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Volume 2

A REVIEW OF THE PHYSICAL OCEANOGRAPHY OF THE GREAT BARRIER REEF AND WESTERN CORAL SEA

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PART 2—THE WESTERN CORAL SEA

G. L. Pickard
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Preface

The object of this study is to review what is known of the physical oceanography of the waters of the Great Barrier Reef and Western Coral Sea. Because the two regions are sharply different topographically (the first being a reef-studded strip of shallow coastal water, generally well mixed vertically, while the second is chiefly 1000 to 5000 m deep with marked water structure in the vertical), they can best be treated separately with references to their interactions where appropriate (or, more exactly, where known). In neither case is the available information sufficient for a full description.

In the presentations for both areas, the topography is described briefly and available climatic information is summarised as background. Then descriptions are given in turn of the surface distributions of water properties, the subsurface characteristics and their distributions, and the circulation, referring to the sources of information in each case. Finally, a short summary is presented.

For Part 1 on the Great Barrier Reef lagoon, information is limited, and some suggestions are offered for possible future investigations of the physical oceanography of this region. In this connection, it should be noted that there are very few data on the physical oceanography of *any* barrier reef lagoons to which one can refer for guidance. An opportunity is available here for pioneering work. (A project for the study of the New Caledonia barrier reef lagoon is already under way.)

For Part 2 on the Western Coral Sea, there is more information; here the salient papers are reviewed specifically, and then an attempt is made to summarise the present state of knowledge of the region. For some readers, the summary may be sufficient for their needs, while it is hoped that the review as a whole will form a useful introduction to this region for physical oceanographers prior to study of the original papers for a fuller understanding of the development of the knowledge and of the limited extent of the data available at present.

Much of the review is a presentation of the analyses of previous workers, although the mode of presentation of results is sometimes different from theirs. However, some of the material in this review is derived from new analyses of existing data. If the original author is not quoted it may be assumed that the results presented are novel in this review.

A common bibliography is attached. Most of the items are referred to in the text but some, such as data records used by some of the authors, have been included for completeness though not specifically quoted in this text.

G. L. Pickard
June 1976

Acknowledgments

Having acquired an interest in the water circulation patterns in reef and lagoon areas during many visits to Pacific islands, the senior author was pleased to accept Dr M. Gilmartin's suggestion that he review existing knowledge of the physical oceanography of the Great Barrier Reef and adjacent Coral Sea as background for further studies of this area. He is grateful to Dr Gilmartin, as Director, for making available to him facilities to work at the Australian Institute of Marine Science; to Dr K. R. Allen and Messrs B. V. Hamon, D. J. Rochford, and R. J. Edwards of the CSIRO Division of Fisheries and Oceanography, Cronulla, and to P. D. Scully-Power of the Royal Australian Naval Research Laboratory, Sydney, for assistance in locating and evaluating information; to many members of the Section d'Océanographie, O.R.S.T.O.M. Centre de Nouméa, for suggestions and assistance related to both parts of this review; to Mr J. Ngai for his excellent drafting of the figures; and to his collaborators in Part 2.

He wishes to thank the Director-General of O.R.S.T.O.M. and M. Legand, Director of the Centre de Nouméa, for permission to use the facilities of the centre at Nouméa and for other courtesies during his stay. He is particularly grateful to M. Henri Rotschi, until recently head of the Section d'Océanographie, who first roused his interest in the south-west Pacific and fostered it during two previous visits to Nouméa including participation in two major cruises in the western equatorial Pacific in N.O. *Coriolis*.

Permission to reproduce figures as indicated in the legends is gratefully acknowledged.

PART 1

The Great Barrier Reef

by

G. L. Pickard

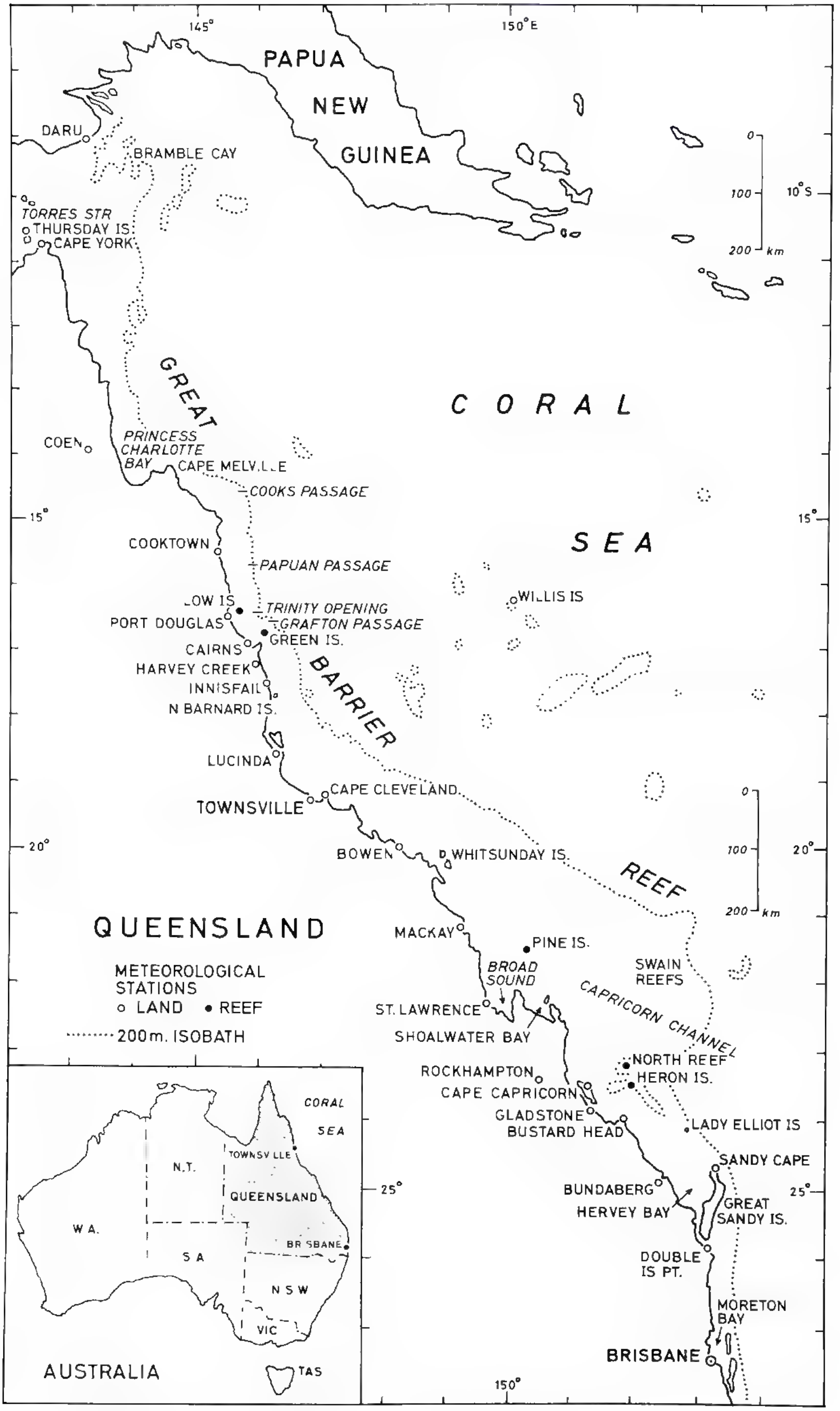


Fig. 1 Australian Great Barrier Reef region.

I
Introduction

The Great Barrier Reef off Queensland, Australia, extends more than 2000 km from about 9.1 S, just south of Papua New Guinea, to about 24 S (Fig. 1). Although a considerable number of biological investigations have been carried out in the region, relatively few studies have been made of the physical oceanography (water properties, currents, etc.). The main ones are those on water properties by Orr (1933 a,b) and Moorhouse (1933) (both at Low Isles during the Great Barrier Reef Expedition) and by Brandon (1973), and on the tides by Easton (1970). The *Australia Pilot*, Vol. IV (British Admiralty, 1962) gives some information on currents and the annual *Australian National Tide Tables* (e.g. 1976) on tides and tidal currents. Maxwell (1968) has described the geographical, geological and other features at length. There is also information on water properties and climate in *Weather on the Australia Station* (RAAF, 1942), *Sea areas around Australia* (Roy. Neth. Met. Inst., 1949), and the *Monthly Oceanographic Charts, Tasman and Coral Seas* (CSIRO, 1974).

The present paper will review current knowledge of the physical oceanography of the Great Barrier Reef region for the use of marine scientists working in the area, and will suggest directions for future study.

II
Topography

The Great Barrier Reef is an assembly of coral reefs and lagoons off the east coast of Queensland. The coral reefs are found as far north as Bramble Cay at about 9.1°S, close to the coast of Papua New Guinea; this cay will be taken as the northern limit of the Barrier Reef region for physical oceanographic consideration. A southern limit of 25°S is arbitrarily selected; this latitude is in the vicinity of a marked feature of the coast, Great Sandy Is., and is just south of the southernmost coral reefs. The western boundary is taken as 142°E in Torres Strait and the Queensland coast to the south. The eastern boundary is taken as the position of the 100 m depth contour just outside the outer reefs, a depth greater than those found between the shore and the outer reefs, and close to the drop-off to the continental slope. The seaward limit will not be adhered to too rigidly and, in the south, the Capricorn Channel will be included west of a line from outside the Swain Reefs to Sandy Cape.

For this review, the term '(Great) Barrier Reef' will be used to refer to the region as a whole from west to east boundaries. The term 'outer reef' will be used for the main boundary structure on the eastern side, and the term 'lagoon' to the main body of deeper water between the land and the outer reef. The word 'reef' alone will be used to refer to individual features of the coral structures of the region; these may enclose their local (shallow) 'lagoons'. However, attention will be devoted chiefly to the main lagoon rather than to the local lagoons.

Despite its name the Great Barrier Reef is not continuous and certainly does not present an impermeable barrier to the passage of water. Fig. 2 shows schematically the general character of the outer reef. The linear distance scale is taken along the eastern face of the outer reef, and the intersections with parallels of latitude are indicated; the latter scale is non-linear because of the changes in the orientation of the reef face. The northern 40% of the reef, from 9.5° to 16.5°S, is one of the more continuous stretches, with reefs coming close to the surface for about 90% of the distance. Then from 16.5° to 20°S shallow reefs occupy only about 10% of the distance along the reef. There is a short stretch of dense reef from 20° to 21°S, followed by the Swain Reefs to about 22.5°S, in which the reefs are scattered but the east-west width is greater than elsewhere. The Capricorn Channel is open to the south and provides a wide and deep entrance to the southern end of the lagoon. The southern 60% of the outer reef length is thus only about 20% occupied by actual coral reefs. The above figures are approximate but do indicate that the lagoon waters inside the outer reef are by no means isolated from the Coral Sea outside. In addition, it should be noted that in the more continuous stretches of reef, water from the sea may enter not only through the gaps between the coral reefs ('passages' etc.) but also over the reefs as swells break on them.

The Reef as a whole extends roughly in a NW–SE direction, with an outer reef length of about 2300 km; the width from shore to outer reef varies from 23 km at 14°S to 260 km at 22.5°S and averages 100 km. The area between land and outer reef is about 230 000 km^2.

A more significant dimension oceanographically is the depth of water. An estimate of the distribution of depth in 20 m intervals has been made from Maxwell's (1968) Figs. 16A-E. The areas between 0–10, 10–20 fm etc. were estimated by $\frac{1}{4}$ degree square units for each of Maxwell's five regions and are shown in Fig. 3A as percentages of the area in that

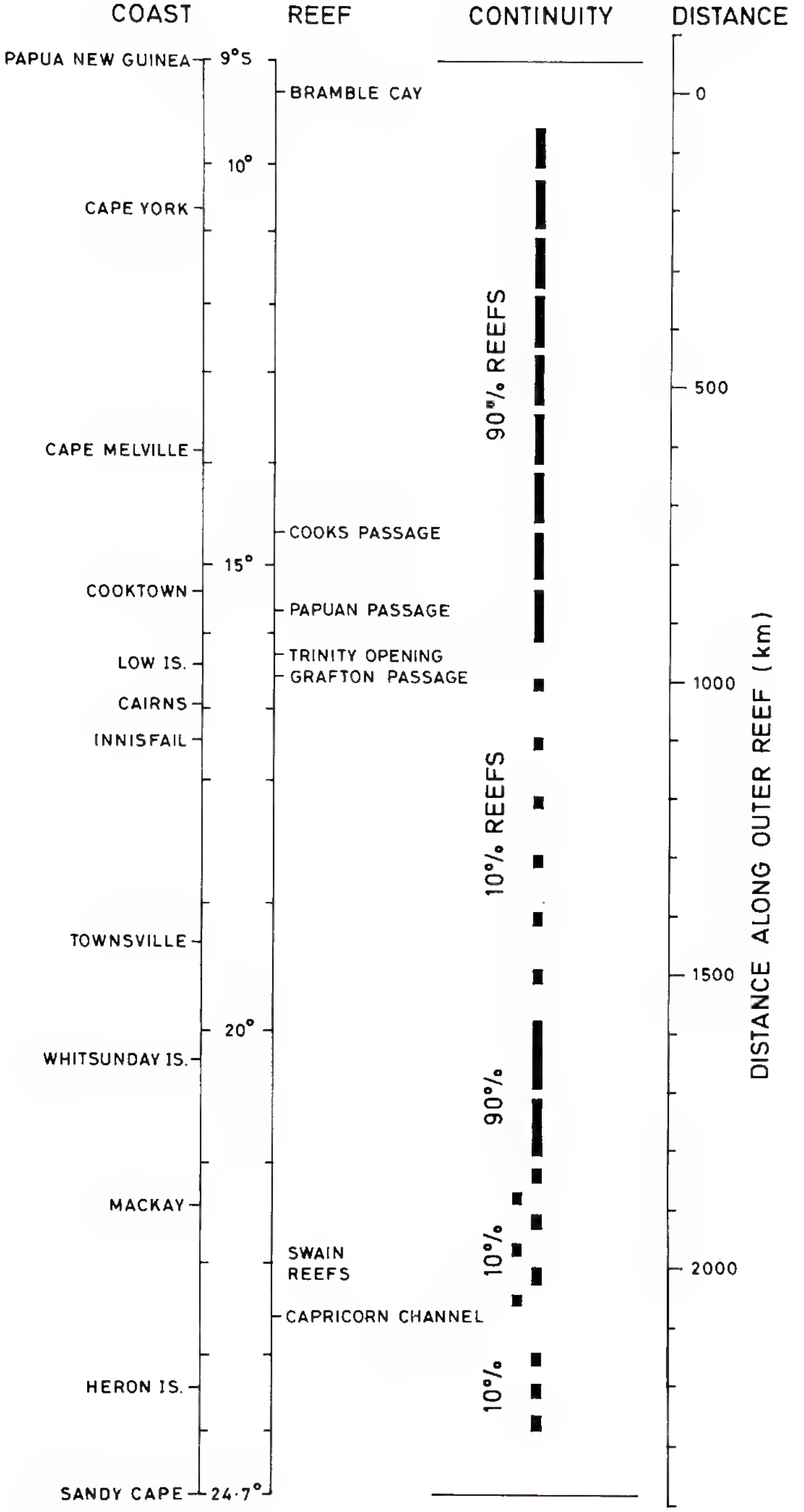


Fig. 2 Schematic representation of outer reef continuity, Great Barrier Reef.

region (shore to 50 fm). There is also a component of uncertain depth in most regions because of the incompleteness of the hydrographic surveys. In Fig. 3B are presented the areas within the depth zones for the Reef area as a whole. From this graph the values for zones 0–20 m, 20–40 m etc. were interpolated (extrapolated for the 100 m value) and are presented in Table 1. From this it is estimated that the mean depth of the surveyed area of the lagoon is about 35 m, and depths over 60 m are uncommon. The unsurveyed areas are probably mostly in the shallow end of the depth range. It should also be noted that aerial photographs are available for about 80% of the Reef region (some sources are given at the end of the References).

Fig. 3 (A) Depth distribution in Great Barrier Reef lagoon by 10 fathom intervals in each of Maxwell's 1968) regions, expressed as percentage of area of each region,
(B) Hypsometric curve for Great Barrier Reef lagoon, derived from diagram A above.

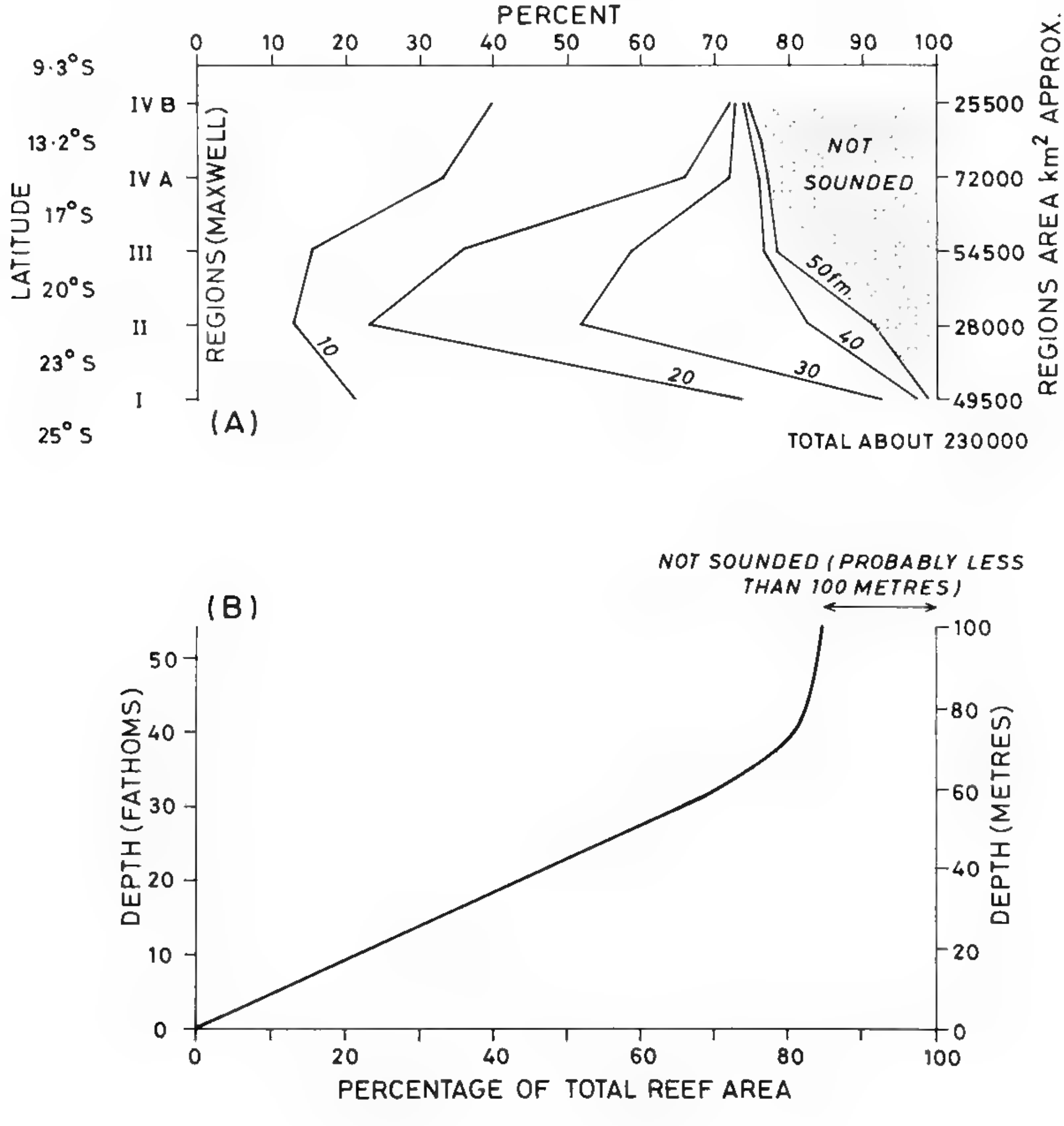


Table 1. Percentage of Great Barrier Reef area in various depth zones

Depths (m)	0		20		40		60		80		100	Not surveyed
Areas (%)		23		25.5		22.5		11.5		2.5		15

Mean depth 35 m; total area about 230 000 km^2

III
Climate

Information on some aspects of the climate particularly relevant to the physical oceanography of the Barrier Reef has been extracted from *Weather on the Australia Station* (RAAF, 1942), the *Australia Pilot* (1962), *Sea areas around Australia* (Roy. Neth. Met. Inst., 1949) etc., and are summarised in this section. One important factor is that most of the regular observing stations are on land; in this regard, two points must be noted. First, the local topography is likely to affect the meteorological factors, particularly wind direction and rainfall. Second, the degree to which land station measurements can be applied to the neighbouring sea areas, particularly at distances as great as 250 km, is always uncertain. However, there are some island stations which afford an opportunity to evaluate this factor to some extent.

WINDS

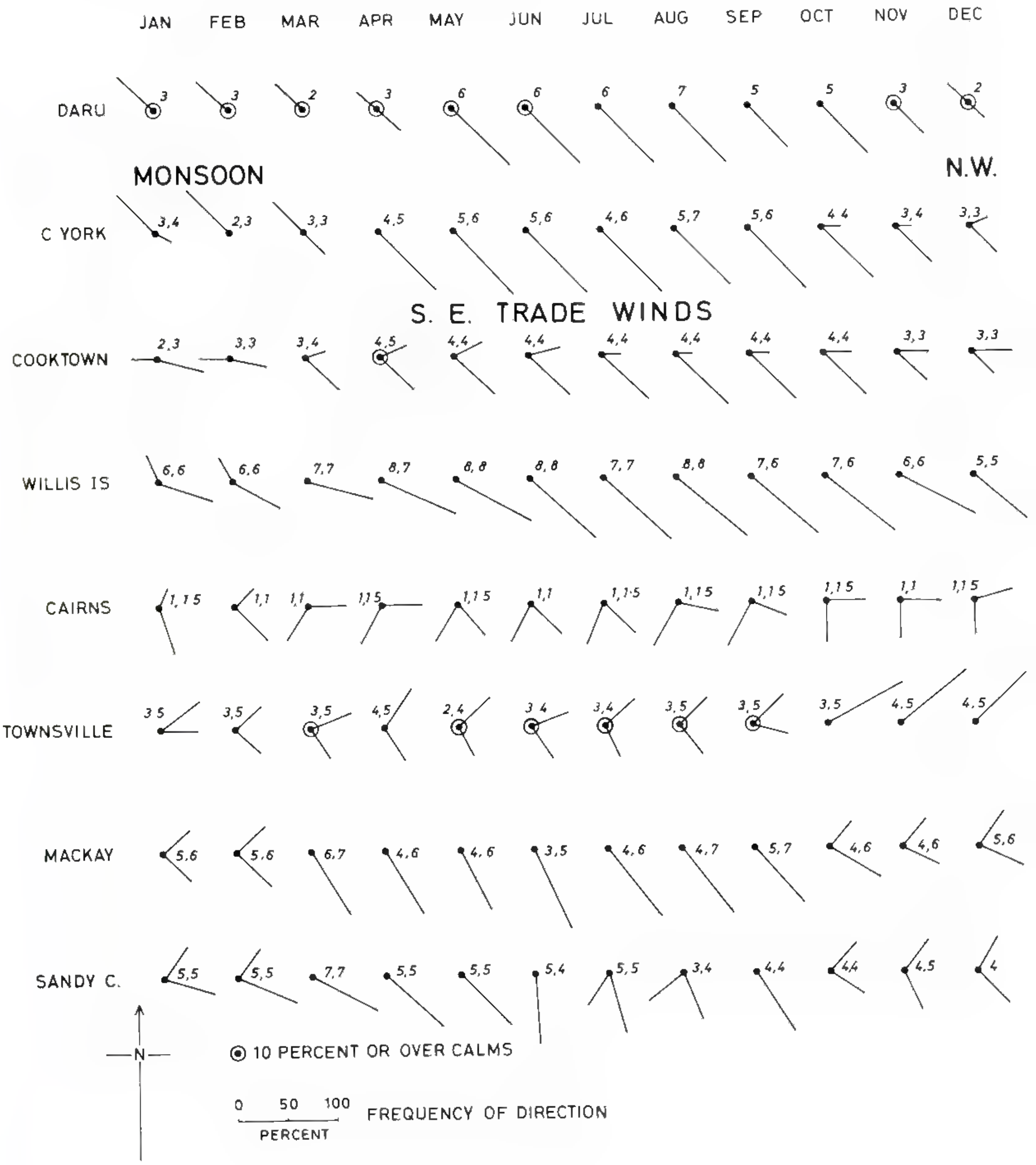
South of 15° S, the SE trade winds prevail and the wind direction is generally from between east and south. North of 15° S the NW monsoon invades the region. In the north, the NW winds start in December, develop through January and February and die out in March to be replaced by SE winds. Their effect is felt as far south as 15° to 16° S in lessened degree. Increased rainfall is associated with this wind direction.

The most common wind directions and typical speeds are shown in Fig. 4 for a selection of stations near the Reef. Willis Is. is included in this and other climate tables, although it is 460 km east of the reef, because it is the only continuous long-period reporting station representative of open sea conditions with little topographic interference (the island is only about 8 m above sea level). The above information is taken from *Weather on the Australia Station* (RAAF, 1942), in which the frequency of occurrence of winds is given for eight directions (and calm) on a monthly mean basis. The speed is given as a single monthly mean value for 0900 hr and 1500 hr. The monthly sheets of the General Air Circulation in *Sea areas around Australia* (Roy. Neth. Met. Inst., 1949) show only a single arrow in each 1° square to represent the general direction and speed; this information agrees well with that in Fig. 4. The effect of the NW monsoon is chiefly to decrease stability and to introduce westerly to northerly components of wind to 15° to 16° S. South of this latitude, an easterly component of wind prevails from August to January or February, with southerly winds prevailing for the rest of the year. A feature in the Cairns–Townsville area (17°–19° S) particularly, and to some extent for other southern areas, is for the wind to back by 45° to 90° (from SE toward NE) between 0900 and 1500 hr during much of the year.

CYCLONES

On the average, two cyclones per year affect the Queensland coast, the associated heavy rainfall in short periods of time probably being the most important factor oceanographically. Cyclones originate in the Intertropical Convergence Zone between 8° and 18° S in the northern Coral Sea and are most common (about 76%) in January to March, with another 18% occurring in December or April. They initially move to the west. Those north of about 12°S tend to continue west across the Cape York peninsula, while the more southerly ones tend to curve SE and parallel the coast. On the average there are the same number of lesser disturbances each year, 80% of which occur between January to July inclusive.

Fig. 4 Preponderant wind directions in the Great Barrier Reef region. Wind blows toward the dot, numbers represent the mean wind speed (m/s) for 0900 and 1500 hrs (Daru 0900 hr only). For stations from Daru to Willis Island the two wind vectors indicate two predominant directions during the month (associated with the NW monsoon), while from Cairns to Sandy Cape the two vectors indicate that the wind backs from the 0900 hr observation (the more clockwise vector) to the 1500 hr observation. Circles indicate 10% or more calms in the month.

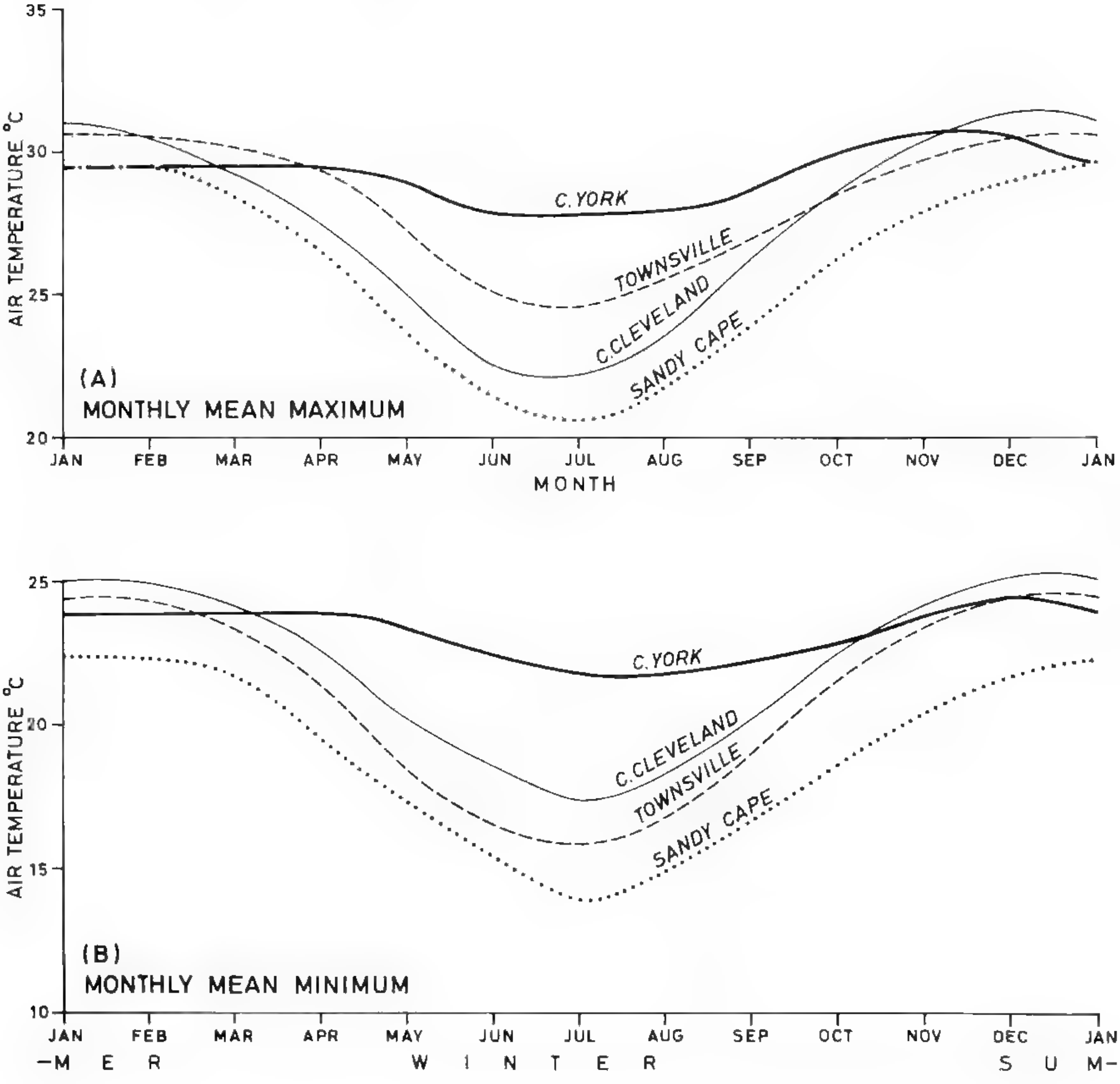


AIR TEMPERATURE

The air temperature cycles for monthly mean maximum and minimum temperatures show a maximum in December or January and a minimum in August. Curves for selected stations at the north (Cape York) and the south (Sandy Cape) are shown in Fig. 5. The curves for Townsville and Cape Cleveland are shown partly to represent an intermediate latitude and partly to show how much difference there may be between neighbouring stations. These two are only 20 km apart and at the same latitude. It is concluded that for any heat budget studies, it would be essential to use actual observations for the locality being investigated.

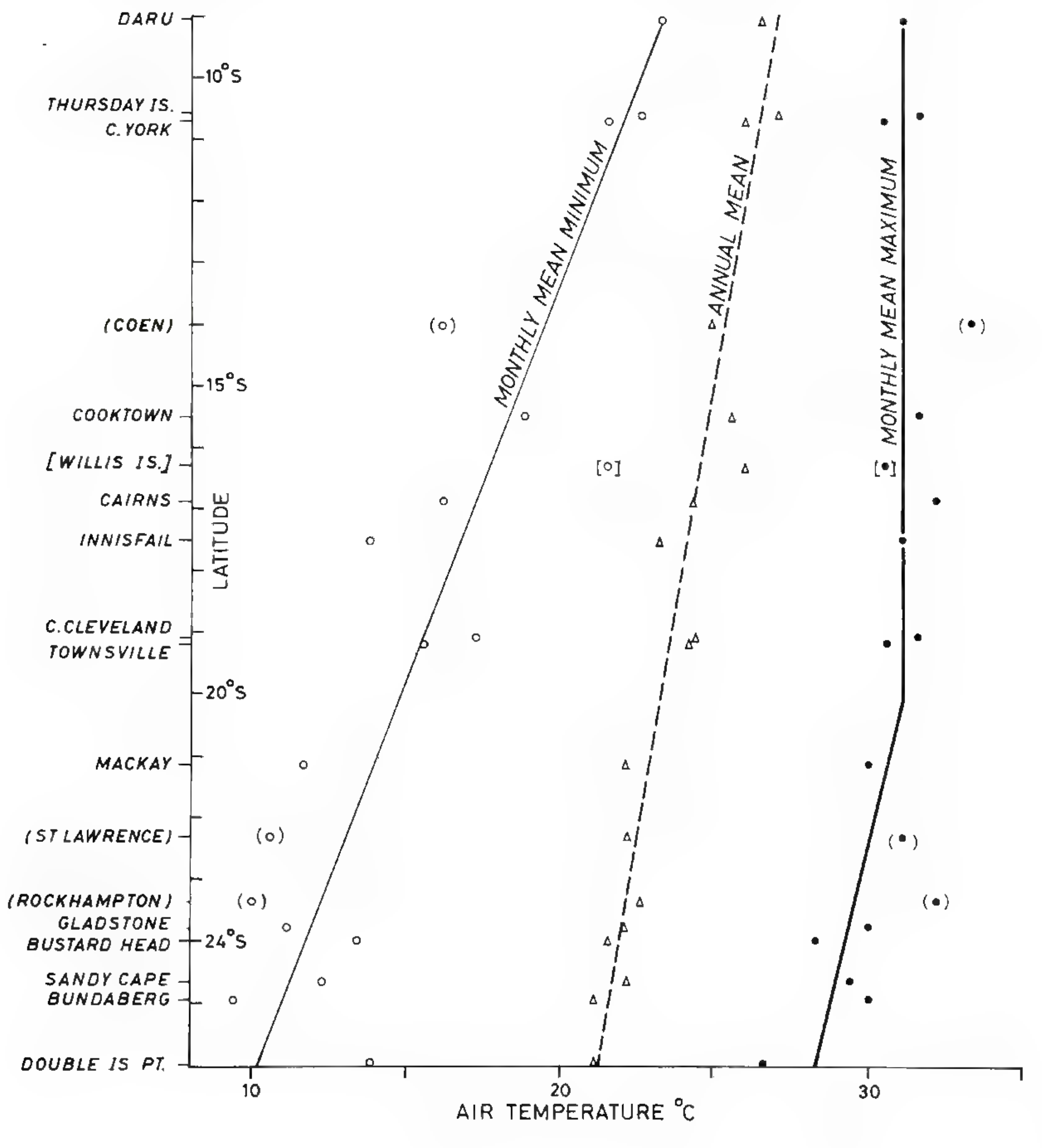
Sea areas around Australia (Roy. Neth. Met. Inst., 1949) has monthly charts of mean air temperature averaged by 1 squares with whole number isotherms interpolated on the plots. For the Barrier Reef region temperature time curves for 11 S, 19 S and 25 S have been compared with the maximum and minimum plots of Fig. 5. The Dutch data values fall half way between the maximum and minimum values for Cape York (10.7 S), Townsville (19.2 S) and Sandy Cape (24.7 S) (within $\pm$ 0.5C), except that the Dutch values fall about 1.5C lower near the minimum.

Fig. 5 Seasonal variation of air temperature for selected typical stations along the Great Barrier Reef coast. (A) Monthly mean maximum, (B) Monthly mean minimum. Cape York 10.7 S, Cape Cleveland—19.2 S, Townsville 19.2 S, Sandy Cape –24.7 S.



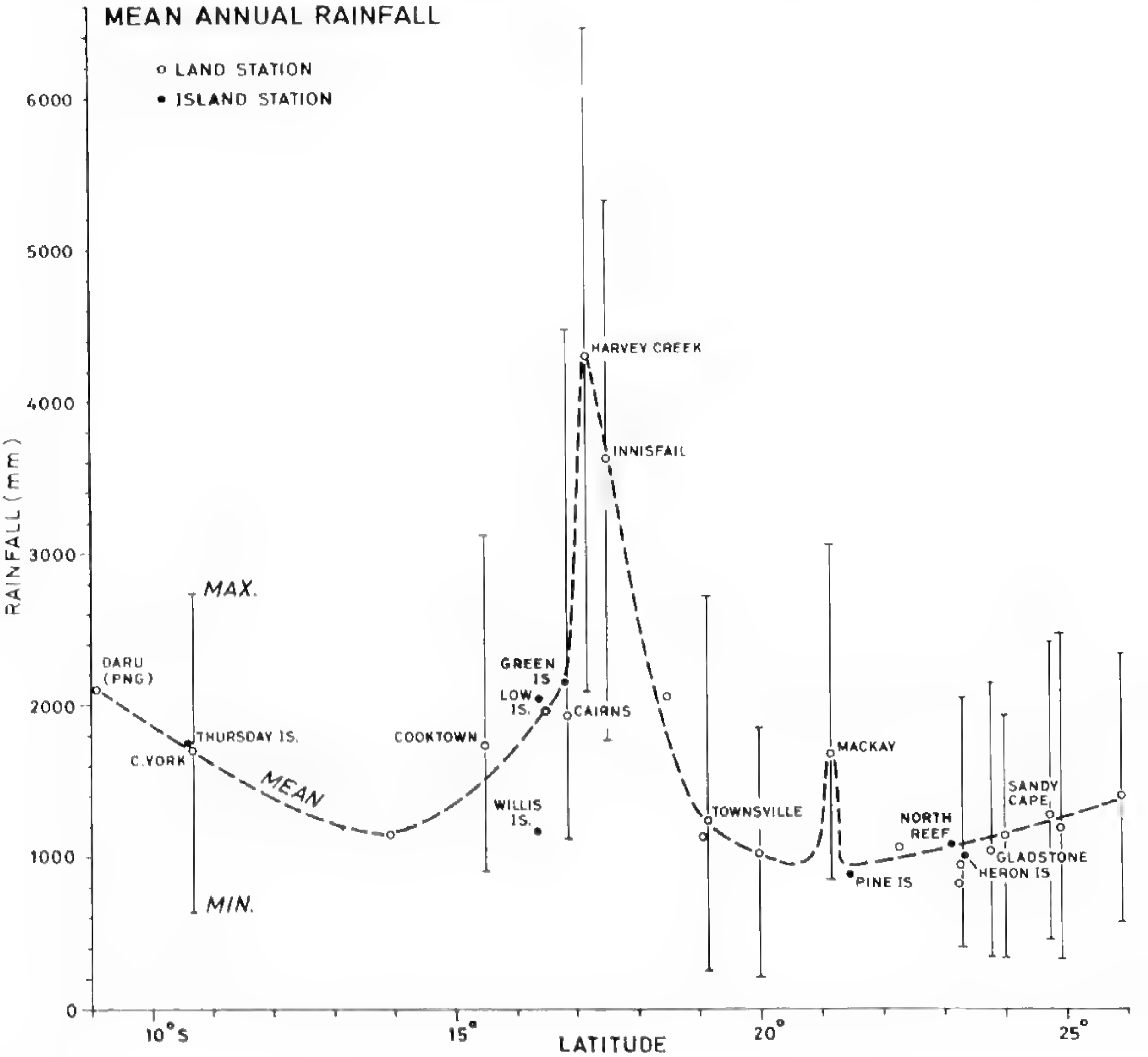
An indication of the geographical scatter of mean air temperatures is given in Fig. 6 in which the monthly means of daily maximum and minimum temperatures (RAAF, 1942) and the monthly mean temperatures, are plotted against latitude. Mean lines have been visually drawn through the points, with reduced weight being given to stations more than 10 km inland from the coast and to Willis Is. offshore. It will be seen that the maximum is substantially constant from 9 to 20 S and then decreases southward, while the minimum decreases steadily to the south. The annual mean air temperatures derived from the Dutch data above lie about 0.4C higher than those in Fig. 5.

Fig. 6 Minimum and maximum values of monthly mean air temperatures, and annual mean air temperature, for stations along the Great Barrier Reef coast. Means are of at least 20 years observations to 1939 except for Daru (16), C. Cleveland (8). ( ) = more than 10 km inland, [ ] - Willis Is., about 460 km east of outer reef.



In coastal seas particularly, rainfall and river runoff are important factors in their effect on salinity. Australia is a continent of tremendous variation in rainfall and the Queensland coast is the wettest part of the country. This point is often overemphasised as the mean annual rainfall along the coast is not high by world standards (about 1500 mm, the same as Vancouver, one of the drier parts of the British Columbia coast). What may be more important oceanographically (and socially-economically) are the very large variations in space and time of the rainfall. As this section of the review is intended primarily for orientation, not as a source of climatological statistics, tabulations of detailed data will not be presented. These are available in *Weather on the Australia Station* (RAAF, 1942), *Australia Pilot* (1962), or from the Australian Bureau of Meteorology as the basic source of climatological data for this country. Rather, the rainfall will be described graphically as are the other climatological factors. For any analysis of specific oceanographic field data, it will be mandatory to use actual weather information, rather than climatological averages, because of the large variations with time (day to day or year to year) which are characteristic of this coast. Data from standard observing stations may be available, but in

Fig. 7 Mean annual rainfall along the Great Barrier Reef coast and range from recorded minimum to maximum annual rainfall



view of the significant spatial variations it may be necessary in some cases to schedule weather recording for the area of oceanographic study.

Rainfall values have been rounded off to the nearest ten millimetres as the precision implied in the published figures to the nearest millimetre seems inappropriate when year to year variations may be measured in *metres* (e.g. Fig. 7).

Mean annual rainfall

Fig. 7 shows the long-term mean annual rainfall as a function of latitude, with a few names added for convenience and the land and island stations distinguished (Sources: RAAF, 1942; Brandon, 1973). It will be seen that the mean annual precipitation is between about 1000 and 2000 mm except for the notorious but restricted zone near Innisfail (17.5 S). Also it is noted that the island stations lie on the same curve as the land stations (except for Willis Is. far offshore). This point will be discussed later.

Rainfall variability

Fig. 7 also has bars indicating the range between recorded minimum and maximum annual rainfalls (Source: RAAF, 1942). This figure shows one aspect of the variability of rainfall on this coast, that the variation is often greater than the mean. A plot (not shown) of the differences between recorded maximum and minimum against long-term mean annual values shows a roughly linear relationship from 1000 to 4000 mm yr. A few values are:

Long-term mean annual rainfall (mm)	1000	2000	3000	4000
Difference, recorded max.-min. (mm)	1700	2500	3300	4100

This table gives an indication of the long-term variability, although it must be noted that the differences are from records of 50 to 72 years duration and such large variations need not be expected very frequently.

In records of maxima and minima for individual months, the variability is even greater than that shown by the annual maxima and minima. A few examples from tabulations in *Weather on the Australia Station* (RAAF, 1942) will suffice to indicate the tremendous ranges of rainfall to be expected. For Innisfail (17.5 S), January rainfalls from 30 to 1580 mm (mean 510 mm) and August falls from 0 to 450 mm (mean 130 mm) have been recorded; for Bowen (20 S), the January range is 5 to 1180 mm and for April 0 to 640 mm. Ranges such as these are typical, not rare.

On a still smaller time scale of days, the variability of rainfall can be very large, particularly during the wet season when the heaviest falls are associated with cyclonic systems moving through the region. Practically every coastal station south of 15 S has received at least one fall exceeding 250 mm in 24 hours (RAAF, 1942). The recorded 24-hour maximum rainfall values in the climatological tables (RAAF, 1942), when plotted against mean monthly values on a scatter diagram (not shown), can be summarised as follows:

	Monthly average (R_M)	24-hr maxima
Dry season	up to 150 mm	0.8 to 5 times R_M
Wet season	100 to 650 mm	0.5 to 2 times R_M

Although the dry season 24-hour maximum factor may be larger (up to 5 times), it is the wet season 24-hour maxima which are likely to be more significant oceanographically because of their greater volume.

A generalised picture of the seasonal variations of rainfall during the year is presented in Fig. 8. Mean monthly rainfall values for each station were normalised by dividing by the mean annual rainfall for that station. Curves drawn of normalised rainfall against month show the well-known features of (a) distinct wet and dry seasons and (b) more marked distinction between the seasons in the north and centre areas than in the south. Mean curves were presented for these three zones in order to avoid the confusing appearance of a large number of curves (for all the stations) on one diagram. (Note that there are only three stations, widely spaced at 10.6°, 10.7° and 14.0°S, for the north zone.) Because Fig. 8 is a simplification from the original diagram, which shows considerable scatter about these mean curves, it should not be used to scale off values for individual stations (from their mean rainfall values) except for very approximate values. Tables of climatic records should be used for this purpose, e.g. RAAF (1942), *Australia Pilot* (1962), Brandon (1973) for immediate reference, or the Bureau of Meteorology as the basic source, especially for recent data. However, Fig. 8 does show the two basic features of the rainfall distribution noted above. The concentration of rainfall (about 70% of the annual amount) in the January to March period for the north and centre zones is well shown.

Note that Innisfail, in the centre maximum rainfall zone, does not fall clearly on any of the curves (it is shown by the symbol 'I' on the diagram). It has an extended wet season similar to the south zone but falls between the centre and south zones in the dry season. This is attributed (RAAF, 1942) to orographic showers occurring in the nominal dry season.

Comparison of rainfall on land and on islands

Earlier it was noted in reference to Fig. 7 that the rainfall statistics for the islands of the Reef were not much different from those on the land stations nearby. Brandon (1973) examined this aspect by comparing the rainfall at islands and land stations for the same group of years (the data in Fig. 7 are for different numbers of years for the different stations). The ratios which he obtained were, for the same years for each comparison but not the identical years for all:

(a) Low Is./Port Douglas	=1.02	
(b) Green Is./Cairns	=1.09	
(c) Pine Is./Mackay	=0.51	
(d) Pine Is./Rockhampton	=1.09	
(e) Heron Is./C. Capricorn*	=1.60	*Eight years only

To these are added, before discussion:

(f) Pine Is./St Lawrence	=0.83	
(g) Heron Is./C. Capricorn**	=1.23	**All data
(h) Heron Is./Gladstone	=0.98	
(i) Heron Is./Bustard Hd	=0.84	

Note: the latter are not for the same groups of years in each case.

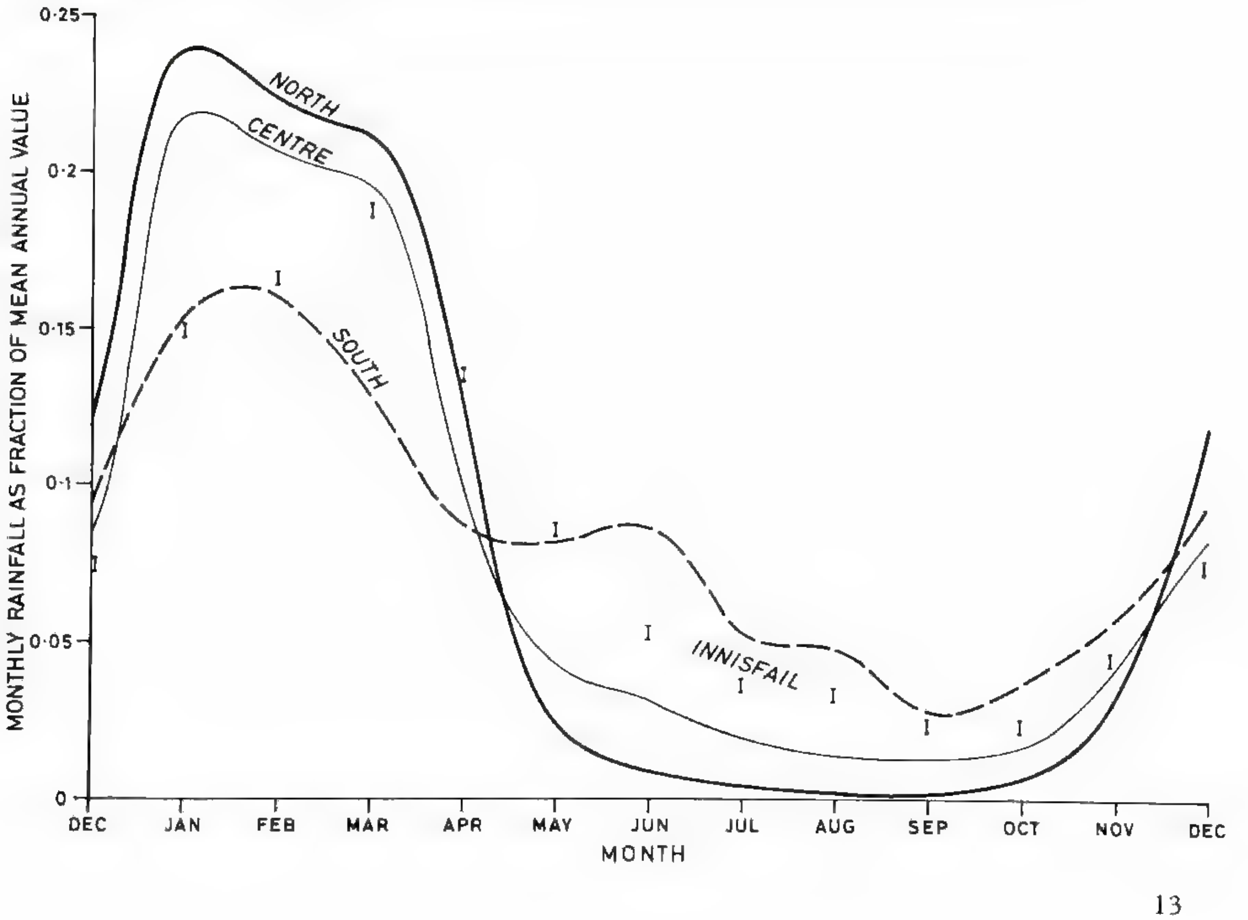
For Heron Is., Brandon concluded from the ratio 1.60 (c) that rainfall at the island was significantly higher than at the neighbouring coast station. He did not point out that the rainfall at C. Capricorn for the 8 years for which Heron Is. data are available was substantially below its long term average (600 mm against 810 mm) and that use of this latter figure would yield the lower ratio of 1.23 as in (g) above. Also, the ratios for Heron Is. rainfall to two other stations at the same distance as C. Capricorn are (h) 0.98 and (i) 0.84. Brandon regarded the Pine Is. Rockhampton ratio of 1.09 (d) as more significant than that to Mackay of 0.51 (c), which station is nearer but in a local high rainfall area. Note the Pine Is./St Lawrence ratio of 0.83 (f), St Lawrence being nearer than Rockhampton and the same distance as Mackay.

Overall, the evidence above suggests that the rainfall over the Reef area is probably not very different (±15%) from that on land in the vicinity (same latitude), and that for climatological calculations the mean rainfall curve of Fig. 7 could be used for the lagoon. However, it would be desirable to have more data for the Reef area itself to verify this opinion, particularly from positions further from land, and it is not expected that the very high coastal rainfall near 17° S, related to orographic effects, extends very far across the lagoon. (Ref. Chapter X, Reef Climate.)

RIVER RUNOFF

Rainfall on the lagoon is not the sole cause of reduced salinity; river runoff from precipitation on land is also a factor in coastal areas. Previous descriptions of salinity distributions in the Barrier Reef lagoon have attributed reduced salinity in part to river runoff, but curiously only one paper (Endean *et al.*, 1956a) has given any values for river

Fig. 8 Seasonal variation of rainfall along Great Barrier Reef coast, expressed as fraction of mean annual value:
North zone: 10.5° to 15° S, mean annual rainfall 1750 mm, Jan.–Mar. — 70% of annual;
Centre zone: 15.5° to 21.2° S, mean annual rainfall 2000 mm, Jan.–Mar. — 70% of annual;
South zone: 21.5° to 25° S, mean annual rainfall 1000 mm, Jan.–Mar. — 45% of annual.



runoff and no one has presented any quantitative comparison of river runoff and rainfall effects. Therefore an attempt was made to evaluate the relationship between these two factors.

Only limited information on river runoff is available, the two prime sources being *Stream Gauging Information, Australia, December 1969* (Aust. Water Res. Council, 1971), abbreviated to S.G.I. hereafter, and 'Surface Water Resources' in the *Atlas of Australian Resources* (Aust. Dept. of Nat. Dev., 1967), hereafter S.W.R. S.G.I. lists all river basins with their catchment areas and, in some cases, annual discharge figures. The North-east Coast Division is the one related to the Great Barrier Reef. Runoff information is available for about 318 000 km², i.e. about 76% of the total drainage area of 417 000 km² from Cape York to 25.5° S. Unfortunately, much of the catchment area for which runoff is measured is in low rainfall areas inland (less than 50 mm/yr) which do not contribute much to the total runoff. Many of the short rivers in the high rainfall regions near the coast are not metered at all. In fact, only one-third of the estimated annual rainfall of 8.3×10^{10} m³ (S.W.R. Commentary Text) is actually measured.

When calculating river runoff from rainfall data in a catchment area which is not generally saturated with moisture, it is necessary to allow for water which is retained in the soil and for that which is lost by evaporation (the actual river runoff is as low as 10% of rainfall in much of Australia including the inland areas of Queensland). It should therefore be noted that rainfall maps, such as Fig. 2 in Brandon (1973) or Fig. 53 in Maxwell (1968) can be misleading as far as river runoff is concerned. Because of increased losses inland, the runoff decreases much more rapidly than does rainfall as one proceeds inland from the coast. As an example, in the same distance inland at 18° S the rainfall decreases by a factor of 5 but the runoff by a factor of 60.

Fortunately, S.W.R. gives isopleths of runoff per unit area superimposed on the drainage basins; the runoff from each basin was estimated by numerical integration as suggested in the S.W.R. Commentary. For the basins for which the measured runoff is given in S.G.I. and for which the gauged area includes most of the catchment area, there was a reasonable correlation between runoff estimated from the S.W.R. chart and the actual gauged values in S.G.I., with the exception of the Burdekin River. For this, the estimate was only 40% of the gauged figure. The total runoff for the North-east Drainage Basin was estimated as 80% of the average annual runoff quoted in the S.W.R. Commentary Text, presumably obtained in a similar manner but with larger size charts. The discrepancy is attributed to the small scale of the published S.W.R. chart which makes it very cramped in the coastal high runoff area. Also, isopleths for more than 1500 mm/yr rainfall are not given in the published chart (because of crowding). Accordingly, estimates for individual basins were increased by 100/80 (with the Burdekin River value increased to the measured value) and presented in Fig. 9A.

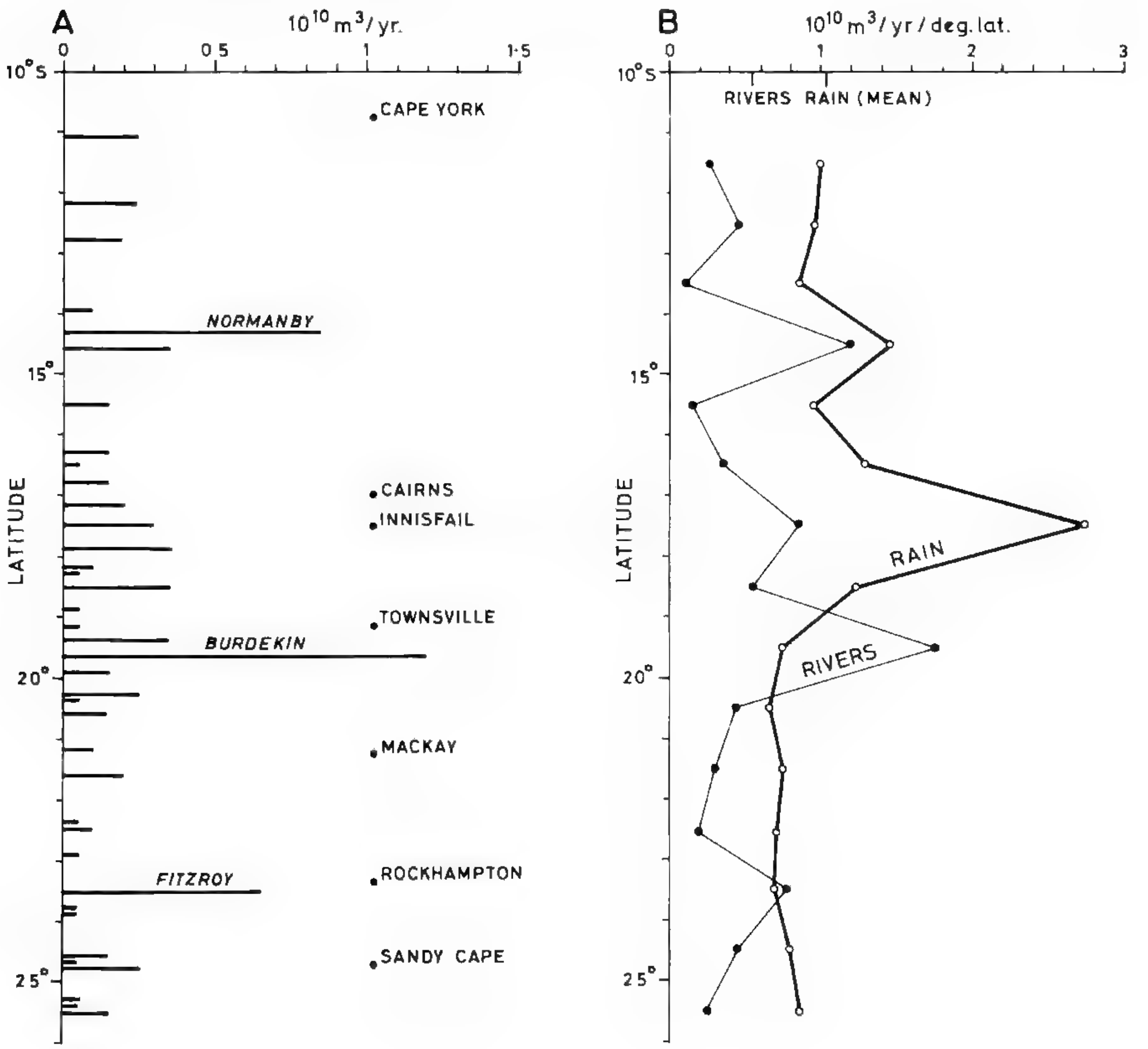
As these figures are for annual runoff *volume*, they cannot be compared directly with rainfall figures which represent volume per unit surface area, i.e. *depth* of water. To provide some idea of the relative importance of river runoff and rain components of fresh water input, the river flow value has been compared with rainfall volume over a selected area of the lagoon. The latter was divided into 1° latitude zones and for each the fresh water volume for the annual mean rainfall (Fig. 7) was calculated for an area from the shore to the outer reef or to 60 km east from the shore, whichever was the smaller distance. (The narrow part of the lagoon, in the north, has an average width from shore to outer reef of close to 60 km, hence the use of this figure where the actual lagoon is wider.) The river runoff into each of the same 1° latitude zones was determined and plotted (dashed line) with the rainfall value (full line) in Fig. 9B. On this basis the river runoff is about 50% of the rainfall volume.

Several criticisms may be offered. The difficulty of integrating the published chart has been mentioned, but the errors are not likely to be more than ±25% from this source (after normalising to the published total runoff figure). However, the information on which the S.W.R. is based is admitted to be very limited and more extensive data would certainly improve the quality of the estimate. For the present, the value of trying to improve the runoff estimates is doubtful because of the extreme variability in time of river runoff.

The variations from year to year are very large. The Burdekin River (19.7° S) has the largest recorded mean annual flow for the coast, 0.97 x 10^{10} m^3, and its minimum and maximum recorded flows are 4% and 300% respectively of this mean value. For the Fitzroy River (23.6° S) the figures are 5.1 x 10^{10} m^3, 3% and 560% respectively. The rivers north of 19° S generally do not show such extreme ranges of flows (e.g. average 40% to 210% of mean annual) as those south of that latitude (e.g. average 4% and 390%).

It should be noted that the mean *seasonal* variation of river flow, from the shorter rivers at least, is very similar to the mean seasonal rainfall pattern. S.W.R. gives figures for the Barron River at about 16.8° S, close to the coast, and for the Nogoa River at 23.6° S, about 110 km inland. The seasonal variations of runoff from these are very similar to those for rainfall for the centre and south zones respectively (Fig. 8). In shorter time intervals, the coastal river flow follows rainfall within a day or two but the smaller inland component may be delayed.

Fig. 9 (A) Mean annual river runoff volumes estimated from *Surface Water Resources* (Aust. Dept. of Nat. Dev., 1967) and *Stream Gauging Information* (Aust. Wat. Res. Council, 1971).
(B) Comparison of river runoff volume with rainfall volume on lagoon to reef or to 60 km from shore, whichever is least.



Another criticism of the rainfall versus runoff comparison of Fig. 9B concerns the calculated rainfall volume. For instance, the high rainfall component in the 17 to 18 S zone occurs because the local coastal rainfall figure was used; however, the substantial orographic effect here may overstate the rainfall volume calculated for the lagoon in this zone. Second, the 60 km width of zone for the southern half of the lagoon was chosen rather arbitrarily; if the full width of the lagoon were used, the rainfall component would be increased south of 18 S. Third, the tacit assumption in this comparison is that whatever width of zone is chosen, the river and rainfall components are distributed equally and uniformly over it. In fact, this is not likely to be the case for the runoff component because the rivers are essentially point sources at the coastline and their effects will be emphasised near their mouths. This is another reason for not calculating the rainfall volume over too wide an area of the lagoon for comparison. It would be desirable to make some measurements of runoff distribution as a function of time after a heavy discharge. Salinity depth measurements over an area would be desirable but a first order estimate might be made by using the turbidity of the river water as a visual tracer.

Another way to compare river runoff with rainfall is to assume the river component to be uniformly spread over an area of the lagoon as for the rainfall. If this is done, the river water layer thickness would vary from about 15 cm to 255 cm (compared with rainfall depths ranging from about 90 to over 400 cm). Expressed this way, it is convenient to note that 100 cm of water added to a column of 35 m depth (mean depth of the lagoon) would decrease the mean salinity by about 1 if mixed uniformly through the column. While rainfall is distributed over an area, river runoff is initially concentrated near the river mouths and therefore may have a greater effect locally in reducing the salinity. A frequently quoted example is Hedley's (1925a) description of the destruction of a coral reef by an exceptionally large river flood.

It is concluded from this discussion that river runoff does introduce a component of fresh water to the lagoon which is quantitatively comparable to the rainfall component. In the main, it will be contributed in phase with the rainfall but, being introduced at specific points along the coast, it could have greater effect in reducing salinity locally.

CLOUD AND HUMIDITY

Two other meteorological factors relevant to heat budget studies are cloud amount and the humidity of the atmosphere above the sea. According to the data available, neither shows much variation.

Cloud amount

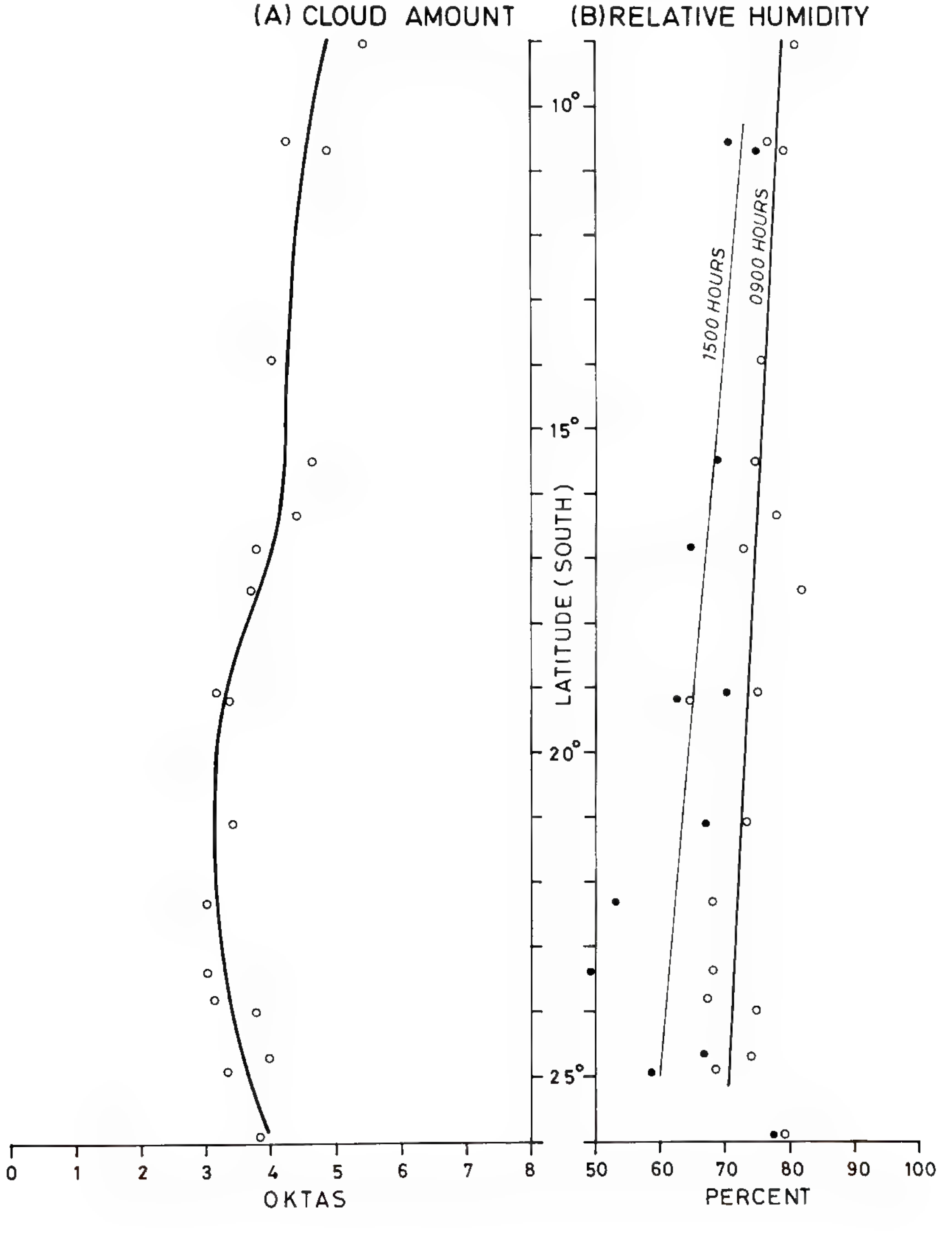
Fig. 10A shows that there is a small variation of cloud amount with latitude, the lowest values occurring between about 19 and 24 S. There is also some seasonal variation (Fig. 11A) with rather more cloud during the summer wet season than during the winter. The lower mean cloud amount in the south appears to be a result of less cloud all year round as is seen when curves a and b are compared in Fig. 11A, although the range of scatter of points about each line is 1 to 1.5 oktas (eighths) or rather more than the separation of the lines. The mean amount of cloud, 4.5 oktas of sky covered in the north in the monsoon season, seems to be low but it should be noted that for the three stations from 10 to 14 S the values are for 0900 hr observation only, which does not take account of any build-up during the day. Most of the others are for the mean of 0900 and 1500 hr observations. The summary in the *Australia Pilot* (1962) of reports from ships at sea shows much the same cloud conditions as described above.

The above remarks apply to all cloud observed from the stations.

Humidity

The relative humidity (Fig. 10B) shows a slight decrease southward, with lower values in the afternoon than in the morning, which is usual in coastal regions. The humidity also has slightly lower values in late winter (Fig. 11B) and 10% lower values through the year (curve d against curve c) for the same southern group of stations which show lower cloud amount (Fig. 11A).

Fig. 10 Variation with latitude along Great Barrier Reef coast of:
(A) Cloud amount (1 okta = one-eighth of sky covered),
(B) Relative humidity.



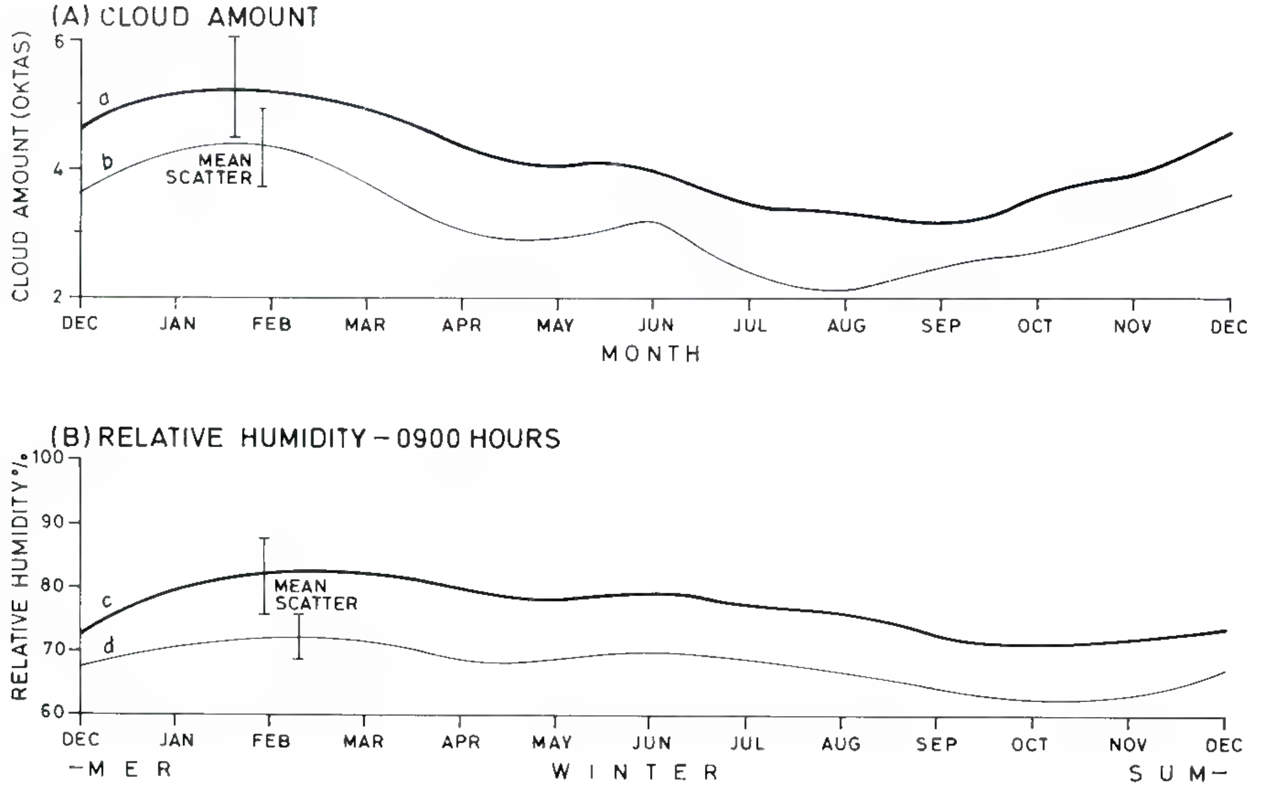


Fig. 11 Seasonal variation along the Great Barrier Reef coast of:
(A) Cloud amount: (a) 10°–18°S plus 24°–25°S, (b) 19°–23.8°S,
(B) Relative humidity. (c) 10°–18°S plus 24°–25°S, (d) 19°–23.8°S.

IV
Tides

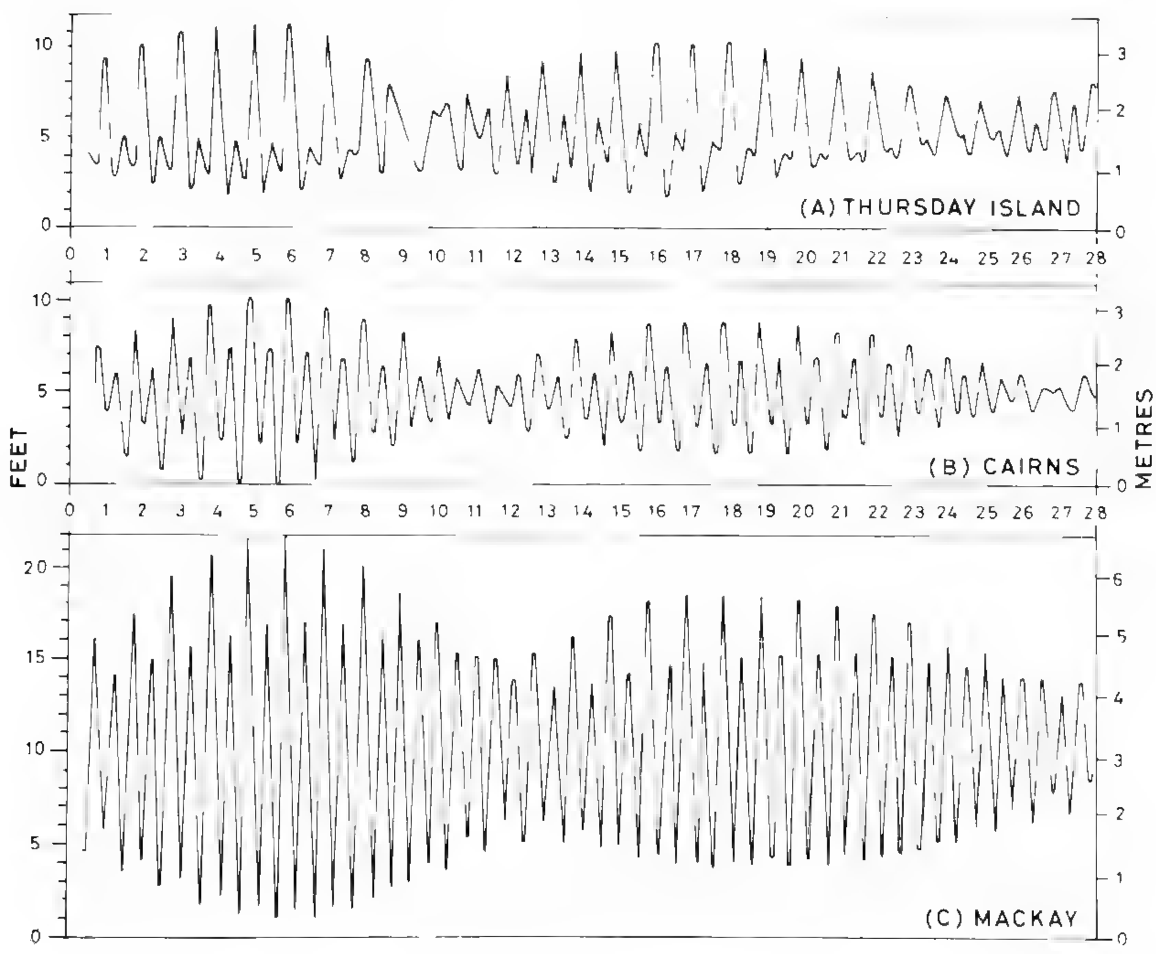
Easton (1970) has described the tides of Australia comprehensively and most of this section is based on his work, with references to the *Australia Pilot* and the *Australian National Tide Tables*. The Barrier Reef lies in two of Easton's zones, the North Queensland and the Mackay zones.

TIDE LEVELS

North Queensland zone (*Cape York, 10.7 S, to 19.5 S, north of Mackay*)

Cairns is taken as the standard port because its records are regarded as very reliable. The tidal rise and fall is semi-diurnal in character with significant variation from springs to neaps (3.3 to 0.3 m at the equinoxes, March and September); see Fig. 12. There is considerable diurnal inequality, particularly in the height of successive high waters, amounting to over 1 m at times (Fig. 12). This should be borne in mind if one runs a ship

Fig. 12 Typical tide height records for three stations along the Great Barrier Reef coast (from Maxwell, 1968).



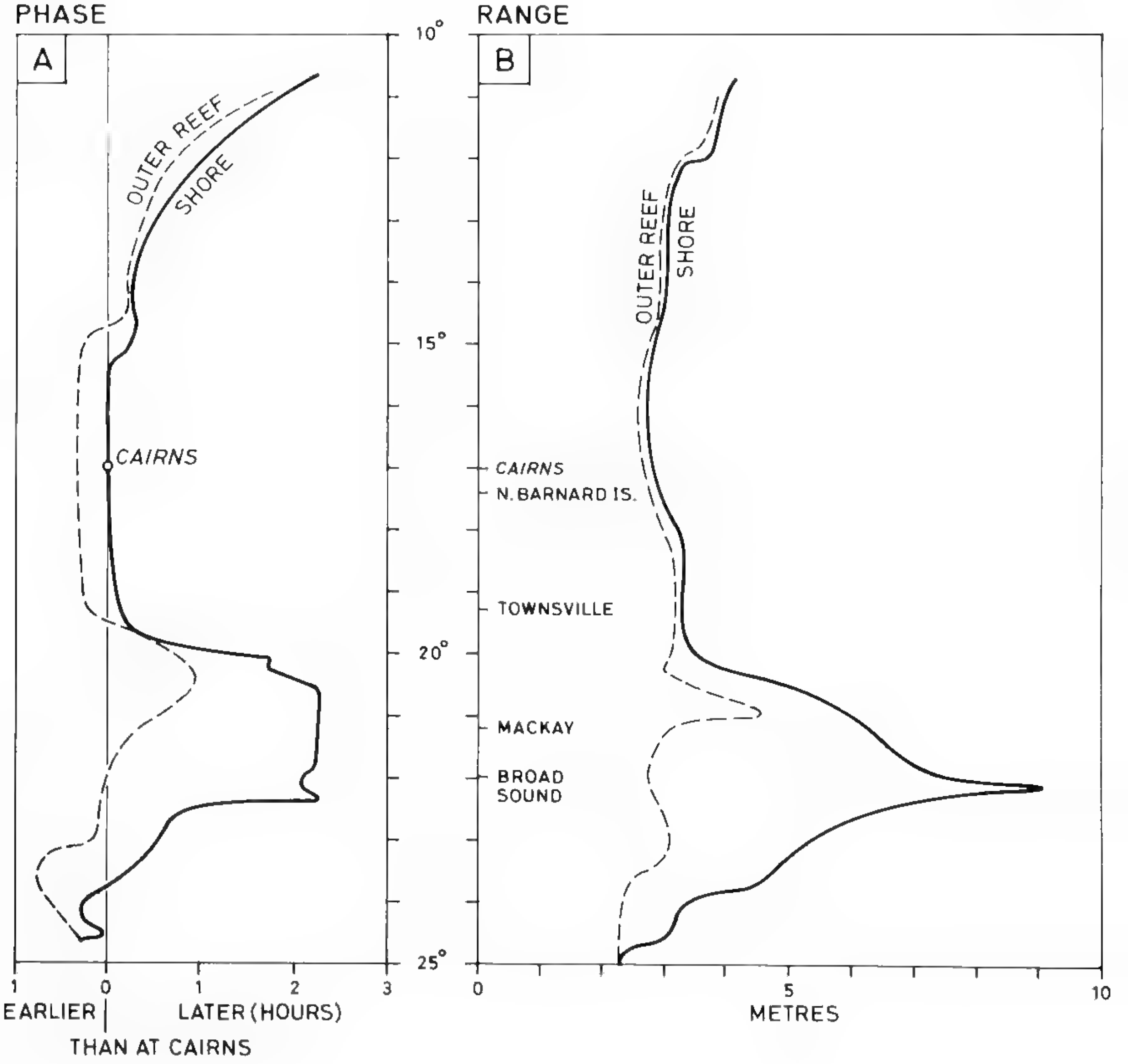
aground. Spring tides occur 1 or 2 days before full or new moon. At neap tides there are usually one or two days of essentially diurnal tides.

The tidal wave progresses eastward from the Coral Sea toward the shore and then north-westward north of Cairns, south-eastward south of Cairns (Maxwell, 1968, Fig. 41). Fig. 13A shows the time of high water along the shore (full line) relative to that at Cairns. The tides occur earlier on the reef (e.g. 15 min earlier at Green Is. compared to Cairns, 30 km to the west). The dashed line in Fig. 13A shows the time of high water at the outer reef, estimated from Maxwell's co-tidal chart (1968, Fig. 41).

Fig. 13B, from Maxwell's co-range chart (1968, Fig. 42) shows that the tidal range increases somewhat north of Cairns at the coast (full line) and at the reef (dashed line). Because of the very limited amount of tidal data other than at the shore stations, the reef values for phase and range must be regarded as only approximate.

Fig. 14A from Easton (1970) shows the percentage frequency of occurrence of hourly tide heights (full line) and of low and high tide levels (dashed lines) at Cairns. The full line shows the frequency along the ordinate, in terms of the tide level at hourly intervals, for which the sea level is at or above the corresponding height on the abscissa, e.g. the hourly

Fig. 13 (A) Tide phase relative to Cairns for Great Barrier Reef region.
(B) Tide range at springs for Great Barrier Reef region.
(Full line — shore, dashed line — outer reef.)



sea level is at 1.0 m (above datum) or higher for about 76% of the time, at 1.5 m or higher for 43% of the time, at 2.0 m or higher for 16% of the time, etc. The high tide line shows that the high water level occurs at 1.0 m or higher on almost 100% of occasions, at 2.0 m or higher on 55% of occasions, at 2.5 m or higher on 15% of occasions, etc. The low tide curve shows that low water level is at 0.5 m or higher on 72% of occasions, at 1.0 m or higher on 22% of occasions, and at 1.5 m or higher almost never. This information may be useful in estimating reef exposures in shallow waters. A minor point to note is that a few (of the lower) high tides occur below mean sea level, because of the pronounced diurnal inequality of the high tides.

Mackay zone *(about 19.5° to 25° S)*

The salient characteristic here is a very large tidal range, with maximal values in Broad Sound (22° S) south of Mackay (21.2° S).

The tides are semi-diurnal with marked inequality of the high tides (up to 1.8 m at the solstices) but little or none in the low tides (Fig. 12C). Easton stated 'categorically' that the higher tides occur during the night in winter and the day in summer. As the spring tide range is greater at the equinoxes than at the solstices (6.4 m compared to 5.8 m) and the mean sea level is lowest in September, the lowest water levels occur in September–October and afford the maximum exposure of corals.

The spring tide reaches a maximum of over 9 m in Broad Sound (Fig. 13B).

Fig. 14B, from Easton, shows the percentage frequency of occurrence of hourly tide heights and of low and high tide levels for Mackay.

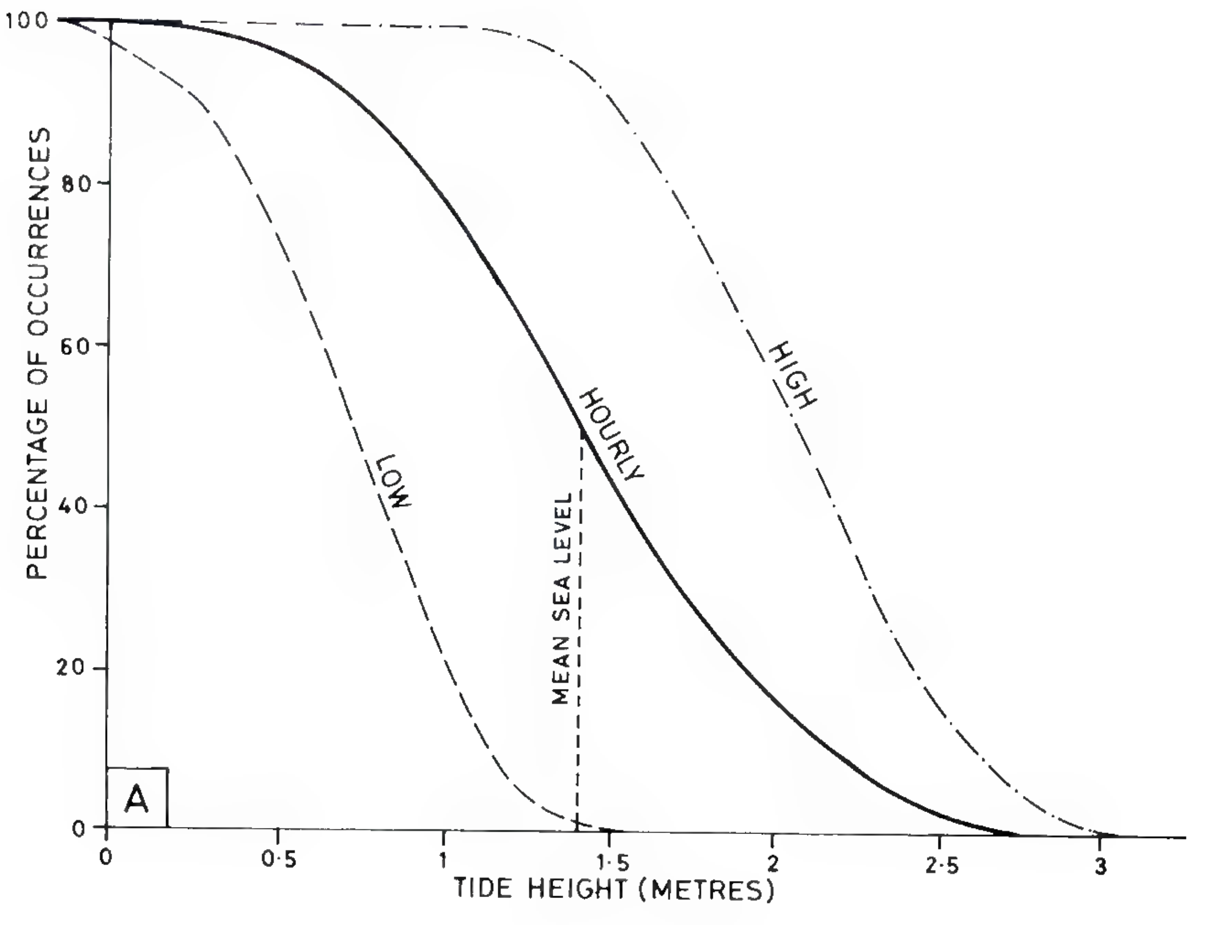
Fig. 13A shows that the delay in the tide, relative to that at Cairns, reaches a maximum of about 2.25 hours between 20.5° and 22.5° S and then decreases, while Fig. 13B shows the marked increase of tidal range to a maximum in Broad Sound and then a decrease to the south. At the outer reef the delay is less or negative (leading the tide at Cairns) and the amplitude is much less than at the shore.

Easton attributed these features (delay and increase in range at the shore) to 'the offshore break in the Barrier Reef and the presence of Broad Sound'. As the outer reef directly offshore from Mackay is one of the more continuous stretches of the whole outer reef, presumably the 'break' to which he refers is the deep Capricorn Channel opening SE of Mackay. Other than this he attempts no explanation of the tidal features. Presumably the topography is the main cause, i.e. the existence of a basin to be filled (Broad Sound and Shoalwater Bay) together with the reduction in depth in the approaches, as in other estuaries. However, there are other regions on this coast which have similar topography, e.g. Princess Charlotte Bay (14° S) and Hervey Bay (25° S), which do not exhibit such extreme tidal features. Possibly the deep Capricorn Channel opening is the critical feature. Hervey Bay is open to the Coral Sea with no reefs but does not have as deep a channel as Capricorn Channel, while Princess Charlotte Bay has extensive inner reefs and a fairly continuous outer reef between it and the Coral Sea. (The *Australia Pilot* (1962) does mention radial flood and ebb flows near Princess Charlotte Bay, similar to those for Broad Sound to be described below, but less noticeable.) An alternative possibility is that the extensive shoals of the Swain Reefs area slow the tidal wave and give rise to refraction and consequent focusing to Broad Sound.

Torres Strait

Technically this may not be a part of the Barrier Reef, but it is in the northern extremity of the region under review and, because of the unusual nature of its tides and currents, it warrants a brief description, based on Easton (1970) and the *Australian National Tide Tables* (1976).

The Strait lies between the Barrier Reef on the east with predominantly semi-diurnal tides, and the Gulf of Carpentaria on the west with chiefly diurnal tides. The largest semi-diurnal components in the east occur 2 days before full moon, whereas in the west they



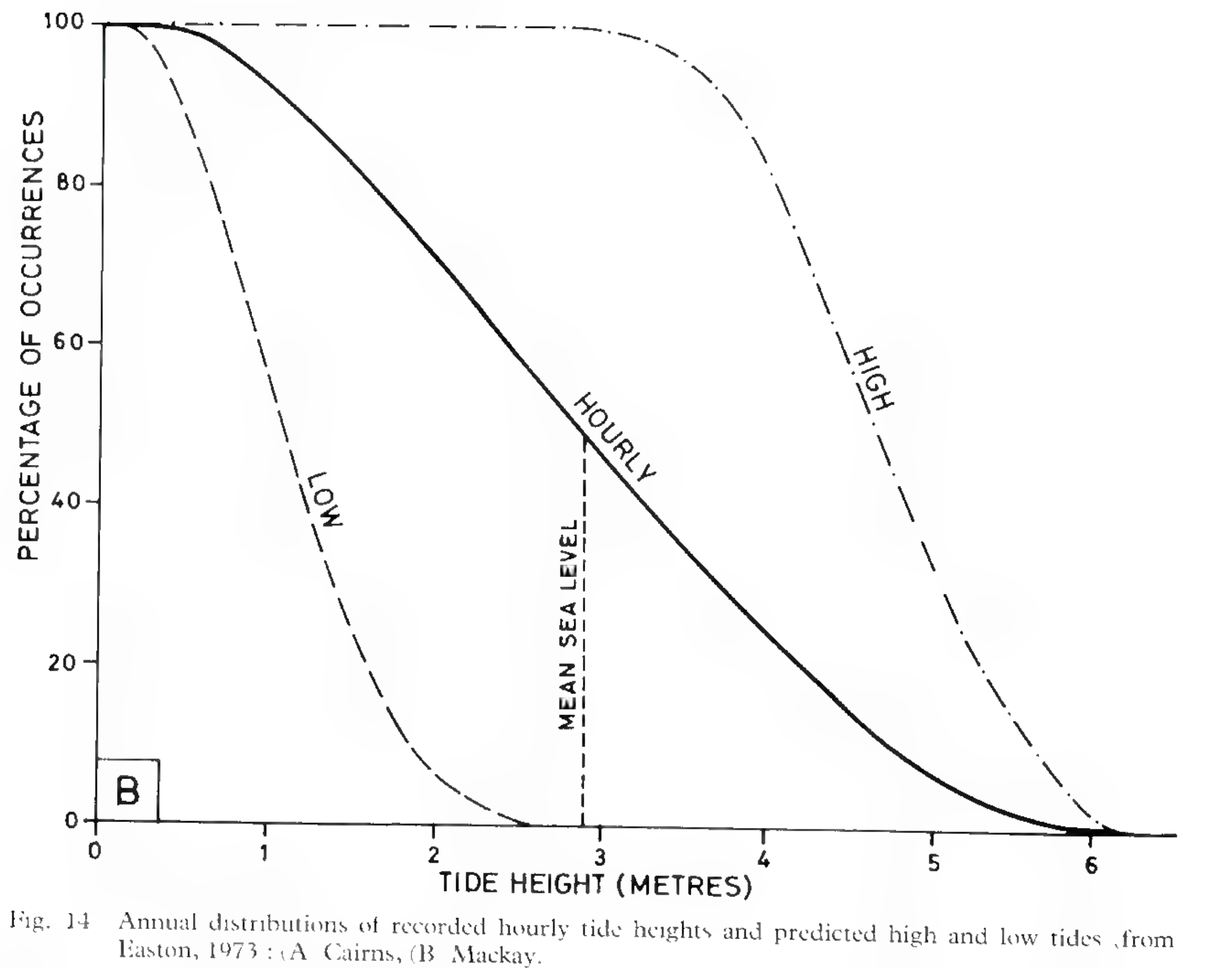


Fig. 14 Annual distributions of recorded hourly tide heights and predicted high and low tides (from Easton, 1973): (A) Cairns, (B) Mackay.

occur 2 days after full moon; in the Strait they occur from 7 days before to 7 days after full moon. Thus it can be spring tides at one end of the Strait and neaps at the other, and neap tides can occur at full moon. The diurnal tide is the same through the Strait. The character of the rise and fall is indicated in Fig. 12A. The information on tides is available for the southern quarter only of the gap between Australia (Cape York) and Papua New Guinea, as the northern part is shallow and not much used.

MEAN SEA LEVEL

Annual cycle

The monthly mean sea level (m.s.l.) shows an annual cycle, and three sets of measurements have been published. Values for selected locations are presented in Table 2. On the north-east coast of Australia, monthly mean values for Cairns, Townsville and Gladstone in the International Geophysical Year, July 1957 December 1958, showed a sharp peak in the autumn and a flatter minimum in spring (Hamon & Stacey, 1960). Easton's (1970) data for 1966–68 show less difference between highest and lowest m.s.l. The *Australian National Tide Tables* (1976) point out that monthly m.s.l. may vary by 0.07 m from year to year and that it can stand ± 0.3 m relative to the average for as long as a month.

It may be concluded that relative to the annual mean sea level, the monthly mean is likely to be about 0.15 m high in March April and 0.1 m low in September–October.

In the North Queensland zone, Easton (1970) stated that the mean sea level is not related directly to the wind, in contrast to the Mackay zone where the mean sea level is attained under the influence of a 5 m s southeasterly wind, which is typical for most of the year (Fig. 4). He presented interesting examples (his Fig. 5.8.9) showing the response of mean sea level to wind changes. In particular, an increase of SE wind from the 5 m s normal to about 15 m/s resulted in an immediate increase in mean sea level of 0.3 m.

Mean sea level and latitude

Hamon & Grieg (1972) drew attention to the fact that mean sea level apparently rises relative to geodetic levelling by 1.7 m from 30 S to 11 S along the east coast. This change is opposite in direction to that in North America and Europe where sea level falls

Table 2. Monthly mean sea level relative to annual mean sea level

Location		*Variation in mean sea level (m)* *Highest*	*Lowest*		*Annual Range*
Hamon and Stacey (1960):					
Cairns	17 S	April + 0.23	Oct.–Nov.	−0.09	0.32
Townsville	19 S	April + 0.27	Oct.–Nov.	−0.10	0.37
Gladstone	24 S	April + 0.26	Oct.	−0.10	0.36
Easton (1970):					
Cairns	17 S	March + 0.13	Sept.	−0.10	0.23
Townsville	19 S	March + 0.13	Sept.	−0.11	0.24
Mackay	22 S	March + 0.14	Sept.	−0.14	0.28
Australian National Tide Tables (1976):					
Cairns	17 S	Feb.–Apr. + 0.12	Sept.	−0.12	0.24
Townsville/ Mackay	19 –22 S	Mar.–Apr. + 0.12	Aug.–Oct.	0.10	0.22

equatorward, although in South America there is an equatorward rise by 0.4 m from 23°S to 4°S. The rise off Australia was not explained by the change in sea water density, and no satisfactory explanation for the equatorward rise was available.

The age of the semi-diurnal tide

This is the time interval between the time of new or full moon and the time of the local spring tide. Webb (1973b) has pointed out that the area from North Queensland to the Samoan Islands is one of the few regions in the world where the age is negative, i.e. the spring tide occurs before new or full moon (by 43 hours at Townsville). Webb (1973a) suggested that this is due to a resonance in the Coral Sea with a period of about 1.97 cycles/day (from tidal data for Cairns).

TIDAL CURRENTS

North Queensland and Mackay zones

Easton (1970) stated, without qualification, that in the North Queensland zone the flood is to the north and the ebb to the south. However, the *Australia Pilot* (1962) states that the flood is generally to the north or north-west when north of North Barnard Is. (17.7°S) and to the south when south of that point. Exceptions are in the vicinity of Princess Charlotte Bay (14°S) and Broad Sound (22°S). The latter description (in the *Pilot*) would appear to be the more likely in view of the relative phases of the tide along the coast (Fig. 13A). In the vicinity of the outer reef, the directions may be modified by the flows through the passes which are into the lagoon (W or SW) on the flood and out (E or NE) on the ebb. Speeds are greater in the narrow passes than in the wider ones, with values up to 1.5 m/s during springs.

Within about 1° of latitude (110 km) of Broad Sound, the flood sets radially toward the Sound and Shoalwater Bay and the ebb radially away. A similar pattern is observed over a smaller area around Princess Charlotte Bay (*Australia Pilot*, 1962). In the vicinity of the Capricorn Group of islands and reefs (23° to 26°S) the charts and *Pilot* note that the flood direction is to the west. It is not clear how much of the flow to Broad Sound comes by this route and how much through the clear opening of Capricorn Channel (22.5°S) or through the Swain Reefs (21° to 22°S).

The tidal streams are generally semi-diurnal in character, flood and ebb being approximately opposite in direction. North of about 21°S, the diurnal inequality becomes marked with the stronger streams (flood or ebb) some 50% greater than the average, and the weaker streams 50% less than average. Away from constrictions to the flow, the speed is about 0.5 m/s in the southern half of the lagoon and 0.25 m/s in the north. Speeds of up to 2 m/s are found between islands and in the entrances to coastal inlets.

It should be noted that when the SE Trades are effective, the current due to these winds in the open areas is stated to be greater than the tidal currents, and a continuing northerly drift of the water may be expected with a tidal perturbation in speed. This matter is discussed further is Section VIII. In the north, between about 11° and 15°S, the NW monsoon wind drift (in a southerly direction) may be greater than the tidal flood to the north, but the lighter winds of the monsoon season generally result in the tidal current being more important then than during the SE trades season.

Torres Strait

Although the tidal rise and fall has a marked diurnal character, the tidal currents are predominantly semi-diurnal and equal in either direction with maximum values up to 3.8 m/s (*Australian National Tide Tables*, 1976, Hammond Rock). There are considerable variations in speed in different locations and further observations are being made (B. V. Hamon, personal communication).

V
Water Properties in the Lagoon

The chief water properties used by physical oceanographers and for which there are some measurements for the Barrier Reef lagoon are temperature and salinity (independently as tracers and together for the calculation of density), dissolved oxygen and water transparency. There are some measurements of other chemical characteristics (phosphate, nitrate, etc.). As the water column in the lagoon is generally well mixed, the surface values for the first three properties (T, S and O_2) give a good idea of the overall distribution and will be described first; comments on the vertical distributions will follow. Variations in the vertical are chiefly in salinity, associated with rainfall and river runoff, and occur mainly near the coast.

TEMPERATURE

Surface temperature at specific locations

Orr (1933a) described the data obtained at a 'fixed' station in the main lagoon channel 5.5 km east of Low Isles (station at 16.35 S, 145.6 E) in 32 m of water. This station will be referred to hereafter as 'Low Is.' Temperature (and other properties to be described later) was routinely measured at six depths from 0.5 m ('surface' value) to 28 m, on 47 occasions at approximately weekly intervals for a year from 30 July 1938. The surface water temperatures are plotted in Fig. 15A from Orr's data. The minimum value was 21.5 C in mid-August and the maximum 29.9 C in Mid-February. Short term fluctuations were generally larger (*ca.* 1C) in summer than in winter. During the warming period from September to December, the water temperature was generally about 2C less than the daily mean air temperature. During the summer maximum the two were about the same, and during the cooling period the water was about 1C warmer than the mean air temperature. According to Orr, the wet and dry bulb thermometer readings indicated 'a certain amount of evaporation all the year but the difference in vapour pressure between sea and air showed no seasonal variation.' He gave no calculation of the volume of water evaporated or of the heat loss.

Moorhouse (1933) presented data and a graph of the temperature taken at 0900 and 1500 hr daily for almost a year at the surface and at 1 m depth at the Anchorage on the north side of Low Is., but he did not present any analysis of the data. Day to day variations in temperature at the Anchorage at 0900 hr averaged 0.3C with a maximum of 1.5C , while at 1730 hr the average variation was 0.5C with a maximum of 4.2C . Diurnally, the 1730 hr temperature averaged about 1C higher than the 0900 hr value, with a maximum of 4.5C higher. The larger differences both diurnally and from day to day usually occurred when the winds were light.

The Anchorage temperatures at 0900 hr were close to the Low Is. station values, being on the average 0.2C lower, while the 1730 hr values at the Anchorage were generally higher by about 1C on the average and up to 3.5C .

Endean *et al.* (1956b) gave temperatures for August 1952 to August 1954 obtained from the Marine Branch, Commonwealth Department of Shipping and Transport, for

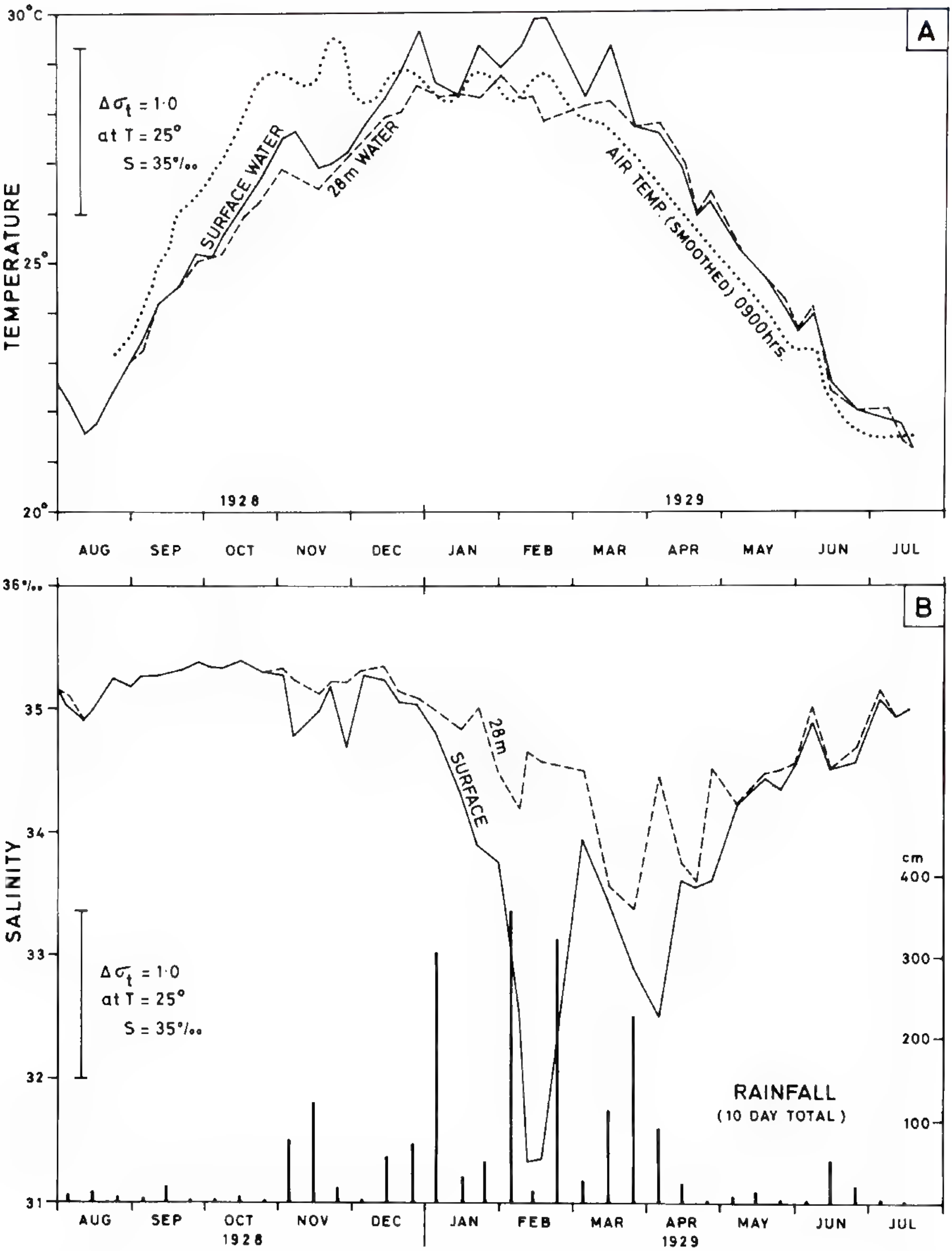


Fig. 15 At Low Is. station, Great Barrier Reef (16.4 S, 145.6 E), one year's records (data from Orr, 1933a) of:

(A) Water temperature: full line = surface, dashed line = 28 m depth, dotted line = smoothed air temperature,

(B) Salinity: full line = surface, dashed line = 28 m depth; and rainfall by 10-day periods.

four islands. Unfortunately only the monthly *range* of values (from 15 or more observations per month) was given and not the mean value. If one takes the mean of the range bars shown, the Low Is. values for 1952–54 average 1.0C lower (2.5C maximum) than Orr's values, while the annual range of the means is 6.4C against Orr's 8.0C. Although the location and procedure for obtaining the Marine Branch values were not stated, the differences suggest that year to year variations may be expected.

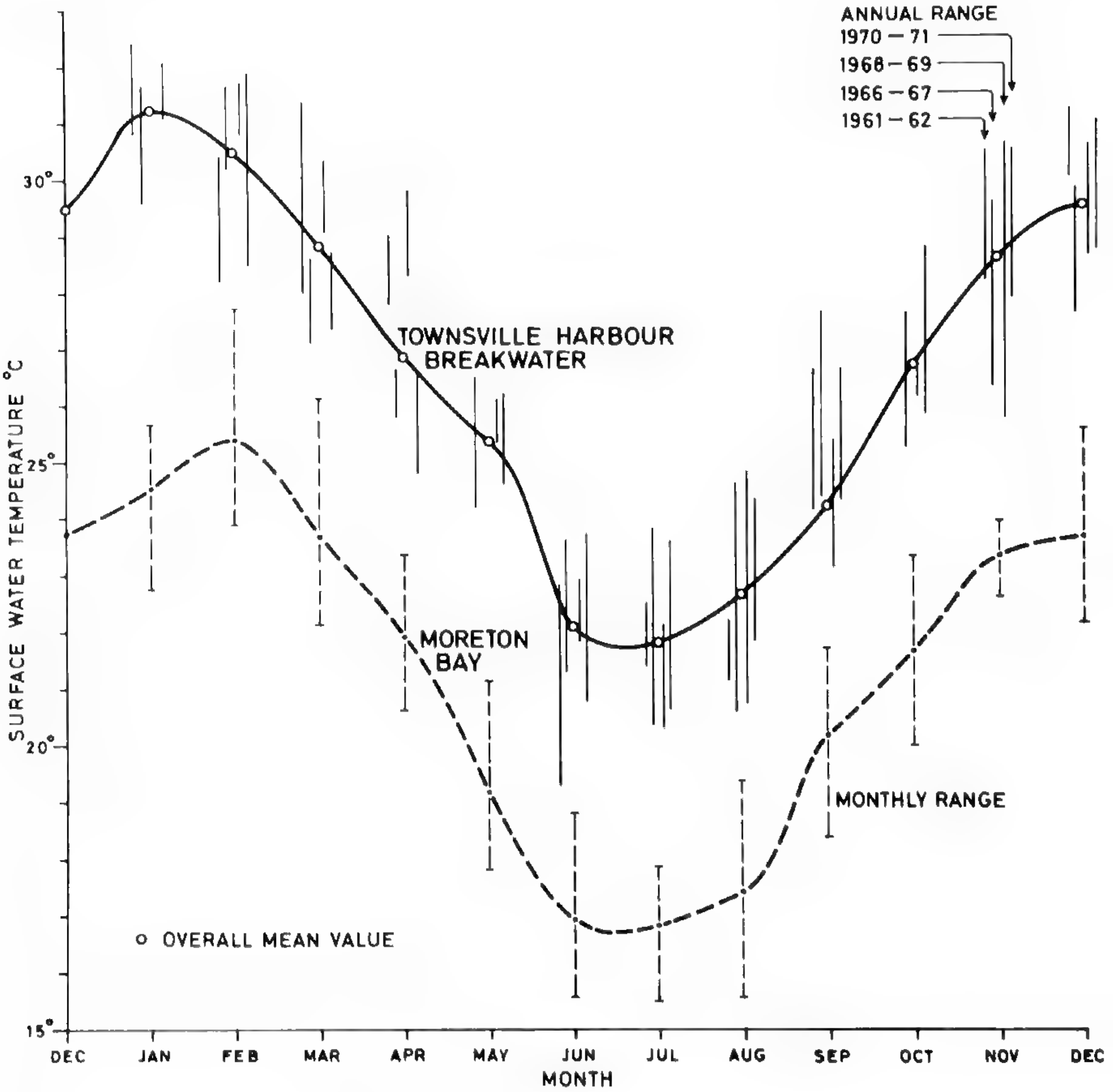
In February, at stations 130 to 180 km north of Low Is., the temperatures were within 0.5C of those at Low Is., while in Papuan Pass (16.8 S) and in Cook's Passage (14.5 S) the temperature was slightly lower than at Low Is. Between August and November at a station in Trinity Opening (east of Low Is.) the water was 1C warmer than at Low Is. At these times, then, temperature did not change much over about 2 of latitude (220 km) along the lagoon in this region. Orr briefly summarised temperature measurements (presumably surface values) made by the Commonwealth Navigation and Lighthouse Service at positions along the lagoon northward from 25 S for several years and quoted a maximum recorded temperature of 28.9 C, the same as the maximum at Low Is., and a minimum of 17.8 C at the south. He also noted that the maximum range of temperature during one month from south to north was 7C and the minimum range was less than 1C (this must have been during the summer; see Fig. 17). Orr gave no further data from this source.

Kenny (1974) measured the sea temperature in the top 25 cm of water, and the air temperature above the water on some occasions, at the seaward end of the Townsville Harbour eastern breakwater (19.25 S, 146.83 E) at irregular intervals and varying times of day during 1961–62, 1966–67, 1968–69 and at weekly intervals at 1400 hr EST during 1970–71, making a total of 212 observations. Fig. 16 (upper curve) presents Kenny's overall mean values by month (joined by a curve) and the ranges of values observed in each of the years (vertical bars). (The individual values were not tabulated in Kenny's paper.) The mean values show a minimum of 21.8 C in July and a maximum of 31.2 C in January (compared with 21.5 C and 29.9 C in a single year at Low Is.). The individual temperature readings were plotted but not identified by year; the monthly ranges of temperature for the four years vary from 2.0C to 4.4C, which is not negligible compared to the annual range of means of 9.4C. Kenny pointed out that the range of values in one year may lie completely outside that for another year for the same month, e.g. March and April.

Kenny stated that water temperature (T_w) was linearly related to air temperature (T_a) at 1 m above the water surface (in the 1970–71 series) by the relation: $T_w = 0.83\ T_a + 3.31$. (The simpler relation $T_w = 0.95\ T_a$ fits the data just as well, considering the considerable scatter in the T_w, T_a correlation plot.) Both formulae give a sea temperature less than air temperature (over the range of values recorded) all year round, although Kenny did not remark on this. This result contrasts with Orr's (1933a) note that water temperature was less than air temperature during the spring warming season, the same during the period of maximum temperatures, and greater during the cooling season (see Fig. 15A). Possibly Kenny's result of constantly cooler water than air is an artifact arising from the fact that in deriving the water/air temperature relation he lumped together all his 1970–71 data (his Fig. 3), not attempting to distinguish seasons. However, more than 90% of the points on his Fig. 3 plot of T_w versus T_a show the water temperature lower than the air temperature which does suggest predominantly cooler water than air (as his data points were taken at uniform intervals of time).

Hedley (1925c) presented a series of daily (0900 hr) measurements of temperature of a bucket sample drawn from 1.8 m depth below the surface at the Pile Lighthouse (27.3 S, 153.2 E) in Moreton Bay for a year from 1 June 1924. Although this location is a little south of the present area under review, it is included here because of the paucity of data for the Reef area, and because it is one of only two series of *daily* observations available. The monthly means and ranges of values are presented in Fig. 16 (lower curve). The cycle is seen to be similar to that at Low Is. and Townsville, although the maximum at Townsville occurs a month earlier than at the other two locations. The monthly ranges at Townsville (0.5C° to 4.9C° over four years) and Moreton Bay (1.3C° to 4C°) are greater than at Low Is. (0.6C° to 2C°). In the Moreton Bay series the change between successive days averages 0.5C° with 85% of changes being 1.1C° or less and the maximum being 2.2C°.

Fig. 16 Seasonal variation of surface water temperature at Townsville Harbour Breakwater (19.25°S, 146.83°E): full line — overall mean, vertical bars — monthly range for each year (from Kenny, 1974); and at Moreton Bay (27.3°S, 150.2°E): dashed line — mean, vertical bars — monthly ranges for June 1924 to May 1925 (from Hedley, 1925b).



Surface temperatures along the lagoon

Aurosseau (1938) transcribed some records of surface water temperature and specific gravity made by Capt. Ogura en route between Nagasaki and Sydney and return. Values in the Barrier Reef lagoon are presented in Table 3. These temperatures are similar to those given by Brandon, discussed below (see Fig. 17).

Table 3. Surface water temperature, air temperature, and specific gravity in the Barrier Reef Lagoon. (Data from Aurosseau, 1938)

Time (hr)	*Date (1928)*	*Lat.*	*Temperature (°C)* *Water*		*Air*	*Sp. Gr. (15°/4°)*
1751	28 July	9.6°S	25.0	$\Delta T = 3.8$	24.6	1.0253
0630	3 Aug.	24.1°S	21.2		17.1	1.0264
0636	30 Aug.	9.7°S	25.0	$\Delta T = 3.4$	25.0	1.0259
0600	25 Aug.	24.6°S	21.6		21.4	1.0264

Brandon (1973) wrote a review of some of the water properties of the Great Barrier Reef province, using (a) his own observations (temperature measured with bathythermograph and reversing thermometers) collected during four cruises between September 1967 and August 1968, (b) those of Orr (1933a) and Moorhouse (1933), and (c) data from the CSIRO Division of Fisheries and Oceanography, described in his text as unpublished, and not referenced in his bibliography. (These data are probably from the CSIRO data bank from which their 'Oceanographic Charts, Tasman and Coral Seas' were prepared—present reference CSIRO, 1974.) Brandon generally did not distinguish the data sources in his review and unfortunately gave inadequate information to judge the statistical significance of his mean values and ranges. (See note at end of Chapter X.)

Brandon (1973, Fig. 3) presented graphs of mean temperature against latitude by 1° intervals for January to November (December being omitted because of inadequate data although December values were referred to in his text). These graphs are mostly very irregular and lines for individual months cross over each other apparently at random. He gave no indication of numbers of observations but it is difficult to believe that the long term average values would be as irregular as those in his plots. He summarised the surface temperature extremes as:

Temperature	*North*	*Centre*	*South*
Maximum	January	January	February
Minimum	June–July	to	July–August

These observations agree with the maxima shown in Fig. 16, but the Moreton Bay minimum in the extreme south is earlier than Brandon suggested.

To show the seasonal cycle and the latitude variation, Brandon's (Fig. 3) temperature values were averaged by month for zones 10.5° to 14.5°S, 15.5° to 19.5°S, and 20.5° to 24.5°S in an endeavour to smooth the data; temperature/time plots are presented in Fig. 17. Even with this averaging there is still considerable scatter remaining, particularly in the January to May period.

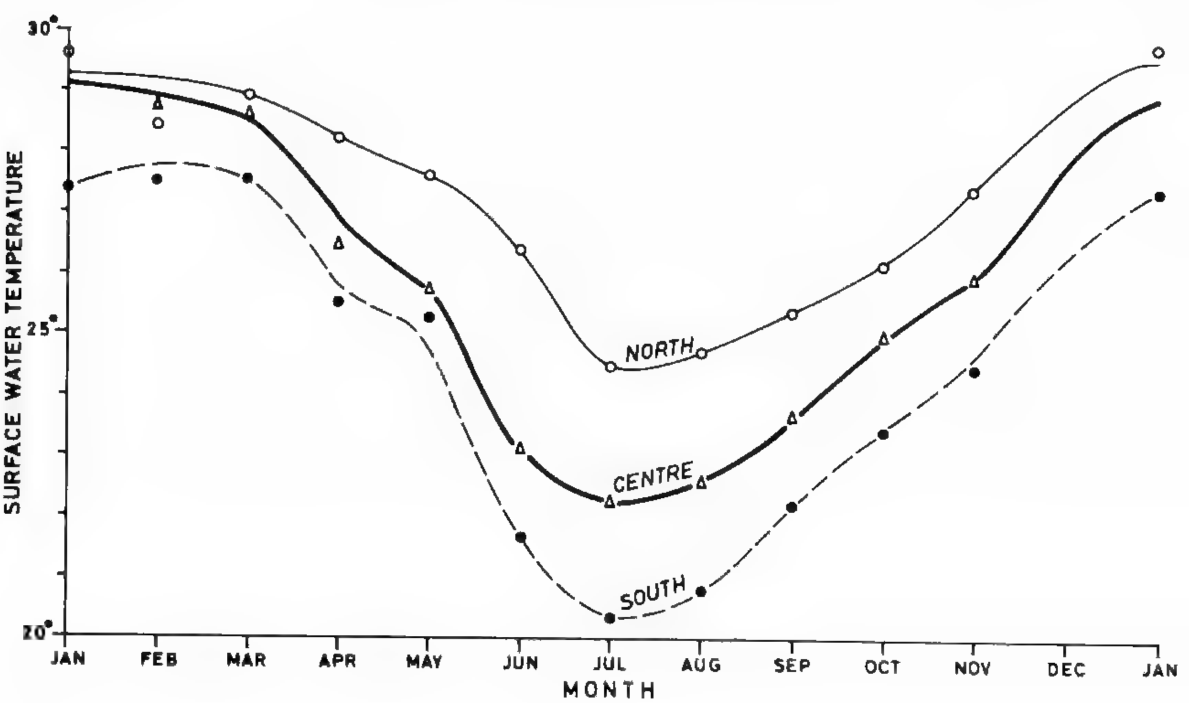
Sea areas around Australia (Roy. Neth. Met. Inst., 1949) has monthly charts for sea surface temperature averaged by 1° squares with whole number isotherms drawn on the plots. For the Barrier Reef region, temperature/time plots drawn from these data show variations similar to those in Fig. 17, but the absolute values average about 0.7C° lower than those in Fig. 17. There are much larger numbers of values (30 to 150 per 1° square) than Brandon can have had, but despite this there is considerable scatter (±0.5°C) in some areas of the Dutch data and the positioning of the isotherms in the charts is by no means unequivocal. In addition, the original data will have been taken with a variety of instruments, probably not calibrated frequently, so the scatter is not unexpected. Thus, Brandon's data and the Dutch data are probably reasonably consistent.

The Marine Branch values quoted by Endean *et al.* (1956b) for August 1952 to August 1954 compare with Fig. 17 as follows:

Station		*Marine Branch values average:*
Booby Is.	10.7° S	0.1°C lower Jan.-June than Fig. 17, NORTH; 1.0°C higher July–Dec. than Fig. 17, NORTH,
Low Is.	16.6° S	1.0°C lower for the year with minimum difference in winter and maximum of 2.5°C lower in Oct.,
Trent Is.	20.5° S	Less than 0.1°C difference from Fig. 17, SOUTH.
Pine Is.	21.5° S	

The range of temperature between annual maximum and minimum, irrespective of month, for each degree of latitude from Brandon's Fig. 3 is shown in Fig. 18. Also included are the annual ranges for Low Is. (Orr, 1933a), Townsville (Kenny, 1974) and Moreton Bay (Hedley, 1925c). The first and last are close to the mean of Brandon's data but the Townsville value is considerably higher. Kenny (1974) attributed the larger Townsville range (than at Low Is.) to the 'more oceanic locality' of the Low Is., and also noted that the range between extreme temperatures at Townsville (12.4°C) compared more nearly with the extreme range at the Low Is. Anchorage (12.7°C). However, the latter range is between the lowest 0900 hr reading for the year at the Anchorage and a

Fig. 17 Seasonal variation of surface water temperatures along the Great Barrier Reef, inshore stations (data from Brandon, 1973). North zone—10.5° to 14.5° S, Centre zone—14.6° to 19.5° S, South zone—20.5° to 24.5° S.



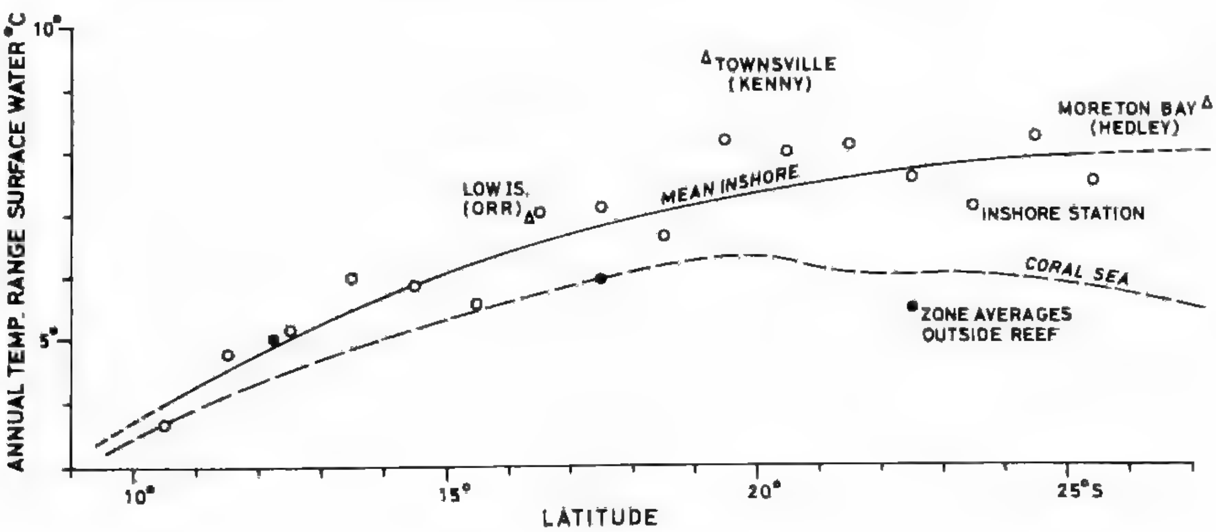
pronounced peak in 1730 hr readings which are generally higher than at 0900 hr. A more realistic figure for the Anchorage would be 10.0C for the 0900 hr range. Therefore the higher than average range for Townsville may be attributable to the location being very close inshore where surface water property ranges are often greater than those offshore due to the presence of river runoff giving a more stable surface layer.

It may be noted that the fairly detailed Low Is. records (Orr, 1933a) showed the highest water temperature in December through March but there were four subsidiary maxima during that period, while the daily Low Is. Anchorage data (Moorhouse, 1933) showed a series of subsidiary maxima and minima of about 25 days period during December through March. The warming and cooling periods were less irregular. The fluctuation in surface water temperature in the north in summer might be due to more frequent periods of light winds during the NW monsoon, allowing greater surface layer heating than in the south where mixing induced by the SE trade winds may be expected throughout the year. Brandon (1973) commented on two periods of lower temperatures between 14 and 15 S and remarked (p. 198) that 'This area of the shelf is unique in another respect as it contains the large, shallow Princess Charlotte Bay indentation of the coast.' It is not clear why Princess Charlotte Bay was considered topographically unique as there are other similar areas along the coast, such as Halifax Bay (19 S) and Broad Sound (22 S). He continued, 'It is felt that the water temperatures here are a combination of shelf conditions, wind and weather. This area is somewhat more independent than other shelf areas immediately north or south in that a larger number of factors can influence the water column here.' The statement is grammatically faulty and very vague, and its meaning is not clear.

Sub-surface temperatures

At the Low Is. station (Orr, 1933a) the difference between the surface and the 28 m depth values was generally small, 38% of the differences being less than 0.1C, 60% less than 0.2C and only 15% were greater than 0.5C. As may be seen in Fig. 15, the large values occurred during the summer when the surface layer had a low salinity and the upper part of the water column was more stable than usual. The surface water was generally warmer than the 28 m water during spring and summer. For 28% of the stations, the surface water was cooler during the autumn when the water was losing heat, but the water column was stable or neutral within the probable accuracy of measurement.

Fig. 18 Annual range of surface water temperature versus latitude for Great Barrier Reef. Full line and circles – mean for inshore stations (from Brandon, 1973), dashed line – Coral Sea (from Roy. Neth. Met. Inst., 1949), dots = zone averages outside reef (data from CSIRO, 1974).



Brandon (1973) described the vertical temperature distribution for the lagoon, although only qualitatively, essentially as summarised above for Low Is. He also stated that 'in the Capricorn Channel, vertical temperature variation is only 1 to 2C on the average' but did not say over what depth range nor which way the temperature changed with depth. (This channel has depths to 120 m close to the reef line and increases to over 400 m just outside.) Brandon also stated that his bathythermograph measurements over the shelf revealed essentially isothermal water with a few tenths of a Celsius degree warming in the upper few metres, but he did not state which depth range bathythermograph he was using (standard depth ranges are to 60, 135 or 270 m).

SALINITY

Surface salinity at a specific location

The annual cycle of values for 1928–29 at Low Is. is shown in Fig. 15B from Orr's (1933a) data. Orr commented that the maximum values (35.40 at the surface and 35.47 at 15 m in October) are 'a little lower than would be expected for this latitude' but he did not say on what he based his expectation. He attributed the low values to 'the proximity of the coast and the considerable land drainage' without giving any data for the latter, although he did quote a few rainfall figures for the coast. He attributed the variations in salinity chiefly to reduction by rainfall, with subsequent return to higher values due 'to wind mixing more saline water upward.' He did not mention the possibility of increase due to evaporation, having previously noted that the 'difference between the vapour pressure of water and air shows no important seasonal variation.' Orr was probably in error in dismissing evaporation as unimportant because the rate of loss of water vapour (and hence increase in salinity as well as loss of heat) is also a function of wind speed, increase of which increases the eddy diffusive transport from the sea surface. In the Low Is. area the winds are steadiest and strongest in the dry season (e.g. Fig. 4, Cooktown) and evaporation could be a significant factor. (Brandon did suggest evaporation as being a significant factor as will be mentioned later.)

Orr noted the minimum surface salinity of 31.3, remarked that lower values might have occurred in the intervals between occupations of the station, and warned that minimum values must be expected to fluctuate considerably from year to year. He commented that on 28 February the Daintree River (17 km NW of Low Is.) was in flood and its turbid water was visible at Low Is. This river is in a moderately high runoff area but no figure for its flow is given in the Australian Water Resources Council's *Stream Gauging Information* (1971). (My estimate, 0.15×10^{10} m^3/yr, is a little less than the coastal average of 0.2×10^{10} m^3/yr). Orr also remarked on the rapid increase in salinity after the reduction due to rainfall, e.g. in late February and in mid-April.

The vertical dashed bars in Fig. 15B show the 10-day accumulated rainfall from Orr's daily values, as an indication of the relationship between precipitation and surface salinity decrease, e.g. a short term effect in November and a longer term and more marked salinity decrease in January to March, presumably associated with the increased rainfall. If these events are directly correlated, the response of salinity is rapid, within a few days at most. However, the heavy rainfall in the last week of February is associated with a sharp rise of salinity, which is difficult to understand. One possibility is that some rainfalls are very localised and this, combined with currents, may move a lowered salinity patch of water into an area where observations were being made but which did not itself receive much rain. Alternatively, a lowered salinity patch after rainfall might be moved away from the site before the next observation was made.

Surface salinity along the lagoon

Brandon (1973, Figs 4, 5 and 6) presented graphs of monthly mean and of maximum and minimum values of surface salinity for restricted latitude bands from 11° to 12°S, 16° to 17°S and 22° to 23°S. The average values are presented here in a single figure to facilitate comparison (Fig. 19) and smoothed curves are drawn through them. The maximum and minimum value curves presented by Brandon are omitted from Fig. 19 to avoid confusion. Because the number of observations on which they are based is not given, their significance is uncertain but the range between maximum and minimum values, varying from about 0.06‰ to 3.0‰, is very wide. The greatest range, for April in the centre zone, is almost as large as the mean annual range for that region (3.7‰).

It is seen that the minimum value occurs in the first part of the year (February to May) for all zones, with the maximum in the last third. The lowest values occur in the centre zone (in association with the coastal rainfall maximum, Fig. 7), and this minimum dissipates more rapidly than that in the north zone. The difference in behaviour between the north and centre zones is puzzling because the distribution in time of the rainfall is the same in these two zones (Fig. 8) and the centre zone has rather more rain on the average. One possibility is that Brandon's figures were based on limited data and the difference in behaviour in Fig. 19 is associated with the variable nature, in both time and space, of the rainfall in this region. On the other hand, it is seen that the Low Is. data, for a different period, compare well with Brandon's centre zone curve (apart from the April value). Another possible explanation is that Brandon's centre zone curve is for 16° to 17°S only, and he did state that this salinity/time curve is the 'most extreme for the centre zone', although the highest rainfalls occur between 17° and 18°S. Brandon himself attributed 'the great annual range of salinity . . . not only to the high rainfall and runoff (no values given) during the monsoon season *but also to evaporation* which can create localised zones of high-salinity water.' This latter statement is surprising because the great range in the centre zone is due chiefly to the very low wet season value, not to a high dry season salinity, i.e. to evaporation. In fact, the centre zone has the *lowest* maximum salinity of the three. Brandon attributed the high winter salinities in the north to evaporation but produced neither quantitative nor qualitative evidence to support this, although he did make meteorological measurements including wind speed and wet and dry bulb air temperatures. It is agreed that evaporation is likely to be significant during the dry months but it would have been more convincing to have given some actual estimates from the meteorological data.

Figs. 11 and 4 together do support the thesis that evaporation is likely to be significant in the spring and early summer (September to November) because the relative humidity decreases during this period, while the winds are steadiest and relatively strong at this time. Evaporation is usually calculated from a relation of the form:

Evap. (gm/cm^2/sec) = Constant x wind speed x (Vap. press. at water surface–Vap. press. in air at 10 m height)

and rough calculations suggest that the potential for evaporation in October–November is 1.5 to 2.5 times that for January–February for the north zone, 1.3 times in the centre zone and 1.1 times in the south zone.

Wyrtki (1961b) made some estimates of evaporation values for the Arafura Sea and Timor Sea, where evaporation exceeded precipitation from April to November and June to November respectively. He obtained net rates of loss of about 25 cm/month from the water column. This rate in a column of depth 30 m would give rise to an increase in salinity of about 0.25‰ per month or about 0.75‰ in three months of relatively low humidity. This is about the same as the amount noted in the north zone in the second half of the year (Fig. 19). These rough calculations support the suggestions that evaporation is a significant factor in increasing the salinity in the dry season in the lagoon.

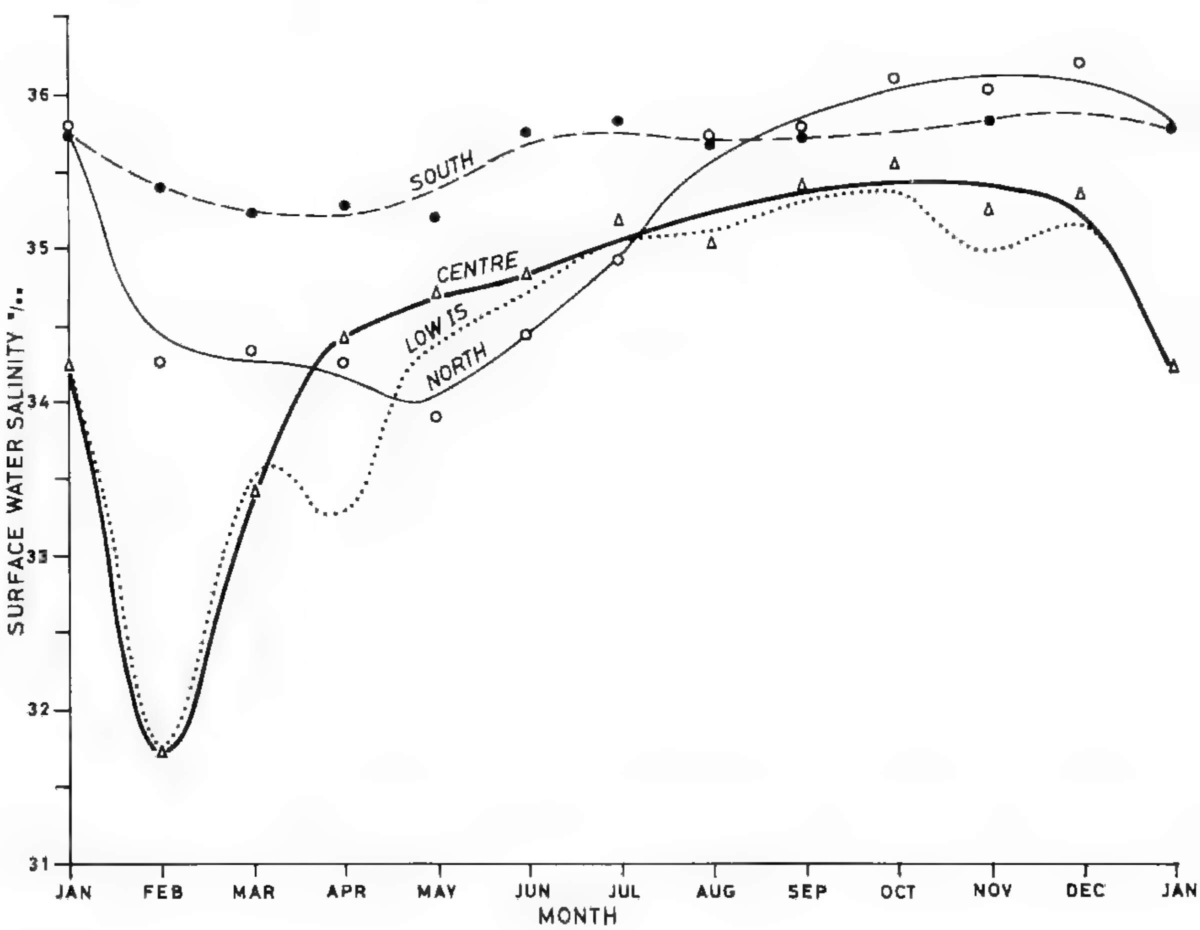
The small annual change in salinity in the south (22° to 23° S near Capricorn Channel) was attributed by Brandon to the area being relatively open to mixing with the Coral Sea waters (ignoring the fact that the Coral Sea waters have an annual salinity cycle) and to the predominance of the SE Trades throughout the year (presumably to their mixing effect). He could also have added that the south zone rainfall is more uniformly distributed through the year than that further north, and the annual amounts are only about one-half of those in the centre and north zones, and the lagoon is much wider here than further north.

Unfortunately, Brandon did not specify where the salinity values used for the above described graphs were obtained in the lagoon. The inference is that they were obtained in the ship channel which is generally close to the land (on the average about one-quarter of the distance from shore to outer reef). This point is relevant to the next section.

Surface salinity gradients across the lagoon

The salinity variations shown in Fig. 19 are for locations near the land, and the marked reductions in summer are assumed to be due both to direct rainfall on the sea and to river runoff from the land. Further offshore, in the lagoon, the latter contribution of fresh water will not apply directly. In addition, as the reef is approached, the proximity of the Coral Sea waters may be expected to moderate the seasonal variations (although the Coral Sea waters show significant seasonal variation, described later). In consequence, one may expect that during the wet season the salinity will increase from the shore to the reef, while in the dry season, when the inshore salinities increase, a decrease of salinity from shore to reef may be expected. A few scattered tests of this thesis are available from Orr's (1933a) and Brandon's (1973) data, as presented in Table 4. These observations are reasonably consistent with the thesis but are few.

Fig. 19 Seasonal variation of surface water salinity for one degree wide latitude strips. North zone — 11° to 12° S, Centre zone — 16° to 17° S, South zone — 22° to 23° S (data from Brandon, 1973), and for Low Is., 16.4° S (data from Orr, 1933a).



It will be noted later that less consistent results are obtained when the inshore salinities of Fig. 19 are compared with Coral Sea values near the reef (Fig. 24) and in a short section near Low Is., Orr's (1933a) data show an increase in salinity to seaward in August when one might expect a decrease or isohaline conditions (see the next section).

Sub-surface salinities

At Low Is. the salinity at 28 m (deepest measurement) had its seasonal maximum in October and minimum in March (Fig. 15B), following the surface salinity change, and was always equal to or greater than the surface value within the probable precision of measurement (not stated by Orr, 1933a). In winter the difference between surface and deep values was less than 0.2 (average 0.05) except for two occasions in November following moderate rain. In summer, January to April, differences ranged from 0.05 to 3.35 (average 0.8), the two values over 2 being associated with heavy rain (February, Fig. 15B). The greater part of the salinity difference occurred in the top 5 to 10 m.

Orr drew attention to the abrupt *increases* in deep salinity associated with *decreases* at the surface on two occasions, 13 February and 5 April. He considered it unlikely that this was due to advection from the south, where the rainfall is also generally heavy, but then said that in the south there are many openings in the reef (through which, presumably, more saline water might enter the lagoon). He also referred to tidal currents through Trinity Opening east of Low Is. In other words, he did not really attempt any explanation of the phenomenon. One possibility is that the large input of fresh water may generate a temporary estuarine circulation with outflow (to and through reef openings) in the surface layer and consequent inflow below (e.g. Pickard, 1975, Ch. 8). Some observations on other tropical areas which appear to be relevant to this phenomenon are described later in the section on Tropical Estuaries. At the same time it may be noted that there were occasions when the deep salinity decreased with decrease of surface salinity, e.g. early November, from mid-December generally to early February, early March. Therefore, although there may be a phenomenon to be explained it would be best to have more substantial data with which to work before spending much time on it.

At stations 120 to 200 km north of Low Is. at the end of February, deep salinities were within about 0.2 of those at Low Is. at the same time, but surface values were much higher, the range of values in the column being only 0.4 to 0.6 . At Trinity Opening, 40 km east of Low Is., the salinity in the column was within 0.1 of that at Low Is. in August, September and November.

Table 4. Salinity gradients across the lagoon (selected examples). O = Orr (1933a); B = Brandon (1973)

			Change			
Zone	*Latitude* (S)	*Month*	*Salinity* ( )	*Direction*	*Temp.* (C)	*Source*
North	14.5	February	0.2	increase to reef	(isothermal)	O
	11.7	Oct. or Nov.	0.6 to 0.8	decrease to reef		B
Centre	15.8	March	0.1	increase to reef	(0.3 decr.)	O
	14.7	Mar. or Apr.	2.0	increase to reef	(isothermal)	B
	17	April	1.1	increase to reef		B
	17–18	April	1.9 to 2.9	increase to reef		B
	19	April	0.1	increase to reef		B
	14.5–16.5	July	isohaline		(2.6 incr.)	B
	16.4	October	0.15	decrease to reef	(0.3 incr.)	O
	16.4	November	0.1	decrease to reef	(0.4 decr.)	O

At a group of stations along a line 50 km long from the mouth of the Daintree River and past Low Is. to the inside end of Trinity Opening in August, the salinity change at all depths was within 0.4 and the temperature change within 1.75C , the highest values being in Trinity Opening for both properties.

Brandon (1973) referred to making Nansen casts (for water samples and temperatures) but he presented no data on vertical profiles of salinity. He stated 'The vertical salinity profile on the Queensland shelf is, for the most part, isohaline for the majority of the year. The only exception to this is during the rainy season when the surface salinity may be greatly reduced' and also 'From May to the commencement of the rainy season, salinity differences between the surface and bottom waters on the Northern Queensland shelf probably rarely exceed 0.1 . Local variations may occur during this time after a rainfall, but these would be exceptions and of short duration. This is most likely true of the southern shelf also as the SE Trades remain dominant over the year and are capable of keeping the water column mixed.' The speculative nature of these remarks is surprising if Brandon had data of his own on which he could have based more firm statements. Brandon also reviewed some of Orr's observations and speculated about lagoon salinities north of 14 S during the wet season.

DISSOLVED OXYGEN

Orr (1933a) made regular measurements of dissolved oxygen at all depths at Low Is. and found relatively small variations with time or depth, the water generally being undersaturated. His results may be summarised as:

	Mean O_2 conc. (ml/l)	90% of values between:	Mean sat. (%)	90% of values between:
Surface	4.6	4.3 to 4.9	95	92 to 99
28 m	4.55	4.1 to 4.8	93	88 to 97

Slightly lower values were observed at all depths from January to April than at other times, but the seasonal variation was small. Orr considered that there was a significant oxygen demand by the particulate material and as this was continually mixed through the column, the demand showed little or no variation with depth most of the time. Only in calm periods was there a possible greater reduction of oxygen content in the deeper water than in the upper waters. Orr remarked on the large diurnal changes in oxygen content which occur in the shallow waters of the reef flats but considered that the volume of water involved was too small for the lagoon waters to be significantly affected away from the immediate vicinity of the reef.

Kinsey & Kinsey (1967) measured oxygen content over and near Heron Is. reef and showed that while large changes, particularly between day and night, occurred over the reef (7.5 to 1.5 ml/l) the changes at 2 m depth only 100 m outside the reef showed a range of only 4.66 to 4.92 ml/l (95 to 102% saturation). The value 15 km SE of Heron Is. and 5 km from the nearest reef was 4.76 ml/l (97% saturation), very similar to the Low Is. values.

Brandon (1973) reported no measurements of dissolved oxygen.

OTHER CHEMICAL PROPERTIES

Orr (1933a) reported that dissolved phosphate showed 'no seasonal character' although his data table showed variations from 0 to 8 μgm/l. Most of the values were between 3 and 5 μgm/l with an average of 4 μgm/l with no significant difference through the water column, and no systematic seasonal variation.

A few measurements were made of silicate, giving values between 40 and 110 μgm l. A very few measurements were made of nitrate but these were regarded as uncertain because of long storage.

Orr's (1933a) measurements of hydrogen ion concentration gave pH values of 8.26 ± 0.01. Brandon (1973) stated that he made pH measurements during September–November 1967 but as no significant variations or correlations with other data were found the measurements were discontinued.

TRANSPARENCY

Orr (1933a) made a secchi disc measurement at each Low Is. station and at the other stations in the lagoon and outside the reef. The Low Is. values ranged from 3.5 to 25 m, averaging 12 m, with no seasonal variation perceptible but apparently a correlation in which low secchi disc depths were associated with high wind speeds and lasted for a few days after such a wind.

From Orr's data it can be shown that the secchi disc depth (S) in metres is related to the wind speed (W) during the previous 24 hours approximately by:

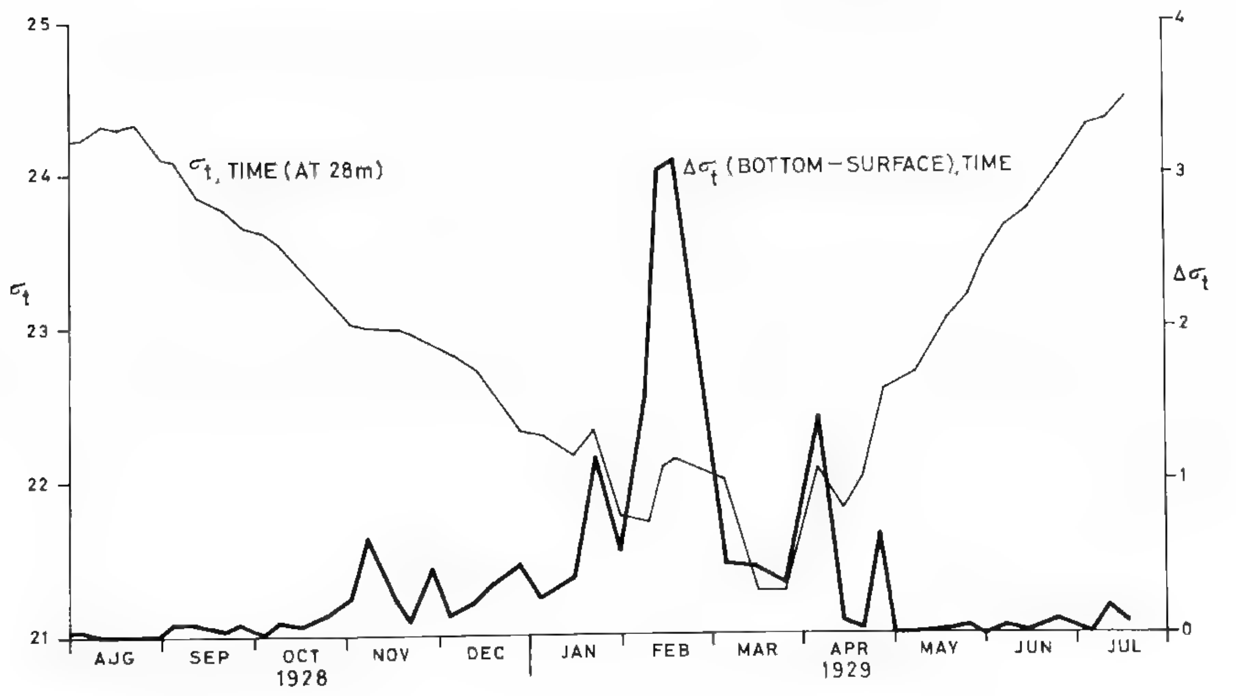
(a) W in knots :	for $W = 0$ to 8 kts,	$S = 27 - 2W$,
	for $W = 8$ to 15 kts,	$S = 19 - W$,
(b) W in m/s :	for $W = 0$ to 4.5 m/s,	$S = 27 - 4W$,
	for $W = 5$ to 9 m/s,	$S = 19 - 2W$.

The standard deviation of the original points about these mean lines was about $\pm$ 2.5 m.

Hedley (1925b) recorded secchi disc depths of 2 and 2.5 m respectively at the jetties at Townsville and Cairns, while in the lagoon he recorded values of 5 to 33 m.

The reduction in transparency with increase of wind speed was attributed by Orr to stirring up of the fine grey sediment characteristic of inner passages of the lagoon (clay size fraction about 35%).

Fig. 20 Seasonal variation of water density (as σ_t) at 28 m depth, and difference ($\Delta\sigma_t$) between 28 m depth and surface at Low Is., 16.4 S (data from Orr, 1933a).

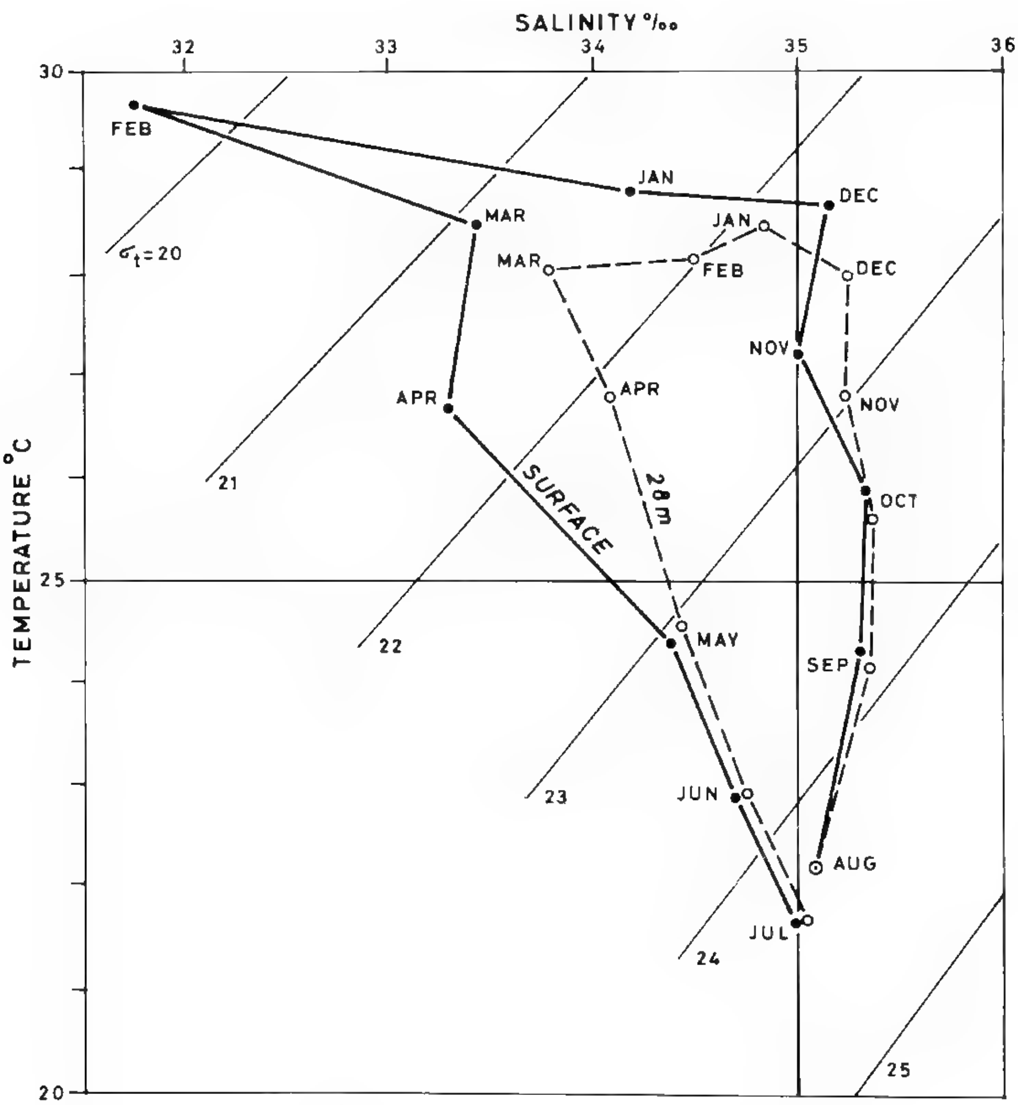


Approaching the outer reefs, in Trinity Opening, secchi disc depths of 11 to 30 m were recorded, being associated by Orr with the coarser bottom material there. To seaward of the outer reef values from 14 to 40 m were measured. (I have observed the same correlation between poor visibility in the presence of fine bottom sediments in a lagoon contrasted with good visibility and coarse bottom sediment near or outside the reef in many areas, e.g. Glovers Reef, Tikehau, Majuro and Nomoi. This is the case even when the lagoon is much calmer than the reef area.)

DENSITY

Orr (1933a) presented a density (as σ_t) versus time plot for the Low Is. data. As the surface value curve is very similar to the salinity/time plot (Fig. 15B), it has not been reproduced here; however, Fig. 20 presents the 28 m depth σ_t values versus time as well as the difference ($\Delta\sigma_t$) between 28 m and surface values. This graph shows the marked decrease of σ_t in summer, while the $\Delta\sigma_t$ curve gives an indication of the gravitational stability of the water ($\Delta\sigma_t/\Delta z$). Actually, in the summer most of the change of density $\Delta\sigma_t$ took place in the top 10 m (5 m for the cases where $\Delta\sigma_t$ was greater than 1) and so the stability of the upper layer is generally greater than indicated by this curve.

Fig. 21 T,S, time diagram for surface and 28 m depth at Low Is. station, 16.4 S (data from Orr, 1933a).



The similarity of the salinity time and the density time curves led Orr to state that 'It is salinity rather than temperature which is the determining factor in the stability of the sea in the Barrier Reef lagoon.' This statement is misleading in that it is only true for one third of the year, the wet season from December to March; at other times, temperature plays a major role in determining density.

This is evident from Fig. 21, in which the monthly average values of temperature and salinity at Low Is. are plotted on a T,S diagram and connected in temporal sequence. Curves for the surface and for 28 m are presented. At the surface, for December to March the change is mainly of salinity, and the σ_t change *can* be attributed to this factor, but for July to December the change is almost isohaline, and the σ_t change must be due to change of temperature. For the period March to July both temperature and salinity play a part. At 28 m, salinity plays an even smaller role than at the surface.

Fig. 21 also shows clearly the uniformity of the water column during the winter dry season because the T,S time curves for all depths lie between the surface and 28 m ones which are almost coincident.

PROPERTIES IN OTHER AREAS

New Caledonia barrier reef lagoon *(22°S, 166.4°E)*

H. Rotschi and Y. Magnier (personal communication) of O.R.S.T.O.M., Centre de Nouméa, made observations of water properties for a year in 1961–62 along a section from the Tontouta River in the Baie St Vincent (22°S, 166°E), west coast of New Caledonia, to the barrier reef. The water depths ranged from 6 m at the inner station to over 200 m near the reef. The rainfall in this region is typical of the west coast of New Caledonia, with a January maximum then falling steadily to November (5:1 ratio) before rising again, the annual average being 1100 mm (compared to twice this on the east coast).

The property distributions showed a sequence from salinity stratified water during the wet season, January to April, to a relatively homogeneous water column in the drier season, August to November. At stations near the middle of the Baie St Vincent (Stn 3, depth 21 m) and near the reef (Stn 6, depth 100 m) the mean differences in the water column from the surface to 20 m depth were:

		Stn 3 (shore)		Stn 6 (reef)	
Sfc. to 20m	Season:	Wet	Dry	Wet	Dry
ΔT (°C)		0.8	0.2	0.2	0.3
ΔS (‰)		0.6	0.1	0.3	0.2
ΔO_2 (ml l^{-1})		0.1	0.1	0.3	0.1

At the deeper station (Stn 6) the property changes deeper than 20 m were small compared to those for the upper 20 m.

These results are similar to those found at the Low Is. and neighbouring stations (Orr, 1933a) of the Great Barrier Reef, with a well-mixed water column except during the wet season.

P. Bourret (personal communication) of O.R.S.T.O.M., Centre de Nouméa, made available surface temperature and salinity measurements for 10 months in 1966 at Pam in the north of New Caledonia (20.3°S) about 6 km from the mouth of the Diahot River in a region with an annual rainfall of 1500 mm with a January maximum and October minimum (12:1 ratio). A T,S, time plot of these data was very similar to that for the centre zone of the Great Barrier Reef (Fig. 23) but with a less pronounced February salinity minimum. The temperature and salinity ranges for the period February to November were 7°C and 4.5‰ respectively, with the temperature minimum in July and salinity maximum in October/November. The larger salinity range at Pam than in the Great Barrier Reef data is attributed to the fact that Pam is closer to the river and in a more restricted waterway than the inshore channel of the Barrier Reef lagoon for which Fig. 23 data were obtained.

The correspondence between these two sets of results for the New Caledonia lagoon and those for the Great Barrier Reef lagoon suggests that neither is a unique region and that there may be many features in common between the various barrier reef lagoons.

Tropical estuaries

Relative to the speculation that estuarine circulations may develop in the lagoon after heavy rainfall, Yves Magnier, O.R.S.T.O.M., Centre de Nouméa, drew attention to two studies made by himself and Piton in Madagascar (Baie d'Ambaro, two years' observations, Piton & Magnier, 1971; and Baie d'Ampasindava, one year's observations, Magnier & Piton, 1972) which suggest that the estuarine circulation hypothesis is reasonable. These bays are subject to a precipitation and river runoff regime very similar to that of the North Queensland coast, although they do not have any barrier reef outside. Ambaro is an open bay while Ampasindava is narrower.

The runoff into the bays had a maximum of about 500 m^3/s in February–March falling in exponential fashion to less than 10 m^3/s in October–November and then rising rapidly. The vertical profiles of water properties were similar to those at Low Is. (Orr, 1933a) with vertical differences as:

Difference Sfc. to 15 m	Season (Baie d'Ambaro) Wet (March)	Dry (Sept.)
Δ T (C)	1.0	0.50
Δ S ( )	10.0	0.02
$\Delta \sigma_t$	7.5	0.15

(Most of wet season changes were in the upper 5 m).

Calculations for an estuarine circulation suggested outflow speeds in the upper layer of about 4 km/day.

The observations in the Baie d'Ampasindava gave very clear indications of estuarine circulation. In the dry season (e.g. October) the water was isohaline to within 0.1   from top to bottom, and had a uniform dissolved oxygen content of 4.5 ml/l and nitrate-N of less than 0.2 μg at/l. By mid-December, when the runoff had started, there was a salinity difference of 5   between the surface and 20 m depth, and the oxygen content had decreased to 4 ml/l in the bottom 10 m (40 m water depth) near the head of the bay. By February (runoff maximum) the bottom water oxygen content had fallen to less than 2.2 ml/l and nitrate-N increased to over 6 μg at/l. These marks of stagnation at the bay head were clear indications of the development of an estuarine circulation. The surface outflow driven by the river runoff entrained and carried out salt water which was replaced by a subsurface inflow, trapping a pocket of water below the surface at the estuary head (e.g. Pickard, 1961). As the river runoff decreased in April–May and the surface outflow consequently diminished, the subsurface inflow decreased and the stagnant pocket of water at the bay head dissipated, the water column becoming homogeneous by July.

Therefore, in the Great Barrier Reef where the runoff characteristics are similar to those in Madagascar, with a sharp rise in January, the associated development of an estuarine circulation with outflow of the surface layer and inflow developing below may be expected. The formation of a pocket of stagnant water is typical of the conditions at the head of a bay and probably would not occur in the open lagoon of the Barrier Reef. The real extent of the estuarine circulation is something which will have to be determined by observation.

Piton & Magnier (1971) also described very clearly, from results at a 50-hour station, the effect of wind in causing mixing. For the first 24 hours, the wind averaged 2 m s and the water (12 m depth) remained distinctly stratified with a salinity difference top to bottom of 1.6‰. The tidal amplitude was 3 m at this time. Then, in a period of about 2 hours, the wind rose to 7 m s and within 9 hours the water had become completely isohaline from surface to bottom. The salinity stratification was redeveloping within 6 hours of the wind starting to decrease from 7 m s to 4 m s.

VI
T,S Characteristics of Surface Waters

T,S DIAGRAMS

Brandon (1973) presented T,S scatter diagrams for the surface waters, which fairly well represent the water column much of the time. In such diagrams, the T,S combination for each station for a cruise is indicated by a dot, and the dot distributions are then studied to see if they show any systematic groupings which might assist in describing the distribution in space of combinations of T,S properties. A comparison of such diagrams for a series of cruises may then give some ideas about relations between regions and about changes with time. However, one must remember that at the surface, temperature and salinity are not conservative properties and if a cruise extends over a significant period of time the seasonal changes of the properties may distort the distribution of points on the diagrams.

Five T,S scatter diagrams, for spring (Sept. to Nov., 1967), autumn (March to April, 1968) and winter (June to July, 1968) are given by Brandon (1973). Unfortunately, although the individual points are shown on the T,S diagrams, the locations of most of the stations are not given in the paper. On the diagrams, the geographical locations are indicated only in very general terms. Rather than reproducing Brandon's five scatter diagrams (which use different scales), mean lines have been drawn through his groups of points and presented together on one diagram (Fig. 22) to facilitate comparison between locations and seasons. (It should be noted that the actual points scatter over a zone of width ±0.1 to ±0.2 (for isothermal water) or over a zone of width ±0.5C (for isohaline water) about the mean lines.) Because the locations for the points on Brandon's diagrams are located for broad areas only, there was some difficulty in drawing the mean curve for the 10.5 to 18.5 S part of the Inner Shelf (March–April), curve A.2. Note also that the June–July cruise extended only to 17 S, whereas the others extended to about 25 S.

Some of the features shown by Fig. 22 are:

(a) the seasonal temperature and salinity cycles for lagoon waters in the sequence of curves A.1, A.2, A.3 (see also the next section),

(b) a significant seasonal T,S cycle for Coral Sea waters just outside the northern reef (curves C.2, C.3),

(c) the large salinity gradient across the shelf for the autumn (A.2 at about 16.5 S, B.2, C.2),

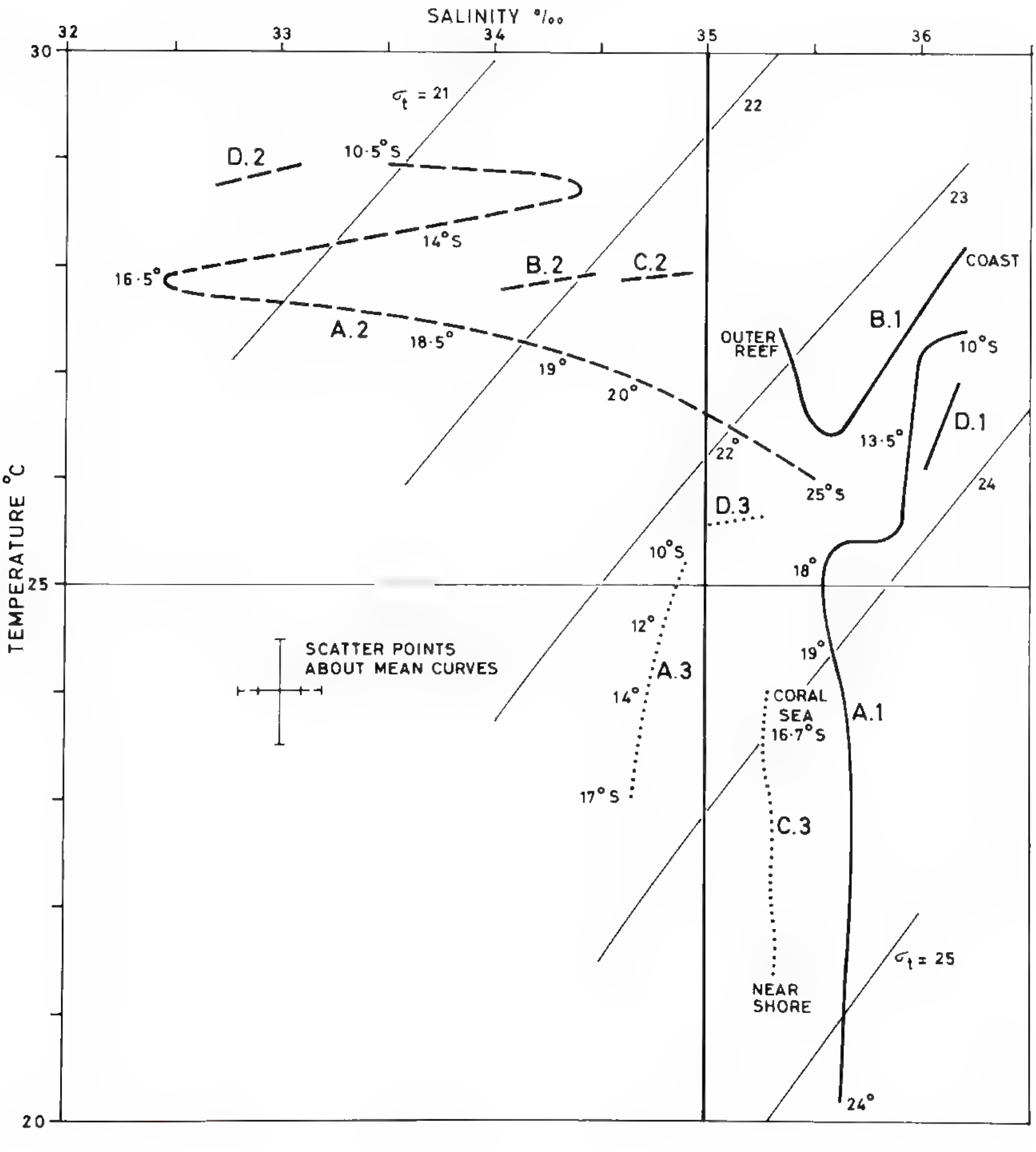
(d) the cycle in the Torres Strait (D.1, D.2, D.3) including the low salinity (D.2) due to eastward transport of low salinity water from the Arafura Sea and northern Gulf of Carpentaria during the NW monsoon.

One notices the gap between curves A.3 and C.3. As the latter represents a transect from outside the reef to the shore, one would expect the shoreward end of C.3 (low temperature) to approach the 17 S end of A.3 which is for the inner (shoreward) part of the lagoon. Brandon stated that 'The T,S values on the shelf south of Cape Grenville (12.0 S) to Princess Charlotte Bay (14.3 S) are not shown but they reflect the trend of gradually increasing salinities from the low values registered during the monsoon season'.

Possibly the A.3 curve represented values during June while C.3 represents later values in July when the salinity on the shelf had increased seasonally.

Another feature of Brandon's T,S scatter plots is an apparent bunching of points geographically. For instance, on his Fig 8 (Sept. Oct.) there is a gap with no points in the temperature dimension between 18 and 19 S, and in the vicinity of 13.5 S (latitudes taken from his text description). In his Fig. 11, there is a gap of 0.6C and 0.4 at 22 S, of 0.7 between 19 and 18.5 S, and of about 1C and 1 at 14 S. If these gaps in the occurrence of water properties are real, representing step increases in properties over short distances, rather than resulting from spatial gaps in the station distribution, they present an interesting feature to be explained.

Fig. 22 Mean T,S, curves for surface waters of areas of the Great Barrier Reef lagoon, the Coral Sea just outside the reef, and the Torres Strait, for 1967 68 (data from Brandon, 1973):
Inner shelf: A.1 Sept., Oct., A.2 Mar., Apr., A.3 June, July,
Centre shelf: B.1—Nov. (10.5 13.5 S), B.2 Mar., Apr. (14.5 17 S),
Coral Sea: C.1 omitted (no data), C.2 Mar., Apr. (14.5 16.5 S), C.3 July 16.7 S),
Torres Strait: D.1 Oct., D.2 Mar., Apr., D.3 July



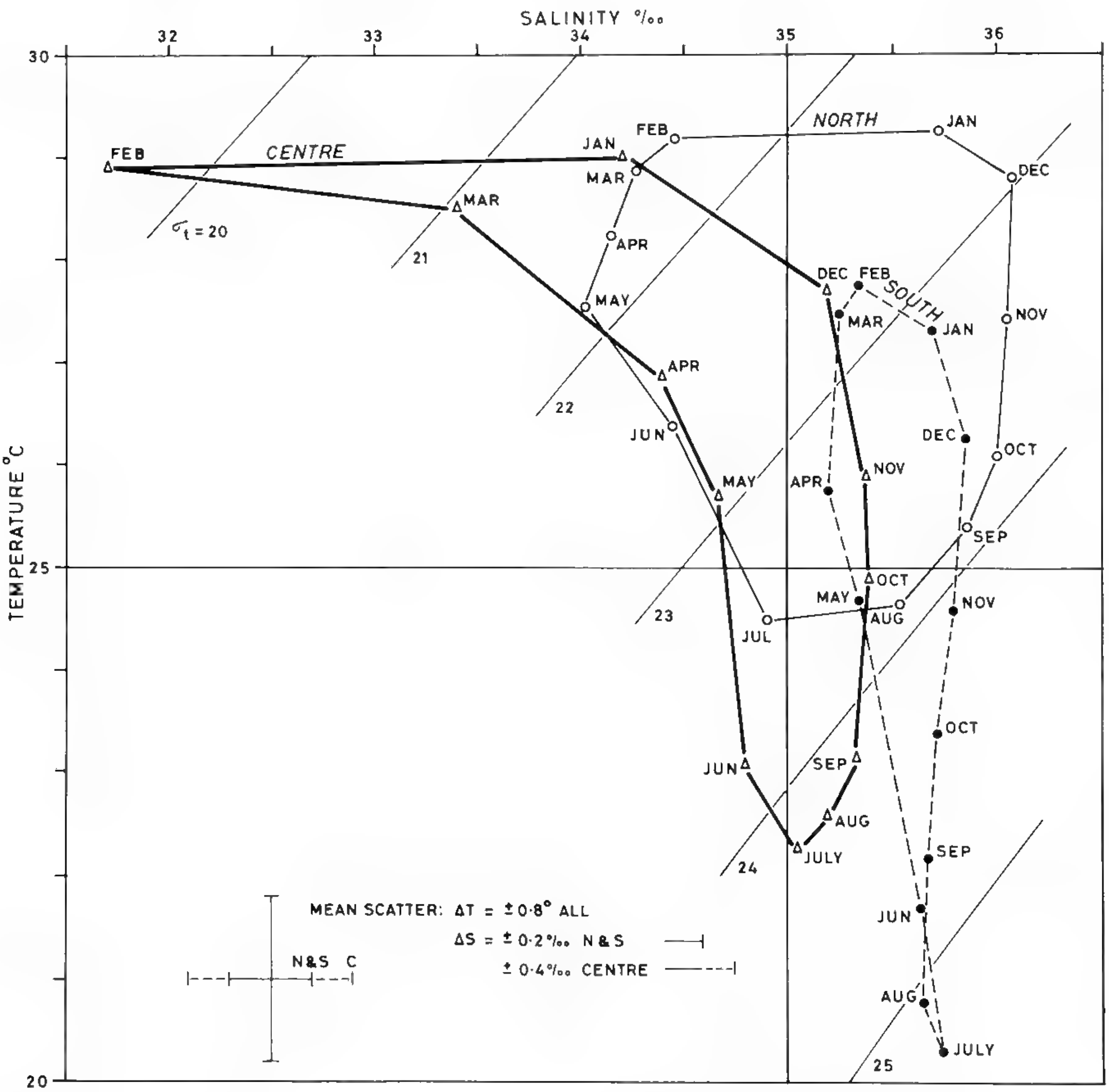
The T,S, time diagram for the Low Is. data (Fig. 21) has already been discussed.

From Brandon's (1973) data via the present Figs. 17 and 19, T,S, time diagrams of monthly mean values are presented in Fig. 23. (Note that these data are not homogeneous in that the monthly temperature data (Fig. 17) are for latitudinally wider zones (4 to 5 degrees) than are the salinity data (Fig. 19, 1 degree wide zones). However, the only effect of this will be to emphasize the reduction in salinity in the wet season for the centre zone.) An indication of the scatter about the monthly points is shown in the diagram ($\pm$0.8C , and +0.2 for north and south zones and $\pm$0.4 for centre zones).

Fig. 23 T,S, time diagrams for surface waters of the Great Barrier Reef lagoon, shore side, for zones as:

	Temperature	Salinity
North zone:	10.5 -14.5 S,	11 12 S,
Centre zone:	14.6 19.5 S,	16 17 S,
South zone:	20.5 24.5 S,	22 23 S,

(data from Brandon, 1973)



Data from some stations taken from F. V. *Degei* in August 1965 (CSIRO, 1968a) between 22° and 24° S fit these curves within the scatter given, being about 0.5C warmer on the average and 0.2 more saline.

Fig. 23 reveals very well the cycle of temperature and salinity changes in the lagoon, and the different emphasis in the three zones. The most obvious feature is the greater extent of salinity variations in the north and centre zones than in the south, related to the rainfall cycle. The second feature shown is the greater difference in minimum temperature between the zones than in maximum temperature. The third feature is that, as remarked for Low Is., the annual cycle of density is determined both by temperature and by salinity changes; in fact, in the south zone the temperature plays the major role because the salinity change is quite small compared to that in the other zones.

VII
Water Properties Outside the Reef

INDIVIDUAL PROPERTIES OUTSIDE THE REEF

Orr (1933a) made a few measurements of water properties just outside the outer reef line at Trinity Opening (16.4 S) east of Low Is., at Papuan Pass (15.8 S) about 75 km north of Low Is., and at Cook's Passage (14.5 S) about 200 km north. At Trinity Opening in October and November (dry season) the surface temperature and salinity values were essentially the same as at Low Is. at the same time. At Papuan Pass in March (end of the wet season) the temperature was the same and the salinity greater than at Low Is. by 1.2 , and at Cook's Passage in February (wet season) the temperature was 1.6C higher and the salinity 1.7 higher. The oxygen content was essentially the same at Low Is. and outside the reef in all three cases.

Below the surface all properties were much the same as at the surface to 50 to 100 m depth (wind mixed layer). Below this a thermocline extended to the maximum depth sampled (to 10 C at 600 m). There was a salinity maximum of about 35.7 at 100–200 m and an associated oxygen minimum of about 3.5 ml l. Orr regarded the salinity maximum as unexpected but it was, of course, characteristic of the Pacific Subtropical Lower water of wide distribution in the south-west Pacific (see Part 2 –Western Coral Sea).

As the depth of the wind-mixed layer outside the reef (up to 100 m) is greater than that of most of the lagoon (Fig. 3B), it is the properties of only this layer which are significant in exchanges between the sea and lagoon. Also, because the layer is well-mixed, the surface values for the sea outside provide most of the information needed when considering the effects of the outer sea on the lagoon waters.

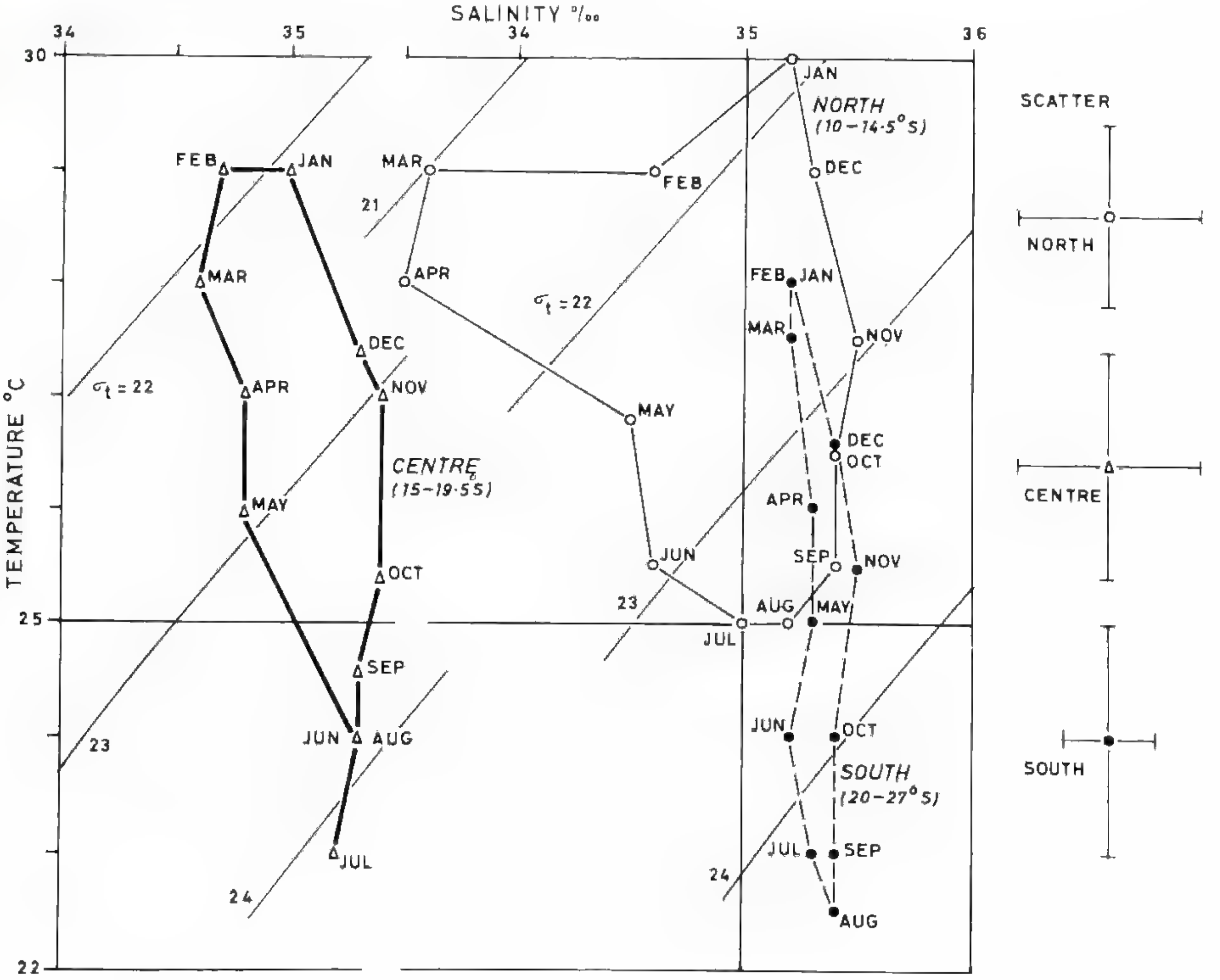
Brandon (1973) discussed conditions outside the Reef but presented no data of his own, relying on other accounts and particularly on three sections into the Coral Sea made from the *Umitaka Maru* in December 1967 (no reference given) starting at 13 , 16.5 and 18.5 S. He was particularly concerned about Orr's (1933a) and Maxwell's (1968) suggestions on the possibility and significance of upwelling outside the Reef. He concluded that there was some evidence in the *Umitaka Maru* data for limited upwelling, possibly from between 50 and 100 m depth. I do not think that the data show this; and Brandon himself, earlier in his paper, had accepted Wyrtki's (1960) suggestion of downwelling against the Reef. (It should be noted that Brandon's technique (1973, section V.B) for calculating geostrophic currents in the upper layers is not acceptable dynamically, nor is his subsequent treatment of these currents as absolute currents.)

A feature of the *Umitaka Maru* data as presented by Brandon, but upon which he did not comment, was the almost complete absence of an upper mixed layer. The temperature decreased almost linearly from the surface to 250 m at all three lines of stations (from about 28 to 17 20 C). Salinity data were not shown but density decreased steadily from the surface to 250 m with a slightly smaller rate of decrease in the upper 30 m. This lack of a marked mixed layer is unexpected in this region and when the SE trades are still blowing (December).

From the 1966–74 *Monthly Oceanographic Charts, Tasman and Coral Seas* (CSIRO, 1974), Coral Sea surface temperature and salinity values just outside the reef have been estimated for the three zones: north (10° to 14.5°S), centre (15° to 19.5°S) and south (20° to 25°S). The data in the charts are averaged by 1° squares for each month. Because of the limited number of observations in most months in the north-western Coral Sea, interpolated (and sometimes extrapolated) isotherms and isohalines had to be used in most cases. The procedure was to estimate the range of values for each month (1966–74) for each zone, reject the highest and lowest months, and take the mean of the remainder and also estimate a range (±) which included all or most of the remaining values, rounding off to the nearest 0.5C° or 0.1‰. The mean values for the three zones are presented in T,S, time plots in Fig. 24 (the centre zone plot is displaced to the left to reduce crowding). It should be noted that data are missing or inadequate to make estimates of temperature or salinity values outside the Reef for 32% of months for the north zone, 26% for the centre and 6% for the south. In many cases, particularly in the north, the number of actual values for the water properties was small and the interpolated values cannot be considered very reliable.

A conspicuous feature is that the north zone shows the lowest salinities, rather than the centre zone as is the case for the lagoon waters. This is probably due to the seasonal eastward flow through Torres Strait of low salinity Arafura Sea water under the influence of the NW monsoon (Rochford, 1959), together with a possible reduction of salinity due to river runoff from Papua New Guinea (Scully-Power, 1973a).

Fig. 24 T,S, time diagrams for Coral Sea just outside Great Barrier Reef, mean of 1966–74 with indication of scatter about mean (data from CSIRO Atlas, 1974).



Orr's (1933a) data for stations just outside the Reef compare quite well with these T,S, time diagrams except for his 18 March values outside Papuan Pass (north zone) where he measured 34.6 against the value of 33.6 from the CSIRO data. Brandon's (1973) values (Fig. 22) agree with Fig. 24 if one associates his 14.5 to 16.5 S Coral Sea values with my centre zone (15 to 19.5 S) values. Values obtained from F.V. *Degei* in August 1965 (CSIRO, 1968a) just outside the reef between 17 and 18 S and at 24 S fit the T,S, time curves of Fig. 24 within the scatter indicated.

TEMPERATURE AND SALINITY VARIATIONS ACROSS THE LAGOON FURTHER REMARKS

The difference in temperature and salinity between inshore lagoon waters and Coral Sea waters has also been estimated, by subtracting the Coral Sea values in Fig. 24 (CSIRO data) from the inshore values of Fig. 23 (Brandon's data). The results are shown in Fig. 25.

Some of the expected features of the shore to Coral Sea salinity changes are evident, e.g. in the dry season the salinity decreases seaward in the north (and possibly in the south) but not in the centre zone, and in the wet season the salinity increases seaward in the centre zone. An unexpected feature in the north is a decrease in salinity to seaward in the late wet season (March and April). This feature is a consequence of the marked drop in salinity in March and April of the Coral Sea water (Fig. 24) which was not taken into account in the discussion above. The CSIRO (1974) data on which this March and April salinity drop is based are very scattered for this region and, in the absence of direct evidence, the features should be regarded as uncertain (i.e. both the low salinity in the Coral Sea just off the Reef in March and April and the consequent decrease in salinity from shore to sea in the north zone at the same time). The few available data on shore to sea changes (plotted in Fig. 25) show rough agreement, although the large values for salinity increase to seaward in the centre zone, wet season (Brandon's data), occur later than the curve suggests. The smaller salinity differences in the south zone are to be expected from the smaller and less concentrated rainfall there than in the north and centre.

For temperature differences, the few values available from Orr and Brandon are also plotted on Fig. 25. Again Brandon's value in July in the centre zone is much higher than the curve values, but Orr's centre zone values are smaller and close to the curve except for November. The remaining conspicuous feature is the marked temperature rise to seaward in the winter in the south zone.

Having derived those curves and discussed their features and Orr's and Brandon's data, a note of caution is in order. Looking at the two figures (23 and 24) from which Fig. 25 was derived, one notes the information on scatter about the points (about ± 0.8C and ± 0.4). These scatter magnitudes are indicated on Fig. 25 and suggest that possibly the only features which are statistically significant are the salinity increase to seaward in the centre zone in summer and the temperature increase to seaward in the south zone in winter. If property gradients from shore to sea turn out to be important, it will be necessary to verify or redetermine the Fig. 25 information by direct measurement along transects. The best way to carry out such measurements would probably be to use continuously recording instruments mounted below the surface in order to avoid the errors introduced by short term variations (see Fig. 15 for examples of variations associated with weekly sampling or the graph of daily temperature readings presented by Moorhouse, 1933).

In his Ph.D. thesis, Brandon (1970) included the oceanographic data obtained during his three cruises in *Cape Moreton* and copies of *Umitaka Maru* data as follows:

Brandon

(1) Cruise GBR-DB1 67: 17 Sep.-21 Nov. 1967 from 27.0 S to 10.5 S and return to 15.0 S, surface samples and vertical profiles.

(2) Cruise GBR-DB2/68: 17 Mar.–17 Apr. 1968 from 10.6 S to 27.0 S, surface samples only.

(3) Cruise GBR-DB3/68: 15 June–29 July 1968 from 16.8 S to 10.5 S and return to 17.2 S, surface samples and vertical profiles.

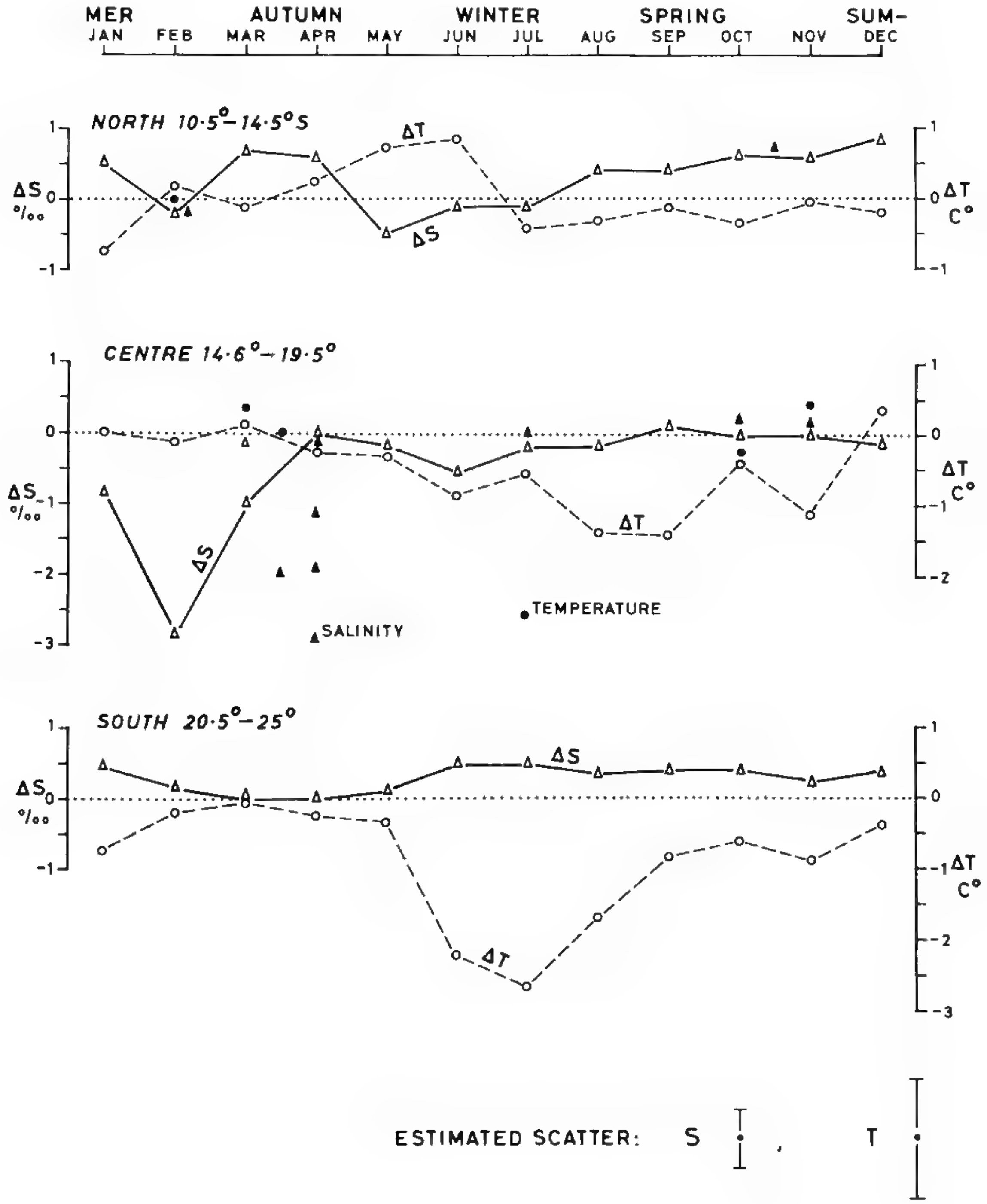
Umitaka Maru

(4) Stations UM6715-6730, 6–12 Dec. 1967 in the Western Coral Sea from 12.0 S to 18.5 S, surface to 1000 m or deeper.

Brandon did not present tables of his data obtained on transverse sections across the lagoon from the yacht *C-Gem* (Brandon, 1970, p. 11).

It would probably be profitable to review Brandon's data in detail.

Fig. 25 Seasonal variations of salinity and temperature differences across Great Barrier Reef lagoon inshore value minus Coral Sea value. Full line—ΔS from Figs. 23, 24; Dashed line—ΔT from same Figs., Points triangles ΔS, dots ΔT (from data of Orr, 1933a, and Brandon, 1973).



VIII
Currents

GREAT BARRIER REEF LAGOON

The main sources of information on currents are the *Australia Pilot* (1962, 1973) and *Sea areas around Australia* (Roy. Neth. Met. Inst., 1949), both of which base their statements on ship's estimates from their navigation records. In addition, Woodhead (1970) made some drift float measurements in the Capricorn Channel area.

According to the *Pilot*, the total current is a combination of that due to the wind and that due to the tide. Except in narrow passages, the wind driven current is stated to be the major component. Over most of the lagoon this is due to the SE trade winds and is therefore to the north or north-west, setting fairly along the main channels with a speed of 0.25 to 0.6 m/s but somewhat less south of 20 S. The reversing tidal currents are superimposed on the wind-driven current. In the open lagoon, this means that there will be a general north or north-west set varying in speed semi-diurnally with the tide. In narrow passages the tidal currents may be stronger and the total current may change direction four times in each 25 hours. In the north zone, the current due to the NW monsoon wind is less strong than that due to the tides, generally resulting in irregular currents in this zone in December to March with, perhaps, a southerly tendency less than 0.4 m/s.

There are a number of remarks in the *Pilot* about currents in various places along the lagoon, and it is suggested that anyone interested in a specific locality should refer to that publication for any data which may be available. Such information however, comes from an unspecified number of observations irregularly spaced in time and can, at best, be regarded as only an indication of possible water movements.

In Torres Strait, the tidal currents are strong and variable. There is considered to be a net set (mean flow) to the west from March to November but an eastward set during the NW monsoon in January and possibly also in December and February, according to the *Pilot*. Hamon (CSIRO, 1958) states that there is a net flow to the east between December and March and to the west between May and October, the annual mean transport being zero. The maximum net transport is $0.9 \times 10^6 m^3/s$ in February. (The U.S. Navy Pilot Charts (U.S.N.O.O., 1955) show a westward flow through Torres Strait even in December to February but this must be an error.)

Sea areas around Australia (Roy. Neth. Met. Inst., 1949) presents information on currents in the Reef area in two forms: (a) monthly charts of mean current vectors in one degree squares and (b) current roses for two locations in the lagoon. The data were obtained from ships' logs from several countries and for different periods between 1880 and 1939.

As Wyrtki (1960) has pointed out, vector averages give too small values for the mean speed and no information at all on variability. In addition, the number of observations in the Barrier Reef lagoon area 1 squares varies from 1 to 23 per month. South of 19 S there are usually 5 or more observations for each square but north of that there are often none or only 1 or 2 observations. All months in the first set of charts above, with five or more current observations in the lagoon, were reviewed. With that criterion there is no information from 10 to 15 S. From 15 to 20 S there is a net flow to the north for most of the year, with southward flow in October to December. South of 20°S there is a net flow south, which is contradictory to the information in the *Pilot*, although the mean speed is only about 10 km per day (0.1 m/s). Probably only limited weight should be given to this source of information for scientific use. Its main value is presumably to alert masters of vessels to regions where significant currents have been observed in the past (and therefore might be in the future).

The second presentation is limited to two locations for the lagoon, at 19°S, NE of Townsville, and at 23.5°S, NE of Rockhampton. For these positions, current roses are given with frequency of occurrence and speed for 16 directions for each month. Most directions are represented for most months but the predominant ones are:

Position		Av. obs. per month	Direction sector of flow: Calm	W to N	E to S	Av. speed
19°S	147.5°E	49	16%	33%	32%	0.4 m/s
22.5°S	150.1°E	52	10%	23%	39%	0.4 m/s

At 19°S, the W to N direction of flow is favoured for the first half of the calendar year and the S to E direction for the second half; at 22.5°S the E to S direction is favoured all year. It is hard to reconcile this information with the *Pilot's* preference for a predominant N or NW set, but equally hard to ignore it. The E to S tendency at the 22.5°S location is consistent with Woodhead's results, to be described next.

Woodhead (1970) made some measurements of water movements in the Swain Reefs to Great Sandy Is. region (22° to 24°S) by means of surface drifters consisting of a 22 cm diameter polypropylene plate with a 1 m long rod perpendicular to it and ballasted to float with most of the rod submerged. The drifters were dropped in bundles of a dozen from an aircraft. To determine 'the extent to which the surface drifters were affected by wind driven movements of the surface layers' Woodhead compared the deduced drift directions for drifters released near Heron Is. with the wind at that station. During the period of the experiment, the directions *towards* which the wind was blowing were in the quadrant from NW to SW while the drifters were found in a quadrant from W to S. Woodhead concluded from this that 'the prevailing winds had not had predominant effects on the movements of the drifters.' In this conclusion, Woodhead ignored the fact that a wind-driven current would tend to be directed somewhat to the left of the wind, i.e. more toward the direction in which the drifters moved, than in the actual wind direction. He also used only the 0900 hr wind at Heron Is. whereas at that time of the year the winds tend to back in the afternoon, their direction then tending towards the W to S quadrant, near to the observed drifter motion. In other words, it is probable that the drifter movements were not really independent of the local wind, nor is it probable that they should be (e.g. see von Arx's (1948) comment quoted below, and results under 'The barrier reef lagoon off Nouméa, New Caledonia'.)

Drifters were released at 5 to 7 stations each on four lines oriented at about 060° true starting close to the mainland as shown in Fig.26. Lines 2, 3 and 4 were laid on 18 September 1966 and line 1 on 3 October. About 25% of the drifters were recovered, mostly on the central Queensland coast between 23.5° and 26°S, but some from as far as southern N.S.W.

As usual, only the release and recovery points were known, while the time from release to recovery was an upper limit to the drift time, so that any calculated drift speed was a lower limit. Woodhead gives only two speeds—to Jervis Bay (35°S) at 0.39 m/s (32 km/day) and to '450 miles of NSW coastline' with a mean speed of 0.3 m/s (25 km/day). Most of these travels would be in the East Australian Current.

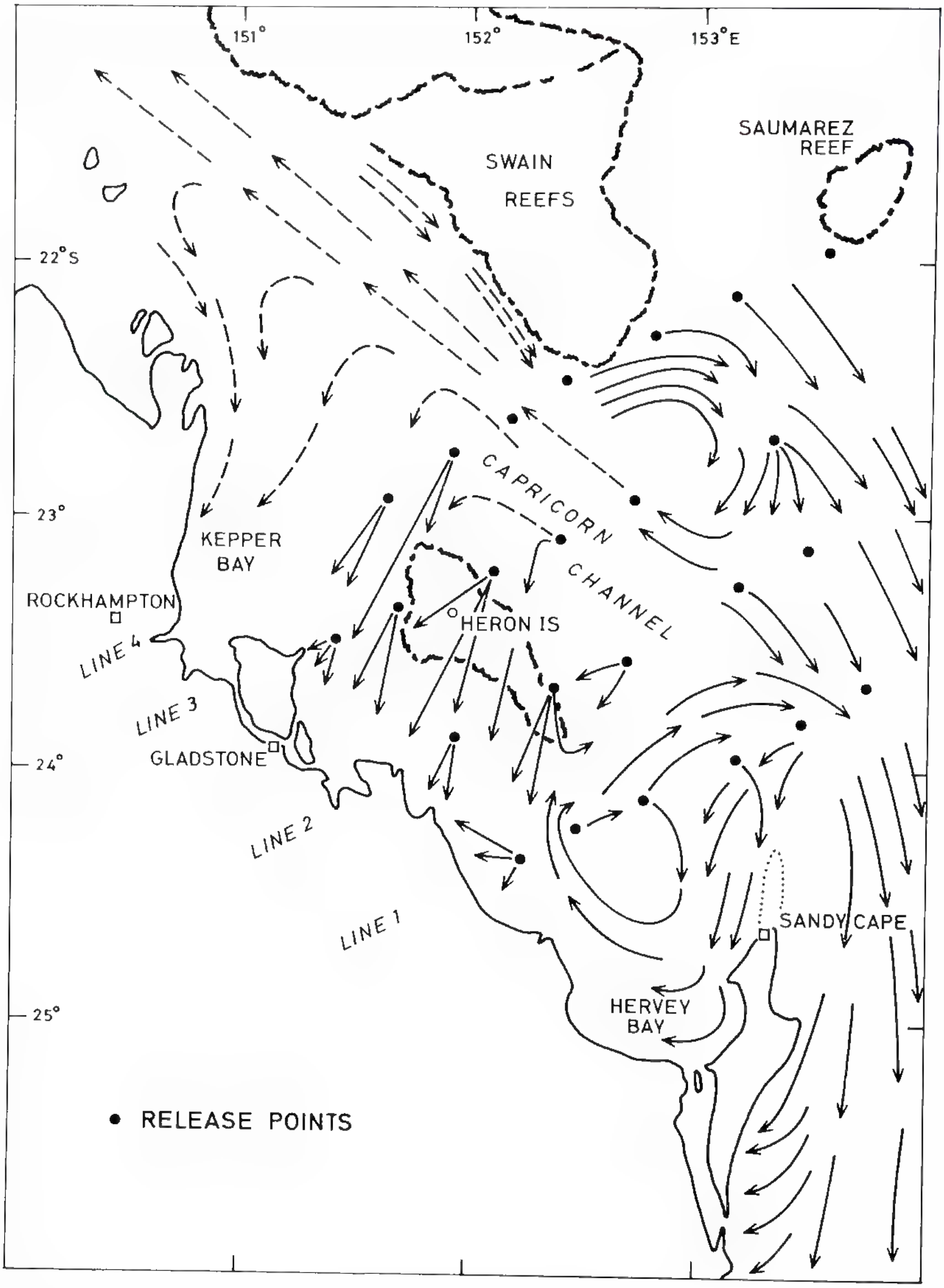


Fig. 26 Surface circulation pattern in Capricorn Channel area of Great Barrier Reef, Sept. to Dec. 1968, according to Woodhead (1970)

Many of the lines drawn from release to recovery points crossed, for all lines of releases and particularly from lines 1 and 3. This made the interpretation difficult. Fig.26 (redrawn from Woodhead's Fig.8) shows Woodhead's interpretation of the circulation, assuming a steady state over the period of $3\frac{1}{3}$ months to the end of 1966.

Referring to Fig.26, the north-westward flow up the Capricorn Channel was deduced from three drifters from lines 3 and 4 together with the lack of any recoveries to the south of the stations from which these came. This is somewhat negative evidence, although a NW flow under the influence of the SE trades is to be expected (by the *Pilot* at least). Woodhead assumed that all of the NW flow could not continue up the lagoon and that some of it must return in his postulated SE flow immediately south of the Swain Reefs. It is not certain that this countercurrent is necessary —water could equally well flow out over the outer reef or through it. The clockwise circulation in Hervey Bay (25°S) is attributed to the trade winds which 'would also help maintain such an eddy within the Bay.' Woodhead does not point out that lateral shear across the wind system would be necessary to generate the vorticity associated with such a circulation. One of the features which is difficult to accept for a steady state circulation is the apparent crossing of flow directions north of Sandy Cape (at about 24°S).

The 22.5°S current rose position in the *Sea areas around Australia* atlas is in the region of Woodhead's study where there are both NW and S components of flow according to him, so the two are consistent if his results are not from a steady state circulation but from one which changed with time.

It may be noted that Wyrtki (1960) paid little heed to the Barrier Reef as an obstacle to surface water flow. In his monthly charts for the Coral and Tasman Seas he showed current arrows and streamlines passing over the wider part of the Reef between 19° and 23°S (Swain Reef area) for all months and also stated 'to the north of Gt. Sandy Is. . . .the Coral Sea water masses which flow over the shelf between the mainland and the Gt Barrier Reef are integrated into the (East Australian) current'.

OTHER LAGOONS

In view of the paucity of data on circulation in the Barrier Reef lagoon relevant portions of several papers concerned with other lagoon areas are reviewed.

Bikini and Rongelap Atolls *(Marshall Is., approx. 11.5°N, 166.0°E)*

Von Arx (1948) described a fairly detailed quantitative study of the circulation in two atolls, Bikini and Rongelap. While there are notable differences between an atoll and the Great Barrier Reef lagoon, particularly the impervious barrier at the leeward side of the latter compared to the leaky barrier of an atoll, there are some similarities so that the information about an atoll may at least give hints for the Barrier Reef. Two statements by Von Arx should be noted initially, first that 'most of the water motion in the lagoon is produced by wind traction at their surfaces' and second that 'the exchange of lagoon water with that of the sea is accomplished in the trade wind season by tides *and wave action*.'

An atoll basically consists of a shallow lagoon bounded by a reef, usually with passes connecting the sea with the lagoon. The atoll reef consists of a broad annular waterfilled terrace bounded on the seaward side by a bulwark of coral (marginal shelf reef), over and through which water passes, and on the inner side by an island strip interrupted by passes. For Bikini, the terrace water level was about 0.5 m higher than in the lagoon and about one-third of the daily new water inflow to the lagoon came by this route from the ocean, over the outer reef into the terrace and thence through the passes between the islands. The average speed of flow across the terrace was 0.5 m/s.

The wind stress over the lagoon (average depth about 50 m) generated a downwind flowing surface layer current of 5 to 20 m thickness (average 13 m during the trade wind season) at a speed equal to 3% of the average wind speed over the previous 12 hours. Only a portion of the water transported in this upper layer was exhausted over the leeward reef, the remainder returning upwind as a bottom current. Near the windward reef some of this bottom current upwelled and some diverged horizontally to flow along the lagoon side of the reef. There were thus both vertical and horizontal circulations in the lagoon.

The openings between ocean and lagoon for Bikini were on the S and SW sides, downwind relative to the trades. Flow through them was tidal but despite relatively high speeds (up to 1.5 m/s) their effect on replacement of lagoon water was small because much of the water entering on the flood was drawn out on the following ebb. It was estimated that only 30% of the flood water remained in the lagoon. For at least one of the passes in Rongelap, the flow was constantly outward with speeds from 2.5 to 5 m/s.

For the Bikini lagoon, of volume about $28 \times 10^{9} m^{3}$, about $1 \times 10^{9} m^{3}$ entered and left per day. Of this about 35% came *over* the outer windward reef and the remainder through the passes *through* the reef. It was calculated that if all incoming water remained in the lagoon while outgoing water on the next ebb was resident lagoon water, it would require 13 days to exchange all lagoon water with the ocean. A more realistic estimate, allowing for the fact that much of the incoming flood water through passes was exhausted on the next ebb, was considered to be about 40 days.

One factor contributing to the mixing of lagoon water was the 'Enyu spiral' motion (with horizontal axis) which was generated by interaction between the lagoon bottom current being diverted by the reef topography and an inflowing current through a pass from the ocean. The spiral extended from surface to bottom and was some 3000 m wide. It contributed significantly to keeping the water column well mixed.

Von Arx described some secondary results from drift measurements of dye spots and standard drift poles. He gave a useful diagram of error (too high speed) indicated by drift poles, due to windage, as a function of wind speed and amount of pole exposed to the wind. For instance, with 0.3 m of a 5 m pole exposed in a 10 m/s wind, the speed was 10% too high (relative to dye spots in the water). The rate of expansion of dye spots due to turbulent diffusion varied from about 10 m/hr in the centre of the lagoon to 125 m/hr at the windward side.

Some comments on the possible relevance of these atoll results to the Great Barrier Reef region will be offered. The effect of the wind stress due to the SE trades causing a N or NW flow in the upper layers of the Barrier Reef lagoon is generally accepted, although no direct measurements have been made to verify it, and the review above of current 'information' suggests that the circulation may be more complicated than hitherto assumed. Whether or not there is any bottom return flow in the Barrier Reef lagoon is not known. A return flow over a considerable distance seems unlikely in view of the observed longitudinal variations of water properties but local vertical uniformity. However, return flows of limited extent, possibly controlled by bottom topography, may occur in the main lagoon, while in enclosed reef features, local circulations such as that at Bikini may occur. The possibility of return flows needs study. The other result from Bikini which is certainly significant is that considerable flow takes place *over* the outer reefs. In the southern regions of the Barrier Reef where the gaps are large compared to the reef structures this may not be a major factor but in the north (10° to 16° S) where the Reef is more continuous this component of inflow to the lagoon may be significant. Dr J. E. N. Veron (personal communication) has pointed out that aerial photographs of many of the passes in this northern area indicate strong jets of water flowing out of the passes and evident for several miles from the reef face. It is possible that these outflow jets are relieving the lagoon of water flowing in over the reef. (I have also experienced this feature on a smaller scale in the lagoons on the south sides of Tahiti and Moorea where surf flows continuously over the reef and generates a strong current along the lagoon before venting through passes to the ocean. At those islands the tidal range is small, of the order of 0.2 m, and so tidal flows are insignificant.)

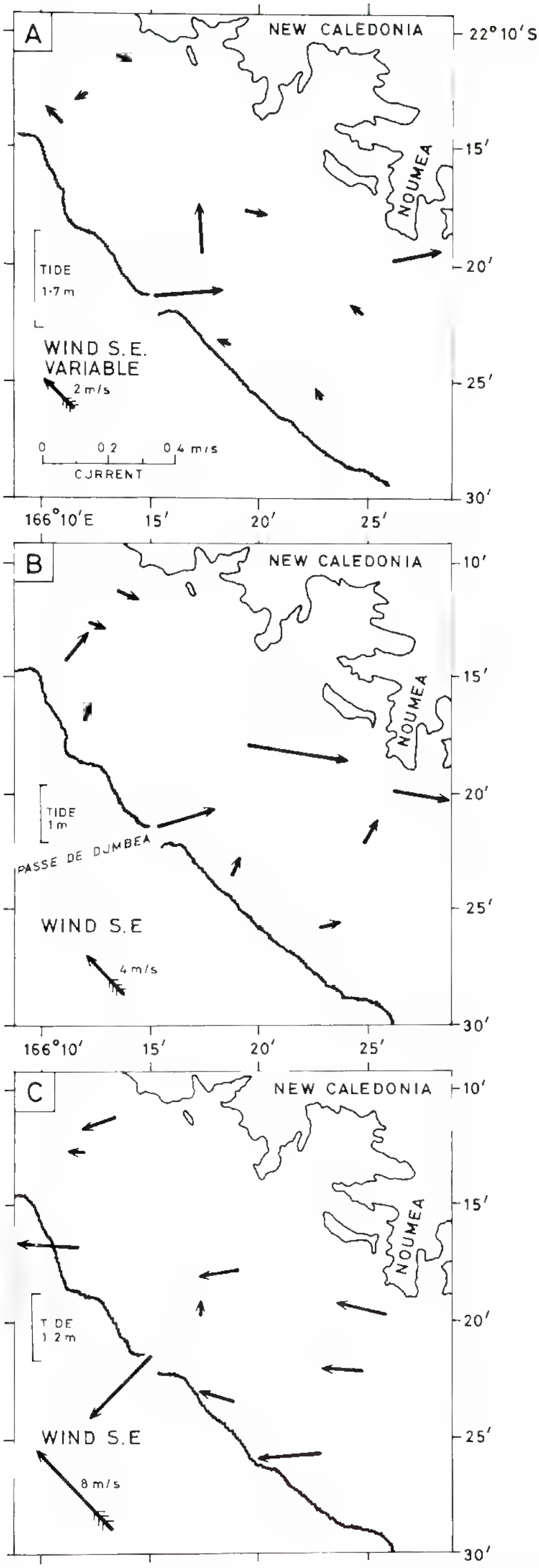


Fig. 27 Mean flow patterns in New Caledonia barrier reef lagoon off Nouméa for three combinations of wind and tide: A light wind, spring tide, B, light wind, neap tide, C strong SE wind, intermediate tide.

In the complicated structure of the Barrier Reef lagoon, there are likely to be many regions where currents may meet and generate vertical components of motion, after the fashion of the 'Enyu spiral' at Bikini, and assist in vertical mixing.

Ouotoa Atoll (*Gilbert Is., 1.8 S, 175.5 E*)

Cloud (1952) described some observations of water movement on the reef flat and edge on the east (windward) side of Ouotoa Atoll where there are extensive islands blocking flow into the lagoon. During the ebb, dye placed in the water on the reef flat showed a tendency for seaward flow at the bottom, eventually reaching the surge channels leading to the ocean. No measurements were made during the flood.

Addu Atoll (*Maldive Is., 0.6 S, 73.2 E*)

According to the *West Coast of India Pilot* (quoted by Stoddart, 1966) there is a reversing tidal current through one of the SE passes but a constant outflow through the neighbouring pass only 4 km away. The same situation occurs in the two passes on the north side only 2 km apart. It was also stated that 'continual wave action on the reef edge, together with tidal variation, sends a continuous sheet of water across the reef flats, particularly between islands', and that current measurements with floats and fluorescein dye at high water gave current speeds of 0.5 to 1.0 m s lagoonward.

Rangiroa Atoll (*Tuamotu Is., 15.0 S, 147.5 W*)

Michel *et al.* (1971), in a study of the atoll of Rangiroa, found that while the barrier reef permitted ocean water to enter the lagoon over the reef when the ocean swell from the east broke on the outer edge, especially near high water (tidal amplitude about 1 m), very little water passed out over the reef even on the 'down-swell' side of the atoll. Apparently all the discharge was through the passes on the north side (240 and 300 m wide, 14 and 6 m deep respectively). Current measurements in the deeper of the passes gave values up to 2 m s for both flood and ebb, with a rapid change of direction and very brief slack water. (The flood and ebb appear to be of equal speed and duration and therefore it is not clear why it was argued that all the over-the-reef inflow had to go out via the passes, unless the volume of reef inflow was small compared to the tidal component through the passes. Von Arx found the reef inflow about 30% of the total.

At times, when a particularly heavy swell broke over the reef, the water level in the lagoon was raised and the flood period was reduced from about 6 hours to as little as 2 hours.

Another significant feature related to the flow through the pass was that the strong currents generated an upwelling of water from below sill depth on both flood and ebb and carried this water into or out of the lagoon. This was evident both from observations of water properties and from direct measurements of currents close to the passes. Although volume flows were not estimated it was observed that lagoon water properties were always close to those of the ocean water outside and it was judged that exchange between lagoon and ocean must have been fairly rapid.

Fanning Atoll (*Line Is., 3.8 N, 159.3 W*)

Current and tidal measurements in Fanning Atoll lagoon were described by Gallagher *et al.* (1971) and showed many interesting (and puzzling) features. Those which relate to the Barrier Reef are (a) that the currents through the passes were tidal and showed a very rapid change from flood to ebb and vice versa, as for Rangiroa; (b) that there was very limited mixing between the clear oceanic tidal water inflow and the very turbid lagoon water, as von Arx found for Bikini; (c) the water going through the main pass formed a sharply defined jet into or out of the lagoon, as has been observed, at least for the outflow, for the Barrier Reef passes.

The barrier reef lagoon off Nouméa (*New Caledonia, 22.3° S, 166.4° E*)

The most ambitious current measurement project to date in a barrier reef lagoon was carried out off Nouméa on the SW side of New Caledonia between 6 December 1974 and 10 January 1975. This was a joint study by the O.R.S.T.O.M. Centre de Nouméa, the Horace Lamb Institute of Oceanography, South Australia, and Flinders University, South Australia (Jarrige *et al.*, 1975). Eleven current measurement stations and five tide gauge stations were established in a section of the New Caledonia lagoon, about 28 km long in a NW-SE direction and 17 km wide, between the barrier reef and a line along the outlying points of the New Caledonia mainland. (There are several extensive shallow bays on the landward (NE) side of this line.) The reef is continuous except for a major pass (Passe de Dumbea) near the centre of the section studied. The mean water depth is about 19 m and the current meters were set at 5 m from the bottom in all cases. To the south of the section there are numerous wide openings in the reef; to the north the reef closes the land and the water becomes shallower.

Three periods between 27 December and 7 January when the records were most complete were selected for analysis, with the following results (see Fig. 27 for mean flow patterns, items (iii) below):

(a) light wind, spring tide (1.7 m range):
- (i) flood — general flow to the NW in the lagoon with inflow at the pass;
- (ii) ebb — general flow to the SE in the lagoon with outflow at the pass;
- (iii) mean flow (averaged over a whole number of tidal cycles to eliminate, as far as possible, tidal effects) — net flow to the NW inside the reef and SE near the land, with net flow in through the pass.

(b) light wind, neap tide (1.0 m range):
- (i) flood — currents weaker than in (a) (i) with some indications of NW flow inside the reef area and SE along the land; inflow through the pass,
- (ii) ebb — currents weaker than (a)(ii) with some indication of SE flow everywhere; inflow through the pass,
- (iii) mean — shoreward flow inside the reef and SE flow near the land; net flow in through the pass.

(c) strong SE trades, intermediate tide (1.2 m range):
- (i) flood — W or NW flow everywhere and slight inflow through the pass,
- (ii) ebb — W or NW flow everywhere and strong outflow through the pass,
- (iii) mean — chiefly W to NW flow and outflow through the pass.

The most conspicuous feature was the marked effect of the SE trades (as in (c) (iii)), the strong W flow becoming established within one day of the wind starting. It is also interesting to note that across the southern part of the region, the mean displacement of a water particle in 24 hours was of about the same magnitude as the dimensions of the region, i.e. the flushing characteristics should be good. It was pointed out in the discussion of the results that there are indications of significant flow over the reef, especially in light winds and neap tides (case (iii) above), but no estimate was made of the relative magnitude of this component (P. Rual, personal communication). The reasons for the net flow (tidal effect removed) during light wind conditions i.e. (a) (iii) and (b) (iii) above, are not yet understood. It is noted however that for the (a) and (b) cases the wind was not zero, but about 3 m/s compared to 8 m/s for case (c).

O.R.S.T.O.M., Section d'Océanographie, plans an intensive field program to study the New Caledonia barrier reef lagoon starting in June 1976.

IX
Summary

The Great Barrier Reef extends for about 2300 km along the east coast of Queensland from about 9 to 25 S (Fig. 1) with the outer reefs at 23 to 260 km from the shore. It bounds a lagoon, very much broken up by reefs, having a mean depth of 35 m and in which depths over 60 m are uncommon. The most continuous deep passage is near the shore.

The winds are chiefly from the south-east, but the NW monsoon winds penetrate as far south as 15 S in December to February (Fig. 4). The annual mean air temperature and the range from annual minimum to maximum are, respectively, 27 C and 9C at 11 S and 22 C and 19C at 25 S (Figs. 5, 6).

The mean annual rainfall is about 1500 mm with a peak of about 4000 mm at 17 S (Fig. 7). Year-to-year variations are large, and very heavy rainfalls in short periods of time are characteristic of the January to March period when tropical depressions and cyclones occur. About 70% of the annual rainfall occurs in January to March in the 10 to 20 S zone but it is more uniformly distributed south of 20 S. Information on rainfall away from the land is scanty and on river runoff is incomplete, but it is estimated that the rivers contribute about one half as much fresh water as does rainfall directly on the lagoon (Fig. 9). As the river runoff is highly localised at the coast, this component of fresh water can be expected to be important both physically and biologically.

Tides have a range of about 3 m at springs along most of the coast, increasing to 6 to 9 m between 21 and 23 S (Broad Sound area, Fig. 13). They are basically semidiurnal with diurnal inequality increasing to the north until they become almost diurnal in Torres Strait (Fig. 12).

The mean surface water temperature has its maximum in January or February and minimum in July; these values average 29.5 C and 24.5 C in the north third of the lagoon, decreasing to 27.5 C and 20.5 C in the south third (Fig. 17). Temperatures during four years at Townsville (19.3 S) and one and a half years in Moreton Bay (27.3 S) showed ranges of temperature during individual months of up to 4C when the annual range of monthly mean temperature was about 9C (Fig. 16).

Surface salinity in the north has a flat minimum of 34 from February to May and a maximum of 36 in November–December. In the south, the minimum is 35.2 and maximum 35.8 at the same times. In the central third of the lagoon the salinity has a sharp minimum of less than 32 in February increasing to a maximum of over 35 in October (Fig. 19).

The seasonal cycle of temperature and salinity is well shown in the T,S, time diagrams of Fig. 23.

For most of the year the water column is well mixed vertically; stratification occurs only as a consequence of the fresh water input of rain and river runoff in January to March or April, and then mainly in the upper 10 m (Figs. 15, 20, 21). Density changes in the water are determined chiefly by temperature changes from April to December but by salinity changes from January to March (Figs. 21, 23).

Dissolved oxygen has only small variations at all depths, e.g. for a year at Low Is. at 28 m depth, 90% of the values were between 4.1 and 4.8 ml l (88 to 97% saturation).

It should be noted that only one systematic time-series of oceanographic observations of the water column has been made, by Orr near Low Is. (16.4 S) during the Great Barrier Reef Expedition 1928–29 (Figs. 15, 20, 21). The remaining observations are from cruises covering parts of the lagoon during periods of a few weeks, or from irregular observations of surface properties at various points along the lagoon.

There is very little information on interaction between the waters of the lagoon and those of the Coral Sea outside. Surface data compiled by CSIRO indicate that there are significant annual cycles of temperature and salinity outside the Barrier Reef (Fig.24).

The tidal currents are semi-diurnal in character. North of 17.7°S the flood is generally to the north or north-west at average speeds of about 0.25 m/s in the open waters, while south of 17.7°S the flood is to the south or south-east averaging 0.5 m/s. Within about 100 km of Broad Sound (22°S) the flood and ebb tend to be radially in or out respectively. At spring tides the speed is about 1.5 times the average; at neaps it is about 0.5 times the average. In passes and constrictions, currents of up to 2 m/s are experienced.

Information on mean currents is sparse and conflicting. The only actual measurements of any sort appear to be from the drifter study by Woodhead in the south. No records of direct measurements in the water column below the surface have been located. The only sources of information are the *Australia Pilot* and the Royal Netherlands Meteorological Institute atlas, both for surface currents. These two sets of information were derived from ship's navigation logs.

The *Pilot* states that the mean current is to the north or northwest along the whole lagoon generally at 0.25 to 0.6 m/s but less than this south of 20°S and north of 15°S during the NW monsoon. The Dutch atlas, in its one degree square mean current vector set, has no information from 10° to 15°S; from 15° to 20°S it shows a southerly set from October to December and northerly from January to September; and from 20° to 25°S, a southerly set of about 0.1 m/s. In the current rose data set, for 19°S the rose indicates that 33%, of recorded sets (predominantly in January to June) are directed between west and north, while 32% (predominantly in July to December) are between east and south. The 23°S rose shows 23% of the currents directed between west and north and 39% between east and south, the latter being distributed over the whole year. The speed values average about 0.4 m/s at both locations.

Woodhead's observations of drifters released at 22° to 24°S in September–October and recovered during the following three months showed prevailing net flow to the south or south-east, in agreement with the Dutch atlas information for 23°S (Fig.26).

A series of current measurements in the New Caledonia barrier reef lagoon in 1974–75 showed that while both wind and tide contributed significantly to the circulation, other (undetermined) factors may also have influenced the flow.

PART 2

The Western Coral Sea

by

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J. R. Donguy
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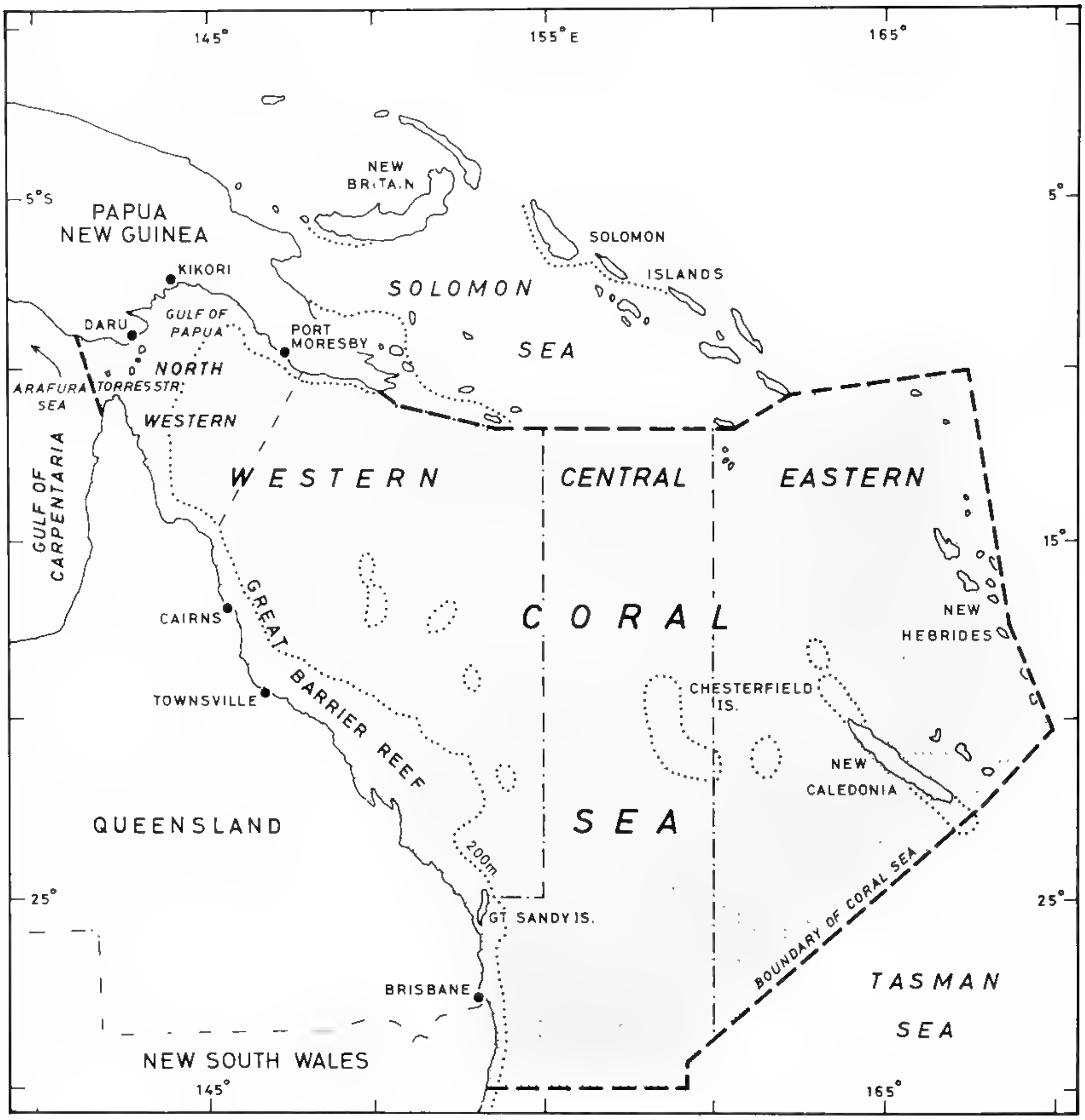


Fig. 28 The Coral Sea, and divisions used in this review.

I
Introduction

Rotschi & Lemasson (1967) reviewed in considerable detail the knowledge available on the oceanography of the whole of the Coral and Tasman Seas up to about 1965. The present work is a review up to 1975 of the main features of the physical oceanography of that part of the Coral Sea proximate to the Great Barrier Reef and thus likely to affect the properties of the Barrier Reef lagoon waters.

The formal boundaries of the Coral Sea are set out in *Limits of oceans and seas* (Int. Hydrog. Bureau, 1937) and are shown in Fig. 28. For the present review the limits adopted are the formal boundaries on the west and north (the Australia and Papua New Guinea coasts), the 155 E meridian, and the 25 S parallel as shown by the dashed line in Fig. 28. This part is referred to as the 'Western Coral Sea', abbreviated to WCS. In addition, 'Central' and 'Eastern' Coral Sea divisions have been established for convenience in reference. The eastern and southern boundaries for the WCS have been chosen arbitrarily and areas outside of them will be considered when necessary to understand the Coral Sea itself.

No water masses are formed in the Coral Sea and, in fact, the source areas of most of the Coral Sea water masses are at considerable distances, including areas north of the equator, the eastern Pacific and the Antarctic. Most of the flow into the WCS is across 155 E, north of 20 S, with a seasonal inflow to the North-west Coral Sea through Torres Strait during the NW monsoon; there is outflow in the north to the Solomon Sea and in the south to the East Australian Current.

This review will be concerned with the upper waters, from the surface to about 1000 m depth, as this is adequate to cover exchanges with the Barrier Reef lagoon. However, the data available are quite limited both in space and time. It is believed that the main features of the water masses are known but, as is the case in most of the oceans, their variation with time is incompletely understood and there is much to learn yet about the circulation.

The chief papers on the properties and circulation of the waters deeper than the Antarctic Intermediate (about 1200 m) are those by Rochford (1960c) and Wyrtki (1961a, 1962a). These and other papers were well summarised in the review by Rotschi & Lemasson (1967) to which reference may be made. There have been no significant deep water studies in the Western Coral Sea since that review.

The sequence will be to describe the topography of the region briefly (the deep bottom topography is of little concern here) and the climate, then to summarise the main descriptions available of the water mass characteristics and inferred flow patterns, and the determinations of the circulation by observation and dynamic methods, and finally to summarise the present knowledge of the region.

II
Topography

In Fig. 29 are shown the 200 and 2000 m isobaths in the Western Coral Sea, with the 1000 m isobath added where the other two are significantly separated (data from Mammarickx *et al.*, 1974). The main features are the Queensland Plateau off the Great Barrier Reef with depths less than 2000 m (much of it less than 1000 m), the Papuan Plateau in the northwest, and the Coral Sea Basin with depths of more than 4500 m. The shallow area of the Chesterfield Is. is just outside the WCS but with depths of less than 200 m in the vicinity of the main inflow it must have a significant influence on the sub-surface circulation to the WCS.

The connection northward to the Solomon Sea is limited to 200 m depth between Papua New Guinea and 154 E but has depths to 3800 m between 156 E and the Solomon Is. To the east between the Solomon Is. and the Chesterfield Is., the sill depth is greater than 3000 m. To the south, the sill depth between the Chesterfield Is. and the Barrier Reef is about 3300 m but this is in a very narrow gap and the main trough is less than 1500 m deep. The connection through Torres Strait to the west is less than 20 m deep.

Typical dimensions for the WCS are given in the Appendix.

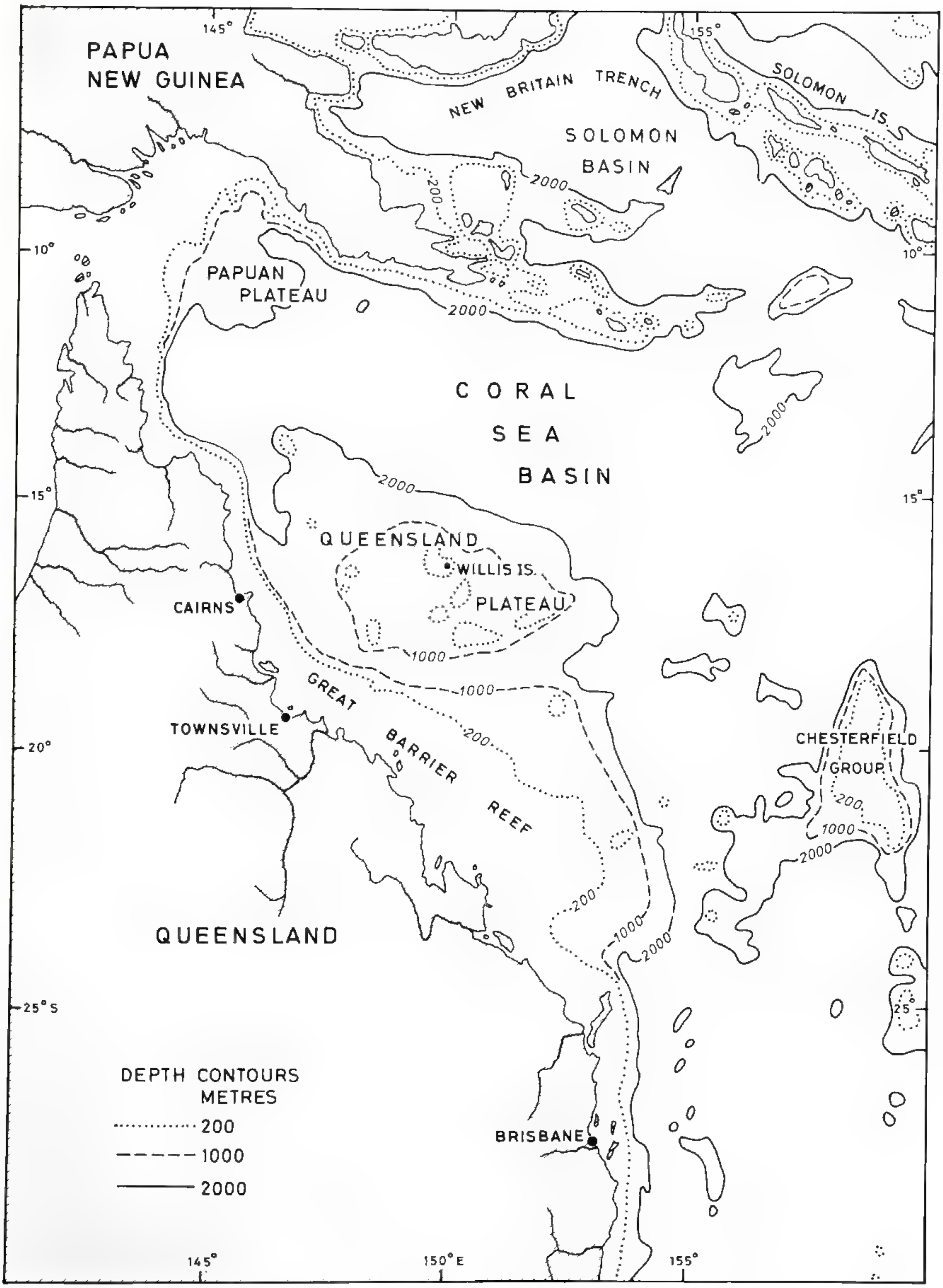


Fig. 29 Bathymetry of the Western Coral Sea, based upon J. Mammerickx *et al.*, South Pacific, Sheet 11, revised 1974.

III
Climate

WINDS

The main wind systems affecting the Coral Sea are the SE trade winds for most of the year and the NW monsoon winds in summer. *Weather on the Australia Station* (RAAF, 1942) presents quarterly charts for the WCS with wind frequency but no speeds. *Sea areas around Australia* (Roy. Neth. Met. Inst., 1949) gives wind information in two forms, monthly charts of the 'General Air Circulation' giving the vector mean wind by 1° squares, and monthly charts with wind roses by 5° squares with frequency and wind speed for 16 directions.

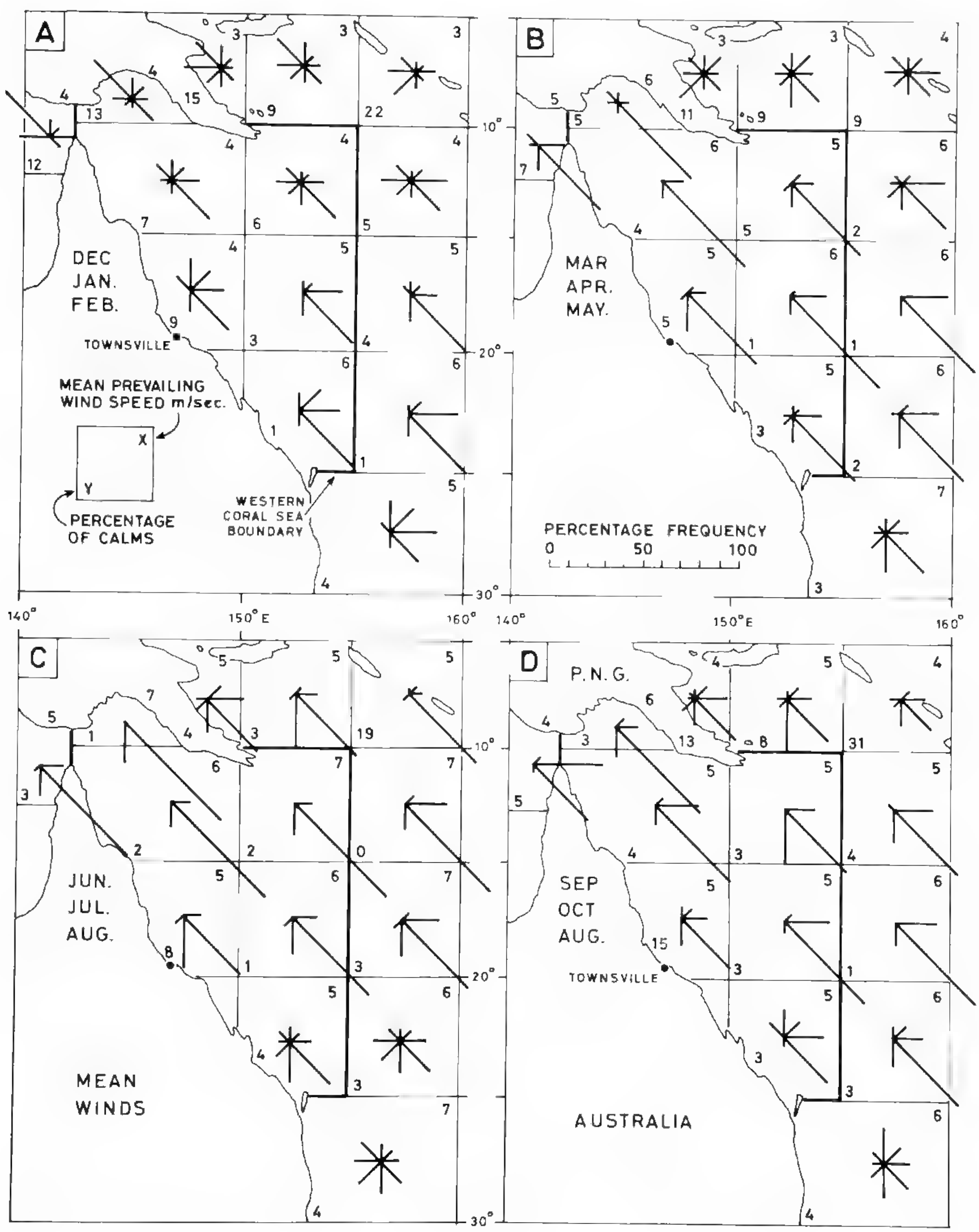
To provide a simpler picture of the wind character for this review, the wind rose charts have been used to prepare four quarterly mean wind rose charts for December–February, March–May, etc. To simplify the diagrams the 16 directions have been reduced to 8 (NNE combined with NE and attributed to NE, ENE combined with E and attributed to E, etc.). The results are shown in Fig. 30. In this figure, the wind roses represent the information available for the sea areas within the nominal 5° squares. At the bottom left of the square is shown the percentage frequency of occurrence of calms, and at the top right is the mean wind speed in m s for the prevailing direction in that square. These diagrams display the main features of the wind systems. During the period from March to November (Fig. 30B,C,D) the SE trade winds predominate over the entire area; in December to February (Fig. 30A) the effect of the NW monsoon is evident to 15°S. It will also be noted (Fig. 30C) that in winter, as the SE trades move north the westerlies intrude into the area and give rise to increased westerly components south of 20°S.

The General Air Circulation charts by 1° squares (Roy. Neth. Met. Inst., 1949) emphasise these features where the winds are predominantly from one direction, but are not very helpful where there is much variety in direction because the procedure of vector averaging conceals variety in direction (as well as tending to give too low a mean wind speed). However, these charts include the number of observations available by 1° squares and this is sometimes illuminating. For instance, the region to the east of the Great Barrier Reef between 10° and 20°S is notably deficient in observations, many squares having none at all.

Wyrtki & Meyers (1975) prepared monthly mean surface wind stress charts for the area from 30°N to 30°S and from 125°E to 75°W at 10° meridian intervals. The 145° and 155°E sets show the stress effect of the wind very well for the WCS. At 155°E, the northern limit of the NW directed stress (of the SE trades) moves from about 14°S in February to north of the equator in September. The maximum stress values occur in July at 15°S. At this time the stress has veered until at 25°S it is directed almost north (cf. Fig. 30C).The effect of the NW monsoon is seen by the wind stress at 145°E having a predominant easterly directed component of stress as far south as 14°S in January and February, but being small or north-westerly directed for the rest of the year at these latitudes.

On the average, two cyclones per year affect the WCS. They originate in the Intertropical Convergence Zone between about 8 and 18 S in the northern Central and Eastern Coral Sea and are most common in January to March, with less frequent occurrences in December and April. They initially move to the west; those north of 12 S tend to continue west while those south of that latitude tend to curve southeast.

Fig. 30 Wind roses for the Coral Sea for four quarters: (A) Dec. Feb., (B) Mar. May, (C) June–Aug., (D Sep.–Nov. Bars show percentage frequency of wind direction; wind blows toward junction of frequency bars. Bottom left figure is frequency of calms; top right figure is mean speed of prevailing winds (data from Roy. Neth. Met. Inst., 1949).



Presumably the main oceanographic effects of cyclones at sea are to cause some reduction in salinity from the associated rainfall, together with an increase in the mixed layer depth due to the strong winds. Rougerie & Donguy (1975) observed a significant heat loss attributable to a cyclone during the 'Gorgone 1' cruise. Cyclone Diane remained stationary from 10 to 15 December 1972 at 15° S, 163° E. Crossing this area on 16 December the thermograph on N.O. *Coriolis* registered a drop in surface temperature from 27° to 25° C and evidence of a decrease in temperature relative to neighbouring stations which indicated a loss of heat of 9000 cal cm^{-2}. There was no upwelling, simply the decrease of temperature.

AIR TEMPERATURE

Sea areas around Australia (Roy. Neth. Met. Inst., 1949) gives mean monthly air temperatures from ship observations, and a few isotherms are included in Fig. 34. The isotherms are roughly zonal in alignment. Temperature values in the WCS range from over 28° C in the north to 24° C in the south in the summer, and about 26° C in the north to 18° C in the south in the winter.

RAINFALL

Using ground station data, supplemented by deductions from satellite cloud-cover photographs, Taylor (1973) prepared an *Atlas of Pacific Island Rainfall* with monthly and annual charts. Fig. 31 shows the estimated maximum (February), minimum (September) and annual total values for the WCS from Taylor's *Atlas*. Most of the monthly charts have the same pattern of rainfall as the annual one, with increasing rainfall to the north-east to a maximum at about 10° S, 168° E north of the New Hebrides. In the south-west Pacific, the mean monthly rainfall at this maximum off the New Hebrides is almost uniform throughout the year at about 400 mm per month, while the minimum rainfall area lies off the Queensland coast, migrating from about 25° S, 160° E in February–March to 10° S, 145° E in August–October. According to Taylor's *Atlas*, the mean rainfall over the WCS ranges from a monthly maximum of about 250 mm in February to a minimum of 50 mm in September. It should be noted that the only ground station in the Coral Sea from which Taylor had data was Willis Island.

Kilonsky & Ramage (1975) described a technique for estimating open ocean rainfall from the distribution of highly reflective clouds (HRC) from visual satellite picture mosaics of the tropical Pacific Ocean, having determined the correlation between this parameter and measured rainfall at coral island stations all less than 30 m high. Although there was considerable scatter about their (linear) regression relationship between HRC and measured rainfall, the correlation was reasonably significant and offers a method for obtaining open ocean rainfall over large areas almost simultaneously.

Kilonsky & Ramage estimated rainfall with this technique for the period May 1971 to April 1973, and compared it with earlier estimates for the 20° N to 20° S band of the Pacific. All estimates agreed in showing a peak at about 5° N and little variation with latitude from 0° to 20° S. However, there were differences between the rainfall amounts, Taylor's (1973) values being among the highest. Kilonsky & Ramage considered Taylor's estimates too high, possibly because his ground truth stations included a number of 'high' islands where orographic effects are known to increase the rainfall. From HRC charts for three years, May 1971 to April 1974, made available to O.R.S.T.O.M., Nouméa, by C. S. Ramage, rainfall has been estimated for 5° to 20° S, 150° E (the western limit of the charts for these latitudes) to 160° E. The mean annual rainfall for the three years is shown in Fig. 31D for comparison with Taylor's values (Fig. 31C). Taylor's values are higher than the

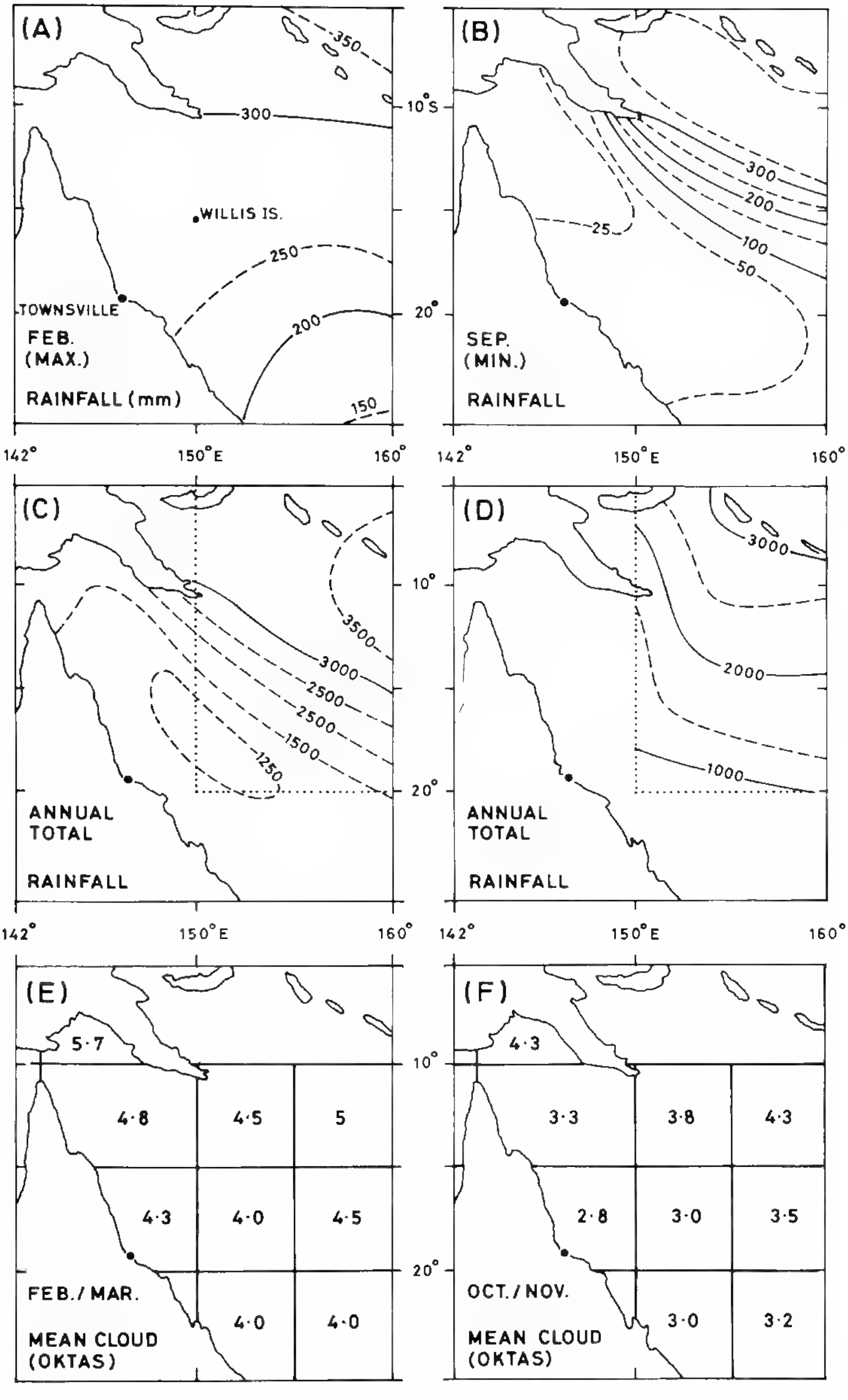


Fig. 31 Estimated rainfall (mm), Coral Sea: (A) Maximum monthly, (B) Minimum monthly, (C) Annual (A,B,C from Taylor, 1973), (D) Annual (from Kilonsky & Ramage, 1975). Cloud amount (oktas): (E) Maximum, (F) Minimum (from Atkinson & Sadler, 1970).

Kilonsky–Ramage technique values by about 250 mm/yr in the south-west of the common area, by over 1000 mm/yr in the middle and by 500 mm/yr in the north-east (Solomon Sea).

The monthly values from Kilonsky & Ramage show a seasonal cycle north of 18°S with the maximum in February–March and the minimum in September–October. The ratio of maximum to minimum is largest (3.5) at about 10°S, 155°E and decreases to the south (to about 1.2 at 20°S, 150°E).

For the WCS, probably the best estimate at present for open sea rainfall would be to use 80% of Taylor's (1973) *Atlas* values. However, it must be realised that, where satellite photographs are the source of information, both the Taylor and the Kilonsky-Ramage values are based on only a few years of data for the open sea.

CLOUD

Sea areas around Australia (Roy. Neth. Met. Inst., 1949) gives the cloud amount by the same 5° squares as used for wind roses, while Ramage (1970) gives the mean cloudiness for January and July 1967 determined from weather satellite observations. Both sources indicate a small decrease in cloud cover from about 5 oktas (eighths of sky covered) at 10°S to 4 oktas at 25°S, with slightly lower values near the coast and higher at 155°E.

A more recent analysis by Atkinson & Sadler (1970) showed a tendency for cloud amount to be maximal in February–March and minimal in October–November over the Western Coral Sea, with lower values prevailing south of 15°S than north of this latitude. Mean values (in oktas) for approximate 5° areas are given in Fig. 31E,F.

WILLIS ISLAND

Some data for this location (position in Fig. 31A) were included in Part 1 but as this station is close to the centre of the WCS and is a low island, so that data should be representative of open sea conditions, some of the statistics will be summarised here (for the 1922–41 period):

	20-year mean	*Notes*
Air temperature:	Max. 28.3°C January Min. 23.9°C July–August	Long-term extreme values were ±5.5C° relative to these (cf. ±12C° at Cairns)
Rainfall:	Max. 283 mm February Min. 17 mm October Annual 1180 mm	Rainy days = 10/month Rainy days = 1/month
Wind.	Annual 5% from NE 30% from E 17% from SE 10% from S 8% various	Mean speed 6.7 m/s, all directions (cf. coastal stations 1 to 4 m/s).

Weather on the Australia Station (RAAF, 1942) states that 'rainless periods of 20 to 40 days are usual during the dry season and spells of 50 to 80 days have been recorded particularly from June to November, while in the wet season dry spells of 10 to 15 days are not uncommon'. This implies that rainfall is concentrated in time (3 days per month on the average from May to December) which would contribute to variability in time of surface salinity.

It should be noted that the meteorology and climatology of Willis Island is currently under study by the Bureau of Meteorology using all available data (personal communication, Dr J. W. Zillman, Superintendent, Physical Research). Some aspects of the SE trades of the Coral Sea have been discussed by A. B. Neal (1975) using regular and special observations at Willis Island. Neal states that 'the station is fully equipped for surface observations which are taken routinely every three hours (except midnight) and include sea temperatures at 0600 and 1800 hours measured at buoys moored in deep water beyond the western reef'.

IV
Water Masses, Properties and Deduced Flow Paths

INTRODUCTION—SALIENT CHARACTERISTICS

For orientation purposes, a brief summary of the salient characteristics of the WCS water mass properties will be given before reviewing the papers upon which our present knowledge is based.

Fig. 43 shows examples of the temperature and salinity distributions at the surface during the early winter, the gross features being a decrease in temperature and an increase in salinity from north to south, and a tongue-like distribution of the isopleths near the Australian coast south of about 25 S (the start of the East Australian Current system). The basic change to summer conditions is an increase in temperature of 2C in the north and 5 or 6C in the south, with the disappearance of the low salinity in the Gulf of Papua by early summer and its reappearance later (January). This low salinity is attributed to Arafura Sea water driven through Torres Strait during the NW monsoon, but river runoff from Papua New Guinea may also contribute significantly.

It should be noted that the data on which Fig. 43 is based are from the only near-simultaneous set for the WCS. They were obtained during three Royal Australian Navy Research Laboratory cruises in May–July 1968 (Scully-Power & France, 1969a, b, c; area shown in Fig. 45A), and described by Scully-Power (1973a, b). With the exception of the description of the Central Coral Sea by Rougerie & Donguy (1975); O.R.S.T.O.M. 'Gorgone 1' Cruise, November December 1972, see Fig. 45A) all other descriptions or analyses of the western half of the Coral Sea have been based on more limited data distributed over several years, although there are data for other cruises ('Iule' 1965, *Shoyo Maru* 1973, and 'Gorgone 2' 1975) for parts of the WCS. The 'Gorgone 2' data are currently being analysed.

In the vertical, Fig. 32A shows an almost 'textbook' example of the structure in the upper 1200 m of the WCS, using an R.A.N.R.L. station from the 1968 cruises referred to above. The location of the station (CS 4/2 Stn 14) is shown in Fig. 45A. The major features are:

Temperature

(a) an upper mixed layer of as much as 150 m depth from the surface;
(b) a monotonic decrease in temperature from the bottom of the mixed layer to below 1000 m, forming a permanent thermocline with its maximum gradient between the mixed layer and about 500 m depth.

Salinity

(a) an upper mixed layer as for temperature;
(b) an upper salinity maximum, usually sub-surface from 50 250 m depth but reaching the surface in the south of the region (Subtropical Lower water);
(c) a salinity minimum at 650–1100 m depth (Antarctic Intermediate water).

Density

Below the mixed layer, this increases with depth, opposite to the temperature change. Density changes are determined more by changes of temperature than of salinity.

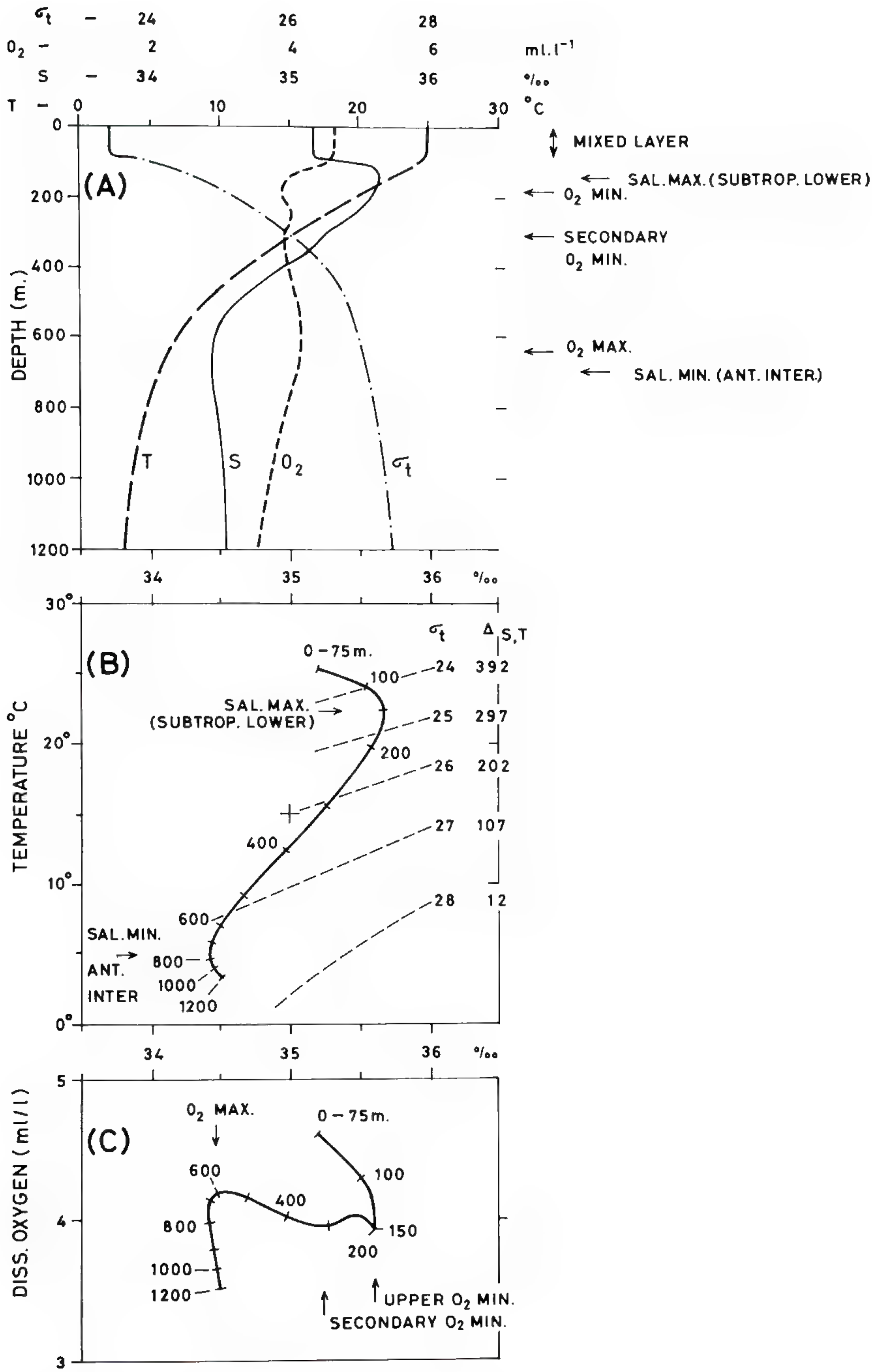


Fig. 32 (A) Typical vertical profiles of temperature (T), salinity (S), density (σ_t) and dissolved oxygen (O_2) for the Western Coral Sea (R.A.N.R.L. Cruise CS4 2, Stn. 14 (15.0 S, 149.5 E), June 1968) (data from Scully-Power & France, 1969b),
(B) T,S diagram for the same station,
(C) S,O_2 diagram for the same station.

Dissolved Oxygen

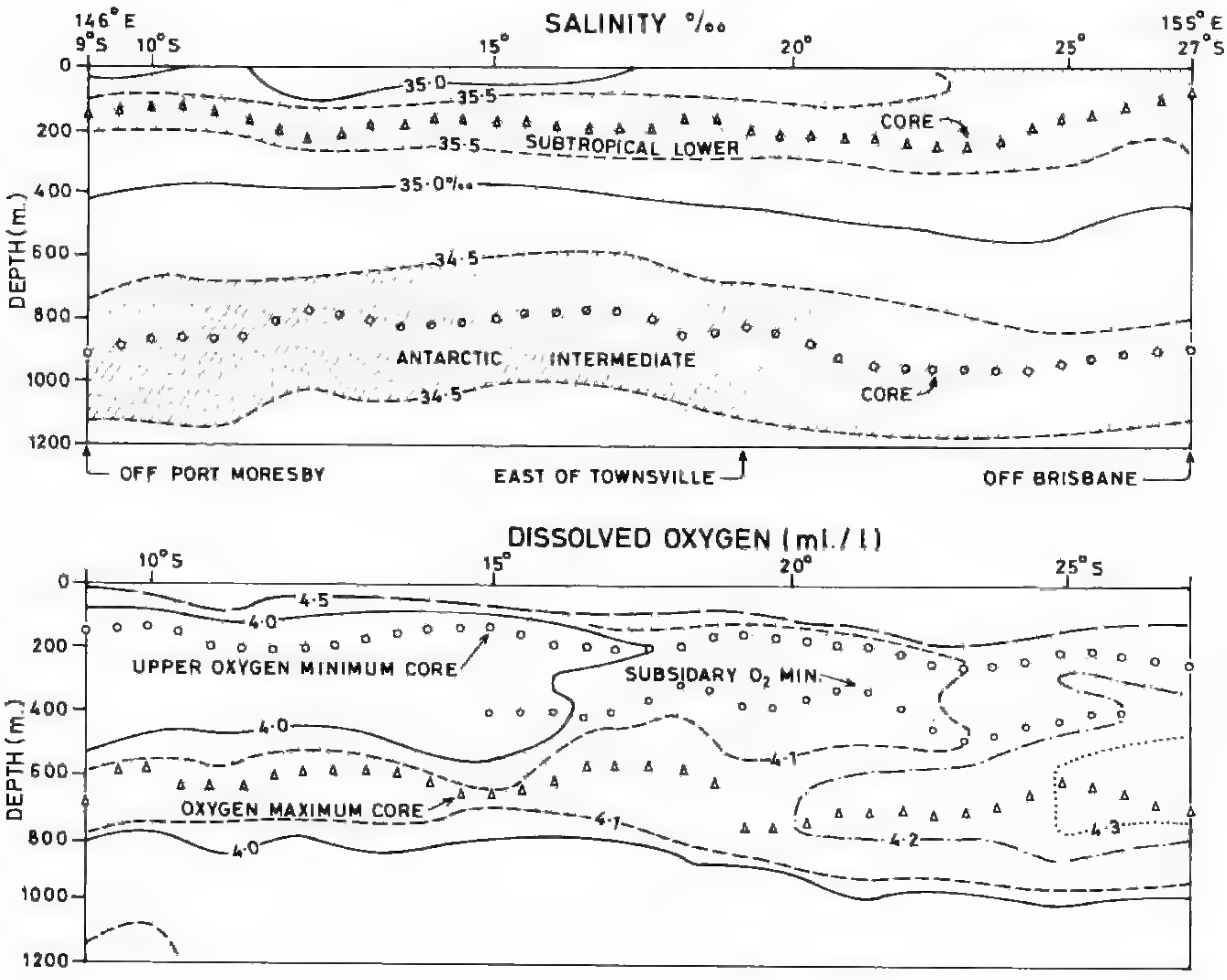
(a) an upper oxygen minimum at 150–500 m depth, typically a little deeper than the upper salinity maximum (at 170 m in Fig. 32A);

(b) an oxygen maximum at 400–800 m, typically shallower than the salinity minimum.

A minor feature which has been mentioned only by Scully-Power (1973a) is the occurrence of a double oxygen minimum (in Fig. 32A the second one is at 300 m). Scully-Power stated that this was observed at about 25% of the 94 stations in May–July 1968, apparently occurring with no clear geographic distribution (but see the note in the next paragraph). Scully-Power did not discuss it further but this feature also appears in the Central Coral Sea 'Gorgone 1' data (Donguy *et al.*, 1972b). In fact, multiple maxima and minima frequently occur below the upper salinity maximum and, on a single vertical profile, it may be difficult to single out any one as the significant minimum. This feature should be studied; possibly it is related to successive inflows of Subtropical Lower water.

Fig. 33 shows the distribution of salinity and dissolved oxygen for a north-south vertical section through the WCS from near Port Moresby to east of Brisbane, the station positions being shown in Fig. 45A. The salinity and oxygen features described above are shown, except the mixed layer which is too thin to show clearly on the depth scale used. The boundaries of the Subtropical Lower and Antarctic Intermediate waters have been taken as 35.5 and 34.5‰ respectively following Scully-Power (1973a). The subsidiary oxygen minimum mentioned above appears in the section of Fig. 33 at seven successive stations and seems to be a continuous and systematic feature. The oxygen maximum in the upper part of the Antarctic Intermediate water is very conspicuous in the south, and the

Fig. 33 Vertical sections of salinity and dissolved oxygen for a north-south section of the Western Coral Sea, May–July 1968 (data from Scully-Power & France, 1969a, b, c; station positions shown in Fig. 45A).



low oxygen northern component of the Subtropical Lower water in the north. The Subtropical Lower water mass is seen to be at the surface in the south.

Vertical profiles, such as those in Fig. 32A, are generally used only in the first stages of checking data; most of the analysis of water masses has been carried out with characteristic diagrams, generally T,S and S,O_2 diagrams, although T,O_2 and S, phosphate diagrams have been used in the SW Pacific. To show how such diagrams relate to the profiles, Figs. 32B,C present T,S and S,O_2 diagrams corresponding to the vertical profiles of Fig. 32A. The linear portion of the T,S curve between 250 and 600 m in Fig. 32B corresponds to Sverdrup's (1942) Western South Pacific Central water. This is not recognised as a specific water mass in the Coral Sea, while Sverdrup did not recognise the Subtropical Lower water as a specific water mass, although he did describe the subsurface (upper) salinity maximum. It should also be noted that the curves of characteristic diagrams are notoriously non-linear in depth scale (see Fig. 32B,C) and depth interpolation should not be carried out on such a diagram alone.

It must be realised that the area on a T,S diagram representing a water mass does not indicate its volume. For instance, the Antarctic Intermediate water is represented by a very compact area in Fig. 61 compared to the Subtropical Lower water, but the former has about twice the volume of the latter in the Western Coral Sea (see Fig. 33).

Because the depth of a particular water mass may vary from place to place, it is often difficult to determine the distributions of such masses on surfaces of constant geometrical depth (apart from the water-air boundary surface) and most studies have been carried out using either the 'core method' (Wüst, 1935) or isentropic analysis (Montgomery, 1938). In the former, a 'core' is defined as the level where a property reaches an extreme value in the vertical direction, and a plot of the depth of this core for a region defines a surface called the 'core layer'. The location where a property has an extreme value on the core layer is called the 'origin' and flow is assumed to take place along the core layer in the direction of increase or decrease of the property (due to mixing with water having less extreme values). In isentropic analysis, flow and mixing are assumed to take place along surfaces of constant density (σ_t), which approximate to isentropic surfaces, and distributions of conservative properties (e.g. T, representing heat, or salinity) and to some extent quasi-conservative ones (e.g. oxygen) indicate flow patterns. These procedures help to identify both sources of water and flow patterns to and in a region.

The flow patterns may also be studied by direct measurements of currents or indirectly by the geostrophic method.

SURFACE WATER CHARACTERISTICS

Surface temperature—mean distribution

Sea areas around Australia (Roy. Neth. Met. Inst., 1949) gives monthly charts of sea and air temperature by 1° squares, with interpolated isotherms at 1°C intervals. Fig. 34 is based on this source. The smaller scale charts in Sverdrup *et al.* (1942) agree with the Dutch data. The numbers of observations in each 1° square in the Dutch atlas vary from none at all in many squares east of the Great Barrier Reef, to less than ten per month in most of the WCS, and to a hundred or more near major ports or in major shipping lanes. The main 'holiday' areas are listed in the legend. There is considerable scatter between neighbouring squares and the preparation of the isotherms must have required a considerable amount of personal judgment.

According to this atlas the water temperature in the WCS ranges from 26° to 29°C in summer (30°C appears in a few individual 1° squares) and from 21° to 26°C in winter, and averages about 0.4°C higher than the air temperature above it.

Away from the land, the isotherms are oriented zonally. Approaching the Barrier Reef they trend equatorward from April to September (winter, Fig. 34B), i.e. the water near the

Reef is cooler than that further offshore at the same latitude. South of 20 S, a southward tongue of warmer water associated with flow into the East Australian Current is evident both in winter and summer. This feature is much more conspicuous in the current itself south of the WCS area covered in Fig. 34.

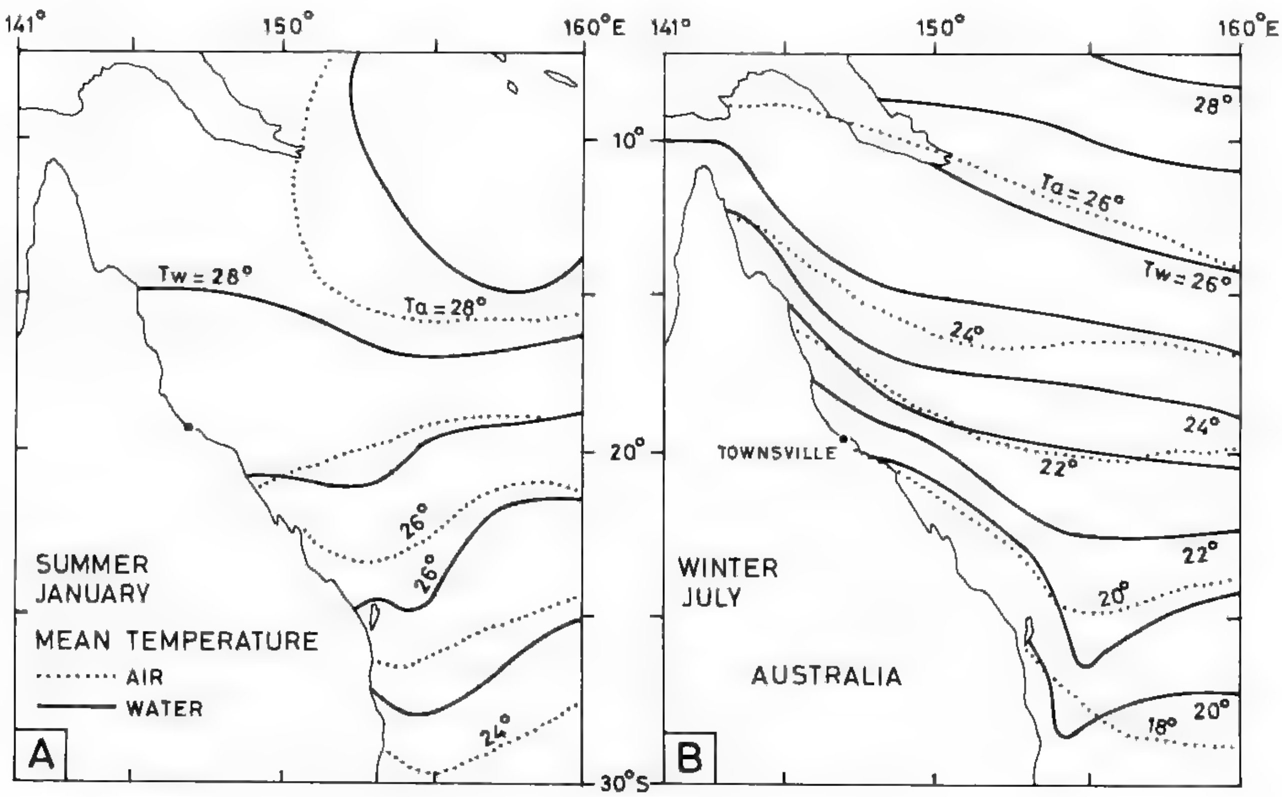
The *Monthly Oceanographic Charts, Tasman and Coral Seas*, 1966–74 (CSIRO, 1974), referred to hereafter as the 'CSIRO Atlas', present monthly accumulated temperature and salinity observations for the surface waters. The individual charts present the station positions and interpolated isotherms at 1C intervals. The station density was quite variable and for some months large areas were blank. In these cases, some of the interpolations to prepare the isotherms became essentially extrapolations, which are always uncertain, especially in a region as complicated as the Coral Sea. In addition, there were some areas, particularly east of the Barrier Reef, where there were few or no station positions for any year (see below and Fig. 37 for more details).

Mean monthly surface temperature charts were prepared from the Atlas but, as will be explained shortly, their significance is limited because of the large variations with time.

The procedure used was to select a month and to trace the positions of a particular isotherm on one diagram for all years, then drawing a mean isotherm for that month for the whole period 1966–74. To reduce the uncertainties associated with the interpolations on the charts, only those portions of isotherms lying between two stations not more than 100 km (about 1 of latitude) apart were used. Values inside the Barrier Reef were excluded. The procedure was repeated for several isotherms for the months of January, April, July and October.

This process indicated that the annual range of surface temperature values was about 20 to 30 C. The positions of individual isotherms extended over very large areas when the nine years of data were combined. Fig. 35 shows the areas of occurrence of the isotherms 24 , 26 , 28 and 30 C, representative of the bulk of the values occurring in the WCS. It is clear that the WCS is a region of considerable variability of surface water temperature (and of salinity, as will appear shortly). It is evident that attempting to

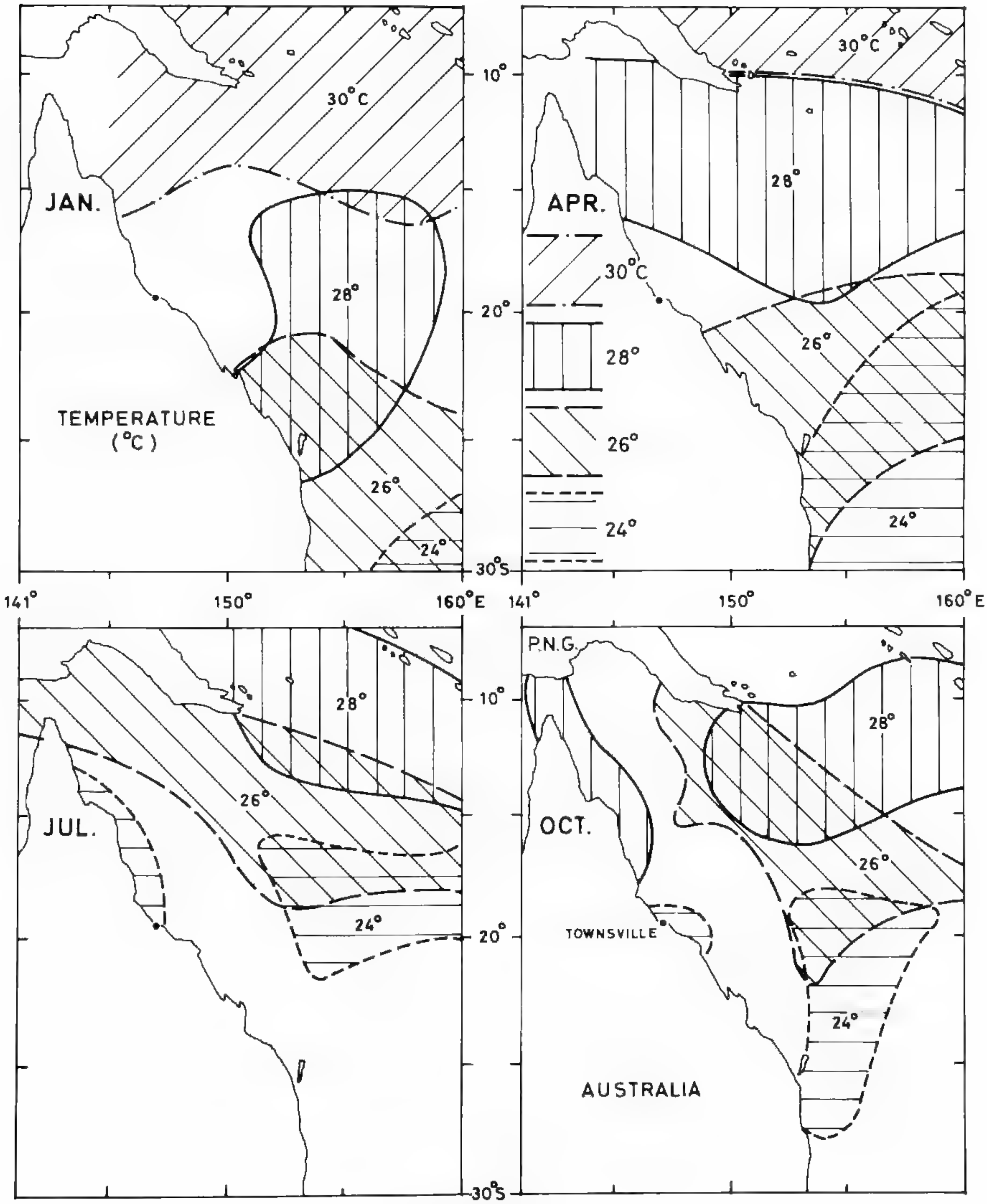
Fig. 34 Mean surface water (T_w) and air (T_a) temperatures, Coral Sea: (A) Summer (Jan.), (B) winter (Jul.) (data from Roy. Neth. Met. Inst., 1949). Note: There are few data for most months in areas (10 13 S, 144 -146 E), (15 -20 S, 148 -152 E), (10 20 S, 155 -160 E).



determine a mean picture of surface conditions by combining data from a number of cruises is likely to be of dubious value. Mean isotherms (Fig. 36) were drawn to show the trend of seasonal variation over the area, rather than to specify mean positions of isotherms for each month. In the main body of the WCS and within the limitations of the scatter shown in Fig. 35 there is evident:

(a) the usual trend to warmer temperatures in summer and cooler in winter at each location; and

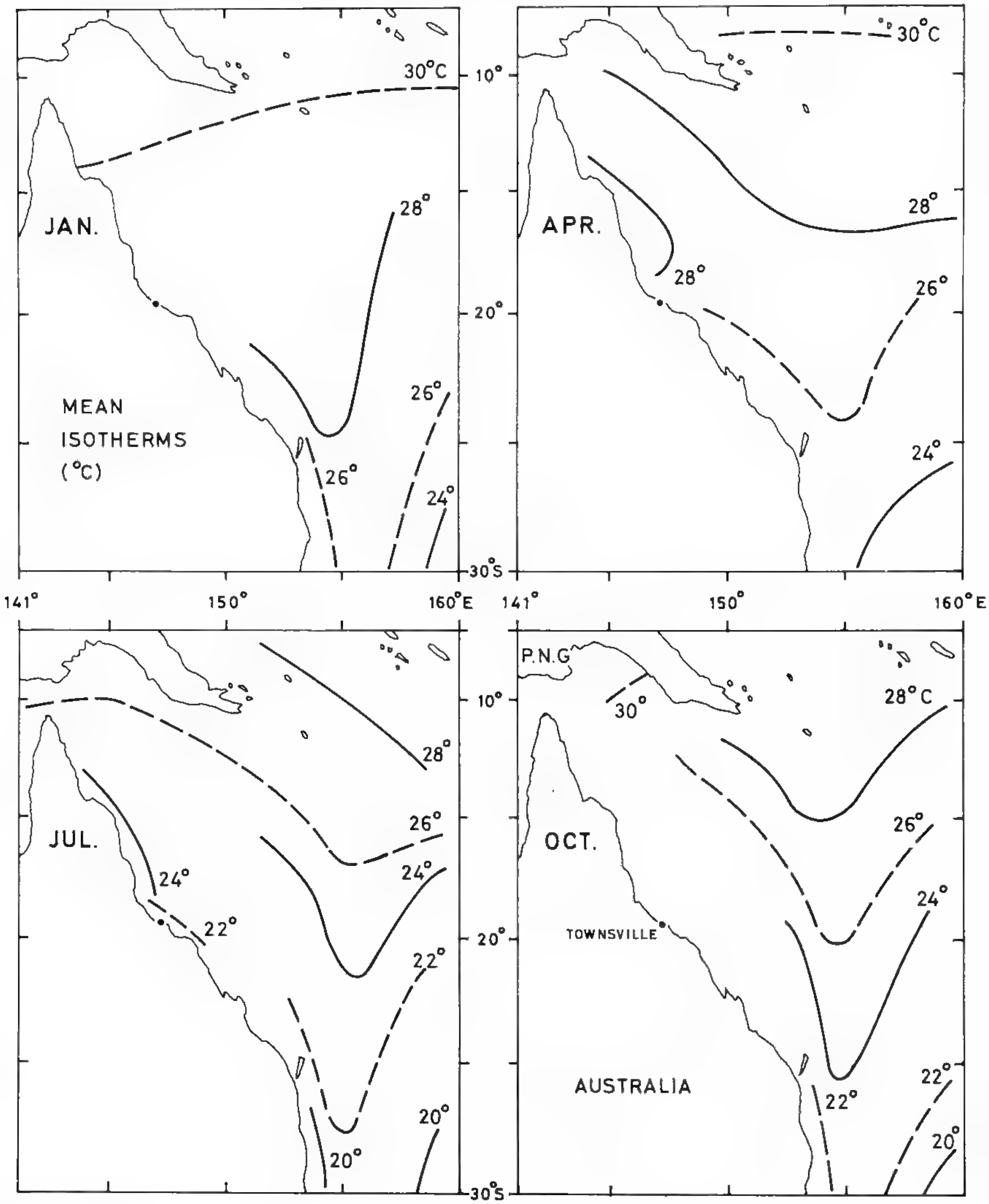
Fig. 35 Surface temperatures, Western Coral Sea, areas of occurrence of 24°, 26°, 28° and 30°C water for January, April, July and October 1966–1974 (data from CSIRO, 1974). Note: For all months there are gaps in the data off the Great Barrier Reef, see Fig. 37, and some shaded areas should probably extend further west.



(b) the shape of the isotherms from a roughly zonal orientation in the north to a tongue shape in the south associated with the start of the East Australian Current.

A criticism is appropriate here. If one had available only the material (isotherm spot positions) from which Fig. 35 was prepared it is doubtful if the tongue form in Fig. 36 would have been drawn. It was prompted by the individual monthly charts, most of which show this feature clearly. However, the tongue is quite narrow and it shifts slightly east or west (i.e. transversely) from year to year so that the accumulated isotherm positions on the tracing spread over an area, such as the 24 C area in Fig. 35, October, and obscure the tongue.

Fig. 36 Surface water temperatures, Western Coral Sea, mean isotherm positions for January, April, July and October, 1966–1974 (data from CSIRO, 1974). Note: The termination of some isotherms in mid-sea is probably due to gaps in data coverage.



The termination of isotherms in mid-sea is usually due to gaps in data coverage rather than to the occurrence of convergences or divergences.

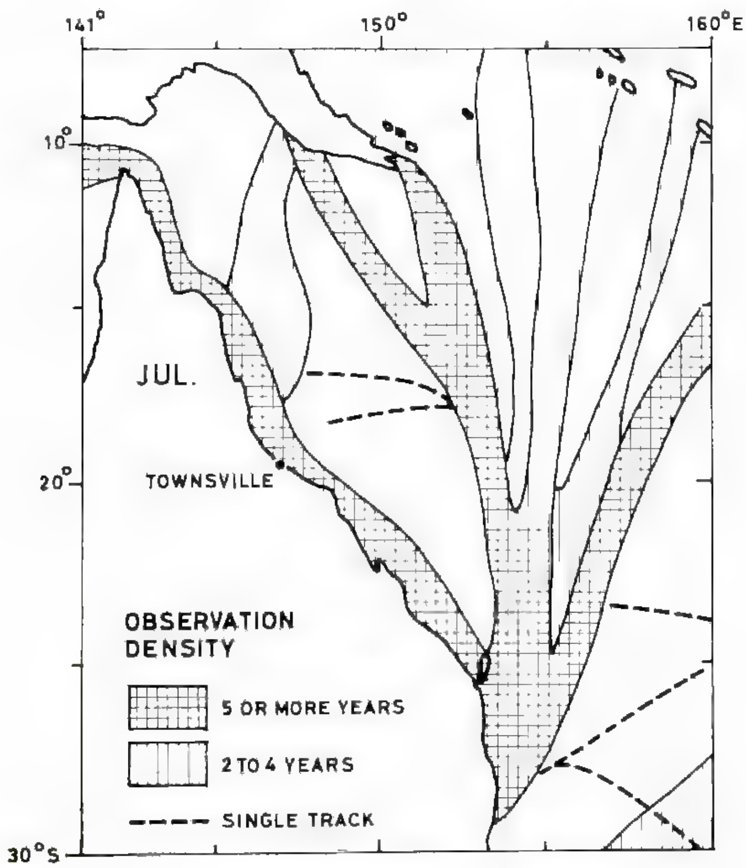
The isotherms in the Dutch atlas (Fig. 34) and those from the CSIRO Atlas data (Fig. 36) differ in two respects. The tongue form in the south is much more evident in the curves derived from the CSIRO Atlas than in the Dutch ones, and the CSIRO values are generally 1 to 2 C higher than the Dutch ones for corresponding areas. With regard to the shape, it is likely that the construction of the curves of Fig. 36 in the present study was influenced by the shapes of the individual monthly isotherms in the CSIRO Atlas where the author of the Dutch atlas isotherms may have been working with the totality of his data (by 1 squares) and not had access to ready-drawn individual charts for inspiration. The reason for the difference in mean temperature values is not known.

Of the two figures, Fig. 36 indicates the character of the isotherm shapes in the area, although in a very smoothed form as the isotherms for individual months show numerous small features or irregularities. Fig. 35 is the more realistic for describing the environment on a long-term basis and probably for relating to biological observations of fixed features such as coral reefs. For comparison with biological records of a specific (past) expedition one might be able to find data in the relevant CSIRO Atlas chart for the period 1966–74 (and later years in due course), but for future projects it would be wise to plan to include physical (and chemical) measurements in parallel with any biological ones.

Finally, when using Figs. 35 or 36 one should bear in mind that the distribution of observations over the area available for preparing the CSIRO Atlas was far from uniform. Fig. 37 shows qualitatively the density of observations for a typical month. It will be seen that there are some areas for which there are no observations at all, notably and unfortunately off the Barrier Reef. As mentioned previously, this is why several isotherms terminate in this region.

An alternative treatment of the CSIRO data is offered in the next section and may be sufficient for many purposes.

Fig. 37 Density of observations of surface temperature and salinity for a typical month, Western Coral Sea, 1966–1974, in CSIRO, 1974. (Refer to Figs. 35, 36, 39, 40.)



Rochford (1973) examined surface temperature and salinity values in the Tasman and Coral Seas for 1966–70 for annual and longer term variations. He determined the annual range of mean monthly temperature as shown in Fig. 38A. The range increased from 2C in the northeast (Solomon Is.) to about 5C at the Barrier Reef (and 8C in the south zone of the Lagoon). In a 1 square off the Swain Reefs (A in Fig. 38A) there was little or no indication of any long-term change in mean temperature.

The surface water property distributions for 1968 obtained by Scully-Power (1973a) and shown in Fig. 43 will be described later to maintain the continuity of that 1968 data set information and after the possible source areas for waters in the Coral Sea have been discussed.

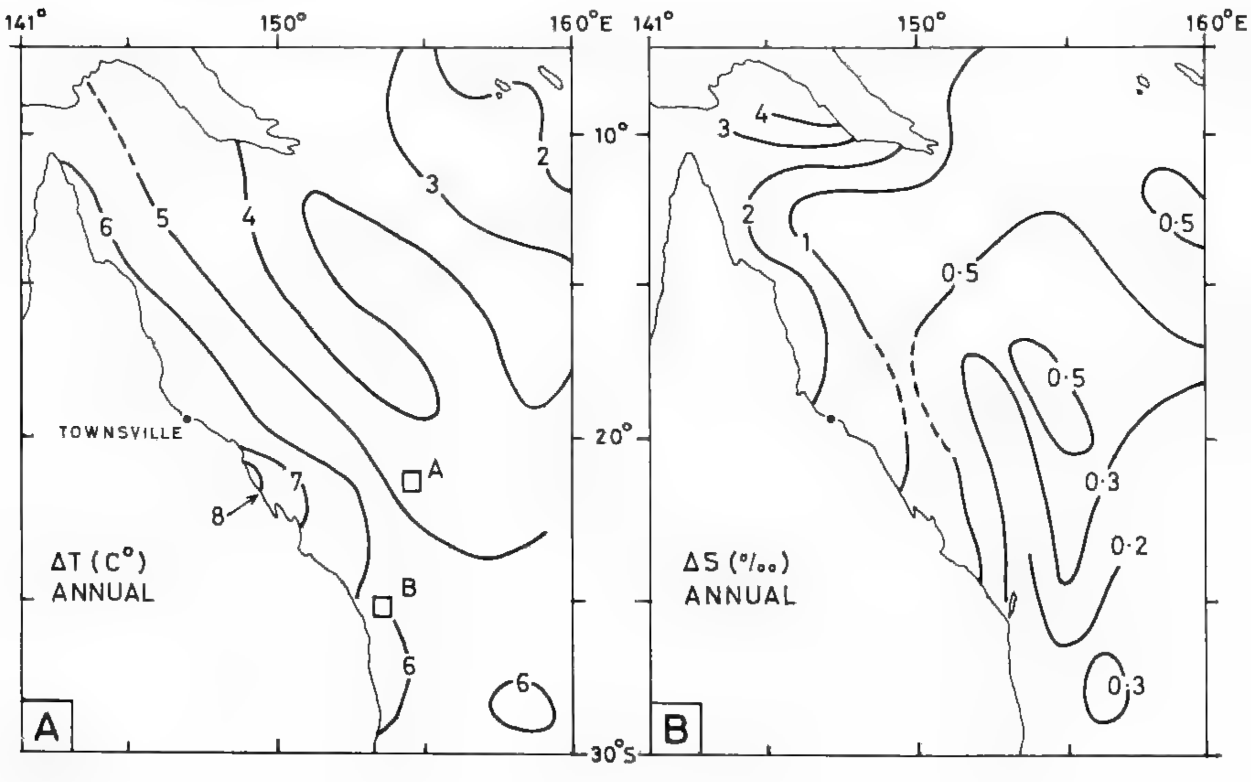
The daily temperature measurements at Willis Island reported by Hogan (1925) were taken over the reef structure at various stages of the tide and were reported to be affected by solar heating. Unfortunately, therefore, they are not likely to be of much value in describing short-term changes and are not summarised here.

Surface salinity—mean distribution

As no chart of mean surface salinity values with any detail in the WCS was available (the chart in Sverdrup *et al.*, 1942 has only the southern winter and that has only one isohaline for the whole of the WCS) one was prepared from the CSIRO Atlas in the same manner as for the temperature charts.

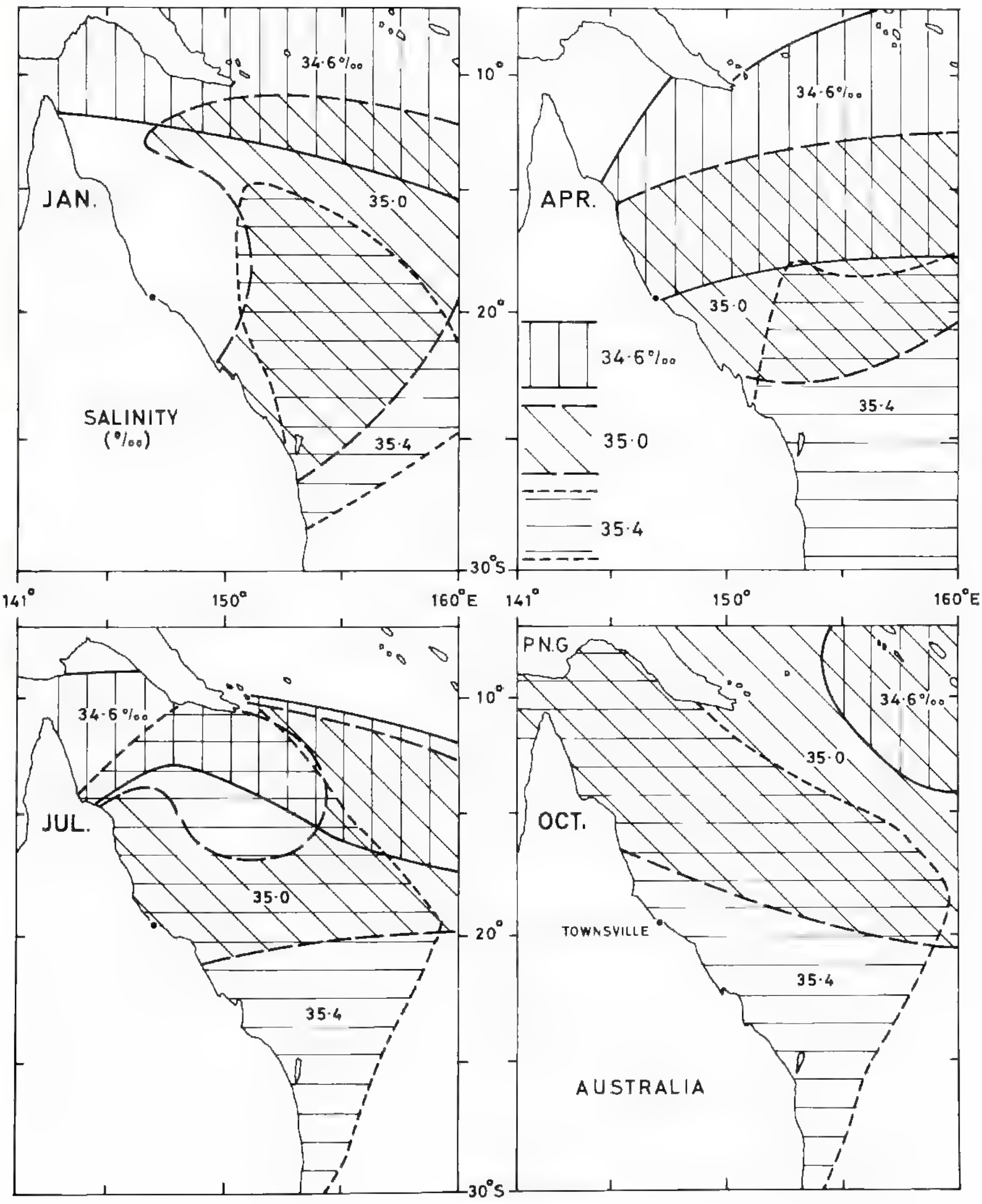
This indicated that the salinity values were mostly between 34.0 and 35.7 in the main body of the WCS with seasonal low values to less than 32 in the North-west Coral Sea. The values below 34 were usually recorded off Port Moresby in December to April. They may have been typical of the whole Gulf of Papua but there were insufficient observations in the Gulf to determine this. After April the minimum salinity in the WCS increased each month to about 34.5 in August then started to decrease again. The maximum value was usually 35.4 to 35.5 in the south-east corner of the WCS.

Fig. 38 Mean annual ranges of temperature (ΔT) and salinity (ΔS) in upper 5 m, Western Coral Sea (based on Rochford, 1973).



As for temperature, the positions of individual isohalines extended over very large areas during the nine-year period. Fig. 39 illustrates this, showing the areas of occurrence of three isohalines, 34.6, 35.0 and 35.4‰, representative of the bulk of the values observed. The mean positions of the isohalines are shown in Fig. 40, again to show the trend of seasonal variation rather than to specify geographic positions for mean monthly values. In the main body of the WCS and within the limitations of the scatter of the values, Fig. 39 shows that the salinity distribution for 35‰ and higher in the south-east half of the WCS is fairly steady, while most of the changes take place in the north-west half. One of the most obvious features is the occurrence of very low salinity water in the North-west

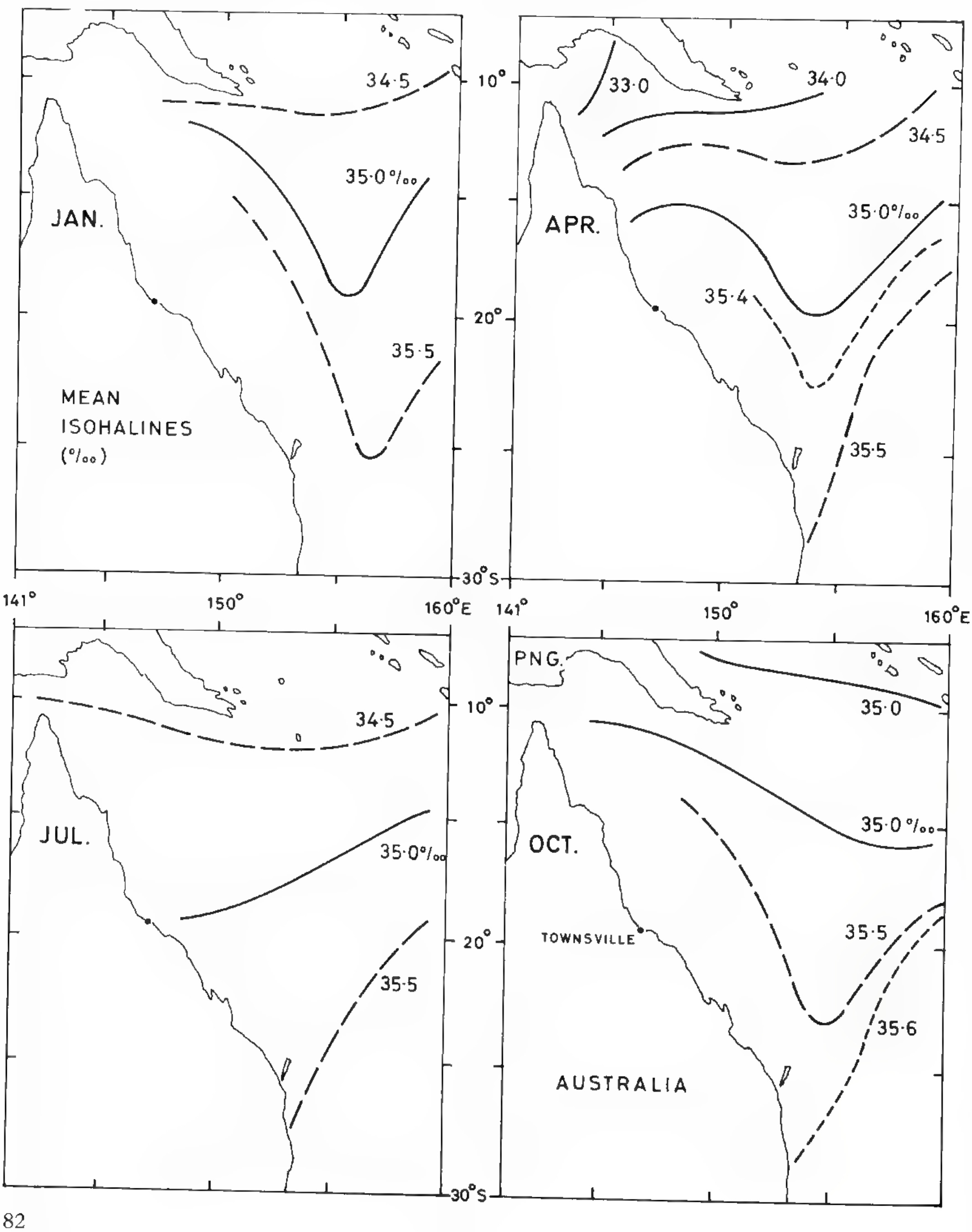
Fig. 39 Surface salinity, Western Coral Sea, areas of occurrence of 34.6, 35.0 and 35.4‰ water for January, April, July and October, 1966–1974 (data from CSIRO, 1974). See note to Fig. 35.



Coral Sea in the monsoon season, generally attributed to inflow from the west through Torres Strait coupled with runoff from the river system of Papua New Guinea. (The relative influence of the low salinity Arafura Sea water west of Torres Strait and of the fresh water from the rivers is not known yet, but further comments are offered in the section on Surface waters—Scully-Power.)

In the north-east sector, the lowest salinities occurred at the end of the monsoon season, e.g. April, Fig. 40. This has been confirmed in recent studies by Donguy & Henin (1975a) who showed that, for the four-year period 1969–73, a salinity minimum

Fig. 40 Surface salinity, Western Coral Sea, mean isohaline positions for January, April, July and October, 1966–1974 (data from CSIRO, 1974). See note to Fig. 36.



progressed south-east across the Solomon Sea (around 10 S, 155 E in Fig. 40), occurring in March at 7 S to May at 12 + S. Donguy & Henin demonstrated that this salinity minimum was the result of local rainfall associated with the development of the westerly (monsoon) winds in this region rather than of advection of low salinity water from the north of Papua New Guinea as had been thought previously.

The figures for mean salinity distributions derived from the CSIRO Atlas are believed to be the only ones available for the WCS. A similar comment to that for temperature is appropriate, i.e. for a description of the long-term environment Fig. 39 is most realistic, while Fig. 40 shows the character of the temporal variations rather more clearly. In addition, the earlier comments referring to Fig. 37 on the uneven area distribution of observations should be noted.

Less confidence should be placed in the significance of the isohalines of Fig. 40 than in the isotherms of Fig. 36, particularly for the January picture (Fig. 40) for which the north-eastward turn at the east end of the 35.0 and 35.5 isohalines is uncertain.

Rochford (1973), in his study of annual and longer term variations, showed that the annual salinity range (Fig. 38B) varied from more than 4 in the Gulf of Papua in the North-west Coral Sea to less than 0.3 in the south-east. The long-term salinity values showed a tendency to decrease by about 0.2 in six years off the Swain Reefs (area A in Fig. 38A) and a smaller decrease with time off Great Sandy Is. (area B, Fig. 38A). A conspicuous feature was a cycle with marked minima occurring at 2-year intervals at these two locations off the Queensland coast. The reasons for these long-term changes were not known.

Mean seasonal variations of surface temperature and salinity by areas

In an endeavour to better describe the local variations of surface properties with season, the Western Coral Sea was divided into six approximately '5 areas' as shown in Fig. 41. The mean surface temperature and salinity for each area (for the sea outside the Reef) was estimated by eye from the CSIRO Atlas for each month and the long-term mean for 1966–74 then calculated. The temperature/time and salinity/time curves are presented in Fig. 41A–D and the corresponding T,S, time curves are plotted in Fig. 41E, F from the smoothed curves above. (There were insufficient data for area A, Gulf of Papua, to plot any curves.)

It is evident that clear and similar variations with time occur in all areas, with differences mainly in the magnitudes. For temperature, the mean values and annual ranges are slightly higher in the eastern areas than in the western ones, while for salinity the eastern areas have slightly smaller ranges but essentially the same mean values as the western ones. Noticeable is the small range of salinity variation in area F.

It must be stressed that these are mean value curves. The average standard deviations about the monthly means were about ± 0.5C and ± 0.3, while each individual monthly value was a mean of a range of values within the '5 area'. These monthly ranges were from ± 0.5 to ± 2C and from ± 0.1 to ± 2 (occasionally in area B). It should also be noted that the T,S,t diagrams of Fig. 41 are not identical with those of Fig. 24 in Part 1, for which values were selected close to the Reef, not for the sea areas as a whole.

Sources of surface waters in the Coral Sea—Rochford

No water types are formed in the Coral Sea; thus the waters therein all come from external sources. In one of the first studies of the water masses in this area, Rochford (1959) analysed the surface characteristics in the Coral and Tasman Seas using T,S,f plots (T,S diagrams with the frequency of occurrence (f) of T,S combinations included to make the display semi-quantitative; Montgomery, 1955). Mean curves were drawn through the areas of most frequent occurrence of T,S combinations. (Rochford used chlorinity (Cl) in his paper, but for convenience this has been converted to salinity (S) by the current relationship S = 1.80655 Cl.)

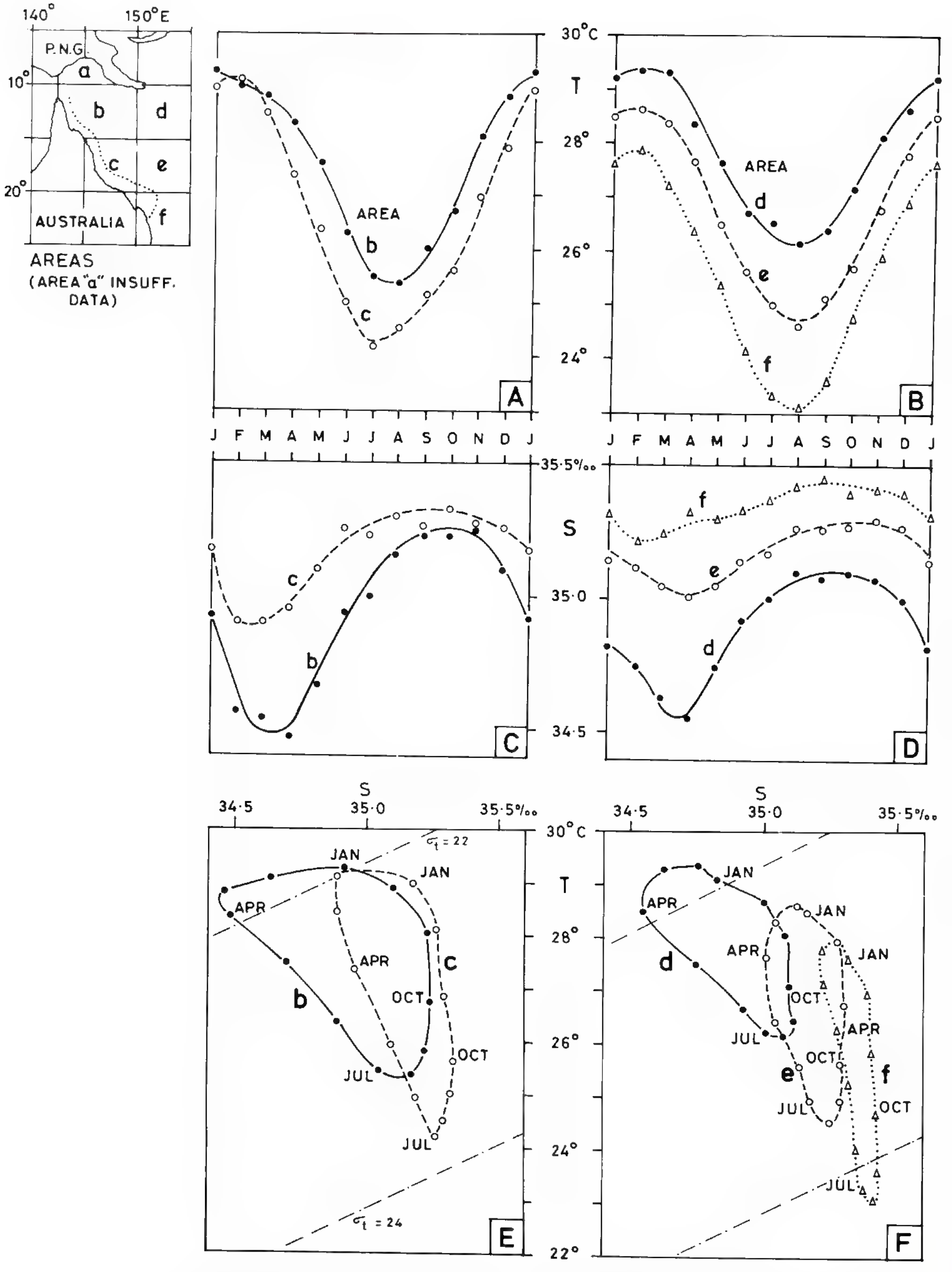


Fig. 41 Seasonal variations of surface water temperature and salinity, Western Coral Sea, by approximate 5 degree areas: (A,B) Temperature time, (C,D) Salinity time, (E,F) T,S, time diagrams (data from CSIRO, 1974).

Rochford made the basic assumption that the effects of local evaporation and precipitation were negligible compared with those due to advection; i.e. salinity was regarded as conservative even in the surface layer. The validity of this assumption is dubious in view of Taylor's (1973) figures for rainfall in the Coral Sea showing that precipitation is significant (1500 mm yr) and that the monthly amounts vary by a factor of five over the year. There is no information available on evaporation in the Coral Sea. Measurements or estimates would be very desirable.

Presumably Rochford also regarded temperature, i.e. heat content, as conservative but he made no mention of this. Most of the data available were from surface sampling from merchant ships, although these only travel along restricted lanes across the seas. For instance, in Rochford's area 9, which corresponds closely to the defined WCS, there was only one shipping lane, from Gt Sandy Is. to the south-east tip of Papua New Guinea, and only 24 samples per month on the average.

T,S,f plots and mean T,S curves were prepared by Rochford for four quarters (November–January, etc.). The general character of the mean curves is indicated in Fig. 42A which is an envelope of all the T,S curves with the Coral and Tasman Seas not differentiated. Rochford divided this envelope into three main zones: (1) above 28 C where there was little annual temperature change but considerable salinity change (presumably the north Coral Sea area), (2) from 28 to 19 C where salinity increased as temperature decreased, with greater annual changes of temperature than above 28 C, and (3) below 19 C where salinity decreased with decrease of temperature and where there were considerable annual ranges of variation (mostly Tasman Sea samples).

Rochford compared these surface T,S curves with vertical T,S curves for stations in the area between Australia and 155 W for winter (envelope in dashed lines in Fig. 42B) and summer (envelope in dashed lines in Fig. 42C). The mean surface T,S curves for the Coral Tasman Seas are shown in full lines in these figures and the latitude scales at the left give some indication of which parts of the surface T,S curves are pertinent to the present review of the WCS.

From these T,S curves Rochford determined three major and three minor water types, mixtures of which could produce the vertical or horizontal T,S curves of Fig. 42A, B, C. These types were identified as in Table 5. The major types and the Arafura Sea water are indicated on Fig. 42B, C by number. The two remaining water types (5 and 6) have not figured significantly as such in subsequent discussions of the Coral Sea waters.

Rochford's description of the surface T,S characteristics does indicate the probability of the four water types (1,2,3,4) referred to above being the main contributors to the Coral Sea surface waters. (It should be noted that the word water 'type' here does not imply a large volume of completely homogeneous water as represented by a point on a T,S diagram (Sverdrup's definition) but rather the *mean* temperature and salinity of a water body, it being understood that the range of values about the mean is small compared to the

Table 5. T,S characteristics of Coral Tasman Sea water types (from Rochford, 1959)

	Water Type	*Temperature* *(C)*	*Salinity* *( )*
Major:	1. South Equatorial (from N of 10 S)	28.2–28.8	34.7
	2. West Central South Pacific (from 15 –20 S, 150 W)	26.0	36.5
	3. Sub-Antarctic Surface (from S of 45 S)	9.0–11.8	34.7
Minor:	4. Arafura Sea	28 –29	34.1 or less
	5. Tropical high salinity	29 –30	35.6
	6. Temperate high salinity	20 –21	36.5 or more

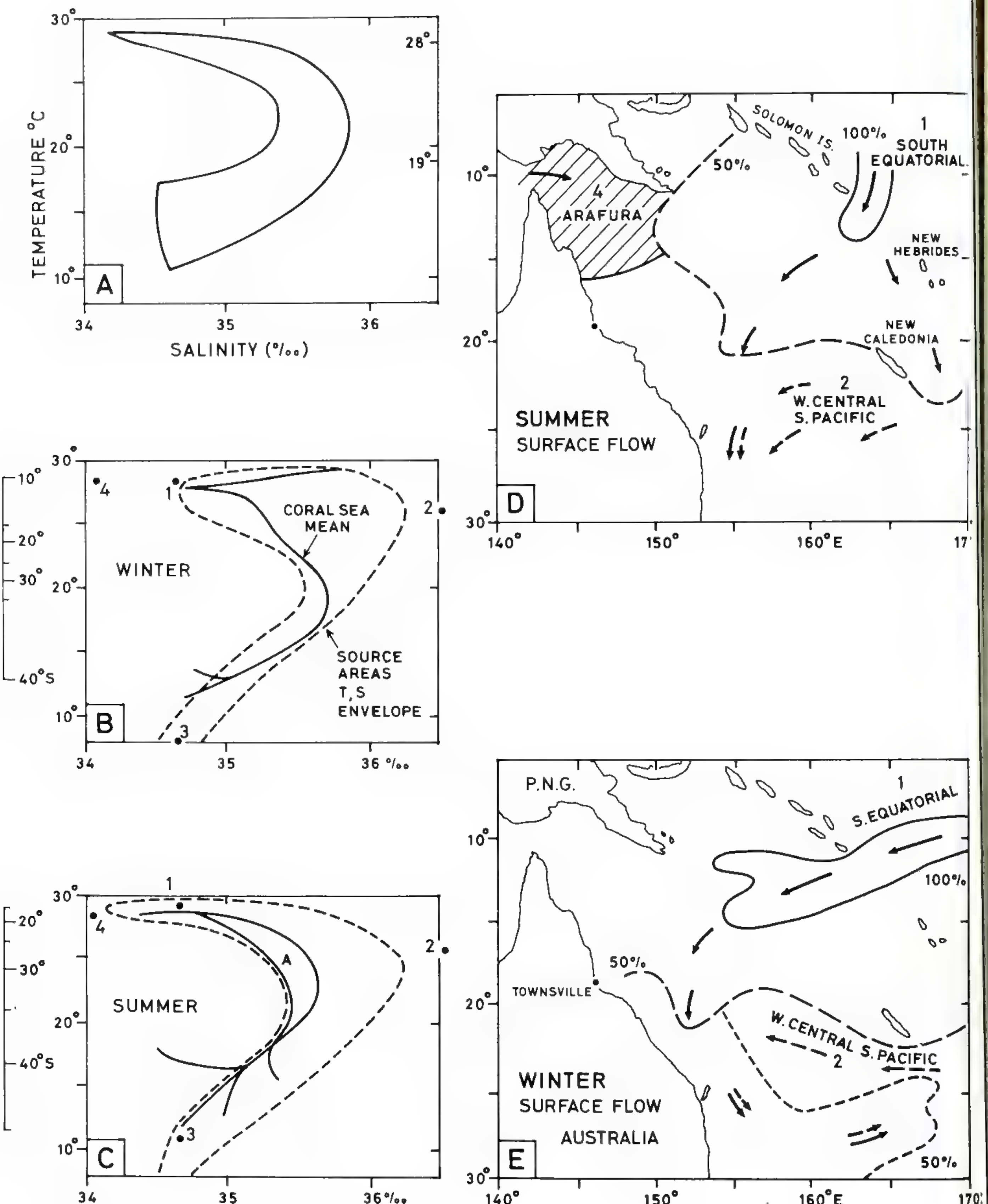


Fig. 42 (A) Envelopes of surface T,S values, Coral Sea,
(B) Full lines—mean surface T,S curves, winter, Coral Sea; dashed lines—envelope of vertical T,S curves for source areas; numbers four major water types contributing; (1) South Equatorial, (2) West Central South Pacific, (3) Subantarctic Surface, (4) Arafura Sea,
(C) As for (B) but summer,
(D) Summer, and (E) Winter flow patterns, for water types of (B). (All adapted from Rochford, 1959.)

differences between those of the water types contributing to the region.) Presumably for the WCS the two higher temperature types (1 and 2) would be the most important. (This is evident in Scully-Power's data (1973a) shown in Fig. 44.)

On this basis, Rochford then used the method of the mixing triangle (ref. Appendix) on the T,S diagram to determine the percentage of each of the three major external water types contributing to the make-up of each sample in the Coral and Tasman Seas and to deduce the surface flow patterns for the four water types as shown in Fig. 42D, E. In summer (Fig. 42D) the flow was primarily meridional except for some westerly flow of West Central South Pacific water at about 25 S. For late winter (Fig. 42E) the flow was chiefly zonal with a strong westward flow of South Equatorial water across 160 E into the Coral Sea and inflow from the south-east of West Central South Pacific water (and some outflow to the east at about 30 S of a mixture of these two waters). The mixture of South Equatorial and West Central South Pacific waters formed at about 27 S was called 'Coral Sea' water by Rochford. He did not specify the water characteristics in his paper but from his diagrams they would appear to be about 27 C and 35.6 . The Arafura Sea water was recognised in the North-west Coral Sea at this time and might be expected also to occur later (February to April).

Rochford also examined the total phosphorus content of the surface waters and considered that it could also be used as an identifying water property. In particular, he noted that the phosphorus content of the West Central South Pacific water was low (0.1 to 0.16 μg at/l) compared to that of the South Equatorial and Sub-Antarctic waters (0.65 to 1.0 μg at/l).

Surface waters—Scully-Power

The most systematic set of observations for the WCS was made by Scully-Power (1973a, b) for the winter period, between 4 May and 20 July 1968, when three cruises comprising 94 stations were completed. The station positions are shown in Fig. 43A. Because of the coherence of this data set and its coverage of the WCS, it will be discussed in some detail.

The surface temperature and salinity distributions are presented in Fig. 43A, B to show that a reasonably simple pattern may be present when the data are comprehensive and quasi-simultaneous (although the circulation did not appear to be simple: see later). These distributions resemble the very much smoothed mean distributions, Fig. 36 and 40, constructed from the CSIRO Atlas data.

The isotherm and isohaline patterns were similar except for the feature due to a low salinity at one station in the Gulf of Papua. The surface density pattern was very similar to the surface temperature pattern, σ_t values increasing from 22 in the north-west to 25 at the south.

The T,S and S,O_2 diagrams for the surface waters showed small scatter (Fig. 44, full lines), the surface T,S values being almost all within the envelope of vertical T,S curves for the WCS (dashed line).

Scully-Power discussed the low-salinity waters in the North-west Coral Sea (area *ab* in Fig. 44) and suggested that continuing river runoff into the north-west Gulf of Papua was probably the major factor but that there might also be pockets ('clouds' would be a better word) of Arafura Sea water still present from the NW monsoon inflow through Torres Strait. No figures are at hand for the runoff of the extensive river system of Papua New Guinea which empties into the north-west Gulf of Papua but it is noted (Brookfield & Hart, 1966) that there are some curious features of the rainfall around the Gulf. At Daru (Fig. 28) the maximum rainfall period is from January to April (57% of the annual total) whereas from about 143.5 to 146 E, as typified by Kikori, the maximum is later (May to September), when 56% of the annual total falls. To the east of 146 E the pattern reverts to a January to March maximum. The annual total at Kikori is 5760 mm compared to 2075 mm at Daru, and 995 mm at Port Moresby. The high rainfall area extends inland

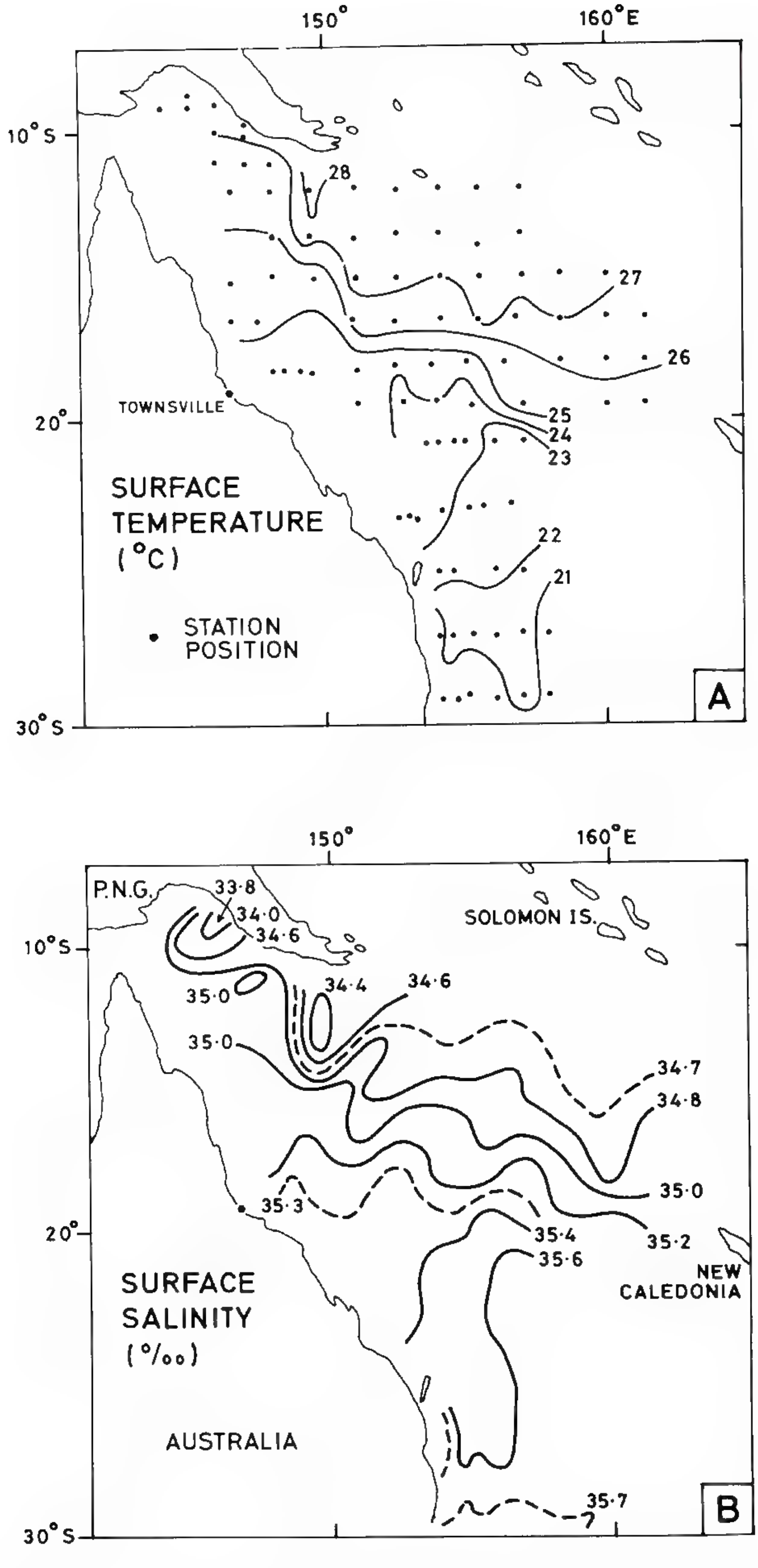


Fig. 43 (A) Surface temperature and (B) surface salinity, Western Coral Sea, May-July, 1968 (Scully-Power, 1973a).

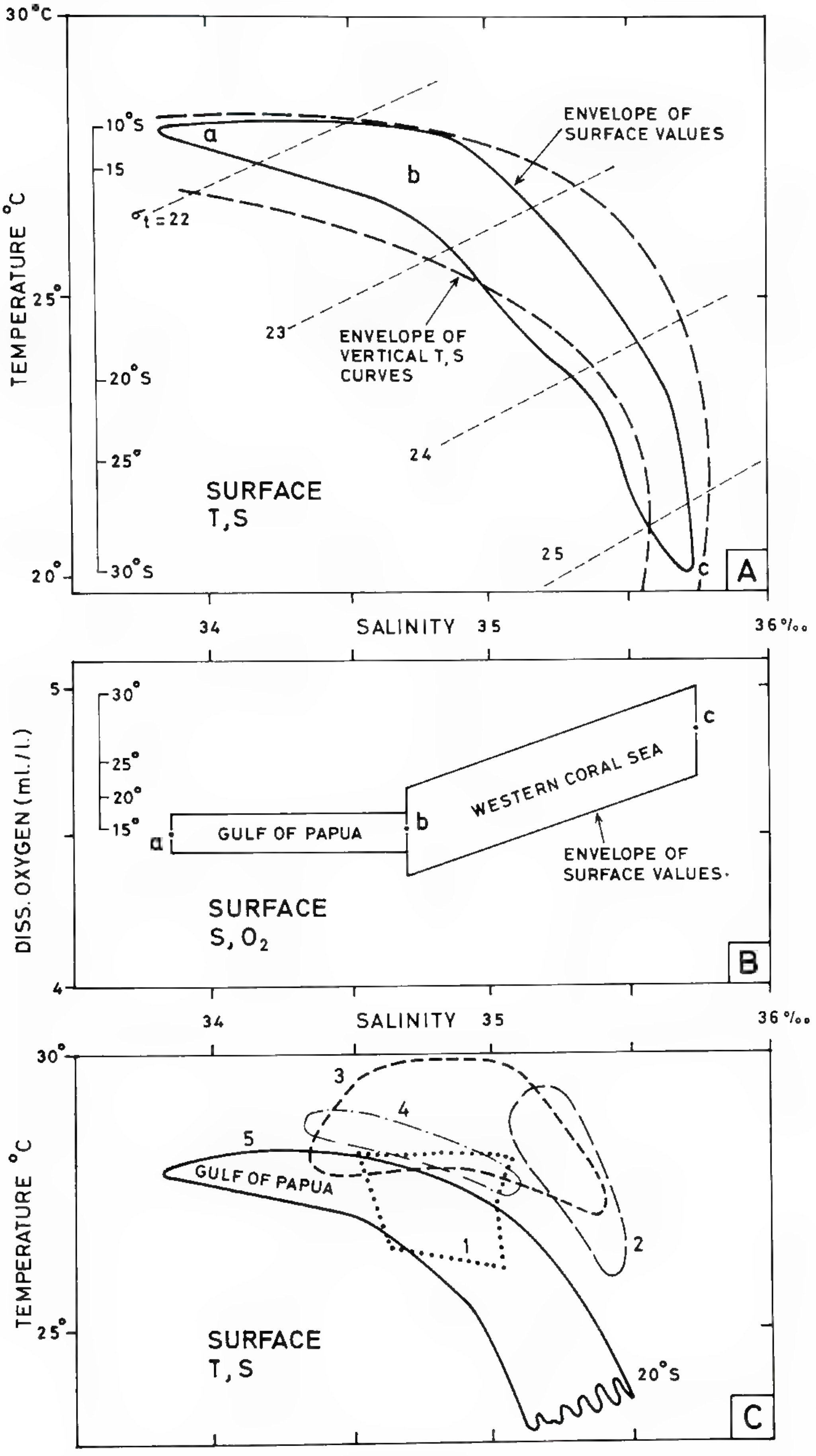


Fig. 44 (A) T,S and (B) S,O_2 diagrams for surface waters, Western Coral Sea, May–July, 1968 (Scully-Power, 1973a),
(C) Comparison of surface T,S characteristics for several cruises in the Western Coral Sea: (1) *Shoyo Maru*, Oct.–Nov. 1973, (2) 'Gorgone 1', Nov.–Dec. 1972, (3) 'Iule', Jan. 1965, (4) 'Gorgone 2', May–June 1975, (5) R.A.N.R.L., May–June 1968.

along a strip lying at about 300 true from Kikori. These differences in rainfall pattern along the north side of the Gulf of Papua are remarkable in the relatively short distances and may be responsible for some of the peculiarities of salinity patterns which have been noted in this area (e.g. CSIRO Atlas, April 1969, May 1972, etc.).

Water of type *b* (Fig. 44A, B) was identified as South Equatorial (surface) water (Rochford, 1959), while type *c* was identified as basically the southern component of Subtropical Lower water.

The distribution of properties at the surface was consistent with a westward flow into the Coral Sea north of about 19 S, with most of the flow turning north on approaching the Barrier Reef, the division being at about 19 S also. This flow pattern agreed with the geostrophic circulation discussed later.

(Data from a May 1972 R.A.N.R.L. cruise in the North-west Coral Sea are currently being studied—personal communication, P. D. Scully-Power.)

Other surface data in seasonal sequence

Envelopes of surface T,S characteristics for five cruises which covered substantial areas of the WCS (i.e. more than a single line of stations) have been assembled in Fig. 44C for comparison. The cruises used are listed below and the areas covered are shown in Fig. 45A, B:

Spring : Curve 1 — *Shoyo Maru*, Oct.–Nov. 1973 (Far Seas Fish. Res. Lab., 1973),

Summer ; Curve 2 — 'Gorgone 1', Nov.–Dec. 1972 (Donguy *et al.*, 1972b, NODC 350077; only stations west of 159 E and south of 11 S used),

Curve 3 — 'Iule', Jan. 1965 (O.R.S.T.O.M., 1965, unpublished data, NODC 350081),

Winter : Curve 4 — 'Gorgone 2', May–June 1975 (O.R.S.T.O.M., 1975, unpublished data; only stations west of 159 E and south of 11 S used),

Curve 5 — R.A.N.R.L., May–July 1968 (Scully-Power, 1973a; only stations north of 20 S used).

For temperature there is some indication of a seasonal change, the January cruise (curve 3) having the highest temperatures. However, it is by no means clear-cut as the 'Gorgone 2' and R.A.N.R.L. cruises (curve 4 and 5) were at about the same time of year (winter) but the former show higher temperatures by about 1.5 C .

For salinity, the shaded, low-salinity part of the R.A.N.R.L. data envelope (curve 5) was for the waters of the typically low salinity Gulf of Papua, further north-west than any of the other cruises. The difference in salinity between the two 'Gorgone' cruises may be attributed to the different seasons, 'Gorgone 1' (curve 2) being at the end of winter (high salinity period) while 'Gorgone 2' (curve 4) was after the wet season when low salinities are now known to occur systematically in the Solomon and north Coral Seas due to local rainfall (Donguy & Henin, 1975a). In addition there may also be some effect due to possible year-to-year variations.

The larger range of salinity for the R.A.N.R.L. cruise was probably because this penetrated further into the low salinity Northwest Coral Sea, but the lower temperature for the R.A.N.R.L. cruise is probably indicative of year-to-year changes because the two envelopes are entirely separate in the temperature direction despite the fact that the two cruise areas overlap between 12 and 20 S. This emphasises (as has been shown already) that year-to-year variations in the surface layer characteristics can be significant.

Speed of movement of water masses—Rochford

Fig. 41 shows that the lower salinity (South Equatorial) water moves south in the summer. Rochford (1973) gave two examples of estimates of the speed of southward

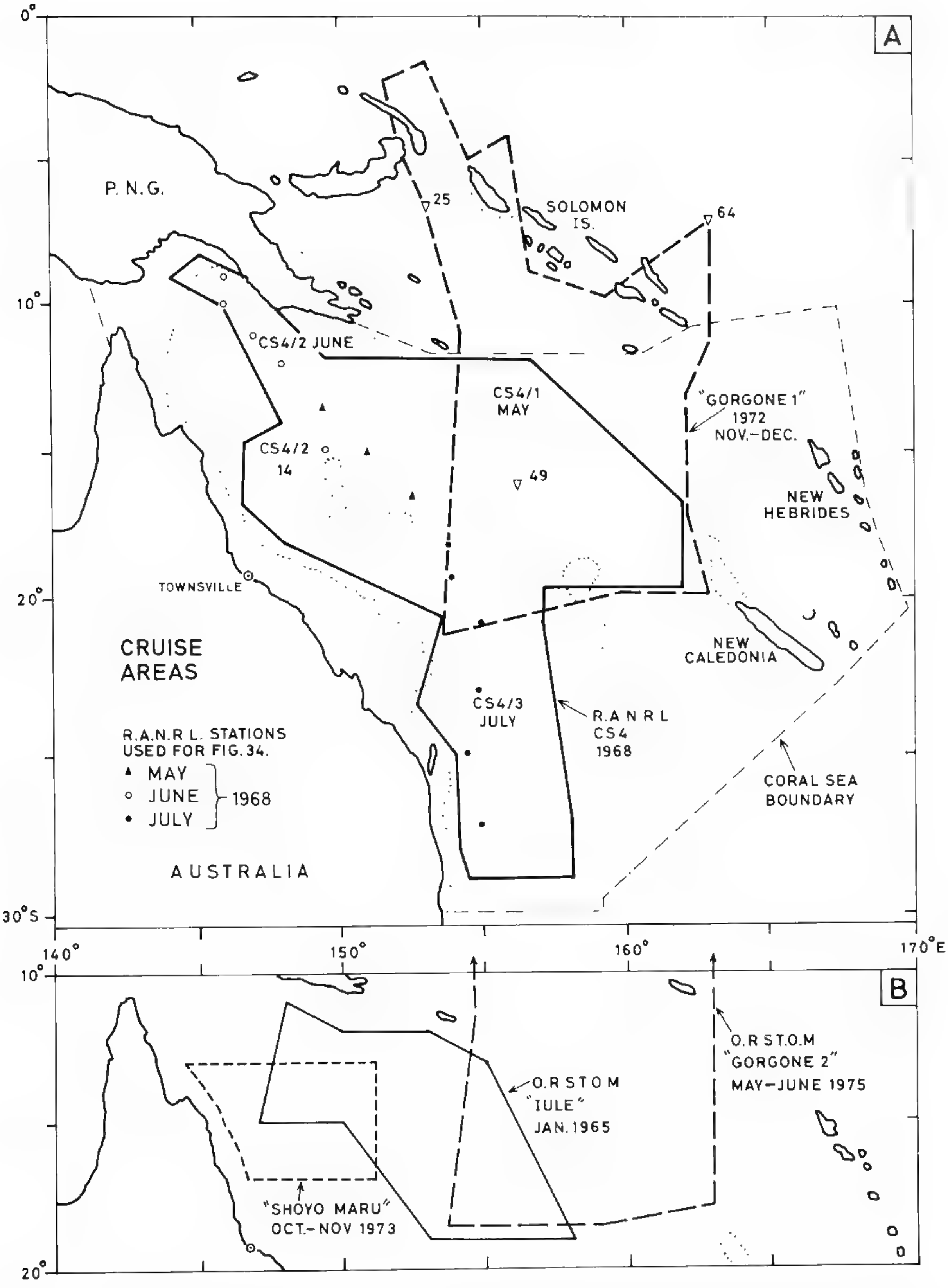


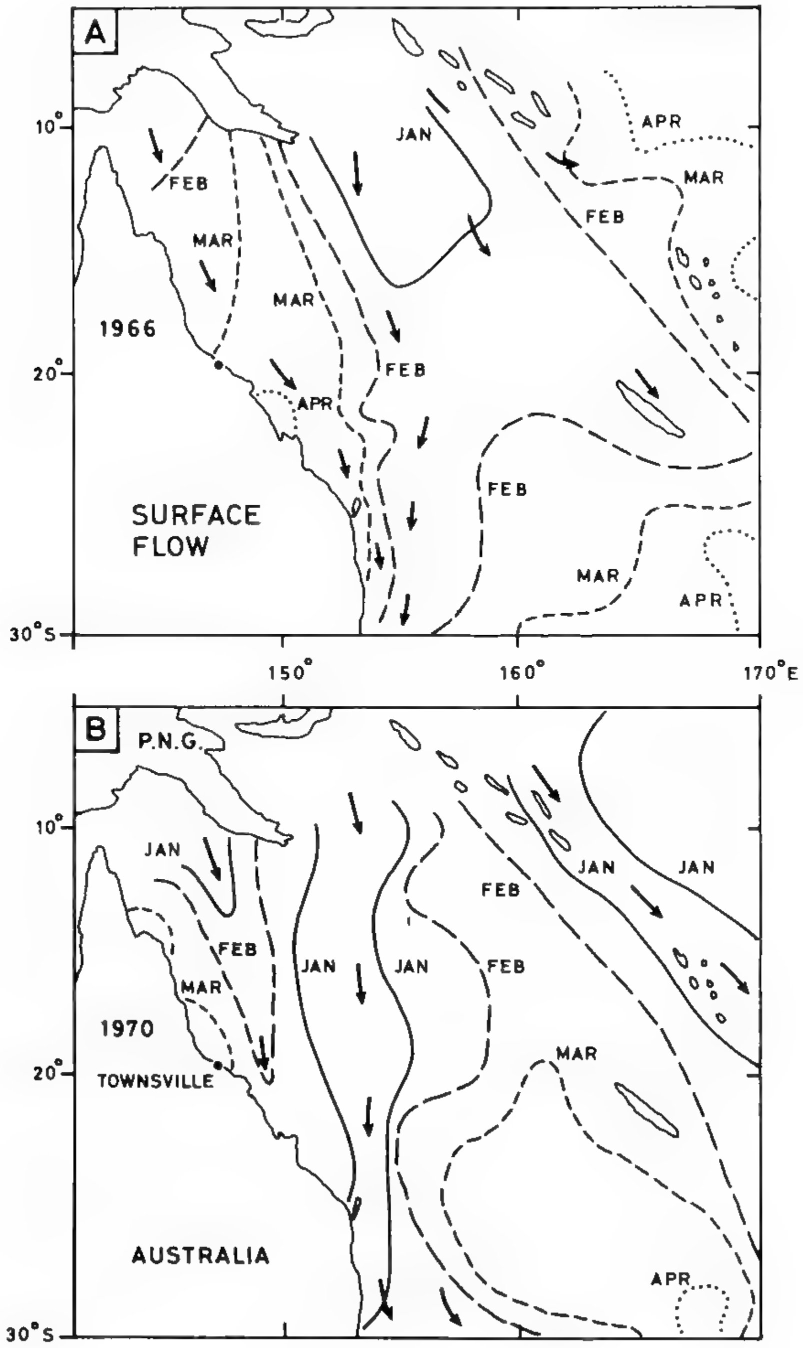
Fig. 45 Cruise areas, Coral Sea: (A) R.A.N.R.L. Cruises CS4 1, 2, 3, May–July 1968 and locations of stations for Figs. 32 and 33 (Scully-Power, 1973a), O.R.S.T.O.M. 'Gorgone 1' cruise, Nov. Dec. 1972 (Rougerie & Donguy, 1975), (B) O.R.S.T.O.M. 'Iule' cruise, Jan. 1965; *Shoyo Maru* cruise, Oct.–Nov. 1973; O.R.S.T.O.M. 'Gorgone 2' cruise, May June 1975.

penetration of this water from the southward advance of lower salinities in successive months on the CSIRO Atlas plots. Fig. 46 shows these estimates for January to April 1966 and 1970. They yielded speeds of the order of 22–44 km/day or 6 to 12 degrees of latitude/mo along the main flow directions and about 4 km/day perpendicular to the main flows.

Mixed layer depth

Because there is often a wind-mixed layer in the Coral Sea of depth comparable to those of the passes through the Great Barrier Reef (less than 100 m), the surface water characteristics may often be sufficient to characterise the WCS waters when considering exchange between the Sea and the Lagoon. Therefore the mixed layer depth was

Fig. 46 Southward progress of low salinity (South Equatorial) water in the Western Coral Sea in January–April, 1966 and 1970 (Rochford, 1973).

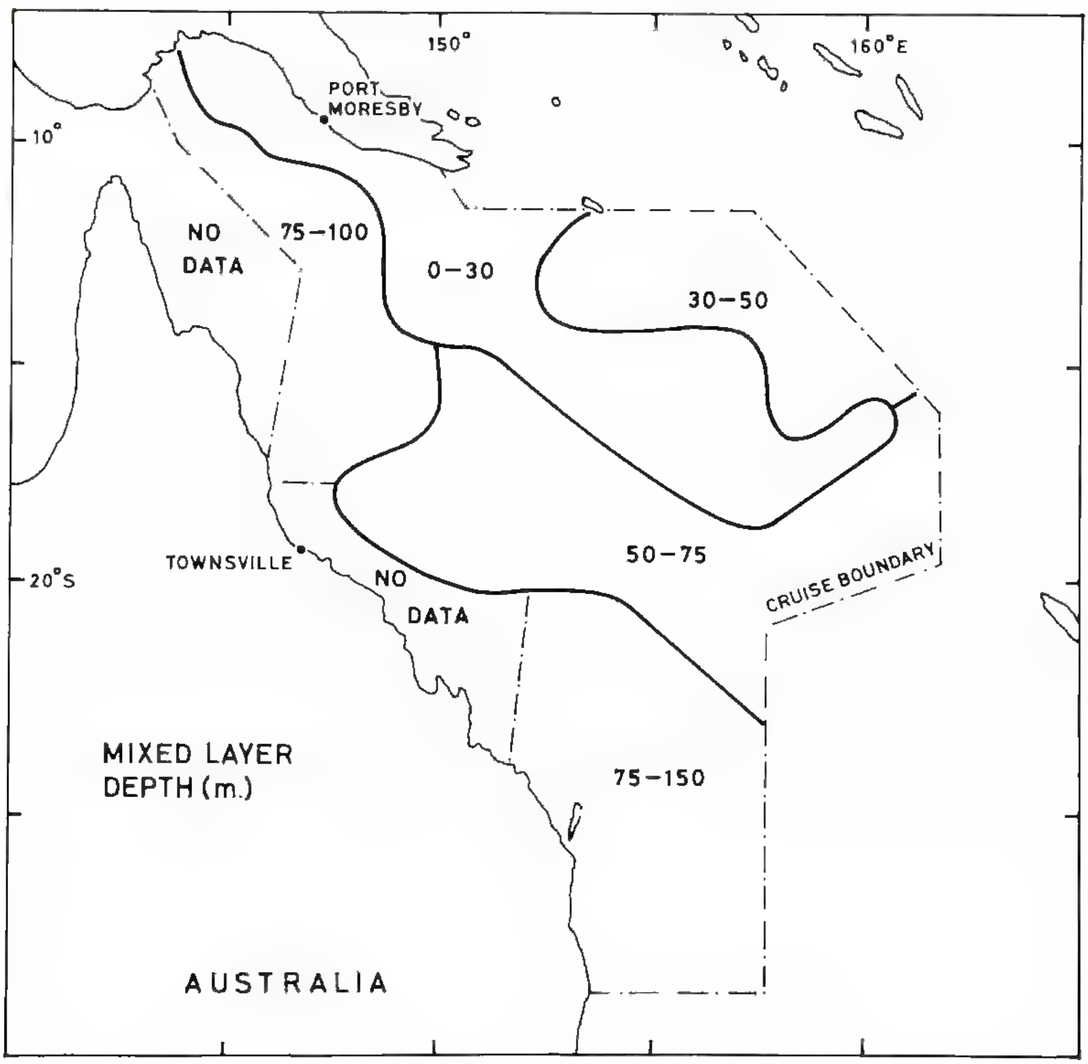


estimated from the R.A.N.R.L. 1968 cruise records (Scully-Power & France, 1969a, b, d) and plotted on a chart; an attempt was made to contour this feature. No simple pattern was found, if the rules of contouring were followed strictly, because of the sharp changes between some pairs of stations. A broad look at the field of values resulted in Fig. 47, which indicates that the mixed layer was deepest near the Reef and shallowest along a line south-east from the Gulf of Papua. Wind speeds during the three cruises varied from 2 to 15 m/s and averaged 6 m/s. No significant correlation between layer depth and wind speed was found.

An earlier R.A.N.R.L. cruise in November–December 1966 (Scully-Power, 1969a) between Cairns and Papua New Guinea indicated mixed layer depths of 20 to 70 m, which were smaller than the 1968 values on the direct line between Cairns and Port Moresby but greater to the east of this. In April–May 1967 (Scully-Power, 1969b) in the same area, values north of 12° S were between 0 and 25 m while at 13° and 14° S they were 20–35 m. Winds were from 2.5 to 9 m/s during the 1966 cruise, and 4 to 6 m/s at those stations where it was recorded in 1967.

For the O.R.S.T.O.M. 'Gorgone 1' cruise in the Central Coral Sea in November–December 1972 (Donguy *et al.*, 1972b), the shallowest sample below the surface was taken at 50 m nominal depth and only at one or two stations was there any indication of a mixed layer reaching to this depth. This is consistent with Scully-Power's data in the region of overlap (see Figs. 47 and 4).

Fig. 47 Surface mixed-layer depth, Western Coral Sea, May–July 1968 (data derived from Scully-Power & France, 1969a, b, c).



The *Shoyo Maru* (Far Seas Fish. Res. Lab., 1973) made 75 bathythermograph casts in an area 13–17° S, 144–151° E (north-east of Cairns) in October–November 1973, the temperature values being reported at 25 m intervals from the surface. From these it appeared that the mixed layer depth varied from 0 to 50 m, the values along the Reef being 0–25 m. The wind speed was mostly from 4 to 12 m/s and there was some indication of greater mixed layer depths being associated with greater wind speeds.

One concludes that, as for other characteristics, the mixed layer depth is very variable in the WCS.

SUBSURFACE WATER MASSES AND FLOW PATTERNS

Introduction

The main contributors to the study of the subsurface water masses in the Western and Central Coral Sea have been Rochford (using isentropic analysis), Wyrtki and Scully-Power (core analysis), and Rougerie & Donguy (isentropic analysis). Papers by these authors will be discussed substantially in chronological order.

Isentropic analysis—Rochford

The 27.2 σ_t surface. Rochford (1960a) discussed aspects of intermediate depth waters on the 27.2 σ_t surface, which is at 700 to 900 m depth in the WCS and near the core of the Antarctic Intermediate water. When considering this paper it should be noted that the region north of 25° S and west of 162° E (i.e. an area greater than the entire WCS) was represented by only one line of 10 stations (*Umitaka Maru*, 1959, unpublished, and one *Planet* station) at about 156° E. For these stations, on this surface, the temperature was close to 6° C, salinity was about 34.45 ‰, dissolved oxygen increased from about 3.7 ml/l in the north of the line of stations (mid-WCS) to 4.05 ml/l in the south, and phosphate-P increased from 1.8 to 2.05 μg at/l from north to south.

For the analysis of waters on the 27.2 σ_t surface, Rochford placed considerable emphasis on S,PO_4 relations and identified three water types as:

	Salinity (‰)	*Phosphate-P* (μg at/l)
(7) Pacific Equatorial Intermediate	34.60	3.10
(8) South-west Pacific Intermediate	34.70	0.50
(9) Antarctic Intermediate	34.02	1.88

He contoured the percentages of each on the 27.2 σ_t surface using the mixing triangle method. The result showed water type 7 entering the WCS from the north through the Solomon Sea, type 8 from the north-east between the Solomon Islands and New Caledonia, and type 9 chiefly from the east by the same route (but entering the Tasman Sea from the south). The major outflow from the Coral Sea on this surface was to the south along the Australian coast (East Australian Current).

The 25.0 σ_t surface. Rochford (1969) averaged salinity and oxygen data by 5° squares for the south-west Pacific (0°–50° S, 140° E–160° W) to study the origin and circulation of water types on the 25.0 σ_t surface which is close to the core depth of the Subtropical Lower water. He identified four types (essentially subdivisions of this water) as:

Type	*Name*	*Salinity* (‰)	*Oxygen* (ml/l)	*Origin*
A	: Tropical high salinity	36.00	3.50	Central South Pacific
A′	: Tropical low salinity	35.25	3.10	North Equatorial Pacific
B	: Subtropical high salinity	35.75	5.15	Central Tasman Sea
B′	: Subtropical low salinity	35.46	5.15	West of North N.Z.

North of 15° S, types A and A′ drifted west near the equator but east around 20° S; south of 35° S, types B and B′ drifted east and north. Types A and A′ were essentially the northern component of the Subtropical Lower water, while types B and B′ were southern component waters.

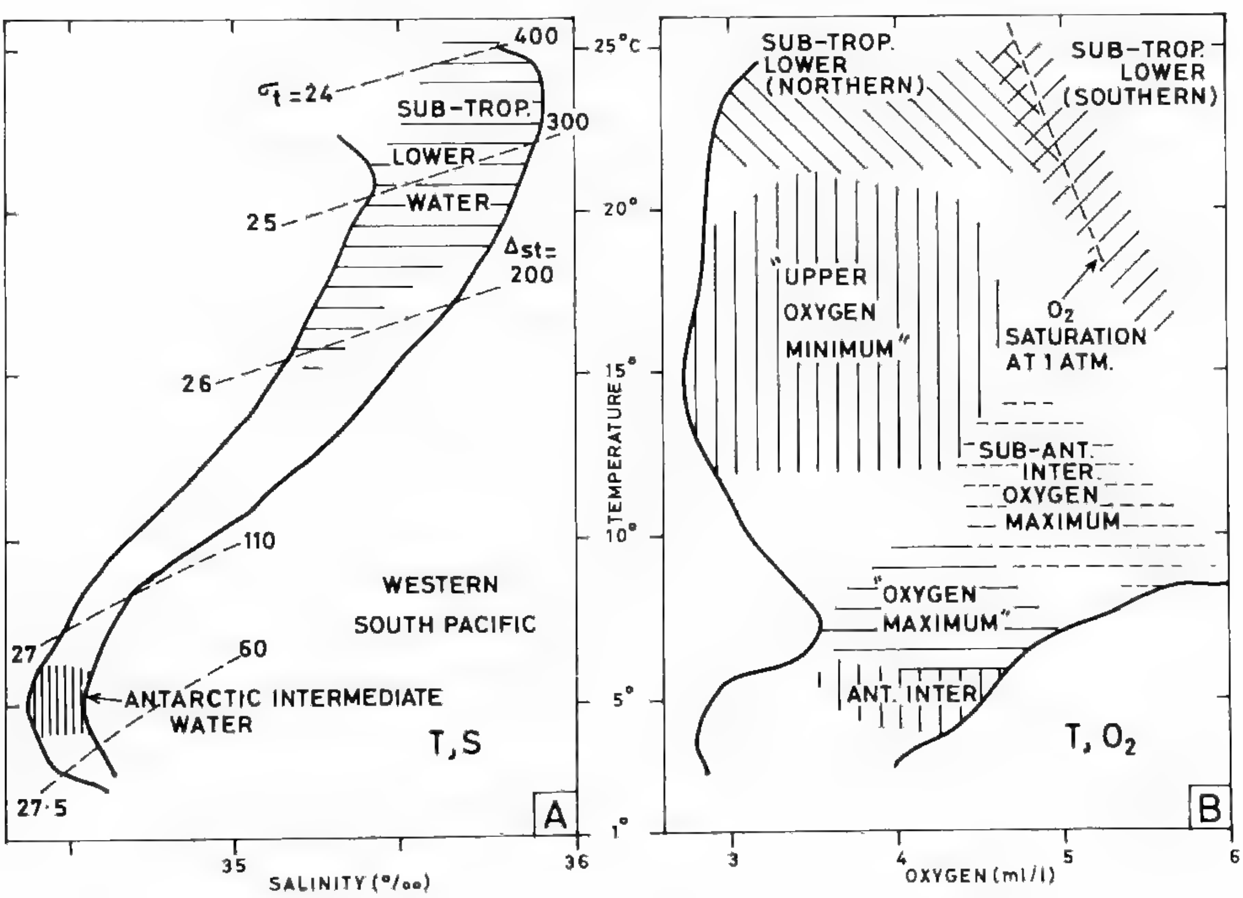
A comparison of winter and summer values was possible in some areas and indicated that:

(a) tropical waters (A,A′) drifted south along the Australian coast in the summer to winter period;
(b) subtropical waters (B,B′) drifted north into the Central Coral Sea in the winter to summer period.

Core layer analysis—Wyrtki

Wyrtki (1962a) carried out a core layer analysis using fairly homogeneous data from CSIRO *Gascoyne* cruises in 1960 and 1961 in the area between the Australian coast, New Zealand, Fiji and the Solomon Is. supplemented by the *Umitaka Maru* data for 1959 for the east edge of the WCS as used by Rochford (1960a, b) and also some *Orsom III* data south-east of New Caledonia (Rotschi, 1960c). Current nomenclature for the subsurface waters in the Coral Sea, as used in the introductory paragraph and subsequently, is based on this paper by Wyrtki.

Fig. 48 (A) T,S and (B) T,O_2 diagrams for Western South Pacific waters (adapted from Wyrtki, 1962a).



Wyrtki used T,S and T,O_2 diagrams for his analysis. Fig. 48A is a simplified version of his T,S diagram for the salinity core-layers, replacing the original station points with general shading to indicate concentrations of points, and omitting the deep and bottom water points. Fig. 48B simplifies his T,O_2 diagram in a similar manner. From these and other characteristic diagrams Wyrtki distinguished three main water masses in the upper 1100 m. Using the T,S diagram he identified;

(10) Surface water: T > 24 C, S from 34.0 to 35.6 , σ_t from 24.0 to 25.5 (discussed by Rochford, 1957–1959, and not discussed in Wyrtki's paper or included in his T,S diagrams),

(11) 'Subtropical Lower' water: Salinity maximum, T from 18 to 25 C, S from 35.5 to 36.0 , core depth 50 to 150 m in the WCS,

(12) 'Antarctic Intermediate' water: Salinity minimum, T from 4.2 to 6.0 C, S from 34.37 to 34.53 , core depth 700 to 1000 m in the WCS.

The T,O_2 diagram revealed further features of the water masses:

(a) The Subtropical Lower water clearly subdivided into a lower oxygen component (3 to 4 ml/l) at stations in the northern part of the region where the salinity maximum was below the surface ('northern component' of the Subtropical Lower water), and a higher oxygen component (above 4.4 ml/l) from subsurface and surface levels and found at stations further south ('southern component' of the Subtropical Lower water),

(b) between 24 and 12 C, below the Subtropical Lower water, a layer of minimum oxygen in the vertical was found (the 'Upper Oxygen Minimum'),

(c) between 10 and 5.5 C was a layer with maximum oxygen in the vertical ('Oxygen Maximum').

Wyrtki argued that the oxygen minimum was formed *in situ* by biochemical reduction, thus qualifying it as a separate water mass, but that the oxygen maximum resulted simply from vertical mixing of the lower part of the Antarctic Intermediate water with low oxygen water below it, and therefore did *not* qualify as a separate water mass.

Examining the distribution of properties on the core layer of the upper salinity maximum (Subtropical Lower water), Wyrtki showed that two salinity maximum (>35.9) water masses were apparent, one entering the Coral Sea from the east in the vicinity of the New Hebrides and the other via the Tasman Sea between New Caledonia and New Zealand (Fig. 49A). The oxygen content in this core showed low values (~ 3.2 ml/l) associated with the northern salinity maximum and high values (5 ml/l) with the southern salinity maximum (Fig. 49B). The salinity and oxygen distributions suggested that the boundary between these two maxima lay approximately along 20 S to the north of New Caledonia and thence west-north-west toward the Gulf of Papua. The core layer of the northern component sloped upward from about 150–200 m in the northern Coral Sea (Fig. 49A). The southern component was at the surface at about 30 S in the Tasman Sea and sloped down to about 100 m at 20 S. Wyrtki then identified the source of the Coral–Tasman Seas Subtropical Lower water as the Subtropical Surface Water of the South Pacific formed between 15 and 25 S, 100 to 150 W whence the southern component flowed west between 23 and 33 at the surface, retaining its high oxygen content, while the northern component sank and spread to the west north of 23 S, oxygen being consumed *en route*. The above remarks refer to the Subtropical Lower *core* layer. Wyrtki suggested using 35.0 as limits to enclose, above and below, the Subtropical Lower water *mass*. With this definition, the southern component would extend from the surface to 400 m depth and the northern from 50 to 300 m. Such relatively shallow masses would be expected to follow the surface circulation and Wyrtki considered that the general movements of the Subtropical Lower water inferred above

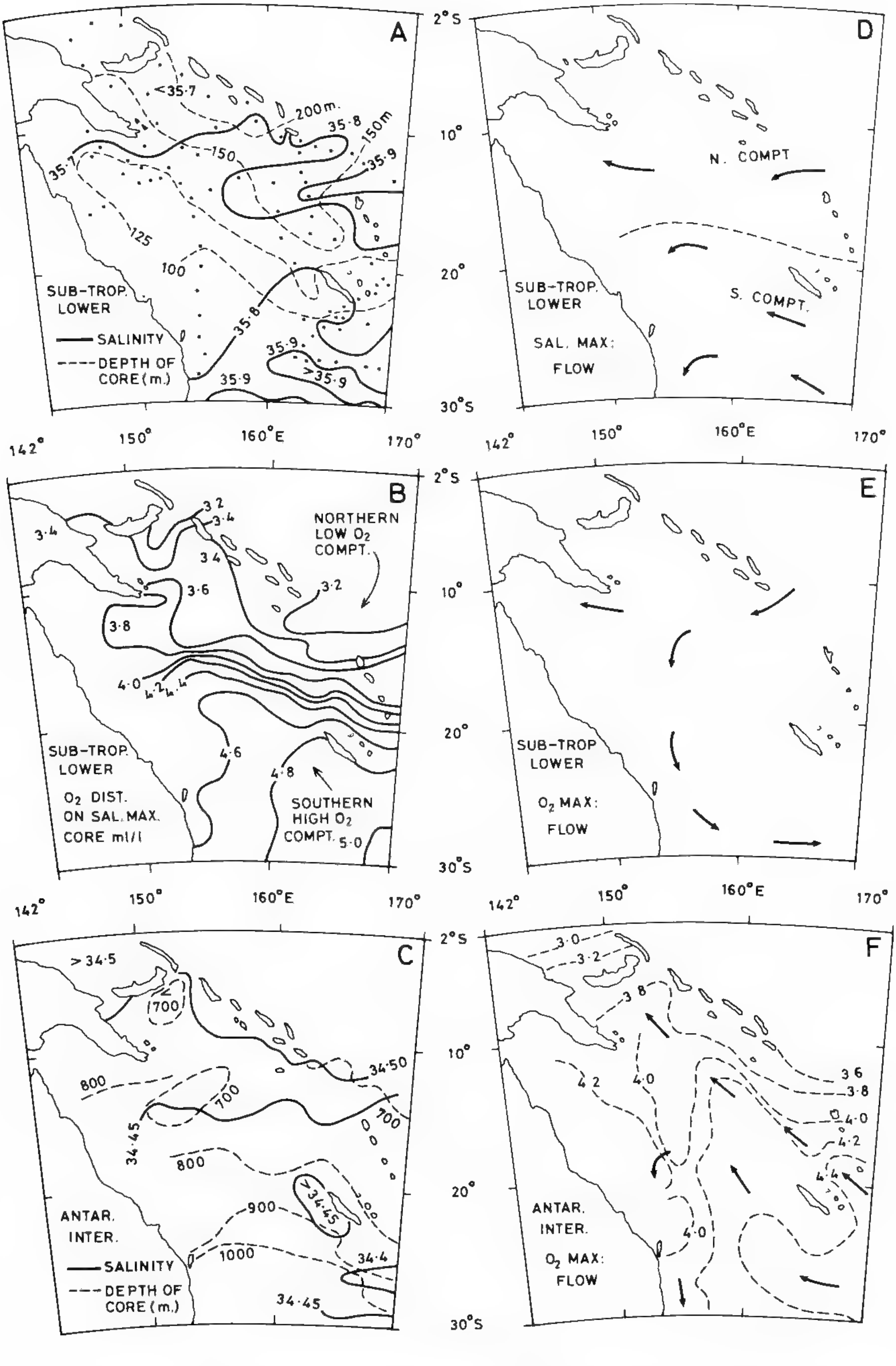


Fig. 49 Coral Sea property distributions and flows: (A) and (D) Subtropical Lower salinity maximum core layer, (B) and (E) oxygen distribution in salinity maximum core, (C) and (F) Antarctic Intermediate salinity minimum. Dots represent station positions (Wyrtki, 1962a).

(Fig. 49D) were in accord with his description of the surface circulation (Wyrtki, 1960, and in the surface circulation section following).

Wyrtki showed that the flow of the oxygen minimum water mass between 150 and 500 m (< 3.0 ml l in the north and 4.4 ml l in the south), shown in Fig. 49E, was similar to that of the salinity maximum above it. The next core, the oxygen maximum above the salinity minimum, was not regarded as a separate water mass, as explained above, and no effort was expended in tracing its movement.

Wyrtki next examined the salinity minimum layer, the Antarctic Intermediate water. An interesting feature of this water mass was that the greater part entered the Coral Sea not from the south but from the east, between the New Hebrides and New Zealand (Fig. 49F). This was evident both from the salinity distribution (Fig. 49C) and from the oxygen distribution at the level of the salinity minimum (Fig. 49F), with values of 4.4 ml/l on entry north and south of New Caledonia decreasing to 3.8 ml l in the Solomon Sea. The depth of the core decreased from 1000 m near 30 S to 700 m in the northern Coral Sea (Fig. 49C). (Rochford, 1960a, had shown a similar distribution in his discussion of properties on the 27.2 σ_t surface which is close to the salinity minimum core.)

In summary, Wyrtki listed the properties of the subsurface water masses. The values relevant to the WCS are presented in Table 6.

Table 6. Properties of subsurface water masses in the Coral Sea

Water Mass	*Feature*	*T(°C)*	*S(‰)*	*O_2 (ml/l)*	*Depth (m)*
Subtropical					
Lower	S max.				
Northern Compt.	(lower O_2)	21–24	35.7 –35.95	3.2–4.2	125–150
Southern Compt.	(higher O_2)	18–25	35.75–35.85	4.5–5.2	50–125
Upper Oxygen Minimum	O_2 min.	12–21	34.9 –35.9	2.7–4.6	150–300
Antarctic Intermediate	O_2 max.	5.4–9.0	34.4 –34.8	4.0–4.7	500–900
	S min.	4.2–6.0	34.42–34.47	3.9–4.4	700–1000

Continuity of water masses along the western boundary of the Tasman and Coral Seas—Rochford

Bearing in mind the limited number of stations on which Wyrtki's (1962a) study above was based, it is interesting to review Rochford's (1968a) description of the water masses along the Australian coast, using a few more stations. The station positions (predominantly for the summer season) are given in Fig. 50A which shows the isohalines in the core layer of the Subtropical Lower water in the WCS and the oxygen distribution by shading. The arrows show Rochford's interpretation of the flow, on the assumption that the oxygen gradients were too high to be the result of local consumption but must be maintained by flow. The 'oxygen poor' water may be identified as Wyrtki's northern component of the Subtropical Lower water and the 'oxygen rich' water as the southern component.

The depth of the salinity maximum layer increased from about 140 m in the North-west Coral Sea to 200 m at 20–25 S before rising to the surface at about 30 S. Wyrtki (1962a) showed the layer rising steadily from the North-west Coral Sea to the surface at about 30 S and did not show any deep patch comparable to Rochford's 200 m one.

Fig. 50B shows the salinity values in the core of the Antarctic Intermediate salinity minimum. This layer had a depth of over 800 m round the margin of the North-west

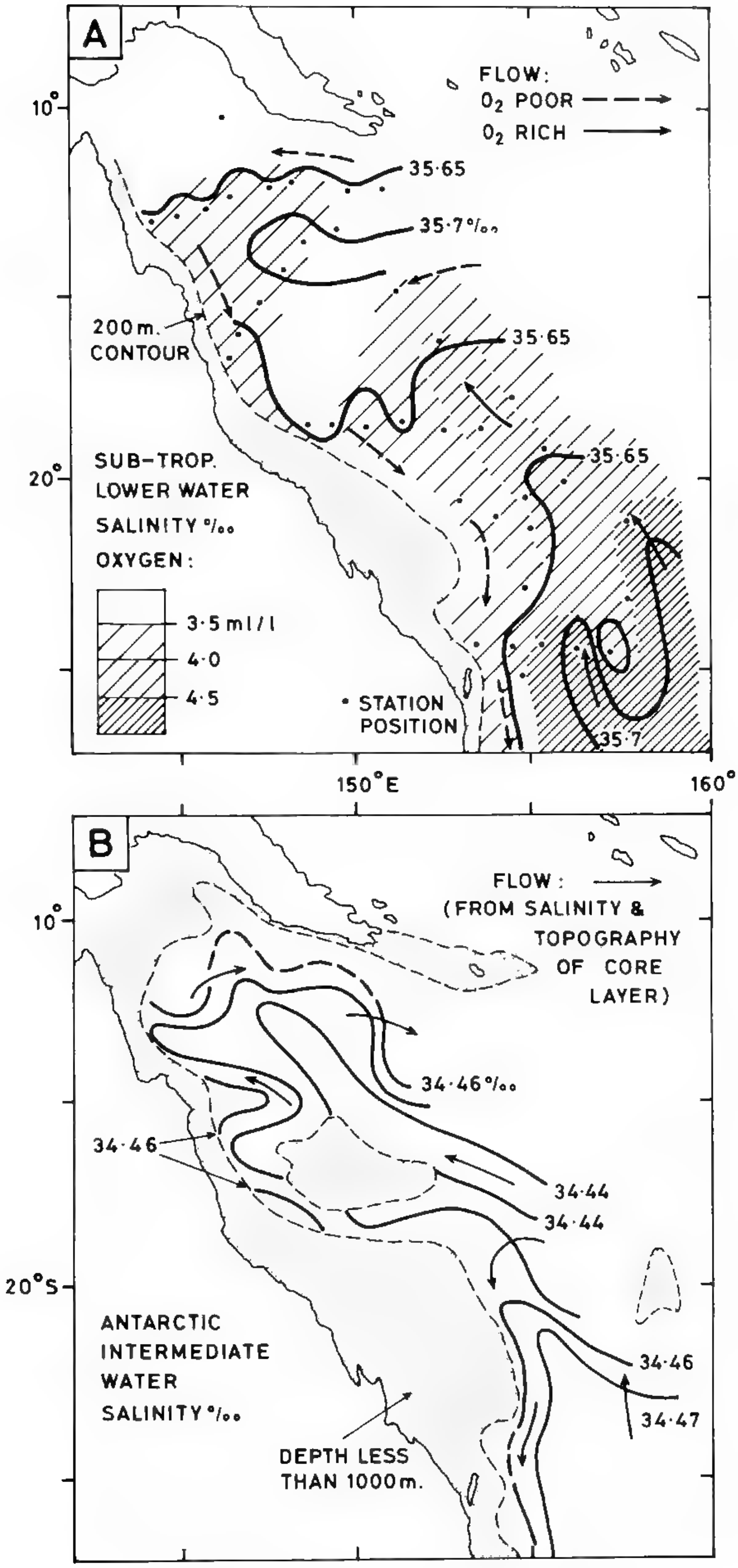


Fig. 50 Water masses and deduced flow patterns in the Western Coral Sea:
(A) Subtropical Lower water, salinity and oxygen distributions,
(B) Antarctic Intermediate water, salinity distribution (Rochford, 1968a).

Coral Sea, doming to less than 700 m in the centre of this area and then increasing to over 900 m in the south-east corner of the WCS. In suggesting flow directions (Fig. 50B), Rochford was perhaps influenced more by the topography of the core layer than by the salinity distribution.

A comparison of Wyrtki's (1962a) and Rochford's (1968a) results is appropriate at this stage.

Rochford's salinity values for the Subtropical Lower water were about 0.05 to 0.1 lower than Wyrtki's, his oxygen values about 0.3 ml/l lower, and his core layer depth greater by about 50 m in the north-west and 100 m in the south-east. For the Antarctic Intermediate Water the salinities and depths were similar in the two analyses.

The general character of the flow for the Subtropical Lower water was essentially the same in Rochford's as in Wyrtki's interpretations, but for the Antarctic Intermediate water Rochford showed a clockwise circulation in the North-west Coral Sea while Wyrtki did not commit himself to any direction of flow in this region. Rochford suggested that the southward flow across 20°S branched off from the North-west Coral Sea circulation but it could also be a southward branch of the original westward flow into the Coral Sea.

Rochford pointed out that while the Subtropical Lower water had a wide range of oxygen values in the WCS (from 3.5–6.5 ml/l) the Antarctic Intermediate Water had a much more restricted range (3.9 to 4.3 ml/l), more closely related to the southern component of the Subtropical Lower water than to the northern component (although only marginally so). He concluded that the major flow of Antarctic Intermediate water into the Coral Sea occurred south of Fiji and the New Hebrides (i.e. south of about 20°S), which agreed with Wyrtki's (1962a) deduction, and that little flow occurred at 800–1000 m from the Solomon Sea south into the Coral Sea in contrast to the inflow at shallower depths.

Core analysis—Scully-Power

The May–July 1968 data set taken and analysed by Scully-Power (1973a, b) was introduced earlier and the surface water characteristics described there. The subsurface water mass descriptions are now presented.

Subtropical Lower Water (upper salinity maximum). An example of the variation of properties with depth (Fig. 32) has already been described, using one of Scully-Power's stations in the WCS. This pattern was typical for the area, the differences being chiefly in the depth of the mixed layer and the southward increase of salinity in this layer, so that at some of the southern stations the upper salinity maximum was at the surface. Accompanying the increase in mixed-layer salinity there was a decrease in temperature so that the start of the thermocline was less sharp and the density discontinuity layer less intense.

Fig. 51A shows the envelope of all vertical T,S curves for Scully-Power's WCS stations, showing the well-defined character of the water column over the whole WCS area. The usual main features were the upper salinity maximum and the salinity minimum below this. The depths of these features vary over significant ranges (see Fig. 33) despite the tightness of the envelope. (This is one of the reasons for using the T,S and other diagrams as analytical tools.) The salinity maximum occurred at $\sigma_t = 24.75$ in the north, increasing to $\sigma_t = 25.20$ in the south, while the salinity minimum occurred close to $\sigma_t = 27.20$ everywhere in the WCS.

The upper salinity maximum (Wyrtki's 1962a Subtropical Lower water) was below the surface north of 27°S and at or close to the surface with the upper 200 m being nearly isohaline south of 27°S. The core salinity value was 35.59 to 35.78‰ except for two lower values close to the Barrier Reef.

Fig. 52 shows the distribution of (A) salinity and (B) dissolved oxygen in the salinity maximum core layer. These distributions were consistent with an inflow of a low oxygen, relatively high salinity, water from the northeast and a higher oxygen water inflow from

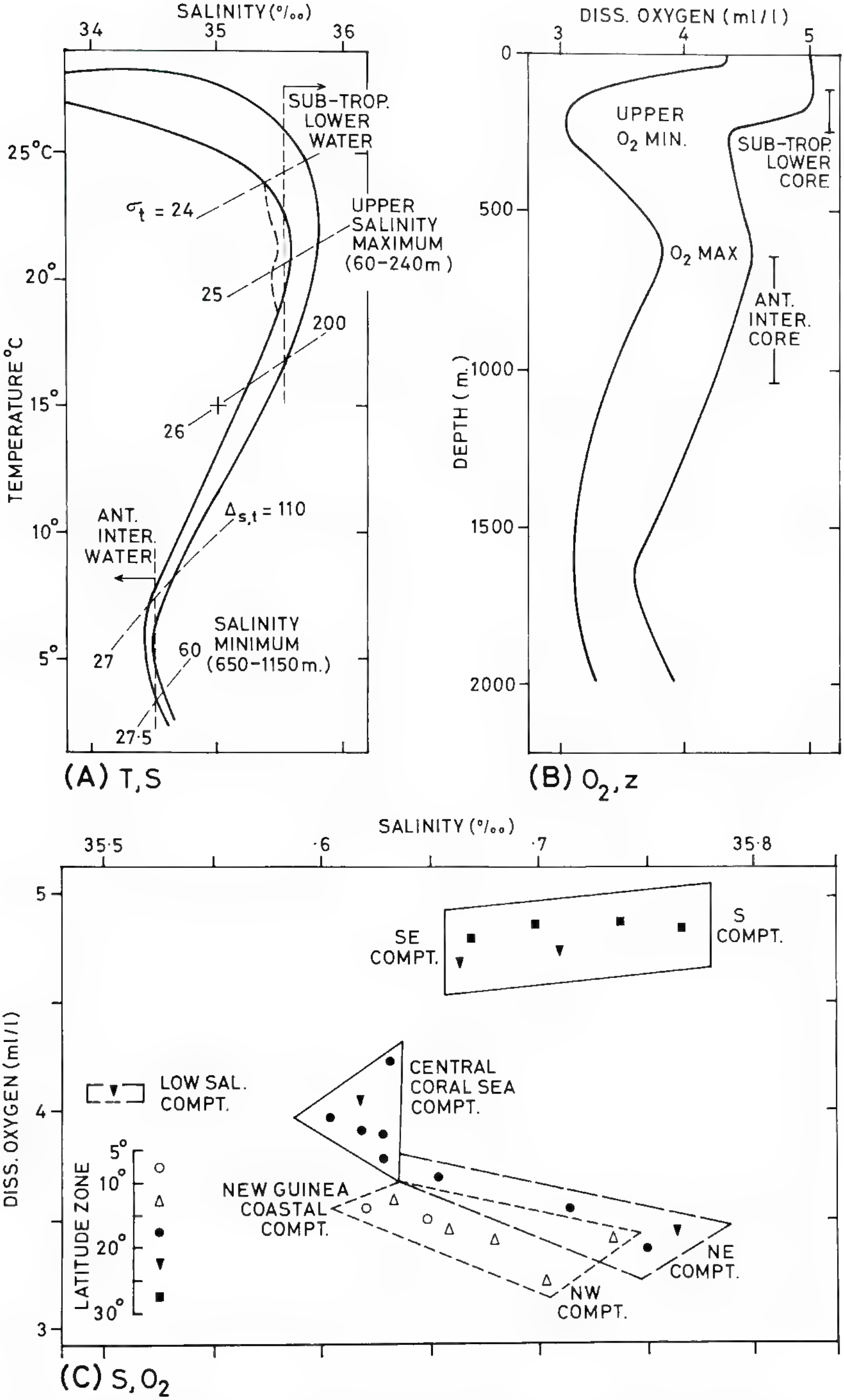
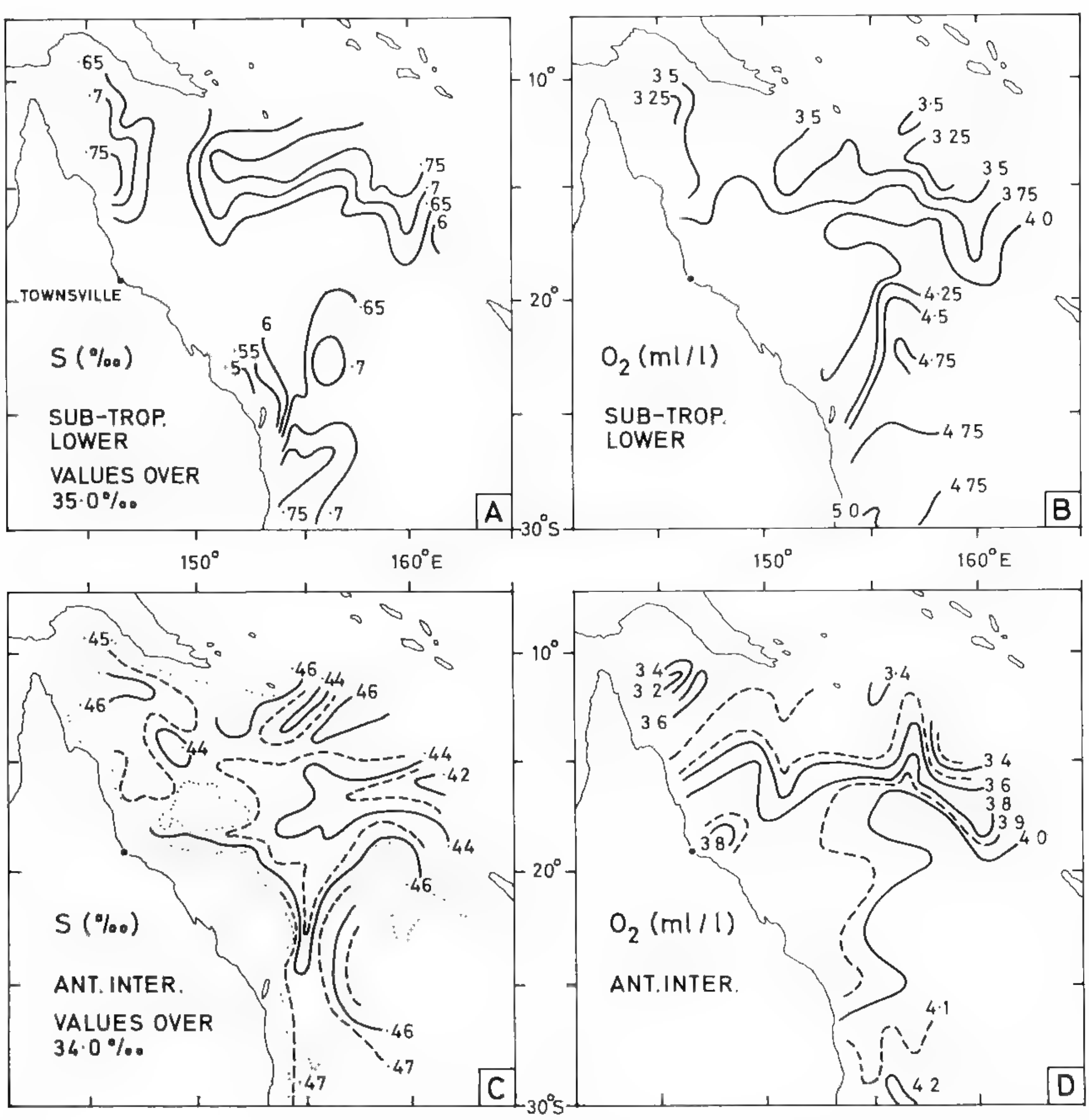


Fig. 51 Envelopes of (A) T,S and (B) O_2,z curves, Western Coral Sea, May–July 1968, (C) S,O_2 diagram for Subtropical Lower water components, Western Coral Sea, May–July 1968 (Scully-Power, 1973a).

the south (or south-east the distribution of stations here was such as to leave this uncertain, although the salinity distribution suggested a northerly flow close to the Australian coast). Over most of the area the salinity maximum core layer depth was between 110 and 200 m depth and the thickness of the layer (for salinities over 35.50 ‰) average 180 m. In the core, the temperature ranged from 19.3 to 23.3 C, and dissolved oxygen from 3.2 to 5.0 ml l.

In discussing the water masses Scully-Power then reviewed in some detail the characteristics of the Subtropical Lower water in the WCS; as this, together with the surface water, is likely to be significant in considering exchanges with the Barrier Reef lagoon, his conclusions will be summarised.

Fig. 52 (A) Salinity and (B) oxygen values in the core layer of the Subtropical Lower water, Western Coral Sea, May–July 1968, (C) Salinity and (D) oxygen values in the core of the Antarctic Intermediate water, Western Coral Sea, May–July 1968 (Scully-Power, 1973a).



The salinity distribution in the core layer of the Subtropical Lower water (Fig. 52A) showed three regions of high salinity values (to above 35.75 ‰) referred to from their locations as the north-east, southern and north-western components (Fig. 51C). The other main feature was the presence of a uniform salinity mass (35.61 to 35.65 ‰) in the centre of the area, named by Scully-Power the 'Central Coral Sea component'.

The north-east component evidently represented an inflow into the Coral Sea of northern component Subtropical Lower water (Wyrtki, 1962a).

The southern component had its highest salinity of 35.78 ‰ close to the shore at 27°S. Scully-Power suggested that this high salinity water might originate in the Barrier Reef lagoon and flow south, quoting CSIRO (1968a) for evidence of water over 36.00 ‰ in the Lagoon and Woodhead (1970) for southward flow. However, Scully-Power did not explain why there was lower salinity water between the exit from the Reef lagoon (presumably by Capricorn Channel at 23°S) and the location of the southern high salinity water at 27°–28°S. The T,S diagrams for Reef lagoon waters (Fig. 23, Part 1) show that in the southern zone, surface water of T = 25.6°C, S = 35.75 ‰ and $\sigma_t = 25.25$ occurs in July. These properties are almost identical with those in the WCS 100–125 m depth salinity maximum at Scully-Power's July stations 9 and 11 at 27°S, 154.5° and 156°E, i.e. T = 20.67°C, S = 35.78 ‰, $\sigma_t = 25.20$. The agreement is almost too good because such water offshore would require some time to get there and would probably have its properties modified by mixing *en route*. The lagoon waters earlier in the year are usually warmer and less dense, e.g. May, T = 24.5°C, $\sigma_t = 23.7$ and in June, T = 22.0°C, $\sigma_t = 24.7$. The Fig. 23 values are means and undoubtedly both more and less saline waters occur from time to time in the southern lagoon. However, a more telling point against lagoon origin of waters studied on the 1968 July cruise was that, according to the CSIRO Atlas, the lagoon salinities in April to July 1968 were all below 35.5 ‰ and densities were less than 24.5, significantly lower than the WCS Subtropical Lower values outside the Reef. It is also doubtful if the lagoon could produce sufficient quantities of high salinity water to supply the southern WCS.

Discussing the north-west high salinity component, Scully-Power (1973b) advanced arguments against (a) inflow through Torres Strait at any time, (b) formation *in situ*, and (c) flow from the Barrier Reef lagoon. He concluded that it must have come from the north-east at an earlier time, possibly in October–November at the end of the SE trades season. Data from earlier cruises in the area (Lockerman & Scully-Power, 1969) supported this suggestion. The Barrier Reef lagoon was dismissed as unlikely to provide sufficient high salinity (35.70+ ‰) water. The CSIRO Atlas indicates that water of sufficient salinity, over 35.8 ‰, was present in the lagoon in January 1968 and October–November 1967 but it is agreed that this is an unlikely source for large quantities of this water even though outflow from the lagoon does occur in the north zone (see Part 1). The characteristic which chiefly tells against the lagoon as a source of the high salinity Coral Sea water is the latter's low oxygen content (<3.5 ml/l), although Scully-Power did not mention this point.

Scully-Power identified some minor components (Fig. 51C), a high oxygen south-east component, a New Guinea coastal component and a low salinity component occurring close to the coast at 23–25°S, possibly resulting from mixing with lower salinity surface water. The south-east component was essentially Wyrtki's Subtropical Lower water, southern (high oxygen) component. This entered the WCS at 21–24°S, 157°E, and temporarily divided at 23°S to the north-west and south-west (Figs. 52, 58B) but rejoined to flow south along the Australian coast.

Scully-Power regarded the Central Coral Sea component as being derived from the low oxygen, north-east component (Subtropical Lower water, northern (low oxygen) component) after vertical mixing with the waters above and below it.

Antarctic Intermediate Water (intermediate salinity minimum). The salinity minimum was apparent on the S,z profiles (e.g. Fig. 32) but more conspicuous on the T,S diagrams (e.g.

Fig. 32A, 51A) with a very limited range of values of only 0.05 at the core layer. The salinity distribution at the core layer (Fig. 52C) showed low salinity water entering the Coral Sea from the north-east and turning south along 155 E. Scully-Power considered that this diagram also showed a secondary tongue of low salinity water entering from the south-east at about 24 S, and described the low salinity region in the north-west as a 'cell', presumably because there could be no inflow of intermediate water there. The inflows were identified as Antarctic Intermediate water. The core layer of this water lay between 700 and 900 m over most of the WCS, increasing to 1100 m in the south and for the small cell in the north-west. Using 34.50 as the maximum value for this water mass, it had a mean thickness of 375 m. In the core, the salinity varied from 34.42 to 34.47 , temperature from 4.95 to 6.20 C and dissolved oxygen from 3.8 to 4.3 ml/l.

Upper oxygen minimum. Some 75% of the stations showed a single upper oxygen minimum (Fig. 51B), the remainder showing a double minimum below the salinity maximum. The distribution of oxygen on the oxygen minimum surface was very similar to that in the core of the salinity maximum (Fig. 52B). Scully-Power considered that this indicated that the two water masses moved with the same flow pattern.

Oxygen maximum. All stations showed an oxygen maximum about 200 m above the salinity minimum of the Antarctic intermediate water (Fig. 32). Scully-Power agreed with Rochford (1960b) that on the basis of available information, this oxygen maximum water could not be identified as a separate water mass.

Isentropic analysis—Rougerie & Donguy

'Gorgone 1' 1972, late winter. The most recently published account of waters in the Coral Sea is that by Rougerie & Donguy (1975) for the Central Coral and Solomon Seas between 2 and 20 S, 153 to 163 E, with 72 stations completed between 14 November and 20 December 1972 (O.R.S.T.O.M. 'Gorgone 1' 1972 cruise), i.e. at the end of the SE trades season (see Fig. 31). This cruise overlapped the area of the R.A.N.R.L. May–July 1968 cruises by Scully-Power in the region 12 to 20 S, 153 to 163 E (Fig. 45A).

During this cruise, the general characteristics of the water structure for the part of the WCS covered were similar to those described in previous accounts. The Subtropical Lower water had a core layer salinity of over 36.0 north of the Solomon Is., 35.9 to 35.8 in the Solomon Sea and decreased to 35.65 in the centre and south of the Coral Sea. T,S and S,O_2 diagrams are shown in Fig. 53 for typical stations representative of these three regions, the station positions being shown in Fig. 45A. The northern salinity maximum occurred at a thermosteric anomaly of about 340 cl/t (corresponding to $\sigma_t = 24.5$—see Appendix), while the southern maximum was at about 300 cl/t ($\sigma_t = 25.0$). These two waters correspond to Wyrtki's northern and southern components of the Subtropical Lower water and were also clearly distinguished by their oxygen content. Rougerie & Donguy located the boundary between these two components at about 14 S with a region of overlap at about 15 to 18 S, 153 to 156 E.

At thermosteric anomalies of 230 to 90 cl/t ($\sigma_t = 25.7$ to 27.2) the linear part of the T,S diagram showed a mixture of Subtropical Lower and Antarctic Intermediate waters (Fig. 53A and cf. Fig. 51A) common to all the 'Gorgone 1' stations and similar to the R.A.N.R.L. ones. The S,O_2 structure was, however, much more complex as is evident in Fig. 53B. The strong oxygen minimum around Stn. 65 north of the Solomons can be traced back to the low oxygen layer in the eastern Pacific near Peru (Tsuchiya, 1968). The upper part of this oxygen minimum layer passed through the gaps in the Solomon Is. chain and thence to the north part of the Coral Sea.

The oxygen maximum of the Antarctic Intermediate water was also evident in the S,O_2 diagram (Fig. 53B), occurring at 500 to 700 m with values as high as 4.5 ml/l in the Coral Sea. Rougerie & Donguy (1975) referred to this as 'Coral Sea Water' (34.6 to 34.8 , 4.0 to 4.4 ml/l), not to be confused with Scully-Power's 'Coral Sea Component' of the Subtropical Lower water (about 35.6 , 4.0 ml/l).

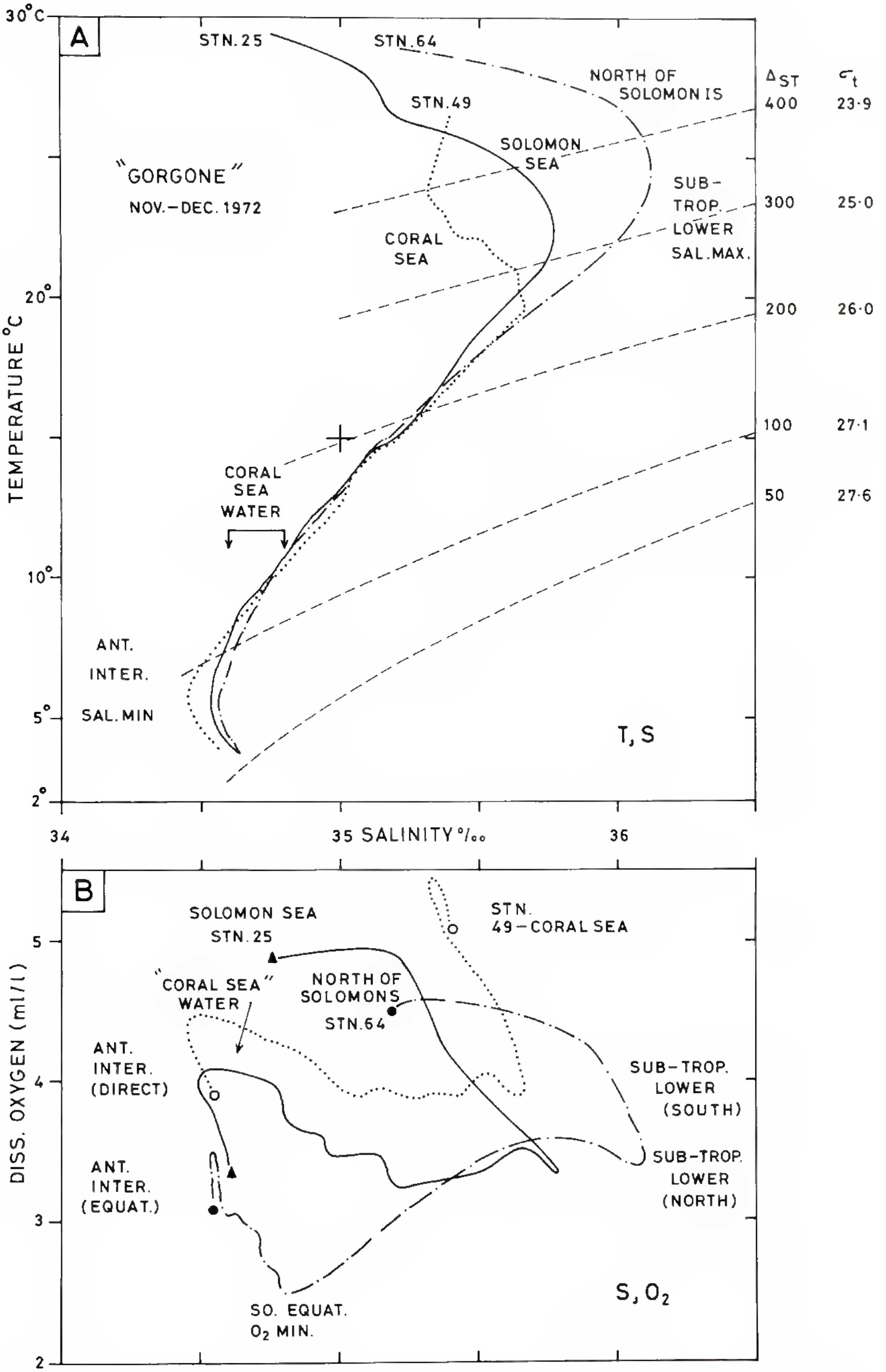


Fig. 53 (A) T,S and (B) S,O_2 curves for selected stations, Solomon and Coral Seas, 'Gorgone 1' cruise, Nov.–Dec. 1972 (Rougerie & Donguy, 1975). Station positions in Fig. 45.

The salinity minimum of the Antarctic Intermediate water was found to have a salinity between 34.45 and 34.55 ‰ and oxygen content of about 4.2 ml·l in the Coral Sea whereas that in the Solomon Sea was about 4.0 ml l and north of the Solomon Is. about 3.5 ml l. It was concluded that as Reid (1965) and Johnson (1973) had suggested, the Antarctic Intermediate water could enter the Coral Sea both from the south-east and also from the north-east passing south of the Solomon Is. after making a wide circuit through the equatorial regions.

'Gorgone 2' 1975, late summer. Although the analysis of the 'Gorgone 2' data (7 April to 7 May 1975) is not complete, some comparisons with the 'Gorgone 1' late winter cruise can be made.

Along the 156 E meridian during 'Gorgone 2' the upper layer of salinity less than 35 ‰ extended to 16 S in the Coral Sea and was twice as deep (60 m average) as during 'Gorgone 1'. This southward spreading of the low salinity South Equatorial water may be attributed to the NW monsoon wind stress, in consequence of which the New Guinea Coastal Current attains its maximum strength at this time (Wyrtki, 1961) and brings into the Solomon Sea water from the western equatorial Pacific whose salinity is further decreased by heavy rainfall in the Solomon Sea.

Below the surface, the 35.5 ‰ isohaline in the transition zone with the Subtropical Lower water (southern component) was at 160 m depth in the Solomon Sea but rose sharply to the south until in the Coral Sea it was 50 to 60 m shallower than during 'Gorgone 1'. At the core of the Subtropical Lower water, the salinity was not over 35.8 ‰ and the vertical salinity gradient was much less than during 'Gorgone 1'. In these tropical waters where the salinity has a significant effect on the density field, a result was that during 'Gorgone 2', in April–May, the vertical stability was relatively small so that vertical advective movements were able to produce 'doming' at 12 to 13 S and 17 to 18 S. In November–December 1972 ('Gorgone 1') the doming was slight and contributed little to increasing the typically low nutrient values of the upper waters.

The dissolved oxygen distributions were generally similar for the two cruises. However, the oxygen maximum of the subequatorial water which was present at 300 m depth to the north of the Solomon Is. and between 10 and 12 S during 'Gorgone 1' had almost disappeared at this southerly position during 'Gorgone 2'. In the summer, therefore, it appears that the extension to the south-east of the upper waters has an effect as deep as 300 m and partially prevents the movements into the Solomon Sea of low oxygen water from the eastern Pacific. This depth of 300 m is that at which the T,S curves for the two cruises come together, perhaps indicating the limit to the depth of penetration of climatic effects.

Consistency of subsurface water characteristics

In order to estimate the consistency with time of subsurface water characteristics in the WCS, envelopes of T,S data from 50 to 1200 m depth were prepared for each of nine cruises within the area 10 to 19 S, 144 to 159 E (although not all cruises covered the whole area). The cruises used were from the five sets listed in 'Other surface data in seasonal sequence' from 1965 to 1975 together with two other R.A.N.R.L. cruises for the North-west Coral Sea, i.e. cruise CS1 for Nov.–Dec. 1966 and CS2 for Apr.–May 1967 (Scully-Power 1969a, b). The 1968 R.A.N.R.L. data set was divided into its three constituent cruises to make nine envelopes in all. The T,S envelopes were very similar in position and width on the diagram, the main differences occurring above 20 C, i.e. above the salinity minimum or above about 200 m.

Seven of the envelopes are shown in Fig. 54, the other two duplicating the November and May periods (envelopes 2 and 5). Table 7 below shows the mean position of the centre lines of the envelopes and the scatter in position about the mean.

The variation in mean T,S characteristics was about ±1C or ±0.1 ‰ above 20 C, i.e. above the salinity maximum, and only ±0.2C or ±0.02 ‰ below 20 C.

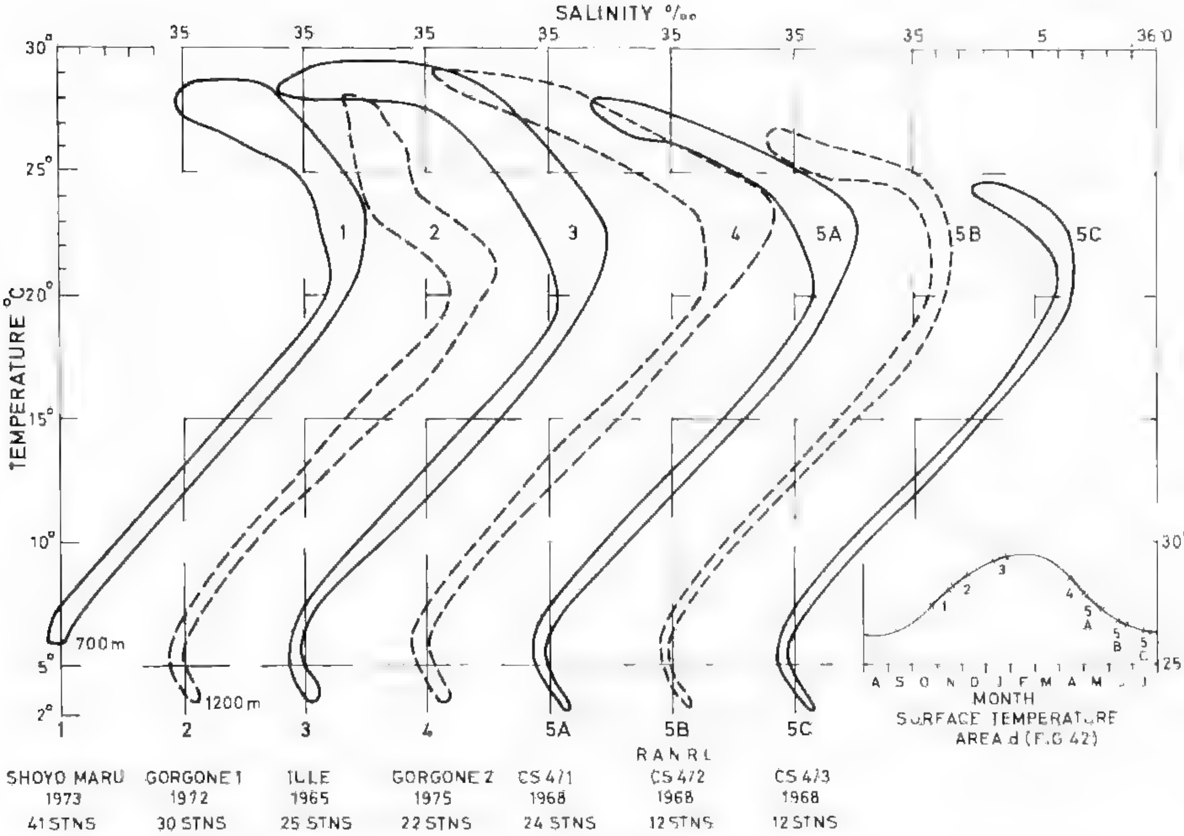


Fig. 54 T,S envelopes for data from 50 to 1200 m depths (700 m only for curve 1) in the northern part of the Western Coral Sea (11° to 19° S). Time of year shown on inset with surface temperature curve for area d (see Fig. 41).

The widths of the envelopes were much the same for all the data sets, the average width perpendicular to their centre-lines being equivalent, above the salinity maximum (i.e. above about 22°C or 150 m), to 1.5C° or 0.15‰ on the T,S diagram and below 20°C or 200 m to less than 1C° or 0.1‰ (i.e. less than $0.2\sigma_t$).

The envelope width in Fig. 61 is wider than these values because it covers data from all three constituent R.A.N.R.L. cruises together and from a more extensive area, both north, west and south, than do the data from the diagrams in Fig. 54.

Bearing in mind that the cruises took place in different seasons and were distributed over a ten-year period, the above analyses indicate that below the surface layer, the T,S characteristics of the major part of the WCS show only small changes with time.

T,O_2 and S,O_2 envelopes were prepared but these were generally not as well defined as the T,S envelopes and it was not possible to compare the cruises meaningfully for these combinations. On the T,O_2 envelopes the upper minimum and lower maximum of oxygen were present but not clearly defined as there was much more scatter than for the T,S plots. (The envelopes had a width in the oxygen dimension of 50 to 75% of the total range of oxygen values below the surface (1 to 1.5 ml/l width compared to a total range of about 2 ml/l)). The envelopes became narrow (0.2 to 0.4 ml/l) only below the Antarctic Intermediate water. For the S,O_2 diagrams, when all the data from a cruise were plotted no characteristic envelope was evident in most cases. This is to be expected in view of the convoluted nature of even individual S,O_2 curves (e.g. Fig. 32C, 53B). The exception was for the *Shoyo Maru* cruise for which both the T,O_2 and the S,O_2 envelopes were narrow in the oxygen dimension (only 0.2 to 0.4 ml/l). For this cruise the Subtropical Lower water was entirely northern (low oxygen) component, whereas some southern (high oxygen) component was present for the other cruises. The probable reason was that the *Shoyo Maru* cruise covered a smaller area than the other cruises and was restricted to the northwestern part of the WCS (west of 151°E) whereas the others extended as far as 7° further east and 2° further south.

Wyrtki (1962a) noted that the oxygen content of many of the southern component Subtropical Lower water samples in the Coral and Tasman Seas was above the (one atmosphere) saturation value for their temperature (Fig. 48). In the northern part of the WCS this was rarely the case in the Subtropical Lower water which was chiefly the northern component whose oxygen content was well below saturation. However, many of the samples in the upper waters above the salinity maximum in the nine cruises discussed above did have an oxygen content above saturation.

These results indicate that most variation occurs above the salinity maximum whose depth in the WCS is generally 200 m or less. Because the variations in the upper layer are presumably due chiefly to climatic changes, this suggests that the limit to downward penetration due to such effects may be less than the 300 m estimated from the analysis of the 'Gorgone 1 & 2' results described earlier. The reason for this depth limitation is probably because the layer immediately above the salinity maximum generally has a maximum of gravitational stability and this acts as a discontinuity layer restricting downward turbulent transfer of water properties.

Table 7. Mean of centre lines of T,S data envelopes below 50 m depth for nine cruises from 1965–75 for Western Coral Sea, and range of positions about the mean

Co-ordinates of mean line		*Range about*	*Co-ordinates of mean line*		*Range about*
Temp. (C)	*Sal. ( )*	*mean ( )*	*Sal. ( )*	*Temp. (C)*	*mean (C)*
25	35.40	±0.10	34.5	28.5	±0.5
20	35.62	±0.03	35.0	27.0	±1.2
15	35.24	±0.02	35.5	24.2	±0.6
10	34.75	±0.02	35.5	17.8	±0.3
5	34.46	±0.02	35.0	12.5	±0.1
			34.5	6.8	±0.2
			34.5	4.2	±0.2

V
Circulation

INTRODUCTION

In Chapter IV, the distributions of water properties were described together with inferences on the flow *paths* of the various water masses but with few estimates of the speed of travel being available from this source. This chapter will review the available information on the velocity of water motion, i.e. the path followed together with some estimate of the speed —either directly in distance per unit time or as volume transport per unit time across a vertical section (units discussed in the Appendix). The sources of this information have been:

(a) ship's navigation logs in which the difference between the course and speed through the water and the track and speed made good over the ground was attributed to water motion (for the surface layer only), or

(b) dynamic considerations related to the distribution of density of the water (geostrophic method) for the surface and sub-surface waters.

As far as is known, no direct measurements of currents are available for the WCS (although there are some for the East Australian Current further south).

SURFACE CIRCULATION

Wyrtki, 1960, 1962b—Current atlas and geostrophic circulation

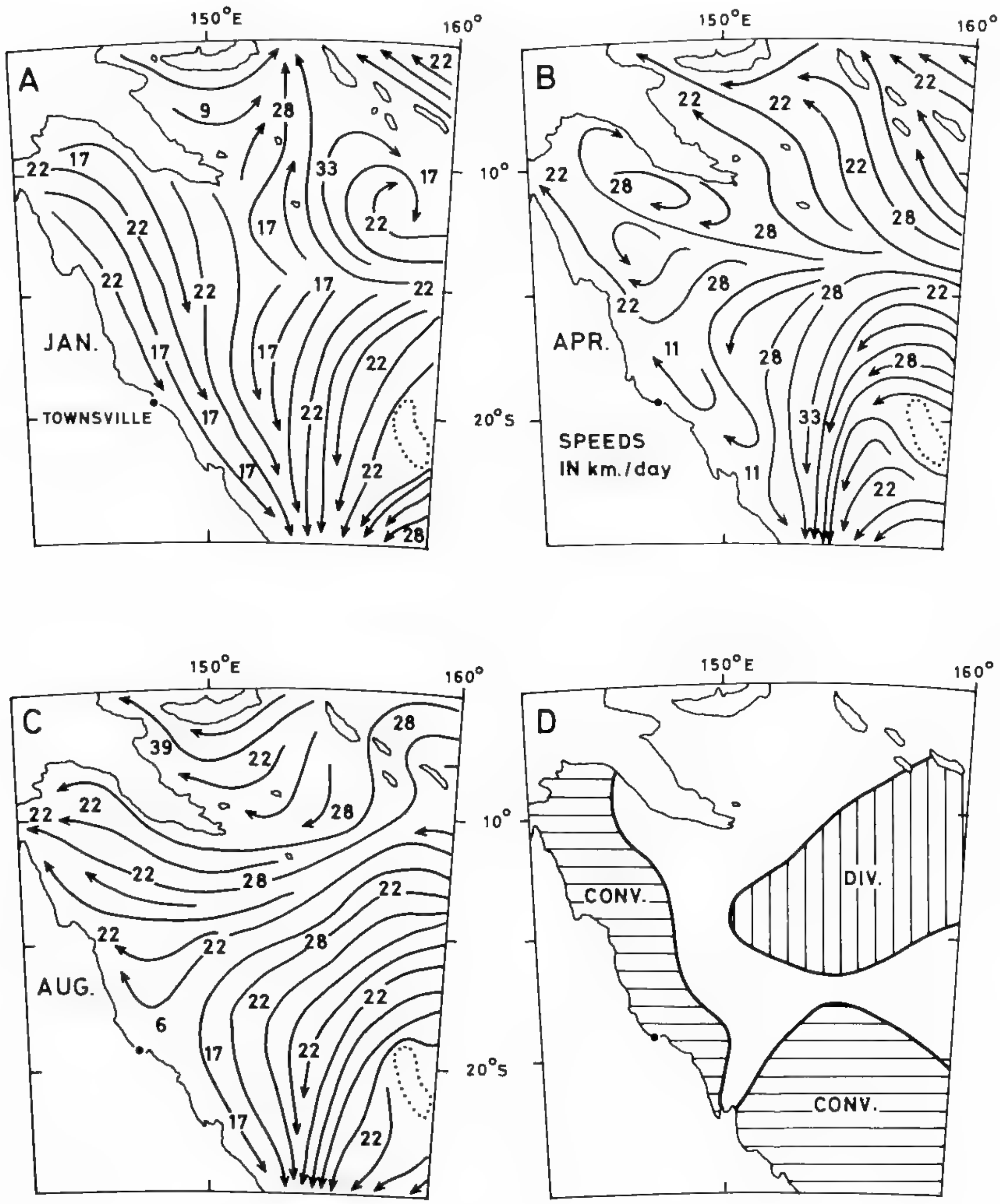
The most ambitious surface current description for the Coral and Tasman Seas was by Wyrtki (1960), based on the *Atlas of surface currents, south-western Pacific Ocean* (U.S.N.H.O., 1944) with reference also to *Sea areas around Australia* (Roy. Neth. Met. Inst., 1949) and other atlases. Wyrtki presented the surface currents for an area from 5° to 48° S, 142° to 180° E in two sets of twelve monthly charts, one showing current arrows with speed indicated and the other in the form of streamlines. The latter show the direction of the current at each point along their length but do not indicate the speed as directly as the coded current arrows. (It should be noted that *streamlines* show an instantaneous pattern of flow and are not the same as *trajectories*, the path followed by particles over a period of time, except in the steady state when the circulation does not change with time. If the thickness of the moving surface layer remains constant, then crowding of streamlines implies increase of speed and *vice versa*, but if the layer thickness varies, this indication of speed will be obscured.)

Although Wyrtki's current charts look very complete (and are frequently used as references), later studies have revealed differences in many aspects. This is not surprising, because the material on which the charts were based was inhomogeneous (many sources) and had numerous gaps in coverage of the area, so that considerable interpolation must have been necessary to produce the apparent complete cover of Wyrtki's charts. Therefore, only parts of three charts will be reproduced here, selected as samples to show the character of the current patterns deduced by Wyrtki. These are in Fig. 55A,B,C, for the months of January, April and August. A selection of speed values, in km/day has been added from the current arrow chart. The major features of the WCS surface flow patterns according to Wyrtki's charts were:

(a) westward or south-westward flow (into the WCS) across 160 E from 10 to 25 S all year (Wyrtki's 'Trade Drift'),

(b) at 155 E, from 15 to 25 S, a south-west or south flow all year (the start of the East Australian Current); at 155 E, from 10 to 15 S, flow to the west or south-west from May to December, to the north in January, to the south in February, and west or north-west in March and April,

Fig. 55 Surface flow patterns for (A) January, (B) April, (C) August, and (D) regions of convergence and divergence, Coral Sea (Wyrtki, 1960). Numbers represent speeds in km day.



(c) outside the Barrier Reef (an area notably lacking in information in the original Atlases) the current was shown as:
   (i) at 9° to 11°S (Torres Strait), west from April to November, and east from December to March (NW monsoon),
   (ii) from 11° to 19°S, north or north-east from March to November, and south or south-east from December to February,
   (iii) between 20° and 25°S, south-east all year, except for a weak northerly flow at 20°S in June.

In Fig. 55 the January chart is reasonably representative of Wyrtki's December to March charts, the April chart for April to June and the August chart for July to November. Typically, the original January and August charts and their respective periods showed relatively simple circulations, while the April to June ones were more complex. Wyrtki deduced regions of convergence and divergence from the starting and termination of streamlines (although this seems to be a somewhat uncertain procedure in view of the subjective manner in which the streamline charts were prepared). In general, as Fig. 55D shows, there appeared to be areas of divergence in the north-east and areas of convergence in the west against the Barrier Reef and in the south at the start of the East Australian Current. This might imply sinking at the Reef but probably not much because the water column is very stable below the mixed layer. Most of the convergence here resulted in a division of flow north-west and south-east parallel to the Reef as shown for August (Fig. 55C). The position of this division was at about 15°S in February, 18° to 20°S in March to September, and then moved north again to about 14°S in December. There was no division in January when Wyrtki had a strong south-east streamline pattern emanating from Torres Strait and continuing down the coast. (Note that this did not imply that Torres Strait water reached as far south as the East Australian Current because the speeds were not sufficient—only about 17 to 22 km/day or 5 to 6 degrees of latitude per month.) The eastwood flow through Torres Strait was attributed to NW monsoon wind stress, and Wyrtki also showed a strong flow into the north of the Coral Sea from the Solomon Sea in February and March.

For most months, Wyrtki showed a significant flow over or through the Barrier Reef between 19° and 23°S into the lagoon and then out again north of Gt Sandy Is. (24°S) to join the East Australian Current. He did not comment on this, nor has anyone else. It implies a considerable flushing of lagoon waters by WCS waters and could be a significant feature in the exchange of these waters if it is true. This feature warrants investigation in connection with Barrier Reef lagoon oceanography.

It may be noted in passing that the *Australia Pilot*, Vol. IV (1962) used four of Wyrtki's charts but had the July and October charts reversed.

In a later paper on the geopotential topography (see Appendix) and circulation in the Western South Pacific, Wyrtki (1962b) combined data from January to April from three years and showed the topography of various pressure surfaces relative to the 1750 db surface (db = decibar, see Appendix). Unfortunately, during this period of the year considerable changes take place between months in the surface circulation according to Wyrtki's (1960) charts (cf. Fig. 55A,B). The surface circulation from his 1962 calculation showed the convergence to the East Australian Current as in all months, a southeast flow in the Solomon Sea as for the February chart (and possibly March), and an eastward flow to the south of Papua New Guinea as for January and March to April in his monthly charts. Essentially, he had a clock-wise circulation occupying the WCS, and an anti-clockwise one in the Central Coral Sea (13° to 30°S, 155° to 165°E) with little net westward flow across 160°E into the Coral Sea, which was surprising. Wyrtki commented that the westward surface flow across 160°E in his monthly charts ('Trade Drift') was due to the wind stress and would not appear on the distribution of geostrophic currents, citing a similar situation in the Indian Ocean. He maintained that the wind stress flow should be added to the geostrophic flow (see Appendix) giving a general westward flow into the Coral Sea across 160 E between about 10 and 20 S, although this might be less regular than the subsurface flow. (This argument is of doubtful validity.)

In summary, the January to April (3 years) compilation agreed with the monthly charts in the southeast corner of the WCS (south of 15 S, east of 155 E) all the time and with the March chart over the whole area, but disagreed with the January and February charts in the WCS (and with the January and April charts in the Solomon Sea). This was probably as good agreement as could be expected for a variable period of the year for the surface circulation.

In a recent calculation of the dynamic topography for the whole Pacific, Wyrtki (1974) presented mean topographies for the sea surface relative to 1000 db for two-month periods. The contours in the diagrams were at 10 dyn cm intervals which is rather coarse for this small region but there was a general tendency for inflow to the Coral Sea across 160 E from 10 to 15 S, and outflow from 15 to 20 S at the surface.

Rotschi, 1958–61—Earlier O.R.S.T.O.M. cruises

Five cruises by the Institut Français d'Océanie (now O.R.S.T.O.M., Centre de Nouméa, Section d'Océanographie) (Rotschi, 1958a,b, 1959c, 1960d, 1961b) were referred to by Wyrtki (1962b) and these have been reviewed together with a sixth cruise (Rotschi, 1961c) for the area between the Solomon Is., the New Hebrides and New Caledonia, a little to the east of the present area under review. All but one of these cruises (May 1960) showed a westward flow at the surface approaching 160 E between the Solomons (11 S) and about 14 S. Between 14 S and New Caledonia (20 S) the surface flow was sometimes to the west, sometimes to the east. The net transport to the west above 1000 m varied from 16 to 37 sv. (See Appendix for definition of 1 sv.)

These earlier cruises, together with later ones, for the area between 10 to 19 S, 155 to 165 E have been re-examined by Donguy & Henin (1975b) and their deductions will be reviewed later.

Takahashi, 1959, 1960—Eddy in Coral Sea

Takahashi (1959, 1960) showed a cyclonic (clockwise) eddy in the eastern Coral Sea which does not seem compatible with Wyrtki's or O.R.S.T.O.M. results. The southward flow (Takahashi) at 162 C might well be associated with Wyrtki's flow into the Coral Sea but his northward flow at 15 S, 150 E was opposite to the most persistent feature of all twelve of Wyrtki's (1960) charts and his 1962 results. Actually, it is doubtful if Takahashi had sufficient stations to delineate his eddy fully. (Note that this eddy is incorrectly referred to as a 'counterclockwise' eddy by Rotschi & Lemasson, 1967, possibly a misinterpretation of Takahashi's use of the phrase *contra solem*, ref. Sverdrup *et al.*, 1942, p. 437.)

Donguy, Oudot & Rougerie, 1970—Review of 1956–68 northern Coral Sea data

Donguy *et al.* (1970) reviewed the surface and subsurface circulations of the Solomon and Coral Seas, using data from 32 cruises between 1956 and 1968, and assembled current schemes for the summer and winter seasons.

For the summer (Fig. 56A) they identified from north to south (modified in the light of Donguy & Henin's 1975b findings), the following currents and related water masses:

(a) Equatorial Current to the west—Subtropical water, northern component (Sverdrup *et al.*, 1942, called this the 'South' Equatorial Current),

(b) New Guinea Current to the east—Equatorial water, continuing as

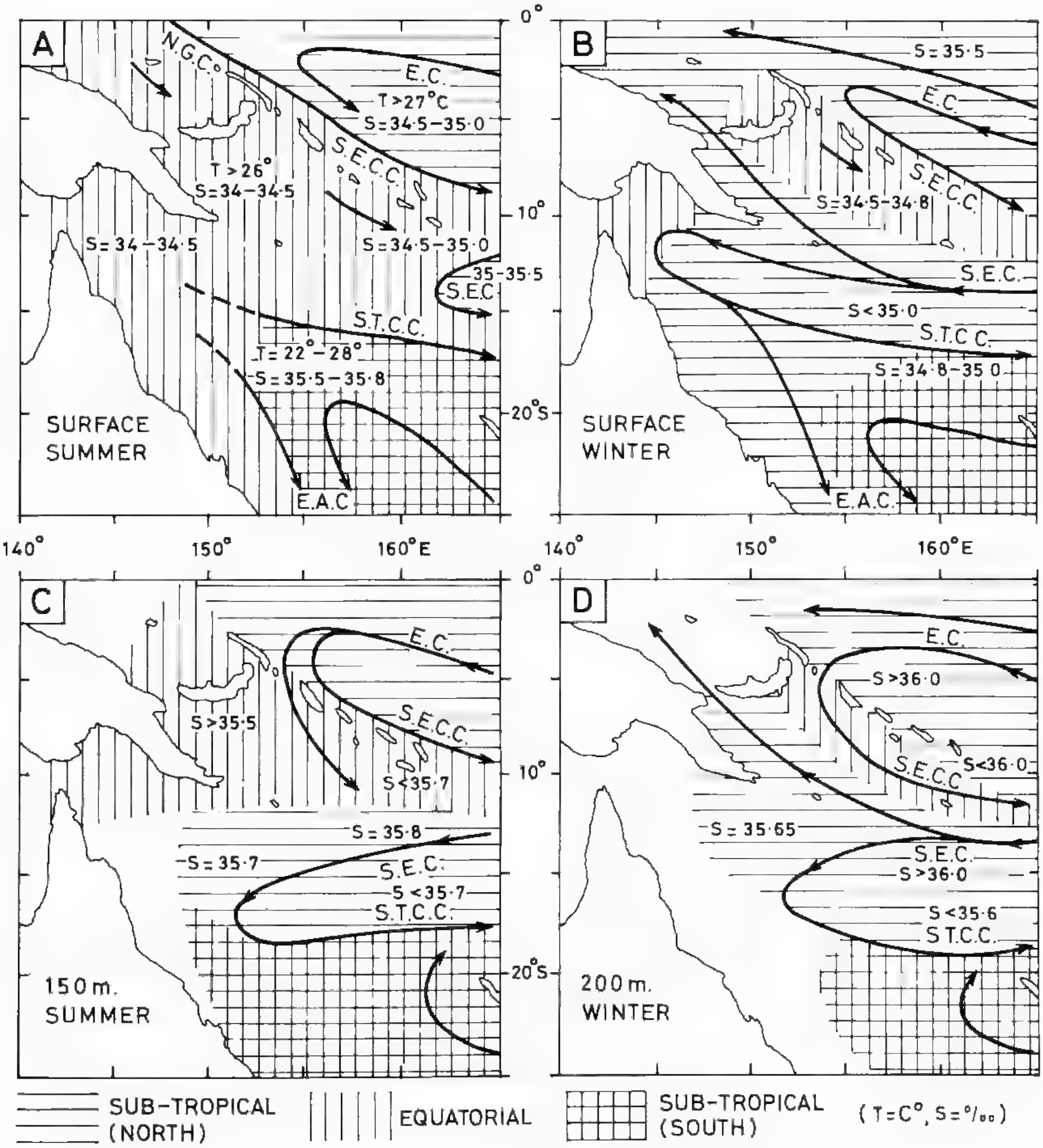
(c) South Equatorial Counter Current to the east,

(d) South Equatorial Current to the west — Subtropical water, southern component,

(e) South Tropical Counter Current to the east (from the Coral Sea, ref. Donguy & Henin, 1975b),

(f) East Australian Current to the south-east.

Fig. 56 Currents, Coral and Solomon seas, (A) surface, summer, (B) surface, winter, (C) 150 m, summer, (D) 200 m, winter (Donguy *et al.*, 1970). Abbreviations for current names: E.C. – Equatorial Current, N.G.C. – New Guinea Current, S.E.C.C. – South Equatorial Counter Current, S.E.C. – South Equatorial Current, S.T.C.C. = South Tropical Counter Current, E.A.C. – East Australia Current.



The surface water of the Coral Sea in the summer was identified as mainly the low salinity equatorial surface water from the north, together with a component of Arafura Sea water coming through Torres Strait.

In the winter (Fig. 56B) the main feature was a considerable extension to the west of the South Equatorial Current due to the SE trades. Part of this South Equatorial Current flowed northwest through the Solomon Sea to join the Equatorial Current and part contributed to the East Australian Current. The Subtropical Counter Current was slightly further south and more saline (34.8 to 35.0 ‰) than in summer. The contribution of the Equatorial Current to the South Equatorial Current was also more saline (34.5 to 34.8 ‰) than in summer. The speeds in these currents were generally small, 1 to 5 cm/s.

Most of the surface water in the Coral Sea in the winter was the Subtropical Surface water of the South Pacific diluted by some Equatorial water.

It must be borne in mind that the above description was of broad features and that significant differences in detail between years may be expected, for example as mentioned in the next section.

Rougerie & Donguy, 1975—'Gorgone 1' 1972 cruise, northern Coral Sea

In November–December 1972 during the 'Gorgone 1' cruise (Rougerie & Donguy, 1975), regarded as a winter circulation period because it was still in the SE trades regime, the South Equatorial Counter Current was evident only north of the Solomon Is. (not south as well) and the South Tropical Counter Current which was conspicuous in 1956 between 15° and 18° S was, in 1972, only evident just north of New Caledonia (see also the next section). The strong westward flow across 160° E was clear in 1972 from 10° to 18° S. (A curious feature which often occurs in the surface dynamic topography about 16° to 17° S, 156° E is a cyclonic gyre of diameter about 300 km.)

Donguy & Henin, 1975b—Review of flow at 158° and 163° E

Donguy & Henin (1975b) assembled the available data to 1972 (13 cruises) for the area between New Caledonia and the Solomon Is., forming two lines of stations close to 158° E and 163° E respectively. They determined mean dynamic heights relative to 1000 db for the two sections, omitting two cruises which were notably different from the others. Fig.57 shows the currents identified across the two sections from the mean dynamic heights. The presently unnamed current (U in Fig.57) north of the Chesterfield Is. was possibly identified with the northerly flow to the west of New Caledonia described by Scully-Power (1973b) and the next section. At the right in Fig. 57 are given the maximum mean speeds at the surface relative to 1000 db, the maximum mean speeds in the upper 100 m, the maximum observed speeds and estimates of the volume transports for two of the currents. (As the northern limit of the South Equatorial Counter Current was not determined, its volume transport was not calculated.) One of the cruises omitted from the mean dynamic height calculation was the 1972 'Gorgone 1' cruise which showed westward flow across the whole section at 158° E and westward over most of the section at 163° E.

Scully-Power *et al.*, 1969, 1973a, b—Western Coral Sea

Lockerman & Scully-Power (1969) calculated geostrophic currents for a limited area in the North-west Coral Sea for the end of November 1966 and the end of April 1967. At the surface in November there was a clockwise circulation with easterly flow at 25 to 40 cm/s between 10° and 12.5° S and a westerly flow of 20 to 30 cm/s between 14° and 15° S. In April a similar circulation was observed with speeds of 20 to 60 cm/s. The November circulation was opposite to Wyrtki's (1960) surface current chart which showed anti-clockwise circulation in November with a flow west through Torres Strait, and a weak clockwise circulation in December. Lockerman & Scully-Power's April circulation was basically in agreement with Wyrtki's April and May charts, and with Wyrtki's (1962b) geostrophic estimate from January to April data which showed a clearly developed clockwise circulation at the surface centered at 13 S, 148 E to the SSE of Port Moresby.

The most complete coverage of the Western and Central Coral Sea, albeit only for the winter season, was that described by Scully-Power (1973a, b, c) based on the three cruises in May, June and July 1968 (Fig.45A) and on data for May, June 1971 (R.A.N.R.L. Cruise CS7, unpublished data). In Fig.58A, which also indicates the station positions, the surface dynamic topography relative to 1500 db is presented to show the circulation. Scully-Power noted that the surface circulation was rather complex but drew attention to two features:

(1) although there was considerable westerly flow into the Coral Sea across 160 E, most of this water flowed out to the north into the Solomon Sea rather than turning south across 20 S to feed the East Australian Current. This was not in keeping with usual ideas of flow in this region, e.g. Wyrtki (1960, 1962b),

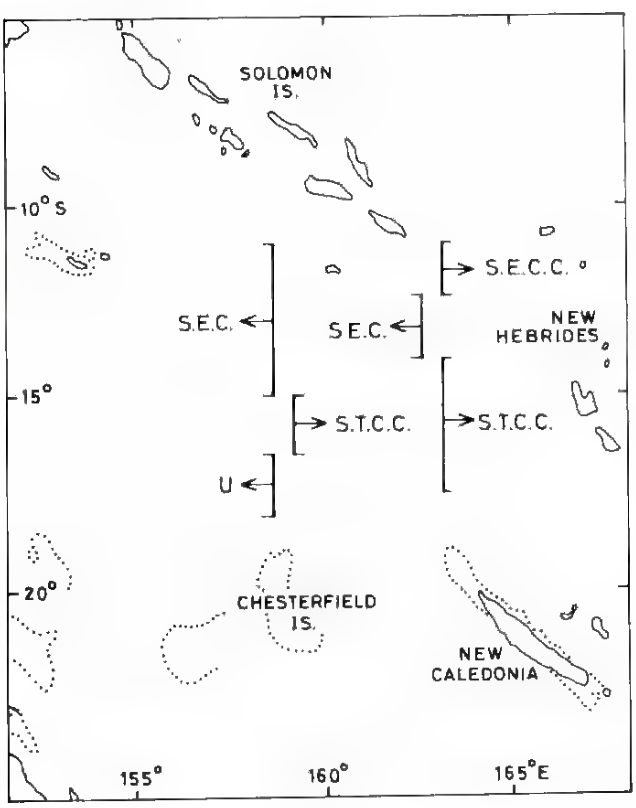
(2) an anticlockwise eddy was present between 20 and 26 S, off the Capricorn Channel area of the Reef.

In addition, attention is drawn to:

(3) the very strong flow south at about 24 S close to Gt Sandy Is.

It is noted that, although not mentioned by Scully-Power, the U.S.N.O.O. Pilot Charts for the South Pacific (1955) show a similar feature to item (1) for winter. For September to May (summer), the main surface flow shown is west or south-west across 160 E with much of this flow proceeding south across 20 S to feed the East Australian Current system, but for June-August (winter) the westward flow across 160 E divides at about 25 S, part going south and part *north* across 20 S. The pattern resembles Scully-Power's surface and 150 m winter flow patterns with the division at 25 S rather than at

Fig. 57 Currents and transports in the Central Coral Sea (Donguy & Henin, 1975). Abbreviations for current names: S.E.C.C. = South Equatorial Counter Current, S.E.C. – South Equatorial Current, S.T.C.C. – South Tropical Counter Current, U Unnamed current.



	SPEED (cm./s) MAX SFC. 1000db	MEAN UPPER 100m	MAX. OBS.	VOLUME TRANSPORT (SFC. TO 100m.) (SV) MAX.	MEAN
S.E.C.C.	4	20	45	–	–
S.E.C.	20	20	45	6·7	3·5
S.T.C.C.	15	15	25	5	2

20°S as he found it. These Pilot Charts show a southward component of flow in summer from the Solomon Sea into the North Coral Sea as do Wyrtki (1960, 1962b) and Donguy *et al.* (1970). However, a curious feature in the Pilot Charts is that in summer (the December–February chart) a significant *westward* current is shown through Torres Strait, contrary to all other accounts. The Pilot Charts show speeds of 20–35 km/day (0.4–0.8 kts) in the body of the Western Coral Sea, increasing to 25–55 km/day at the south toward the East Australian Current.

Surprisingly, the origin of the strong flow to the south (item 3 above) was not explained although in discussing the water masses Scully-Power referred to the possibility of high salinity water flowing from the Barrier Reef lagoon. He referred (1973b) to this water as flowing southward (inside the reef) and escaping at the southern extremity. (This possibility was discussed earlier with the conclusion that the lagoon was not a likely source of large quantities of water to the WCS.) It is possible that this feature might have been a transient one. In any event it depends on the observations at a single station (Stn 13, Cruise CS 1/3, Scully-Power & France, 1969c), as the four stations north of this were in much shallower water (less than 420 m) than the reference level of 1500 db used for the geostrophic calculations.

Scully-Power also pointed out that the topographic high at about 25°S, 155°E and associated anticlockwise circulation also appeared on Wyrtki's (1962b) pattern for late summer (January to April) and, although less intense in winter, was probably a permanent feature of the WCS circulation pattern. Finally for the surface circulation, Scully-Power described some results for the North-west Coral Sea for the summer of 1966 and winters of 1967–70, all of which showed a northerly surface flow over the deep water off Cairns (17°S) which turned east when approaching the Papua New Guinea coast. The surface speeds varied from 5 to 45 cm/s.

SUBSURFACE CIRCULATION

Hamon, 1958—Inflow to the northern Coral Sea from the east

Hamon (CSIRO, 1958) estimated the flow into the Coral Sea between the Solomon Is. and New Caledonia from the 1° square current vectors in *Sea areas around Australia* (Roy. Neth. Met. Inst., 1949), obtaining a mean speed of 7 cm/s and a volume transport of 9 sv assuming a layer depth of 200 m. Hamon emphasised that the choice of 200 m for the upper layer flow was only an estimate and that the volume transport should only be regarded as an order of magnitude value. It was about one-half of the mean of the values below calculated by Wyrtki.

Wyrtki, 1962b—Geostrophic circulation in the Coral Sea

Wyrtki (1962b) also determined the geopotential topographies of the 100, 200, 400, 700, and 1100 db surfaces relative to 1750 db. (These can be taken as approximating the same depths in metres.)

At 100 and 200 m, the westward flow into the Coral Sea was better developed than at the surface, being stronger at 200 m than at 100 m. The circulation at these depths compared well with the spread of the Subtropical Lower Water (Wyrtki, 1962a) as described previously. The westerly flow across 160°E was still evident at 400 m, and at 700 m where it consisted of Antarctic Intermediate water. At 1100 m there was little relief in the dynamic topography indicating no distinctive circulation at that level.

Rotschi, 1958–61—O.R.S.T.O.M. earlier cruises, volume transports

Between 100 and 500 m all six cruises (see above) showed a westward flow into the Coral Sea. For these cruises, Wyrtki (1962b) showed the 300 m flows which were characteristic of the 100 to 500 m layer. He regarded the 100 m and deeper dynamic topographies and associated geostrophic circulations as indicative of the total flow below 100 m but for the surface the wind stress flow had to be added, in his opinion.

From the O.R.S.T.O.M. data Wyrtki (1962b) calculated the volume transport (at about 163 E) into the Coral Sea between the Solomon Is (11 S) and about 18 S where the reef system extending northwest from New Caledonia ends, and obtained, from the surface to 1000 m:

Nov. 1956	23 sv	Feb. 1960	25 sv
June 1958	26 sv	May 1960	12 sv
Nov. 1958	6 sv	Aug. 1960	15 sv
	Mean 18 sv		

The transport maximum occurred at 100–300 m depth and on two occasions there was a small net transport to the east between the surface and 100 m. The speed of this flow was small, only 3 to 5 cm/s at its maximum.

Donguy, Oudot & Rougerie, 1970—Review of 1956–68 northern Coral Sea data

In their review of the Coral Sea circulation, Donguy *et al.* (1970) found that below the surface, at 150–200 m (Fig.56C, D), the same currents were present as at the surface but the South Equatorial Current penetrated well into or across the Coral Sea in both seasons, and the salinities were higher than at the surface. The speeds in the vicinity of 160 E averaged about 3 cm/s.

Rougerie & Donguy, 1975—'Gorgone 1' 1972, late winter

During the 'Gorgone 1' cruise (Rougerie & Donguy, 1975), the flow below the surface was generally similar to the flow at the surface except that the (eastward) counter currents were weaker and shallower than the westward currents. At about 150 m (salinity maximum) and at 300 to 500 m (oxygen minimum) the westward flow predominated. The South Equatorial Counter Current was present north of 10 S but the South Tropical Counter Current had practically disappeared. At 500 to 700 m (oxygen maximum) the flow was zonal in the eastern and southern parts of the Coral Sea but the part north of 15 S turned to the north into the Solomon Sea at about 155 E.

The westward transport of the South Equatorial Current was 37 sv across 153 E. The South Tropical Counter Current carried 3 sv at 153 E.

Rougerie & Donguy (unpubl.)—'Gorgone 2' 1975, late summer

Although the analysis is not complete, some preliminary comparisons between this 'Gorgone 2' late summer and the 'Gorgone 1' late winter results can be offered.

The end of the summer is characterised by the marked development of eastward flows. Between 10 and 12 S the South Equatorial Counter Current reaches 50 cm/s at the surface and still has a speed of 20 cm/s at 200 m. Its depth decreases eastward and on leaving the Solomon Sea the 20 cm/s isotach is at only 100 m depth. Between 15 and 17 S at the end of the summer the South Tropical Counter Current is slower and shallower than the South Equatorial Counter Current but shows the same decrease in speed and depth as it progresses eastward. Its southern boundary coincides with a thermohaline front where the salinity exceeds 35.0 ‰ and the temperature falls below 28 C.

Dynamic height calculations relative to 1000 db indicated the presence in this zone during 'Gorgone 2' of a trough identical to that observed during 'Gorgone 1' and at the same position, 16.5 S, 156 E. This continuing dynamic structure is associated with the presence here of an isohaline, nutrient-poor layer which is about 100 m deep and was of considerable horizontal extent during 'Gorgone 1'. This trough is at the centre of a cyclonic gyre with which the eastward flow appeared to be closely related. The continuance of the gyre may be associated with the flow but it is possible that it is only when the SE trades weaken (in the summer) that the waters start moving to the east and develop the South Tropical Counter Current. This was inconspicuous during 'Gorgone 1' (at the end of the SE trades season) but reached a speed of 15 to 35 cm/s at the surface

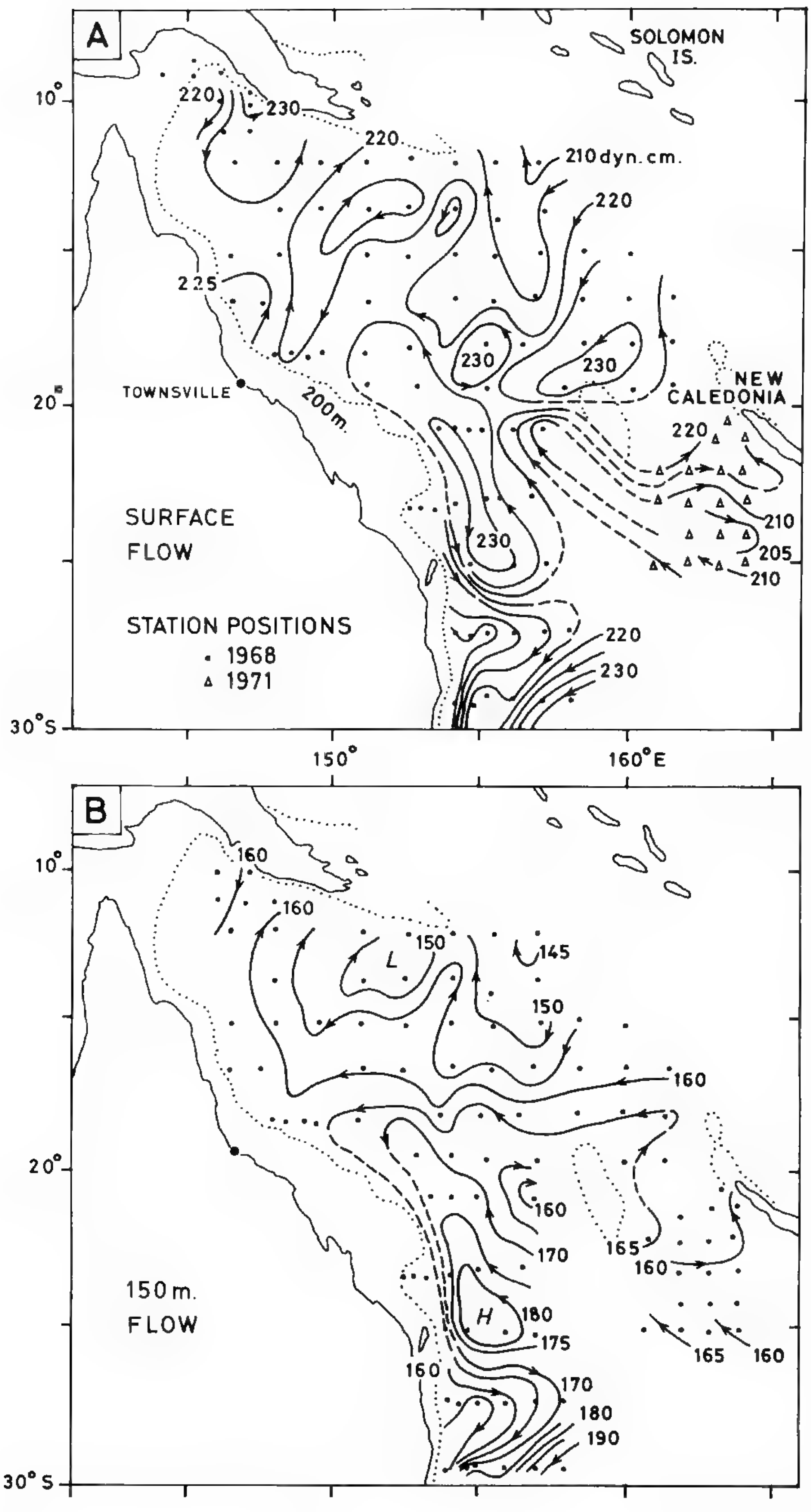


Fig. 58 Geopotential topography and flow patterns relative to 1500 db, Western Coral Sea, May–July 1968, (A) surface, (B) 150 db level (Scully-Power, 1973a).

during 'Gorgone 2'. During this cruise, the South Equatorial Current, squeezed between the two counter currents and opposed by the NW winds, had a surface speed of less than 20 cm s. In the north-west of the Solomon Sea the westward flow had a similar speed but below the surface had a core of about 100 m thickness with a speed of 30 cm s.

Scully-Power *et al.*, 1969, 1973 a,b,c—Geostrophic circulation May-July 1968 and volume transport budgets, Western Coral Sea

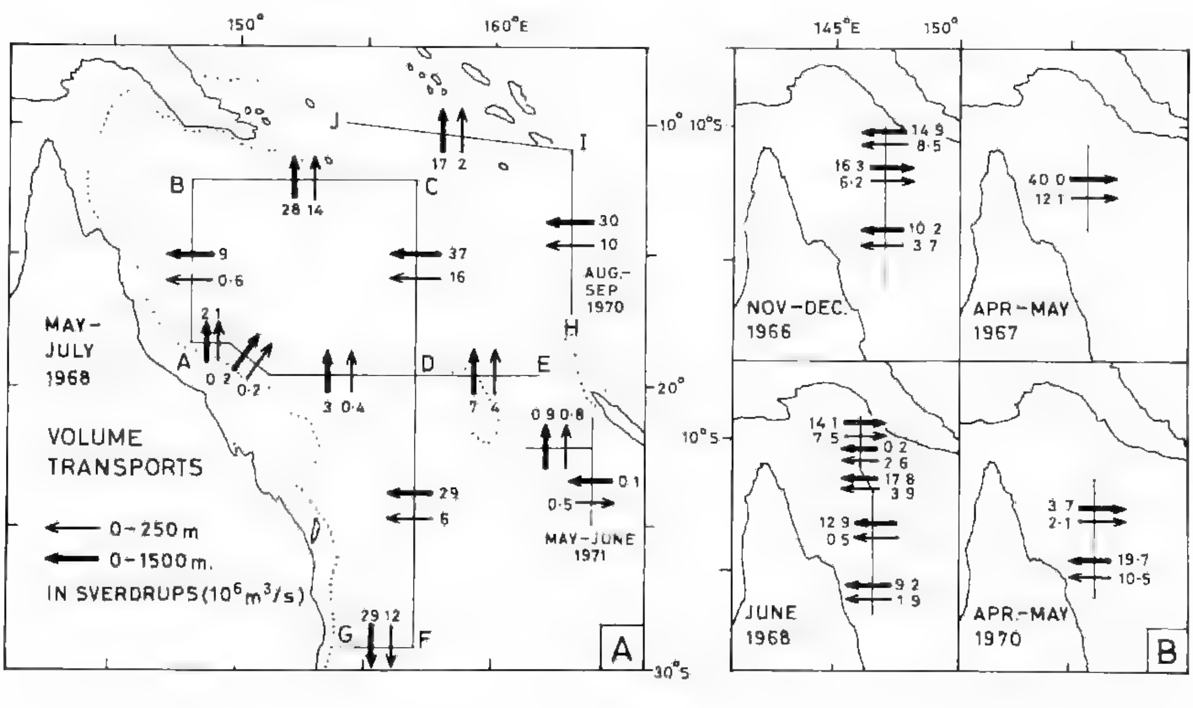
Lockerman & Scully-Power (1969) found clockwise circulation in the North-west Coral Sea at the 900 db level (about 900 m) in November 1966 with speeds of 5 to 8 cm s, and in April 1967 they found what appeared to be the northern half of a clockwise circulation with speeds of 15 to 20 cm/s. This meant that the whole column from the surface to 900 m had a clockwise circulation. Wyrtki's (1962b) calculations for this region showed little movement below 400 db.

Fig.58B shows the circulation at about 150 m, the level of the core of the Subtropical Lower (salinity maximum) water in the WCS, from Scully-Power's (1973a,b) study of the winter regime. The circulation at this level was simpler than at the surface (Fig. 58A) but had the same main features. The division of the main westward flow at 18.5 S when it reached the Barrier Reef was clearer than at the surface where it occurred at about 19 S, close to the average for May to July in Wyrtki's (1960) charts.

Scully-Power pointed out that the dynamic topography slopes at 150 m were not very different from those at the surface, and he considered that the flow pattern at this level was probably representative of the mean flow of the whole upper layer, the irregularities in the surface pattern probably being due to local wind stress variations. The circulation at 900 db (Antarctic Intermediate water) relative to 1500 db was basically the same as at 150 m although much reduced in intensity (speeds about one-fifth of those at 150 m), and the strong flow to the south off Gt Sandy Is. was absent.

Scully-Power (1973c) went on to calculate volume transport budgets for the Coral Sea by selecting quasi-synoptic (i.e. near simultaneous) sections and calculating the flow across each of these from the surface to 250 m and surface to 1500 m depth (Fig. 59A). This showed a westward flow of 37 sv across 157 E (CD) into the WCS. Of this 28 sv

Fig. 59 Volume transports in sverdrups (10^6 m^3 s), (A) Western Coral Sea, May–July 1968, (B) North-western Coral Sea (Scully-Power, 1973c).



flowed out to the north into the Solomon Sea across BC (Fig. 59A), 9 sv into the North-west Coral Sea (AB) and only 2 sv south (AD), apparently into the Barrier Reef Lagoon. The entire southward flow of 29 sv across 20°S (EC) into the East Australian Current was supplied from the east across 157°E south of 20°S (DE). The pattern was the same for the upper layer flow above 250 m.

In August and September 1970, data from a R.A.N.R.L. cruise (Wood, 1971b) showed westward flow across 163°E (HI in Fig. 59A) from the Solomon Is. to 15°S and a strong clockwise eddy between 15°S and New Caledonia. The westward flow across HI had a maximum speed at about 300 m (Subtropical Lower water) while the northward flow across section IJ into the Solomon Sea had its maximum at about the same depth (the upper layer flow across this section being weak and to the south). These subsurface flows corresponded to the subsurface components of the South Equatorial Current described by Donguy *et al.* (1970), some penetrating into the WCS and some north-west through the Solomon Sea.

Scully-Power (1973c) described transport calculations for the North-west Coral Sea for the summer of 1966 and winters of 1967, 1968 and 1970, all of which showed a northerly surface flow off Cairns turning east near the Papua New Guinea coast. The subsurface flow had the same pattern, always a northerly component flow along the north Queensland coast. The transports calculated between individual stations are shown in Fig. 59B. The main feature here was the variability with time, a characteristic of the WCS in general and of the North-western Coral Sea in particular. Scully-Power remarked on 'the only common feature being the westerly flow in the south part of the (North-west Coral Sea) region and the easterly flow north of this'.

In summarizing, Scully-Power (1973c) considered that the most striking feature of the winter regime in the WCS was the north-westerly outflow to the Solomon Sea and the lack of southerly flow across 20°S in contrast to previous concepts, mostly from summer data, of the westerly flow between the Solomon Is. and New Caledonia into the Coral Sea north of 20°S converging to supply a continuous East Australian Current to the south along the Australian coast (e.g. Reid, 1961; Wyrtki, 1960, 1962b). Scully-Power pointed out that if *Gascoyne* cruise 1/63 summer data (CSIRO, 1967) were added to the data used by Wyrtki (1962b) 'this continuity of the south-west flow in the Coral Sea during summer would be broken up into a series of anticlockwise eddies and the assumption of a continuous flow to the south from 15°S may have to be modified'. He suggested instead a series of southward meandering anticlockwise eddies originating at about 15°S in summer and about 20°S in winter. He also noted that the winter pattern agreed with that proposed by Donguy *et al.* (1970) although there was no evidence in his data of the South Tropical Counter Current.

Scully-Power went on to discuss possible aspects of the dynamics of the East Australian Current as a western boundary current but this is beyond the scope of this review. (Hamon, e.g. 1965, 1968, 1970, 1973, 1974 and Godfrey, e.g. 1971, 1973a, b, have described and discussed various aspects of this Current and reference may be made to their papers.)

Finally, Scully-Power commented that the North-western Coral Sea was the most complex area of the WCS. He suggested that as the flow through Torres Strait (maximum estimated as 0.9 sv, CSIRO 1958) was an order of magnitude less than the other flows calculated for the area (Fig. 59B) the North-western Coral Sea could be considered a closed basin and the flows as being in geostrophic balance during the winter. In the summer, however (e.g. November, December 1966, Fig. 59B), a southward flow along the slope off Cairns would be needed to balance the flow budget. The results of the study of the May 1972 R.A.N.R.L. cruise in the North-west Coral Sea are awaited with interest.

FLUSHING CHARACTERISTICS OF THE WESTERN CORAL SEA

It is interesting to use Scully-Power's volume transports to estimate the flushing characteristics of the WCS, i.e. the relations between the volume flows and the volumes of water in the basins. This has been done for three areas of the WCS, the North-west Coral Sea, the main body between about 12 S and 20 S, and the southern part between about 20 S and 29 S. These areas were chosen to enable Scully-Power's (1973c) volume transports to be used. It has been assumed that the transport in the upper 1000 m would be 90% of Scully-Power's values calculated to 1500 m, and the Reef areas have been assumed to be 100 m deep. The figures obtained are shown in Table 8.

For areas 2 and 3 the annual inflow is greater than the basin volume of the upper layers, which implies, to a first approximation, that the water will be replaced in less than one year ('replacement time'). In estaurine oceanographic jargon these basins are 'well flushed' for such large areas. The value of 5 years replacement time for the 0–250 m layer in area 1 follows from the net transport of only 0.6 sv into the area (across section AB, Fig. 59A) which appears unreasonably low by comparison with the larger values (by a factor of ten) across this section for other cruises (Fig. 59B). A more likely replacement time would be about 0.5 to 1 year, similar to the values for the other areas.

It will be appreciated that these estimates, which extrapolate values from one three-month period to annual values, must be regarded as only approximate; but as there is no indication that the circulation changes drastically during the year, they are believed to be realistic. Naturally, year-to-year variations are to be expected.

UPWELLING OFF THE EAST AUSTRALIAN COAST

Godfrey (1973) made some calculations of transport relative to 1300 db off the east Australian coast between positions approximately as follows: (A) 18 S, 147 E; (B) 19 S, 157 E; (C) 28 S, 158 E; (D) 39 S, 155 E; (E) 38 S, 150 E, using such data as were available near to those points. Across ABC there was a very small net outflow above 100 m and an inflow from 100 1300 m of about 18 sv, with its maximum at 300 m. There was an indication that most of this inflow was across the north-south section BC. Across CD there was a strong outflow (to the east) with its maximum at the surface and most of the flow above 300 m; across DE there was a less strong outflow with its maximum near the surface. The sub-surface inflow and strong surface outflow implied upwelling between the coast and the line ABCDE, probably within 50 km of the coast. The vertical flow was calculated to have its maximum at 250 m depth with a value of 7.5 sv, corresponding to a vertical speed of about 10 m/day which is a high value for upwelling. It should be noted that the upwelled water was not high in nutrient content. Typical values for P-PO_4 were:

Depth:	Sfc	100 m	200 m	400 m
P-PO_4:	0.1	0.15	0.3	1.0 μg at/l.

Table 8. Basin volumes and volume flows into the Western Coral Sea

Area			*Sfc. to 250 m (incl. reefs ass. to be 100 m deep.) (x10^{14}m^3)*	*250 to 1000 m (excl. reefs) (x10^{14}m^3)*	*Replacement time = basin volume/inflow per yr* Sfc. to 250 m (years)	*250–1000 m (years)*
NW Coral Sea	Vol	:	1.0	2.3	5	1
(west of 148 E)	Inflow/yr	:	0.2	2.4		
Main WCS	Vol	:	2.0	5.9		
(148 E to 157 E.					0.4	0.9
12 to 19.5 S)	Inflow/yr	:	5.3	6.9		
South WCS	Vol	:	1.2	2.8		
(west of 157 E,					0.5	0.4
19.5 to 29 S)	Inflow/yr	:	2.2	6.9		

VI
Summary

WATER MASSES

Introduction

The previous paragraphs have reviewed the majority of the papers relating to the Coral Sea and that material on the Solomon and Tasman Seas necessary for physical continuity and to relate the Coral Sea information to possible source areas of its water masses. Figs. 60, 61 and 62 summarise, from the above review, the main characteristics of the waters of the WCS itself; most weight has been placed on data from the R.A.N.R.L. 1968 cruises described by Scully-Power and on those parts of the O.R.S.T.O.M. 'Gorgone' cruises which overlapped the WCS and were described by Rougerie and Donguy.

The usual way to summarise water mass characteristics is numerically in table form; the alternative is to do it graphically using characteristic diagrams. While the table form is convenient for reference and for quotation it has some disadvantages. The first is that the ranges of properties in a water mass and the relations between masses are less easy to appreciate numerically than in a diagram. The second is that a table can be misleading. For instance, the conventional table form description of the linear part of the T,S characteristic in Fig. 51A would be T = 8–20°C, S = 34.5–35.8‰, which specifies a rectangle on the T,S diagram whereas the actual T,S combinations observed in the sea are limited to a diagonal strip occupying only 20% of the rectangular area. The precision possible with the numerical statement is rarely needed. Accordingly this summary of water properties is presented in graphical form.

Surface waters

Characteristic diagrams. Fig. 60 shows first the envelope of actual surface water T,S characteristics for the WCS in winter (full line) from Scully-Power (1973a, b). To his envelope has been added a scale of latitude because the surface T,S values are distributed along the envelope from the Gulf of Papua values at the high temperature, low salinity end to the values south of Brisbane at the low temperature, high salinity end.

In addition, the following have been added on Fig. 60:

(a) an estimate of summer surface T,S values (dashed line) based on CSIRO Atlas (1974) data,

(b) T,S characteristics of external water masses which probably contribute to the make-up of the WCS surface waters.

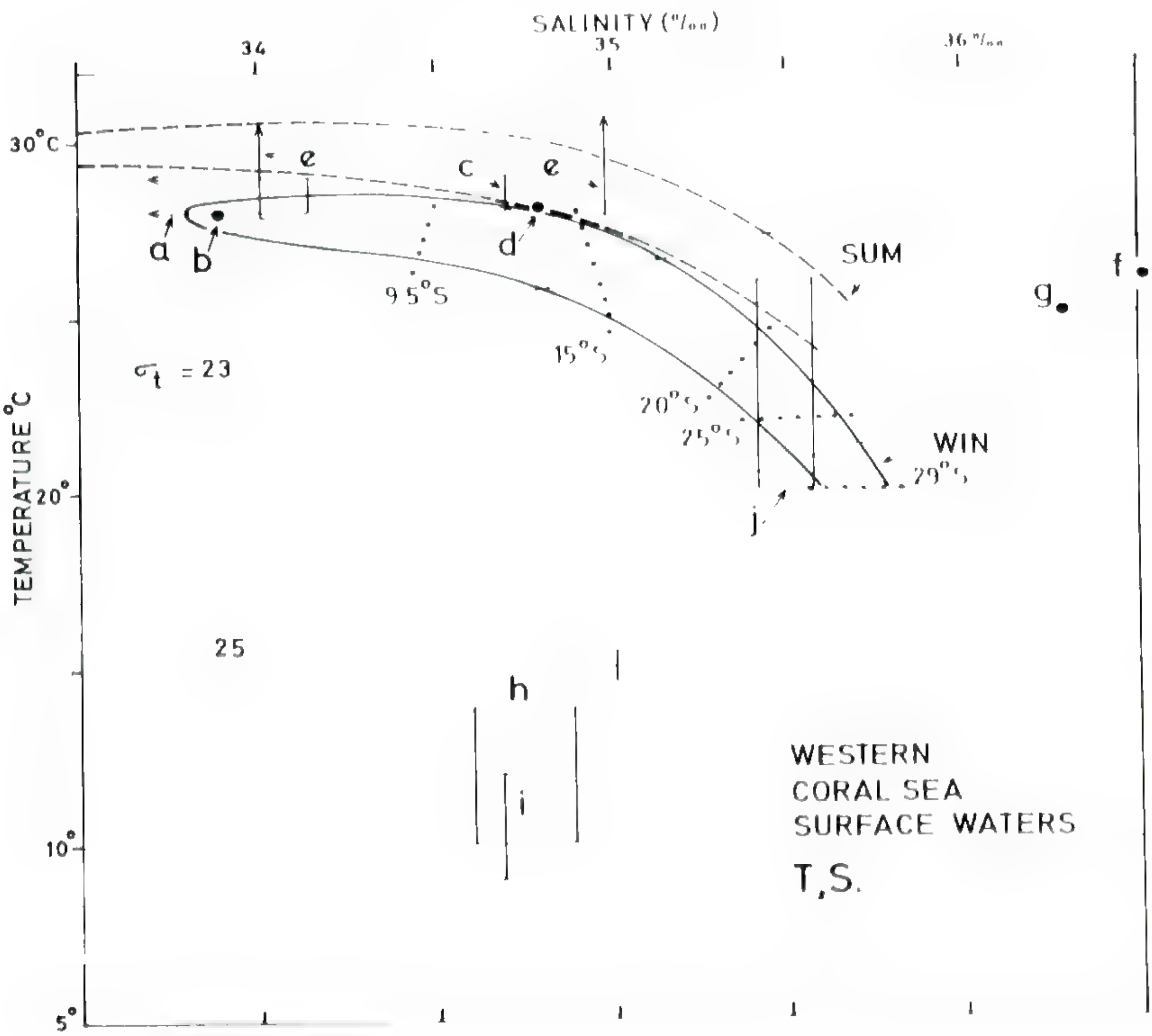
In Fig. 62, the envelope of surface water T,S values for the two westerly lines of stations in the Coral Sea during the O.R.S.T.O.M. 'Gorgone I' cruise is shown. This covers a smaller area in the diagram than that for the R.A.N.R.L. cruises, probably because the stations used covered a smaller area of the Coral Sea and particularly because the cruise did not extend into the North-west Coral Sea where were found the low salinity values which extended the R.A.N.R.L. envelope.

S,O_2 diagrams for the surface waters are not presented because they generally do not give much more information than the T,S diagram. The reason is that the surface waters are usually very close to being saturated with dissolved oxygen and, as the saturation value is determined chiefly by temperature, an S,O_2 diagram for surface waters is basically an S,T diagram with increasing oxygen replacing decreasing temperature (because the saturation value for oxygen decreases as temperature increases).

Geographic distributions and seasonal variations. The presentations of surface temperature and salinity in Figs. 35, 36, 39 and 40 are the best that can be given at the present. They should be used subject to the limitations discussed in the text.

The semi-geographic presentations of Fig. 41 may be adequate for some purposes, and also show the seasonal cycles well, both as T,time and S,time plots and as combined T,S,time diagrams.

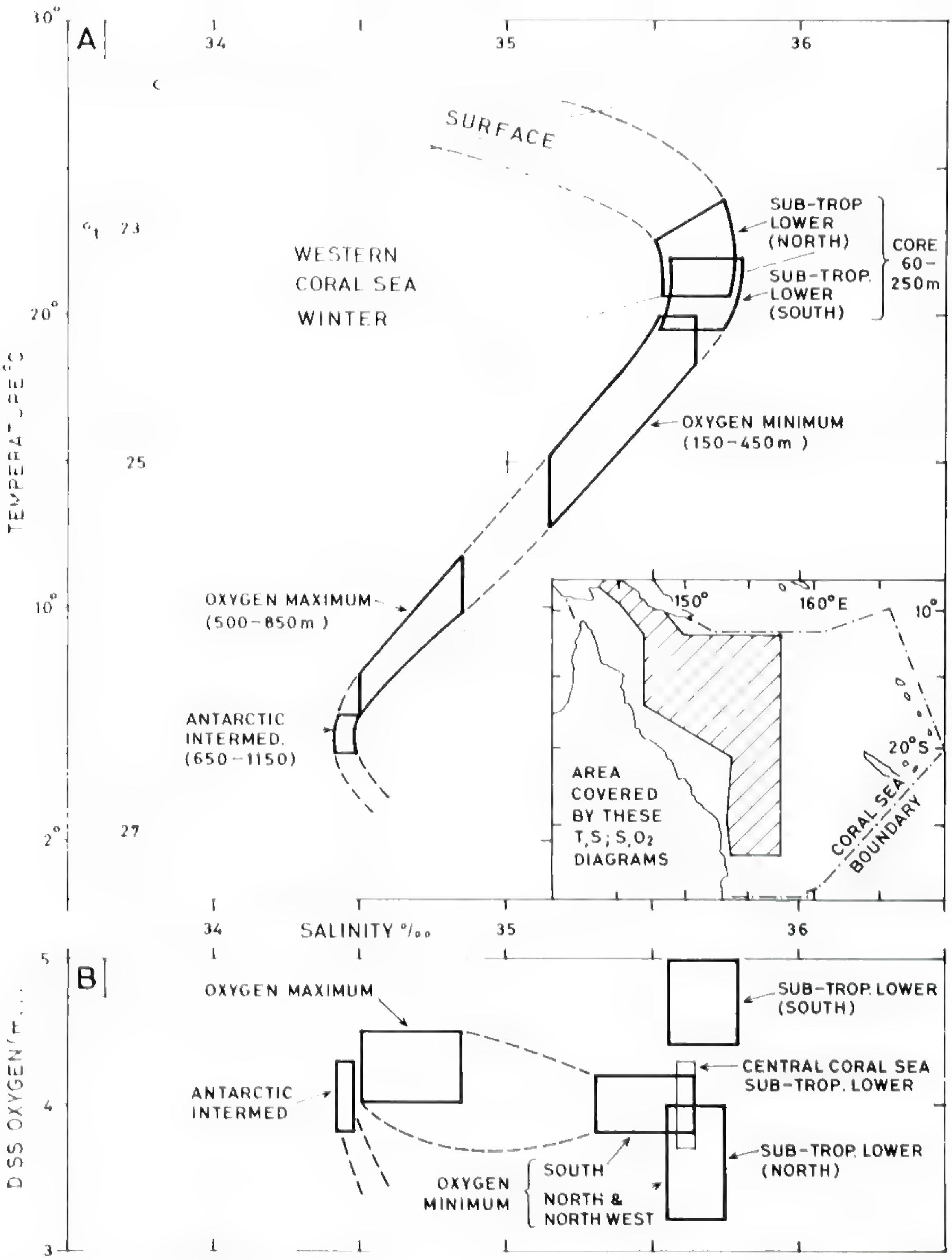
Fig. 60 T,S diagrams, Western Coral Sea, surface waters, winter and summer, and external source waters. Key: Western Coral Sea, j (Coral Sea surface, Rochford, 1959), WIN (winter envelope, Scully-Power, 1973a), SUM (summer envelope, estimated). External water masses: Arafura Sea, a (Rochford, 1959), River runoff type, b (Scully-Power, 1973b), South Equatorial, c (Rochford, 1959), d (Scully-Power, 1973a), e (Rougerie & Donguy, 1975), West Central South Pacific, f (Rochford, 1959), g (Rotschi & Lemasson, 1967), Subantarctic surface, h (Rochford, 1959), i (Rotschi & Lemasson, 1967).



Subsurface waters

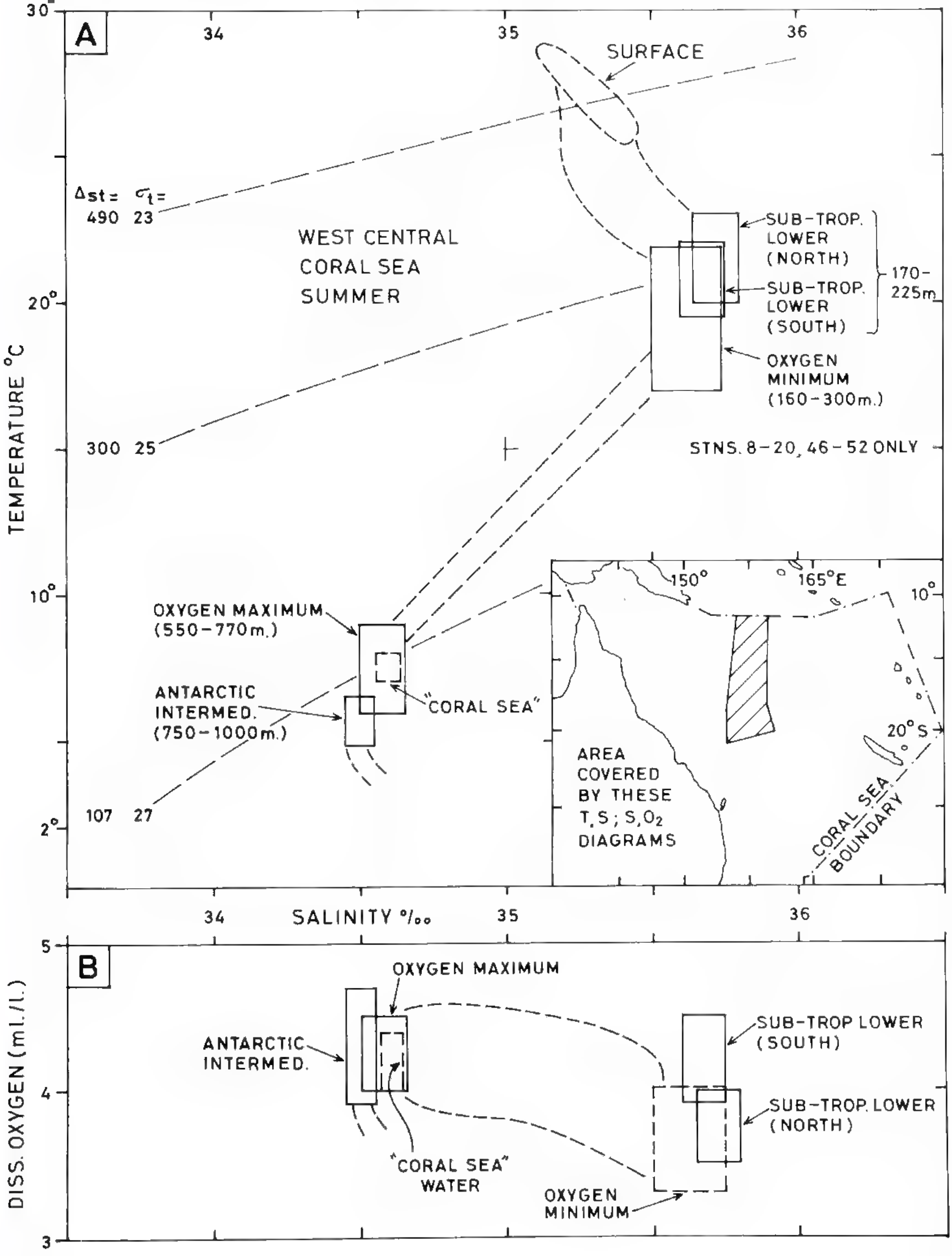
Characteristic diagrams. Figs. 61 and 62 present the subsurface property envelopes for T,S and S,O_2 to 1200 m depth during the R.A.N.R.L. 1968 (winter) and the O.R.S.T.O.M. 'Gorgone I' 1972 (summer) cruises. The greater extent of the oxygen minimum and maximum areas in the R.A.N.R.L. data is probably due to the larger area of the Coral Sea covered. In the S,O_2 diagrams, the major difference is the lower oxygen

Fig. 61. (A) T,S and (B) S,O_2 diagrams, subsurface water, winter, Western Coral Sea (data from Scully-Power, 1973a; Scully-Power & France, 1969a, b, c)



content of the Subtropical Lower water, southern component, in the 'Gorgone 1' data. This is probably because the cruise area did not extend as far south as the R.A.N.R.L. one, and therefore did not pick up as much of the higher oxygen southern component. (Much of the Subtropical Lower water in the R.A.N.R.L. cruise area south of the 'Gorgone 1' area had oxygen values of 4.5 to 5.0 ml l.)

Fig. 62 (A) T,S and (B) S,O_2 diagrams, subsurface water, summer, West Central Coral Sea (data from Rougerie & Donguy, 1975, and 'Gorgone 1' data record, Donguy *et al.*, 1972b).



Of the data at present available, the R.A.N.R.L. set, Fig. 61, is recommended for describing the WCS subsurface waters, chiefly because it covers the defined WCS area most completely. The O.R.S.T.O.M. 'Gorgone I' set both supports it and suggests that seasonal changes are minor, as do the data in Fig. 54.

Geographic Distribution. The distribution of the main subsurface water masses are shown as follows:

(a) Subtropical Lower	:	by salinity	Figs. 49A, D, 50A, 52A,
		by oxygen	Figs. 49B, E, 52B,
(b) Antarctic Intermediate	:	by salinity	Figs. 49C, 52C,
		by oxygen	Figs. 49F, 52D.

The alternatives above are offered to emphasise that the water mass locations can only be shown approximately as there are doubtless variations from year to year as for the surface circulation, but there is insufficient information to specify limits to regions of occurrence of particular isopleths.

'Coral Sea water'

Three different water masses using the 'Coral Sea' designation should be noted:

(1) Coral Sea surface water, Fig. 60(f) Rochford (1959),

(2) Central Coral Sea Subtropical Lower water, Fig. 61B Scully-Power (1973a, b),

(3) Coral Sea water of the oxygen maximum above the Antarctic Intermediate water, Fig. 62B Rougerie & Donguy (1975).

CIRCULATION

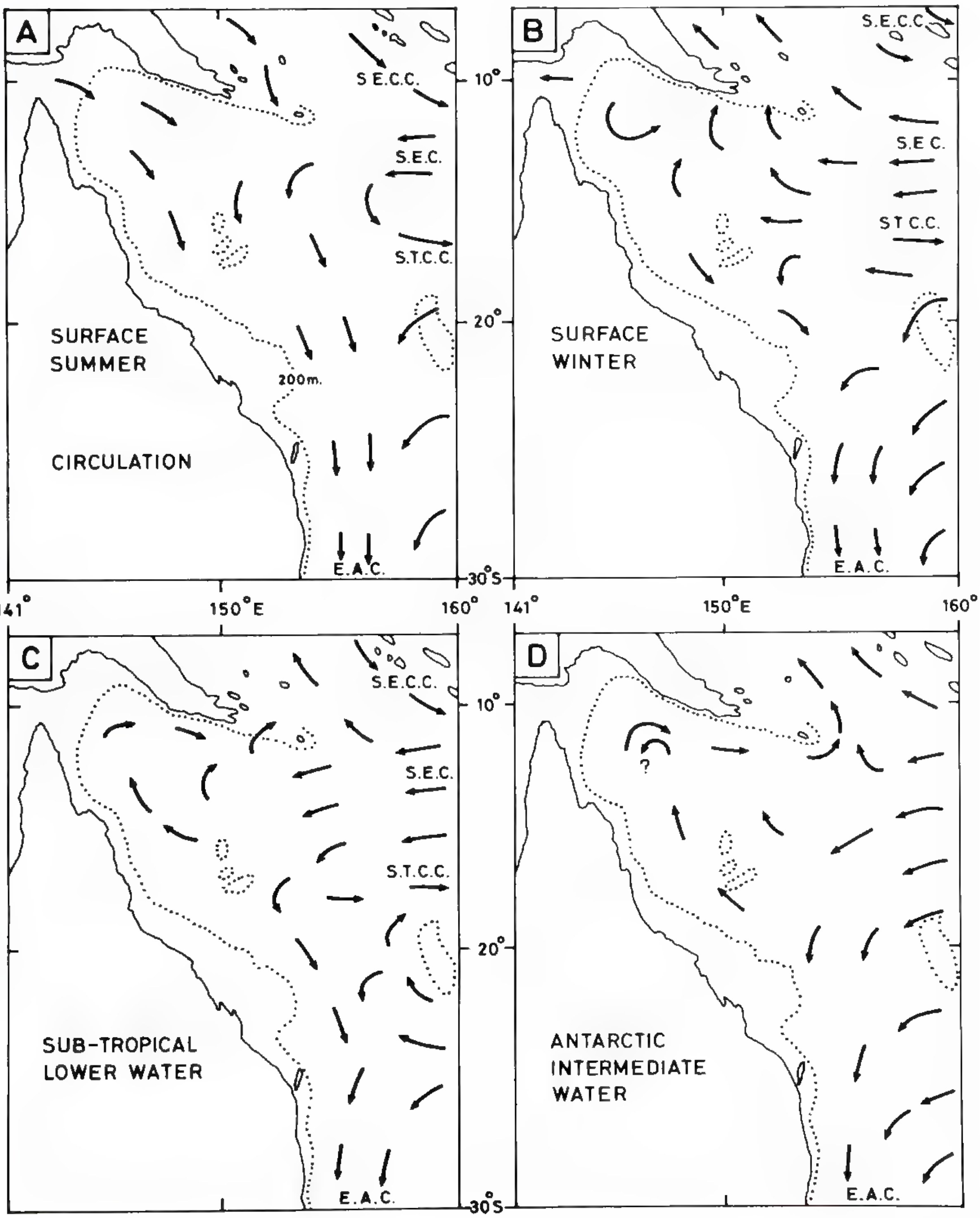
The most difficult aspect to summarise was the circulation, and it was not possible to produce a mean circulation chart which would satisfy all the suggestions. There does seem to be evidence of seasonal change in the surface circulation, but there is insufficient data to identify seasonal changes in the circulation of deeper waters. Even in the surface waters there is not enough information to bring Wyrtki's (1960) current atlas up to date with much confidence even though there are known to be discrepancies between it and later data.

Fig. 63 shows most of the features of the circulation at the surface (summer and winter), and for the Subtropical Lower and Antarctic Intermediate waters. The major features are inflow (to the west into the WCS) across 160°E north of about 15°S (the South Equatorial Current), outflow (to the east) between 15° and 17°S (South Tropical Counter Current) and inflow (to the west) south of 20°S at all levels. There is outflow much of the year north west into the Solomon Sea and south across 30°S to the East Australian Current all year. Scully-Power (1973a) stressed that in the winter study of 1968 most of the latter flow was fed from south of 20°S (across 160°E) with little net flow to the south across the 20°S parallel, but it is difficult to discount evidence of southward flow across 20°S at some times. At the surface, some inflow (eastward) through Torres Strait occurs during the NW monsoon for two or three months, with westward outflow for the rest of the year. However, the volume transport either way is probably only about 1 sv, which is much smaller than the other flows in the WCS.

Many of the details of these circulations are uncertain. In particular, in the North-west Coral Sea the results of Lockerman & Scully-Power (1969) show a clear clockwise circulation at the surface and at 900 db whereas Scully-Power (1973a) shows anticlockwise circulation at the surface and 900 db and less clearly at 150 db. In addition, it must be expected that variations in the flows will take place from time to time, and that the surface circulation will be subject to local short-term variations due to wind stress variations.

From the flow budgets calculated by Scully-Power an analysis suggests that the waters of the upper 1000 m of the Western Coral Sea are replaced in one-half to one year, i.e. the region is well flushed.

Fig. 63 Mean circulations, Western Coral Sea, surface: (A) summer, (B) winter; subsurface: (C) Subtropical Lower water, core depth 50–250 m, layer thickness 200 m ($>$ 35.5), (D) Antarctic Intermediate water, core depth 650–1150 m, layer thickness 400 m ($<$ 34.5). Abbreviations for current names as for Fig. 56.



Appendix

Units, conversion factors and glossary

1. Length:

1 nautical mile	1 n ml	= 6080 ft		= 1.85 km	
1 degree latitude (mean for 10°–25° S).	59.8 n ml			= 110.7 km	
At latitude	10°	15°	20°	25°	30° S
1 deg long	59	58	57	55	52 n ml approx.
	110	108	105	101	96 km approx.

Typical dimensions of the Western Coral Sea (to 155° E):

Linear: N–S:	15 deg lat	900 n ml	1700 km approx.
E–W:	10 deg long	600 n ml	1100 km approx.

	Reef area	Deep ocean	Total
Area	3.3×10^5 km^2	11.5×10^5 km^2	15×10^5 km^2
	3.3×10^{11} m^2	11.5×10^{11} m^2	15×10^{11} m^2
Volume	0.33×10^{14} m^3 (ass. 100 m deep)	11.5×10^{14} m^3 (to 1000 m depth)	12×10^{14} m^3

2. Speed:

Mariners normally use one knot = 1 n ml/hr. Oceanographers sometimes use knots but usually use 1 cm/s for slower currents and 1 m/s for faster ones. While these units are satisfactory for comparison of currents, they are not immediately related to the physical sizes of seas or everyday units of time. The following approximate conversion factors may be convenient for reference:

	10 cm/s	= 9 km/day	= 60 km/week	= 260 km/month
			= 0.5 deg lat/week	= 2.4 deg lat/month
1 kt	= 52 cm/s	= 44 km/day	= 310 km/week	= 1350 km/month
			= 3 deg lat/week	= 12 deg lat/month

3. Volume transport or flow:

The usual unit is 10^6 m^3/s. For compactness this is called 1 sverdrup = 1 sv = 1×10^6 m^3/s. (Ref. Pickard, 1975).

4. Density and σ_t; specific volume and $\Delta_{s,t}$:

The density (ρ) of a sample of seawater at atmospheric pressure is usually expressed in units of g/cm^3 but oceanographers normally use σ_t (sigma-t) defined as $\sigma_t = (\rho - 1) \times 10^3$. If ρ is in g/cm^3, then σ_t is in mg/cm^3. However, it is usual to omit the units for σ_t and treat it as a pure number. (Strickly speaking this is correct because operationally the quantity measured by oceanographers and called ρ is really the specific gravity, i.e. the ratio of the density of a seawater sample to that of pure water, which is a pure number. This fact is often forgotten.)

An alternative quantity, specific volume $\alpha = 1/\rho$, is used for dynamic oceanography calculations and related to this is the thermosteric anomaly, $\Delta_{s,t}$ which is often used in place of σ_t. The two are directly related as:

$\sigma_t =$	23	24	25	26	27	27.2	28
$\Delta_{s,t} =$	488	392	297	202	107	88	12 cl/t.

Thermosteric anomaly is usually stated with units of centilitres/tonne (cl/t) although it also is really non-dimensional.

5. Glossary:

Cyclonic — clockwise (in the southern hemisphere).

Isopleth — a general term for a line joining points of equal value on a two-dimensional plot, e.g. a contour line. Used when there is no specific name (e.g. isotherm, isohaline) in common use.

Decibar (db) — unit of pressure, 1 bar = 10 db = 1000 mb = 750 mm Hg. (In the sea, a pressure of 1 db is close to that exerted by a column of 1 m of sea water, so that the 100 db level is close to the 100 m depth etc.)

Dynamic height — really a unit of work, despite its name. If data from a number of oceanographic stations are available, the dynamic height of a given pressure surface may be plotted on a chart and contoured. Then (if friction is ignored) flow on that surface will be parallel to the contours of dynamic height and, in the southern hemisphere, the direction will be such that the greater dynamic height will be on the left when facing in the direction of flow.

The statement 'dynamic height (or topography) of the 150 db etc. surface relative to 1500 db' (for example) implies that it is assumed that the water at the 1500 db pressure level is stationary so that the speed may be calculated at the 150 db etc. levels. For more detail, refer to a text on dynamic oceanography, e.g. Sverdrup *et al.* (1942), Neumann & Pierson (1966).

Geostrophic flow — literally 'earth turned'; steady flow compatible with a balance between pressure forces due to the mass distribution and the (virtual) Coriolis force due to the rotation of the earth (and ignoring friction forces).

Mixing triangle method — See, for example, Rochford (1959, 1960a).

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Note: These references relate primarily to the physical oceanography of the area, and refer basically, although not exclusively, to the area west of [illegible] E and north of [illegible] S to the coasts of Australia and of Papua New Guinea.

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Some sources of aerial photographs of the Great Barrier Reef region (Dr J. Veron, personal communication):

1. Central Mapping Authority, Brisbane & Sydney
2. Commonwealth Department of Services & Property, Brisbane
3. Commonwealth Aerial Photography, Division of National Mapping, Department of National Resources, Canberra
4. RAAF Base, Laverton, Victoria

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