The Surface Circulation in the Coral and Tasman Seas

By K. Wyrtki

Division of Fisheries and Oceanography
Technical Paper No. 8

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CORRIGENDA

"The Primary External Water Masses of the Tasman and Coral Seas"
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Page 12, line 3: *For* occasional change *read* its seasonal change.

Page 13, Figure 8A, caption: *For* The curve 1A refers to the North New Zealand water mass *read* The point 1A refers to the tropical high chlorinity water mass (Table 3).

Page 16, Figure 10A, caption: *For* Curve 2A is characteristic of the high temperature, high chlorinity waters in the extreme north of the Coral Sea *read* Curve 2A is characteristic of the temperate high chlorinity water mass.

Page 26, Table 3, column 2, line 1: *For* 28.2–22.8 *read* 28.2–28.8.

THE SURFACE CIRCULATION IN THE CORAL AND TASMAN SEAS

By K. WYRTKI*

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Summary

Monthly charts of surface currents and streamlines have been prepared from ships' observations for the waters to the east of Australia between 5 and 48° S., 142 and 180° E. The seasonal variations of the different current branches, their interactions, and their role in the general circulation are discussed. The positions of the Subtropical Convergence and of the Tropical Convergence were determined. An area of divergent movements and upwelling exists as a permanent feature in the Coral Sea. The observed departure of the East Australian Current from the coast of New South Wales south of 32° S. was also confirmed as a permanent phenomenon, being related to a divergent flow pattern. When strong southerly winds blow the East Australian Current is accompanied by a counter-current, or vanishes completely. Regions of divergence and convergence have been investigated, and it is shown that the surplus of inflow into this region is almost balanced by the sinking in the two convergences.

I. Introduction

Charts of the surface circulation in the oceans form the basis for the consideration of the distribution of many properties. For the waters to the east of Australia such presentations exist in the current atlases published by the United States Navy Hydrographic Office (1954), the Royal Dutch Meteorological Institute (Nederlands Meteorologisch Instituut 1949), and the British Meteorological Office (Great Britain. Meteorological Office 1938); but these atlases give a presentation of statistical material for the use of navigators rather than an analysis of the circulation as required by the scientist. Such an analysis is given by Schott (1935, 1942) only for larger parts of the oceans, including the area discussed in this paper, and only for the summer and winter seasons.

Consequently, a more detailed analysis of the surface circulation and its annual variations in the Coral and Tasman Seas seems to be desirable for the future study of the oceanographic conditions in the region. The area covered by this study is bounded by 5 and 48° S., and 142 and 180° E., thus excluding the South Equatorial Current in the north and the Circumpolar Current in the south. In this area the land barrier formed by New Guinea and Australia forces the Trade Drift to turn south and leads to the formation of the East Australian Current. When this current meets the water masses of the West Wind Drift, the Subtropical Convergence is formed between Tasmania and New Zealand.

The presentation of the surface currents of this region is not limited to the drawing of charts of the average current arrows for every month, but an analysis of the circulation is given in streamline charts. These streamline charts provide

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material for investigating the convergences and divergences of the surface flow and allow conclusions to be drawn on the structure of the water masses in the upper layer.

II. Construction of the Current Charts

For the construction of the charts the current vectors for 1° squares and for every month have been used, as given in the atlases of the United States Navy Hydrographic Office and the Royal Dutch Meteorological Institute. The atlas of the British Meteorological Office, giving current vectors for the four seasons and for "squares" of 2° of latitude and 4° of longitude, has been used only for comparison. The Dutch atlas consists of observations made by Dutch (66 per cent.), German (21 per cent.), English (10 per cent.), and other (3 per cent.) merchant ships, and all observations have been used to compile the average current vectors. The American atlas, on the other hand, consists only of observations from American ships prior to 1935, but all observations have been omitted where wind, sea, or swell of force 6 or above were recorded. By this method approximately 10–20 per cent. of the observations are omitted in lower latitudes (compare Table 1) and up to 40 per cent. in the stormy west wind region south of 40° S.

These different methods of selecting the observations for presentation have given a completely different appearance to the charts presented in the two atlases. In the American atlas the current vectors form a rather uniform pattern and give, at least in the areas where sufficient observations are available, a fairly consistent picture of the circulation. In the Dutch atlas, on the other hand, the scattering of the observations is considerable even in regions with a uniform current character, and almost all directions of currents appear. The main direction of the flow in a certain area can often only be found by consulting the current roses which accompany the current vector charts. Therefore, the American atlas has been used as a basis for the construction of the current charts and the observations shown in the Dutch atlas have served only in regions where the number of observations is small in the American atlas, or for comparison.

As discussed by the author in an article describing the principles of presenting ocean currents (Wyrtki 1960), the vector averages of current observations cannot be considered as representative components of the circulation because they consistently give too small values for current velocities. Consequently, the average velocities in the most frequent direction are used in the current charts (Figs. 1(*a*)–12(*a*)). In determining these components, the current roses in the Dutch atlas have been widely used. The currents are shown by arrows of equal length which are arranged to cover the area most effectively. The velocity is indicated in steps of 3 nautical miles per day. The arrow for 3 miles per day is also used in cases where tidal currents are prevailing, or where the observations were too scanty or the direction too variable to draw conclusions. No mention of the stability of the currents is made in the charts; for this, the current roses of the Dutch atlas must be consulted, but it can be said that the variability is normally high, even in the more strongly developed current systems. A high stability is found only in the northern parts of the Trade Drift and in the East Australian Current.

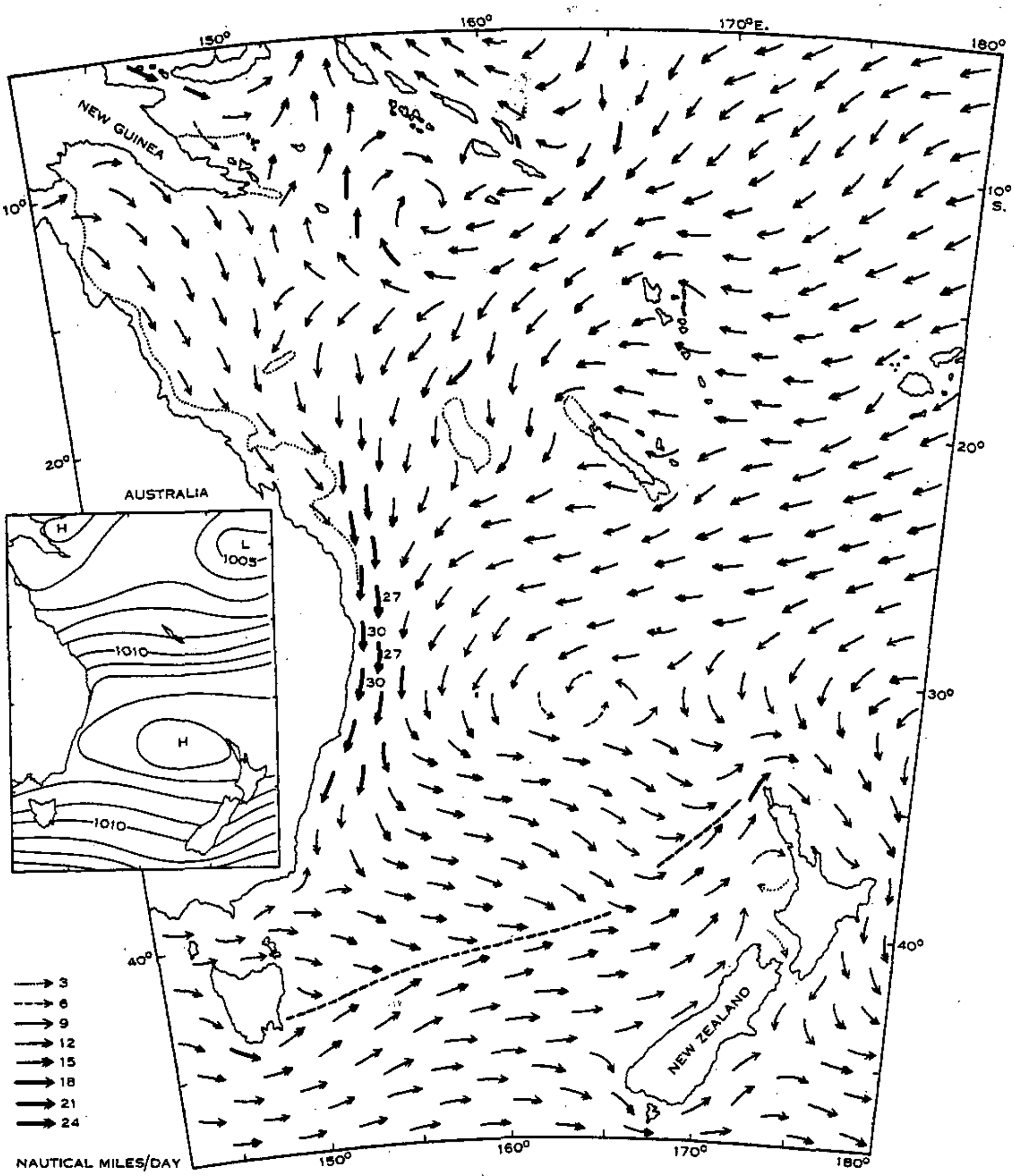

Fig. 1(*a*).—Surface currents in the Coral and Tasman Seas in January. Inset map shows distribution of atmospheric pressure.

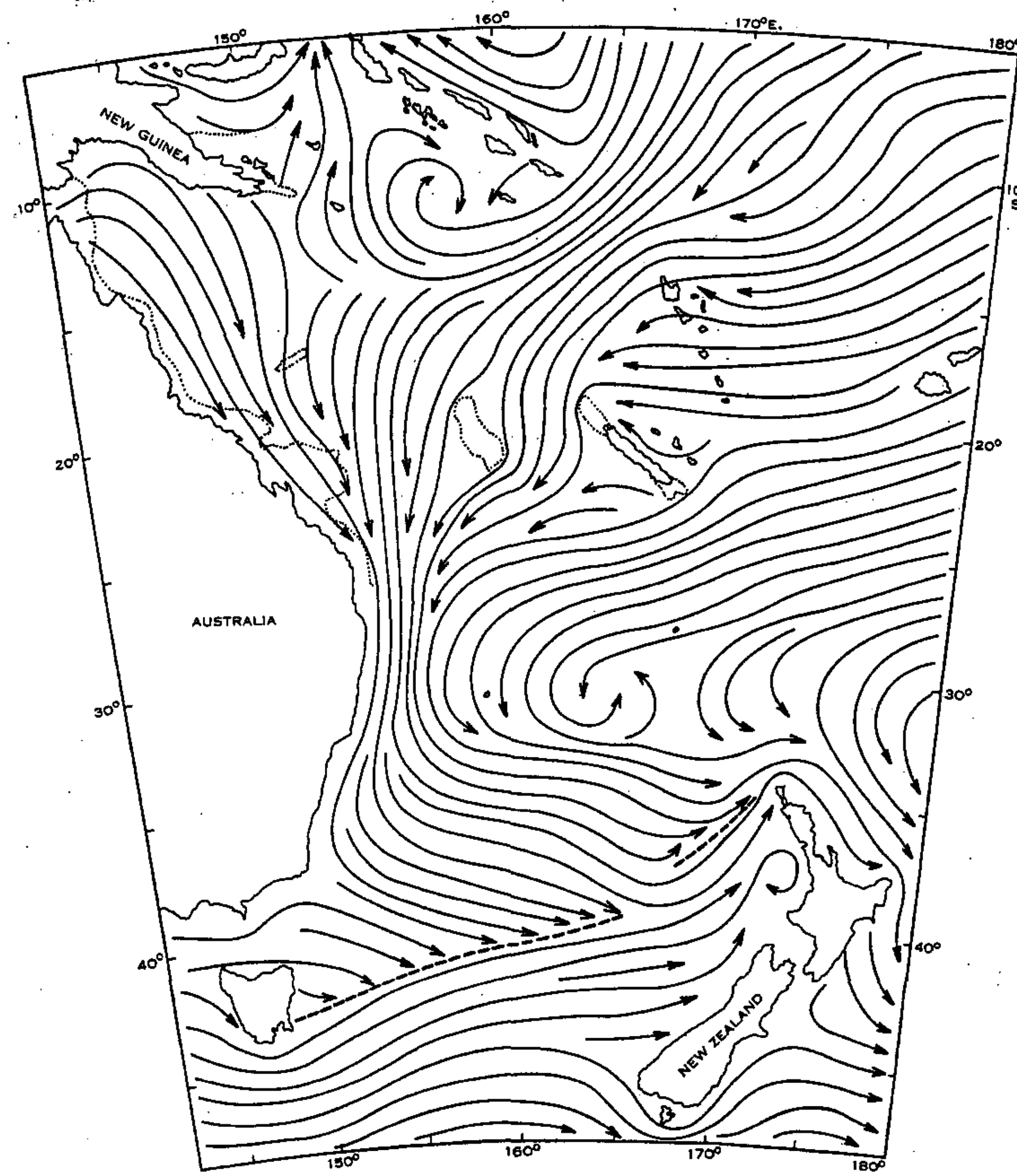

Fig. 1(*b*).—Streamlines of the surface circulation in the Coral and Tasman Seas for January.

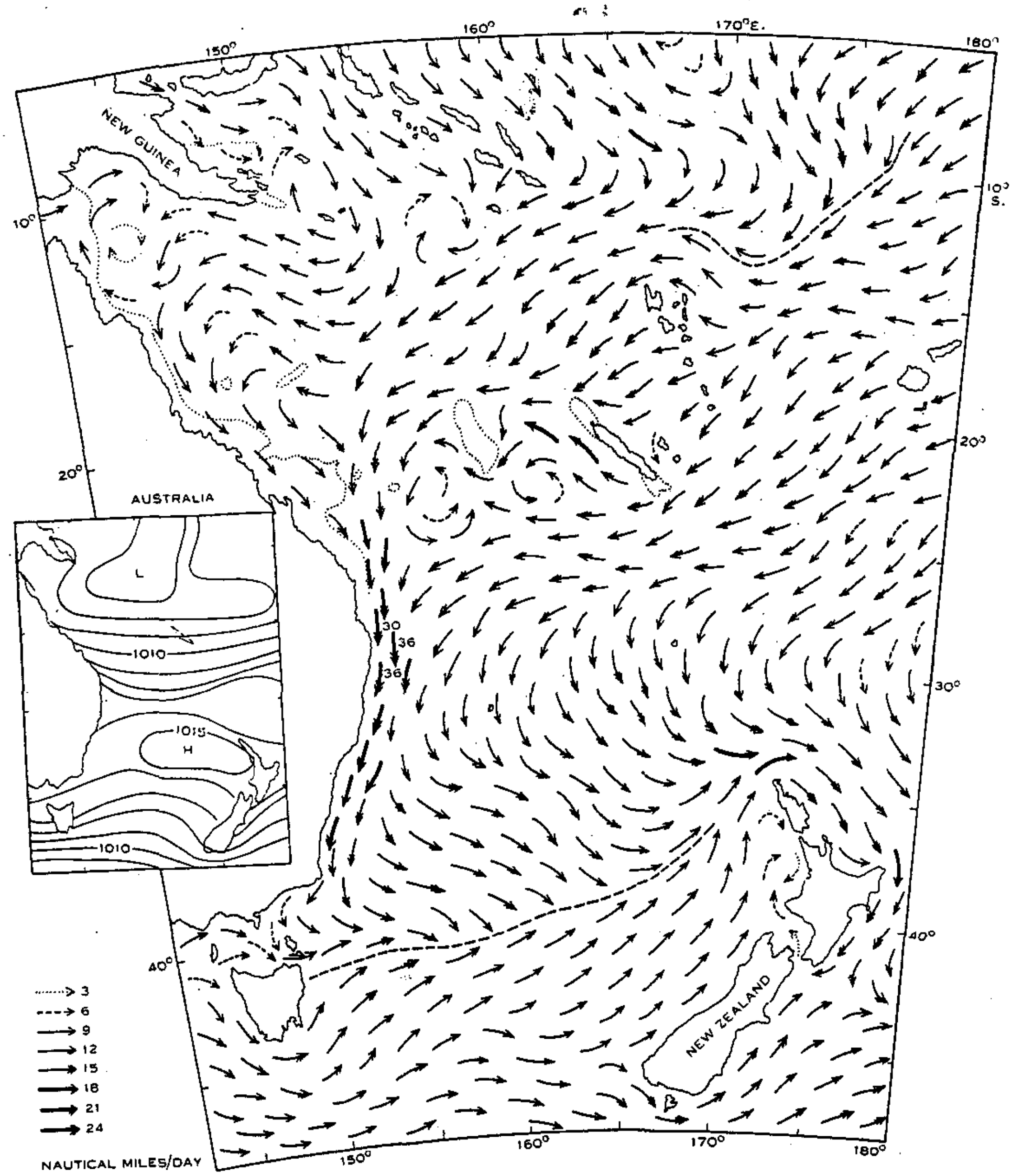

Fig. 2(*a*).—Surface currents in the Coral and Tasman Seas in February. Inset map shows distribution of atmospheric pressure.

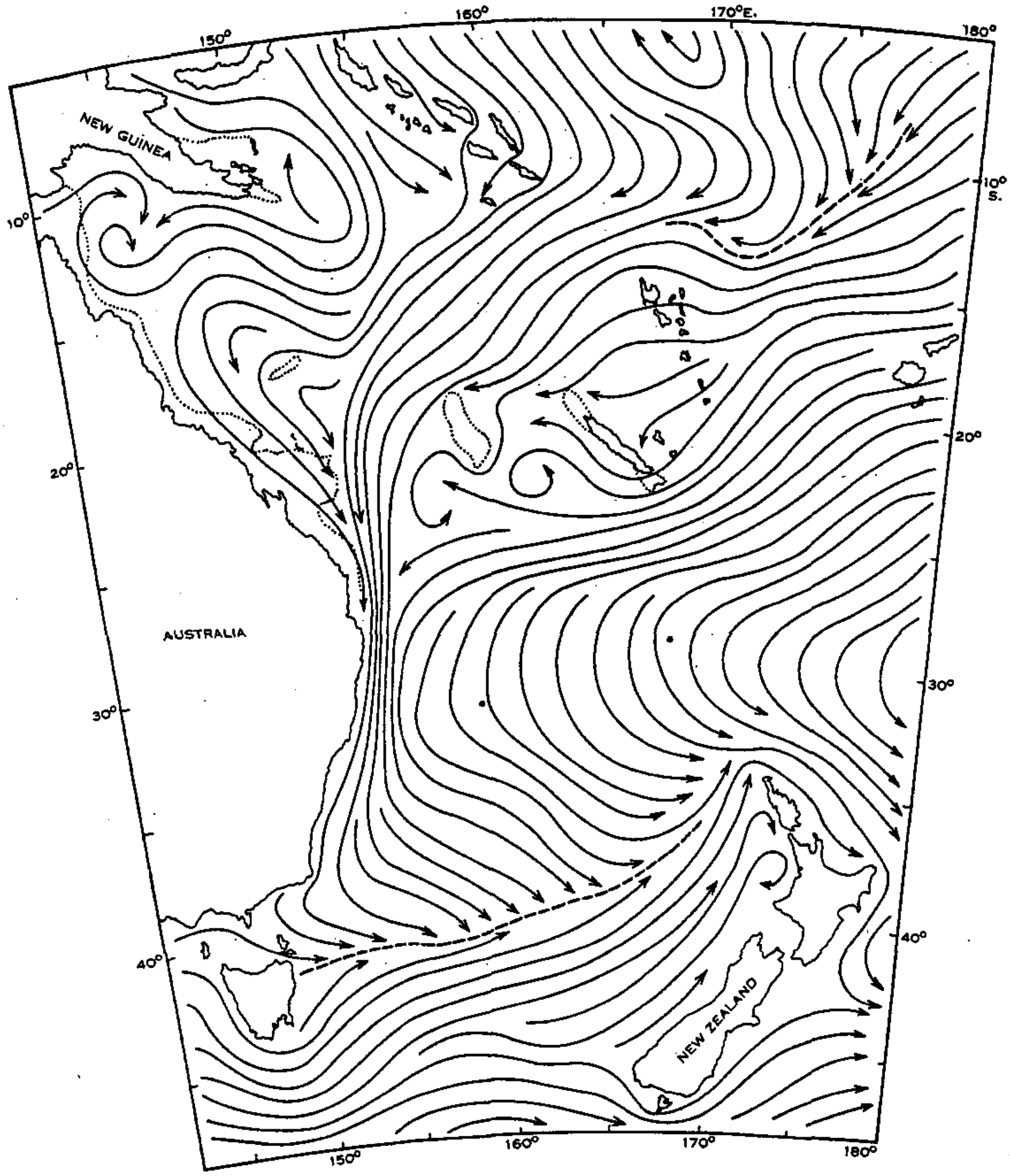

Fig. 2(b).—Streamlines of the surface circulation in the Coral and Tasman Seas for February.

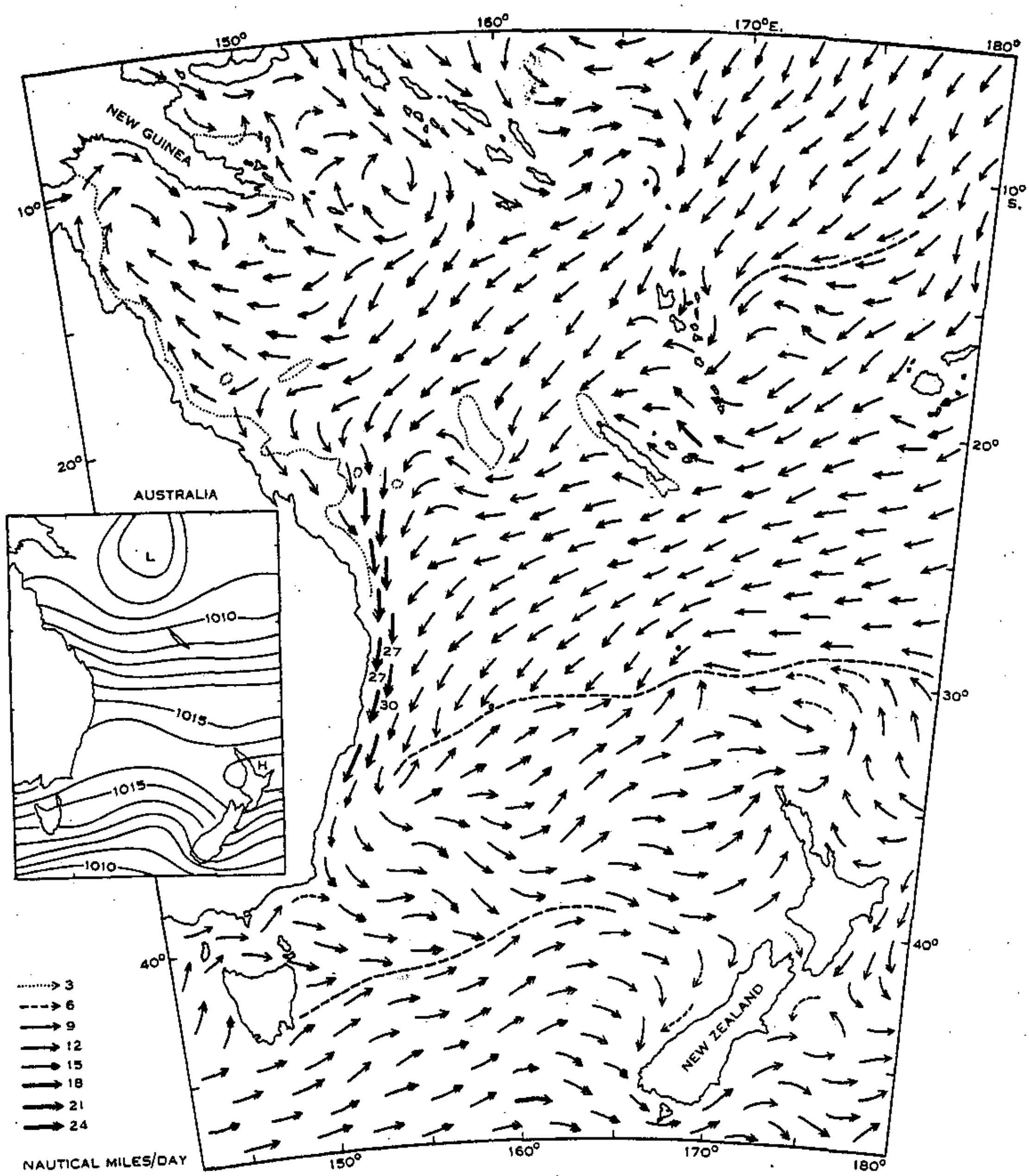

Fig. 3(a).—*Surface currents in the* Coral and Tasman Seas *in* March. Inset map shows distribution of atmospheric pressure.

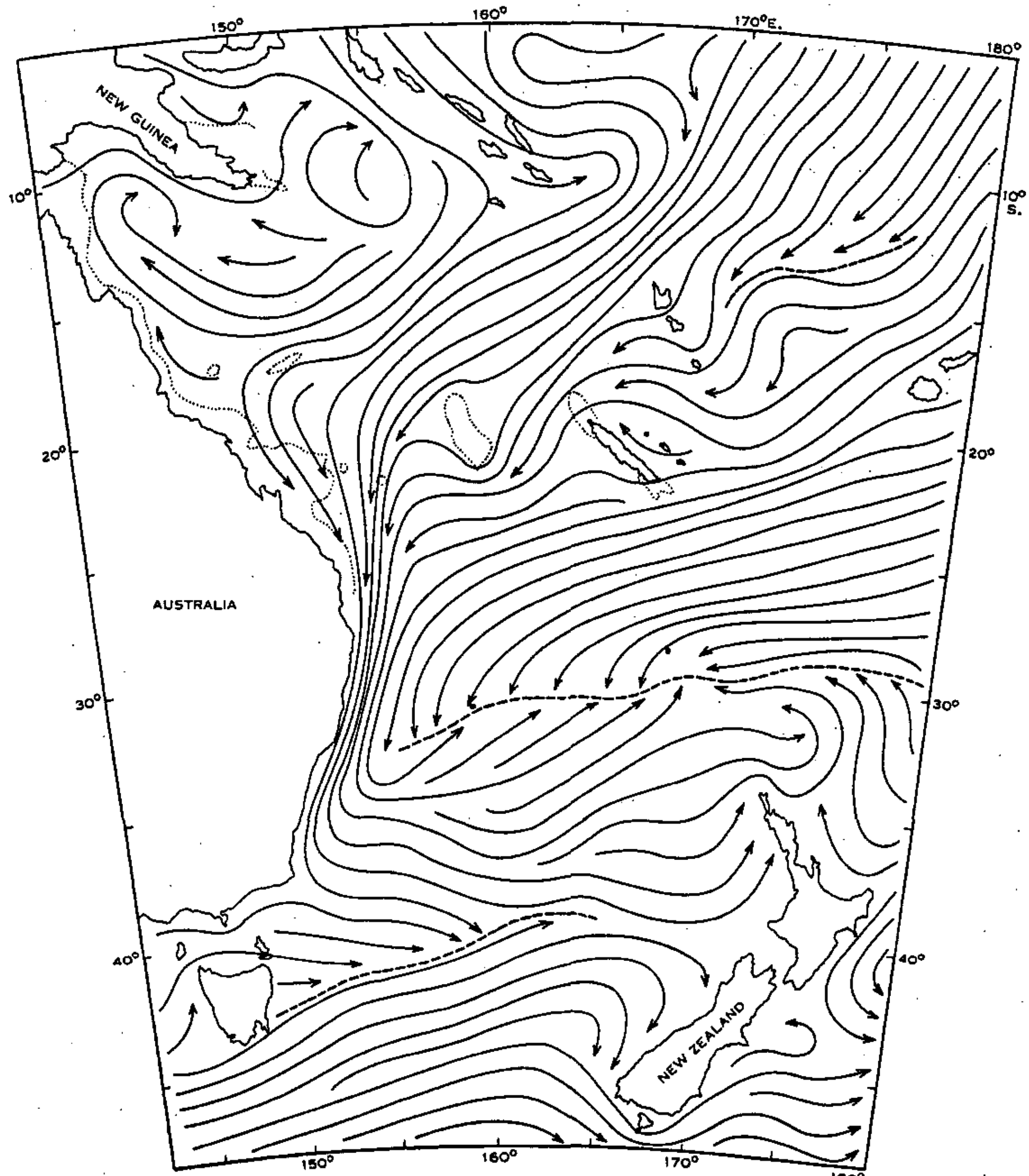

Fig. 3(b).—Streamlines of the surface circulation in the Coral and Tasman Seas for March.

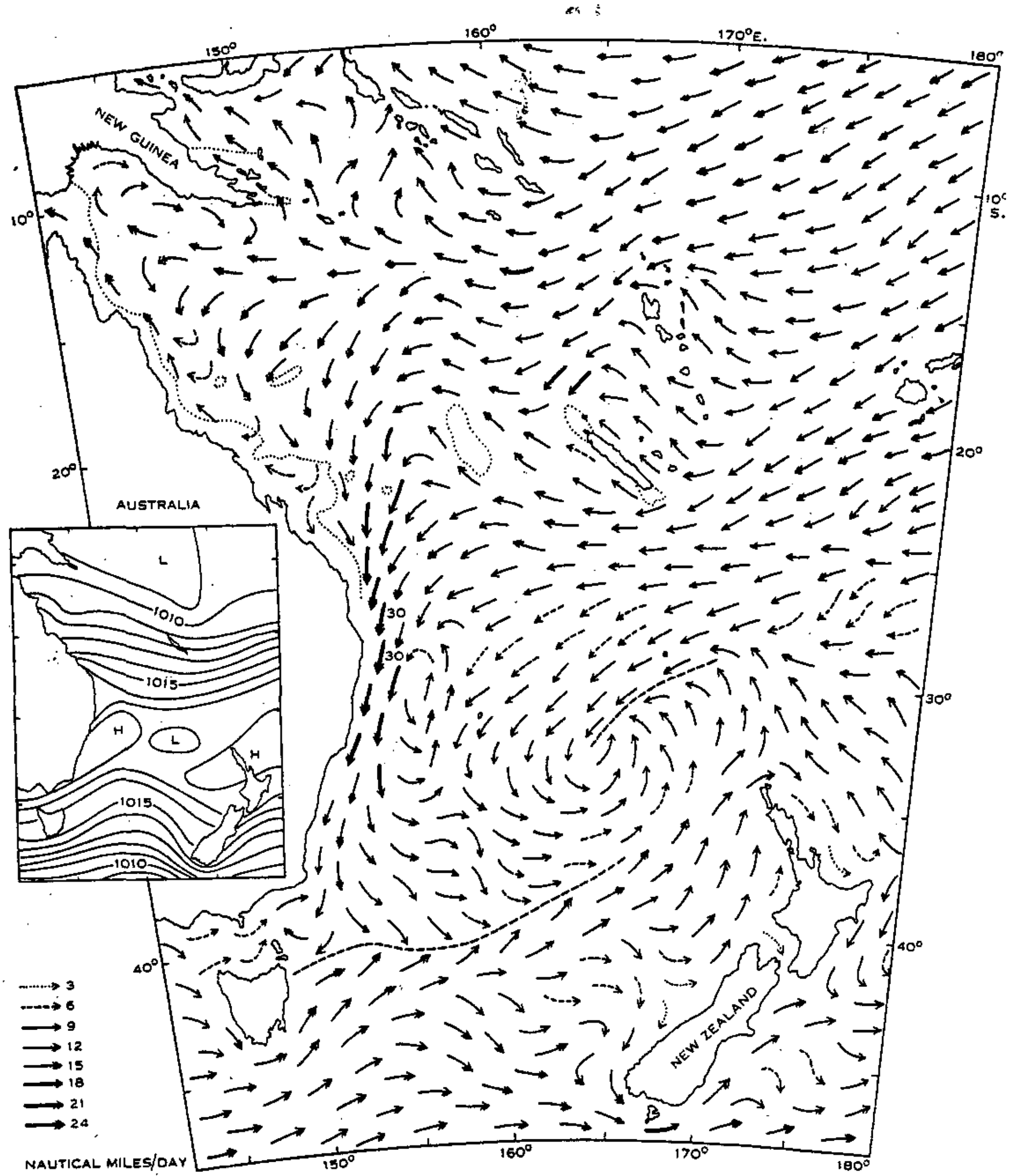

Fig. 4(a).—Surface currents in the Coral and Tasman Seas in April. Inset map shows distribution of atmospheric pressure.

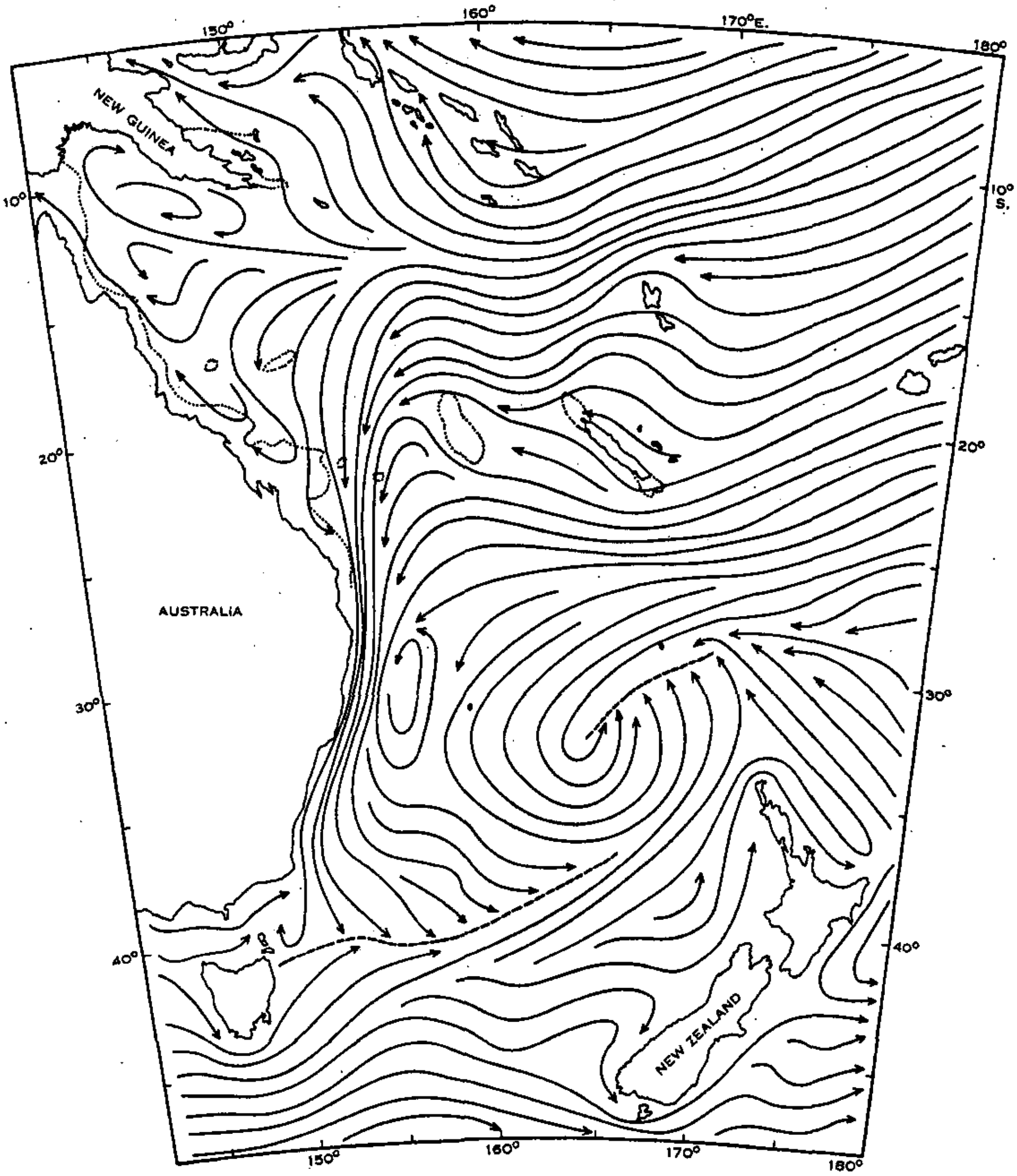

Fig. 4(b).—Streamlines of the surface circulation in the Coral and Tasman Seas for April.

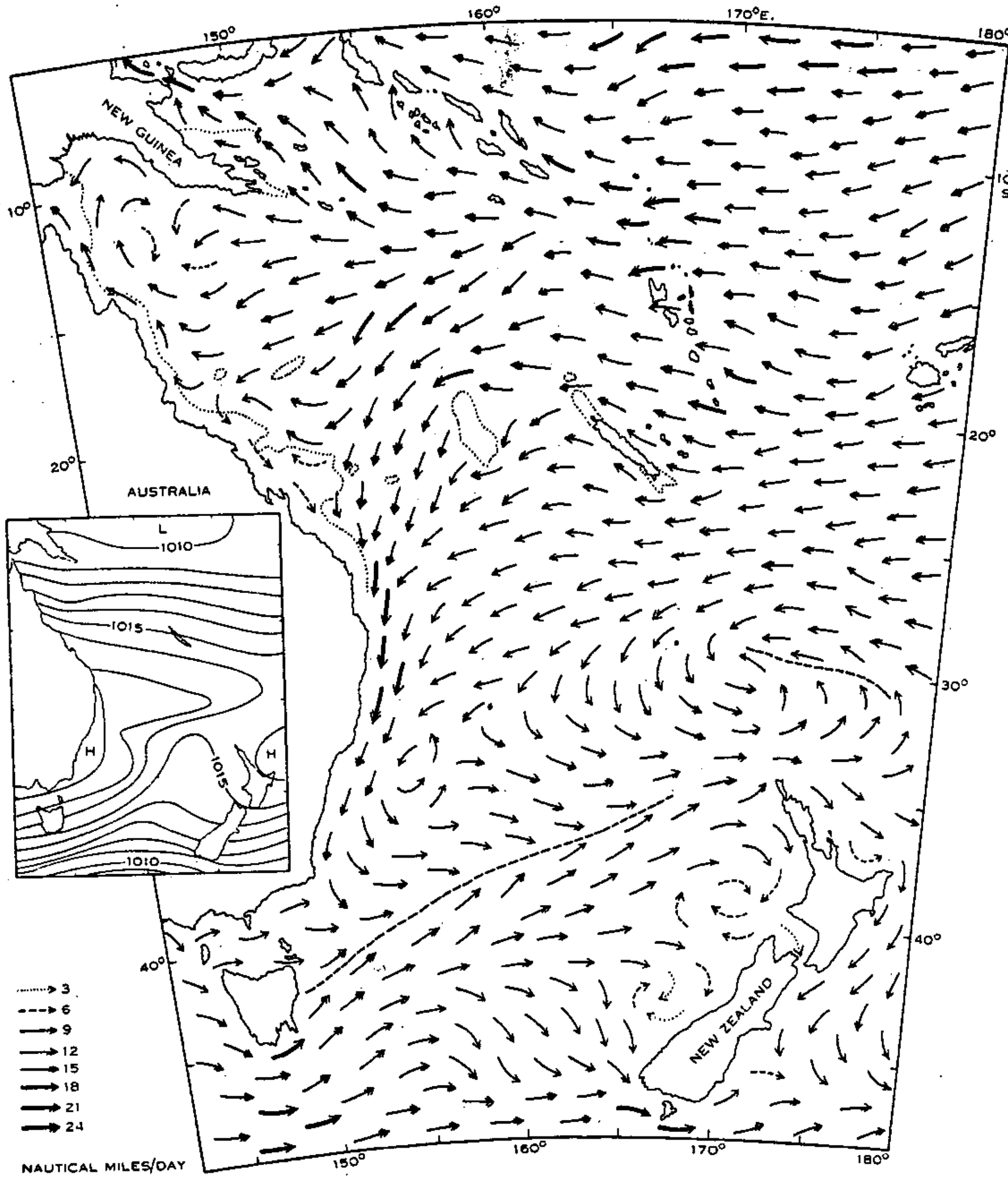

Fig. 5(*a*).—Surface currents in the Coral and Tasman Seas in May. Inset map shows distribution of atmospheric pressure.

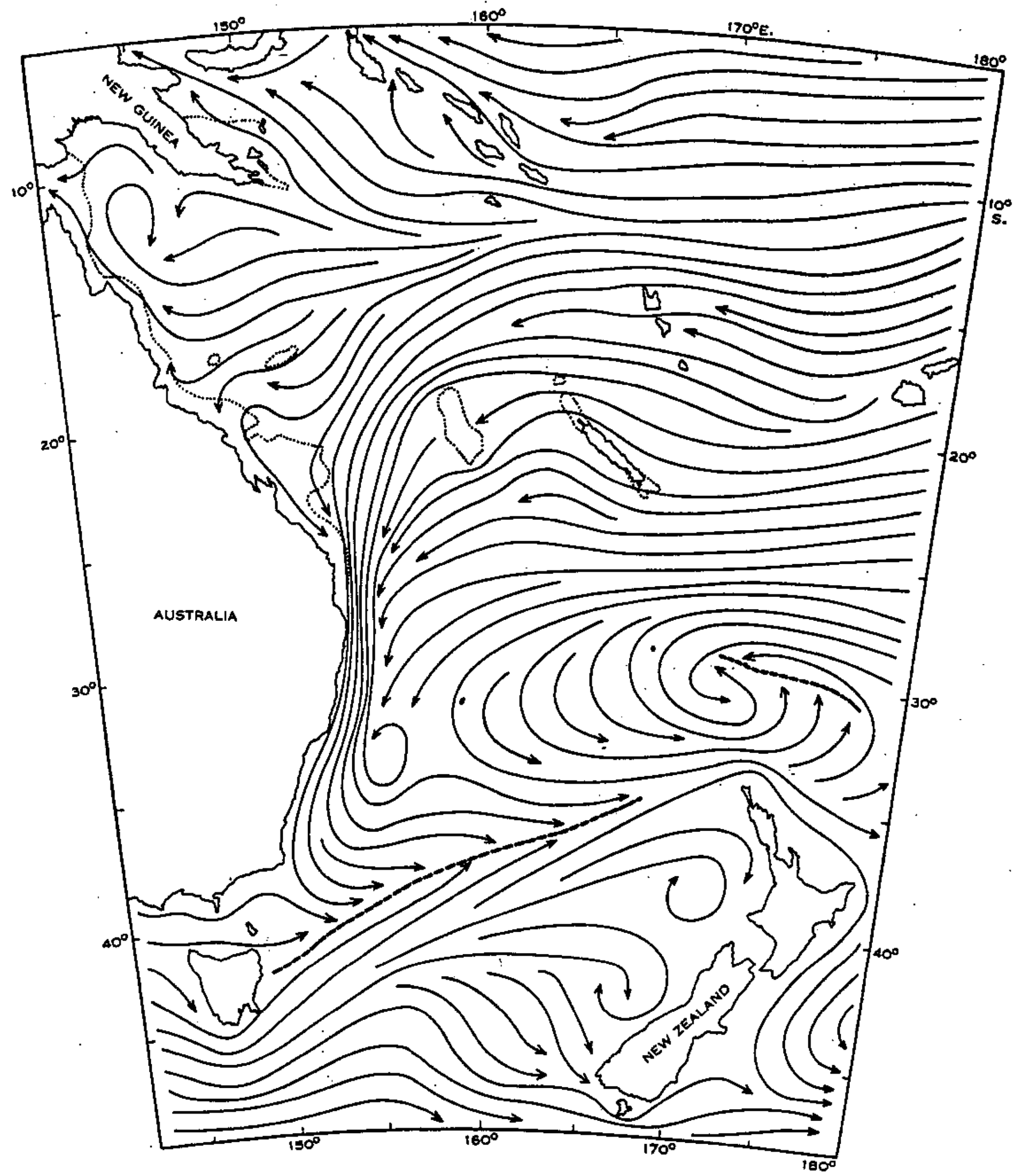

Fig. 5(*b*).—Streamlines of the surface circulation in the Coral and Tasman Seas for May.

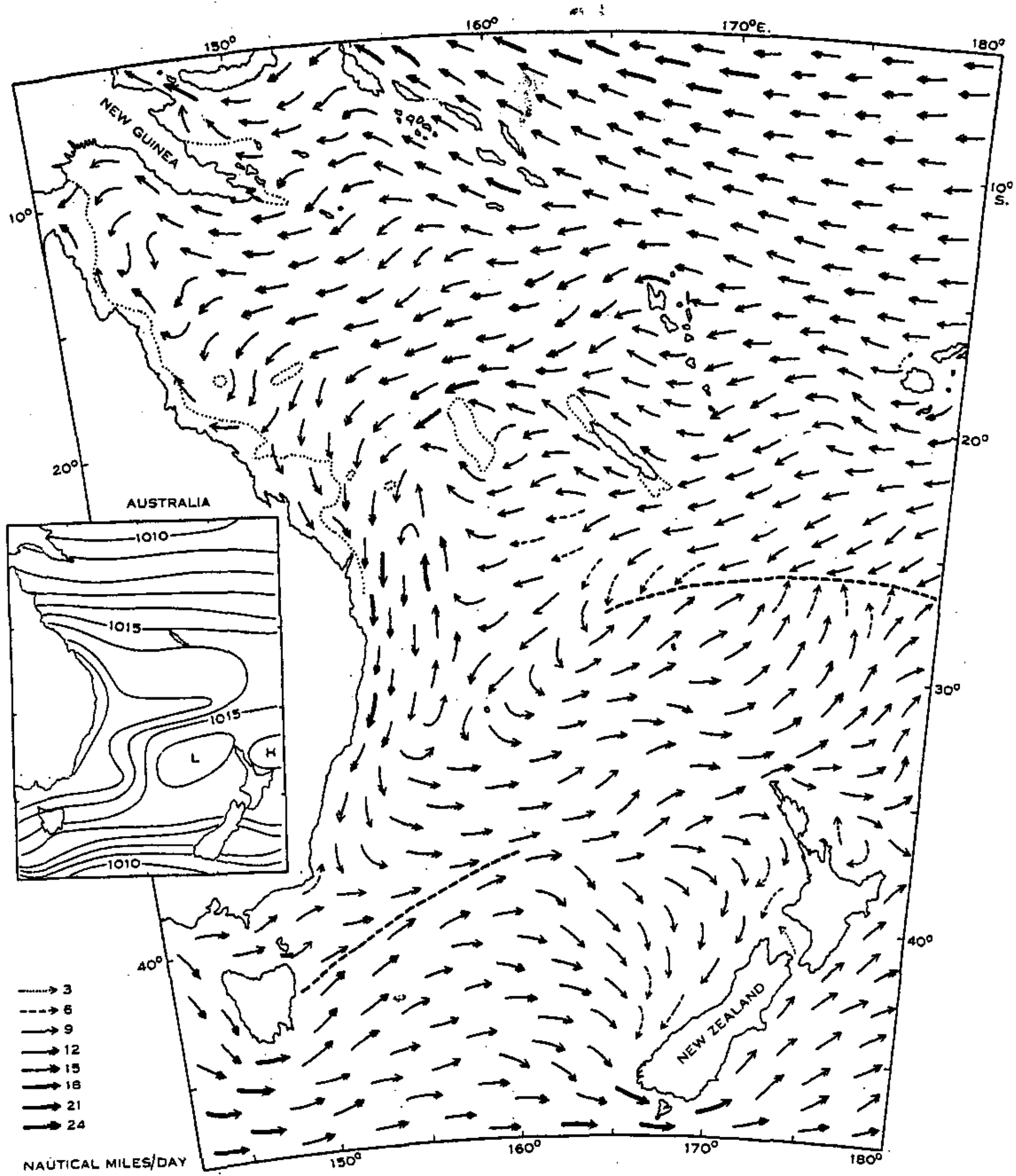

Fig. 6(*a*).—Surface currents in the Coral and Tasman Seas in June. Inset map shows distribution of atmospheric pressure.

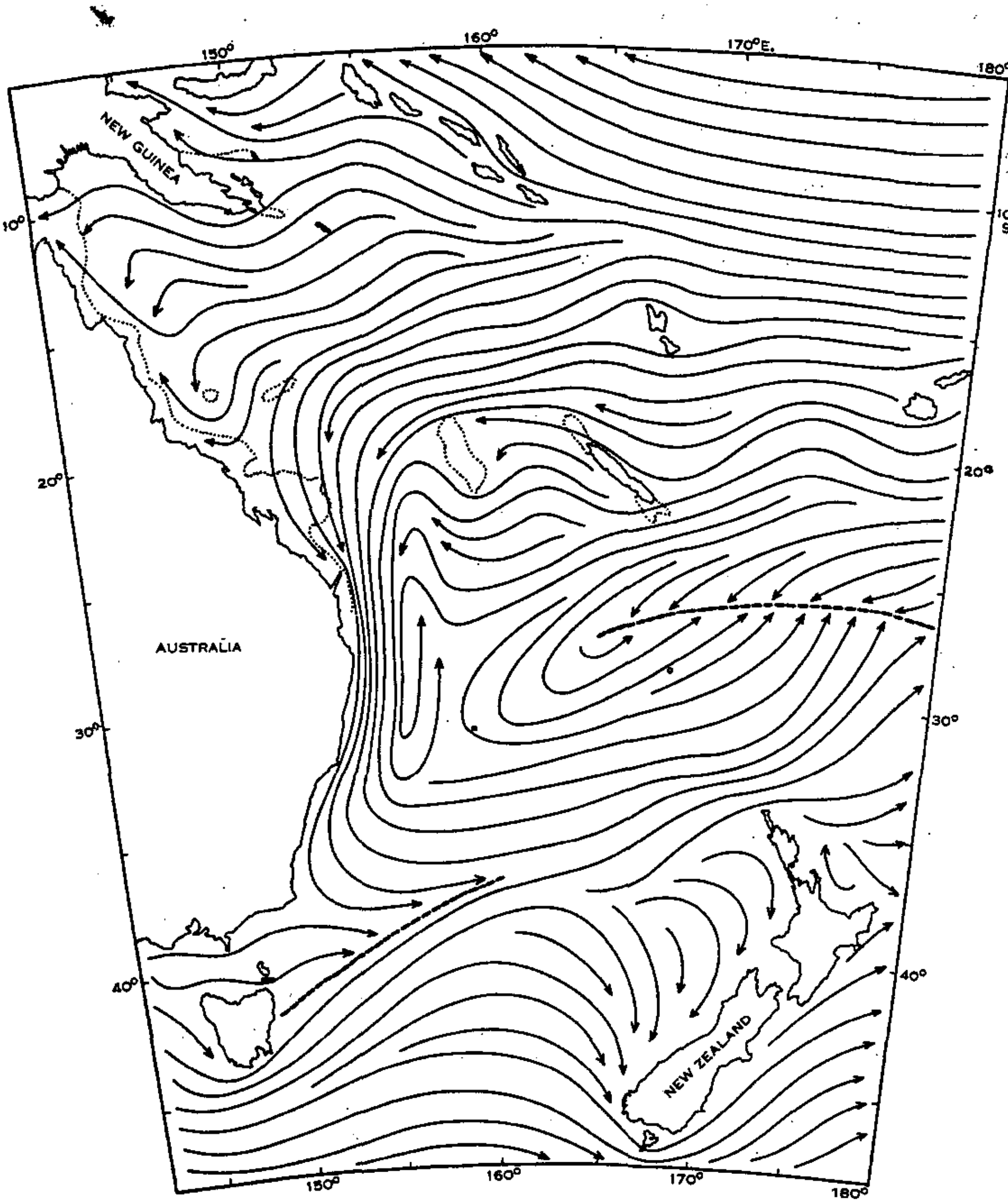

Fig. 6(b).—Streamlines of the surface circulation in the Coral and Tasman Seas for June.

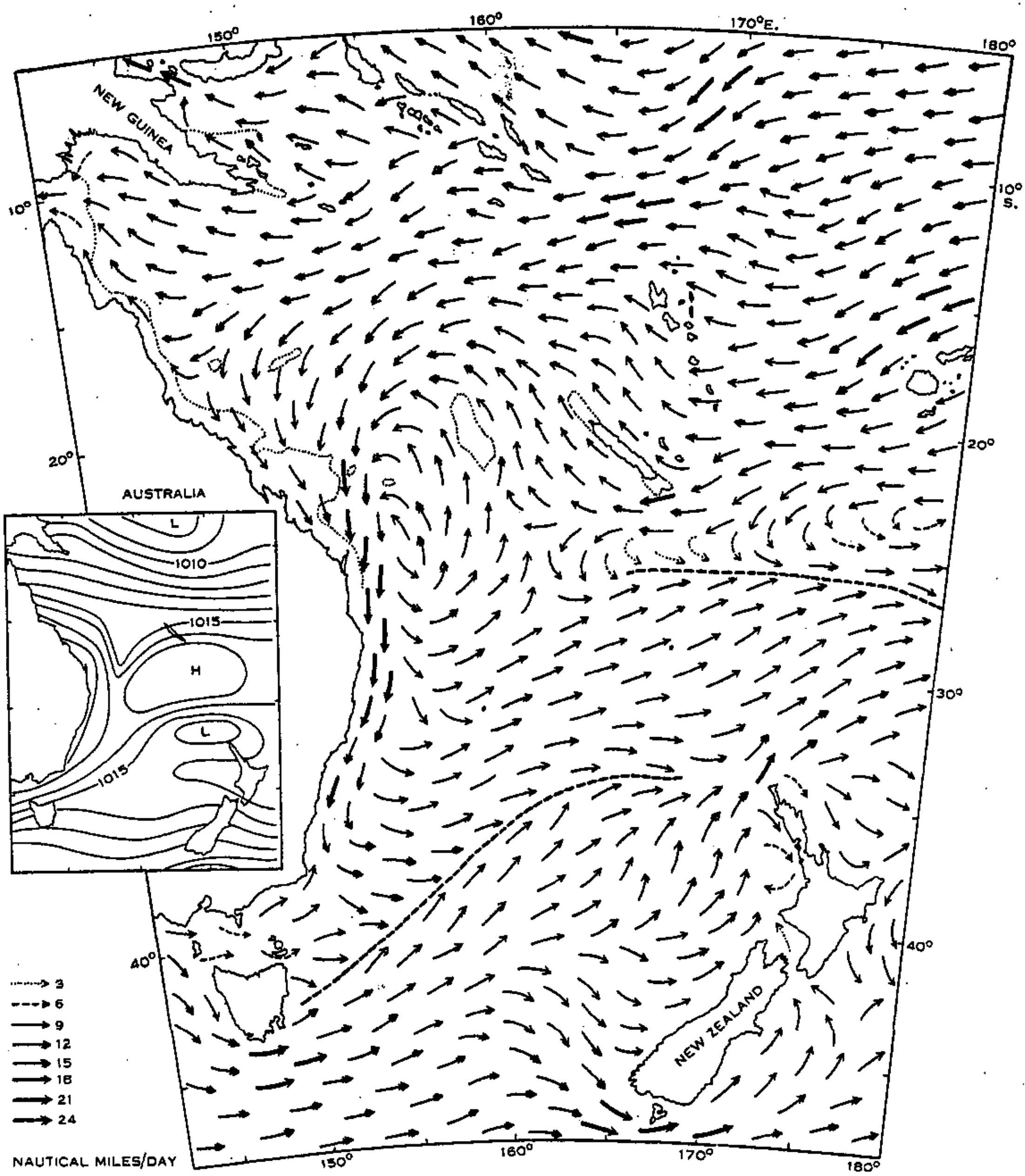

Fig. 7(*a*).—Surface currents in the Coral and Tasman Seas in July. Inset map shows distribution of atmospheric pressure.

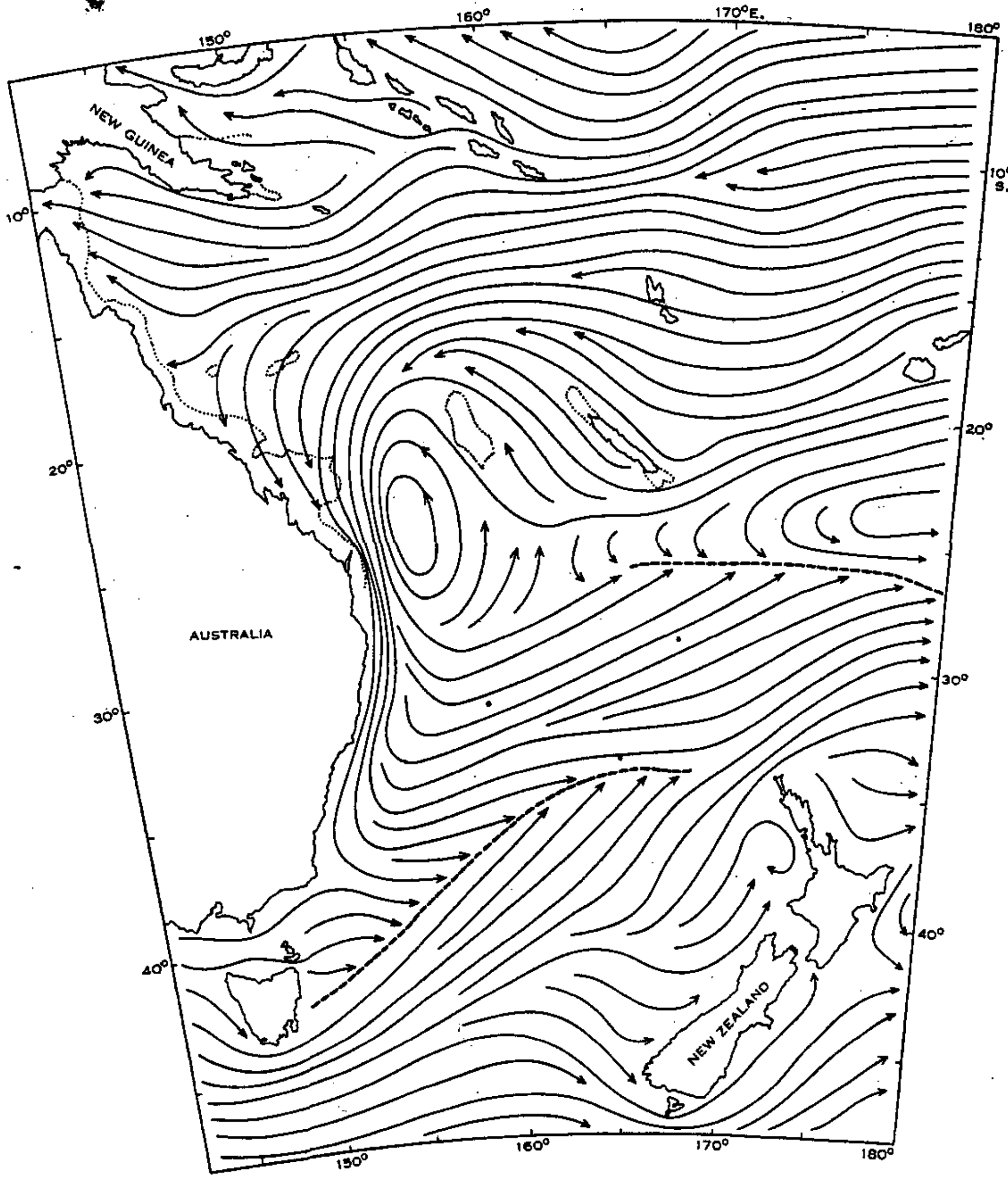

Fig. 7(*b*).—Streamlines of the surface circulation in the Coral and Tasman Seas for July.

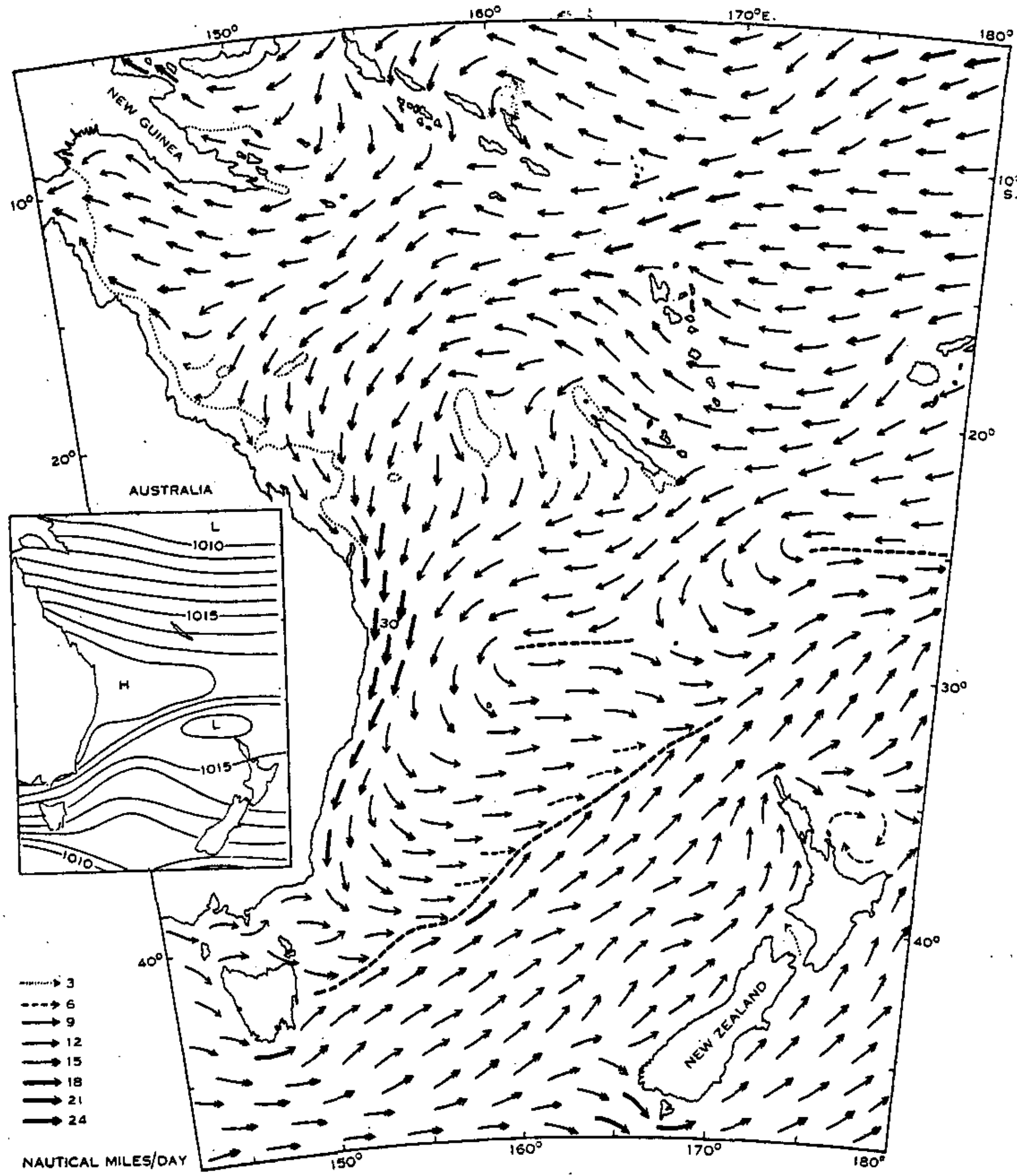

Fig. 8(*a*).—Surface currents in the Coral and Tasman Seas in August. Inset map shows distribution of atmospheric pressure.

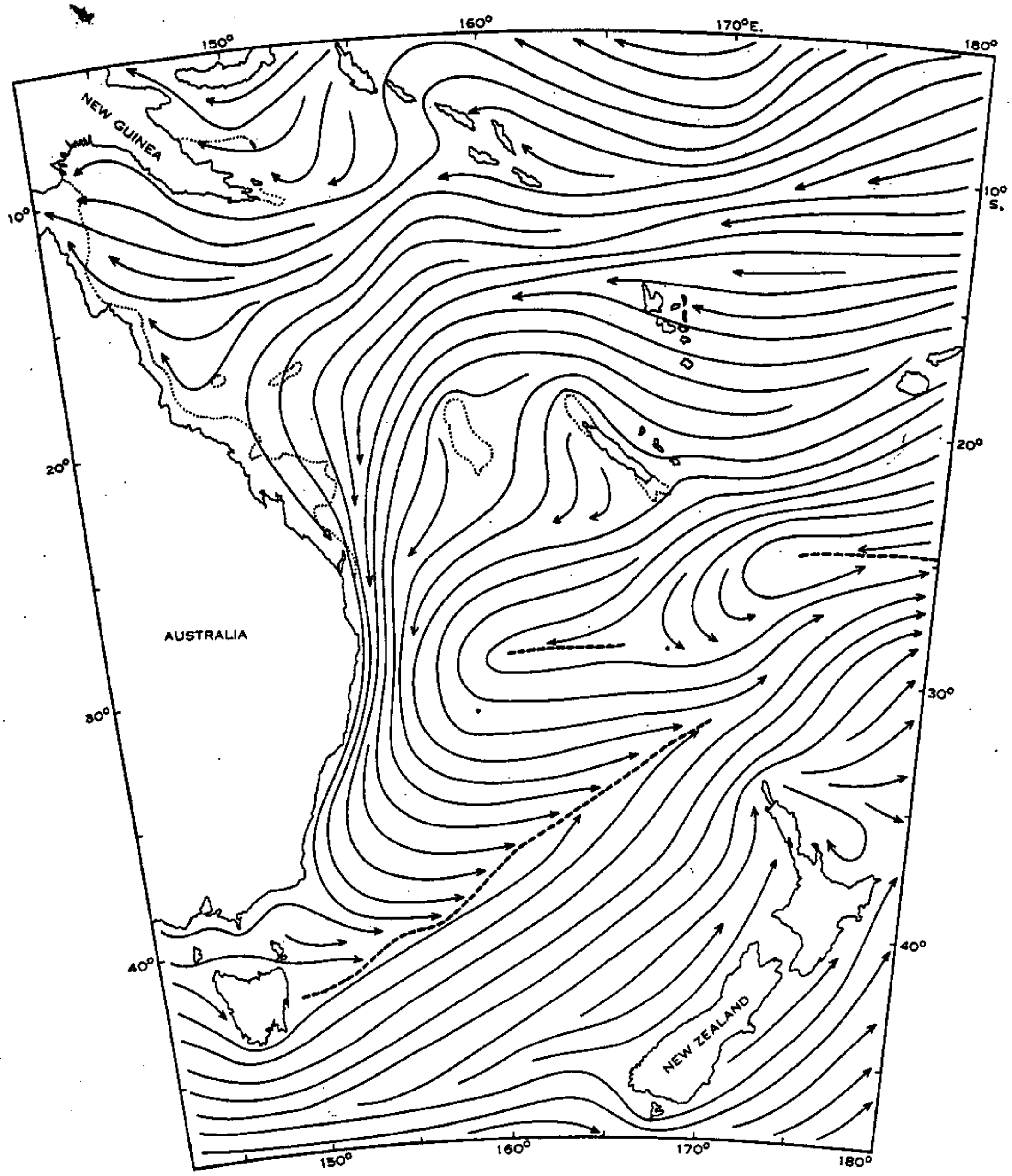

Fig. 8(*b*).—Streamlines of the surface circulation in the Coral and Tasman Seas for August.

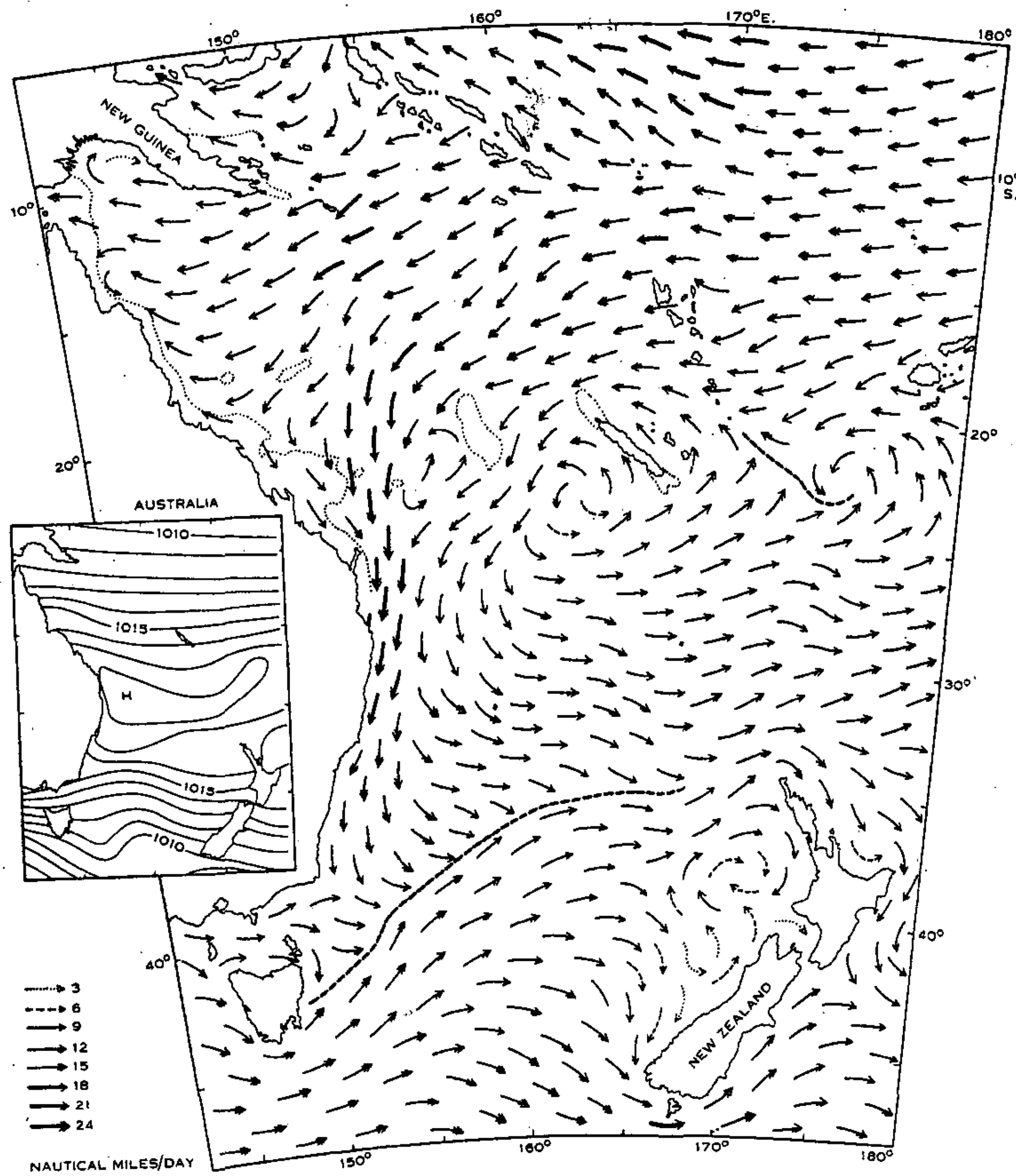

Fig. 9(*a*).—Surface currents in the Coral and Tasman Seas in September. Inset map shows distribution of atmospheric pressure.

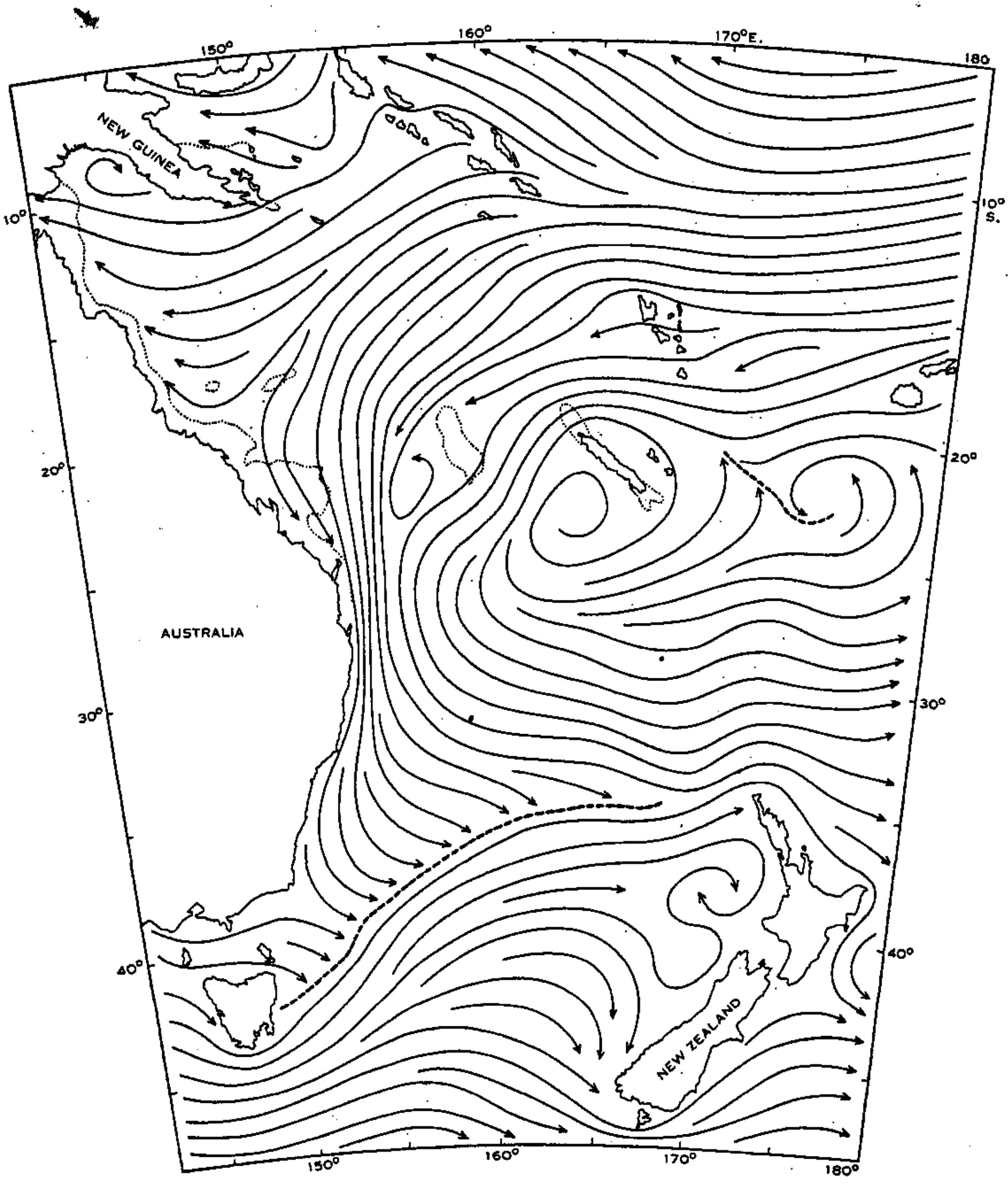

Fig. 9(b).—Streamlines of the surface circulation in the Coral and Tasman Seas for September.

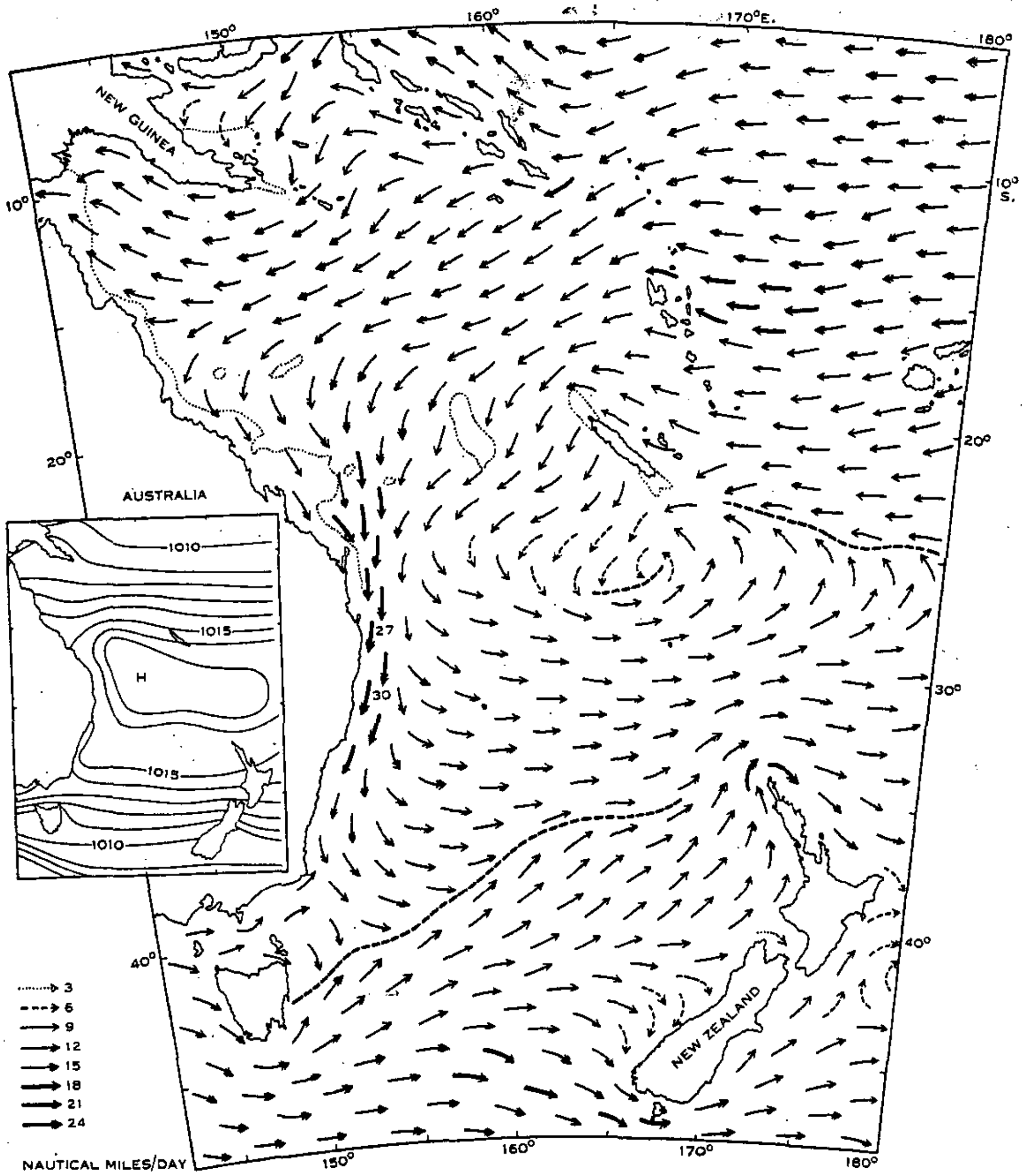

Fig. 10(a).—Surface currents in the Coral and Tasman Seas in October. Inset map shows distribution of atmospheric pressure.

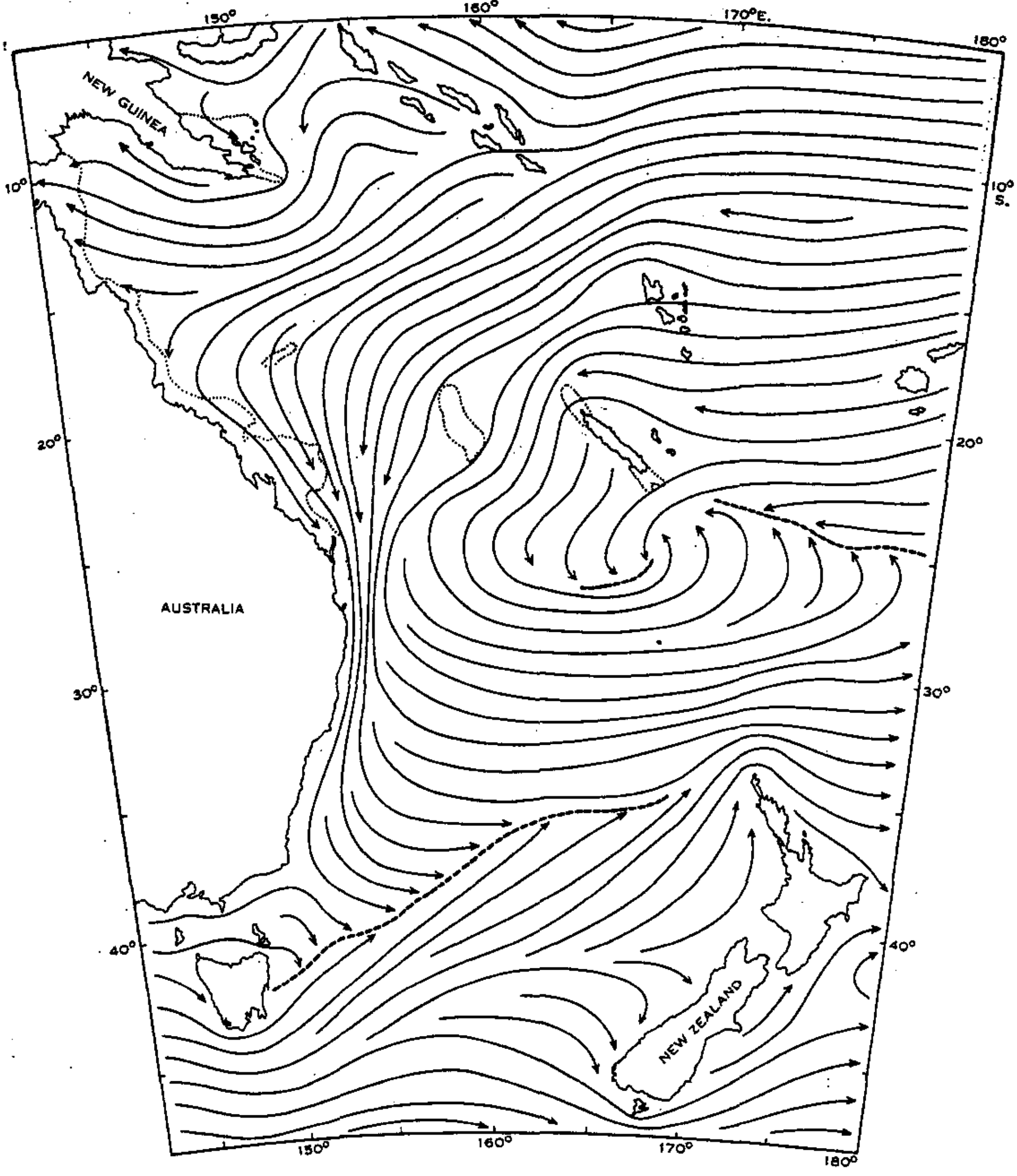

Fig. 10(b).—Streamlines of the surface circulation in the Coral and Tasman Seas for October.

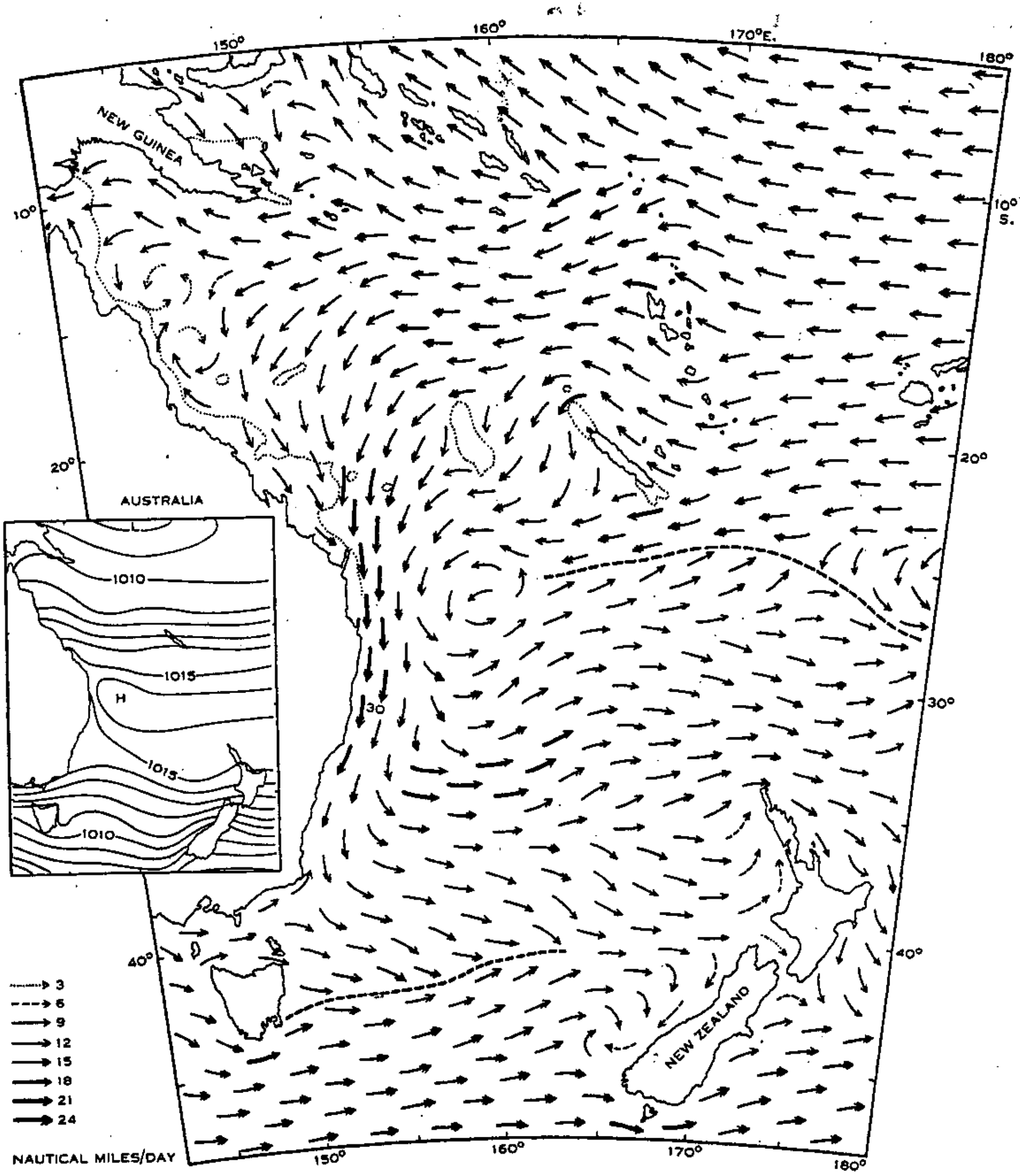

Fig. 11(*a*).—Surface currents in the Coral and Tasman Seas in November. Inset map shows distribution of atmospheric pressure.

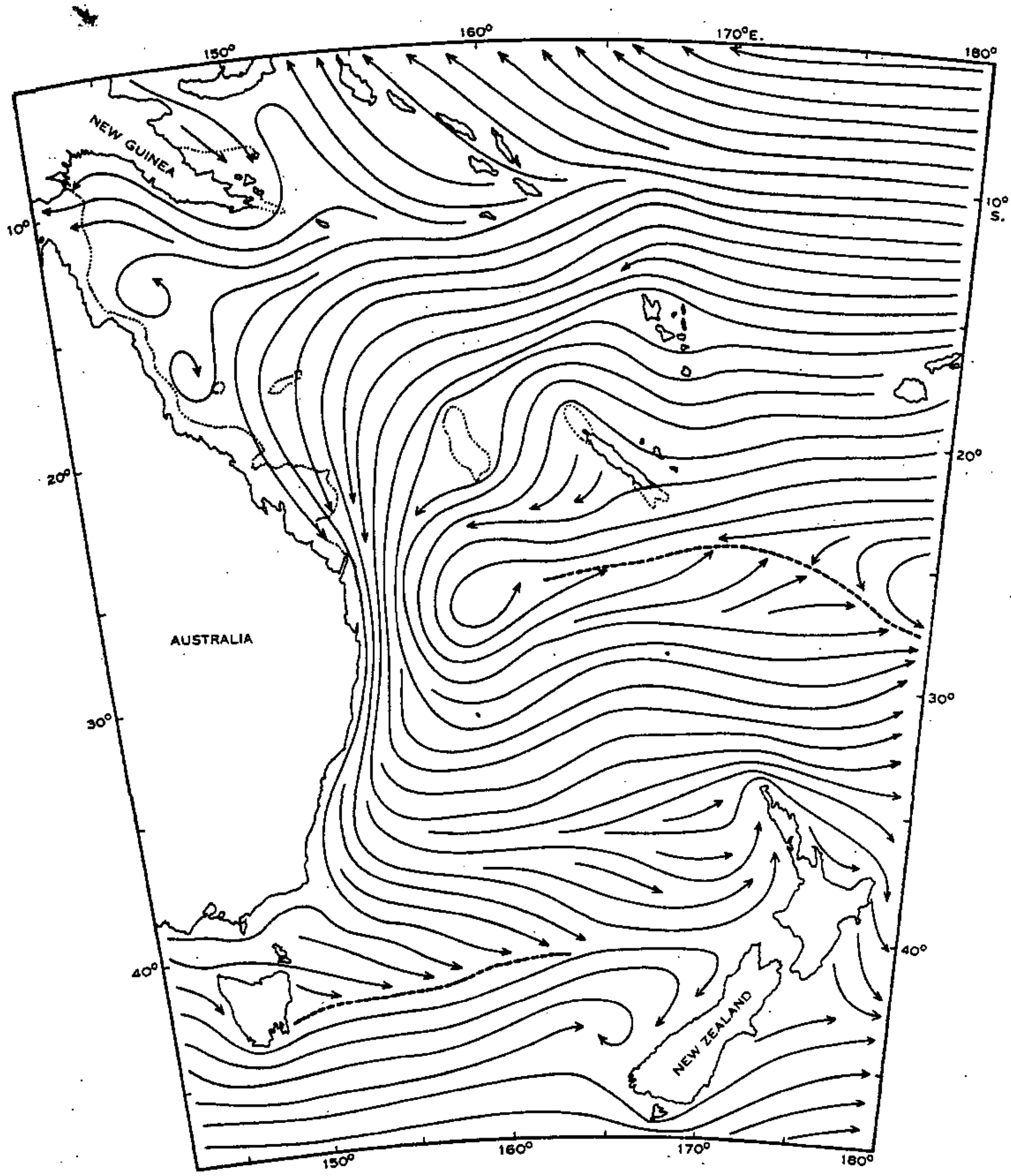

Fig. 11(*b*).—Streamlines of the surface circulation in the Coral and Tasman Seas for November.

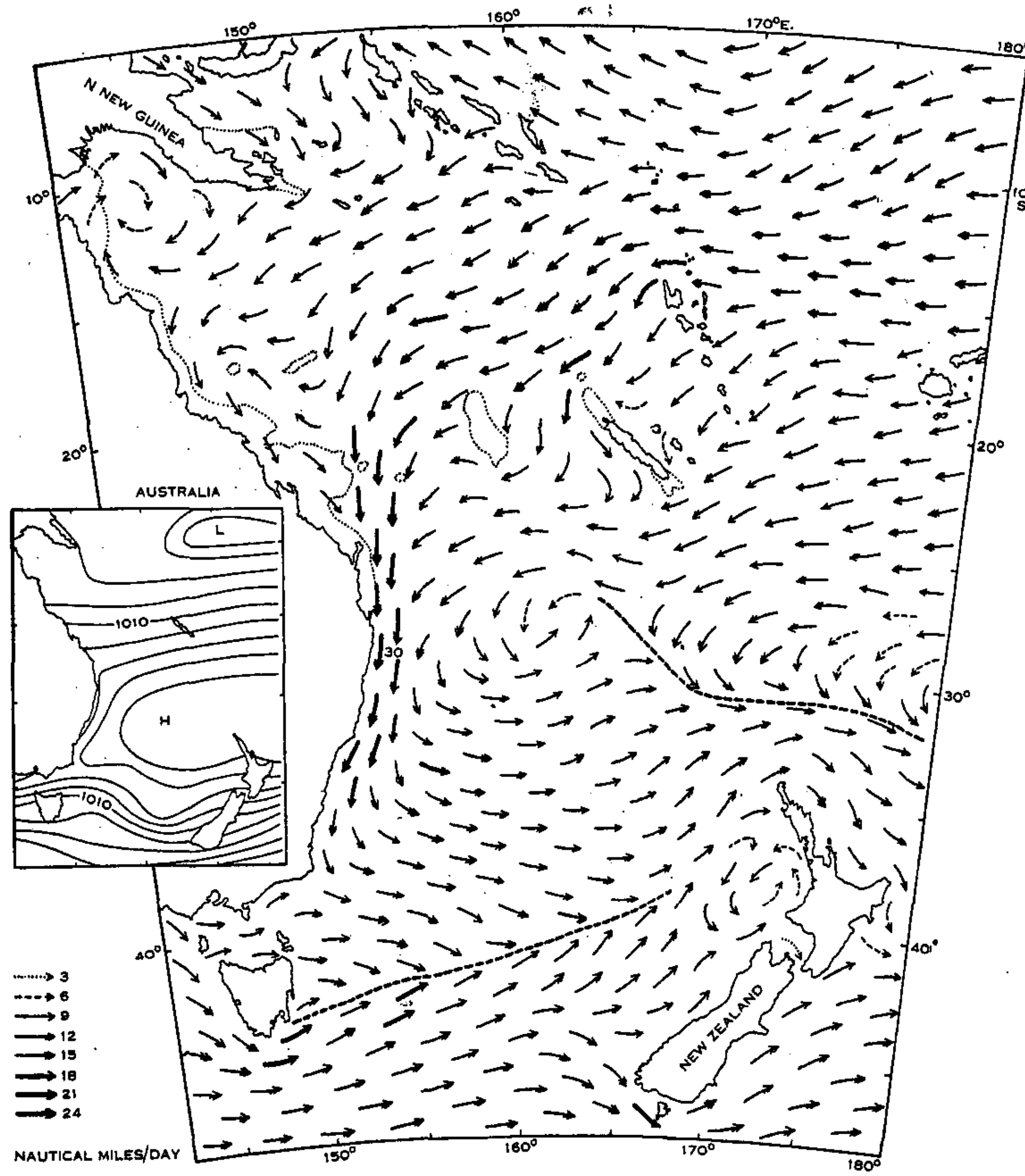

Fig. 12(*a*).—Surface currents in the Coral and Tasman Seas in December. Inset map shows distribution of atmospheric pressure.

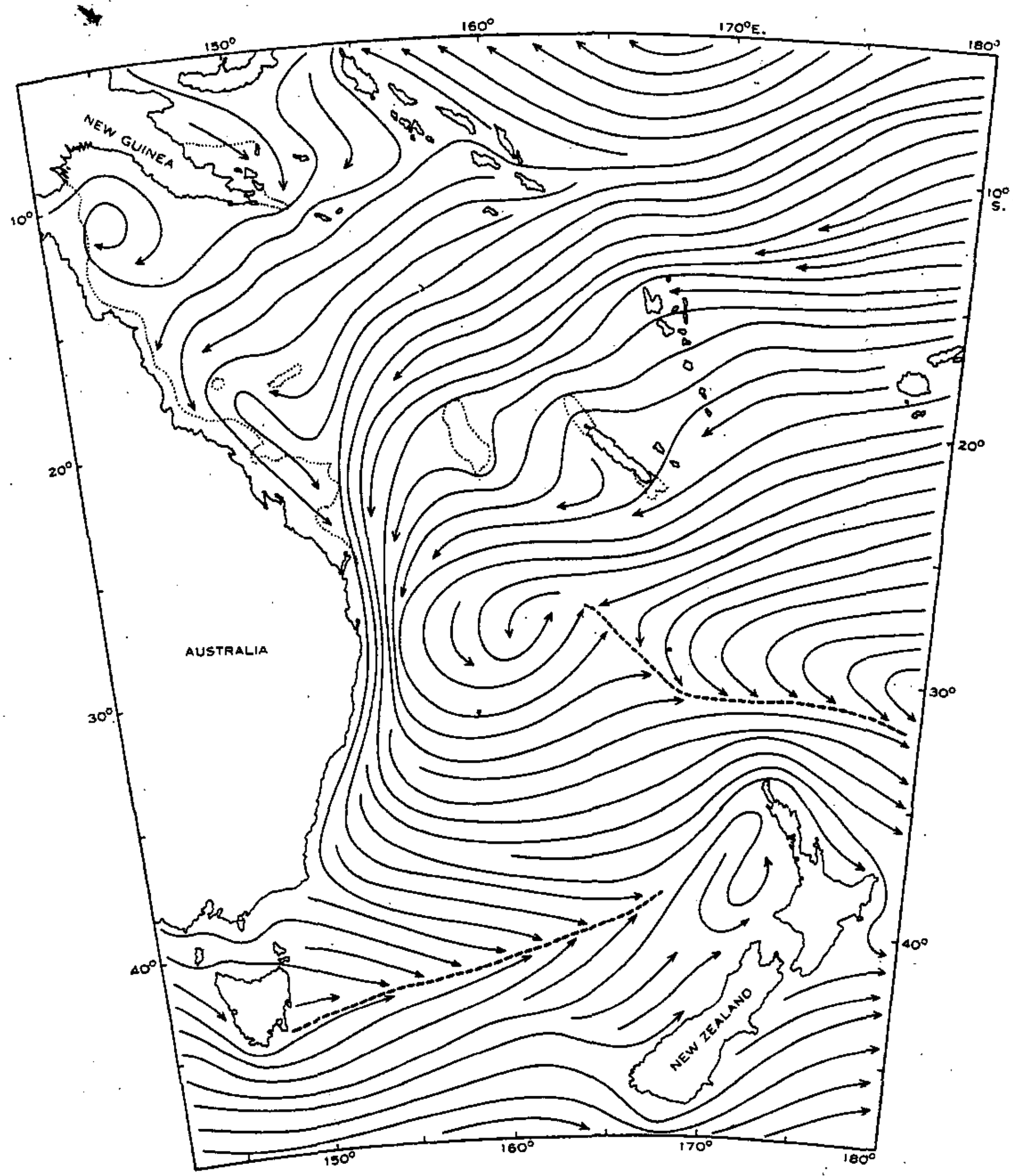

Fig. 12(*b*).—Streamlines of the surface circulation in the Coral and Tasman Seas for December.

III. The Construction of the Streamline Charts

In order to analyse the current charts and to derive further conclusions, streamline charts (Figs. 1(*b*)–12(*b*)), based on the current charts, have been constructed for the region. These streamlines show the direction of the surface flow in a particular month, *but give no information on the velocity*. *They should* not be confused with the trajectories showing the track of a particle or drift bottle over a longer period. It can be seen that the streamlines converge or diverge in certain areas. This can be due to different reasons; convergences in streamlines may indicate that the current velocity increases in the direction of flow, or that the current is deepened, or both together, as is the case at the formation of the East Australian Current between 20 and 25° S. The opposite processes cause a divergence in the surface flow. On the other hand, the beginning or ending of streamlines at a coast is certainly a sign of upwelling or sinking in that area. It is normally accompanied by a decrease of the velocity towards the coast. The ending of streamlines at an angle to others indicates a convergent movement, which is related to sinking. This process is seen in the Tropical and Subtropical Convergences. On the other hand, upwelling could occur in a field of parallel streamlines if *the velocity were to increase in the direction of* the flow, without being indicated in the streamline charts. This combination or the reverse situation seems to be unlikely.

IV. The Wind Systems and the General Circulation

Atmospheric circulation over the region under consideration is characterized by steady trade winds over the northern part and by very variable winds of prevailing westerly direction in the southern parts. The trade winds blowing from directions between east and south-east are of highest velocity and stability from May to November, and extend from about 20 or 25° S. to the equator. From December to April, when the equatorial trough is situated to the south of the equator, the trade wind belt is displaced also to the south. Its southern limit is then about 30° S., its northern limit between 10 and 15° S. North of the equatorial trough, a monsoon wind blows from the north, being a branch of the North East Trades. Its direction varies between north-west and north-east, and in February it reaches as far south as the New Hebrides and the Fiji Islands.

In the south of the region the atmospheric circulation is extremely variable owing to the depressions travelling east. The northern limit of prevailing west winds is found at about 40° S. During the period from April to October these west winds turn north and pass into the trade winds, so that chiefly south-westerly winds are found over the Tasman Sea. From November to March on the other hand, the trade winds branch off to the south and turn into the west wind belt, so that northerly winds are more frequent over the Tasman Sea. Maps of the pressure distribution are added to the current charts (Figs. 1(*a*)–12(*a*)) to demonstrate the pattern of the atmospheric circulation.

Oceanic circulation develops in accordance with these wind systems. The surface currents flow principally in the direction of the winds with a slight deflection to the left. Where land barriers obstruct this flow, the currents must develop in relation to them and these processes produce regions of upwelling and sinking. The main features of the circulation in the region are shown schematically and generalized in Figure 13.

The Trade Drift sets on both sides of the Fiji Islands and the New Hebrides, into the Coral Sea. This sea is practically closed to the west with the exception of a few narrow passages, permitting only a small transport of water. Therefore the water

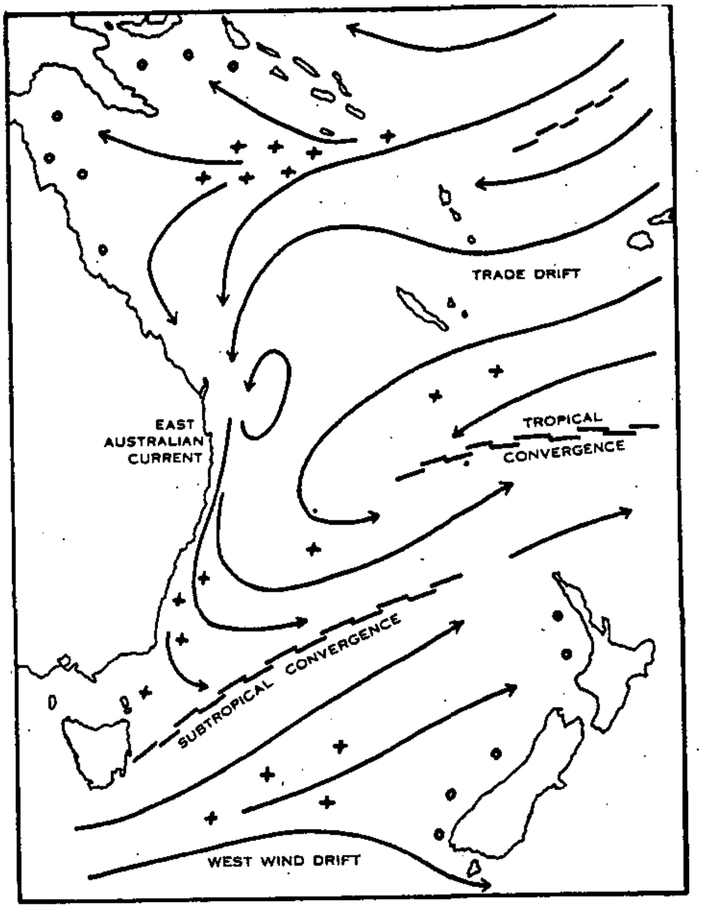

Fig. 13.—Generalized current pattern in the Coral and Tasman Seas. + Regions of divergence; ○ regions of convergence; —·—·— lines of convergence.

masses assembled in the Coral Sea must find another way to leave it. This leads to the formation of the East Australian Current flowing along the Australian east coast to the south, but also to considerable sinking in the Coral Sea itself. The East Australian Current follows the coastline to the south until it comes under the influence of the west winds. There it deviates from the coast and turns to the east. Between Tasmania and New Zealand parts of the water masses of the West Wind Drift branch off and flow north-east where they meet branches of the East Australian

Current. This convergent movement, together with the effect of the winds, causes the formation of the Subtropical Convergence. Further to the north, along the southern boundary of the trade winds, the Tropical Convergence is formed, where the branches of the East Australian Current meet the water masses of the Trade Drift. This whole current system moves with the wind system either north or south according to the season, and the different current branches are strengthened or weakened by their interaction.

V. The Trade Drift

In the northern parts of the region, below the trade winds, the Trade Drift is developed. This drift must be clearly distinguished from the South Equatorial Current, which flows with much higher velocities close to the equator and lies outside these current charts. There is, however, no sharp limit between the South Equatorial Current and the Trade Drift, but the first forms a well-defined current band, while the second is a broad and diffuse drift. Because of the high constancy of the trade winds the current velocities induced by them are comparatively high. The extent of the Trade Drift varies naturally with that of the trade winds and is therefore subject to considerable annual fluctuations.

From April to December the water masses under the trade winds flow in a general easterly direction, only slightly influenced by the different island groups. Especially north of the New Hebrides, of New Caledonia, and of the Chesterfield Reefs, a compression of the streamlines and an increase of the current velocity are observed. The flow is in general slightly convergent, as indicated in the streamline charts. The region of convergent movements is shown in Figure 16 as the Trade Drift Convergence. When approaching the Solomon Islands the drift splits off, one branch flowing north of the islands in a west-north-westerly direction, the other flowing into the Coral Sea.

In the Coral Sea the flow is in general divergent, because the water masses take different directions. The main branch turns rather sharply south and becomes part of the East Australian Current. A weaker drift continues westwards into the western Coral Sea and another north-west into the Solomon Sea. This extensive Coral Sea Divergence extends south of the Solomon Islands between 10 and 15°S., as seen in Figure 16, and seems to be a persistent feature throughout the year. The position of this divergence coincides very well with the position of the richest fishing grounds for albacore in the western South Pacific Ocean (Yamanaka 1956). It verifies the existence of this divergence in which the upwelling of water provides a basis for the development of these fishing grounds.

The water masses flowing into the western Coral Sea can pass through Torres Strait only to a small extent. They are piled up along the coast and must sink; this is shown by the ending of many streamlines indicating convergent water movements. They also flow away along the coast and are integrated into the East Australian Current. The same applies to the Solomon Sea, where strong convergent movements and probably sinking also occur (see Fig. 16).

From January to March, when the monsoon blows over the northern part of the region, the flow pattern changes substantially. Equatorial water masses enter the region from the north and north-east and flow between the Solomon Islands and the New Hebrides south-westwards to form the East Australian Current. In February and March a strong convergence is developed between these equatorial water masses and the Trade Drift to the north-east of the New Hebrides. During this season the Trade Drift is displaced to the south and its main parts are south of the Fiji Islands.

In the Coral Sea also the circulation is under the influence of the monsoon. In January the north-west winds cause a general flow to the south-east parallel to the coast. This flow is related to strong upwelling along the south coast of New Guinea and occurs only during this particular month. In February and March the flow pattern is rather irregular as is to be expected from the variable winds in the range of the equatorial pressure trough.

The southern boundary of the Trade Drift is subject to considerable fluctuations. It normally corresponds to the position of the Tropical Convergence, which is given in Figure 15, but it can also be seen from Figure 17, where the annual variation of the currents along a line from New Caledonia to New Zealand is shown. The water masses of the Trade Drift, passing north of the Fiji Islands and north of New Caledonia, generally form the East Australian Current, while the water masses passing these islands in the south turn southwards and pass over into the Tropical Convergence. The southern limit of this west to south-west flowing drift current lies at about 30° S. from December to May, during the summer. From June onwards the boundary moves rapidly north and reaches its northern position in September. In this month the flow south of the Fiji Islands is small and weak, and south of New Caledonia it is even reversed. From October to December the boundary moves again southwards.

VI. The East Australian Current

Along the east coast of Australia a comparatively strong but narrow current flows to the south. Its transports are estimated to vary between 10 and 25×10^6 m^3/sec. The current is an effect of the piling up of water in the Coral Sea by the trade winds, and it is forced by the configuration of the coast to flow southwards. The East Australian Current has often been compared with the Gulf Stream and the Kuro Shio. However, it lacks the most important of the main features of these two large northern hemisphere current systems; namely, it does not, like these, form a huge current system which extends eastwards over the whole ocean, but it disappears rapidly when departing from the coast. This phenomenon is conditioned by the fact that the Australian continent ends at 44° S. and that south of the continent there is the large Circumpolar Current which is completely self-contained. Due to this there is no necessity for the East Australian Current to form and supply a large eastward-flowing current system. The Gulf Stream and the Kuro Shio maintain the balance between the high sea-level in lower latitudes and the water masses required for the formation of east-going currents in higher latitudes, while the East Australian Current lacks the second stimulus. This explains its comparative weakness. There is also no "cold wall" formed on its poleward side, which leads to the immense intensification of the two other current systems. So the conditions in the northern part of the East Australian Current are similar to those of the two big northern hemisphere current systems, but those in its southern part are entirely different. The current system itself is affected to a high degree by local weather conditions and, especially in its southern part, is variable.

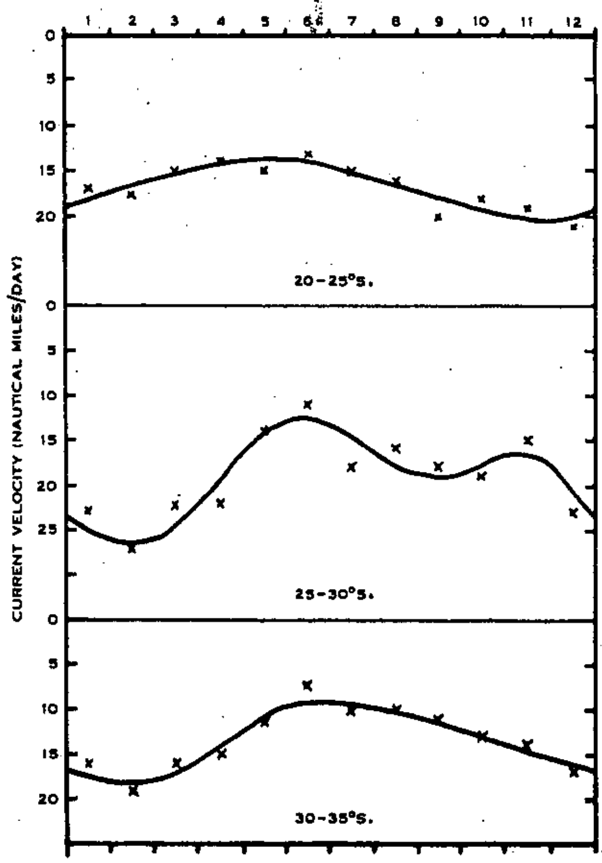

Fig. 14.—Annual variation of the current velocity in the northern, central, and southern sections of the East Australian Current.

The East Australian Current is formed at about 20° S. between the Chesterfield Reefs and the Great Barrier Reef, that is, approximately between 153 and 158° E. From January to March it is supplied with equatorial water masses, driven west-south-westwards by the monsoon winds, from April to December by subtropical water masses coming with the Trade Drift from the central South Pacific Ocean. Between 20 and 25° S. the current becomes narrower and is strengthened by the integration of water masses from both sides. This flow pattern causes a very strong convergence between Chesterfield Reefs and the coast, as seen in the streamline charts as well as in Figure 16, and is related to a considerable deepening of the current. The converging movements are chiefly concentrated in two patches. The first is situated along the right flank of the current to the north of Great Sandy Island, where the Coral Sea water masses which flow over the shelf between the mainland and the Great Barrier Reef, are integrated into the current. The other extends along the left flank of the current and reaches rather far to the south, and here water masses of the Trade Drift, approaching south of the Chesterfield Reefs, are integrated into the current. There is only a small annual variation of the current velocity between 20 and 25° S. (Fig. 14).

TABLE 1

PERCENTAGE OF STRONG WINDS AND CURRENTS WITH COMPONENTS TO THE NORTH IN THE RANGE OF THE COUNTER-CURRENT TO THE EAST AUSTRALIAN CURRENT

Month	Winds of Force 6 and More						Currents with Northerly Components
	From the Four Quadrants				From All Directions	From Southerly Directions	
	NW.	NE.	SE.	SW.			
Jan.	0	0	10	0	10	10	33
Feb.	0	3	9	0	12	9	32
Mar.	0	0	4	0	4	4	30
Apr.	1	1	11	4	17	15	51
May	4	0	11	8	23	19	44
June	0	1	7	7	15	14	42
July	3	2	5	7	17	12	38
Aug.	7	0	3	6	16	9	22
Sept.	5	0	4	5	14	9	26
Oct.	3	1	3	6	13	9	27
Nov.	1	1	3	1	6	4	32
Dec.	0	0	2	0	2	2	30
Mean	2·0	0·8	6·0	3·7	12·5	9·7	—

The East Australian Current reaches its maximal strength between 25 and 30° S., especially off Cape Byron. There it shows a marked annual variation with higher velocities in summer (maximum in February) and lower velocities in winter, when southerly winds prevail. A secondary maximum is found in September (Fig. 14). During the winter a counter-current to the East Australian Current seems to be a rather usual phenomenon. In the American atlas such a counter-current is not shown in any month, but in the Dutch atlas north-going currents between 156 and 158° E. are indicated in every month. Therefore it seems likely that this counter-current is formed only under the influence of strong south winds, and that these observations are not entered in the American atlas, where all observations made of winds above force 6 are omitted. To verify this, the wind observations given in the Dutch atlas in the 5° square off Brisbane (25–30° S., 155–160° E.) have been examined and the results are given in Table 1. The percentage of winds of force 6 and more, blowing from the four quadrants, is given for every month. This statistical examination shows that in 12·5 per cent. of all observations this wind force is exceeded, and it must be assumed that an equal number of current observations is rejected in the American atlas. But about 75 per cent. of these strong winds come from southerly, especially south-easterly directions, which demonstrates that if strong winds occur they are most likely from the south. The percentage of strong southerly winds is greatest in the months April to July, and in these months a counter-current appears most clearly in the current charts of the Dutch atlas. For a comparison the current rose given in that atlas for the area 26–29° S. and 155–160° E. has been examined, and the percentage of currents with components to the north is also given in Table 1. It shows that the percentage of these currents is above 35 per cent. during the period from April to July, just when the frequency of strong south winds is high. From this analysis of the observations it may be concluded that the counter-current to the East Australian Current develops under the influence of strong southerly winds, and is therefore not a permanent feature, but can most likely be found during the period from April to July. Consequently, a counter-current has been drawn in the current charts only when sufficient observations were available in the Dutch atlas to verify it clearly. Thus it appears from April to July. Its position in the different months is entered in Figure 15, but it can also appear in other months when strong southerly winds occur.

After having passed Sugarloaf Point at about 32·5° S. the East Australian Current broadens considerably and major parts of its water masses are given off to the east. This effect is especially strong from July to January. In this area the current comes under the influence of westerly and south-westerly winds, which blow there when fronts of atmospheric depressions pass the region. The deflection of the current away from the coast causes a strong divergence in the surface flow, and is sometimes accompanied by upwelling along the coast. Also the depth of the East Australian Current, which is a gradient current off Cape Byron, decreases considerably when the current becomes an east-flowing wind drift. The average current velocity between 30 and 35° S. is much lower than off Cape Byron (Fig. 14), but shows the same annual variation with maximal velocities in summer.

VII. The West Wind Drift

South of Australia and New Zealand the broad West Wind Drift is situated, in which rather irregular, but prevailing east-going currents exist under the influence of the travelling atmospheric depressions. Owing to the fact that New Zealand reaches further to the south than Tasmania, and that the resultant winds over the area blow in a north-easterly direction, a branch of the West Wind Drift enters the Tasman Sea. The surface flow between Tasmania and New Zealand is principally north-eastwards and is bounded to the left by the Subtropical Convergence. The flow itself is slightly divergent, especially from April to October, when the Subtropical Convergence is in its northern position (Fig. 15). The position of this divergence is shown in Figure 16 and relative values of its strength are given in Table 2.

When this north-eastward flow approaches the coast of New Zealand it becomes weaker and more irregular. Only a relatively small part of the water masses of the West Wind Drift passes around the north point of New Zealand. Consequently, convergent movements, and probably sinking, occur along the west coast of the island. This is concentrated in two patches off the North and the South Islands, as shown in Figure 16. The convergence off the North Island takes up all the water masses, which cannot pass around New Zealand to the north. In this region of variable and weak currents and convergent movements, where the water masses seem to remain rather stationary, an independent water mass is formed (Rochford 1957). The southern region of convergence is partly an indication of the formation of the strong current around the south point of New Zealand, partly it is sinking along the coast owing to onshore winds.

VIII. The Subtropical Convergence

An area of convergent water movements extends from Tasmania to the north point of New Zealand. It corresponds roughly to the boundary between the subtropical water masses carried southwards with the East Australian Current and the subantarctic water masses carried north-eastwards with the West Wind Drift. However, the convergence is not due to the differences between these two water masses, even if their contrast at the surface appears more pronounced, because the sinking movements along the convergence remove the mixing products to a certain extent. Density differences are certainly not the reason for the formation of this convergence; it is dynamically conditioned, and the winds must be principally responsible for its formation. According to Ekman's theory the water transport in a pure drift current under a uniform wind field is, in the southern hemisphere, exactly to the left of the wind. If the wind field is not uniform, convergent or divergent water movements must develop along the discontinuities of the wind field. In the case of the Subtropical Convergence the discontinuity in the wind field is given by the northern limit of the prevailing west winds. Because this limit is a climatological feature the position of the Subtropical Convergence will not be stationary, but will fluctuate according to the general weather conditions. Consequently, it seems to be more likely that the Subtropical Convergence is formed by several strips, in which convergent movements take place, rather than in a continuous line, and it may even be temporarily absent.

The Subtropical Convergence is certainly strengthened by the water masses of the East Australian Current, which attacks the West Wind Drift in its flank. Both processes, the formation of a convergence to the left of a west wind field with northwards decreasing velocities, and the general southward movement of water masses along the Australian east coast, seem to be responsible for the formation of the Subtropical Convergence.

In spite of the assumed variability of the position of the Subtropical Convergence, the suface current data for every month allow the position of this convergence to be fixed, which is shown in the current charts and summarized in Figure 15. It always starts from the east coast of Tasmania, where it is initially formed, when the subantarctic water masses carried east by the strong current flowing around the south point of Tasmania meet branches of the East Australian Current. The Subtropical Convergence is, during the summer months from November to April, in a more southern position and, during the winter months, in a more northern position (Fig. 15). Between October and November it seems to disappear in its northern position and to be formed again in its most southerly. It normally ends between 156 and 170° E. before reaching New Zealand, where no further convergent movements exist and a current is formed, which passes around the north point of New Zealand. An examination of the pattern of the streamlines shows that much more water of subtropical than of subantarctic origin sinks along the convergence. This finding not only justifies the name Subtropical Convergence but is explained quite logically by the fact that water of high salinity flowing south has a tendency to sink

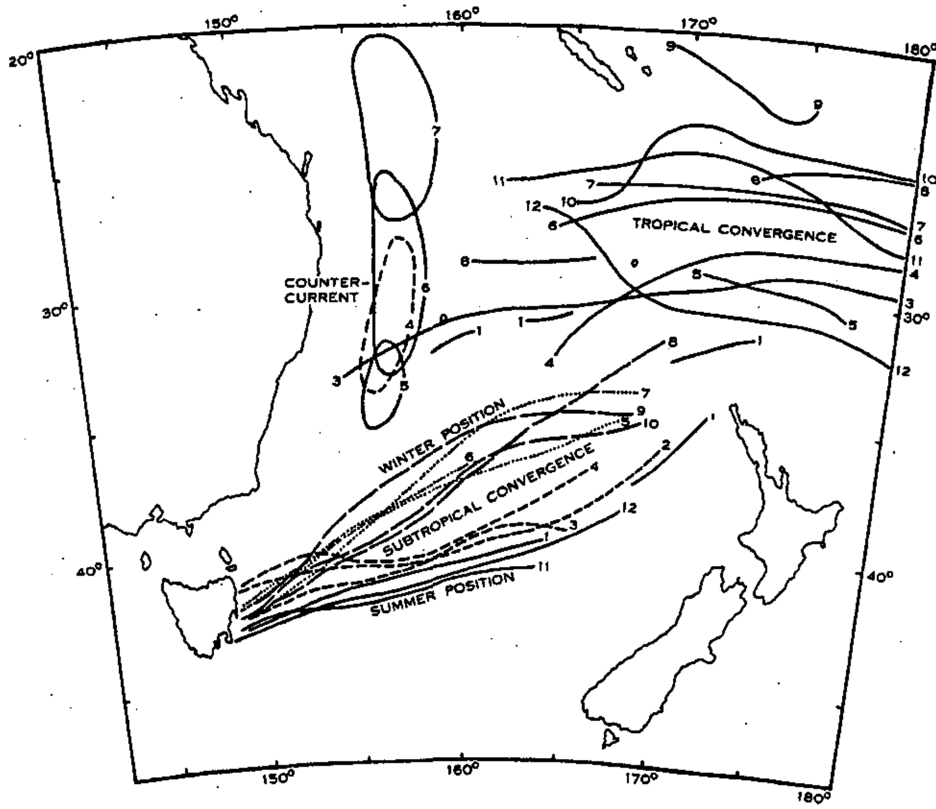

Fig. 15.—Position of the Subtropical and Tropical Convergences and of the counter-current to the East Australian Current in different months. Months are indicated by numbers.

when it is cooled, while the water of lower salinity flowing north does not have this tendency when being heated. There is also a considerable semi-annual variation in the strength of the sinking along the convergence with maximal values in January/February and August (Table 2).

These results, derived only from an analysis of current observations are partly in contrast to the picture given by Deacon (1937). In the charts presented here the position of the Subtropical Convergence is, in all months, further north than that derived by Deacon chiefly on temperature and salinity distributions. The Subtropical Convergence starts always from Tasmania, where it is initially formed, and it is very likely that it does not exist to the west of this island; but the latter is also admitted by Deacon who states that "the absence of a sharp convergence between the subantarctic and the subtropical waters south of Australia is probably due to the smallness of the northwards and southwards components of the two currents". He also states that the Subtropical Convergence appears to be ill-defined in the Tasman Sea west of New Zealand, but this makes it very likely that R.R.S. *Discovery* did not even meet the convergence on its voyage to Auckland, and remained south-east of it; this would appear to be the case from the charts of this paper. There is full agreement about the fact that the Subtropical Convergence is the boundary of the subtropical water flowing with a slight southerly component and the subantarctic water flowing with a slight northerly component, although Deacon derives the position of that boundary from temperature and salinity observations. On the other hand, Deacon believes that it is more likely that the heavier subantarctic water sinks at the convergence. There is no doubt about the fact that subantarctic water sinks also along this convergence, and the streamline charts indicate this clearly, but the larger contribution to the sinking comes, as indicated in the streamline charts, from subtropical water, out of the range of the East Australian current. This water has a tendency to sink, when it is cooled during its advance to the south, while the subantarctic water does not have this tendency when being heated on its way north. This assumption is also in agreement with the more northerly position of the convergence suggested here, which lies at slightly higher salinities and temperatures than that shown by Deacon in this region.

IX. The Tropical Convergence

Between the Subtropical Convergence in the south and the Trade Drift in the north, an area is found where the water movements are generally eastwards. This flow is chiefly supplied by water masses of the East Australian Current, which turn east when the current breaks up, but in some months it receives also a considerable direct contribution of water from the Trade Drift, when its southern branch turns south of New Caledonia in a broad front south, and later east. Parts of these east-flowing water masses pass the north point of New Zealand as a rather strong current, parts turn north-east and sink along the Tropical Convergence.

In contrast to the Subtropical Convergence, which is caused by two factors, a discontinuity in the wind field, and by the general southward flow along the Australian east coast, the Tropical Convergence is an effect only of the wind field. It is related to the southern boundary of the trade winds, where the wind direction changes from south-west to south-east. This change in the wind direction necessitates a converging surface flow. However, it cannot be expected that the Tropical Convergence will be as pronounced as the Subtropical because the wind systems are variable and the change of wind direction occurs gradually; thus, the Tropical Convergence will be more or less an area of converging movements and will be subject to considerable fluctuations due to the actual wind distribution (Fig. 15). Records of the surface temperature along the route from Auckland to Fiji Islands, published by Garner (1955), show that this convergence can also sometimes be detected by a sharp rise in temperature.

February is the only month in which the Tropical Convergence is certainly not developed. During this month the water masses of the southern branch of the Trade Drift turn at about 30° S. in a broad front south and south-east and pass directly into the Subtropical Convergence, which extends in this month as far as the north point of New Zealand. South of New Caledonia the Trade Drift is slightly divergent.

TABLE 2

RELATIVE INTENSITIES OF VARIOUS DIVERGENCES AND CONVERGENCES IN THE CORAL AND TASMAN SEAS IN THE DIFFERENT MONTHS, GIVEN BY THE NUMBERS OF STREAM LINES BEGINNING OR ENDING IN THE RESPECTIVE AREAS

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Divergences:													
West Wind Drift Divergence	—	2	1	5	6	5	6	4	4	7	—	—	40
Divergence of the East Australian Current and off Bass Strait	6	3	5	2	1	1	7	1	4	7	12	8	57
Subtropical Divergence	—	—	—	—	—	—	—	—	—	8	—	—	8
Trade Drift Divergence	1	6	1	3	6	7	3	5	—	1	2	2	37
Coral Sea Divergence	6	1	3	6	9	8	5	5	11	6	9	5	74
Monsoon Divergence south off New Guinea	5	—	—	—	—	—	—	—	—	—	—	—	5
Sum of divergences	18	12	10	16	22	21	21	15	27	21	23	15	221
Convergences:													
Convergence off southern part of New Zealand	1	—	4	2	4	6	2	—	3	2	4	1	29
Convergence off northern part of New Zealand	3	3	3	1	2	—	2	3	3	2	3	1	26
Subtropical Convergence	14	21	5	11	10	4	9	13	10	11	6	10	124
Tropical Convergence	6	—	19	15	6	11	7	6	5	9	7	13	104
Convergence of the East Australian Current	11	10	8	10	11	8	6	5	5	5	6	7	92
Trade Drift Convergence	8	10	8	2	3	—	6	6	—	2	1	6	52
Coral Sea Convergence	3	4	3	2	6	5	5	5	4	4	3	6	50
Solomon Sea Convergence	4	3	2	6	4	2	3	3	1	1	1	1	31
Sum of convergences	50	51	52	49	46	36	40	41	31	36	31	45	508
Convergences minus divergences	32	39	42	33	24	15	19	26	4	15	8	30	287
Tropical plus Subtropical Convergence	20	21	24	26	16	15	16	19	15	20	13	23	229

This situation reflects the extreme summer conditions with a maximum southwards flow of warm water in the whole region. In March the northward shift of the wind system causes the formation of the Tropical Convergence just south of 30° S. It extends from the left boundary of the East Australian Current east of Sydney to the north of New Zealand, where an extensive region of convergent movements is found. The formation of this strong convergence leads simultaneously to a weakening of the Subtropical Convergence.

In April and May the westward extension of the Tropical Convergence becomes considerably shorter, the convergence is weakened, and parts of the water masses of the Trade Drift flow southwards to the west of the Tropical Convergence. In June the Tropical Convergence is formed again more intensively further northwards at

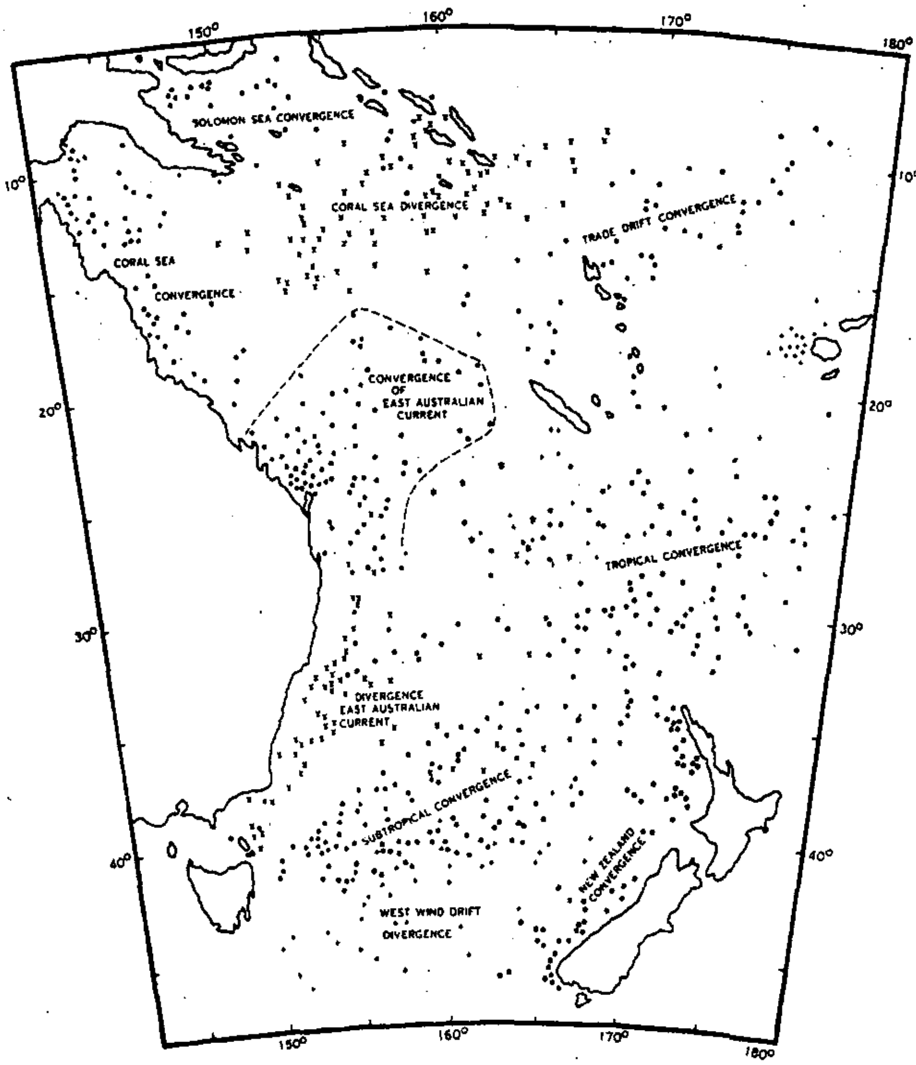

Fig. 16.—Regions of convergence and divergence in the Coral and Tasman Seas. ●, ○ Convergences; +, × divergences; * subtropical divergence, only in September.

about 26°S. Water masses of the Trade Drift still flow between the counter-current and the Tropical Convergence south. This flow is stopped in July when the counter-current has its strongest development. To compensate for this flow the East Australian Current develops a strong divergence and supplies the whole eastward drift between the Tropical and the Subtropical Convergences.

In August, when the counter-current has disappeared, water of the Trade Drift flows southwards again west of the Tropical Convergence and causes also the disappearances of the divergence in the East Australian Current. In September the southern boundary of the Trade Drift reaches its northernmost position. The Tropical Convergence is only weakly developed and lies east of New Caledonia. The supply of the eastward drift between New Caledonia and New Zealand cannot longer be maintained by the East Australian Current alone, and a very strong divergence is formed south of New Caledonia, in which considerable upwelling must occur. In this month, across the whole section from New Zealand to New Caledonia, a flow to the east occurs (Fig. 17), while normally a westward flow takes place in the northern and an eastward flow in the southern parts. In October the Tropical Convergence is formed again at 25° S. and is more strongly developed.

Until December the Tropical Convergence moves slowly southwards. The eastward drift between the two convergences is still broad and produces a considerable divergence in the East Australian Current. Simultaneously the Trade Drift south of the Fiji Islands becomes stronger and leads finally to the disappearance of the Tropical Convergence in January at about 33° S.

X. Regions of Divergence or Convergence

An analysis of the streamline charts has been made to indicate the main regions of divergent and convergent movements. For this purpose the positions where streamlines begin or end are plotted together in Figure 16, and are given numerically for the different months in Table 2. No regard was given to streamlines of short length, beginning and ending in the same region. The figures given in Table 2 are derived from the surface pattern of the streamlines, and are certainly not thought to give accurate numerical values of the amount of water sinking or upwelling. However, they give general information on the relative intensity of these convergences and divergences during the year. The dots in Figure 16 show clearly an accumulation in certain areas, indicating characteristic features of the general circulation as shown in Figure 13.

The Trade Drift Convergence is situated in the north-east of the region. It is most strongly developed during the monsoon period and indicates in February and March the boundary between the equatorial and the subtropical water masses. In July and August, when the trade winds are strongest, the Trade Drift is again convergent. When the Trade Drift turns south, north-west of New Caledonia, the surface flow becomes divergent and the Coral Sea Divergence develops. This divergence is present during the whole year, though it is weakened in February and March during the monsoon period. Two areas of convergence related to sinking are situated in the Solomon Sea and in the Coral Sea along the Australian coast. They absorb large parts of the water masses entering the Coral Sea from the east. An exception is found only in January when, due to the monsoon winds, upwelling occurs in the north-western part of the Coral Sea.

A large area of convergence off the coast of Queensland indicates the formation of the East Australian Current and is due to an increase in current velocity and a deepening of the current. The weakening, spreading, and breaking up of the current is shown by a divergence off the coast of New South Wales.

The water movements of the West Wind Drift are slightly divergent, especially during the winter season. The divergence is located between Tasmania and New Zealand and stretches to the north-east. Along the coast of New Zealand two patches of convergent movements are found, indicating sinking movements, when the water masses approach the shelf. The Subtropical Convergence stretches from Tasmania to the north-east, and its summer and winter positions are clearly indicated by the accumulation of dots (Fig. 16). North of the Subtropical Convergence another large area of convergence is found, indicating the Tropical Convergence which varies widely in its position during the year; thus, it partly overlaps the region in which the Trade Drift is divergent. This Trade Drift Divergence is always situated north of the Tropical Convergence. Only in September, when the Tropical Convergence reaches its most northerly position, are the water movements south of it highly divergent, and this divergence could be called the Subtropical Divergence.

This distribution of convergences and divergences corresponds with that derived by Hidaka (1955) from wind stress data. When comparing his average annual distribution of divergences and convergences with Figure 16 it can be seen that the Coral Sea Divergence appears, as well as the convergence along the coast of Queensland and the Tropical and Subtropical Convergences. Naturally, the convergence and the divergence of the East Australian Current do not appear in his charts because they are not formed directly by the winds but are boundary effects of the coast. In contrast to this, the agreement with the seasonal charts, also drawn by Hidaka (1958), is not so good; this seems to be due to the fact that the wind data for the South Pacific Ocean are still too meagre. A simple comparison of the smoothness of the distribution of divergence and convergence in the North Pacific Ocean with the roughness in the South Pacific Ocean supports this assumption. Moreover, it must be mentioned that Hidaka's values for the season from December to February for the South Pacific Ocean between 130 and 165° E. are based on incorrect wind data.

XI. The Water Balance of the Surface Circulation

The charts of surface currents and surface streamlines given here are used in this section to get some impression about the circulation and the water movements in the upper layer. Observations as well as theories have clearly shown that the boundary between the circulation in the upper and in the lower layers of the oceans lies at the lower boundary of the discontinuity layer, normally at several hundred metres. Even if the velocity of the currents decreases with depth the general direction of the flow is maintained, and therefore the circulation at the surface can be considered to be representative for the circulation in the upper layer of the ocean in general.

Examination of the streamline charts shows that the bulk of the water masses enters the region between the Solomon Islands and the Tropical Convergence with the Trade Drift and that this flow is even strengthened during the period from January to March by equatorial water masses driven by the monsoon winds. Also, between Tasmania and New Zealand there is a continuous surface flow to the north-east of subantarctic water, even if the transports might not be very high. The only area with an appreciable outflow from the region is to the north of New Zealand, between that island and the Tropical Convergence.

To illustrate the extent of this outflow, the surface currents along a line running from New Zealand to New Caledonia have been plotted in Figure 17 for every month. The boundary between the westward flow in the northern part and the eastward flow in the southern part indicates the position of the Tropical Convergence. This boundary is situated from December to May at about 30° S. During the winter months its position is more to the north, at about 26° S. In September the convergence lies as far north as New Caledonia, and in the whole area between New Zealand and New

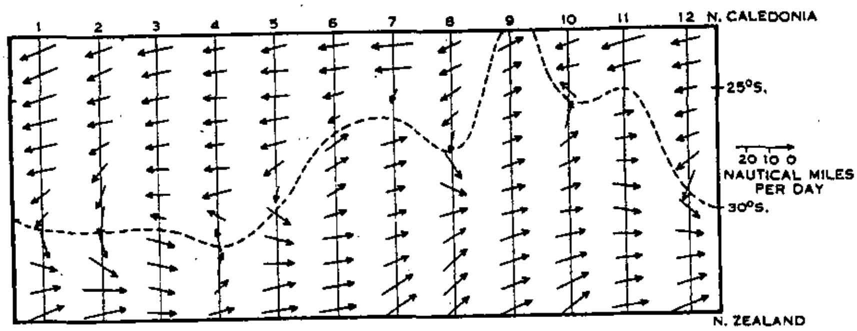

Fig. 17.—Annual variation of the surface currents along a section from New Zealand to New Caledonia and position of the boundary between eastward and westward movements.

Caledonia movements to the east are dominant. North of New Zealand the currents are normally of considerable strength. The annual variation of this flow indicates that during the summer, when the outflow north of New Zealand is comparatively weak, the surplus of the inflow into the region must be considerable and will require strong convergences. In the winter season, on the other hand, a part of the general inflow into the region will be balanced by the outflow north of New Zealand and the tendency for convergent movements will be smaller. This fact is clearly reflected in the totals of the convergences given in Table 2, which shows higher values from December to May and lower values from June to November.

Further, Table 2 shows that the total convergence is more than twice as large as the total divergence in the region and that in every month the convergence exceeds the divergence. This difference has, however, a considerable annual variation, with high values in summer and low values in winter. The difference between convergence and divergence reflects practically the value inflow minus outflow for the region, because

$$\text{Inflow} + \text{Divergence} = \text{Outflow} + \text{Convergence}$$

and therefore

$$\text{Inflow} - \text{Outflow} = \text{Convergence} - \text{Divergence}.$$

It shows that the highest surplus of inflow occurs from December to March. When comparing these differences with the sum of the values for the Tropical and Subtropical Convergences (Fig. 18) it can be seen that the annual variation of the two series corresponds, and that a high surplus of the inflow is related to strong convergent movements. When plotting the two groups of values against each other, as in the lower part of Figure 18, it becomes evident that the regression line does not go through the origin. This means that the Tropical and Subtropical Convergences

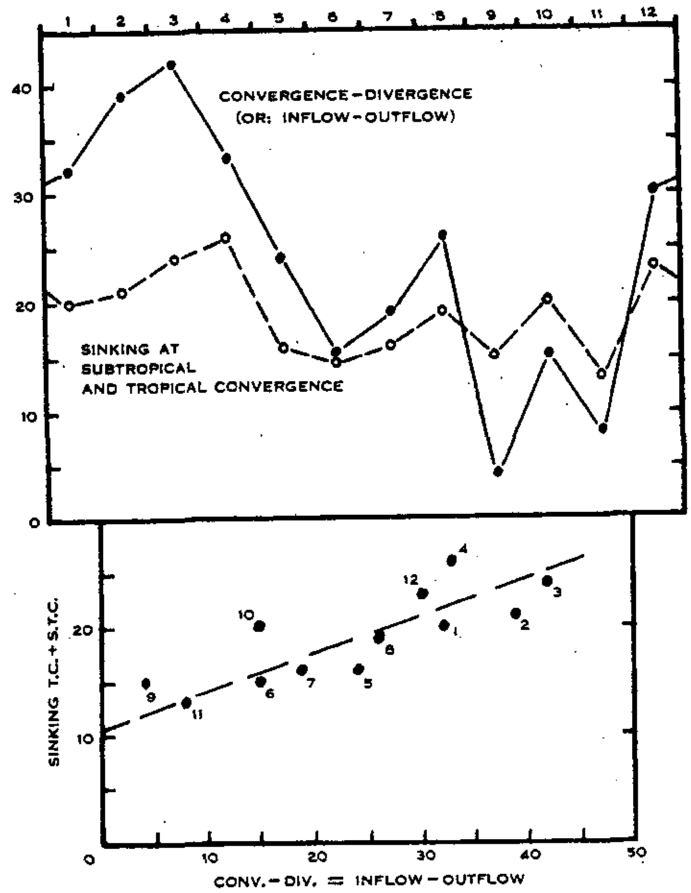

Fig. 18.—Annual variation of the intensity of convergent minus divergent movements in the whole region and of the Tropical and Subtropical Convergences in relative units.

would exist, even if there were no surplus of inflow into the region. From this the conclusion can be drawn that these convergences are an effect of the wind field and are not due to the surplus of inflow into the region; but this is already a well-known fact and is demonstrated by their occurrence in all oceans.

The total annual values show that about 80 per cent. of the surplus of convergent over divergent movements in the region is balanced in the Tropical and Subtropical Convergences. From this the conclusion can be drawn that the surplus of inflow into the region at the surface sinks practically along the two convergences. This then leads to the conclusion that a considerable transport of water out of the region must occur in intermediate or deep layers.

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