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OCEANOGRAPHY OF THE CORAL AND TASMAN SEAS*

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BATHYMETRY AND TOPOGRAPHY OF THE CORAL AND TASMAN SEAS

The Coral Sea extends between the Solomon Islands on the northeast, New Caledonia and the New Hebrides Islands on the east, and the coast of Queensland on the west while to the south it is limited by the Tasman Sea. To the northwest it communicates with the Arafura Sea by the shallow Torres Strait; at the Solomon Archipelago it opens on to the equatorial zone of the Pacific Ocean and comes under the influence of the central and tropical Pacific both in crossing the Archipelago of the New Hebrides and to the south of New Caledonia. The Coral Sea has a mean depth of the order of 2400 m with a maximum of 9140 m in the New Britain Trench.

The Tasman Sea is limited to the north by the Coral Sea, to the east by New Zealand, to the west by the coast of New South Wales and to the south by Tasmania; in the south it is largely under the influence of the Antarctic Ocean and in the west under that of the central South Pacific. The maximum depth is 5943 m.

BATHYMETRY

As is apparent from the most recent bathymetric chart of these oceans (Menard, 1964) they have a complicated structure which is particularly evident in the Coral Sea. The 3000 m level is an excellent indicator of the relative distribution of the principal basins which in general are well marked and separated at their sides by depths near to the mean for the area (Fig. 1).

The Coral Sea

Sprinkled with coral islands, the Coral Sea is essentially composed of three basins which are, from north to south and east to west, the Solomon Basin, the Coral Sea Basin, and the Basin of the New Hebrides. Along the Australian and New Caledonian coasts the sediments are essentially terrigenous; in contrast the Basins are filled with globigerina ooze except in the deepest and

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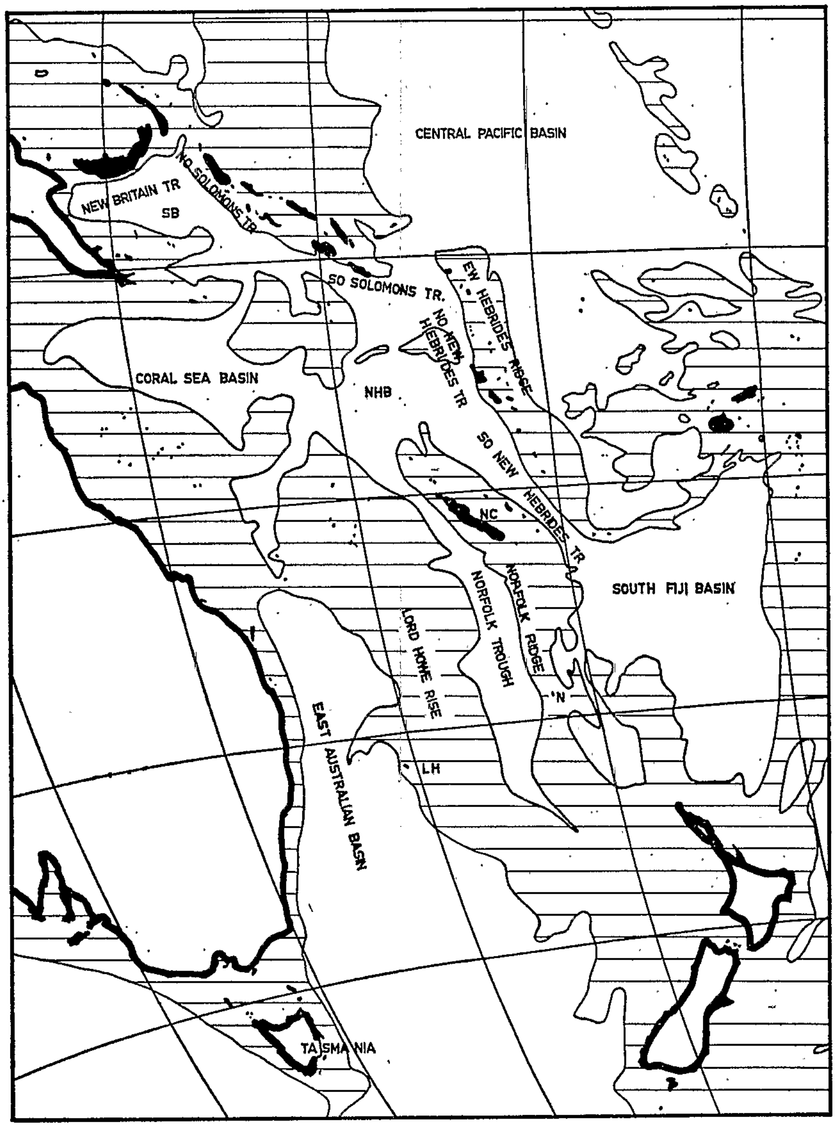


Fig. 1.—Configuration of the Coral and Tasman Seas; the 3000 m isobath clearly indicates the bottom topography (after Menard, 1964).

northern part of the Solomon Basin where one finds red clay. To the southwest along the coast of Queensland the Continental Shelf extends out some distance near to the 1000 m isobath, and, except for the extremely shallow Torres Strait, it is in this region that one finds the shallowest parts of the Coral Sea—from 13 m to 22 m.

The Solomon Basin. This is limited by the Solomon Islands, New Britain, New Guinea, and the Louisiad Archipelago and is divided into northern and southern basins by a ridge stretching from Woodlark Island to New Georgia, with the depth of the dividing sill lying at 3600 m. The southern and deepest part is made up of a basin limited by the New Britain and Bougainville Islands and at the Planet Deep attains its maximum depth of 9140 m. This Deep now termed the New Britain Deep, is prolonged eastwards as the North Solomon Deep. The eastern part, for long considered relatively shallow, in reality includes the South Solomon Deep lying to the south of the Guadalcanal Islands and San Cristobal and this, extending beyond the Archipelago towards the east, reaches the ridge of the New Hebrides and then curves towards the south to form the New Hebrides North Deep, where the bottom exceeds 7300 m.

The assemblage of the Solomon Basin communicates with the central Pacific between a point south of the Solomon Ridge and the northern extremity of the New Hebrides Ridge, traversing a sill which lies at a depth between 3000 m and 4000 m. Between the Islands of New Ireland and Bougainville is a second sill whose depth lies near to 2600 m.

The Coral Sea Basin. An abyssal plain lying at a depth between 4400 m and 4800 m occupies the largest part of the Coral Sea Basin. It communicates with the Solomon Basin at the east of Pocklington Reef by a channel whose sill lies at 3800 m and with the basin of the New Hebrides at the north of the Chesterfield Plateau by a sill which similarly lies at 3000 to 4000 m.

The New Hebrides Basin. This lies between the New Caledonia Ridge and that of the New Hebrides with a very considerable development towards the west, that is, to the north of New Caledonia. It contains the New Hebrides South Deep, with a maximum depth of 7660 m and debouches into the South Fijian Basin over a sill whose depth is greater than 4000 m. Towards 13° 30′ S. it is separated from the Solomon Basin by a ridge orientated east–west and ending at about 3000 m depth while it is prolonged towards the southwest almost to the Queensland coast; at the same time it forms the southern limit of the Coral Sea Basin.

Tasman Sea

Apart from a border of terrigenous deposits along the coasts of Australia, New Zealand, and Tasmania, the bottom of the Tasman Sea is made up of globigerina ooze. To the south of New Caledonia, however, there is a small zone of pteropod ooze and to the south of 30° S. one begins to find siliceous ooze. The Tasman Sea is made up essentially of the east Australian Basin at the westerly part, and the depression of New Caledonia to the east, the two being separated by the Lord Howe Sill joining the continental plateau of New Zealand to the Chesterfield Plateau. To the east the Norfolk Ridge unites the north island of New Zealand to New Caledonia thus separating the New Caledonia Depression from the South Fijian Basin.

The East Australian Basin. This is also called the Thomson Basin and is limited on the west by the Australian coast and on the east by the Lord Howe Sill; it extends to about 55° S. and, although the maximum depth is 4600 m there are many small depressions greater than 5000 m in depth; a maximum depth of 5943 m has been found to the northwest of Sydney. Towards the south this Basin is limited by the Indo-Antarctic Ridge with a depth of less than 3500 m, and this limits the northern movement of deep Antarctic water. The communication between the East Australian Basin and that of the Coral Sea is over a sill of which the depth is generally less than 3000 m.

The New Caledonia Deep. This is also called the Norfolk Deep and lies, as we have already seen, between the Lord Howe Sill and the Norfolk Ridge; its maximum depth, to the south of New Caledonia, is 4005 m. This Deep prolongs towards the south the eastern extension of the New Hebrides Basin from which it is separated by a sill at a depth near to 3000 m. Towards 23° S. a break in the Lord Howe Sill at the south of the Chesterfield Plateau allows communication with the East Australian Basin. Near 35° S., to the west of New Zealand, a narrow channel with a sill lying at 2050 m establishes connection with the Norfolk Basin whose depth exceeds 4000 m and which is itself joined to the South Fijian Basin by a narrow channel orientated north–south and whose depth is greater than 3000 m.

METEOROLOGY

CORAL SEA AND NORTHERN PART OF TASMAN SEA

Two quite different meteorological situations are characteristic of the North and South West Pacific; the one is established during the Australian summer between December and April–May and the other during the Australian winter, October to November. In summer a low pressure area occupies northern Australia, while in July a zone of high pressure covers the south of Australia (Fig. 2).

In the Coral Sea the Trade Winds form a stable wind system and blow from a direction varying between east and southeast. Very strong from May to December, they lie between 20° S. to 25° S. and the equator, and during this period their intensity and direction varies little. On the other hand, from December to April the zone of the Trade Winds is displaced towards the south so that their southern limit is at 30° S. while their northern limit lies between 10° S. and 15° S.; the wind system is less stable than in the Australian winter, the wind direction and force varying considerably, so that the Coral Sea is then under the influence of variable winds which may blow from the north, northwest or southeast.

North of the equator the monsoon comes from the north and is mixed with the Trade Winds from the northeast, which after passing the equator turn to the left; their direction oscillates, therefore, between northeast and northwest. In February the monsoon reaches the New Hebrides and the Fiji Islands (Wyrtki, 1960).

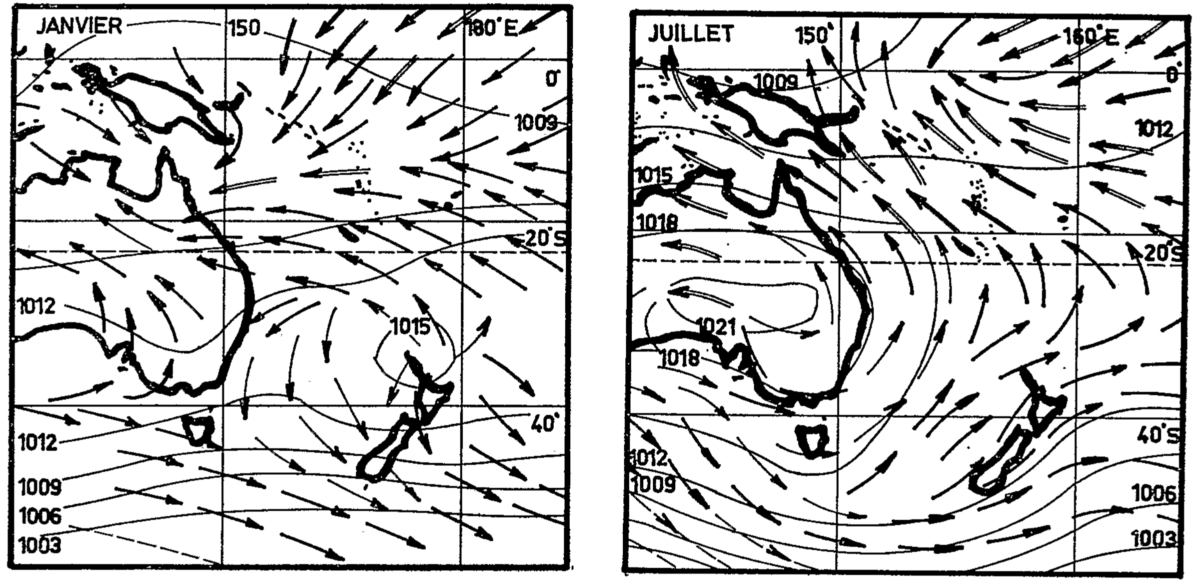


Fig. 2.—Mean meteorological conditions in January and July for the South West Pacific; direction of the prevailing winds; values of the stability of the direction are given as follows,

—▶ 25–40% ═▶ 60–80%
━▶ 40–60% ≡▶ >80%

(after Morskoi Atlas, 1958).

TASMAN SEA

The Tasman Sea is an area of very variable atmospheric circulation; to the south it is traversed by depressions going from west to east. The northern limit of westerly winds is near to 40° S. During the southern winter, from April to October, the northern branch of these winds from the west changes its direction towards the north and comes up against the Trade Winds; during this period, therefore, the Tasman Sea receives frequent winds from the southwest. On the other hand, in the Australian summer from November to March it is the southern branch of the Trade Winds which comes up against the west winds so that in the Tasman Sea, the winds come, more frequently from the north.

SURFACE CIRCULATION

GENERAL CHARACTERS OF THE SURFACE CIRCULATION

The surface circulation of the oceans is closely related to that of the atmosphere and the currents in general follow the direction of the wind, but slightly turning to the left. For example, between 20° S. and 10° S. the atmospheric circulation depends upon the presence over the Solomon Archipelago of a centre of low pressure connected with the Equatorial Depression which in December to April is situated to the south of the equator. This low pressure centre creates to the east of 160° E. northerly winds and induces a surface drift towards the south. There is, therefore, a penetration into the Coral Sea of water originating in the Equatorial South Pacific and traversing the Solomon–New Hebrides Sill. At the end of April, however, the Equatorial Depression approaches the equator and the regime of the Trade Winds is established. The formation of a drift towards the west drives water which originates in the Central South Pacific into the Coral Sea. One finds this drift, the Trade Wind Drift, to the west, to the north and to the south of the Fiji Islands and the New Hebrides, and it extends as far as the Coral Sea. The Coral Sea is closed on the west by the natural barriers of New Guinea and the eastern coast of Australia, and here has only the single opening of the shallow Torres Strait which only allows a weak water transport. The current derived from the west must therefore bifurcate to the south, where it forms the East Australian Current. One part of this excess water transported by the Trade Wind Drift dives, however, along the northern coast of Australia.

The East Australian Current flows towards the south as far as 40° S. where it appears to come under the influence of the westerly winds. At the junction of the southerly current and that derived from the West Wind Drift the former turns away from the coast and flows towards the east. Between Tasmania and New Zealand the northern branches of the westerly drift deviate from the mainstream and are directed towards the northeast where they meet branches of the East Australian Current. This convergent movement of the oceanic circulation which is added to the result of the atmospheric circulation makes up the formation of the Subtropical Oceanic Convergence situated at about 40° S. Further to the north along the southern boundary of the trade Winds and at about 30° S. is the Tropical Convergence. This convergence is the result of the junction of the current derived from the Trade

Winds and of branches of the East Australian Current after it has been deviated and turned away from the coasts.

All these surface currents are under the influence of the meteorological conditions and are displaced to the north or south according to the seasons and the wind regime; the force of the different branches of these currents depends, therefore, on a number of factors and their interaction. Only the

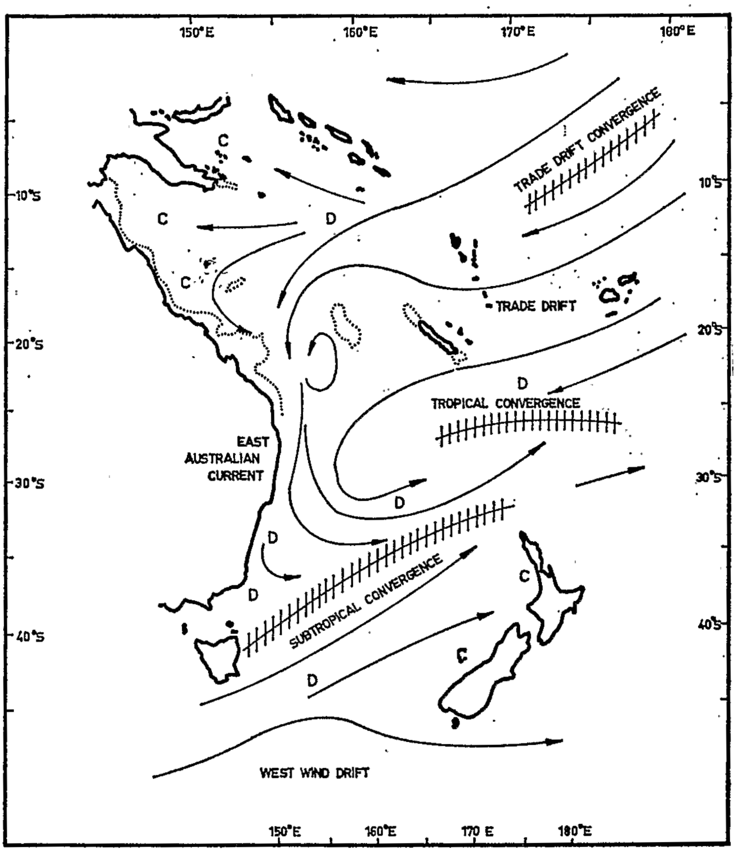


Fig. 3.—General characters of the surface circulation: C, regions of convergence; D, region of divergence (after Wyrtki, 1960).

East Australian Current and the northern part of the Trade Wind Drift have any marked stability. Generally speaking, the circulation in this region is *cum sole* (Fig. 3).

CURRENT DERIVED FROM THE TRADE WINDS

The Trade Wind Drift is found in the northern part of the South West Pacific where the Trade Winds blow and it is to be distinguished from the much swifter South Equatorial Current which lies further to the north in the neighbourhood of the equator. This South Equatorial Current, which can be identified all along the equator as far as about 164° E. is a relatively strong and stable current; it forms a well defined current whilst in contrast the Trade Wind Drift is wide and diffuse. To the west of 164° E, however, it is to be noted that there are considerable variations in the general direction of the South Equatorial Current.

The velocity of the Trade Wind Drift is a function of the season. In the neighbourhood of the Fiji Islands it is strongest between August and October, and weakest between February and April. Similarly, its extension varies with that of the Trade Winds and it is subject to considerable annual fluctuations. It has long been known (Hepworth, 1898) that during the monsoon season, from November to April, the surface current in the neighbourhood of the Fiji Islands instead of being orientated towards the south or southwest forms a strong easterly current; Evans (1938) has put forward the hypothesis that these surface currents are essentially under the influence of local winds, and this correlation is capable of explaining the convergence found by Russel (1898), without any need to appeal to a turbulent current as suggested by Dell (1952).

Trade Wind Drift during the Australian winter

Between April and December the water masses which are under the influence of the Trade Winds become displaced in a general east-westerly direction without being to any extent influenced by the presence of numerous groups of islands. To the north of the New Hebrides, New Caledonia, and the Chesterfield Islands, the width of the current decreases and its strength increases; the flow is therefore slightly converging and a zone of convergence, called the Trade Winds Drift Convergence, appears. Further to the north in the neighbourhood of the Solomon Islands the current divides into several branches. The main branch is orientated principally towards the south where it becomes part of the East Australian Current. Another branch prolongs the Trade Wind Drift towards the west and feeds the eastern part of the Coral Sea, whilst a third branch, turning towards the northwest, in the Solomon Sea, makes up the convergence of that name.

It is apparent, therefore, that in the Coral Sea the flow is generally divergent and that this divergence extends to the south of the Solomon Islands between 10° S. and 15° S.; it appears to persist throughout the season and in consequence becomes a marked character of that region. It may equally well be called the Solomon Divergence (Rotschi, 1961). The position of this coincides very closely with that of the best fishing region for the albacore (*Germo alalunga*) in the southwest Pacific (Yamanaka, 1956); the relative richness of this fishery is an indirect verification of the existence of this Divergence since its vertical turbulence furnishes a basis for the development and maintenance of a pelagic fishery.

As one has seen above, the part of the western branch which continues to be displaced towards the west comes up against the northeastern coast of Australia, and cannot be found in the Torres Straits whose shallow depth does not allow its passage; it must therefore to a large extent plunge deeper down. As a consequence there exists in the northwest of the Coral Sea a zone of convergence which is quasi-permanent. That part which does not plunge down is turned towards the south and becomes integrated with the East Australian Current.

In the Solomon Sea the current lines converge in the same way (Wyrtki, 1960); it is probable, therefore, that the surface water in the eastern part near to New Guinea also plunges down.

The Trade Wind Drift in the Australian summer

Between January and March, when the monsoon blows over the whole northern part of the Coral Sea, the regime of wind driven currents is profoundly modified. Equatorial waters originating from the north and northeast of the Coral Sea flow towards the southwest between the Solomon Islands and the New Hebrides, and then supplement the East Australian Current. Between February and March a very marked convergence develops to the northeast of the New Hebrides; it appears between the monsoon current towards the southwest and the Trade Wind Drift towards the west, although during this period the Trade Wind Drift, itself displaced towards the south, has its principal flow to the south of the Fiji Islands. The surface circulation in the Coral Sea is equally under the influence of the monsoon. For example, in January the northwest winds create a general flow towards the southeast. This gives rise along the south coast of New Guinea to a violent upwelling whose existence is evident only during this month. In February and March, on the other hand, since the presence of the tropical depression creates an extremely variable wind regime, the currents are likewise irregular.

The southern limit of the Trade Wind Drift is very unstable; under the normal meteorological regime it corresponds in position to the Tropical Convergence; in effect, the water of the Trade Wind Drift which passes to the north of the Fiji Islands and New Caledonia is largely integrated into the East Australian Current while the water which is displaced to the south of these islands is deviated southwards and plunges under the surface at the Tropical Convergence where it encounters water derived from the East Australian Current. Between December and May the southern limit of this current towards the west is situated in the neighbourhood of 30° S. From June onwards this limit is rapidly displaced towards the north, the extreme northern position being attained in September; during this month the westerly current to the south of Fiji is reduced in extent and weak in strength; to the south of New Caledonia this current may even be reversed and turn to the east. During October and December the Tropical Convergence is displaced again towards the south.

EAST AUSTRALIAN CURRENT

The East Australian Current, which is found along the Australian coast, is relatively strong but narrow; its transport varies between 10 and 25×10^6 m^3/sec.

Often compared with the Gulf Stream and Kuroshio, the East Australian Current is essentially different because it does not, as do the other two, make up an eddy system extending towards the east across the ocean. On the contrary it disappears rapidly when it leaves the coast because the Australian continent terminates at about 44° S., and further to the south one meets the circumpolar current which itself constitutes a totally independent system. In contrast, the Gulf Stream and the Kuroshio compensate their flow towards the east in temperate latitudes by a flow towards the north of tropical water accumulated by the equatorial circulation; the East Australian Current having only a weak flow towards the east is hardly comparable to the other two. Further, the former is very much influenced by local meteorological conditions which particularly effect its southern extremity.

We have already seen that the East Australian Current is caused by an accumulation in the Coral Sea of water which, being unable to escape towards the west follows the configuration of the Australian coast and turns towards the south. It arises, therefore, at about 20° S. between Chesterfield Island and the Great Barrier Reef, that is, between 158° E. and 153° E. Between January and March it is made up of equatorial water entrained towards the west-southwest by the monsoon drift. Between April and December it is made up of subtropical water originating in the South Central Pacific and transported into the Coral Sea by the Trade Wind Drift. From 20° S. to 25° S. the current is enriched laterally at the same time as it narrows; it is reinforced, therefore, and at the same time the convergence so created increases the thickness of the current. The movements of the convergence are localized in two regions. Along the northern part of the western border the current is enriched by water from the Coral Sea which flows above the shoals between the land and the Great Barrier Reef to the north of Great Sandy Island. Along the eastern border, the current is augmented by water drifting to the south of Chesterfield Island with the Trade Wind Drift; this increase extends quite far to the south. Between 20° S. and 25° S. the annual variations in speed of this current are extremely weak. On the other hand between 25° S. and 30° S., where it attains its maximum intensity, there are very marked annual variations; the speed is maximal in February, and minimal in the southern winter when south winds predominate, but reaches a second maximum in September. To the south of 32° S. the East Australian Current is considerably enlarged and almost the whole of the water which it transports turns towards the east. This characteristic is particularly evident between July and January when the current is under the influence of west and southwest winds accompanying the fronts of atmospheric depressions which traverse the region. When the current deviates from the coast a marked divergence appears which is accompanied by upwelling. The thickness of the East Australian Current which, to about 30° S. is a gradient current, is much diminished therefore when it is turned towards the east. Between 30° S. and 35° S. its velocity is considerably reduced and it varies in the same way as in the northern part with the maximum in summer.

During winter and under the influence of strong south winds a counter-current appears to be developed to the east of the East Australian Current. Such winds, with a force greater than six, only blow from April to July so that the counter current is not permanent.

WEST WIND INDUCED CURRENTS

A current derived from the action of the west wind (West Wind Drift) is present to the south of Australia and New Zealand. Since it is dependent upon the depressions ruling in the south of the Tasman Sea it is irregular in force and direction.

Throughout this region the general direction to which the wind blows is east-northeast and the surface current between Tasmania and New Zealand, is therefore principally directed towards the northeast; because of a latitudinal extension of the barrier which constitutes New Zealand, a branch of this West Wind Drift enters the Tasman Sea, where it comes up against the Subtropical Convergence. Between April and October when this Convergence occupies its most northerly position the current to the northeast is slowly divergent. As it approaches the western coast of New Zealand the northeast current becomes weak and irregular and only a small quantity of the water of this current passes round the north of the Island, the greater part being absorbed by the Subtropical Convergence and by the local convergences which it produces along the west coast of the North Island. Rochford (1957) considers that in this region of weak and variable currents where one finds numerous convergences and where the water masses are relatively stationary the latter form an independent water mass which he has called the "East Central New Zealand Water Mass".

REGIONS OF DIVERGENCE AND CONVERGENCE

Hidaka (1955, 1958) considering the forces arising from the winds has studied the seasonal variations of the zones of convergence and divergence of the surface currents. It appears that during the southern summer a strongly marked zone of divergence occupies all the northeastern part of the Coral Sea from New Caledonia to the Solomon Islands and is prolonged southwards into the centre of the Tasman Sea, as far as 35°S. Along the Queensland coast of Australia there is a strong convergence. In winter the localized divergence in the same region also covers, in the centre of the Tasman Sea, a zone extending from Tasmania to the north of New Zealand, but at the same time its intensity throughout the southwest Pacific is considerably reduced. In the southern spring the whole of the Coral Sea and the northern part of the Tasman Sea are occupied by a weakly marked convergence which extends far to the east between 20° S. and 30° S. In the southern autumn the south and northwest of the Coral Sea is occupied by a poorly defined divergence; also there is a weak convergence between 20° S. and 10° S. at 160° E. and in the Tasman Sea along the same meridian two weak centres of divergence. This scheme put forward by Hidaka on the basis of the wind regime is little different from that derived by Wyrtki (1960) from an examination of the surface currents.

For the practical point of view it is in the northeast of this region that one finds the convergence of the currents derived from the Trade Winds. This convergence attains its maximum development during the period of the monsoon in February–March, that is to say the southern summer, and it indicates the limit between waters of equatorial origin and those of the Subtropical Central Pacific. In July and August, in the southern winter, when the Trade Winds are best established the resultant current is strongly convergent to the east of New Caledonia, that is between there and the Fiji Isles; but, when to the northwest of New Caledonia the current bifurcates towards the south, a divergence arises in the Coral Sea. This divergence exists throughout the year although it becomes weakened in February–March, that is, during the period of the monsoon.

The obstacle which opposes the barrier constituted by Australia and New Guinea to the drift is such that convergences are created at the western border of the Coral Sea. These convergences absorb the excess water entrained in the Coral Sea over that transported by the East Australian Current. One convergence is localized to the north along the New Guinea coast and another along the coast of Queensland; the latter is accompanied by an increase in the speed of the East Australian Current which also increases in thickness. A weak upwelling also develops in January, during the period of the monsoons, in the northwest of the Coral Sea. Near to New South Wales a divergence indicates the weakening, broadening, and change in direction of the East Australian Current.

We have noted that the movement of the West Wind Drift is slightly divergent, particularly during winter when the divergence is situated between Tasmania and New Zealand. Along the coast of New Zealand, as the current reaches the continental shelf, there are two regions of convergence. There is also a relatively weak divergence in the Trade Wind Drift and this is situated to the north of the Tropical Convergence, but in September when this convergence attains its most northerly position the movement of the water towards the south becomes divergent; there appears then to be a seasonal Subtropical Divergence. Meanwhile the most important surface movements and those which play a fundamental role in the dynamics of the southwest Pacific are the Subtropical Convergence extending towards the northeast as far as Tasmania, the Tropical Convergence whose position varies seasonally between New Caledonia, and New Zealand, and the Solomon Divergence in the Coral Sea.

Subtropical Convergence

The region of convergent movement which extends from Tasmania to the northern extremity of New Zealand corresponds largely to the limit between the Subtropical Water Mass transported to the south by the East Australian Current and the Subantarctic Water Mass transported to the northeast by the West Wind Drift. While the Convergence is not entirely due to differences in the physical properties of these water masses it is quite apparent that they are extremely contrasted; in effect the downwelling along the Convergence causes mixing between the water masses of different origin. These differences of density are not the only cause of the formation of the Convergence since the latter is probably favoured by a given meteorological regime.

The West Wind field which causes the drift towards the northeast is far from uniform and there exists a remarkable discontinuity at the northern limit of this wind field; because of a decrease towards the north of the intensity of the west winds, a zone of convergence is created at the level of this discontinuity which is the Subtropical Convergence. The northern limit of the West Wind field, being a climatological characteristic, the position of the Convergence is not stationary but varies with general climatic conditions. One must consider, therefore, that rather than being a continuous 'line' the convergence is formed by the juxtaposition of several zones which themselves produce convergent movements and which may also disappear.

The Subtropical Convergence is certainly reinforced by the water masses of the East Australian Current when they meet the West Wind Drift; but it is quite difficult to make an exact distinction between the parts played by a reduction northwards of the west winds, and by the confluence of a gradient current and a wind driven current in the formation and maintenance of the Convergence. The position of the Subtropical Convergence varies with the season; nevertheless, its western extremity is always near to the eastern coast of Tasmania along which the East Australian Current meets the Subantarctic Water Mass transported eastwards by the strong current circulating along the extreme south of Tasmania. During the summer months from November to April, the Convergence is at its most southerly position; it is displaced towards the north during the winter months. During October–November it seems to disappear to the north to reappear in a much more southerly position. It normally disappears between 165° E. and 170° E. before reaching the north of New Zealand and a part of the current therefore contours the north of New Zealand.

The volume of water of subtropical origin which plunges at the Convergence is greater than that of the water of subantarctic origin downwelling at the same time. The cooling down of the strongly saline water which is displaced towards the south favours the tendency for it to plunge under the less saline water from the south which in contrast, has been warmed up. The amplitude of the downwelling of the waters throughout this Convergence varies with a semi-annual periodicity, the maxima being attained in January–February and in August (Wyrtki, 1960).

The Convergence always appears along the east coast of Tasmania and probably it does not exist to the west of this island. Deacon (1937), who has indicated a much more southerly position than that given by Wyrtki (1960) has suggested that the absence of a definite convergence between the Subantarctic Water and Subtropical Water to the south of Australia is essentially due to the weakness of the northern and southern components of the two currents; the southerly position which he has suggested leads him to believe that in the Tasman Sea to the west of New Zealand the Convergence is badly defined. These two authors are in agreement in considering that the Subtropical Convergence is the limit between the Subtropical Water which flows with a weak component towards the south and the Subantarctic Water which has only a weak component towards the north. It must be noted that Deacon (1937) determined the position of this limit from the distribution of surface temperature and salinity while Wyrtki's (1960) conclusions were based on current observations. According to Deacon (1937) the heavier Subantarctic Water must downwell at the Convergence in greater quantity than the Subtropical Water but Wyrtki (1960) considered the greater part of the downwelling water is made up of Subtropical Water. As we have already seen the more saline Subtropical Water becomes much heavier in its displacement towards the south, while the Subantarctic Water becomes less dense as it is displaced towards the north.

Tropical Convergence

Between the Subtropical Convergence on the south and the Trade Wind Drift to the north, that is, between New Zealand and New Caledonia there is a region in which the current flow is generally eastwards. This current is largely composed of water derived from the East Australian Current which turns towards the east at the latitude of southern Australia; at certain times it receives a considerable body of water transported by the West Wind Drift as is particularly the case when the branch of the Trade Wind Drift passes to the south of New Caledonia and forms a large front which turns first to the south then to the east. Part of the water transported towards the east turns round the northern extremity of New Zealand and part is turned towards the north where it meets the Tropical Convergence along which it downwells. In contrast to the Subtropical Convergence which is formed and maintained by the resultant of two factors, namely, the junction of two currents and the variation of the field of the West Wind, the Tropical Convergence has a single cause, and this is the wind field of the Trade Winds. At their southern limit the Trade Winds turn from southeast to southwest and this change in direction creates a superficial zone of convergence—the Tropical Convergence. The regime of the winds being essentially variable and the changes in direction being produced gradually, the Tropical Convergence is not so well marked as the Subtropical Convergence. It is more a region of convergent movements under the influence of the considerable variations of the wind regime.

Garner (1955), analysing the distribution of surface temperatures between Auckland and the Fiji Islands, has shown that this Convergence can be detected by a distinct thermal front, while Rotschi (1960a, 1962a), and Rotschi and Magnier (1963) have found that between New Caledonia and Norfolk Island the Tropical Convergence is associated with a horizontal temperature gradient of the order of 1° C per 30 miles.

The Tropical Convergence only disappears during the month of February when the southern branch of the Trade Wind Drift, turning at about 30° S., attains the Subtropical Convergence which extends during this period right to the northern extremity of New Zealand; under these conditions the Trade Wind Drift is slightly divergent to the south of New Caledonia. It is in the southern summer that the transport of warm subtropical water in a southern direction attains its maximum. About March, the Trade Winds System being displaced towards the north, the Tropical Convergence appears at about 30° S.; it extends from the East Australian Current at the east of Sydney, to the north of New Zealand where there is a vast region of convergent movements. The formation of this Convergence induces a weakening of the Subtropical Convergence. In April and May the extension of the Subtropical Convergence to the west is reduced, the Convergence itself is weakened and a part of the water, transported by the West Wind Drift, extends towards the west and turns south. In June the Convergence is displaced towards the north attaining 26° S., and is strengthened. One part of the southern branch of the West Wind Drift flows towards the south between the western extremity of the Convergence and the countercurrent to the east of the East Australian Current. When in July the countercurrent attains its maximum development that of the West Wind Drift towards the south is completely inhibited; on the other hand, the East Australian Current develops a strong divergence along the southwestern coast of Australia, and forms the whole of the drift current towards the east between Tropical and Subtropical Convergences. In August when the East Australian Countercurrent has disappeared the water masses derived from the Trade Wind Drift turn towards the south to the west of the Tropical Convergence and at the same time the divergence of the East Australian Current disappears. When, towards September, the southern limit of the Trade Wind Drift reaches its most northerly position, the convergence is weak and situated to the east of New Caledonia. During this period the East Australian Current is unable alone to give rise to a drift current towards the east, between New Caledonia and New Zealand, so that an important divergence appears to the south of New Caledonia; contrary to the normal situation where one finds westerly currents in the proximity of New Caledonia and an easterly current much further to the south, the current during September is to the east throughout the whole region.

In October a more marked convergence appears at about 25° S. and up to December it is slowly displaced towards the south. The easterly current between the Tropical and Subtropical Convergences is still quite wide and creates a noticeable divergence in the East Australian Current. Simultaneously, the Trade Wind Drift at the south of the Fiji Islands is increased and extends further to the south; in January the Tropical Convergence vanishes at about 33° S.

Divergence of the Coral Sea

This Divergence appears to the northwest of New Caledonia between 10° S. and 15° S. in the neighbourhood of 160° E. when the Trade Wind Drift modifies its course and inclines to the south. It persists throughout the year but is weak during February–March. The position of this Divergence is closely dependent upon the strength of the surface currents; it is related to the wind regime with which it varies (Hidaka, 1958).

It shows itself essentially in the form of a dome structure (Rotschi, 1961, 1962a) which can be detected in all the physical-chemical properties of the water. Its apparent influence is limited to the subsurface layers (Rotschi, 1962a), the uppermost 100 m not being modified by vertical movement. But, on account of the extreme transparency of the water the subsurface layers close to the compensation depth are enriched by nutrients, so that this region (also called the Solomon Divergence) is clearly more productive than the surrounding water; the zooplankton biomass (Legand and Rotschi, 1962) and the catches of tunny are greater than further to the south.

The connection between the intensity of vertical movements and the surface circulation which is under the influence of meteorological conditions has been well illustrated; in particular the slope of the isolines depends directly upon the location of the centre of geostrophic depression and the geostrophic slope of the surface. Some observations have shown that the period of attenuation of this Divergence, which on the average is between February and March, may be displaced in June.

WATER MASSES

GENERAL

A study of the water masses may be based on the distribution of any conservative property. For example, in the whole of the Subtropical South Pacific one finds a maximum subsurface salinity between 100 m and 200 m depth. The distribution of this maximum shows that the salinity attains its highest value at the centre of the tropical gyre, where this maximum reaches the surface. This salinity maximum defines therefore a type of water termed Subtropical Lower and this water is found throughout the layer of maximum subsurface salinity (Chaen, 1960). In the same way the minimum value of the salinity which one finds at about 1000m is associated with a layer which emerges in the neighbourhood of the Antarctic Polar Front; it is in this region, therefore, that one finds the lowest salinities and this minimum zone is occupied by Antarctic Intermediate Water, identifiable throughout the layer by its minimum salinity. In consequence there exists throughout the whole southwest Pacific a stratification of the water masses so that one finds

Subtropical Lower Water and then Antarctic Intermediate Water lying above the deeper layers. Even so, the limit between these different water masses is often difficult to define precisely. In effect all the water lying between the centre of the Subtropical Lower Water and the central layer of the Antarctic Intermediate Water is a mixture of these two types. On this account one cannot attribute precise limits to each water mass unless this is defined by a certain percentage mixture, 50% of each for example, the limit being naturally deduced from T-S diagrams, and the properties attributed to each water type.

If, on the other hand, one utilizes as the definition of a water mass the rectilinear part of the T-S diagram expressing the mixture between the subsurface and deep types, all the intermediate layer of the mixture becomes what Sverdrup has called the Central Southwest Pacific Water Mass, which must not be confused with Central South Pacific Water—which in what follows will be termed Subtropical Lower Water and which is slightly modified as it flows towards the west.

SURFACE AND SUBSURFACE WATER MASSES

General characters of the distribution of temperature and salinity

In the tropical and subtropical zone of the southwest Pacific the surface temperature is closely dependent upon the season. In the southern summer the temperature throughout the Coral Sea attains a more or less uniform value between 27°–28° C; in contrast, during the winter a zonal distribution accompanies the cooling and this is particularly apparent in the south of the Coral Sea where the lowest temperature reaches near to 20° C yet to the north, near the Solomon Islands, it is 27° C. In the Tasman Sea (Garner, 1954) the seasonal variations of temperature are more marked and zonation in the temperature distribution is likewise more evident. In the southern winter the temperature is of the order of 10°–11° C in the south and 20° C to the north, whilst in summer the former reaches 14°–15° C and the latter 27° C (Bruns, 1958). The monthly mean temperatures attain their extreme values in February in the southern summer and in August in the winter.

The salinity is maximal, greater than 35·90‰, in the surface waters to the north of New Zealand and from here a subsurface maximum salinity extends northwards at a depth between 100 and 200 m. Between the surface and this subsurface maximum the salinity increases with depth and varies with latitude. It is near to 34·50‰ to the south of New Zealand, reaches 35·50‰ in the latitude of New Caledonia and decreases again in the neighbourhood of the Solomon Islands to 34·50‰; in the north of the Coral Sea, therefore, the surface waters are strongly influenced by equatorial waters which are warm but of lower salinity.

The influence of the seasonal cycle on the properties of the superficial waters between New Caledonia and Australia have been studied in detail by Lemasson (1965) and Rotschi (1960b).

Primary water masses, derived water masses, and modified water masses

Rochford (1957, 1958a, 1959) has attempted to define the nature of the water masses which are found in this region as well as their origin and mode of formation. He has thus been able to define certain primary types with a large geographical range which are formed in precise zones by the action of constant physical factors; the mixture of these primary types gives derived water masses with a less extensive geographical range; under the action of local factors these derived water masses have their properties distinctly changed and are transformed into modified water masses whose distribution is grossly limited.

Three primary types appear to be at the basis of the formation of the surface waters of the southwest Pacific. To the north there is the South Equatorial Water with minimum salinity of the order of 34·69‰ and whose temperature varies between 28·2° C and 28·8° C in summer. To the south is the Subantarctic Surface Water with a salinity also of 34·69‰ but whose temperature is 9° C in August and 12° C in December. The third primary type is made up of the core of the subsurface maximum salinity formed from the Central South Pacific Water or Subtropical Lower Water and the temperature is 26° C and the salinity maximum 36·00‰.

The properties of the surface water depend upon the nature of the mixtures between these three primary types, the mixtures themselves being subject to a seasonal cycle. We may recall that the properties of the surface waters derived from these mixtures vary less in tropical waters than in subtropical waters, and even less than in subantarctic waters. Clearly the properties of the surface water of the Tasman Sea depend on the quantity of tropical water whose properties show relatively little variation with season.

Between August and October the Coral Sea has a layer of surface water with high temperature and low salinity and this layer extends down to the subsurface salinity maximum where the temperature is variable. The intermediate layer is mixed with deeper water which has subantarctic properties and which one finds at the surface in the Tasman Sea. The surface water is formed from three primary waters already defined (Fig. 4). During this period the South Equatorial Water extends from the equator at about 170° W. into the Coral Sea and, while retaining its essential characteristics, its extension towards the south is less along the western border of the Coral Sea and the Tasman Sea (where it disappears at about 35° S.) than along the 170° E. meridian.

The water of the Central South Pacific with high salinity lying towards 150° W. and 15°–20° S., that is in the region where it is formed, represents 80% or more of the total mass of the surface and subsurface waters. To the west and north of this region its abundance decreases in the surface waters which are enriched by equatorial water. In the southwest Pacific, in the southern part of the Coral Sea, and in the northern part of the Tasman Sea is found a surface current which originates in the Central South Pacific. This current, penetrating the region between New Caledonia and New Zealand, is composed partly of Central South Pacific Water and partly of South Equatorial Water. In the Tasman Sea, at the southern part of this current the South Equatorial Water is replaced by Subantarctic Water; the character of the mixture between the Subantarctic Water and the Central South Pacific Water depends only on latitude; this is probably due to the sinking of the Subantarctic Water in its passage northwards.

In December the quantity of South Equatorial Water in the Tasman Sea diminishes; it is more abundant in the eastern part of this Sea where its extension along 170° E. already noted during the southern winter seems to be maintained in summer. The water which reaches the southwest Pacific between New Caledonia and New Zealand contains 75% of Central South Pacific Water and 25% of South Equatorial Water. In contrast, Subantarctic Water is found in small quantities along the eastern coast of Australia. Towards 25° S. at 100 m depth in the Tasman Sea South Equatorial Water is no longer found. To the north of 32° S. the Central South Pacific Water is very abundant; further to the south it is gradually replaced by Subantarctic Water (Fig. 5). In the northern part of the Tasman Sea the hydrological structure is similar to that of the Coral Sea about the month of August. In

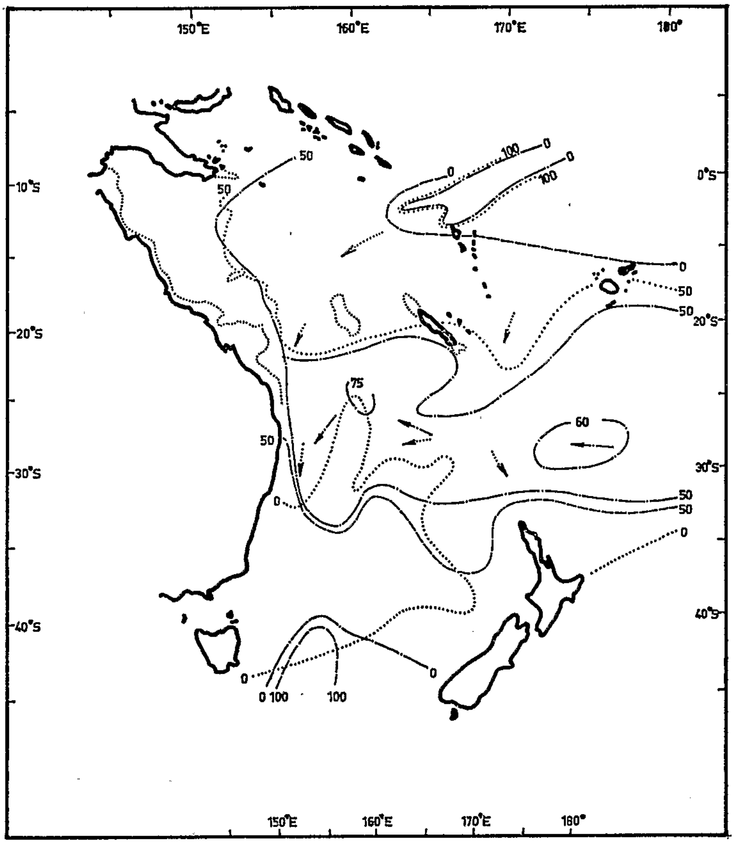


Fig. 4.—Composition of the surface waters in August: ···· Equatorial Water; —·—·— Central South Pacific Water or Subtropical Lower Water; – – – – Subantarctic Water (after Rochford, 1959).

addition, the northwest of the Coral Sea is strongly influenced by a water mass from the area of the Arafura Sea, water which is warm (28° C to 29° C) and of low salinity (34·14‰).

In analysing in great detail the properties of the upper layers in the southwest Pacific, Rochford (1957) has shown the existence of numerous derived water masses and his hydrological description of the region particularly that of the Tasman Sea (Garner, 1959) may be summarized as follows (see Table I).

The primary waters which make an essential contribution to the formation of the surface and subsurface waters of the Tasman Sea are: Coral Sea Water, formed by a mixture of South Central Pacific Water and Equatorial Water, whose temperature lies between 20° C–26° C and salinity between 35·41‰–35·59‰, and which is abundant during October and May and Subantarctic Water, derived from Antarctic Water and abundant between May and September, which is cold (10–14° C) and has a low salinity (34·60–34·87‰). Also present in the Tasman Sea is a primary internal water, the Central

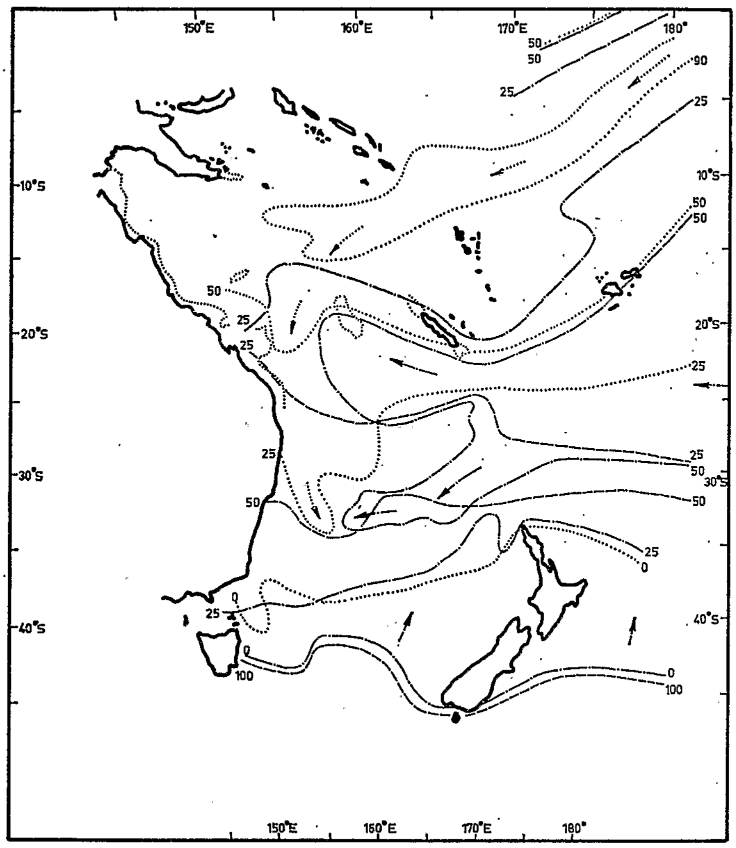


Fig. 5.—Composition of the surface waters in December: ···· Equatorial Water; —·—· Central South Pacific Water; – – – – Subantarctic Water (after Rochford, 1959).

Water of the Tasman Sea which is formed of Coral Sea Water between June and December by cooling at an intermediate depth; its temperature lies between 15° C and 20° C and salinity between 35·50‰ to 35·68‰.

The mixture of these waters results in the formation of several derived and one modified water mass. Between June and December, south of 38° S. in the southwest of the Tasman Sea, there is a water mass which is formed east of the Bass Strait. It is derived from a mixture of Subantarctic Water and Central Tasman Sea Water; this is the water of the southwest of the Tasman

TABLE I

Principal primary and derived water masses (after Rochford, 1957)

	Coral Sea	Subantarctic	Tasman Sea Central	Tasman Sea Southwest	Centre N.Z.	Tasmanian Coasts
S‰	35·41–35·59	34·60–34·87	35·50–35·68	35·23–35·41	34·51–34·87	35·05–35·23
T° C	20–26	10–14	15–20	12–15	15–20	10–14
Origin	N.W. Coral Sea	Australian Ocean	Tropical Convergence	East of Bass Strait	East of Cook Strait	Coasts of Tasmania
Nature	Primary, external	Primary, external	Primary, internal	Derived	Derived	Modified
Formation	Mixture of South Equatorial and Central Pacific Water	Rewarmed Antarctic Water	Rewarmed Coral Sea Water	Mixture of Central Tasman water and Subantarctic	Rewarmed Subantarctic Water	Diluted by run-off
Season of maximal extension	October May	May September	June December	June December	December April	April December
Region of extension	Western Tasman Sea	Surface south of 45° S.	Southern Tasman Sea	South of 38° S., southwest Tasman Sea	West of North Island, New Zealand	Coast of Tasmania

Sea with a salinity lying between 35·23‰ and 35·41‰ and a temperature between 12° C and 15° C. To the west of the North Island of New Zealand the heating of the Subantarctic Water during its passage through the Cook Strait results in the formation of Central New Zealand Water with a salinity between 34·51‰ and 34·87‰ and a temperature between 15° C and 20° C. Finally, dilution by run-off of the waters of the Bass Strait results in the formation between April and December of water with a relatively low salinity (35·05–35·23‰) and a temperature from 10° C to 14° C and this water, specific to Tasmania, is found all round that island.

Chemical properties of the surface and subsurface waters

The chemical properties of the surface and subsurface waters of the northwest Coral Sea and their seasonal variations have been studied in detail during cruises of the ORSON III (Rotschi, Angot and Legand, 1959a, b; Rotschi, Angot, Legand and Desrosières, 1961; Rotschi, Legand and Wauthy, 1961).

In September 1960, at the centre of the Solomon Divergence the concentration of oxygen in the surface and subsurface waters was of the order of 4·10 ml/l, that is, 92% saturation. To the north and south of the Divergence the concentration of oxygen increases rapidly although the water still remains under-saturated; in the neighbourhood of the Solomons, as well as to the north of New Caledonia, the oxygen concentration in the surface layers can attain 4·40 to 4·50 ml/l.

In May 1960 the concentration of oxygen in the surface waters lay between 4·45 ml/l and 4·65 ml/l and varied little with latitude; in general the oxygen content is less in low latitudes when the water is warmer and less saline. The centre of the Divergence also has a zone with a lower oxygen concentration but everywhere the water is at least 100% saturated. Between May and September, 1960, the concentration of oxygen in the superficial waters diminished north of 20° S., and was increased further to the south. For example, the oxygen content in the centre of the Solomon Divergence had decreased from 4·40 ml/l in May to 4·10 ml/l in September. In contrast, at the latitude of New Caledonia the concentration of oxygen had increased from 4·60 ml/l to 4·90 ml/l. These changes are due less to physical factors at the surface than to biological processes; effectively, the salinity has remained virtually constant whereas the temperature has diminished so that the solubility has decreased. In general the concentration of oxygen decreases from May to September because of biological utilization.

In September 1960 the concentration of dissolved inorganic phosphorus was everywhere extremely low, less than 0·15 mg–at./m^3 except in the centre of the Solomon Divergence where the value was somewhat higher. Other studies have shown that in general the phosphate concentration is low everywhere during the year except north of 15° S. where, independent of season, the concentration is somewhat greater. This increase in the concentration in the surface waters is always associated with the centre of the Solomon Divergence.

The pH of the surface water is always less than 8·30; it is minimal in the centre of the Solomon Divergence where a value of 8·22 was found in May 1960 and 8·25 in November and June of 1958.

The alkalinity of the surface waters, less than 2·40 m–eq./l is also minimal in the centre of the Solomon Divergence. It is associated with a specific alkalinity lying between 0·125 and 0·130 which is maximal where the alkalinity is minimal. Finally, the carbon dioxide concentration in the surface waters is always near to 2·0 m.mol/l.

The waters situated to the south of New Caledonia have been less completely studied (Rotschi, 1960c). The distributions of all the chemical constituents appear nevertheless to be affected by the presence of the Tropical Convergence centred between New Caledonia and New Zealand. The lower temperature, much less to the south of New Caledonia than in the Coral Sea, allows a considerable increase in the oxygen content in the surface waters which usually become supersaturated. In May 1959 the oxygen concentration was everywhere greater than 4·75 ml/l and a value greater than 5·00 ml/l (105% saturation) was associated with the Tropical Convergence. The phosphorous content was low, less than 0·25 mg–at./m^3, the lowest values being again associated with the Tropical Convergence; at the same time the alkalinity lay between 2·41 and 2·45 m–eq./l and the carbon dioxide concentration between 2·05 and 2·15 m.mol/l. The pH, lying between 8·25 and 8·30, had its maximum at the convergence.

Circulation of the principal surface water masses.

Seasonal changes considerably effect circulation of the surface water masses.

August to October. During this period there is a stable equilibrium between horizontal and vertical circulation. In the Coral Sea the lowest salinities are associated with high temperatures—a characteristic of the South Equatorial Water Mass. Towards the south the temperature remains relatively constant whilst the salinity increases regularly, and this is a characteristic of mixing with Central South Pacific Water. The circulation is, however, essentially zonal with much reduced movements in a southerly direction while a meridional circulation only becomes effective during the subsequent months.

To the extreme north of the region between the equator and 10° S. a very strong flow of South Equatorial Water turns to the left and penetrates deep into the Coral Sea where it comes up against the east coast of Queensland. To the south of New Caledonia a strong westerly flow from the South Central Pacific penetrates the Coral Sea with one ramification turning towards the southwest between Norfolk Island and New Zealand, and another orientated towards the northwest in the direction of the Coral Sea. The southwestern branch of this current is associated with the displacement towards the west (at an intermediate depth) of the water masses off the north of New Zealand; to the west of 160° E., the southwest water of the Tasman Sea is formed by mixing with Subantarctic waters. The Central Water of the Tasman Sea and that of the southwest are transported towards the north, but only the former attains a latitude of 37° S. Along the eastern coast of Australia, to the south of 23° S., there is a weak southerly current of South Equatorial Water which progressively mixes with Central South Pacific Water; towards 30° S. this current turns towards the east.

November to January. During this period the flow is largely directed towards the south. The South Equatorial Water penetrates into the Coral Sea over the Solomon–Santa Cruz Sill and in the course of its displacement towards the south it gives rise to intense vertical turbulence which results in the mixing of the surface and deeper waters. The displacement of the South Equatorial

Water takes place essentially in two directions. The principal branch is directed towards the southwest in the direction of Queensland and during the course of its displacement this water mixes with South Central Pacific Water and forms the mass of water occupying the Coral Sea; this water reaches as far as Sydney between October and December and also ultimately reaches the southeast of the Tasman Sea. The other branch of the South Equatorial Current curves towards the south along the New Hebrides Ridge and carries semi-tropical water along both the east and west coasts of the North Island of New Zealand. The northwest of the Coral Sea is occupied by warm water of low salinity originating in the Arafura Sea and which has penetrated into the Coral Sea across the Torres Strait; the geographical range of this water mass is always limited. The South Central Pacific Water which is found towards 25° S. and 30° S. is widely distributed; associated with this water mass, and at an intermediate depth, is water from the north of New Zealand which reaches a more northerly latitude than during the previous period. To the south of New Caledonia a surface layer with a relatively constant salinity corresponds to the water of the centre of the Tasman Sea, which has been warmed. The southwest of the Tasman Sea to the west of New Zealand, is occupied by a Subantarctic Water Mass which has been warmed, and which extends northwards in the direction of the Subtropical Convergence. The region around Norfolk Island is characterized by the maximum northern extension of this Subantarctic component.

February to April. Between February and April the hydrological situation like the surface circulation is an extension of that characteristic of the previous period. In the Coral Sea, South Equatorial Water is present in the same proportion and there is always penetration in the northwest of water from the Arafura Sea; however vertical mixing is more intense.

May to July. In general, from May onwards the vertical mixing increases in intensity, whilst any extension of the South Equatorial Water into the Coral Sea is reduced. Under such conditions Arafura Sea Water no longer penetrates the Coral Sea and strong vertical mixing is produced between 20° S. and 25° S. The South Central Pacific Water penetrates in abundance between New Caledonia and New Zealand considerably affecting the northern part of the Tasman Sea. In the south of this Sea there develops an influence of the winter water mass on the characteristics of the region.

Optical properties

In the Coral Sea the horizontal distribution of transparency in the surface and subsurface waters is relatively uniform; underneath a surface layer which is relatively turbid and about 50 m in thickness there is a weak maximum of turbidity situated at about 80 m; beyond 100 m is extremely transparent water. This situation is modified by proximity to a coast.

The extinction coefficient at 25 m compared with that of the deeper water is characteristic of that of the surface layer; it varies between 0·035 and 0·077 m^{-1}; the smallest values, which correspond to the clearest water, are found in the centre of the Coral Sea and the highest values are localized in the Solomon Archipelago where the biological and land-mass effects are most marked (Wyrtki, 1961a). The thickness of the turbid layers situated between 70 and 90 m varies from between 2 m to 8 m, the thickness being proportional to the turbidity; the maximum turbidity in the Coral Sea increases from south to north, the extinction coefficient rising from $0 \cdot 040 \ m^{-1}$ in the Coral Sea to almost to $0 \cdot 060 \ m^{-1}$ in the Bismarck Archipelago. Under the turbid layer the water becomes progressively more transparent until at 125 m the extinction coefficient is smaller than that at the surface, varying between $0 \cdot 006$ and $0 \cdot 040 \ m^{-1}$. The smallest values are found in the centre of the Coral Sea.

Measurements of the penetration of the blue end of the spectrum indicate that the clearest water is found in the Tasman Sea at about 30° S. In general the attenuation is stronger on the surface than in the deeper layers because of the transformation in the 20 m to 40 m layer of the direct light into diffused light. Below 20 m the illumination from above and from below is more or less constant. In the Tasman Sea the depth of penetration of 1% of the incident light varies with the season (Jitts, 1959). Between Australia and New Caledonia this depth varies between 143 m and 224 m but in coastal water it is less. Finally, for 100 miles around Sydney this depth which is at 90 m in April diminishes to 60 m between July and September but reaches almost 120 m in November.

Conclusion

It will be useful to briefly recapitulate the main facts which have been dealt with above. The characteristics of the surface water of the Coral and Tasman Seas depend upon a mixture of three primary external types, South Central Pacific Water, South Equatorial Water, Subantarctic Water and on water masses more localized and of much less importance such as that of the Arafura Sea. The water mass of the Coral Sea is a mixture of South Equatorial Water and South Central Pacific Water and does not arise from the local evaporation of South Equatorial Water. During the southern summer the penetration of South Equatorial Water is essentially localized to the northern part of the Solomon–New Hebrides Sill, with its flow directed towards the south. On the other hand, the zone of penetration of South Central Pacific Water is, throughout the year, over the New Caledonia–New Zealand Sill; however, between January and May this same Sill allows the passage of temperate water with high salinity, which originates to the northeast of New Zealand and which is displaced to an intermediate depth, to emerge at the centre of the Tasman Sea. The surface water masses at the centre and southwest of the Tasman Sea are then formed by the mixture of this water from the northeast of New Zealand with that from the Subantarctic. Along the eastern coast of Australia, as far as Sydney, one finds Coral Sea water only during the Australian Summer; during the rest of the year there is a water mass similar to that at the centre of the Tasman Sea and formed in the middle of the Central South Pacific Water Mass by vertical turbulence.

As regards the chemical properties, the region, which presents all the characteristics of tropical water, is under the influence of the Solomon Divergence and the Tropical Convergence. In the neighbourhood of the first there is a characteristic enrichment of the surface waters which compared with others are relatively poor in oxygen even though they may be near to saturation or even supersaturated. They are equally poor in soluble phosphate; the concentration of the latter rarely passes $0 \cdot 20$ mg–at./m^3, and the total phosphate content is as follows: South Equatorial Water $0 \cdot 65$ mg–

at./m^3; Subantarctic Water much the same; Central South Pacific Water even poorer since with 0·10 to 0·16 mg–at./m^3 (Rochford, 1959). In the Tropical Convergence, however, the oxygen is more than in the surrounding waters and the nutrient salts less concentrated.

INTERMEDIATE WATER MASSES

General

The T-S diagram of southwest Pacific waters allows one to demonstrate the existence in the Coral and Tasman Seas of three primary water masses, namely: the surface water, generally with a high temperature and a salinity lying between 34·00‰ and 35·60‰ and which can, as already shown in the previous section, be distinguished by three components; the subsurface water of maximum salinity between 35·50‰ and 36·00‰ and temperature from 18° C to 25° C which has its core situated between the surface and 250 m; and the water mass of minimum salinity, between 34·37‰ and 34·53‰ whose temperature varies from 4·2° C to 6·0° C and with a sigma-t in the neighbourhood of 27·2 which is found between 650 m and 1100 m.

The Coral Sea. A hydrographical analysis of the centre and northwest of the Coral Sea (Rotschi, 1960b) has shown that this region has a number of specific characteristics. First of all, the T-S diagram of the Intermediate Water is linear between the points 20° C—35·60‰ and 6° C—34·40‰, and in this respect the waters of the Coral Sea approach the characteristics of the Equatorial Pacific and the Southwest Central Pacific as defined by Sverdrup, Johnson and Fleming (1942), in that they correspond to a part of the linear T-S diagram between 15° C—35·15‰ and 8° C—34·60‰ for the Equatorial Pacific and to the 17° C—35·60‰ and 8° C—34·60‰ values for the Southwest Central Pacific. It must be noticed, however, that the slope of this linear portion of the T-S diagram varies with latitude; in the northeast of the Coral Sea it is intermediate between that of the Equatorial Pacific Water Mass and the Central Southwest Pacific Water Mass, while between New Caledonia and New Zealand one finds the same slope as in the Southwest Central Pacific as defined by Sverdrup (see Lemasson and Magnier, in press). On the other hand, at depths greater than 300 m the properties vary little during the year. Beyond this level the stratification of the properties can be considered quasi-permanent and the water masses are extremely stable and, as we have already seen, this stands in marked contrast to the surface and subsurface water masses which, together occupying all the upper zone down to the maximum of salinity, are extremely variable. Finally, whilst the salinity minimum is constant the value of maximum salinity depends upon the locality as well as the season.

Three primary water masses essentially form the intermediate water of the Coral Sea. The superficial waters which are hot and with low salinity are derived, as we have seen, from a mixture of South Equatorial Water and South Central Water or Subtropical Lower Water. It is near to the Solomon Islands that one finds the warmest water with lowest salinity (temperature 28·5–29° C, salinity lower than 34·70‰ and even as low as 34·50‰). These waters have a distinctly equatorial character and Dietrich and Kalle (1957) amongst others, consider that they are derived from a water type (29° C and 34·30‰) distributed in the upper layers of the Equatorial Current.

We know that the salinity maximum is derived from the Subtropical Lower Water or Central South Pacific Water (temperature 26° C, salinity greater than 36‰); it forms a marked subsurface salinity maximum throughout the whole of the southwest Pacific between 100 m and 200 m. According to Wyrtki (1956) this Subtropical Lower Water is divided during its displacement into two branches readily identifiable by their oxygen content. When the oxygen content changes little with salinity it may be South Subtropical Lower Water and when the oxygen increases rapidly with salinity it may be the northern branch of Subtropical Lower Water; in general the southern branch will have a high salinity and low oxygen tension and where the two cross a double salinity maximum is found.

Because of the lack of observations in the central Pacific there are diverse opinions regarding the origin of the Subtropical Lower Water or South Central Pacific Water. According to Schott (1935) the warm saline water is found at about 18° S. between 120° W. and 150° W. during February; in the zone of the Tropical Convergence the surface water will then be at a temperature of 27° C and a salinity of 36·20‰. According to Sverdrup, Johnson and Fleming (1942) the core of strongest salinity at 36·50‰ is found at 120° W. and 20° S. but according to Dietrich and Kalle (1957) the salinity will only reach 36·20‰; moreover, whilst according to these authors the temperature will be 24·5° C according to Austin (1957) it will be 25° C. It has been shown during recent cruises of the N.O. CORIOLIS (Rotschi *et al.*, in press) that the zone of convergence where the maximum salinity is formed is localized between 15° S. and 20° S., 140° W. and 130° W., and in that region the surface salinity reaches 36·40‰ and the temperature 27° C. From this region, the salinity maximum sinks towards the north, west and south.

To summarize, the upper 1000 m of the Coral Sea, of the New Hebrides Basin, and of the channel between New Caledonia and the New Hebrides are occupied by a derived mass formed from three primary masses of which two are exterior to the region and the third, Antarctic Intermediate Water, is present throughout all the southeast Pacific (Rotschi, 1960b). The characteristics of the types directly influencing the mixture itself are 29° C and 34·40‰ for the South Equatorial Water (Dietrich and Kalle, 1957); 25° C and 36·30‰ for the South Central Pacific (Rotschi, 1960b); and 50° C and 34·40‰ for the Antarctic Intermediate Water (Sverdrup, Johnson and Fleming, 1942).

The Tasman Sea. Near to the Bass Strait the subsurface water masses develop from a mixture of the water of the East Australian Current, Subantarctic Water and a strongly saline Subtropical Water from the Indian Ocean which is present along the whole coast of Victoria. This Subtropical Indian Ocean Water has been identified by Schott (1935) and Sverdrup, Johnson and Fleming (1942). The Subantarctic Water, cold and of low salinity, arises from the Circumpolar Current driven by the west wind; in the southern summer however, the Indian Ocean Subtropical Water is carried away towards the east by the West Wind Drift and can attain the west coast of Tasmania so that each summer tropical and subtropical fauna are recorded in this region (Newell, 1961).

In summer a thin, warm surface layer about 50 m thick which has been warmed near to 4° C is found between Tasmania and New Zealand (Wyrtki, 1962a) and under this is a small salinity maximum localized to the south of a line joining southern Tasmania to Cook Strait. This subsurface salinity maximum is a relic of the water formed in the preceding winter and it is again reached by the heated Subantarctic Water. To the north of this region the maximum salinity is found at the surface. The northern limit of the Antarctic Surface Water approximates to the 35·40‰ isohaline.

Physico-chemical properties

Salinity. Between 200 and 600 m the salinity decreases regularly from the subsurface maximum of the South Central Pacific Water to the minimum of the Intermediate Antarctic Water which at the north of New Zealand lies at about 1100 m depth and at 700 m around the Fiji Islands; to the north of this archipelago its depth remains constant between 700 to 800 m. In the Intermediate Antarctic minimum the salinity varies from 34·34‰ to 34·51‰ with the lowest values between New Zealand and the Fiji Islands; clearly the Antarctic Intermediate Water covers the Southwest Pacific to the east towards 25° S. to 30° S. and further extends north and south in the Coral and Tasman Seas (Fig. 6a). Below the minimum, salinity increases regularly with depth and at about 1500 m exceeds 34·60‰; in general, the salinity is below this value between 500 m and 1500 m and it is in the upper part of this layer that one finds the Antarctic Intermediate Water.

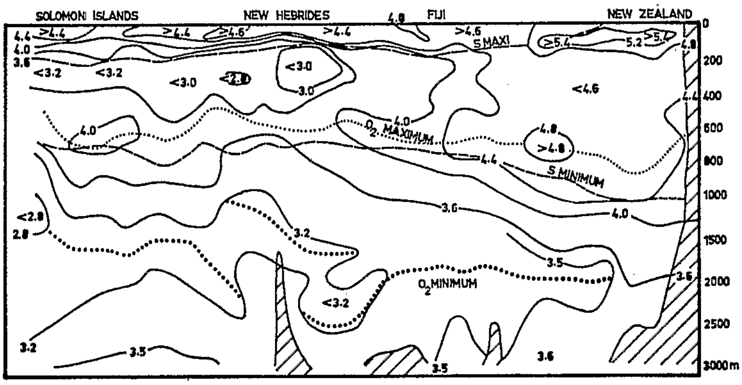
Rochford (1960a) by considering the distribution of salinity along the isopycnal surface $\sigma_t = 27 \cdot 20$ (in which the minimum salinity is localized at all latitudes) has shown that the displacement of the Antarctic Intermediate core takes place in a quasi-isentropic way over the whole of this isopycnal surface where it is responsible for the greatest part of the horizontal mixing. This isopycnal surface sinks rapidly from the Antarctic Convergence, where it is at the surface, to 1000–1200 m at 45° S.; further to the north it rises and lies at about 700 m at the equator.

Oxygen. The highest oxygen contents (greater than 5·00 ml/l) are found in the surface layers to the north of New Zealand where they associated with the highest surface salinities, and there the oxygen decreases regularly with depth (Fig. 6b). To the north of the Fiji Islands where the surface salinity is relatively low the oxygen tension is greater than 4·40 ml/l but it decreases rapidly with depth; immediately under the surface layers, at a depth between 150 and 500 m, and at a slightly lower depth than that of the maximum salinity, there is an extremely well marked oxygen minimum.

The oxygen content of these minimum layers varies considerably; to the north it has a value of 2·80 ml/l at the Solomon–New Hebrides Sill and to the south, near New Zealand, the barely marked minimum has a value of 4·60 ml/l. To the south of the Subtropical Convergence it cannot be detected.

At a depth which is 50–200 m lower than that of the Antarctic salinity minimum one finds an intermediate maximum of oxygen, where its concentration varies from 3·70–4·90 ml/l. The highest values are localized between New Zealand and the Fiji Islands and their depths are extremely close to that of the salinity minimum which, it will be recalled, has there the lowest value anywhere associated with the $\sigma_t = 27 \cdot 70$ surface. At lower levels the oxygen content decreases, so that, at the minimum salinity it is somewhat lower although it is close to the maximum concentration. Between 1000–2000 m the oxygen content is low and its vertical distribution reveals the existence of a deep minimum of 2·80 ml/l in the north and 3·50 ml/l in the south near to New Zealand. Between New Zealand and the Fiji Islands this minimum lies at a depth of 2000 m. The lowest concentrations of oxygen are found to the north in the Solomon Sea at about 1250 m.

Nutrient salts. The study of the distribution of chemical parameters such as oxygen, phosphate, pH, alkalinity, and total carbon dioxide content within



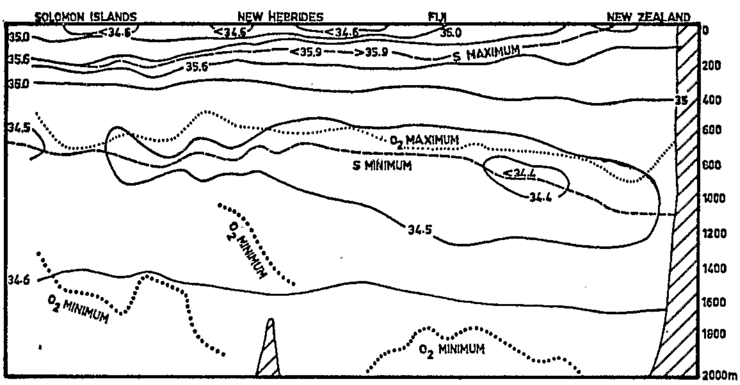


Fig. 6a (upper).—Vertical distribution of salinity in the Coral and Tasman Seas (after Wyrtki, 1962).

Fig. 6b (lower).—Vertical distribution of oxygen in the Coral and Tasman Seas (after Wyrtki, 1962).

the euphotic zone shows evidence of an annual cycle, a characteristic of which is that at the end of the southern summer there is a notable lowering of all the values as compared with those in the spring (Legand and Rotschi, 1962). This seasonal cycle is particularly evident near to the Solomon Divergence (Rotschi, 1961). There the rich deeper waters although not directly reaching the surface of the sea nevertheless carry nutrient salts up to the lower boundary of the euphotic zone. This addition of nutrients results in a relative enrichment of the surface waters and is followed by lower values subsequent to extremely active photosynthesis. Since the Solomon Divergence is a quasi-permanent phenomenon of the north of the Coral Sea, this region has a primary production much more important than that of any nearby zone. On the contrary, the region of the Tropical Convergence is very poor.

With regard to the relation between the oxygen and phosphate values it appears that the Central Pacific and the Coral Sea show a different correlation from that which is found in the Atlantic. It has been shown (Rotschi, 1962b) that the slope of the regression line between the apparent utilization of oxygen (AUO) and the phosphate content, that is, the value of the apparent mineralization (AUO/PO_4-P) varies as a function of longitude in the Central Pacific and with depth in the Coral Sea. In the eastern Pacific this ratio is 328/1 whilst near to 180° it is 185/1. In the Coral Sea, in tropical waters, for the whole of the layer between the surface and the Antarctic Intermediate Water the relation between AUO/PO_4-P appears to be exponential and this indicates that from the subsurface layer to the core of the Antarctic Intermediate Water the apparent value of the mineralization ratio varies regularly from 300/1 near to the euphotic zone at a depth close to 150 m to almost 120/1 at 800 m depth. In fact, between the surface layer and a depth of 300–400 m, where the phosphate concentration is of the order of 0·70 mg-at./m^3 and where the influence of the South Central Pacific Water largely exceeds that of the Antarctic Intermediate Water, the value of the mineralization ratio is very close to the theoretical value of 276/1. As the influence of the Antarctic Intermediate Water increases, the value of the ratio decreases rapidly to a value of the order of 120/1 indicating that under these conditions the quantity of preformed phosphate is equivalent to that which has been introduced (Rotschi, 1960b). Recent studies in the centre of the South Tropical Pacific have shown that the relative distribution of oxygen and phosphate in the tropical and sub-tropical zones has the same characteristics as in the Coral Sea and that it results from the mixing of two water masses having a different preformed phosphate content (Rotschi, 1965a). The mixture is comprised of surface water with a AUO/PO_4-P ratio of 276/1 and which contains 0·4 mg-at./m^3 of preformed phosphate, and Antarctic Intermediate Water which also has a ratio of 276/1 but whose preformed phosphate is about 1·2 mg-at./m^3. The hypothesis put forward (Rotschi, 1962b) that there is a variation in the concentration of preformed phosphate with both longitude and depth appears to be verified. It is essential to emphasize that throughout the whole of the southwest Pacific region, wherever systematic studies have been made on the distribution of carbon dioxide, the apparent mineralization of carbon is near to 1/1—a very different value from the theoretical 2·6/1 (Rotschi, 1962b, 1965b). This has also been observed in the Central Tropical Pacific (Rotschi, 1965a). There is the production of an excess of carbon dioxide over oxygen consumption and this is perhaps due, as in the case of phosphate, to an increase with depth of the preformed carbon dioxide in the deep water, or more probably to an increase in the concentration of calcium carbonate in solution.

At depths below the compensation depth in the Coral Sea, oxygen is a conservative property linked to temperature and salinity by relations which are specific to the different water masses; it follows that the AUO is also a conservative property (Rotschi, 1960b). The temperature of 6° C which is associated with a salinity of the order of 34·40‰ marks the upper limit of the core of the Antarctic Intermediate Water. The water of the intermediate mixed layer between the South Central Pacific Water and the Antarctic Intermediate Water is characterized by a quantitative relation between temperature and oxygen, which as far as it concerns the apparent utilization of dissolved oxygen may be expressed:

$$\Delta \text{ AUO ml/l} = -0 \cdot 118 \, \Delta \, T^\circ \text{ C}$$

this relation being valid for all temperatures above 6° C. In the Antarctic Intermediate Water the relation becomes:

$$\Delta \text{ AUO ml/l} = -0 \cdot 400 \, \Delta \, T^\circ \text{ C}$$

and this equation is equally true for Antarctic Deep Water, in which salinity slowly increases with depth.

The pH of the intermediate water of the Coral Sea is much higher than that which is found in similar latitudes in the Atlantic (Rotschi, 1960c) as well as in the Equatorial Pacific. It decreases from 8·3 at the surface to 8·0 at intermediate depths, and it is only at depths greater than 900 m that it is lower than 8·00. There is a maximum subsurface pH which coincides with minimum total carbon dioxide content and maximum supersaturation of oxygen; this subsurface maximum always lies between the surface and 100 m depth.

Detailed hydrographic analysis of the intermediate water mass

Wyrtki (1962a) has given an excellent analysis of the different intermediate water masses of the region.

Subtropical Lower Water or Central South Pacific Water. The oxygen content in the central layer of the Subtropical Lower Water indicates that a subdivision should be made into two components. The northern component of the Subtropical Lower Water is low in oxygen, 3·00 to 4·00 ml/l; it reaches the southwest Pacific between Fiji and the New Hebrides where the salinity is greater than 35·80‰. In the southern Subtropical Lower Water there is, in contrast, a high oxygen content—greater than 4·40 ml/l; the oxygen values are similar to those at the surface and subsurface salinity maxima which are found to the north of New Zealand.

The distribution of the salinity in the central layers of the maximum confirms the existence of two components of the Central South Pacific Water. To the north of New Zealand there is a region where a salinity greater than 35·9‰ is found in the eastern part of the Tasman Sea as far as 160° E. and this is the southern component. The northern component is easily identified to the north of the Fiji Islands and in its extension into the Coral Sea. The salinity gradient along the axis of this tongue is small but at right angles it is large and there is, therefore, only a weak current in the extension towards the west of the strong salinity core. Between the two branches with their high salinities, along 20° S. is found a region of low salinity, decreasing towards the west, and which indicates the limit between the two components of the Subtropical Lower Water; this limit is associated with a strong horizontal oxygen gradient. It is possible to identify it from the south of the Fiji Islands to the north of New Caledonia and as far as the centre of the Coral Sea; it is probable that its position varies seasonally.

To summarize, the Subtropical Lower Water arises in the southern Central Pacific where it is formed between 15° S. and 20° S. (Schott, 1935; Wyrtki, 1961b, Rotschi *et al.*, in press). The southern component extends towards the west between 23° S. and 30° S. and remains near to the surface so that its oxygen content stays at a high value; the northern component, which in its displacement towards the west is rapidly pushed down to 100–200 m is, in contrast, the site of an intense oxygen consumption.

The limit of the vertical extension of the Central South Pacific Water which forms the Southwest Pacific Water Mass by mixing with either South Equatorial Water or Antarctic Intermediate Water (both with a lower salinity) may be defined by the position of the 35‰ isohaline. In this case the southern component extends from the surface to 400 m and the northern component can be identified between 50 and 300 m; the water masses follow the surface circulation. In particular, the extension of the northern component coincides with the surface current to the north of the Fiji Islands and the New Hebrides, while the southern component penetrates the Tasman Sea with the westerly surface current, which passes between the Fiji Islands and New Zealand; there, the position of the Tropical Convergence situated to the south of New Caledonia coincides closely with the northern limit of the region where the maximum salinity is in the surface waters to the north of New Zealand; to the south of this Tropical Convergence, towards 30° S., the maximum salinity is at the surface whilst to the north it is in subsurface waters, indicating that the Subtropical Lower Water descends all along the convergence.

In the south of the Tasman Sea there is opposition between the Subtropical Surface Water and Subantarctic Surface Water where the temperature and salinity are both much lower. In the southern summer, however, there exists to the south of a line joining southern Tasmania to the Cook Strait in New Zealand a thin surface layer of warmed Subantarctic Water under which there is a weak salinity maximum which is a relic of the surface water formed during the previous winter. During the summer the presence of a thermocline shows that strong vertical movements cannot take place throughout the whole zone occupied by this warmed surface layer. Along the northern border of this Subantarctic Water Mass there is a convergence, namely, the Subtropical Convergence whose limit is indicated by the position of the subsurface salinity maximum. This Subtropical Convergence indicates, therefore, the limit between Subtropical Water and Subantarctic Subsurface Water. Wyrtki (1960) has shown that the position of the Subtropical Convergence in January as deduced from the surface currents corresponds quite well with the northern limit of that region where one finds a maximum subsurface salinity.

In the western part of the Tasman Sea the Subtropical Convergence is accompanied by a strong horizontal salinity gradient; this gradient decreases towards the east, so that near to New Zealand it is virtually non-existent and the Convergence hardly detectable.

Water of the upper minimum oxygen content. At a temperature between 12° C and 24° C and at a depth somewhat greater than that of the core of the Subtropical Lower Water is found an oxygen minimum layer; this upper oxygen minimum is only present to the north of a line joining the Bass Strait to northern New Zealand and its central core does not have any characteristic temperature while its depth varies considerably between 150–500 m; at the north, the oxygen content in the core of this layer is of the order of 3·00 ml/l and to the south near to 4·40 ml/l. This upper oxygen minimum is probably formed *in situ* as a result of the oxidation of organic material accumulated in the euphotic layers; although this layer cannot be considered to be static and although advection must have some effect on the distribution of oxygen, it may be considered that this water is an essentially local formation.

Antarctic Intermediate Water. At a depth which is 50–200 m less than that of the minimum salinity of the Antarctic Intermediate Water there is an oxygen maximum at a temperature lying between 5·50° C and 10° C; the temperature of the central layer of the minimum salinity water lies, however, between 4° C and 6°C; the maximum oxygen and the minimum salinity are both related, therefore, to the same principal water mass of the Antarctic Intermediate Water. Between New Zealand and the Fiji Islands the oxygen concentration in this layer is 4·80 ml/l and it is in this region that the salinity minimum reaches its lowest value; the oxgyen content decreases towards the north to a value of 3·80 ml/l.

At the time of its formation this water has a high oxygen content which decreases as it is displaced; in effect, the Antarctic Intermediate Water flows between waters with less oxygen and this results, at the point when the Antarctic Intermediate Water leaves the surface, in fairly large variations of the oxygen content at the centre layer of the salinity minimum although the salinity variations are small. The fact that the depth of the oxygen maximum and that of the salinity minimum do not coincide is probably due to a loss of oxygen by mixing with waters poor in oxygen and lying under the core of the Antarctic Intermediate Water.

The distribution of oxygen in the deep oxygen maximum layer shows a penetration of deep water into the Coral Sea *via* the New Caledonia–Fiji Sill; this water turns towards the west at the south of New Caledonia and then to the northwest; it is not found to the south of 34° S.

With regard to the minimum salinity water, that is, the true core of the Antarctic Intermediate Water, there are two ways in which it may penetrate the southwest Pacific. The direct passage between Tasmania and New Zealand offers a route to the waters coming from the south with an initial salinity lower than 34·40‰ but rapidly increasing towards the north so that at 40° S. it is 34·45‰. Another branch of the Antarctic Intermediate Water penetrates the southwest Pacific between New Zealand and the Fiji Islands; its salinity is lower than 34·40‰ and it is derived from an important flow directed towards the north which, after passing to the east of the Chatham Ridge, is deviated towards the northwest; at the latitude of New Caledonia one part of this water mass is directed towards the west and penetrates the Tasman Sea while the other, continuously displaced towards the northwest, passes between New Caledonia and the New Hebrides.

At the centre of the Tasman Sea, between 30° S. and 40° S., the uniform salinity of 34·47‰ to 34·49‰ indicates a zone of mixing between the two sources of Antarctic Intermediate Water; to the north the salinity increases gradually to 34·50‰ near to the Solomons.

The oxygen content of the Antarctic Intermediate Water is relatively high, this being the consequence of its formation in the surface waters near to the Antarctic Polar Front; we have already seen that after mixing, the oxygen content decreases and the salinity increases towards the north. The oxygen content of the water flowing to the west, south of the Fiji Islands, is greater than 4·40 ml/l; its distribution in the salinity minimum resembles that of salinity and shows the two tongues of circulation to the south of New Caledonia and along the New Hebrides Ridge. The water penetrating the Tasman Sea at the south is slightly poorer in oxygen, 4·30 ml/l, but it does not appear to penetrate to any considerable extent into the north of this region.

The very irregular variations of oxygen concentration at the centre of the Tasman Sea indicate that at the depth of the salinity minimum the circulation is not well defined; here the oxygen tension may become less than 4·00 ml/l. It is also possible that the southward flow of the East Australian Current limits the penetration of north-going Antarctic Intermediate Water.

Subantarctic Intermediate Water. To the south of 30° S. in the Tasman Sea where the water has a distinctly high temperature (8–14° C) and at a shallower depth than the Antarctic Intermediate core, there is another oxygen maximum; the concentration of this maximum lies between 4·50–6·00 ml/l and it is greater to the south in the direction of the origin of this water. This oxygen maximum is established between 150–450 m when the salinity minimum at this latitude lies near to 1000 m. At this temperature (8–14° C) and salinity (34·60–34·80‰) this water is near to saturation and it must therefore have its origin in the surface waters of the subantarctic region. It is formed at about 50° S. to the north of the Polar Front and travels towards the north at a less depth than the Antarctic Intermediate Water. The formation of this water is probably seasonal.

Oxygen minimum. Throughout the whole layer situated between 1200–2500 m where the oxygen values decrease regularly from north to south the quantity of oxygen is low, being minimal between 30° S. and 40° S. in the East Australian Basin. This deep minimum, characteristic of the whole region, indicates the approximate limit between Antarctic Intermediate and Deep Water. As with the upper oxygen minimum the lower minimun is formed *in situ* in deeper water where large quantities of organic matter are oxidized; it is also the consequence of a long stay of these waters outside the influence of atmospheric oxygen or outside influence of other water masses capable of modifying its chemical characteristics by mixing.

The temperature of the core of this oxygen minimum is of the order of 2 to 3° C and the T-S diagram indicates that it is a mixture of Antarctic Intermediate Water and Deep Water both of which are somewhat higher in oxygen content. At the core, the concentration of oxygen is of the order of 2·80–3·90 ml/l and it increases quite regularly with latitude; in this respect it does not resemble the oxygen content in the upper minimum where the fluctuations are of great importance; the mechanisms of oxidation in the deep waters are much more stable and regular than near the surface. This deep minimum is distributed throughout the whole of the Central Pacific and the mechanism of its formation is always the same. At the greatest depths the oxygen content again increases, to approach the values characteristic of deep and bottom water.

Although the movement of this deep layer may be extremely slow and although the stay of this water at this level may be very long one can see from the distribution of the oxygen in the core of the minimum, several directions of displacement. Thus, it is clear that water with an oxygen content of 2·80 ml/l coming from the north penetrates into the Solomon Sea at about 1300 m depth; leaving the Coral Sea this water with low oxygen content turns to the south along the East Australian Continental Plateau where it sinks to 1600 m. The East Australian Current has, therefore, an influence on the movement of the water to about 2000 m depth and in consequence the deep water of the Coral Sea Basin, with a slightly higher salinity, can only extend in a southerly direction between the flow at 2000 m influenced by the East Australian Current and the depth of the sill of the Coral Sea Basin at 2850 m. In the south of the Tasman Sea the oxygen minimum is only slightly marked, with a value of 3·60 ml/l while further to the south Deacon (1937) has described another deep oxygen minimum.

To the north of New Zealand the depth of the minimum is near to 2000 m and its depth diminishes to the north and to the west to about 1600 m.

Circulation of the intermediate waters

The analysis of the water masses of the southwest Pacific show them to be very clearly stratified, this stratification being typical of tropical and subtropical seas and with the different water masses lying in quasi-horizontal layers; all the subsurface water masses are formed from primary types exterior to the region.

We have seen that the surface circulation is in general anticlockwise with a flow of water from the north and from the east, a flow towards the south along the eastern coast of Australia, and a flow towards the east of the Tasman Sea. The Subtropical Lower Water follows the general tendency of this flow; its northern component enters the Coral Sea and extends in the region from the northeast whilst its southern component, which penetrates the Tasman Sea to the north of New Zealand, sinks along the Tropical Convergence towards 30° S.; along the Subtropical Convergence this Central South Pacific Water meets the Subantarctic Surface Water which is transported towards the northeast.

The upper oxygen minimum in the northern southwest Pacific follows, therefore, the general direction of the surface circulation; the distribution of the oxygen along the minimum indicates in fact an arrival from the northeast and a turning in a southerly direction along the eastern coast of Australia. Part of this water possibly leaves the Tasman Sea north of New Zealand in an easterly direction and at a depth lying between 200–600 m. To the south of 34° S. the core of the Antarctic Intermediate Water has an oxygen content of 4·25 ml/l and a phosphate content of 2·00–2·20 mg-at./m^3, whilst to the north there are 3·75 ml/l of oxygen and 1·80–2·00 mg-at./m^3 of phosphate; we know that between 30° S. and 34° S. the core of the Antarctic Intermediate Water disappears and that it passes from a depth of 1200 m at 28° S. to one of 800 m in the Coral Sea. This water has a double regime of circulation; in the Tasman Sea it penetrates to the south between 160° E. and 165° E. with the limit northwards at 30° S.; on the other hand, the main flow comes from the general northward current east of New Zealand, and it penetrates the Coral Sea at the east to the south of the Fiji Islands. The greater part of this water spreads to the northwest and leaves the region by the north; there is only a weak southerly current along the east Australian coast and only a small quantity of this water mixes in the Tasman Sea at about 30° S. with the water coming directly from the south. The differences between the properties of the Antarctic Intermediate Water to the north and south of 30° S.–34° S. are essentially due to differences in their age, which in turn controls the oxidation of organic matter the latter being more completely oxidized in the older water; that water penetrating the Coral Sea from the east is older. The properties of the surface water, particularly its productivity, are also of importance in their effect on the oxygen content of the Antarctic Intermediate Water.

The water of the lower oxygen minimum is transported from the north towards the south and this displacement is strongly influenced by bottom topography.

DEEP-WATER MASSES AND BOTTOM WATER

General characters

Deep Water. The Deep Water is characterized by a weak salinity maximum of the order of 34·73‰ and a temperature near to 1·7° C; it is the last trace of the North Atlantic Deep Water and is found in the East Australian Basin at a depth between 2500–3000 m; leaving this Basin it fills the Basin of the Coral Sea and that of the Solomons (Wyrtki, 1961a) ; the oxygen content of this water is relatively high.

Bottom Water. This water has minimal temperatures and the salinity is somewhat lower than that of the Deep Water. Its origin is in the Antarctic and it is found in the deepest layers of the East Australian Basin. The water coming from the north which fills the Fiji Basin, the Basin of the New Hebrides and the New Caledonia Depression is Central Pacific Deep Water, itself derived from Antarctic Deep Water.

Vertical structure of the water masses

Temperature and salinity. Throughout the whole region the minimum salinity, 34·50‰, of the Antarctic Intermediate Water is found at about 800–1000 m and near to the 5° C isotherm. At greater depths, the salinity increases regularly as the temperature decreases. The maximum salinity at a depth of 2500 m is near to 34·70‰ to the north of 22° S. and to the south of 34° S. Between these two latitudes the salinity at this depth lies between 34·70‰ and 34·75‰. At depths greater than 2500 m the temperature increases towards the south; at depths greater than 3000 m the temperature in the Coral Sea is from 0·50° C to 0·70° C higher.

Oxygen. The oxygen content which increases with depth to a maximum at about 1000 m has a minimum between 1500–2000 m at values between 2·70–3·50 ml/l. This minimum indicates approximately the limit between Antarctic Intermediate Water and Deep Water. At greater depths oxygen increases with depth; at depths greater than 3000 m the oxygen concentration in the Coral Sea is weaker than elsewhere whilst the minimum value of 3·07 ml/l is lower than that in the Tasman Sea.

Inorganic phosphate. In general at a depth near to 1500–2000 m a layer with a well marked phosphate maximum is found to the west of the Coral Sea and to the north of the Tasman Sea, and more diffusely in the Tasman Sea between 26° S. and 34° S.

To the north of 30° S. the maximum lies between 1·80–2·00 mg-at./m^3 at a depth of 1500 m to 2000 m. To the south of 34° S. a higher and more irregular maximum of the order of 2·75 mg-at./m^3 is found. In the Coral Sea the maximum of 1·80–2·00 mg-at./m^3 is the same as in the Tasman Sea and is found at the same depth. In general the maximum is present in that part of the flow towards the south whose rich phosphorus content arises from the Equatorial Pacific, but the highest maximum in the south of the Tasman Sea is derived from water originating in the Indian Ocean.

Discussion. The distribution of the physico-chemical properties of waters at depths exceeding 2000 m shows that it is in the East Australian Basin that salinity and oxygen values attain their maxima. The poorly developed salinity maximum present at 3000 m in this Basin indicates the position of Deep Water and it may perhaps be interpreted as a survival of north Atlantic Deep Water (Stommel and Arons, 1960). At a depth greater than 3500 m the salinity and the temperature, both slightly lower, are characteristic of Antarctic Bottom Water. To the north of the New Hebrides the salinity and oxygen concentrations at depths greater than 2500 m are the lowest in the whole region and are characteristic of Central Pacific Deep Water; this Water has all the properties of the bottom water of the Pacific, which is a branch of Antarctic Bottom Water entering the region to the south of New Zealand (Wooster and Volkmann, 1960); it has the same origin as the bottom water of the East Australian Basin.

In all the other basins of the South Pacific at depths greater than 2500 m the salinity and oxygen content are intermediate between the extreme values previously noted; the water of these basins is therefore derived from these two regional sources. Moreover, in these basins the potential temperature is high and the depth of their sills is therefore higher than that of the East Australian and Central Pacific Basins.

Horizontal structure of the water masses

The distribution of salinity and oxygen along the isotherm corresponding to a potential temperature of 1·8° C, whose depth is barely greater than that of the sills connecting the basins, helps one to understand the penetration of the deep water into the various basins; the depth of all the sills is near to 300 m yet the depth of the isotherm varies between 2300–2800 m.

Salinity. The greatest salinity, above 34·73‰, is localized in the East Australian Basin; salinity decreases towards the north and in the Coral Sea Basin it is little more than 34·70‰ at the west and a little below this in the east; it also decreases in the direction of the Solomon Basin and towards the east. The lower salinity of 34·67‰ which is found in the northern basin of the Solomons is probably due to arrival at about 2000 m of water originating in the Central Pacific and penetrating between Bougainville Island and New Ireland. The lowest salinity, less than 34·66‰, which is found to the north and east of the New Hebrides is characteristic of the Central Pacific and this low salinity water extends to the south in the Fiji Basin and to a lesser degree into the New Hebrides Basin: in the New Caledonia Depression the salinity lies between 34·682–34·689‰.

Oxygen. We have already seen that the highest oxygen concentrations are localized in the East Australian Basin where they are greater then 4·00 ml/l; they decrease in the direction of the Coral Sea. The lowest oxygen concentrations, less than 3·2 ml/l, are located in the northern part of the Solomon Basin and the New Hebrides Basin; they represent Central Pacific Water; the concentrations increase towards the south in the Fiji and New Hebrides Basins.

Characteristics of the bottom water masses in the different Basins

Wyrtki (1961a) has given a detailed analysis of the different bottom water masses of the southwest Pacific.

East Australian Basin. In this Basin the salinity at a given potential temperature or at a given depth is greater than elsewhere; there is a weak maximum about 34·740‰, at the level of the potential temperature of 1·6–1·2° C, that is to say at a depth near to 3000 m; at greater depths the salinity decreases to 34·735‰. A minimum temperature is usually found near to 4000 m but the potential temperature decreases to 0·80° C at the bottom. Since the depth of the sill between the Basin and that of the Coral Sea is near to 3000 m the water of the maximum salinity layer may penetrate the Coral Sea.

Coral Sea Basin. The bottom water of this is derived from the maximum salinity water of the East Australian Basin; the salinity maximum in the Coral Sea Basin is 34·731‰ and the potential temperature minimum 1·46° C. At 4000 m a minimum potential temperature is usually present which then remains constant to the bottom. The comparison of the potential temperatures in the two Basins would indicate that the sill is at a depth of 2850 m—a value which is in full accord with soundings.

The maximum salinity water of the East Australian Basin penetrates the Coral Sea Basin where it fills the deepest parts and mixes to some extent with the water of higher levels; between the depth of the sill at 2850 m and 4000 m the temperature increases towards the surface, while because of mixing with the adjacent water the salinity decreases; at 2850 m is found, therefore, a potential temperature of 1·79° C and a salinity of 34·708‰, while in the adjacent Basin the values are 1·46° C and 34·736‰ at the same depth.

Solomon Basin. The bottom water of the Solomon Basin has almost the same characteristics as that of the Coral Sea, with a potential temperature of 1·64° C and salinity of 34·711‰, although in the Coral Sea the water lies between 3000 m and 3500 m; it arises, therefore, in the Coral Sea. The distribution of potential temperature indicates that the depth of the sill below the two Basins is at 3400 m.

Since the sill between the Solomon Basin and that of the Central Pacific lies at a depth of 3000 m the deep water of the Pacific does not take part in the formation of the deep water of the Solomon Basin; however, at a potential temperature of 1·7° C corresponding to a depth of 2600 m, namely the depth of the Bougainville–New Ireland Sill, the influence of water of relatively low salinity, namely, that of the Central Pacific, is evident; this water, penetrating across the Sill, participates in the formation of the deep water at depths greater than 3000 m, which is colder than in the Coral Sea Basin. The potential temperature at 2600 m is 1·67° C, that is, 0·03° C above that found in the bottom water; it is therefore, too cold to take part in the heating of the waters in the layers below 3000 m; the potential temperature is virtually constant from 3000 m to the bottom.

New Hebrides Basin. The potential temperature and the salinity of the bottom water of this Basin are hardly greater than those of the Central Pacific Basin. It is considered, therefore, that the bottom water of the New Hebrides Basin is a mixture of Central Pacific Deep Water and water of a greater salinity originating in the Coral Sea Basin and which has crossed the Solomon Basin which it leaves by the sill to the south of New Georgia. This water, with a high salinity, can be traced to the south of San Cristobal where, between 3000 and 4500 m, it has a maximum salinity of 34·718‰ and a potential temperature of 1·50° C. At depths greater than 4560 m the salinity and potential temperature decrease and reach values characteristic of Central Deep Pacific Water.

TABLE II

Characteristics of the bottom water of the Deep Basins of the Coral and Tasman Seas (after Wyrtki, 1961a)

	East Australian Basin	Coral Sea Basin	Solomon Basin	New Hebrides Basin	New Caledonia Trench
Depth, max., m	5941	4899	9140	7660	4005
Depth of sill, m	—	2850	3000	3400	3000
Temperature min., °C	1·15	1·80–1·84	1·87–1·91	1·79–1·81	—
Depth, m	4250	3900	2800	3500–3700	—
Potential temperature, °C	0·80	1·47–1·51	1·67–1·70	1·49–1·52	—
Min. potential temperature, °C	0·79	1·46	1·63	1·48	1·63
at depth, m	4400	4500	7750	4400	3450
Salinity, ‰	34·735	34·722–34·731	34·710–34·713	34·695–34·700	34·694–34·701
Oxygen, ml/l	4·23–4·54	4·21–4·36	3·43–3·73	3·52–3·69	3·57–3·69

It is the mixture of relatively high salinity water originating in the Coral Sea and the deep water of the Central Pacific—a mixture formed at the latitude of the South Solomon Trench—which forms the bottom water of the New Hebrides Basin, where the maximum salinity value is 34·700‰, while that of the Central Pacific Basin only reaches 34·691‰. The potential temperature is 1·48° C and this indicates a sill at a depth of 3400 m between the Eastern Solomon Basin and the New Hebrides Basin.

A salinity of 34·711‰ associated with a potential temperature of 1·52° C could indicate the direct passage of water from the Coral Sea into the New Hebrides Basin over the ridge extending to northwards from the Chesterfield Plateau.

New Caledonia Depression. The water in the bottom of the New Caledonia Trench has almost the same salinity as that of the New Hebrides Basin, but the potential temperature is somewhat higher because of the smaller depth of the basin. The minimum potential temperature of 1·63° C in the Trench corresponds to a sill at 3000 m between it and the Coral Sea Basin. The water of relatively high salinity of the Coral Sea influences the salinity in the New Caledonia Trench, this influence being particularly clear at temperatures above 1·80° C, that is at depths less than 2500 m. The salinity is, therefore, somewhat higher than that of the New Hebrides Basin.

The characteristics of the bottom waters of the deep basins of the south-west Pacific in the Coral and Tasman Seas are summarized in Table II.

Circulation of the deep water masses

In the upper deep water masses between 1500–2500 m in the Coral Sea the maximum phosphate and minimum oxygen are associated. In the western Pacific the waters richest in phosphate are found between the equator and 10° N. at about 2000 m depth, and these waters are displaced towards the east along the equator; one branch enters the Coral Sea between the Solomon Islands and New Britain (Rochford, 1960a) and subsequently turns towards the south into the western part of the Coral Sea between 1500–2000 m, and it joins the Tasman Sea along the coast of Queensland at 22° S. after crossing the sill separating the Coral Sea and the East Australian Basin. Later, deviating towards the east and north to the south of the Chesterfield Plateau, it is possible that part of this water reaches the west coast of New Caledonia. During the course of the displacement towards the south these waters mix with Antarctic Intermediate Water; the salinity and phosphate decrease whilst the oxygen concentration increases.

To the south of 34° S. in the Tasman Sea it is possible that the deep waters rich in phosphate are not derived from the Central Pacific but more probably from the Indian Ocean. During the course of their displacement towards the north along the eastern border of the Tasman Sea these waters mix with Antarctic Intermediate Water and their salinity and phosphate content decrease. After being turned towards the west they form, to the east of Sydney and at about 2000 m depth, the water of maximum phosphate content. In spite of mixing with Antarctic Intermediate Water the waters of the Indian Ocean are easily discernible from a mixture of the former and Equatorial Pacific Water, which one finds to the north of 30° S., because their phosphate content is much higher and their salinity and oxygen much lower. With regard to the Lower Deep Water characterized in the East Australian Basin by a salinity maximum, this penetrates over a sill at 2850 m into the Coral Sea Basin where it forms the bottom water. It is diluted and warmed by mixing with the overlying waters and penetrates over a sill at 3400 m into the Solomon Basin; one part of this mixture forms the bottom water of the New Britain Trench, whilst another part penetrates into the South Solomon Trench where it forms a salinity maximum lying between 3000–4500 m. It is possible, as already noted, that one branch of the high salinity water of the Coral Sea is displaced towards the east between the Chesterfield Plateau and Rennell Island to mix with the water of the New Hebrides Basin.

Water from medium depths in the Central Pacific penetrates the Solomon Sea by the Bougainville–New Ireland Sill, its influence being limited to a layer lying between 2600 m and 3000 m; on the other hand, the deep water of the Central Pacific Basin is displaced towards the south between the Solomon

Islands and the New Hebrides and between the New Hebrides and the Fiji Islands; at the latitude of the South Solomon Trench it mixes with high salinity water situated between 3000 m and 4500 m and this mixture penetrates into the New Hebrides Basin by a sill at 3400 m, and there forms the bottom water. In its displacement towards the south this bottom water divides into two branches, the western one passing by a sill at 3000 m to fill the deeps of the New Caledonia Depression while the eastern branch fills the South New Hebrides Trench and subsequently curves into the Fiji Basin by a sill at 3400 m.

The Coral Sea Basin is an unexplained example of a depression where the entrant flow occurs above the shallower of the two sills and the outflow by the deeper one; a pressure gradient directed from the south to the north and creating a current in the East Australian Basin in the direction of the Central Pacific is perhaps the reason for this current. It is extremely difficult to determine the gradient; at 2850 m, i.e., at the depth of the sill of the Coral Sea Basin, is $27 \cdot 80\ \sigma_t$ in the East Australian Basin and in the Central Pacific Ocean $27 \cdot 74\ \sigma_t$; at depths of this order such a gradient is considerable and is perhaps responsible for the unusual current.

Finally Veronis (1957) believes that a strong current of water from the South Atlantic is present along the western border of the Tonga-Kermadec Trench. It is possible that a branch of this current curves towards the west at the south of Norfolk Island ultimately to effect the deep water of the Tasman Sea at 26° S.–30° S. between 3000–3500 m where one finds the highest salinities and the lowest phosphate and oxygen valves (Rochford, 1960c).

DYNAMIC EQUILIBRIUM OF THE WATERS

SURFACE CIRCULATION

The limit between the circulation in the surface layers and subsurface layers and that in the deeper water coincides in all oceans with the lower limit of the discontinuity layer which is in general at a depth of several hundred metres; in consequence, although the speed of the surface current decreases with depth the general direction of the displacement is maintained and one can consider that in general the surface circulation reflects that of the upper layers.

The greater part of the water masses penetrating into the region between the Solomon Islands and the Tropical Convergence are carried along by the West Wind Drift (Wyrtki, 1960); the general flow to the west is supplemented between January and March by Equatorial Water under the influence of the monsoon; further, between Tasmania and New Zealand a surface current transports Subantarctic Water towards the northeast although the quantity of water so transported is relatively small. The only region across which an appreciable quantity of water is transported out of this region is limited by the Tropical Convergence and the North Island of New Zealand; the limit between the westward flow to the north and the easterly flow to the south dictates the position of this Convergence. Between December and May the Convergence is at a latitude near to 30° S. while in the southern winter it is displaced northwards and reaches near to 26° S. The most northerly position reached in September, is near to New Caledonia and this is when the surface flow between this Island and New Zealand is essentially to the east.

To the north of New Zealand the currents are in general very strong; the annual variations of the flow indicate that in summer, when relatively small quantities of surface water leave this region by this route, there must be strong convergences; in winter the flow leaving to the north of New Zealand better compensates the flow entering the north of the region and the tendency for the formation of convergences is distinctly reduced.

On the other hand, Wyrtki (1960) has shown that in all seasons of the year the tendency to convergence is stronger than that to divergence. In a quantitative treatment which takes into account the distribution of the current lines he has shown that the difference between the convergences and divergences have considerable seasonal variation so that it is greater in summer than in winter; in practice the difference between the convergence and divergence

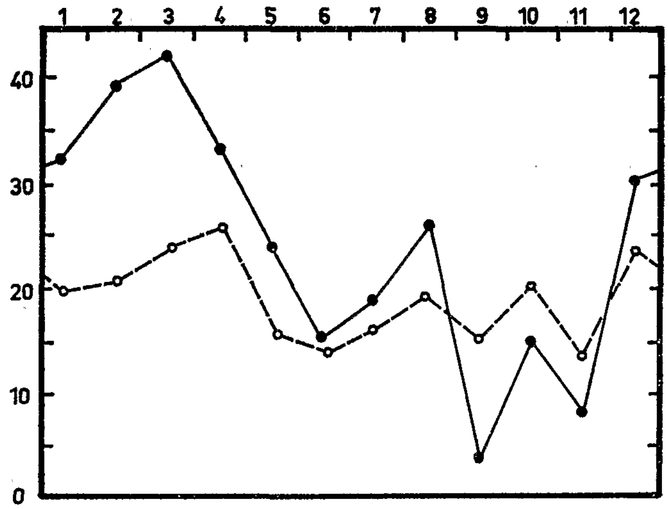


Fig. 7.—Annual variations of the difference between convergent and divergent movements in the region and the sum of the Tropical and Subtropical Convergences in relative units: —— convergence less divergence; – – – – plunging at the Tropical and Subtropical Convergence (after Wyrtki, 1960).

reflects the difference between the entrance and exit of surface water at the limits of the region because the principle of conservation of mass implies that entrance + divergence = exit + convergence. It is, therefore, during December and March that the entering flow most greatly exceeds the outgoing flow.

In comparing the difference between the entrant surface flow and that leaving, or between divergence and convergence, as regards their quantitative importance to the Tropical and Subtropical Convergences expressed in relative values, Wyrtki (1960) has shown that there exists a close correspondence between the annual variations of these variables (Fig. 7) and that a large excess of an entering flow is coincident with marked convergent movements. The correlation between the excess of entrant flow and the sinking at the Tropical and Subtropical Convergences indicates that there will be a convergence even though there is not an excess of entering over exiting water; such convergences must therefore derive from the wind field.

Almost the whole excess of the entrant flow sinks along the Subtropical and Tropical Convergences and there is, therefore, an important exit transport of water by passage into the intermediate and deep layers.

THE PARTICULAR CASE OF THE CORAL SEA BASIN

According to Wyrtki (1961a) the potential temperature in deep basins diminishes exponentially with depth; the form of the curve giving the distribution of temperature is determined by the equilibrium between the thermal conduction from the upper layers and the upward movement of the water masses of the basin.

In a given basin the thermo-equilibrium may be written:

$$Tt_e = Fwt - FA\, dt/dz$$

where T is the rate of entrance of the water in the basin in m^3/sec, t_e the temperature of water, F the area of the basin at the level of the entrant flux, w the speed of the ascending current at the same level, t the temperature of the ascending water and A the coefficient of eddy diffusion with $T = Fw$, so that, $A\, dt/dz = w(t - t_e)$ with the temperature t being assimilated to the potential temperature independent of vertical movements.

If the distribution of the temperature is known one may calculate, w/A as

$$\frac{w}{A} = \frac{dt}{dz}\frac{1}{t - t_e} = \frac{d}{dz}\log_e (t - t_e)$$

In the Coral Sea where the potential temperature of the entering water, t_e, is 1·46°C, w/A increases with depth; if A is constant w must increase with depth—which is logical when the area of the basin decreases.

Calculation shows that between 3000–4000 m, assuming A to be constant and equal to 1 g/cm/sec, w is equal to $1{\cdot}27 . 10^{-5}$ cm/sec and $1{\cdot}90 . 10^{-5}$ cm/sec respectively. These values of the vertical velocity are of the same order of magnitude as those calculated by Stommel (1958); their variation with depth is determined by the variation in the surface area of the basin because the product Fw which is the vertical flux at each depth is constant and equal to $4{\cdot}5 . 10^{10}$ cm^3/sec; such a flux is extremely weak compared with normal oceanic currents.

DYNAMICS OF THE CIRCULATION

CHOICE OF REFERENCE LEVEL

Throughout the whole of this region the layer situated between 1200–2500 m depth has a low oxygen content and moreover its core is formed from the water of the lower oxygen minimum. In the oceans such water can only be formed at depths where advective processes are extremely weak. This oxygen minimum situated at the limit of the Antarctic Intermediate Circulation and of the Deep Water Circulation must coincide with the level of virtually no motion, or where motion is extremely slow. It represents therefore the best possible reference level; Wyrtki (1962b) has accepted 1750 m as the level of no motion. Reid (1961) studying the general oceanographical conditions of the southwest Pacific and Rotschi (1959, 1960c) have taken 1000 m; the difference between the geostrophic circulation at 1750 decibars and that at 1000 decibars is negligible, particularly in the intertropical zone where geostrophic currents between 700 m and 2000 m are extremely weak.

DYNAMIC TOPOGRAPHY OF THE SURFACE

The dynamic topography of the 1750 decibar surface (Wyrtki, 1962) at the end of the southern summer in spite of annual and seasonal changes shows the general characteristics of the circulation (Fig. 8). The East Australian

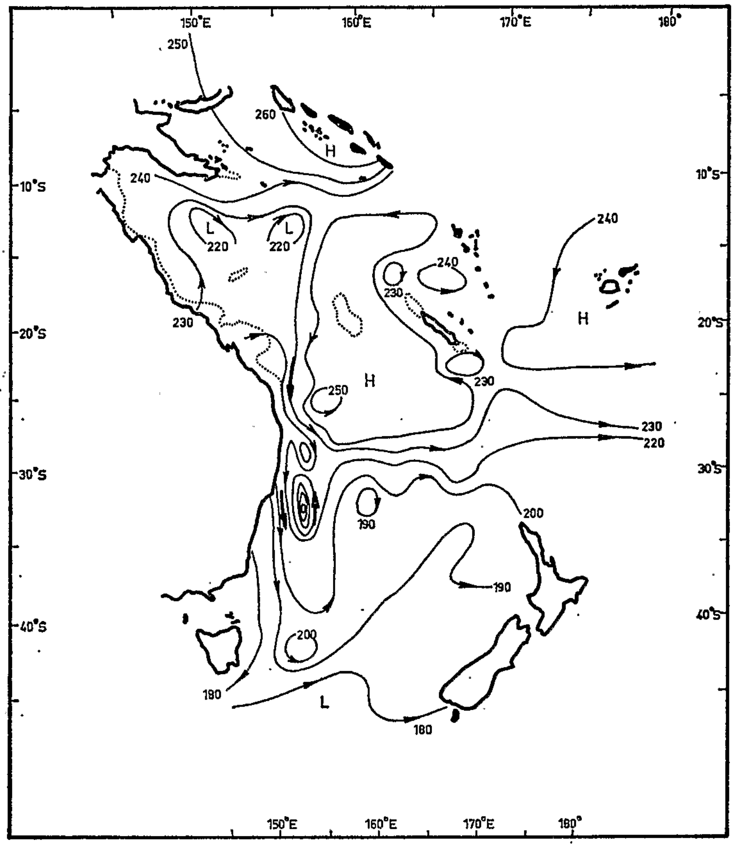


Fig. 8.—Dynamic topography of the surface with respect to that of the 1750 decibar surface (after Wyrtki, 1962).

Current turns in a southerly direction along the western border of a convergence; between 30° S. and 35° S. this Current turns towards the west, traverses the Tasman Sea and leaves the region to the north of New Zealand. During the course of this displacement large meanders are formed which separate and drift southwards along the coast of Australia; some of the anticyclonic eddies create, in general, a northern countercurrent; Hamon (1961) has observed such very variable eddies in the region of Sydney. In the south of the Tasman Sea between Tasmania and New Zealand the northeasterly current is generally weak.

There exist two pronounced dynamic highs, one centred on the Fiji

Islands and the other between New Caledonia and Queensland. Between these two, that is, in the region of New Caledonia and the New Hebrides, a number of eddies are evident; these are only local characteristics of the surface circulation since they are not evident at the 100 decibar level.

The geostrophic surface circulation described by Reid (1961) resembles that given by Wyrtki (1962b) the most noticeable difference being due to the fact that the former has described the general circulation from observations widely dispersed in time, whilst the latter has given the circulation during a well defined season. According to Reid there could be a zone of strongly marked dynamic highs around the New Hebrides and between 15° S. and 30° S. the geostrophic circulation could be towards the east.

Between 10° S. and 30° S. one never finds from the dynamic topography the characteristics of the surface circulation usually shown in current charts; in particular, the general current to the west is limited or non-existent. This flow towards the west which is the current of the West Wind Drift is not apparent in the geostrophic circulation.

COUNTERCLOCKWISE VORTEX OF THE CORAL SEA; SOLOMON DIVERGENCE

Between 10° S. and 15° S. and 155° E. and 165° E. one finds a counterclockwise eddy in the Coral Sea which was first discovered by Takahashi (1959); with respect to the 500 decibar surface this divergence still appears at 150 decibars. This characteristic shows as two dynamic lows in the pattern of circulation described by Wyrtki (1962b; see also Fig. 8). The position of this divergence is closely related to the strength of the surface currents and is, therefore, under the influence of the winds; it is less marked in February and March when the drift to the south is stronger. In the immediate proximity of the Solomons this divergence induces a current towards the east which is part of the South Equatorial Countercurrent. On the other hand, associated with a dynamic slope which can reach 30 cm.dyn./200 miles and with geostrophic currents reaching one knot, this divergence favours the formation of a dome structure and this affects the layers between 200 m and 1000 m; the importance of this structure depends on the dynamic slope of the surface (Rotschi, 1961); the dome structure is reinforced when the dynamic slope of the surface increases. Vertical turbulence is strongest in August at a latitude where, at the surface, one finds the northern limit of a strongly marked divergence. The turbulence also increases when the zone of divergence is displaced. At the beginning of the year the divergence is principally localized to the east of 160° E. and it increases from May to August, subsequently to be displaced towards the west. As a corollary, when the dome structure along 163° E. is increased the vertical turbulence attains its maximum intensity at 11° 30′ S. When the divergence is displaced the dome structure becomes more apparent to the west of 163° E.

The influence of vertical movements on the physical and physico-chemical properties of the water during the summer has been described by Rotschi (1961, 1962a).

SPECIAL ASPECTS OF THE SURFACE GEOSTROPHIC CIRCULATION

Detailed studies carried out on the northeast of the Coral Sea and the north of the Tasman Sea (Rotschi, Angot and Legand, 1959a, b; Rotschi, Angot and

Desrosières, 1960; Rotschi, Angot, Legand and Desrosières, 1961; Rotschi, Legand and Wauthy, 1961; Rotschi and Magnier, 1963; Takahashi, 1959; Lemasson and Magnier, in press) have shown that this region is a complicated system of large eddy circulations in a regime whose general transport is towards the west.

As has been previously noted the Tropical Divergence of the Solomons appears quasi-permanent; a further permanent geostrophic character is the Tropical Convergence localized to the south of New Caledonia and whose position fluctuates seasonally. Apart from these exceptions the dynamic topography is essentially a function of the season. For example, in May to June 1958, there was a geostrophic circulation exclusively from east to west in the northeast Coral Sea; this westerly flow was made up of strongly saline Tropical Water and not of Equatorial Water. The Central South Pacific Water accompanies the westward flow to the south of the New Hebrides. Between New Caledonia and the New Hebrides there was an intense cyclonic circulation affecting the first 200 m and favouring homogeneity of the subsurface waters almost to the disappearance of the subsurface salinity maximum.

In November, the South Equatorial Water which penetrates between San Cristobal and Santa Cruz conserves its characteristics far to the south; on the other hand, along the west coast of New Caledonia there is a geostrophic current to the northwest which transports Central South Pacific Water northwards.

GEOSTROPHIC CIRCULATION IN THE SUBSURFACE LAYERS

To the south of 30° S. the subsurface circulation is identical with that of the surface but in the subtropical region there are notable changes. For example, in the centre of the Coral Sea there is a westerly current which attains its maximum intensity at 200 m while to the north of 13° S. there is an easterly current which is influenced by the Solomon Divergence and which is probably a deep extension of the South Equatorial Countercurrent.

A dynamic high extends from 30° S. to 43° S. along the whole of the Australian coast. This ridge could as well be made up of a succession of cells which correspond to the meanders of the East Australian Current. Between this ridge and the Australian coast the current is southerly—but far offshore to the north. Between 30° S. and 35° S. the current is essentially eastwards.

Between 100–200 m the circulation corresponds to an extension of the Subtropical Lower Water or South Central Pacific Water. It includes a branch penetrating into the Coral Sea to the north of the New Hebrides, the extension towards the south along the Australian coast of water of high salinity, as well as the southern branch of the South Central Pacific Water which penetrates to the south of New Caledonia and which sinks at the Tropical Convergence. In the south of Tasman Sea at 200 m several eddy cells are formed.

At 400 m the East Australian Current is still well marked and it considerably influences the distribution of oxygen; along the Australian coast, water with a low oxygen content extends to the south while offshore it is a water rich in oxygen which is displaced towards the north. In the eastern part of the Tasman Sea off New Zealand there is only a weak circulation which is reflected in the absence of an oxygen maximum. At 700 m between 10° S. and 30° S. the geostrophic current is westerly and corresponds to the entrance into the Coral and Tasman Seas of Antarctic Intermediate Water. The East Australian Current is still present all along the Australian coast.

MASS TRANSPORT OF WATER

The most characteristic feature of the circulation besides the East Australian Current is the surface flow coming from the east and northwest and which enters the Coral Sea and feeds the East Australian Current; furthermore, between 100–200 m there is a flow towards the west of such Subtropical Lower Water.

In the subsurface layers the entrant flow is under the influence of a dynamic high near to New Caledonia and of a depression to the east of San Cristobal; this westerly flow is always present in the Coral Sea but it varies considerably in importance since the geostrophic currents, as well as the wind induced currents, are irregular.

Between New Caledonia and San Cristobal the transport, largely limited to the layer between 100–300 m, varies from 6×10^6 m^3/sec and 26×10^6 m^3/sec with an average geostrophic velocity of 3 to 5 cm/sec. There is no evidence regarding annual variations, but attention may be drawn to a temporary flow to the east which indicates an extreme variability of the currents.

Wyrtki (1962b) has evaluated the transports with reference to the 1750 decibars surface. Between 27° S. and the Solomons, the eastwest transport of 48×10^6 m^3/sec with an average geostrophic velocity of 3·3 cm/sec reaches its greatest development between 200–300 m. The outgoing transport leaving towards the east, localized to the north of New Zealand between 30° S. and 35° S., is of the order of 29×10^6 m^3/sec with a surface geostrophic velocity of 14 cm/sec. Between New Zealand and Tasmania there is a transport towards the south almost uniform between 0–1200 m of 13×10^6 m^3/sec and this plays an important role in the dynamic equilibrium of the region even though the speeds of the geostrophic currents are extremely weak; it is this flow towards the south which prevents the Antarctic Intermediate Water penetrating into the Tasman Sea from more southerly latitudes.

The transport of the East Australian Current between 0–1000 decibars has been evaluated by Hamon (1961) as being of the order of 35×10^6 m^3/sec.

The direction of the transport through the Torres Strait varies with season; from April to October there is a westerly transport of the order of $0{\cdot}5 \times 10^6$ m^3/sec and from December to February a similar transport in the opposite direction.

Between New Caledonia and Norfolk Island Rotschi (1963) has shown that the transport to the east is limited to surface and subsurface layers; the zone of the Tropical Convergence appears mainly to be a region of exit of waters originating in the centre of the Coral and Tasman Seas; Lemasson and Magnier (in press) have shown that between the surface and 1000 decibars the transport towards the east is 12×10^6 m^3/sec.

Rotschi (1963) has shown that the transport into the Coral Sea varies during the year, lying between a maximum of 23×10^6 m^3/sec and a minimum of 6×10^6 m^3/sec and that the eastward transport leaving the region at either the north of the New Hebrides, or to the south of New Caledonia is generally very small and only rarely equal to the entrant flow; this implies an important loss of water to the south of the region.

Near to the Solomon Islands the transport in the South Equatorial Countercurrent, between 10° S. and 12° S., is of the order of 10×10^6 m³/sec.

Hamon (1958) has determined the transport of water entering the Coral Sea from calculations of the mean annual surface currents and has estimated that between the principal Sills—New Britain–Bougainville, Solomon–New Hebrides, New Hebrides–New Caledonia, New Caledonia–Norfolk—the transport in the first 200 m is of the order of 5×10^6 m³/sec in each case. One should notice that the geostrophic calculations often indicate a large transport at greater depths.

Across the Torres Strait the mean annual transport is zero.

TIDES

All the various kinds of tides are represented in the Coral and Tasman Seas, the diurnal tides dominating to the north and the semidiurnal to the south; the amplitudes vary considerably according to the locality and can reach considerable heights, for example, of the order of 10 m along the northeast coast of Australia.

The four most important harmonics of the tides, namely, the M_2, S_2, K_1, O_1, constituents give a relatively complete scheme for the total tides; the cotidal lines for the different values are given by Dietrich (1944), Villain (1951) and Bogdanov (1961).

In the Solomon Sea the amplitude of the M_2 and S_2 constituents is small and on account of the amplitude of the diurnal tides the tide has not a solar character.

In the Coral and Tasman Seas, the tide appears to be due to a constituent derived from the Pacific Ocean and penetrating the Coral Sea between the Solomon Islands and New Caledonia, and the Tasman Sea between New Caledonia and New Zealand. The cotidal time for the M_2 constituent is a little greater than 9 h along the west coast of New Caledonia; the cotidal line for 10 h seems to pass fairly near to Lord Howe and Chesterfield Islands; along the east coast of Australia the cotidal time of the M_2 constituent differs little from 10 h 20 min and the amplitude of this wave lies between 40 cm and 60 cm. To the north of Brisbane, along the coast of Queensland, the cotidal time increases rapidly so that the amplitude of the M_2 constituent reaches a maximum value of 173 cm near to the point of maximal tidal amplitude of 10 m.

The cotidal lines to the north of the Coral Sea converge to an amphidromic point situated in the Solomon Sea near to New Georgia. In the south of the Tasman Sea the cotidal times increase towards the south; the cotidal lines for 11 to 1 h appear to converge at the southern point of Tasmania.

Bogdanov (1961) has determined the position of the amphidromic points which are as follows; M_2, 7° 58′ S.: 156° 40′ E.; S_2 (two amphidromic points) at 45° 45′ S.: 148° 50′ E. and 46° 25′ S.; 178° 40′ E.; the diurnal O_1 and K_1 constituents do not have amphidromic points within this region.

A study of the ratio of the sum of the amplitudes of the two most important diurnal and semidiurnal waves allows one to draw a tidal pattern. Dietrich (1944) has given an account of the distribution of these different types. One finds a semidiurnal tide along the coast of Tasmania, New Zealand, and the

Fiji Islands while the mixed tide has a semidiurnal predominance along the Australian coast, southeast of New Guinea, New Caledonia, and the New Hebrides. In contrast, a mixed tide with diurnal predominance is present in the Solomon Islands. Diurnal tides occur in the centre of the Solomon Sea. The Torres Strait is notable for extremely violent tidal currents attaining a speed of 5 to 6 knots during the spring tides.

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