The contribution of local processus to seasonal hydrology of the Gulf of Carpentaria

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Abstract

The hydrology of the Gulf of Carpentaria, Australia, has been reassessed, based on new data collected from 1975 to 1977. There are enough data to build a reasonable picture of seasonal changes in six properties (temperature, salinity, density, oxygen, nitrate-nitrogen, silicate), and annual cycles of all properties are apparent. The horizontal distribution of these properties is broadly divided into central and coastal regions. Salinities and nutrient levels vary most in the coastal zone due to heavy monsoonal rains. In winter, temperatures are at their minimum and salinities at their maximum and vertically well mixed conditions predominate. In winter nitrate-nitrogen levels are particularly low at the bottom and silicate levels along the east coast are at their maximum. Summer shows the greatest temperature stratification, but salinities are relatively uniform, although the coastal zone may be affected by early monsoonal runoff. The origin of water types previously identified has been re-examined, and it appears that significant changes in Gulf waters take place in situ, *and may be as important as exchange with Arafura or Banda Sea waters. Local processes discussed include wind mixing, tidal stirring, solar heating and terrestrial runoff.*

Key words : Hydrology — Mixing — Seasonality — Gulf of Carpentaria.

Résumé

Rôle des phénomènes locaux dans le rythme hydrologique saisonnier du Golfe de Carpentarie

Sur la base de données nouvelles recueillies de 1975 à 1977, l'hydrologie du Golfe de Carpentarie, Australie, a été réétudiée. Ces données sont suffisantes pour établir un schéma des fluctuations saisonnières de six paramètres (température, salinité, densité, oxygène, nitrate, silicate) et un cycle annuel de chaque propriété est dégagé. La distribution horizontale de ces propriétés définit globalement deux régions, centrale et côtière. Les fortes pluies de mousson engendrent d'importantes variations de salinité et des teneurs en sels nutritifs dans les zones côtières L'hiver est caractérisé par des températures minimales, des salinités maximales et une grande homogénéité de la colonne d'eau ; en outre, les teneurs en nitrate sont particulièrement basses près du fond et les silicates présentent un maximum sur la côte est. En été, la stratification thermique est marquée, la salinité restant relativement uniforme, bien que la région côtière puisse être affectée par les apports consécutifs à une mousson précoce. L'origine des types d'eau identifiés antérieurement a été réexaminée, et il apparaît que la cause des variations observées dans le Golfe est autant à rechercher in situ *que dans les échanges avec les eaux des Mers d'Arafura et de Banda. Les mécanismes locaux discutés comprennent le mélange provoqué par les vents, l'agitation due aux marées, l'échauffement solaire et l'apport d'eau douce par ruissellement.*

Mots-clés : Hydrologie — Mélange — Variations saisonnières — Golfe de Carpentarie.

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INTRODUCTION

The Gulf of Carpentaria, a major feature of the north coast of Australia, is a roughly rectangular (900 km $\times$ 550 km), shallow (70 m maximum depth) body of water. It is an area of high tidal energy dissipation with an average water depth of only 50 m and therefore local processes such as tidal stirring and wind mixing are likely to dominate over advective processes in determining its hydrology.

Two extensive hydrological studies have been made by ROCHFORD (1966) and NEWELL (1973), which identified four different water masses in the Gulf and attempted to trace their origins to the Arafura, Banda and Coral Seas. Since these studies, two years of CSIRO cruises (1975-77) as background to a study of the larval ecology of penaeid prawns in the Gulf have expanded considerably the hydrological data base.

The origins of water masses found in the Gulf have been the subject of some speculation, but it appears from these latest data that seasonal *in situ* changes may be at least as important as the influence of the Arafura Sea. Rochford's hypothesis of the introduction of Coral Sea water in large quantities through the Torres Strait is addressed here on simple dynamic grounds.

OBSERVATIONS

Nine cruises at irregular intervals from October 1975 to May 1977 (listed in Table I) repeatedly occupied 70 hydrology stations, shown in Figure 1. Cruise tracks and station sequences differed slightly between cruises, but essentially the coverage remained constant, except for KL 07/76 and TP 05/77 which were limited to half the Gulf. Type 'A' hydrology stations consisted of Nansen casts with bottles every ten metres, surface to bottom, for temperature, salinity, oxygen, nitrate-nitrogen and silicate plus a bathythermograph digitised every five metres. Type 'B' stations were Nansen casts with three bottles — surface, ten metres and within ten metres of the bottom — for properties identical to type 'A'. Sigma-t (σ_t) values were generated from salinity and temperature observations. Surface and bottom values of each property were examined for horizontal, vertical and temporal variation. The difference between surface and bottom values was also calculated for all properties.

Because only eight out of twelve months of the year were covered by the cruises the results were interpreted by season, not by month. Spring was best covered with four cruises, autumn, with three cruises, while winter and summer had only one cruise each.

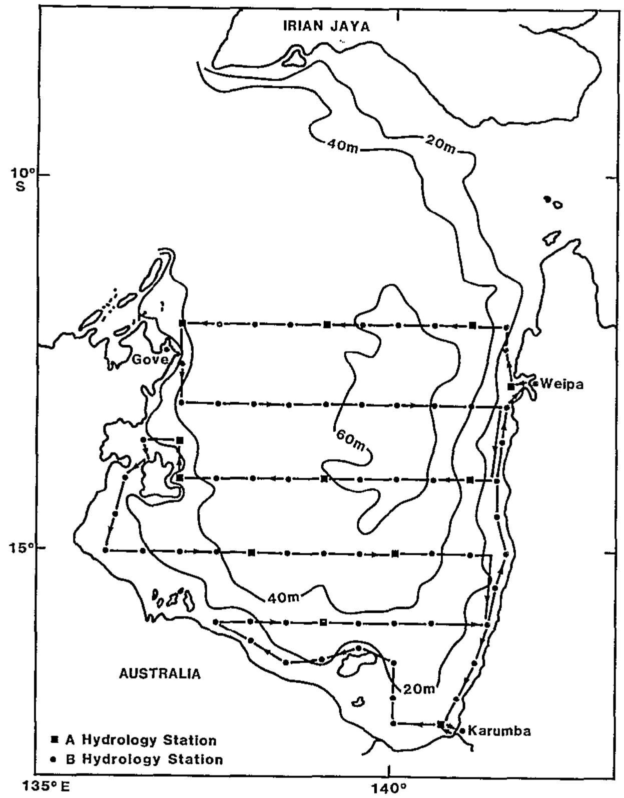

FIG. 1. — Location and bathymetry (depth in metres) of the Gulf of Carpentaria. A sample cruise track shows hydrology sampling stations

Bathymétrie (profondeurs exprimées en mètres) du Golfe de Carpentarie. Positions des stations hydrologiques

TABLE I

Hydrology cruise details

Croisières exploitées

Season	Period	Cruise Number	Time
Winter	June-August	KL07/76	June/July 1976
Spring	September-November	KL09/76	September 1976
		KL03/75	October 1975
		KL06/75	November 1975
		JB02/76	November 1976
Summer	December-February	TP01/77	January 1977
Autumn	March-May	TP03/77	March 1977
		KL04/76	April/May 1976
		TP05/77	May 1977

The coastal and central regions of the Gulf were defined as being separated by the 30 m depth contour.

RESULTS

Surface to bottom differences

The difference between surface and bottom values indicates the degree of mixing or homogeneity in the water column. Criteria used to differentiate between mixed and stratified regions are shown in Table II.

Table III gives a summary by season for each property based on these criteria.

Temperature vs. salinity

Temperature vs. salinity was pooled for the whole Gulf by season and plotted for each season (Figs 2-5). Boxes delineating the water masses A, B and C identified by Rochford (1966) and type D by Newell (1973) are also shown. The characteristics of water masses A, B, C and D and their possible origins are listed in Table IV.

From the T-S plots, it is immediately obvious that except for water mass 'B', salinities measured in the 1975-77 cruises were lower by up to 2 ‰ than in the 1970-71 cruises. A nearly identical range of temperatures was found in autumn, winter and spring. Cruise TP 01/77 is representative of the summer season, but there have been no water mass identifications made for summer from earlier surveys so no comparison can be made.

TABLE II

Simple mixing criteria for 7 water properties in the Gulf of Carpentaria

Critères de mélange de 7 propriétés hydrologiques du Golfe de Carpentarie

Property	Surface-bottom differences		
Temperature	Mixed <	1 °C	< stratified
Salinity	Mixed <	0.5‰	< stratified
Sigma-t	Mixed <	0.5	< stratified
Oxygen	Mixed <	1 mℓ/ℓ	< stratified
Oxygen saturation	Mixed <	10%	< stratified
Nitrate-nitrogen	Mixed <	1 µg atom/ℓ	< stratified
Silicate	Mixed <	4 µg atom/ℓ	< stratified

TABLE III

Gulf stratification by season for 7 properties

État de la stratification par saison pour 7 propriétés hydrologiques

Season	Properties						
	Temperature	Salinity	σ_t	O_2	% O_2	NO_3-N	SiO_2
Winter	Mixed	Mixed	Mixed	Mixed	Mixed	Mixed	Mixed
Spring	Centre stratified	Mixed	Centre stratified	Centre stratified	Centre stratified	Mixed	Mixed
Summer	Centre stratified	Mixed	Centre stratified	Centre stratified	Centre stratified	Centre stratified	Stratified
Autumn	Mixed	Coast stratified	Centre mixed Coast stratified	N.W., N.E. stratified	Coast stratified (except S.)	Centre N.E. stratified	Coast stratified

DISCUSSION

Temperature

A distinct annual cycle is apparent, both at the surface and bottom. Minimum surface temperatures occur in winter, 26 °C in the centre, 20-22 °C at the coast, and minimum bottom temperatures also in winter of 25-25.5 °C in the centre and 20-20.5 °C at the coast. Maximum surface temperatures occur in late spring, 30 °C in the centre and 31 °C at the coast, but maximum bottom temperatures occur in summer, 26.5-28 °C in the centre and 30 °C at the

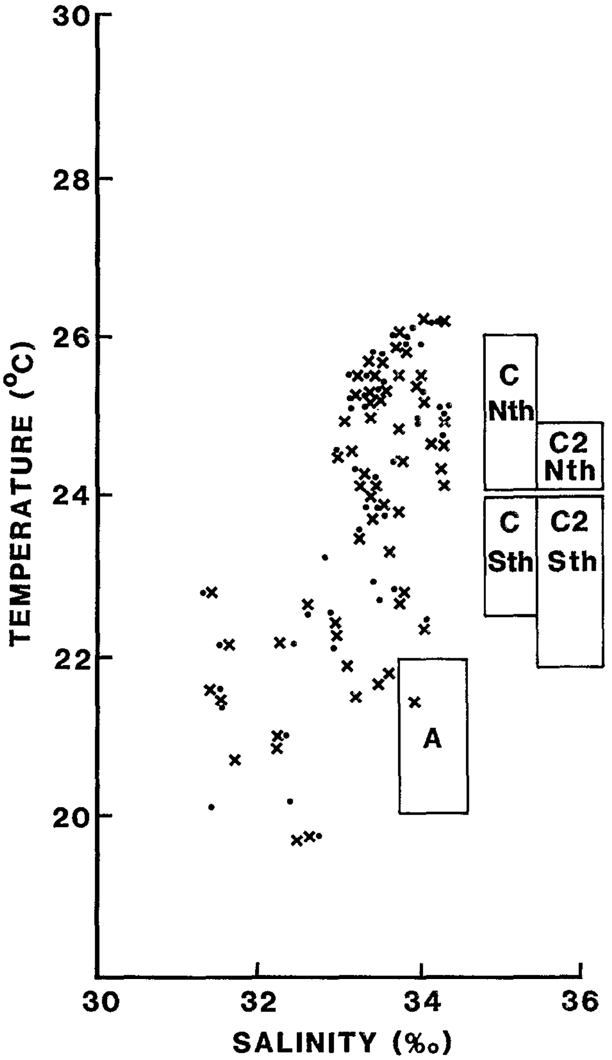

FIG. 2. — T.S. (Temperature vs. Salinity) diagram for winter. In Figures 2, 3, 4 and 5 (•) are surface values and (X) deep values for the whole of the Gulf; previously identified water masses are enclosed by boxes; "Sur" and "Bot" indicate different characteristics in surface and bottom water and "Sth" and "Nth" indicate southern and northern regional differences

Diagramme T.S. (température/salinité) d'hiver. Sur les Figures 2, 3, 4 et 5 (•) indique une valeur de surface et (X) une valeur profonde pour l'ensemble du Golfe; les masses d'eau antérieurement définies sont matérialisées par des cadres rectangulaires; « Sur » et « Bot » signalent des caractéristiques différentes en surface et près du fond; « Sth » et « Nth » signalent des différences régionales entre le Sud et le Nord

coast. Summer surface temperatures at the centre are usually 1° cooler than in spring. This is probably the result of the prevailing northwest winds (which peak in January) producing a deeper mixed layer in the centre than at the coast. If the solar radiation

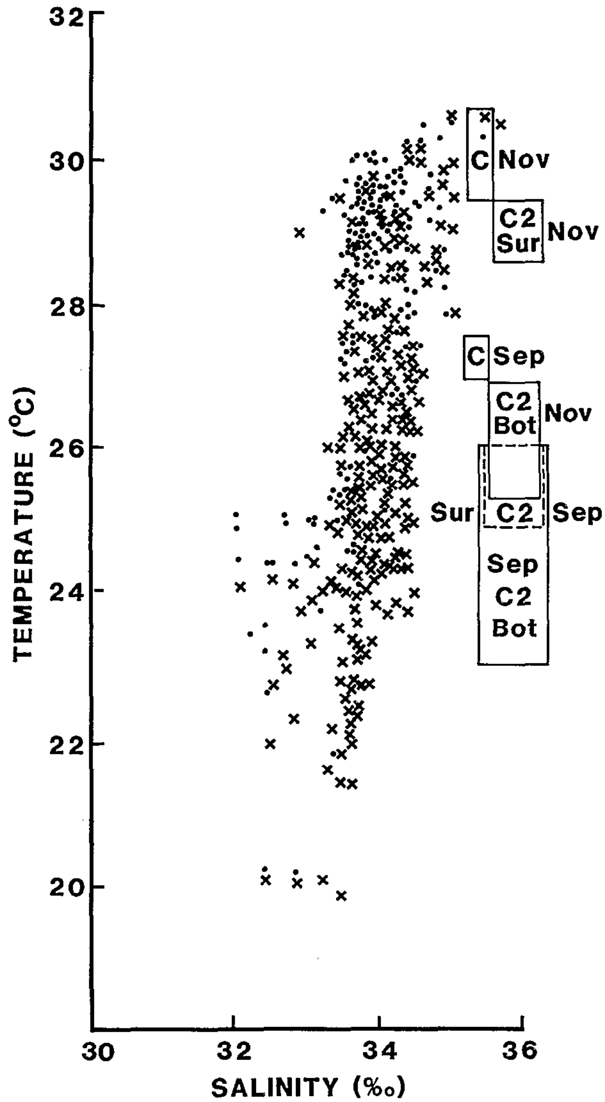

FIG. 3. — T.S. diagram for spring. See Figure 2 for details

Diagramme T.S. de printemps. Voir Figure 2 pour l'explicitation des symboles

input is the same in both regions this would result in lower surface temperatures in the centre, because the same amount of heat is mixed through a greater depth of water.

Salinity

Autumn rains in March appear to have the major influence on surface and bottom salinities. Coastal surface salinities may be reduced to 20 ‰, and bottom salinities to 27 ‰. By June (early winter), coastal surface salinities recover to 31-32 ‰ (0.5 ‰ greater at bottom). During the remainder of the

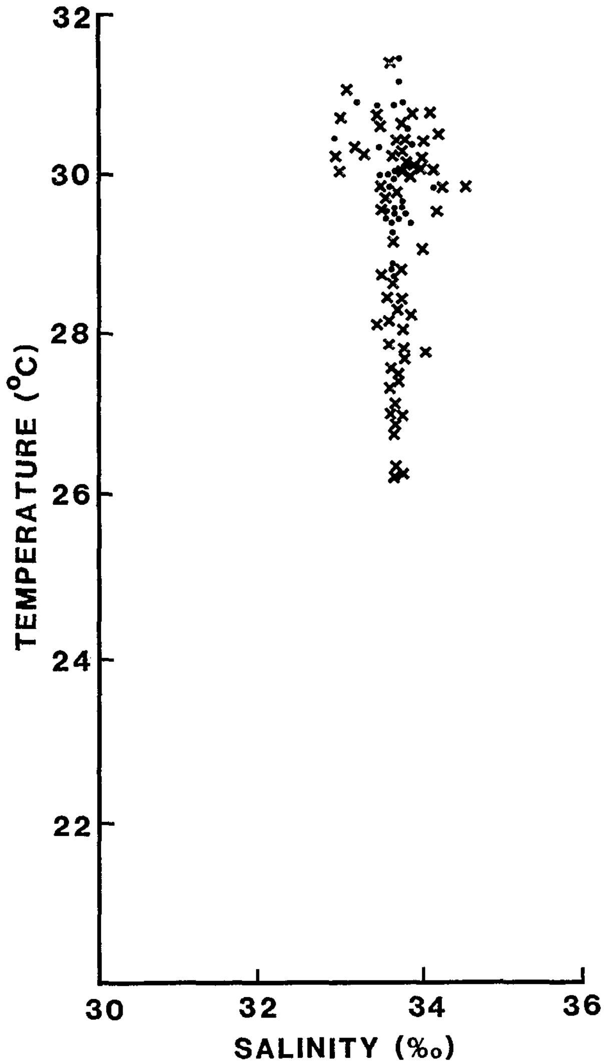

Fig. 4. — T.S. diagram for summer. See Figure 2 for details
Diagramme T.S. d'été. Voir Figure 2 pour l'explicitation des symboles

year, surface and bottom salinities are uniform over most of the Gulf at ~34 ‰. Nowhere were Rochford's high salinity water types C and C_2 or Newell's type D found.

Density (sigma-t)

Winter is the season with highest densities. For the surface centre the density is 22 (σ_t units), for the majority of the coast 23 and for the west coast 24. Bottom winter densities are virtually identical with the surface; 22-23 centre, 23.5-24.5 coast,. because surface cooling and convective overturn ensure relatively well mixed conditions. The lowest densities (except for those affected by runoff) occur in summer due to solar heating; surface centre 21, bottom centre 22, coast 20.5. Runoff resulting from heavy rains in autumn reduces surface coastal densities to 10 (east, southeast), 15 (south) and 16 (west). Bottom coastal densities after monsoonal rains decrease to 17-19.

Oxygen and oxygen saturation

Surface dissolved oxygen concentration is generally higher in the centre (4.8-5.2 ml/l, 100-110 % saturation) than at the coast (4.2-4.6 ml/l, 80-100 %), with only small seasonal variations. Bottom and surface concentrations around the coast are generally the same, but in the centre from spring to autumn there is a steady decrease from 3.2 ml/l (65 %) to 2.6 ml/l (55 %) (northwest centre) to 1.4-2.0 ml/l (30-45 %) (north centre).

The low oxygen bottom water found in the central region may be an intrusion from the Banda Sea as proposed by Rochford (1966) or it may be biological depletion following insulation from surface renewal by summer stratification. An additional property such as nitrate is needed to decide this question.

Nitrate-Nitrogen

Surface levels of nitrate are always small, being $\leqslant 0.5$ µg atom/l, with a minimum of 0.2-0.3 µg atom/l in the centre in summer. Bottom concentrations are generally steady at the coast, being $\leqslant 0.5$ µg atom/l, but in the centre, rise from a minimum of 0.5 µg atom/l in winter to 3.0 µg atom/l in spring, and in the northwest centre, to 2.5-6.0 µg atom/l. Summer bottom concentration decreases to 1.0-2.0 µg atom/l in the centre while the northwest centre remains high, and in autumn, north and east centre increase to 7.5-8.0 µg atom/l.

Nitrate concentrations in the bottom water (7.5-8.0 µg atom/l) in autumn are low compared with 17-18 µg atom/l found by Rochford. They are not high enough to support the Banda Sea source hypothesis for water mass A, but are higher than during the rest of the year, suggesting that nutrient regeneration from bottom sediments may take place.

Silicate

Surface silicate levels vary more widely than nitrate over the Gulf, reaching a maximum along the east coast in winter of 37 µg atom/l, and along the west coast in autumn, 17 µg atom/l. Bottom silicate levels vary in the centre as well as at the coast, reaching a maximum of 14-20 µg atom/l in the centre in autumn, and a minimum of 2-3 µg atom/l in winter. The east coast shows the greatest bottom variability, with a minimum in autumn of

TABLE IV

Water mass characteristics previously identified in the Gulf of Carpentaria (Types A, B, C - Rochford 1966; Type B2, D - Newell 1973)

Caractéristiques des masses d'eau antérieurement identifiées dans le Golfe de Carpentarie

Water mass	Temperature °C	Salinity ‰	Oxygen mℓ/ℓ	Nitrate μg atom/ℓ	Phosphate μg atom/ℓ	Possible origin
A	20-22	33.8-34.7	2-4	17-18	1.4-1.8	Banda Sea
B	26.0-26.5 (at origin)	33.0	4.6-4.7	< 1	< 0.2	West Irian
B2	28.5-29.8 (in Gulf)	28.5-35.5				
C	23-26	35-35.6	4.5-4.8	< 1	< 0.15	N.W. Coral Sea
D	28.8-29.2	36.5-36.7	3.6-3.8	0.7-2.2	-	N.E. Gulf of Carpentaria

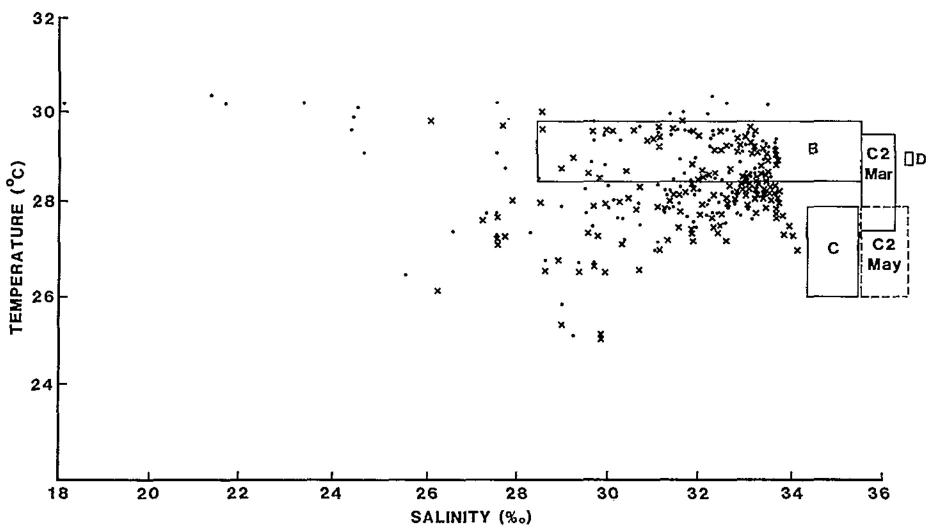

Fig. 5. — T.S. diagram for autumn. See Figure 2 for details

Diagramme T.S. d'automne. Voir Figure 2 pour l'explicitation des symboles

3-7 μg atom/l and a maximum in late winter of 39 μg atom/l.

Surface to bottom differences

Winter is the season which exhibits the most persistent strong winds (southeast Trades) and the sea surface cools significantly. Both of these factors contribute positively to mixing the water column, and it is not surprising to find in a sea as shallow as the Gulf, that for all properties the water column is well mixed. In addition, tidal currents of 0.81 to 1.89 ms^{-1} (FORBES, 1981) can mix the water column in shallow parts of the coastal zone. In spring, with increased solar radiation, the water column becomes temperature stratified in the centre but is relatively uniform in salinity. Oxygen shows a significant surface to bottom difference in the centre, but wind and tidal stirring keep the sallower coastal waters well mixed in summer. The remaining properties, nitrate and silicate also show significant surface to bottom differences in the centre, although again, coastal waters are well mixed.

Autumn is the season of monsoonal rains, and the freshwater runoff caused coastal salinity and silicate stratification. There is some restoration of mixed temperature conditions in the centre, as surface cooling and convective overturn begin to take effect.

Temperature vs. salinity

The only previously identified water mass that is present unchanged (except for slightly higher temperatures) in the 1975-77 surveys of the Gulf is type B (see Table IV). Cruise TP 03/77, which is included in Figure 5 (autumn), found low salinity (18-33.5 ‰), high temperature (28-30 °C) water in the south and central regions of the Gulf. The northern region was dominated by a more restricted salinity (32.5-33.5 ‰) and temperature (27.5-29.5 °C) range, which is nevertheless still within the defined limits of type B water.

Type A water, defined by ROCHFORD (1966) as, salinity 33.8-34.7 ‰, temperature 20-22 °C, oxygen 2-4 ml/l and nitrate 17-18 μg atom/l, may have been present in the winter of 1976. Cruise KL 07/76 (June-July) found low temperatures, 19.5-24 °C, in the south and 21.5-25.5 °C in the central region with low salinities, 31-33 ‰. By July, however, the low oxygen (1.4-2 ml/l) high nitrate (7.5 μg atom/l, north centre) water which was found on the preceding cruise KL 04/76 (April/May) which fits type A characteristics, was no longer evident. Oxygen levels had recovered to 4.4-5.0 ml/l and nitrate levels were uniformly less than 0.5 μg atom/l.

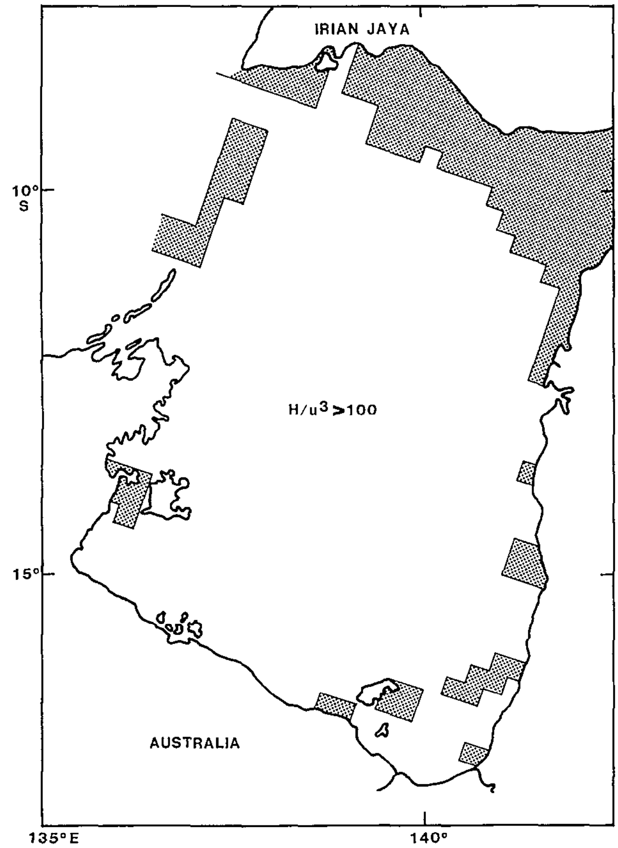

FIG. 6. — Areas of the Gulf of Carpentaria where the tidal mixing criterion (H/u^3) is less than 100. These are shaded

Régions du Golfe dans lesquelles le critère de mélange dû à la marée (H/u^3) est inférieur à 100. Ces régions sont ombrées

LOCAL PROCESSES

Tidal stirring

In discussing surface to bottom differences, wind mixing and tidal stirring were identified as contributing to well mixed conditions for most properties in the coastal zone for most of the year. In winter and spring, wind mixing and convective overturn operate over the whole of the Gulf. Tidal stirring however is dependent on the ratio of water depth (H) and tidal velocity cubed (u^3) (SIMPSON and HUNTER, 1974). The mixing criterion is that this ratio be less than 100. A plot (Fig. 6) of this parameter on a 27×27 km grid was made using velocity data from a numerical model of the circulation of the Gulf (CHURCH and FORBES, 1981) and depths from Admiralty Chart AUS 410. The critical H/u^3 ratio for mixing is reached in shallow areas of the Gulf along the whole Irian Jaya south coast, across Torres Strait as far south as Weipa, and in several patches in the southeastern corner of the Gulf. In the passages south of Mornington Island and Groote Eylandt, and across the sill (depth 50 m) that separates the Gulf from the Arafura Sea where tidal velocities are large, mixing can also take place.

PRECIPITATION

The rainfall and runoff calculations of NEWELL (1973) which were for the year April 1970 to March 1971 were repeated for the two years covering the 1975-77 surveys. Rainfall over the Gulf is taken as the mean of rainfall over four surrounding rainfall districts (Australian Bureau of Meteorology rainfall data). Total runoff is derived from the sum of runoff from four drainage divisions around the Gulf (Atlas of Australian Resources (Department of National Development, 1961)). For each division, the runoff is the product of area of drainage division relative to the Gulf, mean annual percent runoff, and total annual rainfall. Rainfall and runoff figures for 1970/71, 1975/76, 1976/77 and for a long term mean (1925-71) are compiled in Table V.

It is obvious that, compared with the long term average, 1970/71 was a dry year, and that 1975-77 were wet years. In 1975/76 the Gulf received 57 % more rainfall and runoff than in 1970/71 and 42 % more than the long term mean. For 1976/77, there was 32 % more rainfall and runoff than 1970/71, and 20 % more than the long term mean.

This large year to year variation in precipitation may partly explain why salinities in the most recent surveys, 1975-77, were generally 2 ‰ lower than the

TABLE V

Selected years' rainfall and runoff, Gulf of Carpentaria

Données sur la pluie et le ruissellement dans le Golfe de Carpentarie

Year	Mean annual rainfall	Runoff (mm)	Runoff plus rainfall (mm)	Departure from mean (mm)
1925-71	1068	255	1323	0
1970/71	961	238	1199	-124
1975/76	1531	355	1886	563
1976/77	1279	310	1589	266

dry year survey, 1970/71. In the coastal region of the Gulf (30 m depth) where the effects of abnormally high rainfall are quickly mixed through the water column by wind mixing and tidal stirring, the difference between 1970/71 and 1975/76 rainfall and runoff (687 mm) would reduce water of 35 ‰ salinity to 34.2 ‰, so that water types C and C_2 may be present, but at lower salinities. Even water type A, which is inferred by ROCHFORD (1966) to have its origins at 100-150 m in the Banda Sea, and had salinity of 33.8-34 ‰ in 1964, could be present (see Fig. 2) at reduced salinities of 31.5-34.0 ‰ in 1976, due either to high rainfall around the Banda Sea or to mixing with abnormally low salinity Gulf waters as it flows southeast along the bottom and into the Gulf.

External influences

The remaining point which the present study considers is the origin of water type C found in the Gulf. There seems no doubt that water of this type exists seasonally in the Gulf, particularly if allowance is made for the dilution effect of abnormally high rainfall in some years, but the real question is whether type C water could have come from the Coral Sea. ROCHFORD (1966) deduced that Coral Sea water, driven westward through Torres Strait by the southeast Trade winds, displaced Gulf water to produce type C water in four months (May to August). NEWELL (1973) concurred, but stated that the displacement took place over seven months (April to October). Although this may at first seem reasonable, based on the observed characteristic water types that are present during the two distinct seasons — monsoons and trades — neither author made any calculation of the rate at which Coral Sea water would have to be carried through Torres Strait to satisfy the displacement of Arafura Sea water from the Gulf. A simple calculation follows.

Take the volume of the Gulf as 1.9×10^{13} m³. The Torres Strait cross-section from Cape York to Long Reef is approximately 1.8×10^5 m² and if the northern section of approximately 0.9×10^5 m² (although poorly charted from Long Reef to Papua New Guinea) is included, then this totals 2.6×10^5 m². Mean depth used to estimate this crosssectional area was 3 m.

Neither ROCHFORD nor NEWELL estimates the fraction of Arafura Sea water which is displaced from the Gulf, but if we assume that 2/3 of the total volume is exchanged in seven months, then the mean velocity through Torres Strait would be 2.7 m/s. If it takes only four months, the required mean velocity would be 4.7 m/s. If only half of the Gulf water is displaced, the mean velocity would be 2.0 m/s over seven months, and 3.5 m/s over four months.

To see whether these velocities are realistic or not we can calculate the flow from observed mean sea level differences between ends of Torres Strait. If friction is balanced by the pressure gradient along the Strait, then we can write

$$K|u_s|u = hg \frac{\partial \eta}{\partial x}. \qquad (1)$$

where $\frac{\partial \eta}{\partial x}$ is the surface slope, K the friction coefficient is 0.005, $|u_s|$ the scale velocity is 1 m/s, h is the mean water depth, and g is gravitational acceleration. The resulting flow is therefore

$$u = \frac{hg \frac{\partial \eta}{\partial x}}{K|u_s|} \qquad (2)$$

Mean sea level difference between Booby Island (BI) and Frederick Point (FP) in the trade wind season is about 0.8 m and between Goods Island (GI) and Twin Island (TI), 0.5 m. Equation 2 then yields:

$u(BI - FP) = 0.06$ m/s and $u(GI - TI) = 0.09$ m/s.

These velocities are one order of magnitude smaller than mean currents calculated above from water mass exchange considerations, and they are insufficient to support the ROCHFORD/NEWELL hypothesis of major displacements of entire water masses from the Gulf.

Although large velocities are observed in Torres Strait, they are oscillatory tidal currents of semi diurnal period which result in negligible mean flow. It is therefore suggested that the observed seasonal changes in characteristic water types in the Gulf are probably due to *in situ* changes in temperature and salinity and exchange of waters with the Arafura Sea, through a very much larger opening than Torres Strait.

CONCLUSIONS

1. Annual cycles of temperature, salinity, oxygen, nitrate-nitrogen and silicate are apparent in the Gulf.

2. Coastal waters (less than 30 m depth) are generally well mixed for all properties, although monsoonal rains cause significant late summer and autumn stratification. Central Gulf waters (deeper than 30 m) exhibit the greatest stratification for most properties, except in winter when the Gulf is reasonably well mixed vertically. Horizontal variations can persist through winter, however.

3. Oxygen and nutrient concentrations are useful water mass labels, particularly in years when abnormal rainfall (high or low) can make identification based on salinity-temperature relations difficult.

4. Significant changes in Gulf waters take place *in situ*, due to solar radiation, precipitation, wind mixing and tidal stirring, and may well be as important as exchange with Arafura or Banda Sea waters.

5. Only limited exchange can take place between the Gulf and the Coral Sea.

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