and the west coast of Tasmania, from September 1958 to January 1960, and the direction of the prevailing winds in each season: (*a*) winter and (*b*) summer.

along the southern coast of Australia. Such an extension is confirmed at least as far as longitude 128° 28′E. by data collected for this Laboratory. Figure 5 illustrates the positions (*A* to *F*) at which water of chlorinity 19·80 ‰ has been found, and shows the approximate location of the 19·75 ‰ isochlor. South of these lines, at positions *B* to *E*, the chlorinity falls off rapidly in value. The sources of data are given in Table 2.

At first sight it would appear that the high-chlorinity water found in north Bass Strait might be continuous with this eastward extension of Indian Ocean water. However, Rochford (1957) has put forward the alternative explanation that the north Bass Strait water derives from the Spencer and St. Vincent Gulfs region where evaporation produces extremely high chlorinity throughout the year (as high as 26·80 ‰ at Port Augusta in summer (C.S.I.R.O. Aust. 1953*a*). The high-chlorinity areas are shown by diagonal shading in Figure 5. Strong evidence for Rochford's hypothesis is provided (C.S.I.R.O. Aust. 1953*a*) by the results of samples collected at fortnightly intervals from March 1950 to April 1951 at Port Elliston which is shown as position *G* in Figure 5. Were the high-chlorinity water of north Bass Strait continuous with the high-chlorinity Indian Ocean water, one would expect chlorinities of the order of 19·80 ‰ at Port Elliston for most of the year, but especially in winter when the high-chlorinity water in north Bass Strait occupies its maximum extent, implying replacement flow of Indian Ocean water from the west (see below). However, the reverse is the case, for whilst chlorinities of *c*. 20·00 ‰ were recorded at Port Elliston throughout the summer the winter values ranged from an upper limit of 19·75 ‰ to as low as 19·55 ‰ in May and even 19·40 ‰ in July (C.S.I.R.O. Aust. 1953*a*).

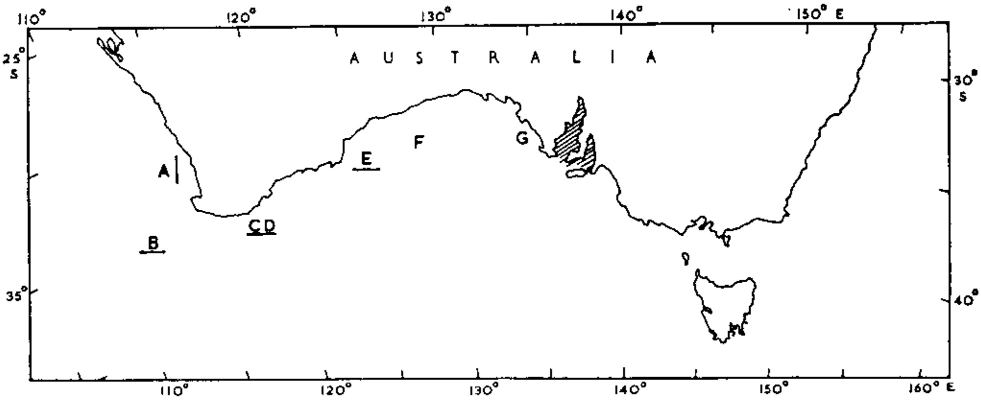

Fig. 5.—Southern coastline of Australia, showing positions (*A*, *B*, *C*, *D*, *E*, and *F*) from which data are available and at which water of chlorinity *c*. 19·8 ‰ was found. Short line near position letter indicates approximate location of the 19·75 ‰ isochlor. *G* indicates Port Elliston. Diagonally shaded areas are the high-chlorinity regions of St. Vincent and Spencer Gulfs.

It is thus proposed to adopt Rochford's (1957) nomenclature and refer to the high-chlorinity water along the Victorian coast as North Bass Strait water.

The East Australian Current is the south-moving current along the east Australian coast. It contains subtropical waters of high chlorinity and temperature originating from sources to the north and east.

The sub-Antarctic water mass consists of cold low-chlorinity water from the Circumpolar West Wind Drift. In summer, subtropical water from the southern Indian Ocean flows eastwards with the West Wind Drift and reaches the west coast of Tasmania. Strandings of subtropical and tropical fauna (e.g. *Physalia*) are regular occurrences along this coast each summer.

TABLE 2

SOURCES OF DATA

Position	Date	Source	Reference
A	November 1947 April, August, December 1948 April, June, July 1949	F.R.V. *Warreen*	C.S.I.R.O. Aust. (1951*c*)
B	February 1960	M.V. *Shoyo Maru*	(Robins, personal communication)
C	January 1951	R.R.S. *Discovery*	C.S.I.R.O. Aust. (1953*b*)
D	May 1948	F.R.V. *Warreen*	C.S.I.R.O. Aust. (1951*c*)
E	January 1951	R.R.S. *Discovery*	C.S.I.R.O Aust. (1953*b*)
F	May 1960	M.V. *Southern Endeavour*	(Kurth, personal communication)
G	March 1950 to April 1951	Port Elliston Station, University of Adelaide Survey, December 1949 to April 1951	C.S.I.R.O. Aust. (1953*a*)

VI. DISCUSSION AND CONCLUSIONS

The winter-summer alternation of surface movements, shown in Figures 2, 3, and 4, is probably due to the north-south migration of the Australian high-pressure zone. In winter, this persistent atmospheric anticyclone moves inland, and the subtropical convergence moves northwards with the wind system, bringing sub-Antarctic water to lower latitudes. West winds predominate along the southern seaboard.

In summer, the subtropical convergence moves south with the anticyclone, so that warm subtropical water (the East Australian Current) is brought south. This southward movement of subtropical water is reinforced by the strong north-east summer winds along the east Australian seaboard. The north-west trend of water along the western Tasmanian coast in summer is probably caused by deflection by the physical barrier offered by Tasmania and by south winds.

It is emphasized that the data used in preparing the figures of this paper have been averaged; it becomes obvious, when the data in Oceanographical Station Lists are examined, that the transitions from winter to summer patterns and vice versa are very variable in time. The extent of penetration of the three primary water masses also varies from year to year. It is also noted that the water found along the Tasmanian coasts is greatly affected by fluvial dilution, and probably by cooling and convective mixing on the continental shelf.

In winter the west winds drive the North Bass Strait water and the sub-Antarctic water eastwards, so that in Bass Strait there exists a mixing gradient from high-chlorinity water along the Victorian coast to low-chlorinity sub-Antarctic water along the north coast of Tasmania. The mixed water occupying the central zone of the Strait continues its movement eastward and north-eastward, eventually meeting the Victorian coast, rounding Cape Howe, and continuing along the south coast of New South Wales.

The penetration of the East Australian Current southwards is limited by the northward movement of sub-Antarctic water up the east coast of Tasmania. In Figure 1 the points follow a geographical pattern, all points representing sub-Antarctic water being derived from data from the Tasmanian coasts and southern Bass Strait. The points representing mixed sub-Antarctic and North Bass Strait water are derived from data from the central zone or belt through Bass Strait. North Bass Strait water was found only along the Victorian coast, and mixed North Bass Strait and East Australian Current water only in eastern Bass Strait. The few values approaching a mixture between sub-Antarctic and East Australian Current all came from the region east of Tasmania, on the offshore edge of the cold sub-Antarctic tongue. All points fell into this pattern; there were no anomalies.

In summer the axis of the eastward drift of sub-Antarctic water moves south and divides at the south-west corner of Tasmania, sending a branch northwards along the west coast of Tasmania. This branch penetrates, to a limited extent, into the south-west portion of Bass Strait, but it also turns north-west flowing towards the Bight. Some North Bass Strait water persists but it is confined to a narrow belt along the coast, west of Wilson's Promontory. The greater part of Bass Strait is filled with a mixture of North Bass Strait water and East Australian Current water, because of the strong invasion of the latter from the east.

B. THE NEW SOUTH WALES TUNA FISHING AREA

I. INTRODUCTION

The New South Wales tuna fishing area extends from Cape Everard in the south to Sydney in the north. Though fishing may occasionally be done outside these limits, it is usually confined to the region of the continental shelf. This shelf region has a complex hydrological pattern, but in this paper only the gross changes occurring during the course of the year are described.

II. DATA AND METHODS

Since July 1957, F.R.V. *Marelda* has carried out continuous and regular sampling off the southern New South Wales coast (C.S.I.R.O. Aust. 1959*a*, 1959*d*).

The section off Eden (to 24 miles) was worked at weekly intervals from July 1957 to March 1959, and the section off Bermagui (to 22 miles) at less frequent intervals. Since April 1959, two additional sections have been worked, one off Bateman Bay (to 22 miles) and one off Jervis Bay (22 miles off Beecroft Head). All four sections are now worked once each month. Stations are at 4-mile intervals as shown in Figure 6, where the horizontal scale has been exaggerated for clarity (ratio of horizontal to vertical scales, 2·4/1).

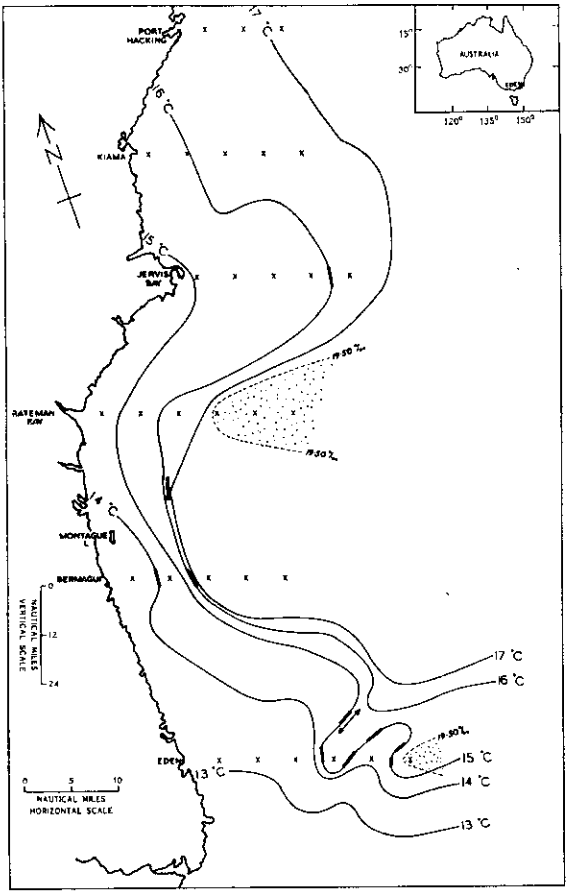

Fig. 6.—Distribution of isotherms off the New South Wales coast in September 1958, showing temperature fronts (thickened lines), a tide rip (double-ended arrow), and the course of the 19·50 ‰ isochlor at 100 m depth (stippled area).

Analyses for chlorinity have been made continuously since July 1957, and dissolved oxygen has been estimated since July 1958.

III. Water Masses in the Region

In general the region is dominated by an interplay between the East Australian Current on the surface, moving south with high velocity in the summer and low velocity in the winter (Wyrtki 1960), and the subsurface sub-Antarctic water, which sinks at the Subtropical Convergence and moves slowly north. The East Australian Current contains principally West Central South Pacific water of high chlorinity and high temperature from the Trade Drift, but in late summer, because of the shift of the wind systems, variable amounts of South Equatorial Current water are entrained from the north into the East Australian Current (Rochford 1958, 1959; Rotschi 1960). Mixing of these primary water masses occurs as they move south, but since the South Equatorial water is less dense than the West Central South Pacific water, mixing is slow, and even at the latitude of Eden, the influence of the South Equatorial water can be perceived in March. The properties of the two primary water masses at source are: South Equatorial, chlorinity 19·20 ‰, temperature 23–28°C; West Central South Pacific, chlorinity 20·20 ‰, and temperature 26°C (Rochford 1959). However, the properties of these waters are considerably modified by the cooling and mixing that takes place during their southward movement. Thus, chlorinities of less than 19·60 ‰ or more than 19·80 ‰ are rarely found at the seaward stations (16, 20, 24 miles) of the Eden section at any time of the year. Similarly, even in summer, when the East Australian Current is at its strongest, temperatures greater than 24°C are seldom encountered, and the more usual summer average is *c.* 20–22°C. It is probable that yet another water mass influences the East Australian Current in the latitude of Eden. This is the North New Zealand water mass of chlorinity greater than 20·2 ‰ and temperature 20–21°C (Rochford 1959). This water mass is a branch of the high-chlorinity zone in the western half of the south Pacific Ocean and moves westwards north of New Zealand at subsurface levels. The extent of its influence is as yet undetermined.

TABLE 3

AVERAGE CHLORINITY FOR EACH MONTH AT STATIONS ON EDEN SECTION

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
(i)	19·73	19·70	19·63	19·69	19·76	19·76	19·67	19·65	19·63	19·67	19·66	19·71
(ii)	19·68	19·63	19·61	19·67	19·73	19·73	19·65	19·60	19·59	19·61	19·63	19·69

IV. SEASONAL SURFACE CIRCULATION

Table 3 shows: (i) the average chlorinity at the surface at the 16, 20, and 24-mile stations off Eden for each month of the year over the period July 1957 to February 1960, and (ii) the average chlorinity at 0–10 m at the 4, 8, and 12-mile stations over the same period.

An annual cycle may be seen, with a tendency for chlorinities to decrease in winter when the predominant west and south-west winds (Royal Australian Air Force 1942; Nederlands Meteorologisch Institut 1949) move the subtropical water of the East Australian Current away from the coast, and to increase in summer when the predominant north and east winds produce the opposite effect. Superimposed on this cycle are, firstly, the low chlorinities of February-April, which, being accompanied by high temperatures of the order of 24°C are more likely caused by South Equatorial water (Rochford 1958; Rotschi 1960) than local uplift, and secondly, the high chlorinities of May and June. The latter are discussed below.

Some upwelling, or uplift of deeper water, occurs for most of the year as can be seen from the lower chlorinities found inshore. An indication of the uplift of isobars towards the coast is given in Figure 7, which illustrates the vertical distribution of isopycnals found on Cruise DH3/57 in April 1957. This is fairly typical of numerous vertical sections normal to the coast worked by F.R.V. *Derwent Hunter* off Sydney in 1957–58. Similarly, the series of vertical chlorinity sections off Eden from July 1957 to May 1958, given by Robins (1958), show more or less continual uplift of sub-Antarctic water at the edge of the shelf, except in May.

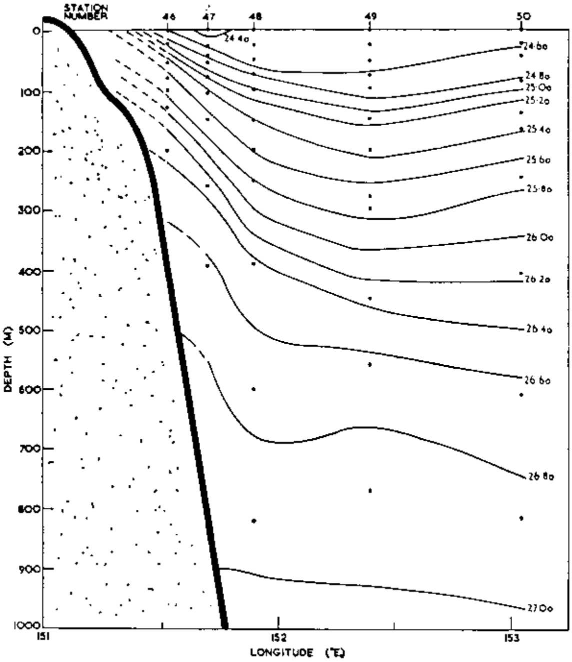

Fig. 7.—Distribution of σ_t along 110° section from Sydney, in April 1957.

This uplift is the result of the divergence zone caused by the east and south-east swing of the East Australian Current away from the land in this region (Wyrtki 1960). In May and June, the velocity of the East Australian Current is at its minimum so that the intensity of the divergence is at its minimum at the same time whilst the West Central South Pacific water mass makes its strongest westward penetration at this time of year (Rotschi 1960). There is thus no uplift during these two months and the shelf is flooded with high-chlorinity surface water. The uplift is further affected by strong offshore winds from July to September, and by the increased dynamic slope of isobaric surfaces of the East Australian Current from October to March.

Thus there occurs in this region the not uncommon situation of a bordering current along a coastline, with a band of water inshore which is a variable mixture of offshore surface water and underlying water, brought to the surface by upwelling. In these circumstances a counter current commonly develops inshore. Such a situation is described by Reid, Roder, and Wyllie (1958) along part of the Californian coast and by Clowes (1954) for the south-west African region. Theoretical discussions of the phenomenon have been given by Stommel (1958) in relation to inshore counter currents along the Gulf Stream, and by Yoshida (1955) who, using the Californian coastal waters, calculates that the counter current will diminish as the upwelling increases in magnitude. Off the southern coast of New South Wales, the counter current is accentuated by entrainment effects past the projections of Jervis Bay peninsula and Montagu Island. Coastwise steamers habitually sail close inshore to take advantage of this counter current when proceeding north, but experience on F.R.V. *Marelda* and F.R.V. *Derwent Hunter* has demonstrated the presence of entrainment effects in the form of south or south-east sets near Montagu Island and Jervis Bay.

Density currents caused by freshwater drainage along the coast, as discussed by Iselin (1940) for the continental shelf off the New England coast of North America, would seem to be negligible in our case, since in only one month in three years (November 1959) was there any appreciable dilution of inshore water sampled at the 4 and 8 mile stations off Eden.

Under such conditions a complex boundary between the inshore and offshore currents may be expected to develop, with horizontal turbulence, meanders, and sharp temperature fronts between the two bodies of water, where one makes an intrusion into the other. Such is found to be the case, and Figure 6 shows the distribution of isotherms from Port Hacking to Eden in September 1958, constructed from the stations and the thermograph records of F.R.V. *Marelda.* This month was chosen because the two additional sections (Port Hacking and Kiama) were available, but any month would give a similar pattern. In Figure 6 sharp temperature fronts (sometimes 2°C change in half a mile) are indicated, and along the 15°C isotherm in the south the presence of a "tide rip" is indicated. Such phenomena have been reported by Japanese workers (Kitano 1958; Uda and Ishino 1958) in the coastal areas of Japan, and denote areas where two opposing currents run parallel. The fronts are often visible at the surface in the form of lines of foam, or more often, of colour changes in the water.

The indraught of subtropical water towards Bateman Bay, noted in Figure 6, has been observed in other months and is akin to that described by Hela (1956) off Florida. Hela ascribed these indraughts to current momentum, but in this case the physical obstacle of the Jervis Bay peninsula is probably a contributing factor.

V. VERTICAL STRATIFICATION

The summer and winter stratifications are shown in Figure 8, which gives density profiles for the Eden section on January 27 and September 29, 1959. In summer the East Australian Current moves shorewards, so that, although some slope in the isobaric surfaces is observed, the shelf is covered with a layer of

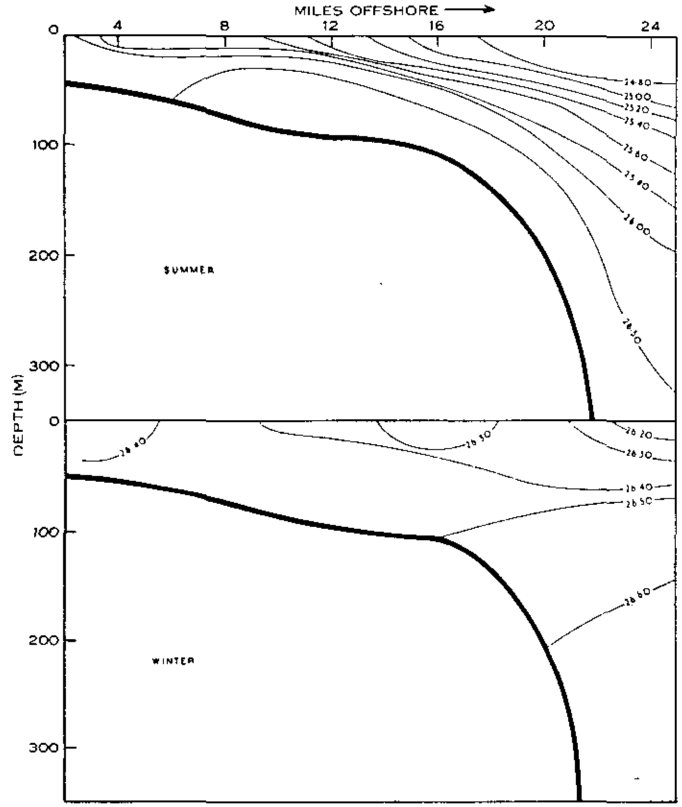

Fig. 8.—Distribution of σ_t along the Eden section: summer (27.i.59) and winter (29.ix.59).

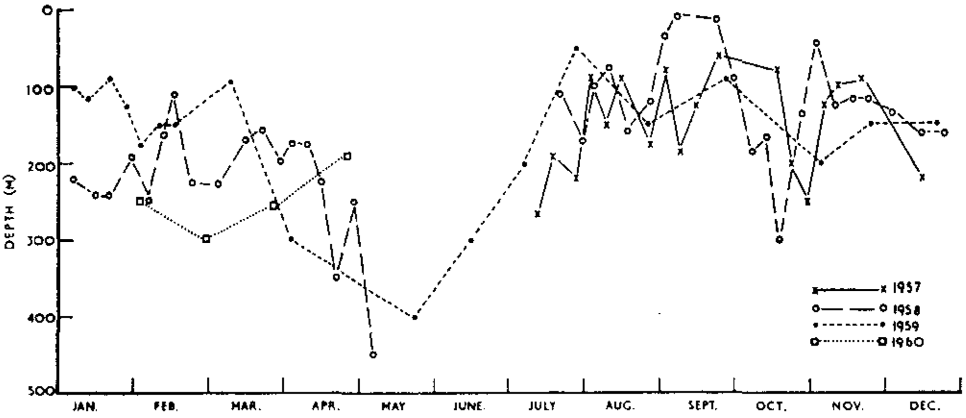

Fig. 9.—Depth of $\sigma_t = 26 \cdot 50$ between the 20 and 24 mile stations in the Eden section during the period 1957–60.

warm light subtropical surface water, overlying colder and denser water which covers the bottom. The density gradient becomes very steep (the isopycnals are drawn at 0·20 intervals only) and a thermocline usually develops.

By contrast, the East Australian Current moves offshore in winter, and uplift and mixing cover the shelf with a water mass of very slight vertical density gradient. Some evidence of a current gyral, or meander, can be seen in the winter section between the 16 and 24 mile stations. Far more complex configurations than this can occur in winter, and some of these are illustrated by Robins (1958).

The contrast between winter and summer is shown in another way in Figure 9. In this figure the depth of $\sigma_t = 26{\cdot}50$ between the 20 and 24 mile stations on the Eden section is shown for each time the station was worked from 1957 to 1960. The flooding of the shelf region in May by high-salinity subtropical water, already discussed with reference to Table 3, can be seen in the deepening of $\sigma_t = 26{\cdot}50$ to 400 m. Uplift in the winter months causes this isopycnal to rise to depths of *c.* 100 m. Winter cooling helps this because it causes the whole water column to become denser, but the 26·50 isopycnal was chosen as an example because its depth is near the lower limit of any likely convective mixing, and therefore this contribution must be very small. From October to April, when uplift is less pronounced, the 26·50 isopycnal is depressed to about 200 m.

The extent of uplift, even in winter, varies from week to week as can be seen in Figure 9, and, in order to determine whether the wind was the major causative factor of this shorter-term fluctuation, similar to that off the east coast of Florida (Taylor and Stewart 1959), various arbitrary measures of degree of uplift were plotted against the effective wind at Gabo Island (off Cape Howe and 30 miles south of Eden) and Montagu Island. Three-hourly records of wind strength and direction were available for these two locations from the Commonwealth Meteorological Bureau log sheets and the method adopted was to total the velocities of all winds from north-east to south-south-west over the 3 days prior to any Eden section, and to call the sum negative (in that such winds would tend to oppose upwelling). Similarly, all winds from south-west to north-north-east were totalled and the sum called positive (in that these winds would favour upwelling). The algebraic sum of these two totals was assumed to be the effective wind over the 3 days. The effective winds thus obtained were then plotted against the average chlorinity, and the average oxygen content from 100 m to the bottom at the 20 mile station (since uplift moves low-chlorinity low-oxygen sub-Antarctic water on to the shelf) on the appropriate date. They were also plotted against the depth of $\sigma_t = 26{\cdot}50$ at the 20 mile station on these dates. No relationship was found, even if the Gabo Island and Montagu Island winds were themselves algebraically summed, and the final result used. Figure 10 is a plot of these combined effective winds against average chlorinity from 100 m to the bottom at the 20 mile station. It is therefore assumed that short-term fluctuation of uplift along the coast in the region of Eden is determined by other factors apart from, or in addition to, the wind. Such factors could be alterations in velocity of the East Australian Current, the movement of its axis towards or away from the coast, or the movement of sub-Antarctic water in pulses due to variations in sinking rate at the Subtropical Convergence. Also of possible importance are smaller-scale factors such as the arrival of internal waves at the edge of the shelf as described by Iselin (1940) for the New England coast, and by Arthur (1954) and Reid (1956) for the Californian coast. Cooper (1947) discusses the possible importance of internal waves in lifting water from mid depths on to a continental shelf, with particular reference to the western end of the English Channel and the Celtic Sea. Variations in current velocity over the shelf can produce vortices and localized uplift of deeper water, and Leipper (1955) has suggested that such vortices are responsible for the elevation of cold deeper water to shallower depths off the Californian coast. Uda and Ishino (1958) have demonstrated vortices and uplift around the coasts of Japan, both from hydrological data and by the use of scale models in tanks. Horizontal plots at various depths down to 200 m of isotherms and isohalines over the four sections worked by F.R.V. *Marelda* do in

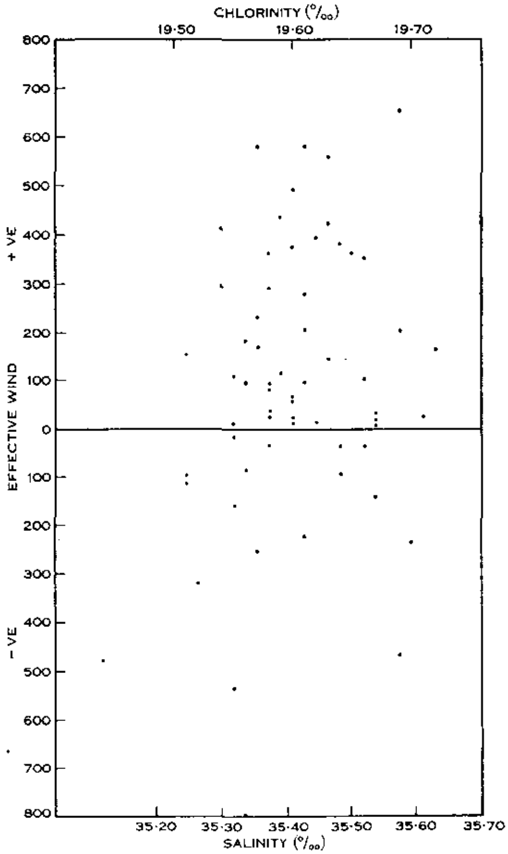

Fig. 10.—Average chlorinity between 100 and 200 m at the 20 mile station in the Eden section on each traverse worked from July 1957 to April 1959, plotted against effective combined wind at Gabo Island and Montagu Island.

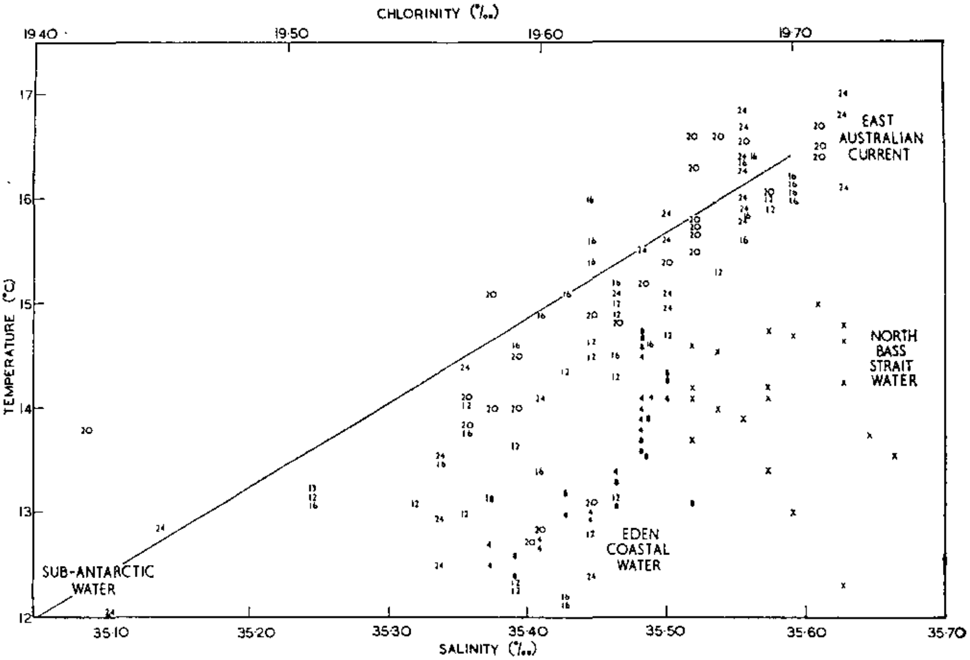

Fig. 11.—Temperature-chlorinity relation at Eden stations 4, 8, 12, 16, 20, and 24 on 25.x.57, 4.viii.58, and 28.viii.59. × Indicates North Bass Strait water.

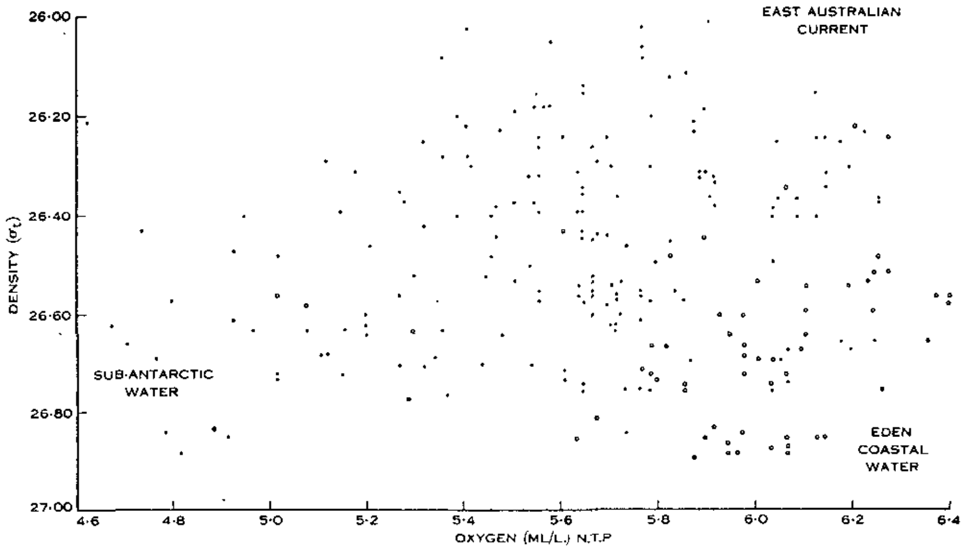

Fig. 12.—Oxygen-density relation in the Eden section.

○ 4, 8, and 12 mile stations on 10.x.57, 11.viii.58, and 28.viii.59.

● 16, 20, and 24 mile stations on 10.x.57, 11.viii.58, and 28.viii.59 and all samples on 9.ix.57, 8.vii.58, and 28.vii.59.

fact show the sub-Antarctic water intrusions to be localized in tongues and two such tongues are indicated in Figure 6 by the course of the 19·50 ‰ isochlor at 100 m depth. However, these local effects are superimposed on the large-scale upwelling pattern shown by *Derwent Hunter* sections (Fig. 7).

VI. Eden Coastal Water

When vertical sections of chlorinity, temperature, density, and oxygen were plotted for Eden in October 1957, July, August, and September 1958, and August 1959, it became apparent that a water mass distinct from the East Australian Current and sub-Antarctic water was present from the coast to about 12 miles offshore. Figure 11 shows the temperature-chlorinity diagram for all samples collected at Eden stations on October 25, 1957, August 4, 1958, and August 28, 1959. It can be seen that the water at the 4, 8, and 12 mile stations was colder than water of the same chlorinity produced by mixing of East Australian Current and sub-Antarctic water. It corresponds, however, to a mixture of sub-Antarctic water and North Bass Strait water (Fig. 11). Those values were obtained from northern Bass Strait and are the 8-year winter averages in half-degree squares of latitude and longitude used in Part A of this paper.

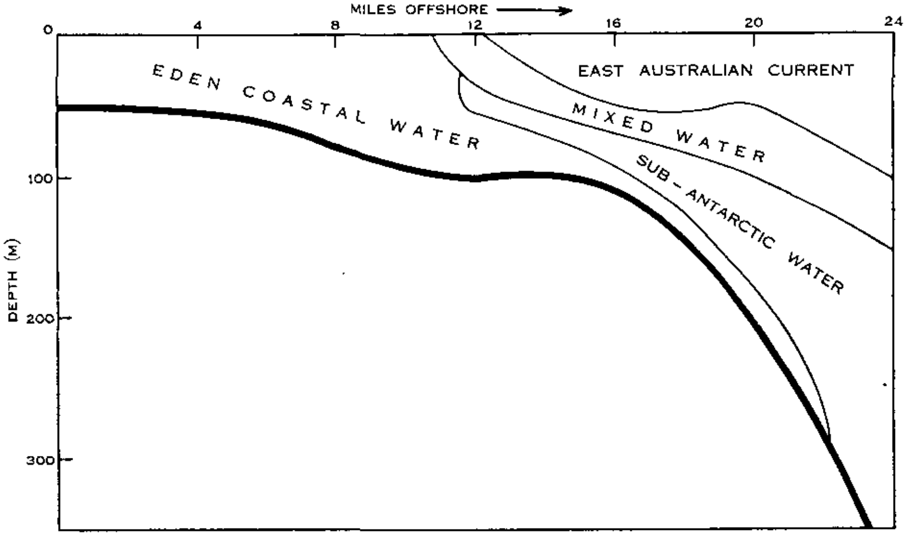

Fig. 13.—Distribution of properties in the Eden section on 22.vii.58:

	Cl (‰)	Temp. (°C)	σ_t	O_2 (ml/l)	P (μg-atom/l.)
Eden Coastal Water	19·62	13	26·75	5·75–6·25	0·4
Sub-Antarctic Water	<19·2	9·2	26·55–26·85	4·5–5·0	>0·6
East Australian Current	19·65	15.4	26·35	5·25–6·00	0·5
Mixed Water	19·60	14	26·45	5·0–5·5	0·55

Similarly Figure 12 gives the oxygen-density relations of all samples collected at Eden on October 10, 1957, August 11, 1958, and August 28, 1959. (Samples on September 9, 1957, July 8, 1958, and July 28, 1959, are included for comparison, and show the usual mixing path between East Australian Current and sub-Antarctic water.) The samples from the 4, 8, and 12 mile stations are in general higher in oxygen than water of the same density on this mixing path.

Using the method of Miller (1950) the water masses present in the Eden section on July 22, 1958, were identified according to the groups into which the samples from the various depths fell when plotted in a TS diagram. The water masses thus identified were accordingly worked on the vertical plot shown in Figure 13. This figure shows the distribution of the three water types present, together with the mixed water intermediate in characteristics between East Australian Current and sub-Antarctic water. Included in the caption to Figure 13 are the average values of chlorinity, temperature, density, oxygen, and inorganic phosphate for the four waters.

It is deduced from the evidence provided in Part A of this paper that the Eden coastal water is formed by mixing between North Bass Strait water and sub-Antarctic water in the north-eastern region of Bass Strait during winter, and that the strong west winds of winter drive this mixed water round Cape Howe and along the south coast of New South Wales. It is significant that two drift bottles released from Cape Northumberland and Cape Otway in June 1959 were recovered on the New South Wales coast in August, the only month during 1959 in which Eden coastal water was detected on the New South Wales coast. Eden coastal water was perceptible as far north as the Jervis Bay section in September 1958 and August 1959. It was not present at Kiama in September 1958. Quite often the water column at the 4, 8, and 12 mile stations is isothermal when the Eden coastal water is present. This suggests that cooling and convective mixing on the shelf contribute to the lower temperature of this body of water. Such cooling would increase the density and could cause the Eden coastal water to flow down the continental slope as shown in Figure 13.

REFERENCES

ARTHUR, R. S. (1954).—Oscillations in sea temperature at Scripps and oceanside piers. *Deep-Sea Res.* **2**: 107-21.

CLOWES, A. J. (1954).—The temperature, salinity, and inorganic phosphate content of the surface layer near St. Helena Bay, 1950-52. Sth. Afr. Comm. Ind. Div. Fish. Invest. Rep. No. 16.

COOPER, L. H. N. (1947).—Internal waves and upwelling of oceanic water from mid-depths on to a continental shelf. *Nature* **159**: 579.

C.S.I.R.O. AUST. (1951*a*).—Hydrological and planktological observations by F.R.V. *Warreen* in south-eastern Australian waters, 1938-39. *C.S.I.R.O. Aust. Oceanogr. Sta. List* **1**.

C.S.I.R.O. AUST. (1951*b*).—Hydrological and planktological observations by F.R.V. *Warreen* in south-eastern Australian waters, 1940-42. *C.S.I.R.O. Aust. Oceanogr. Sta. List* **2**.

C.S.I.R.O. AUST. (1951*c*).—Hydrological and planktological observations by F.R.V. *Warreen* in south-western Australian waters, 1947-50. *C.S.I.R.O. Aust. Oceanogr. Sta. List* **3**.

C.S.I.R.O. AUST. (1953*a*).—Onshore hydrological investigations in eastern and south-western Australia, 1951. *C.S.I.R.O. Aust. Oceanogr. Sta. List* **14**.

C.S.I.R.O. AUST. (1953*b*).—Onshore hydrological investigations in eastern and south-western Australia, 1952. *C.S.I.R.O. Aust. Oceanogr. Sta. List* **17**.

C.S.I.R.O. AUST. (1954).—Onshore hydrological investigations in eastern and south-western Australia, 1953. *C.S.I.R.O. Aust. Oceanogr. Sta. List* **18**.

C.S.I.R.O. AUST. (1956).—Onshore hydrological investigations in eastern and south-western Australia, 1954. *C.S.I.R.O. Aust. Oceanogr. Sta. List* **24**.

C.S.I.R.O. AUST. (1957*a*).—Onshore and oceanic hydrological investigations in eastern and south-western Australia, 1955. *C.S.I.R.O. Aust. Oceanogr. Sta. List* **27**.

C.S.I.R.O. AUST. (1957*b*).—Surface sampling in the Tasman and Coral Seas, 1955. *C.S.I.R.O. Aust. Oceanogr. Sta. List* **28**.

C.S.I.R.O. AUST. (1957*c*).—Onshore and oceanic hydrological investigations in eastern and south-western Australia, 1956. *C.S.I.R:O. Aust. Oceanogr. Sta. List* **30**.

C.S.I.R.O. AUST. (1957*d*).—Surface sampling in the Tasman and Coral Seas and the south-eastern Indian Ocean. *C.S.I.R.O. Aust. Oceangr. Sta. List* **31**.

C.S.I.R.O. AUST. (1958).—Coastal hydrological investigations in eastern and south-western Australia, 1957. *C.S.I.R.O. Aust. Oceanogr. Sta. List* **33**.

C.S.I.R.O. AUST. (1959*a*).—Coastal hydrological investigations at Eden, New South Wales, 1957. *C.S.I.R.O. Aust. Oceanogr. Sta. List* **35**.

C.S.I.R.O. AUST. (1959*b*).—Hydrological investigations from F.R.V. *Derwent Hunter*, 1957. *C.S.I.R.O. Aust. Oceanogr. Sta. List* **37**.

C.S.I.R.O. AUST. (1959*c*).—Surface sampling in the Tasman and Coral Seas. *C.S.I.R.O. Aust. Oceanogr. Sta. List* **36**.

C.S.I.R.O. AUST. (1959*d*).—Coastal hydrological investigations in the New South Wales tuna fishing area, 1958. *C.S.I.R.O. Aust. Oceanogr. Sta. List* **38**.

C.S.I.R.O. AUST. (1960*a*).—Surface sampling in the Coral and Tasman Seas, 1958. *C.S.I.R.O. Aust. Oceanogr. Sta. List* **39**.

C.S.I.R.O. AUST. (1960*b*).—Surface sampling in the Coral and Tasman Seas, 1959. *C.S.I.R.O. Aust. Oceanogr. Sta. List* **43**.

HELA, I. (1956).—A pattern of coastal circulation inferred from synoptic salinity data. *Bull. Mar. Sci. Gulf Caribbean* **6**: 74-83.

ISELIN, C. O'D. (1940).—The necessity of a new approach to the study of the circulation on the continental shelf. *Trans. Amer. Geophys. Un.* **21**: 347-8.

KITANO, K. (1958).—Observations of surface phenomena in ocean and coastal waters near Japan. *J. Mar. Res.* **16**: 175-79.

LEIPPER, D. F. (1955).—Sea temperature variations associated with tidal currents in stratified shallow water over an irregular bottom. *J. Mar. Res.* **14**: 234-52.

MILLER, A. (1950).—A study of mixing processes over the edge of the continental shelf. *J. Mar. Res.* **9**: 145-60.

NEDERLANDS METEOROLOGISCH INSTITUT (1949).—Sea areas around Australia. Oceanographic and meteorological data. Publ. 124.

REID, J. L. (1956).—Observations of internal tides. *Trans. Amer. Geophys. Un.* **37**: 278.

REID, J. L., RODER, G. L., and WYLLIE, J. G. (1958).—Studies of the California Current System. C.C.O.F.I. Prog. Rep. July 1956 to January 1958.

ROBINS, J. P. (1958).—F.R.V. *Marelda* Scientific Report of Cruises, July 1957 to May 1958. C.S.I.R.O. Aust. Div. Fish. Oceanogr. Rep. No. 22.

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. Freshw. Res.* **8**: 369-413.

ROCHFORD, D. J. (1958).—The seasonal circulation of the surface water masses of the Tasman and Coral Seas. C.S.I.R.O. Aust. Div. Fish. Oceanogr. Rep. No. 16.

ROCHFORD, D. J. (1959).—The primary external water masses of the Tasman and Coral Seas. C.S.I.R.O. Aust. Div. Fish. Oceanogr. Tech. Pap. No. 7.

ROTSCHI, H. (1960).—Récents progrès des recherches océanographiques entreprises dans le Pacifique Sud-ouest. *C.C.O.E.C. Cah. Oceanogr.* **12**(4): 239-67.

ROYAL AUSTRALIAN AIR FORCE (1942).—Weather on the Australian Station. Local information. R.A.A.F. Publ. No. 252, Vol. 11A.

ROYAL AUSTRALIAN AIR FORCE (1944).—Weather on the Australian Station. Local information. R.A.A.F. Publ. No. 253. Pt. 6.

SCHOTT, G. (1935).—"Geographie der Indischen und Stillen Ozeans." (C. Boysen: Hamburg.)

STOMMEL, H. (1958).—"The Gulf Stream." (Univ. Calif. Press: Los Angeles.)

SVERDRUP, H. U., JOHNSON, M. W., and FLEMING, R. H. (1942).—"The Oceans—their Physics, Chemistry, and General Biology." (Prentice Hall Inc.: New York.)

TAYLOR, C. B., and STEWART, H. B. (1959).—Summer upwelling along the east coast of Florida. *J. Geophys. Res.* **64**: 33-40.

UDA, M., and ISHINO, M. (1958).—Enrichment pattern resulting from eddy systems in relation to fishing grounds. *J. Tokyo Coll. Fish.* **44**: 105-29.

WYRTKI, K. (1960).—The surface circulation in the Coral and Tasman Seas. C.S.I.R.O. Aust. Div. Fish. Oceanogr. Tech. Pap. No. 8.

YOSHIDA, K. (1955).—Coastal upwelling off the Californian coast. *Rec. Oceanogr. Wks. Japan* **2**(2): 8-20.