EXTERNAL WATER MASSES OF THE TASMAN AND CORAL SEAS

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Summary

Mean quarterly curves of surface chlorinity-temperature characteristics have been prepared by the method of frequency plotting for the Tasman and Coral Seas for 1955–56. The degree of freedom from spurious short-term effects in these curves has been gauged by reference to vertical chlorinity-temperature curves for the region.

On the assumption that local evaporation and precipitation changes were less important than advection, and by utilizing three external water masses, the South Equatorial, the West Central South Pacific, and the Sub-Antarctic, mixing triangles were constructed. From these, the distribution of the mean August and December surface chlorinity and temperature has been described as mixtures of the three water masses.

Charts of the mean distribution of total phosphorus for August and December were prepared and mean total phosphorus values of about 20 μg/l. (0·65 μg at./l.) for the South Equatorial, 3–5 μg/l. (0·097–0·16 μg at./l.) for the West Central South Pacific, and 20–30 μg/l. (0·65–0·97 μg at./l.) for the Sub-Antarctic were calculated.

Circulation charts based upon the distribution of water masses were prepared for August and December.

I. Introduction

In its study of the hydrological characteristics of the Tasman and Coral Seas, this Laboratory has been handicapped by the inadequacy of the data that can be collected by conventional methods from its research vessels. This inadequacy is due to the area involved (see Table 1) in relation to the resources available. In part answer to this, surface sampling from merchant ships was begun in 1953 and an examination of the Tasman Sea surface data for 1953–54 has already been published (Rochford 1957). Since then more vessels and other regions of the Tasman and Coral Seas have been included.

This paper examines the representativeness (in the sense of freedom from spurious short-term effects) of the 1955–56 surface data from this region, by comparing them with available vertical profiles of hydrological properties from within and adjacent to the Tasman and Coral Seas.

II. Material and Methods

The 1953–56 chlorinity-temperature and total phosphorus data have already been published (C.S.I.R.O. Aust. 1955, 1956*a*, 1956*b*, 1957*a*, 1957*b*, 1957*c*, 1957*d*, 1958). Other sources of data are as follows:

*Division of Fisheries and Oceanography, C.S.I.R.O., Cronulla, N.S.W.

H.M.S. *Challenger* (Buchanan 1884)
R.R.S. *Dana* (Carlsberg Foundation 1937)
R.S. *Daifujimaru* (Shizuoka Prefectural Fisheries Experimental Station 1957)
R.R.S. *Discovery II* (R.R.S. 'Discovery II' 1941)
R.V. *Horizon* (Scripps Institution of Oceanography 1957)
S.M.S. *Planet* (Wüst 1929)
R.S. *Shoyo-Maru* (Fisheries Agency, Japan 1957)
R.V. *Stranger* (Scripps Institution of Oceanography 1957)
S.S. *Tahitien* (C.S.I.R.O. Aust., unpublished data).

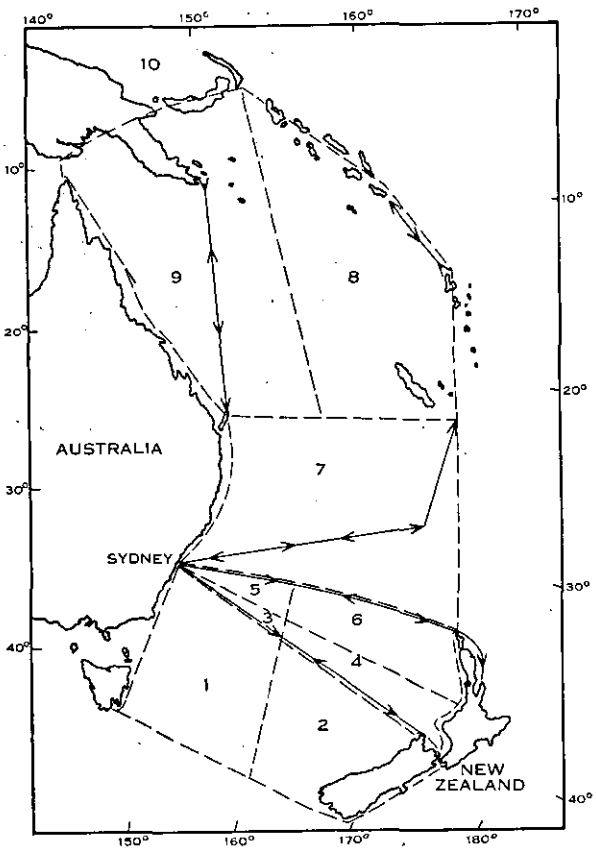

Fig. 1.—Map (using Lambert's conic projection standard parallels 10 and 40° S.) showing routes of ships collecting water samples and extent of areas used in Table 1.

In this paper the frequency diagram of chlorinity-temperature characteristics developed by Montgomery (1955) was used for an examination of the surface data for 1955–56. From such a diagram for quarterly periods of the year a curve or curves were drawn showing the most frequently occurring combinations of chlorinity and temperature in the Tasman and Coral Seas. Such curves were to a large extent

freed of the effects of adventitious local changes in temperature and chlorinity, and therefore were more representative in the description of quarterly conditions. These quarterly curves were then compared one with another and with the properties of the regional water masses of the Tasman Sea (Rochford 1957) to see whether they were consistent in this respect. There is no recognized method for gauging the validity and representativeness of such curves. The method followed in this paper was to use a series of vertical chlorinity-temperature curves, representative of the region, as the standard of reference and to determine to what extent the curves of surface characteristics agreed with their shape and absolute values.

Cochrane (1956) in a study of the frequency distribution of surface water characteristics in the Pacific Ocean used the following definitions. "The term

TABLE 1

SIZE OF AREAS AND AVERAGE QUARTERLY SAMPLES COLLECTED BY MERCHANT SHIPS IN THE TASMAN AND CORAL SEAS

Information used in the preparation of frequency diagrams (Figs. 2–5)

Area	Size (square nautical miles)	Average No. of Samples per Quarter	No. of Samples Required for Density of One per 50 Square Nautical Miles per Quarter	Average Factor Used
1	—	—	—	—
2	—	—	—	—
3	$1{\cdot}6\times10^4$	325	320	1
4	$11{\cdot}9\times10^4$	415	2,380	5·7
5	$2{\cdot}4\times10^4$	330	480	1·5
6	$11{\cdot}8\times10^4$	380	2,360	6·2
7	$57{\cdot}5\times10^4$	62	11,500	190
8	$53{\cdot}7\times10^4$	16	10,740	670
9	$68{\cdot}2\times10^4$	71	13,640	190
10	—	—	—	—
Total	$207{\cdot}1\times10^4$	1,599	41,620	

characteristic denotes a point on the temperature-salinity diagram. Characteristic class refers to the area on the diagram included in a specified temperature and specified salinity interval. The frequency of a characteristic class means its prevalence in extent and duration within the region and period considered." These definitions are followed in this paper.

Montgomery (1955) used intervals of 0·5°C for temperature and 0·10‰ for salinity, whilst Cochrane (1956) used 2·0°C for temperature and 0·40‰ for salinity. In this paper intervals corresponding to those of the former author have been used.

For convenience those parts of the Tasman and Coral Seas, through which the merchant ships cooperating in this programme travel and collect surface samples, have been divided into 10 areas (Fig. 1). However, as Table 1 shows, there is a

great difference in the size of these areas and of the average number of samples collected per quarter. Before these data could be used, an adjustment was made by appropriate factoring so that a sampling density of one per 50 square nautical miles per quarter was obtained. As Table 1 shows, this has involved the use of

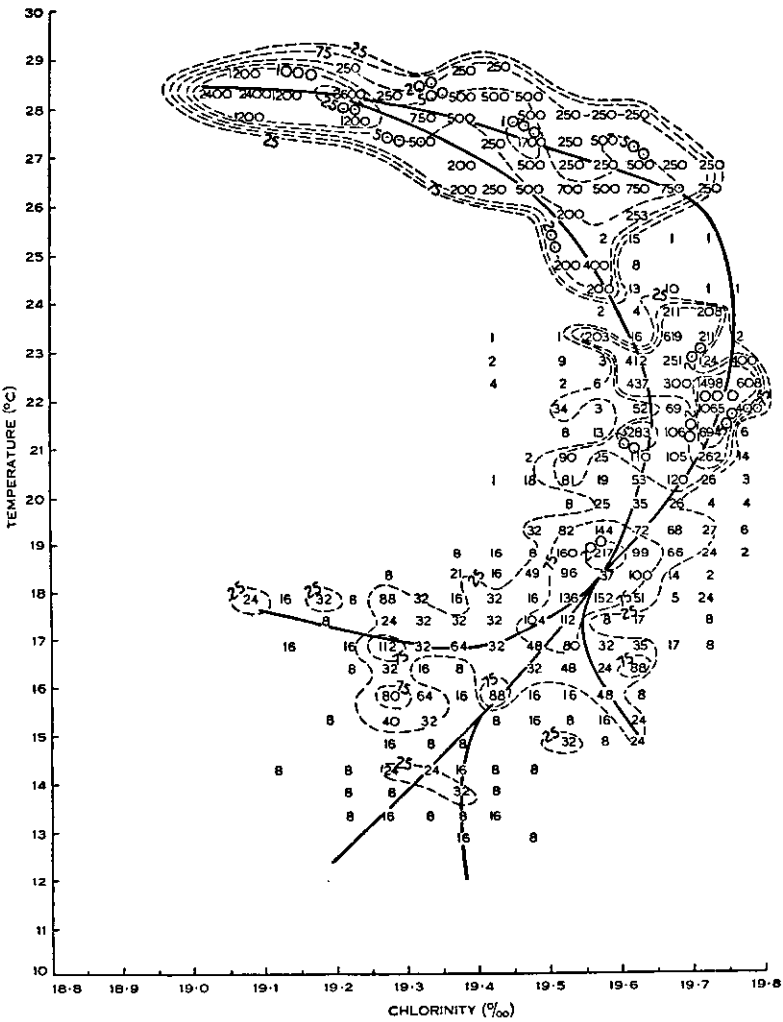

Fig. 2.—Frequency diagram of surface characteristics in November–January. Contour intervals at 25, 75, 200, 500, 1000, and 2500 occurrences per 41,000 values.

very high factors for areas 7, 8, and 9. However, as this adjustment does not alter the frequency of the characteristic classes in each area, but alters only their numerical strength relative to other areas, it cannot affect the frequency pattern of the whole region unless the original sampling was not representative. This latter possibility will be considered later (Section IV).

III. Surface Characteristics of the Tasman and Coral Seas

Figures 2–5 show frequency isopleths plotted at intervals of 25, 75, 200, 500, 1000, and 2500 occurrences. These represent 0·06, 0·18, 0·48, 1·20, 2·40, and 6·00 per cent. respectively of the total occurrences. These are of the same order

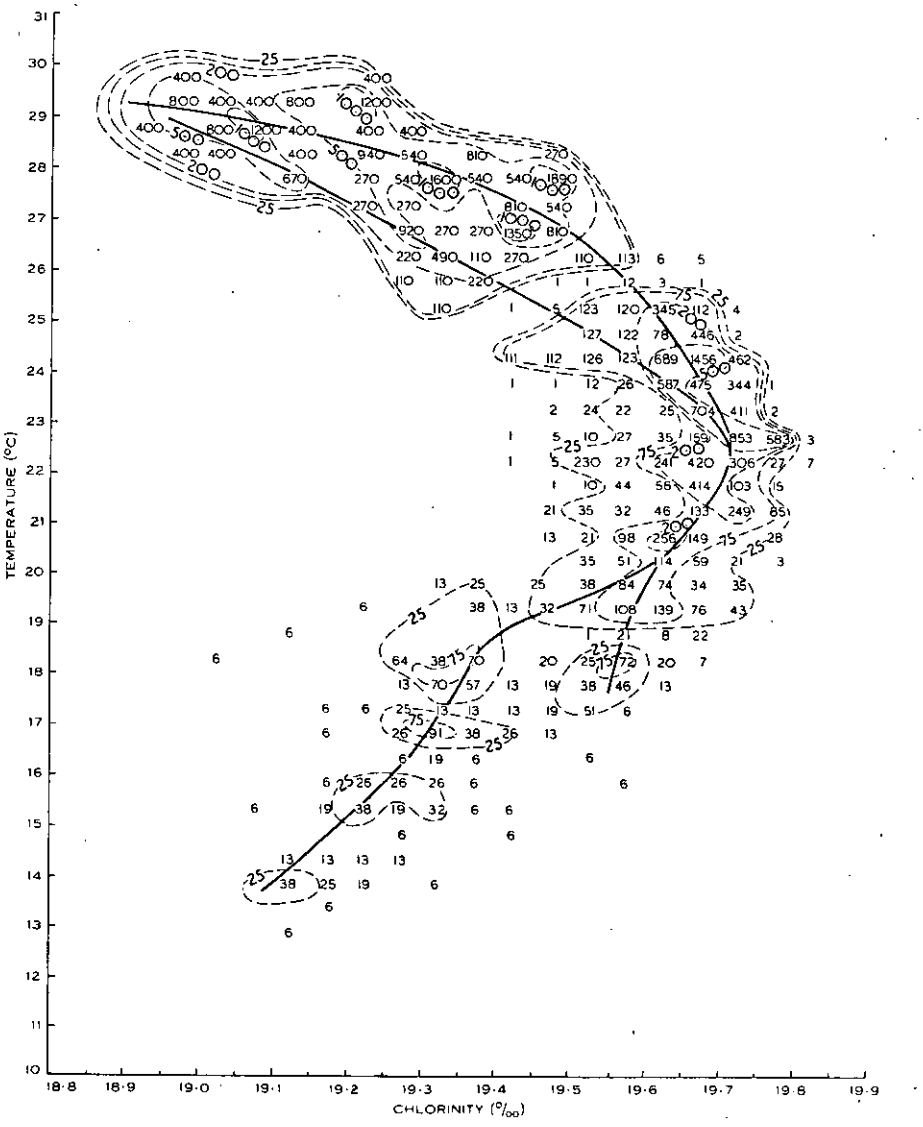

Fig. 3.—Frequency diagram of surface characteristics in February–April. Contour intervals as in Figure 2.

as the frequency isopleths of 0·55 per cent. and 2·15 per cent. used by Montgomery (1955) in the North Atlantic, and of 0·1, 0·4, 1·6, and 6·4 per cent. used by Cochrane (1956) in the Pacific Ocean as a whole.

Mean curves of surface characteristics were entered on Figures 2–5, by following the isopleth pattern and passing through the maximum frequency zones in each temperature interval. Above about 18°C this frequency was defined by isopleths greater than 0·5 per cent., but below this temperature, isopleth values rarely exceeded 0·5 per cent. and the mean curve and its branches were located at frequencies of occurrence less than this value. There can be no doubt that some of the branches of the mean curve at lower temperatures, defined in this fashion, cannot have much statistical significance, but, in view of their relation to the surface water masses previously defined for the southern Tasman Sea (Rochford 1957), their separation seems justified (Section III (*e*)).

(*a*) *November–January*

In this quarter, tropical waters from various sources entered the Coral Sea and were responsible for the flattened nearby isothermal section of the mean curve of surface characteristics at higher temperatures (Fig. 2). The second branch of the mean curve at higher temperatures probably represents the average change in the original properties of these tropical waters as they moved south into the Tasman Sea. These changes were probably brought about by increased mixing with deeper waters. In the lower temperature portion of the diagram, there is less scatter than previously but a single mean curve could not be established.

(*b*) *February–April*

In this quarter the two branches of the mean curve at higher temperatures were again found (Fig. 3), but less separated than previously. This probably indicates that less vertical mixing of the various tropical waters and the deeper layers occurred during their southward passage in this quarter. In the lower temperature portion of the diagram, there was less scatter than previously, but a single mean curve could not be established.

(*c*) *May–July*

In the northern Tasman Sea and Coral Sea as a whole, this quarter was dominated hydrologically by decreasing transport of tropical waters southward and greater vertical mixing, and this is reflected in the frequency diagram (Fig. 4). The two branches of the mean curve at higher temperatures were considered extreme stages in the vertical mixing of the later summer tropical waters with deeper layers during the maximum development of the south-east trades. This mixing was confined to the latitudes 20–25° S. but extended zonally across the Tasman Sea. The various branches of the mean curve at lower temperatures were associated with the seasonal disintegration of the East Central New Zealand water mass and autumn changes in the movement of the Sub-Antarctic water mass in the south-east Tasman Sea.

(*d*) *August–October*

In this quarter (Fig. 5) there was the minimum scatter around a single mean curve except in the higher temperature portion where a branch of the mean curve

was used to include some very high temperature and moderate chlorinity data. The significance of this branch will be discussed in Section IV. It seems probable that a steady equilibrium between the circulation of water of different properties and of their mixing and assimilation was reached in this quarter.

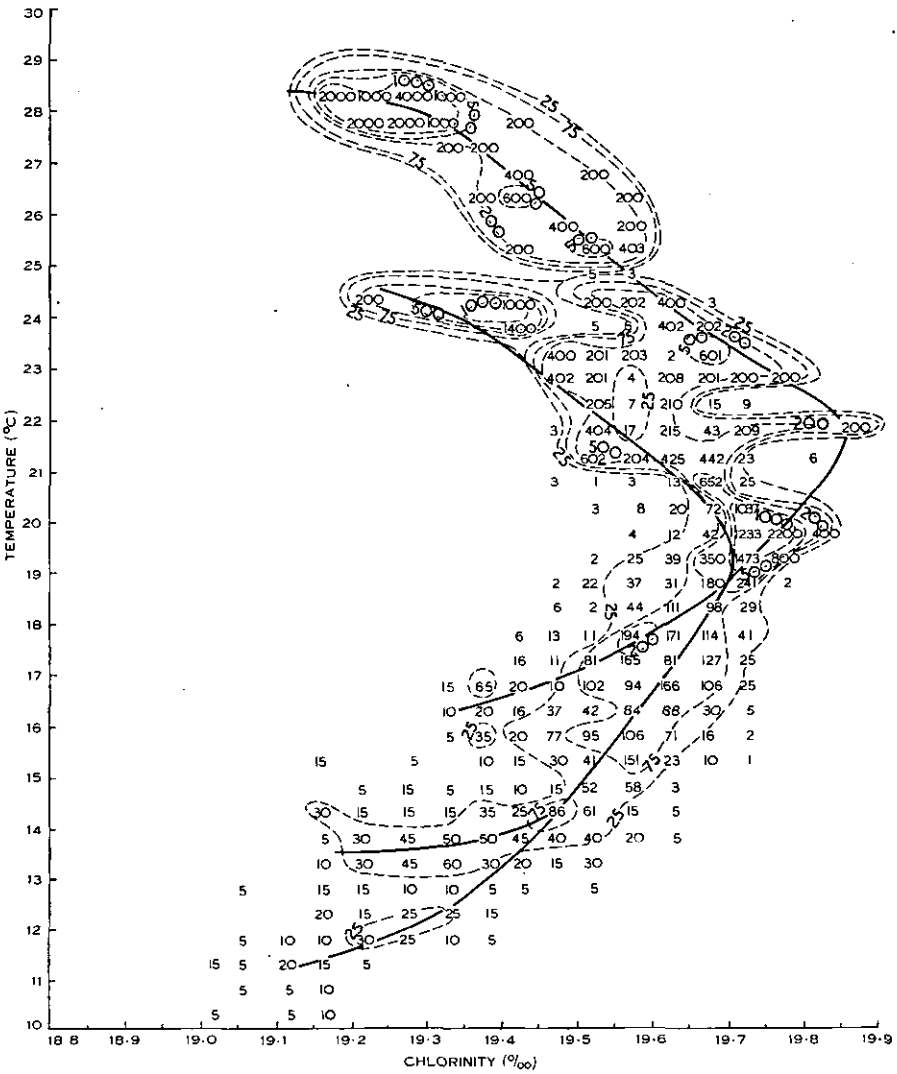

Fig. 4.—Frequency diagram of surface characteristics in May–July. Contour intervals as in Figure 2.

(e) *Comparison of Quarterly Curves of Surface Characteristics*

A comparison of the quarterly curves of surface characteristics (Fig. 6) reveals a number of significant features. At temperatures greater than 28°C there was little seasonal change in temperature but very marked ones in chlorinity, with minimum chlorinities in November–April and maximum values in August–October associated with the secondary branch of the mean curve for that quarter.

Within the temperature range 19–28°C chlorinities increased with decreasing temperatures as also did the range of seasonal change in these properties. Two branches of the mean curve were found in November–July, and this was considered (Section III(*a*), (*b*)) to be an effect of variations in the degree of vertical mixing

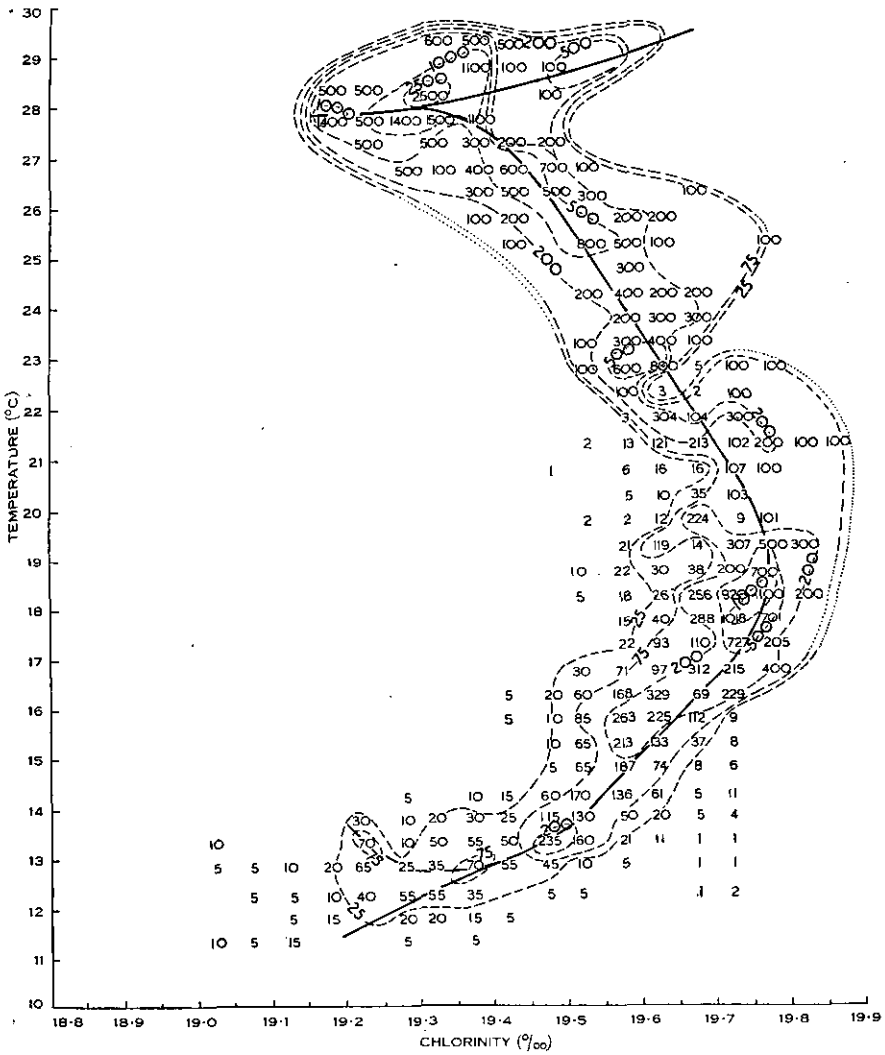

Fig. 5.—Frequency diagram of surface characteristics in August–October. Contour intervals as in Figure 2.

of tropical waters moving south into the Tasman Sea. It is possible that some of this bifurcation was due to variation in the cooling rates in this region, but as waters of these separate characteristics in May–July were often found in the same latitude, this process has been considered of secondary significance.

Around the region of maximum chlorinities on these quarterly curves, values ranged from 19·87‰ in May–July to 19·65‰ in November–January. These values

occurred at a temperature of 22°C for the period November–July, but at about 19°C in August–October. These seasonal changes in temperature and maximum chlorinity characteristics must to some extent have been caused by seasonal changes in the evaporation-precipitation balance, but insufficient data are available for the Tasman and Coral Seas to determine the significance of this process in relation to advection.

At temperatures below 19°C chlorinities decreased with decreasing temperature but there were marked separation of the various quarterly curves and a considerable number of secondary branches. This must have been due largely to the influence

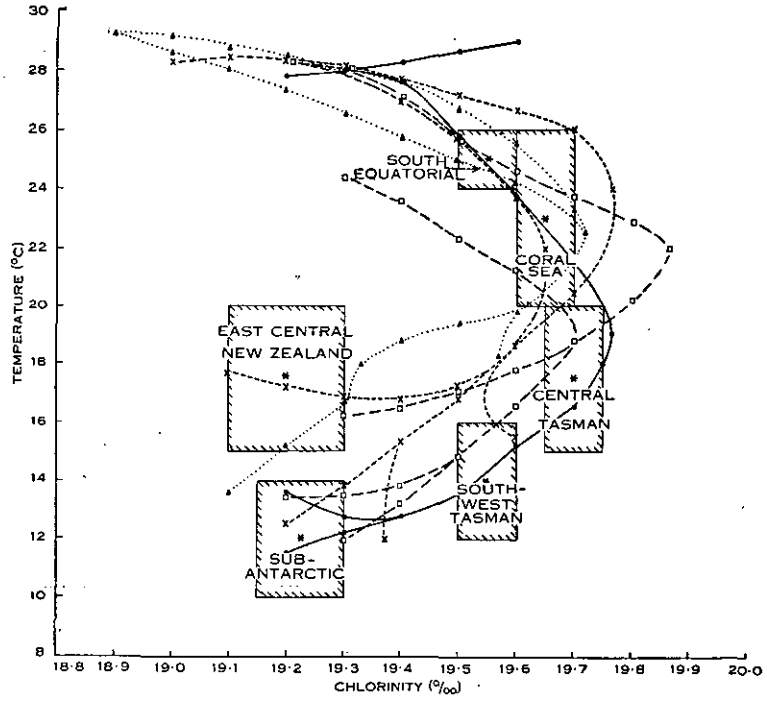

Fig. 6.—The mean curves and branches of surface characteristics of the Tasman and Coral Seas. The rectangles enclose the range of identifying properties of the surface Tasman Sea water masses.

●———● August–October. ×– – – –× November–January.
▲·····▲ February–April. □—— ——□ May–July.

of the East Central New Zealand water mass (Rochford 1957), in November–April. If the branches influenced by this water mass are disregarded the remainder of the quarterly curves are much more restricted in the seasonal changes in chlorinity and temperature.

The quarterly curves in Figure 6 show that minimal seasonal changes occurred in tropical waters with increasing variation towards the subtropical and Sub-Antarctic regions of these curves. To some extent therefore the seasonal variation in properties of the surface water masses of the Tasman Sea would thus depend on their content of tropical water which had relatively limited seasonal

change in composition. Because the regional South Equatorial water mass of the Tasman Sea (Rochford 1957) contains more of this tropical water than the Coral Sea, its occasional change in properties off Sydney is less (Fig. 6). Also the secondary branch with higher temperatures of the quarterly curve for November–January, which could introduce higher-temperature equatorial waters into the southern Tasman Sea, does not occur south of latitude 25° S. (Section III(*a*)).

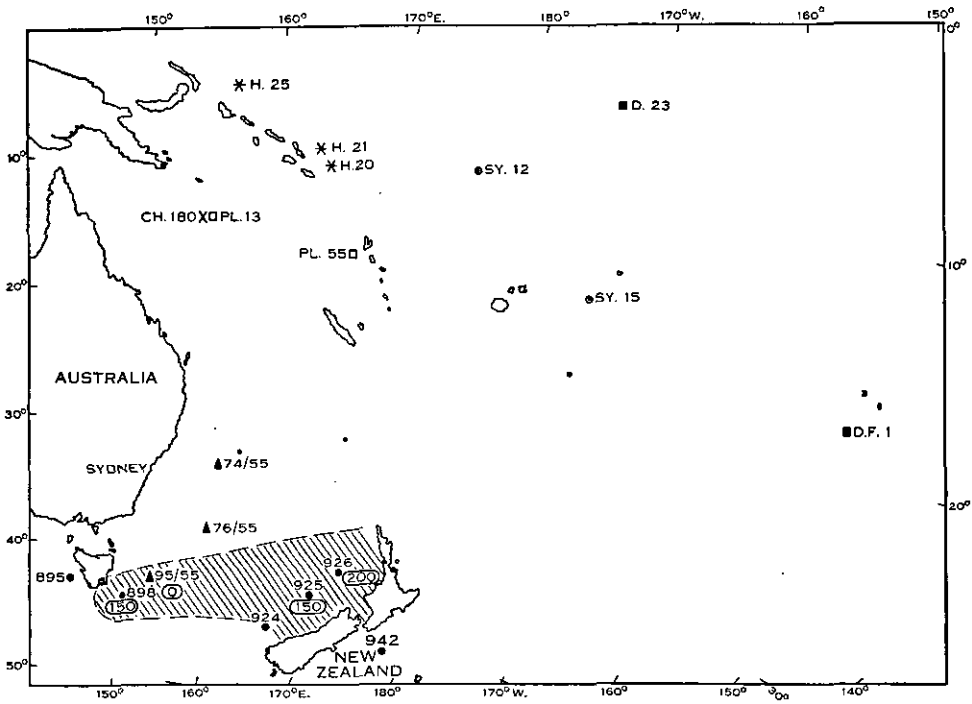

Fig. 7.—Chart showing the position of the winter stations utilized in the preparation of Figure 8*A*. Enclosed figures show depth of maximum chlorinity gradient. Shaded area: lower temperature intermediate waters.

★ *Horizon;* ■ *Daifujimaru;* ● *Discovery;* ▲ *Derwent Hunter;* ○ *Shoyo-maru;* × *Challenger;* □ *Planet.*

There is some discrepancy between the seasonal range of properties, particularly temperature, previously recorded for the Central Tasman, South-west Tasman, and Sub-Antarctic water masses (Rochford 1957) and the seasonal spread of the mean quarterly curves of the southern Tasman Sea. This discrepancy would probably not be so marked if more surface data were available since 1955 in Areas 1 and 2 (Table 1).

Figure 6 shows that the East Central New Zealand water mass was found in the South-east Tasman in the period November–July rather than December–February as previously thought (Rochford 1957). However, local heating and cooling and possibly evaporation and precipitation might be complicating this interpretation. In general the quarterly curves of surface characteristics are

consistent with the regional water masses of the Tasman Sea south of latitude 34° S. as previously defined (Rochford 1957).

IV. Comparison of Surface Characteristics with Vertical Temperature-Chlorinity Properties

In this section the representativeness of the quarterly curves for August–October and November–January are compared with representative vertical temperature-chlorinity curves of the region. Subsequently the source regions of the various external water masses flowing into the Tasman and Coral Seas are identified.

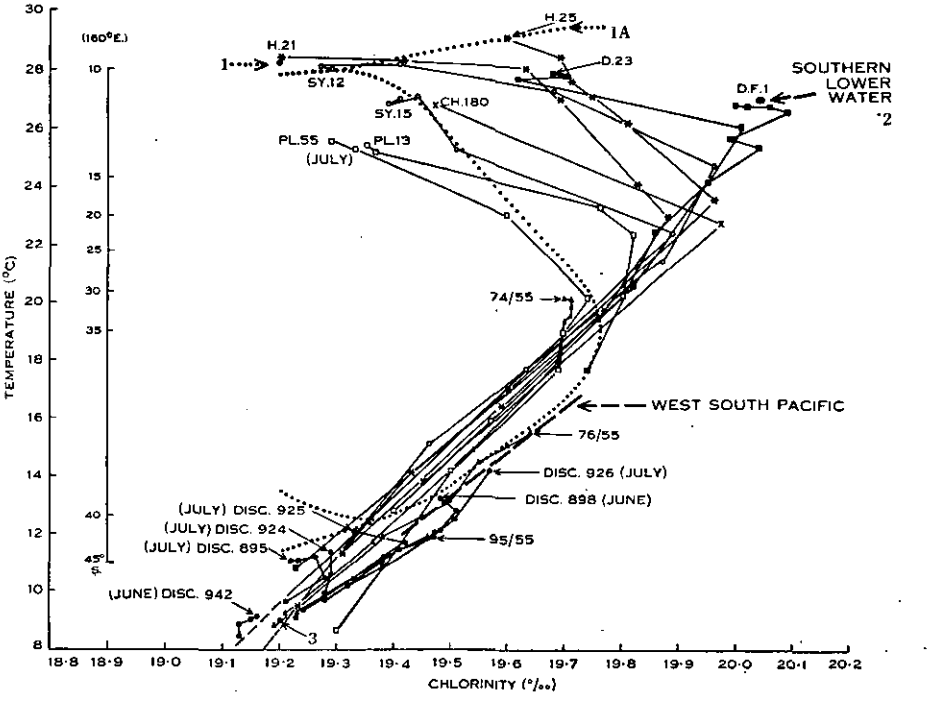

Fig. 8*A*.—Chlorinity-temperature relationships of the waters at the selected stations in Figure 7. The mean curve (·····) and its branches of surface characteristics for August–October and a latitude scale showing the mean position of winter characteristics along the 160° E. meridian are given. Unless otherwise marked, all stations were occupied in August. The points marked 1, 2, and 3 are those used to prepare Figure 8*B*. The curve 1A refers to the North New Zealand water mass. The symbols used are those listed for Figure 7.

(*a*) *August–October*

The locations of the stations examined are shown in Figure 7. These were worked between August and October. Figure 8*A* shows the chlorinity-temperature relationships at these stations in relation to the dominant surface characteristics of the Tasman and Coral Seas. Outside the Tasman Sea the vertical chlorinity-

temperature curves consisted of a surface higher-temperature, low-chlorinity layer extending down to a maximum-chlorinity but variable moderate-temperature layer, followed by mixtures between this intermediate layer and the deeper waters with Sub-Antarctic properties.

Wyrtki (1956*b*) showed that an intermediate depth flow of Southern Lower Water (Fig. 8*A*) was associated with the South Equatorial current. The chlorinity-temperature curves with the above shape are formed by various degrees of mixing between the South Equatorial (Station *H*.21) and the Southern Lower Water (Station *D.F.*1) and the Sub-Antarctic Intermediate Water (Station *Disc.* 942). An exception to this was found at Stations *H*.25 and *D*.23, where temperatures higher

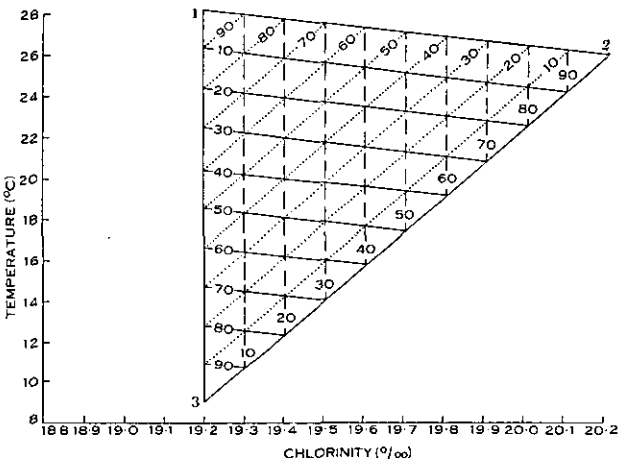

Fig. 8B.—A mixing diagram for computing the percentage of each of the three external water masses in any chlorinity-temperature combinations during August–October.

than those which such mixing could develop were found. This is probably an effect of local heating, but the widespread equatorial distribution of such waters (Section V(*a*), (*b*)) together with their occurrence in the northern Coral Sea in significant amounts (Part 1–1A of curve of surface characteristics) makes them important in the region. Their identification in surface samples from the northern Coral Sea (Fig. 5) therefore confirms the representativeness of this branch of the curve.

The curve of surface characteristics for latitudes south of 35° S. followed closely the vertical chlorinity-temperature curves at selected stations not only in the results from recent sampling (*Derwent Hunter*) but also from previous surveys of this region (*Discovery II*). The curve also had properties very similar to the mean vertical chlorinity-temperature profile of the West South Pacific water mass (Sverdrup, Johnson, and Fleming 1942). The general agreement in shape and absolute value between the curve of surface characteristics and the vertical chlorinity-temperature structure at selected stations throughout the region supports its validity and representativeness in the present study.

(*b*) *November–January*

For this quarter there are no data available for the northern Coral Sea proper and for the adjoining waters to the north-east. However, sufficient *Dana* stations are available to the east of the Coral Sea (Fig. 9) to make an examination similar to that of the previous section for the quarter November–January. Again (Fig. 10*A*) most of the stations external to the region had a vertical chlorinity-temperature profile with a mid-depth high-chlorinity layer separating surface equatorial waters from the deeper Sub-Antarctic intermediate waters.

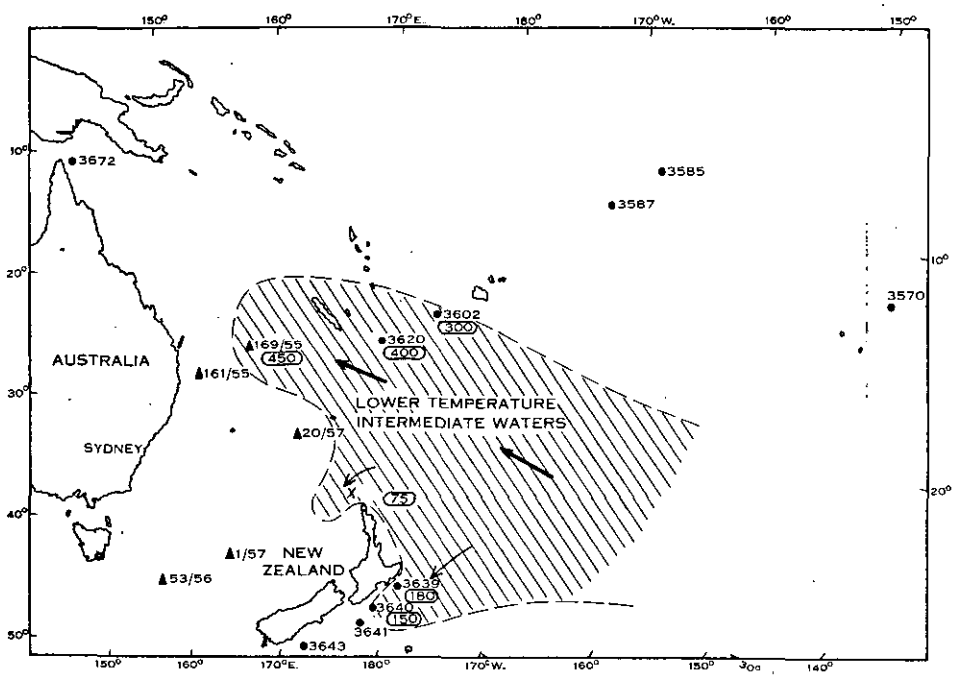

Fig. 9.—Chart showing the position of the summer stations utilized in the preparation of Figure 10*A*. Enclosed figures show depth of maximum chlorinity gradient.

▲ Derwent Hunter; × D.S.I.R. New Zealand Oceanographic Institute; ● Dana.

Within the northern Tasman Sea, waters were found in this quarter (Station 161/55) with mid-depth chlorinity-temperature structure similar to that found in the northern Coral Sea (*Planet* 55, Fig. 8*A*) in the August–October quarter. Also in the November–January quarter, surface waters were found in the north-east Tasman Sea (Station 169/55) with properties similar to those at mid depths at *Dana* Stations 3585 and 3587. A vertical chlorinity-temperature structure intermediate between that at Station 169/55 and at Station 161/55 was found at Station 20/57. The surface conditions at Stations 161/55 and 20/57 both lay within the error limits of the two branches of the curve of surface characteristics. Station 169/55 lay outside the limits of the surface sampling programme and its properties would not therefore be represented in the curve of surface characteristics. The region of the curve with chlorinities less than 19·20‰ at high temperature had properties

similar to those of surface waters at *Dana* Stations 3668 and 3675 in the Arafura Sea in March 1929.

Wyrtki's (1956*a*) charts of surface salinities show that waters of these characteristics are a persistent feature of the Arafura Sea, and this portion of the curve is considered part of an Arafura Sea water mass which has moved into the north-west Coral Sea during this quarter.

It is thought that the lower chlorinity of branch A of the curve in Figure 10*A* was due to decreased evaporation losses in this quarter and an increase in the

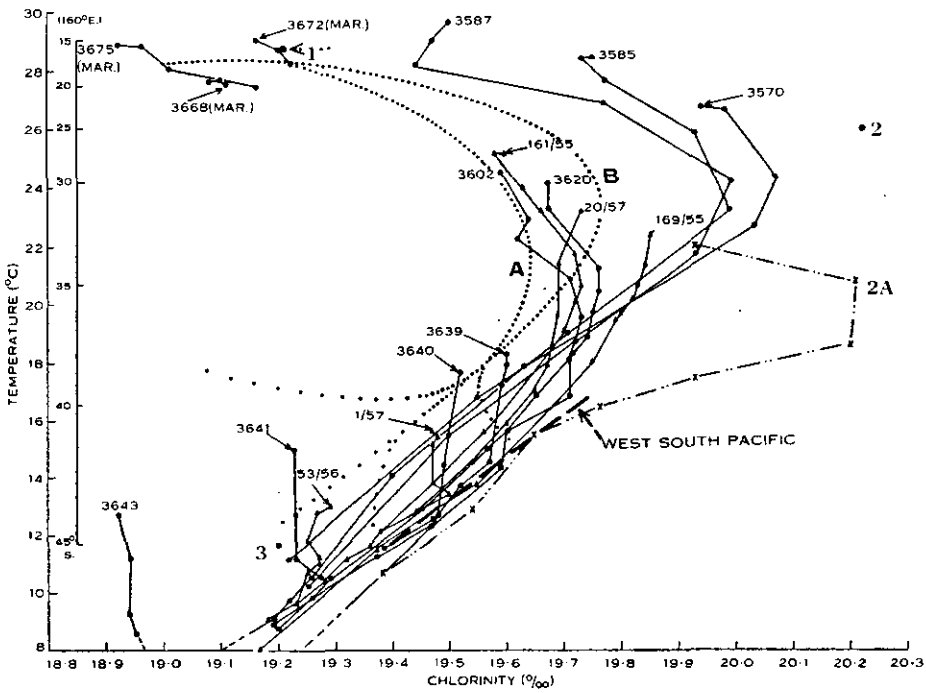

Fig. 10*A*.—Chlorinity-temperature relationships of the waters at the selected stations in Figure 9. The mean curve (·····) and its branches of surface characteristics for November–January and a latitude scale showing the mean position of summer characteristics along the 160° E. meridian are given. Unless otherwise marked all stations were occupied in December. The points marked 1, 2, and 3 are those used to prepare Figure 10*B*. Curve 2A is characteristic of the high temperature, high chlorinity waters in the extreme north of the Coral Sea.

amount of South Equatorial relative to the mid-depth high-chlorinity waters. This branch of the curve was representative of surface conditions along the western side of the Coral and Tasman Seas during November–January. Branch B of the curve, on the other hand, could be due to higher evaporation losses and an increase in the amount of mid-depth high-chlorinity waters relative to the South Equatorial. It was more representative of conditions along the eastern side of the Coral and Tasman Seas.

In the part of the curve with temperatures less than 19°C a series of branches were drawn (Section III(*a*)). However, the main curve fitted most of the surface

properties at the selected stations in the south Tasman Sea and to the east of New Zealand except *Dana* 3641 and 3643 south of Cook Strait. In the corresponding part of the vertical chlorinity-temperature curves there was much more variability than in August–October (Fig. 8*A*). Certain of the selected stations had much colder waters at depth in this quarter than for the winter period.

In February and May 1955, the New Zealand Oceanographic Institute sampled the waters to the north of New Zealand. The February vertical chlorinity-temperature profile (D. Garner, personal communication) revealed (Fig. 10*A*) an extremely high mid-depth chlorinity maximum at a much lower temperature (19°C) than the Southern Lower Water. Any mixture of these North New Zealand and Sub-Antarctic waters would have a lower temperature but similar chlorinities to the same mixture of Southern Lower and Sub-Antarctic waters. The distribution of stations whose chlorinity-temperature structures were influenced by this North New Zealand water mass is given in Figure 9 for the November–January quarter and in Figure 7 for the August–October quarter. This water mass appeared to be more extensively distributed in the former quarter at levels of between 75 and 450 m than in the latter, during which period its depth of occurrence lay between 0 and 200 m. It is probable therefore that its direct influence upon surface characteristics was slight except in rare cases where it appeared at the surface. The two minor branches of the curve of surface characteristics extending into lower temperatures (Fig. 6) were considered effects of such appearance at the surface. It could however be a major influence in the formation each year of the Central Tasman and South-west Tasman water masses (C.S.I.R.O. 1957*a*). The subsurface Western South Pacific water mass of Sverdrup, Johnson, and Fleming (1942) had properties similar to this North New Zealand water mass (Fig. 10*A*), and this suggests that its distribution in the Western South Pacific is rather extensive. A great deal more data will be required to determine the mid-depth circulation of the Tasman Sea and no special examination is made in this paper. As for the previous quarter the good agreement between the mean curve of surface characteristics and its branches and the vertical structure of the waters at selected stations in November–January for the years 1928–1957 is proof of its validity and representativeness.

V. Analysis of the Surface Distribution of Chlorinity and Temperature in the Coral and Tasman Seas in Terms of Three External Water Masses

(*a*) *Properties of Primary External Water Masses*

The general agreement between the curves of meridional distribution of surface characteristics and the vertical chlorinity-temperature curves (Section IV) can be accepted as partial evidence of a similar method of formation of the former. It is known that waters from the equatorial region flow south and those from the Sub-Antarctic region north into these seas (Sverdrup, Johnson, and Fleming 1942). The very high chlorinity Southern Lower Water or its equivalent must flow into them also, either in conjunction with the equatorial water or separately, for the curve of surface characteristics to be formed in this manner.

Assuming that a significant flow of this third external water mass did occur, mean charts of the relative distribution of these water masses were prepared from all data within the months centred around August and December. The mixing triangles of Figure 8*B* for August data and of Figure 10*B* for December data were used to calculate the relative proportions of each of these water masses in surface or 10 m chlorinity-temperature combinations. The mean curves of surface characteristics for the respective quarters (Figs. 5 and 2) were used to select surface data for use in these analyses. The properties of the components of these mixing triangles have been selected from Figures 8*A* and 10*A*.

The South Equatorial water mass was selected at a chlorinity of 19·20‰ and a temperature of 28·2°C in August and 28·8°C in December. The mid-depth layer of maximum chlorinity was chosen at a chlorinity of 20·22‰ and a temperature

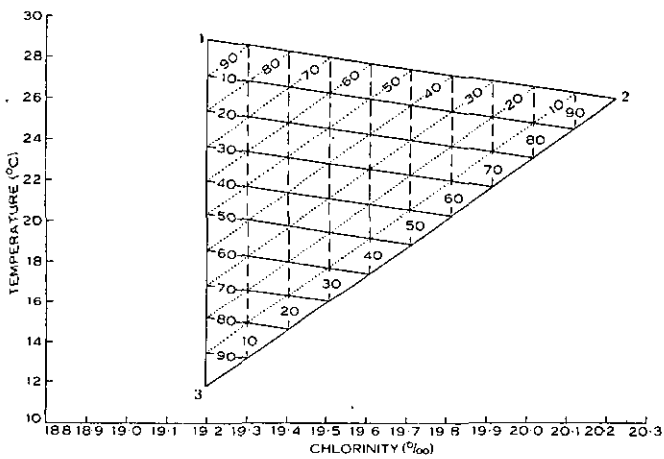

Fig. 10*B*.—A mixing diagram for computing the percentage of each of the three external water masses in any chlorinity-temperature combination during November–January.

of 26°C by extrapolation of the vertical chlorinity-temperature curves of Figure 10*A*. The surface Sub-Antarctic water was characterized by a chlorinity of 19·20‰ and a temperature of 9°C in August and 11·8°C in December. This temperature was an average of surface values for the selected southern Tasman Sea stations in August (Fig. 8*A*) and December (Fig. 10*A*).

In using these mixing triangles data from areas influenced by other water masses such as the Arafura, the high-temperature high-chlorinity water mass 1A (Fig. 8*A*), and the East Central New Zealand and the North New Zealand water masses, which have an independent formation, were disregarded. Moreover, these mixing triangles can be used down to the depth of maximum concentration of the Sub-Antarctic component, only if no other water masses enter at mid-depth levels. This is clearly not the case where the North New Zealand water mass is thought to occur at such depths (Figs. 7, 9). Under these circumstances and because a great part of the data were surface only, the use of these mixing triangles was usually

restricted in this paper to data within the upper 50 m, although they could more profitably have been used at deeper levels where local surface effects were minimal.

(*b*) *August*

Plate 1 shows the relative percentage of each of the three primary external waters in the surface layer of the Coral and Tasman Seas and adjoining waters in August. The South Equatorial component was found as a continuous band extending from the Equator in latitude 170° W. to the northern Coral Sea, with practically no change in properties. Along the western side of the Coral and Tasman Seas it was found in diminishing quantities to at least latitude 35° S. On the eastern side, however, a similar concentration was found only at latitude 25° S. in the region between the New Hebrides and Solomon Islands. This is an indication that more of this equatorial water was moving, or had moved, south along about 170° E. (during this month) than down the Queensland coast.

The high chlorinity water mass which is defined as West Central South Pacific was found around 150° W. in latitude 15–20° S., at about 80 per cent. relative to the other components in Figure 8*B*. To the west and north of this region it was found in decreasing amounts at the surface and was mixed with more of the South Equatorial component. To the south-west, however, a stream of this water was found in the southern Coral Sea and northern Tasman Sea. This stream had entered this region between New Zealand and New Caledonia, and its chlorinity and temperature suggested that it consisted of 50 per cent. West Central South Pacific and 50 per cent. South Equatorial water. Along the southern section of this stream the South Equatorial component was replaced by Sub-Antarctic water.

To the south-west, however, a stream of this water was found in the southern Coral Sea and northern Tasman Sea. This stream had entered this region between New Zealand and New Caledonia, and its properties suggested that it consisted of 50 per cent. West Central South Pacific, 25 per cent. South Equatorial, and 25 per cent. Sub-Antarctic water. Along the southern section of this stream practically no South Equatorial component was found. The Sub-Antarctic component seemed to be mixed with surface layers in a regular manner, depending upon latitude, and this was probably due to progressive deepening as it moved north. On Plate 1 arrows have been entered along the paths of major concentration of the South Equatorial and West Central South Pacific water masses. These can be taken as indications of flow paths, but only on the assumption that the observed August distribution of these water masses could be the result of movements of several months' duration.

(*c*) *December*

In this month (Plate 2) there was less of the South Equatorial component in the Tasman Sea. There was a greater quantity of this water mass to the east of the Tasman Sea and this could be a continuation of its southern distribution in August along 170° E. previously noted (Section V(*b*)).

The West Central South Pacific water mass was found at about 80 per cent. of its postulated value relative to the other components of Figure 10*B* east of 150° W. between latitudes 10 and 15° S. A broad stream of this water mass extended south-west into the Coral and Tasman Seas, between latitudes 21 and 33° S., and in isolated instances along its path its chlorinity and temperature indicated a composition of 75 per cent. West Central South Pacific and 25 per cent. South Equatorial water. The high-temperature, high-chlorinity water mass (1A, Fig. 8.4) was found around 180° E. north of about 10° S. It also occurred in isolated portions in the northern Coral Sea.

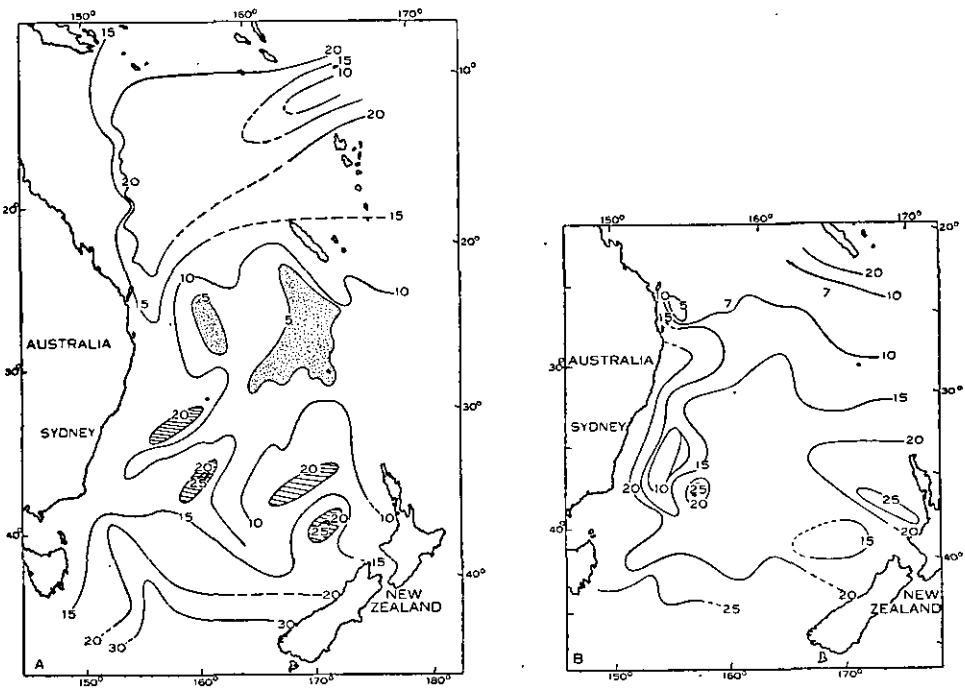

Fig. 11.—The mean December distribution of total phosphorus, from the data sources of Plate 2. *A*, surface; *B*, 100 m.

The Sub-Antarctic component was found in smaller quantities at the surface except along the east Australian coast. At 100 m (Plate 2) the South Equatorial component was absent from the Tasman Sea south of latitude about 25° S. The West Central South Pacific water mass was strongly represented to the north of about 32° S. and decreased in concentration regularly southward where the Sub-Antarctic component dominated.

VI. Distribution of Surface Total Phosphorus

Rochford (1958) has examined the conservatism of total phosphorus in the Coral and Tasman Seas, and despite certain anomalies in this respect considered that it could be used as an identifying property of oceanic water masses. The

relationship between the mean August and December distributions of the total phosphorus and the water mass composition for the same months (Figs. 8*A*, 10*A*) was examined to provide supplementary evidence of the proposed tripartite water mass structure of Tasman and Coral Seas surface waters (Section V).

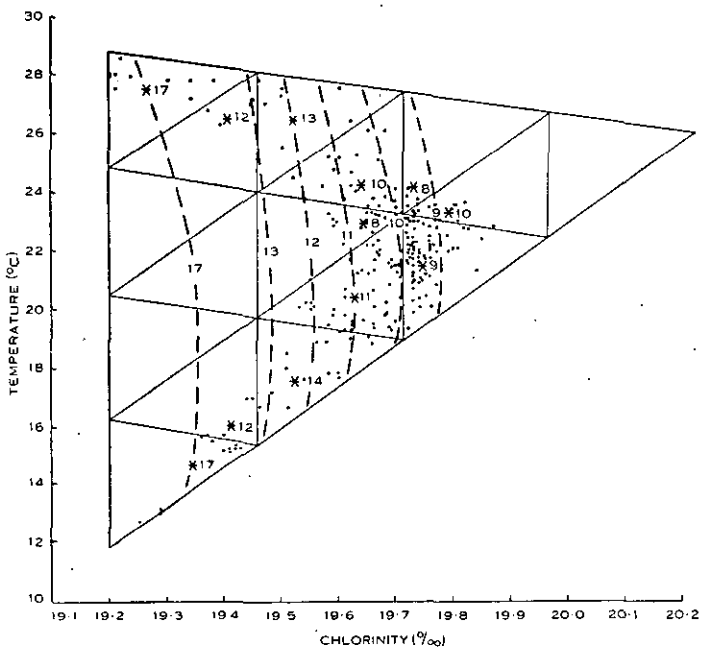

Fig. 12—A division of the chlorinity-temperature data (●) of waters of Figure 11, into sub-areas of Figure 10*B*. At the centre of gravity of these data (★) mean total phosphorus values of the sub-areas have been entered and contours drawn with due allowance for frequency of observations.

(*a*) *December*

Distribution in this month is considered first because of more numerous data. Figure 11*A* shows that total phosphorus was found at the surface in increasing concentrations north and south of a minimum zone between 25 and 30° S. This corresponds closely to the distribution of the South Equatorial and Sub-Antarctic components, north and south of the region of maxmum occurrence of the West Central South Pacific water mass (Plate 2).

At a depth of 100 m the distribution of total phosphorus (Fig. 11*B*) paralleled that of the two water masses at the same depth (Plate 2), although there were anomalies east of Sydney and south of New Caledonia. An estimate of the total phosphorus value of each of the three external water masses based upon its observed distribution in relation to water mass structure in August and December was made using the following four steps:

(i) The December mixing triangle (Fig. 10*B*) was divided into 16 triangular sub-areas of equal size (Fig. 12).

(ii) The December chlorinity-temperature data were then plotted onto the mixing triangle and the mean total phosphorus of all values within each of the smaller triangles calculated.

(iii) The centre of gravity of the points within each smaller triangle was then visually estimated, and the mean total phosphorus for that triangle plotted on this centre.

(iv) A contour plot of these mean values was then made to show the total phosphorus to water mass composition relationship (Fig. 12).

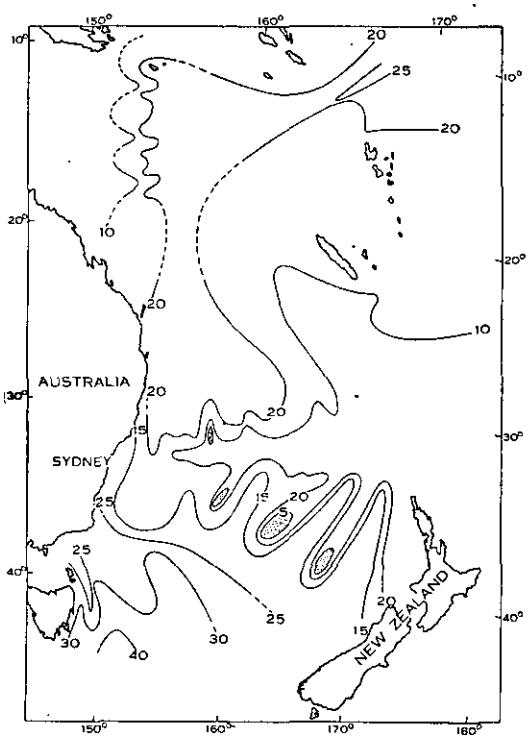

Fig. 13.—The mean August distribution of total phosphorus at the surface, from the data sources of Plate 1.

The contour distribution in Figure 12 indicates that the South Equatorial and Sub-Antarctic water masses in December had total phosphorus values approaching 20 μg/l. whilst the West Central South Pacific value probably was of the order of 3–5 μg/l.

(*b*) *August*

In this month the surface distribution of total phosphorus (Fig. 13) in general paralleled that of the water masses (Plate 1), except for a series of very low values of total phosphorus between Sydney and Wellington. By a similar method to that in Section VI(*a*) a contour plot of the total phosphorus to water mass composition was prepared for the August data (Fig. 14). As there are many less data in this

month than December the accuracy of the contouring is reduced. Within these limitations Figure 14 shows that the total phosphorus contents of the South Equatorial and West Central South Pacific water masses were very similar to the December values, but that the August value of the Sub-Antarctic water mass was higher.

Table 2 summarizes the properties of the three primary external water masses of the Tasman and Coral Seas which have been considered in this Section. A total phosphorus value of 30 μg/l. has been tentatively assigned to the winter Sub-

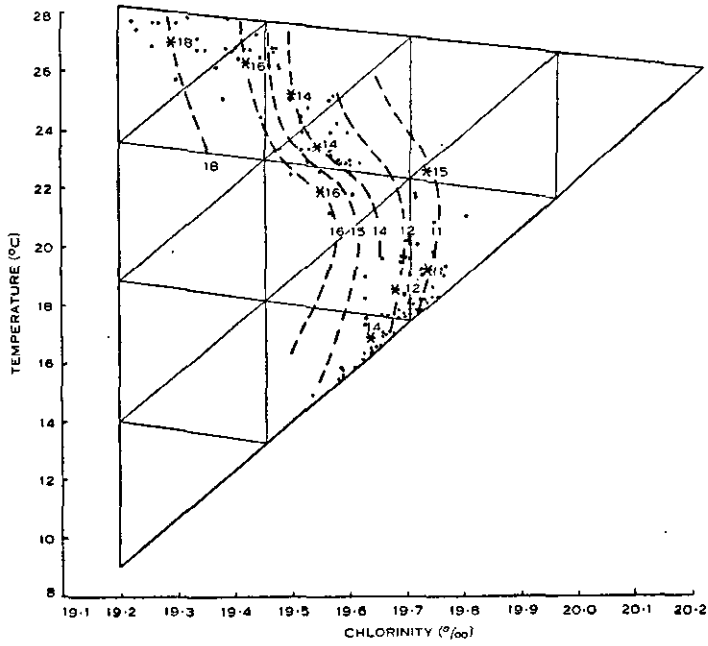

Fig. 14.—An analysis of the August total phosphorus data according to the method used in Figure 12.

Antarctic component. The total phosphorus values of the major external water masses were similar for August and December (Table 2). This is additional evidence in support of the separate existence and paths of movement of these external water masses (*Plates 1, 2*).

VII. The Seasonal Circulation of the Principal Surface Water Masses of the Tasman and Coral Seas

Although a balanced picture of the surface circulation of this region must await direct measurements of the transport volumes through the various entrances where exchange of water occurs, some general features can be postulated from the curves of surface characteristics discussed in Section III, from the source regions of the external water masses in Section IV, and from the analyses of water mass composition in Section V.

In this section the information on surface and mid-depth circulation for the quarters August–October and November–January is collated. Less data are available for the other quarters, and only very general indications of the surface circulation based upon the seasonal transformation of the mean curves of surface characteristics of Section III can be demonstrated for February–April and May–July.

TABLE 2

THE TOTAL PHOSPHORUS LEVELS OF THE MAJOR EXTERNAL WATER MASSES OF THE TASMAN AND CORAL SEAS

Water Mass	Month	Chlorinity (‰)	Temperature (°C)	Total Phosphorus	
				(μg/l.)	(μg at./l.)
South Equatorial	Aug.	19·20	28·8	20	0·65
	Dec.	19·20	28·2	20	0·65
West Central South Pacific	Aug.	20·22	26·00	3–5	0·097–0·16
	Dec.	20·22	26·00	3–5	0·097–0·16
Sub-Antarctic	Aug.	19·20	9·00	30	0·97
	Dec.	19·20	11·8	20	0·65

(*a*) *August–October* (Plate 3)

In this period the circulation appears to be largely zonal with minimal meridional movement. In the extreme north there was a very strong westward flow of South Equatorial waters, which extended well into the Coral Sea. This flow was bounded to the north by high chlorinity water (1A of Fig. 8*A*). South of New Caledonia there was a strong westerly flow of the West Central South Pacific water mass into the Coral Sea with a minor branch flowing south-west, between Norfolk Island and New Zealand into the Tasman Sea. Associated with this latter flow was a mid-depth movement of the North New Zealand water mass (2A of Fig. 10*A*) which rose to the surface west of longitude 160° E. In this region it mixed with sufficient Sub-Antarctic water to form the South-west Tasman water mass. Prior to this the Central Tasman water mass had been formed by dilution with the Sub-Antarctic water mass. Both of these derived water masses flowed to the north but only the latter extended north of latitude 37° S. Along the east Australian coast south of latitude 23° S. there was a slight meridional flow of South Equatorial waters which became progressively mixed with the West Central South Pacific water mass as they moved eastward in latitude 30° S.

(*b*) *November–January* (Plate 4)

In this quarter the flow pattern was almost entirely meridional with zonal flow only found to the west in about 25° S. and to the east in latitude 35–45° S. The tropical high chlorinity water (1A of Fig. 8*A*) was found to the east of its

position in the previous quarter. The South Equatorial water mass, entering the Coral Sea between the New Hebrides and the Solomon Islands, divided into two branches of which the western flowing south-west to the Queensland coast was the major. As it moved southwards this branch mixed with greater quantities of the West Central South Pacific water mass and formed the Coral Sea water mass which arrives off Sydney in October–December of each year (Rochford 1957). This latter water mass flows south-east into the southern Tasman Sea on a broad front. The other branch of the South Equatorial flow moved south along the longitude about 170° E. and introduced semi-tropical waters into the western and possibly eastern sides of North Island, N.Z.

The Arafura Sea water mass occupied the north-west corner of the Coral Sea in this quarter. Compared with conditions in August–October the entry of this water mass and the position of 1A (Fig. 8*A*) indicate a general eastward drift in this region during November–January. The South Equatorial flow into the Coral Sea can be reconciled with such a drift only if a separate branch were involved in this quarter.

The broad distribution of the West Central South Pacific water mass in the middle latitude belt was probably brought about by the zonal flow in the previous quarter. Associated with this water mass was a mid-depth zonal distribution of the North New Zealand water mass, at more northern latitudes than in the previous quarter. The south-east Tasman Sea was dominated by a "warmed" Sub-Antarctic water mass lying to the north of the true subtropical convergence. Along the route of the line AB (Plate 4) Sub-Antarctic dominated waters extended north-east to the maximum extent. The region centred around Norfolk Island where the Sub-Antarctic component (3 of Fig. 10*B*) was at a maximum in the surface layers could be associated with this extension.

(*c*) *February–April*

The change in shape of the mean curve of surface characteristics (Fig. 6) from the previous quarter is interpreted as follows:

(i) The Arafura Sea water mass continued to flow into the north-west Coral Sea.

(ii) South Equatorial waters were present in similar proportions to those of the previous quarter.

(iii) In the southern Tasman Sea the effect of the East Central New Zealand water mass was at a maximum.

(*d*) *May–July*

In this quarter the shape of the curve of surface characteristics (Fig. 6) indicates that these changes have occurred since the previous quarter:

(i) The Arafura Sea water mass was absent from the Coral Sea.

(ii) A secondary branch of the higher temperature portion of the curve indicates that strong vertical mixing occurred during this quarter. This mixing seems most pronounced along a zone between 20 and 25° S.

(iii) The maximum chlorinity on the curve of surface characteristics is explained by a strong influx of the West Central South Pacific water mass into the northern Tasman Sea during this period. It could, however, be a local evaporation change (Section III(*e*)).

(iv) In the southern Tasman Sea whilst the East Central New Zealand water mass was still present, the influence of the winter water masses upon the characteristics of this region was increasing.

TABLE 3

SURFACE CHARACTERISTICS OF MAJOR AND MINOR EXTERNAL WATER MASSES OF THE TASMAN AND CORAL SEAS

Water Mass	Temperature (°C)	Chlorinity (‰)
Major		
South Equatorial	28·2–22·8	19·20
West Central South Pacific	26·0	20·22
Sub-Antarctic	9·0–11·8	19·20
Minor		
Arafura	28–29	18·90 or less
Tropical high chlorinity (1A)	29–30	19·70
Temperate high chlorinity (2A)	20–21	20·20 or more

VIII. Discussion and Conclusions

Sverdrup, Johnson, and Fleming (1942), discussing salinity distribution, are of the opinion "that transport by ocean currents is of minor importance as far as average conditions are concerned", but that "the difference between evaporation and precipitation is of primary importance". Jacobs (1951), on the other hand, from a study of more recent data for the North Pacific and Atlantic considers "that the transport factor is of considerable importance with reference to the local values of the surface salinity".

Unfortunately data similar to that used by Wyrtki (1957) in his calculation of precipitation, evaporation, and energy exchanges at the surface of the south-east Asian waters are not available in sufficient detail for the Tasman and Coral Seas. It has therefore not been possible in these waters to assign an order of magnitude to the advective and energy changes. On the assumption that the energy changes are smaller than the advective changes, a circulation hypothesis, based upon the 1955–56 chlorinity-temperature data and supported by total phosphorus data, has been put forward as a first approximation for future critical examination.

On this assumption the following conclusions have been drawn:

(i) The surface characteristics of the Tasman and Coral Seas can be described in terms of three major and three minor external water masses (Table 3).

(ii) It has been found that the total phosphorus content of the West Central South Pacific water mass is very low compared with the other water masses present (Table 2).

(iii) The Coral Sea water mass (Rochford 1957) is now considered as a mixture of the South Equatorial and West Central South Pacific water masses rather than an evaporated derivative of the South Equatorial alone.

(iv) During August–October the major path of entry of the South Equatorial water mass is between the New Hebrides and the Solomon Islands.

(v) During August–October the major path of entry of the West Central South Pacific water mass is between New Zealand and New Caledonia.

(vi) During January–May the North New Zealand water mass enters the Tasman Sea between New Zealand and New Caledonia, at intermediate levels.

(vii) The South-west Tasman and the Central Tasman water masses of the southern Tasman Sea are formed by mixing between the North New Zealand and Sub-Antarctic water masses.

IX. Acknowledgments

The Merchant Navy officers responsible for the collection of surface samples in the Coral and Tasman Seas during 1955–56 are thanked for their generous cooperation.

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EXPLANATION OF PLATES 1–4

Plate 1.—The mean August distribution at the surface of the percentage mixture of the three external water masses of Figure 8*B*. The extent of the Tasman and Coral Seas affected by water masses 1A and 2A of Figure 8*A* are shown.

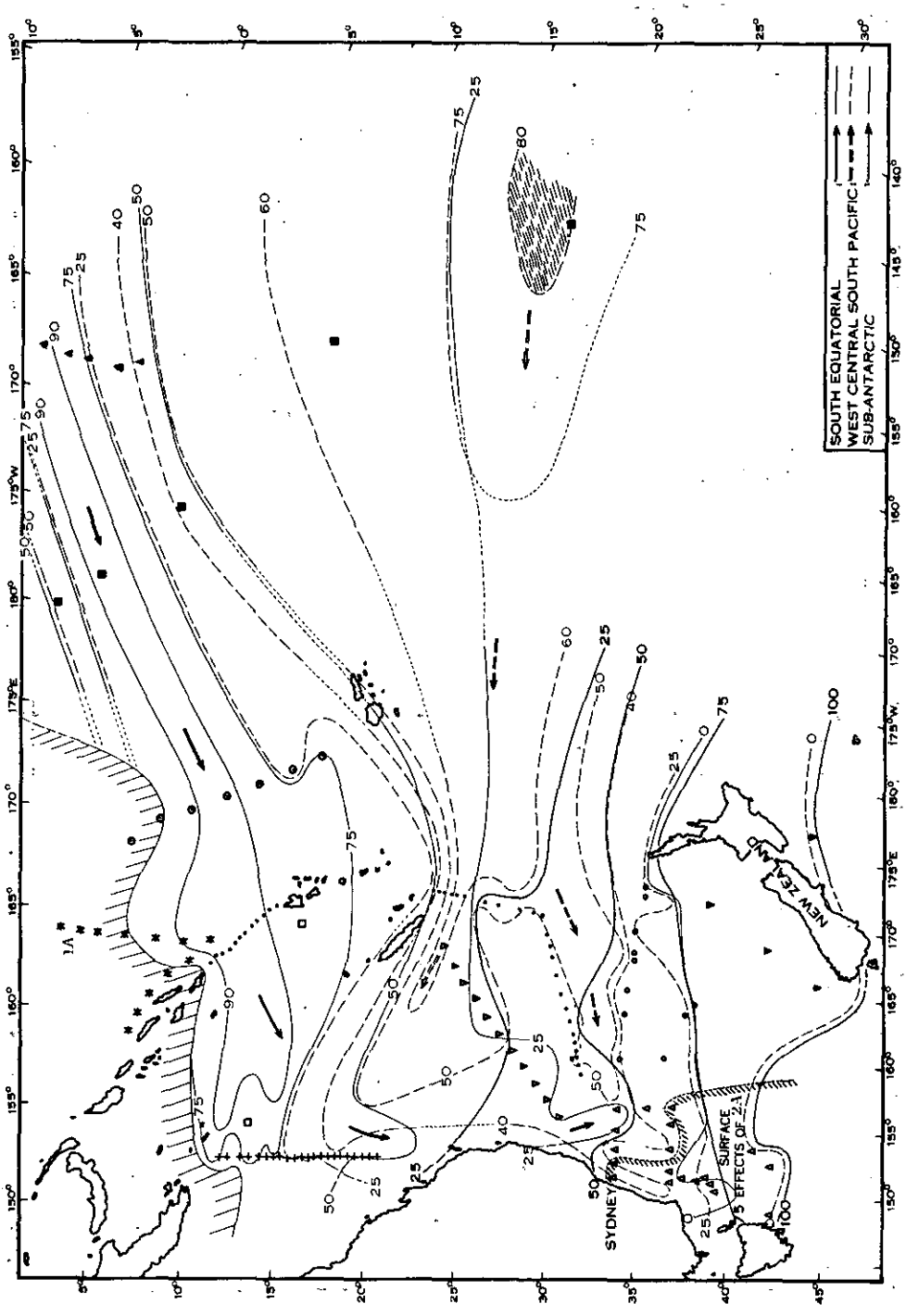
○ *Shoyo-maru*, August 1956; ★ *Horizon*, August 1956; ▽ *Tahitien*, August 1957;
○ *Wanganella*, August 1956; ▲ *Stranger*, August 1956; ● *Tulagi*, August 1956;
▼ *Discovery II*, July 1932; + *Malaita*, August 1956; □ *Planet*, July 1905;
△ *Derwent Hunter*, August 1955; ■ *Daifujimaru*, August 1956.

Plate 2.—The mean December distribution at the surface of the percentage mixture of the three external water masses of Figure 10*B*. The southern water mass of 1A of Figure 10*A* is given. *Inset*: The percentage water mass composition in December at 100 m.

Derwent Hunter: △ December 1954; ▽ Nov.–Dec. 1955; ▲ Dec. 1956–Jan. 1957;
● *Tulagi*, December 1955; + *Malaita*, December 1955; ★ *Dana*, Oct.–Dec. 1928.

Plate 3.—The mean August and October distribution at the surface of the external water masses and of their derivatives in the Tasman and Coral Seas. Lines of percentage composition have been taken from Plate 1. The arrows show the probable dominant direction of movement during or immediately preceding this quarter. Groupings of these arrows indicate regions of mixing between these water masses. — – — – (red) indicates the northern limits of water mass 2A.

Plate 4.—The mean November–January distribution at the surface of the external water masses and of their derivatives in the Tasman and Coral Seas. Plotting symbols as for Plate 3. — – — – (red) indicates the limits of water mass 2A; — — — indicates the source region of the Coral Sea water mass.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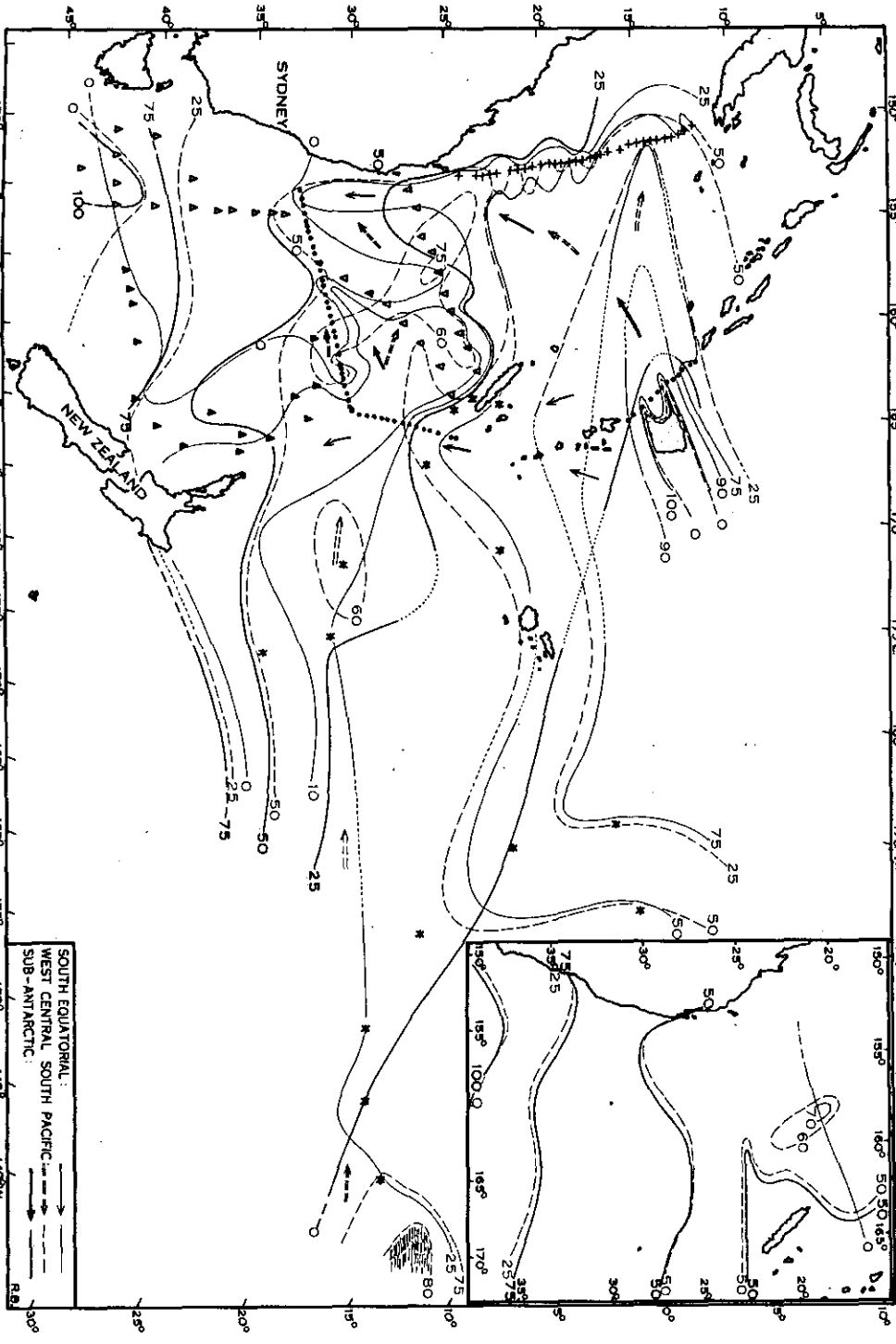
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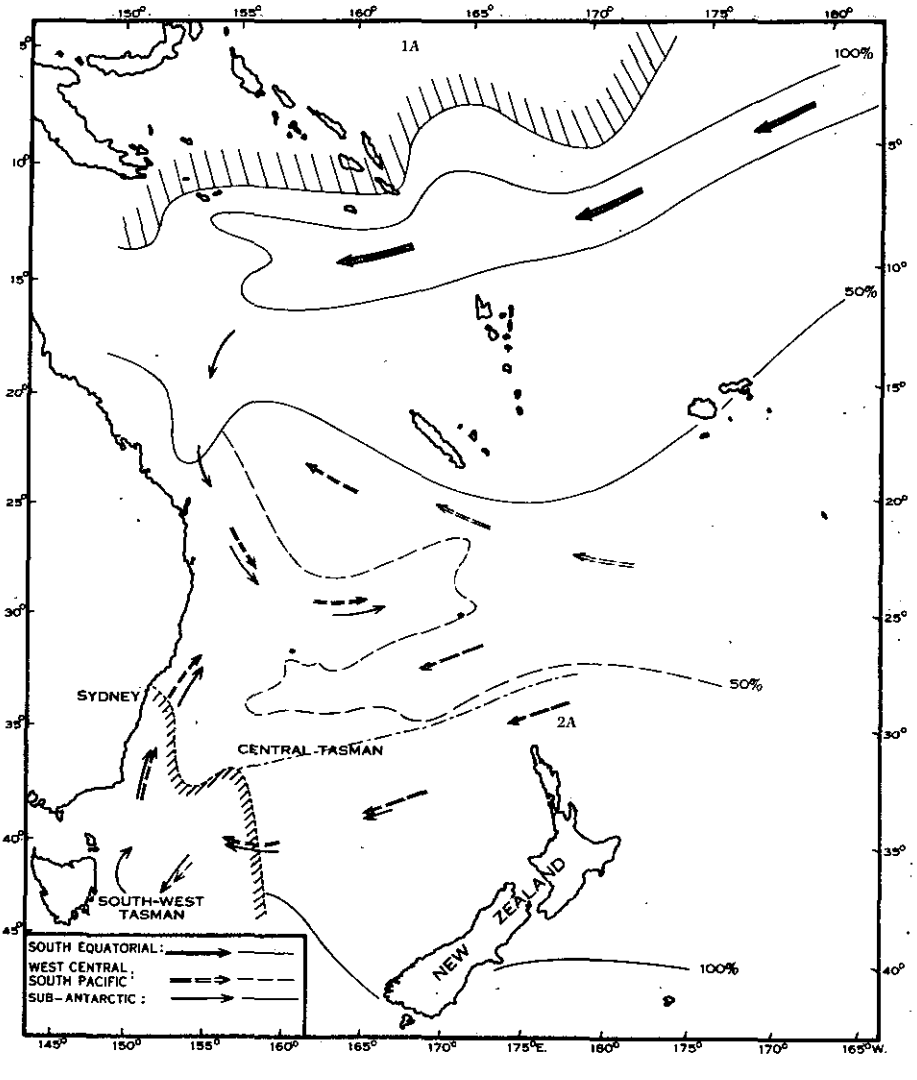
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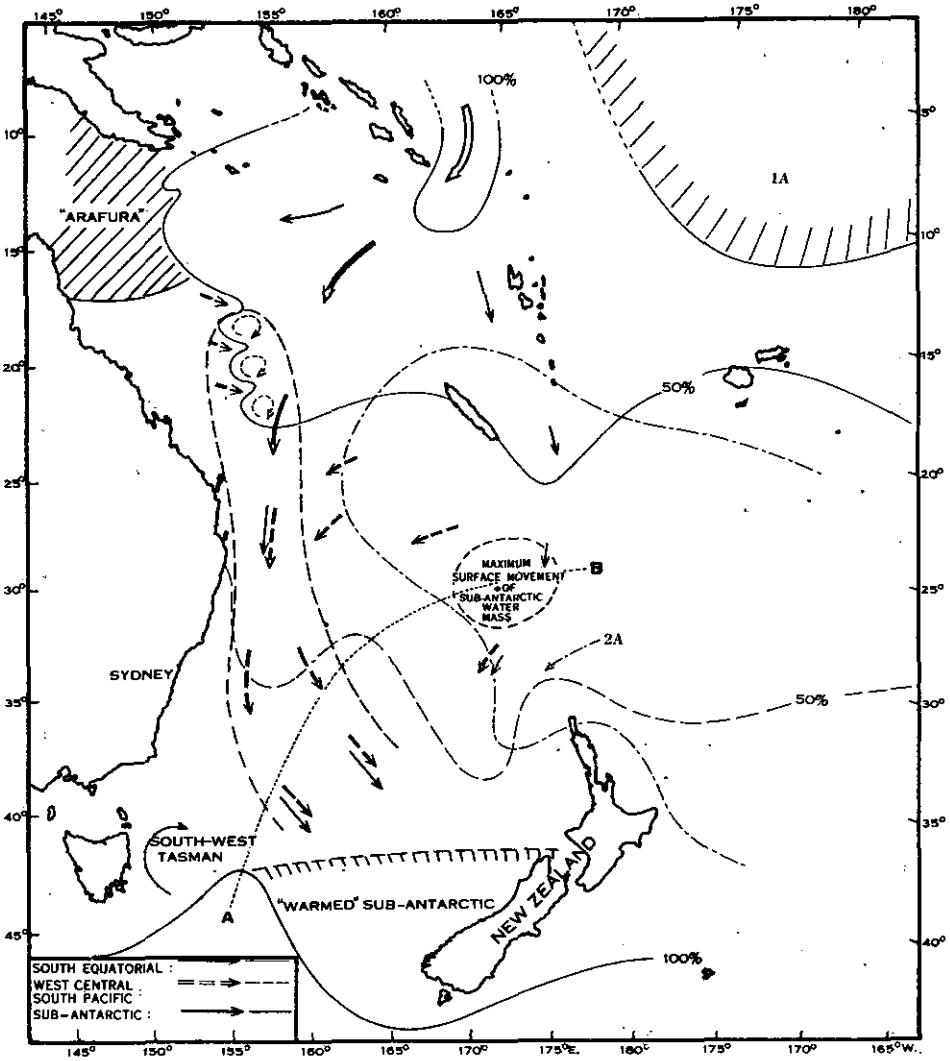
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