Hydrology of the Gulf of Carpentaria, 1970-71

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HYDROLOGY OF THE GULF OF CARPENTARIA, 1970-71

By B. S. NEWELL*

Abstract

The hydrological regime in the Gulf of Carpentaria is subject to an annual cycle. During the north-west monsoon (November to March) low-salinity high-temperature water moves into the Gulf from the Arafura Sea. During the south-east monsoon (April to October) medium-salinity medium-temperature water from the Coral Sea moves westward through Torres Strait and displaces Arafura water from the Gulf. Evaporation produces very high salinities ($>36.00^0/_{00}$) during the south-east monsoon, and increasing radiation in the spring results in pronounced thermal stratification. Cold saline bottom water moves out of the Gulf north-westwards from November onwards. The evaporation–precipitation balance amounts to only a few per cent of the total water volume in the Gulf but exerts considerable influence on the circulation pattern. The distribution of non-conservative properties (oxygen, nitrate, and silicate) is very erratic, but values of nitrate and silicate are generally low (<0.2 μg-atom/l and 0.5 μg-atom/l respectively) except in bottom water isolated by stratification. Levels of chlorophyll were generally less than 1 μg/l.

I. INTRODUCTION

In 1969 the CSIRO Division of Fisheries and Oceanography began an investigation of the various species of commercially important prawns occurring throughout northern Australia. This investigation included a description of the environment which these prawns occupy.

As part of this environmental description an oceanographic programme was mounted in the Gulf of Carpentaria, using a chartered vessel, M.V. *Islander VI*. The results of this programme form the basis for this paper.

II. METHODS

The sampling pattern followed is indicated in Figure 1. This pattern was adhered to on each cruise as far as possible, and the actual positions occupied were always within a few miles of those indicated and most often were identical with them.

At each station, except on the first cruise (May 1970), measurements of salinity and temperature were made with a Hamon S–T meter (Sample Industries, Chippendale, N.S.W.) at 5-m intervals of depth to 40 or 60 m depending on the length of cable available. Temperatures were corrected by use of reversing thermometers and salinities by use of Copenhagen International Standard Sea-water. In May 1970, both S-T meter cables were damaged in rough weather at the first two stations and all measurements were made by Nansen bottles with reversing thermometers.

On all cruises samples were collected by Nansen bottle at 10 m and 40 m (or 10 m above the bottom in shallow areas) and samples withdrawn for analysis.

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Dissolved oxygen, nitrate, and silicate were measured by methods given by Major *et al.* (1972). Total iron was measured by the method of Armstrong (1957).

On four cruises (July, September, and November 1970 and March 1971), 5-l samples were collected at various depths at each station by means of an *in-situ* sampler similar to that described by Williams (1969). The suspended material collected on the 47-mm Millipore HA filter in the sampler was preserved over silica gel in a refrigerator and analysed for chlorophyll *a* by the method described by Major *et al.* (1972).

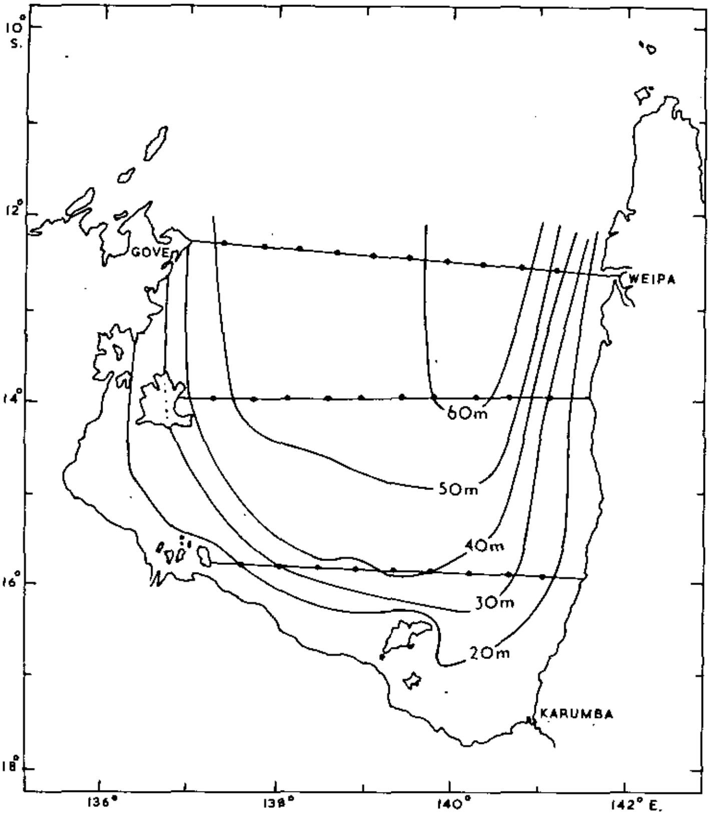

Fig. 1.–Location of sampling stations and bottom topography.

At every station wind velocity was measured by hand-held anemometer (approx. 12 ft above sea surface) and wind direction was estimated from the ship's compass. Wet- and dry-bulb temperatures were obtained with an Assman hygrometer.

III. RESULTS

The vertical and horizontal distribution of properties in the Gulf are described in a series of diagrams (Figs. 8–18). However, in order to describe and interpret the changes observed, reference must be made to previous surveys, the wind system, current system, heat and water budgets, and water type identification. These features are therefore dealt with first.

(*a*) *Previous Surveys*

A previous account of the circulation in the Gulf of Carpentaria (hereafter referred to as the Gulf) has been given by Rochford (1966). Rochford's account was based largely on the results of one cruise in the Gulf carried out in August 1964, although supplementary data from the areas west, north, and east of the Gulf, collected in earlier years, were also used. On the basis of the distribution of properties in August 1964, and previously observed changes to the north and west, Rochford postulated an annual interplay or exchange of three water types provisionally named A, B, and C.

Water type A was of subsurface origin, deriving from 100-150 m depth in the Banda Sea and moving south-eastward into the Gulf along the bottom. Its properties were salinity 33.80-34.70$^{0}/_{00}$, temperature 20-22°C, oxygen 2-4 ml/l, nitrate 17-18 μg-atom/l, and inorganic phosphate 1.40-1.80 μg-atom/l. Type A was not observed on any cruise in the 1970-71 survey, so that its penetration into the Gulf must vary from year to year.

Water type B was traced to an origin along the coast of West Irian where it forms as a result of summer rain dilution and moves eastwards and southwards at the surface under the influence of the north-west monsoon winds. Its properties were salinity 33.00$^{0}/_{00}$ at origin (increasing to 35.00$^{0}/_{00}$ at entry to the Gulf by lateral mixing with type C), temperature 26.0-26.5°C, oxygen 4.6-4.7 ml/l, nitrate <1.0 μg-atom/l, and inorganic phosphate <0.20 μg-atom/l.

Type B was readily detected in the present survey and tended to enter the Gulf in the north-east in March.

Water type C was the dominant water in the Gulf in August 1964 with salinity 35.00-35.60$^{0}/_{00}$, temperature 23.0-26.0°C, oxygen 4.5-4.8 ml/l, nitrate <1.0 μg-atom/l, and inorganic phosphate <0.15 μg-atom/l.

Type C was found in the Gulf throughout the present survey and, as in 1964, was distinguishable from type B by virtue of its higher salinity and lower temperature. Rochford concluded that type C had its origins in the north-west Coral Sea, entering the Gulf via the Torres Strait and increasing in salinity by evaporation in the Gulf itself. The results of this survey tend to confirm this conclusion.

For convenience, Rochford's nomenclature has been retained, and the high-salinity water present in the Gulf is termed type C2 whilst the parent medium-salinity water from the Coral Sea is termed type C. A salinity of 35.50$^{0}/_{00}$ was chosen as a convenient discriminator between type C2 and types B and C.

In addition to these three water types, another distinct water type of high salinity and temperature was found in the bottom layer of the Gulf in May. This has been provisionally named type D and will be discussed below.

(*b*) *Wind Direction and Velocity*

The winds measured have been displayed graphically for each cruise in Figure 2. Each arrow indicates by its length the frequency of winds from each quadrant (also given in numerals). Average wind speed in each quadrant is given as metres per second.

In May and July, winds were fairly strong and mainly from the south-east. In September, winds were lighter and more variable, north-easterly winds becoming more frequent. By November this north-easterly tendency had increased, whilst in March winds were generally beginning to veer to the south-east again. North-west winds were encountered on only six occasions.

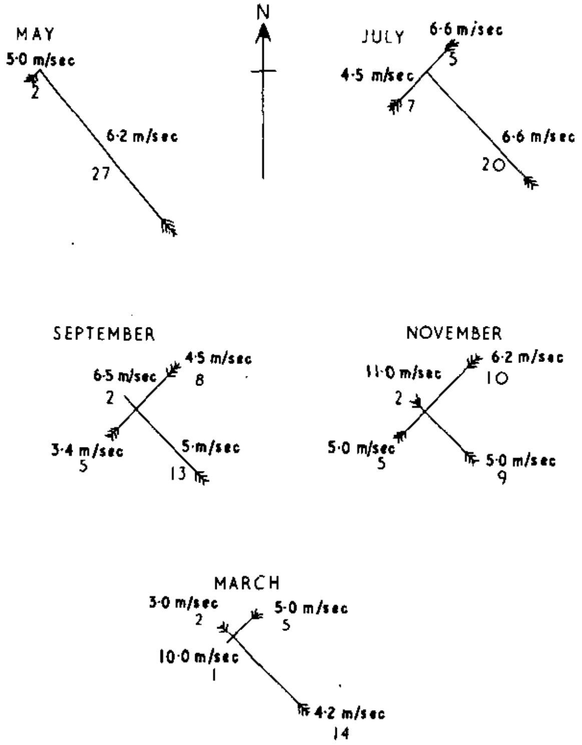

Fig. 2.–Mean wind speed (m/s) and frequency in each quadrant.

The wind pattern observed follows the monsoonal alternation in this region (Wyrtki 1961) except that there were no observations during the full development of the north-west monsoon, i.e. in January or February.

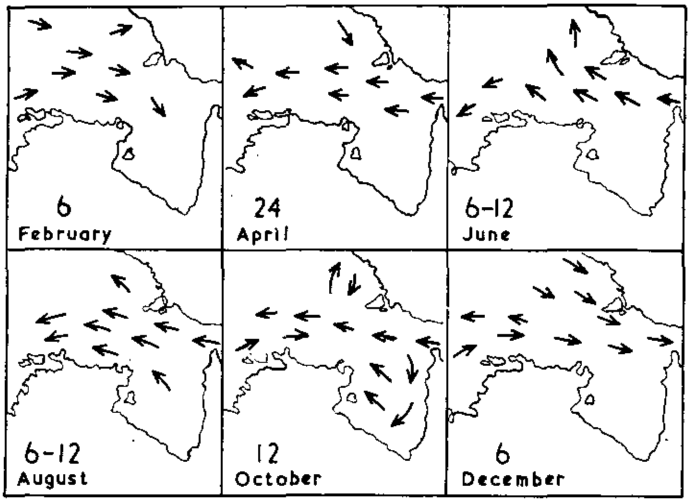

Fig. 3.–Surface currents in the region (after Wyrtki 1961). Numerals are average drift in miles/day.

(c) *The Surface Circulation in the Region*

Figure 3, taken from Wyrtki (1961), shows the surface currents calculated from merchant ship course corrections. During the summer or north-west monsoon (December to February), surface water is driven from the Arafura Sea eastwards into the Gulf and through Torres Strait. During the south-east monsoon (April to October), surface water moves westwards through Torres Strait into the Arafura Sea. In October there is some direct evidence of this water entering the Gulf but observations are lacking for the other three months. However, the alternation of flow provides supporting evidence for Rochford's hypothesis of summer-winter alternation of input to the Gulf.

(d) *Water and Heat Budget of the Gulf*

With measurements of both wind velocity and humidity (wet and dry bulb) at each station, it was possible to calculate evaporation rates from the formula of Wyrtki (1961):

$$E = 0.1\,V\,(e_w - e_a),$$

where E = evaporation (mm/day),
V = wind velocity (m/s),
e_w = water vapour pressure at sea surface (mb),
e_a = water vapour pressure of the air (mb).

No trend in evaporation rates with either position or time of day could be detected when rates were examined graphically; in fact, evaporation rates depended mainly on wind velocity, although there was some fluctuation of humidity ($e_w - e_a$ ranged from about 5 to 15 mb). It was therefore considered justifiable to take the mean of the 29 observations for each cruise and assume that this mean rate applied over the whole Gulf for the 2 months prior to each 8-day cruise. The total evaporation thus calculated is shown in column 9 of Table 1.

With the aid of these evaporation rates it was possible to compare evaporative heat loss in each period with the total effective radiation ($Q_{\text{eff.}}$) given by Wirtki (1961) for the Arafura Sea, the nearest area to the Gulf with available data.

From May to July $Q_{\text{eff.}}$ is about 132×10^6 g cal m^{-2}. Evaporative heat loss over this period was 223×10^6 g cal m^{-2}. The net heat loss (-91×10^6 g cal m^{-2}) would have resulted in a fall in temperature of about 1.8 degC if applied to a water column of 50 m, which is the approximate mean depth of the Gulf (Fig. 1).

From July to September total heat received (168×10^6 g cal m^{-2}) exceeded evaporative heat loss (110×10^6 g cal m^{-2}), so that a rise of about 1 degC could have been expected in the Gulf if no other factors operated.

Between September and November, $Q_{\text{eff.}}$ approximately equalled evaporative heat loss (192×10^6 g cal m^{-2} and 201×10^6 g cal m^{-2} respectively), so that little change in temperature should have occurred. On the other hand, from November to March, $Q_{\text{eff.}}$ (336×10^6 g cal m^{-2}) exceeded evaporative losses (225×10^6 g cal m^{-2}), giving a heat gain that could have produced a rise of 2.2 degC in the Gulf. Assuming similar climatic changes from year to year, evaporative heat loss from May (1970) to March (1971) equalled 202×10^6 g cal m^{-2}, whilst $Q_{\text{eff.}}$ for this time of year is 162×10^6 g cal m^{-2}. This corresponds to a fall in temperature of 0.8 degC.

TABLE 1

RAINFALL, RUN-OFF, AND EVAPORATION FOR GULF OF CARPENTARIA AND SURROUNDING CATCHMENT AREAS FROM APRIL 1970 TO MARCH 1971

1	2	3	4	5	6 Mean rainfall (mm)	7 Run-off (mm)	8 Run-off and rainfall (mm)	9 Evaporation (mm)	10 Water balance (mm)
District	14BC	14DE	29	27					
Area relative to Gulf (%)	0.2	0.9	0.9	0.3					
Mean annual run-off (%)	20	10	4	25					
Apr.	52	27	14	34					
May	41	0	0	22					
Total	93	27	14	56	47		57	348	−291
Run-off	4	2	0	4		10			
June	7	0	0	7					
July	5	0	0	8					
Total	12	0	0	15	7		8	384	−376
Run-off	0	0	0	1		1			
Aug.	1	0	0	3					
Sept.	1	0	0	3					
Total	2	0	0	6	2		2	189	−187
Run-off	0	0	0	0		0			
Oct.	30	5	12	24					
Nov.	133	60	22	81					
Total	163	65	34	105	92		113	345	−232
Run-off	6	6	1	8		21			
Dec.	164	129	41	410					
Jan.	128	69	29	184					
Feb.	167	151	102	291					
Mar.	301	195	320	573					
Total	760	544	492	1458	813		1019	387	632
Run-off	30	49	18	109		206			

In these comparisons sensible heat loss has been ignored. Wyrtki (1961) in fact claims that sensible heat loss in the equatorial region is negligible compared to evaporative losses. As will be seen later, this also seems to be the case in the Gulf. However, some error will arise from using $Q_{\text{eff.}}$ values for the Arafura Sea which may be slightly higher than those over the Gulf.

Since rainfall figures for the catchment areas surrounding the Gulf were available from the Bureau of Meteorology, Melbourne, it was also possible to calculate the water budget of the Gulf.

No rainfall figures were available for the Gulf itself, but the four rainfall areas surrounding the Gulf from north-west through south-west to south to north-east are, respectively, 14BC, 14DE, 29, and 27 (Fig. 4). The actual rainfall in each area in each month is shown in columns 2–5 in Table 1. It was assumed, for practical purposes, that the rainfall over the Gulf itself would be the mean of these four figures, and this mean is given in column 6. In addition to direct rainfall, however, land run-off had to be taken into account. Fortunately the rainfall districts correspond fairly closely to the catchment areas around the Gulf (Fig. 4), so that the percentage run-off for each area given in the Atlas of Australian Resources (Department of *National Development 1961*) could be used to calculate run-off from rainfall. The mean annual run-off percentage for each area is given at the top of Table 1. Use of mean annual run-off introduces an error into the calculations in that run-off almost certainly varies with season. More comprehensive values, however, were not available.

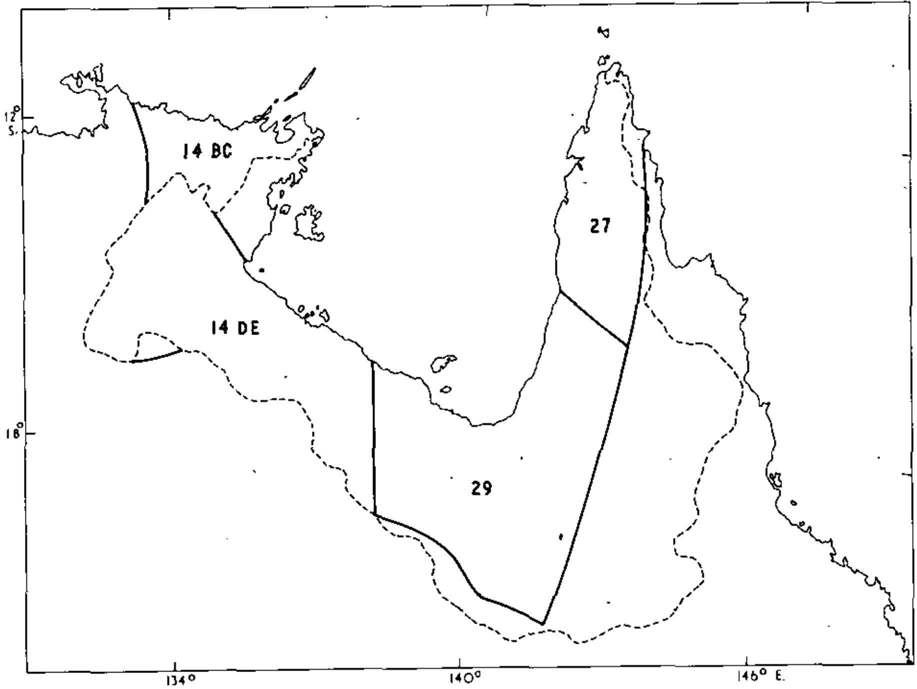

Fig. 4.–Drainage divisions (- - -) and rainfall districts (—) surrounding the Gulf of Carpentaria.

In order to convert run-off to equivalent rain over the Gulf, the area of each rainfall region relative to the Gulf was measured and is given at the top of Table 1. Multiplication of the rainfall in each region by both area fraction and percentage run-off gives a figure which may be added to direct rainfall. The values obtained are given in columns 2, 3, 4, 5, and 7 of Table 1.

When total rain and run-off (column 8) is compared to evaporation (column 9) it may be seen that evaporation exceeds rainfall from April to November but is less than rainfall from December to March. Total rainfall and run-off amounts to 1.2 m for the whole year and total evaporation to 1.6 m, giving an excess of *evaporation* over precipitation of 0.4 m for the whole year.

Since most of the Gulf has a depth range of 40–60 m (Fig. 1), the annual evaporation–precipitation budget is a very small part of the volume of the Gulf, rainfall amounting to about 2.4% and evaporation 3.2% of the whole volume.

From Table 1 (column 10) it may be seen that salinities could be expected to increase in the Gulf during winter and spring. The loss of water by evaporation corresponds, over a water column of mean depth 50 m and for the salinity range 35.00-36.00$^{0}/_{00}$ encountered, to increases of 0.21$^{0}/_{00}$ from March to May, 0.28$^{0}/_{00}$ from May to July, 0.14$^{0}/_{00}$ from July to September, 0.17$^{0}/_{00}$ from September to November, and to a decrease of about 0.25$^{0}/_{00}$ from November to March.

(*e*) *Identification of Water Types in the Gulf*

In Section I it was claimed that three water types (Rochford's B, C, and C2) dominated the Gulf during this survey. Before proceeding it would seem pertinent to justify this claim by reference to the properties measured. Such positive identification also simplifies graphical presentation of the sources and distribution of the water types since only one or two properties need be used, in particular, salinity and temperature.

First examination of the values of salinity, temperature, dissolved oxygen, nitrate, silicate, and total iron showed a very heterogeneous distribution. It proved extremely difficult to ascribe any particular combination of these properties to a water type. Recourse was made to frequency distribution diagrams of the type illustrated by Figure 5, which shows the distribution of properties in November 1970 by station and depth. (This month was chosen for an example because stratification produced a wide separation of modes.) It can be seen that whilst there is considerable overlap some areal identification of ranges in properties can be made, giving three characteristic groupings of type C (surface), type C2 (surface), and type C2 (bottom). Similar groupings could be made for the other four cruises, even though some properties did not always separate into modes. Total iron never showed any grouping and has been omitted.

The results of the frequency mode separation are shown in Table 2. All water of salinity $>35.50^{0}/_{00}$ has been called type C2 because the areas having such high salinity were always isolated from sources outside the Gulf by water of lower salinity and were therefore likely to represent the results of evaporation. The splitting of type C2 into two modes of temperature in July is easily accounted for by differential cooling in the shallow south-western portion of the Gulf. The further splitting into two modes of temperature and oxygen (September), all properties (November), and oxygen, silicate, and nitrate (March) can reasonably be explained as the effects of stratification and consequent isolation of bottom water.

There seemed little doubt that the water of salinity $<35.50^{0}/_{00}$ present from July to November could be named type C. The salinity and oxygen ranges were relatively small and corresponded to those given by Rochford (1966) for water in the north-east region of the Gulf, whilst nitrate was uniformly low (0.0-0.1 μg-atom/l). Furthermore, the salinity values are too high to have derived from the Arafura Sea (Rochford 1966; Wyrtki 1961). Similarly, the low-salinity water present in March 1971 has properties corresponding to those of type B as described by Rochford (1966), except for its higher temperature which is probably a seasonal effect.

However, the medium-salinity water present in May might have been either type B or type C. In May winds were already settled in the south to east quarter

(Fig. 2) so that type B from the Arafura Sea was not likely to be moving into the Gulf, although traces might have remained from the summer. Oxygen silicate and nitrate values (Table 2) show a closer adherence to type C properties than to type B.

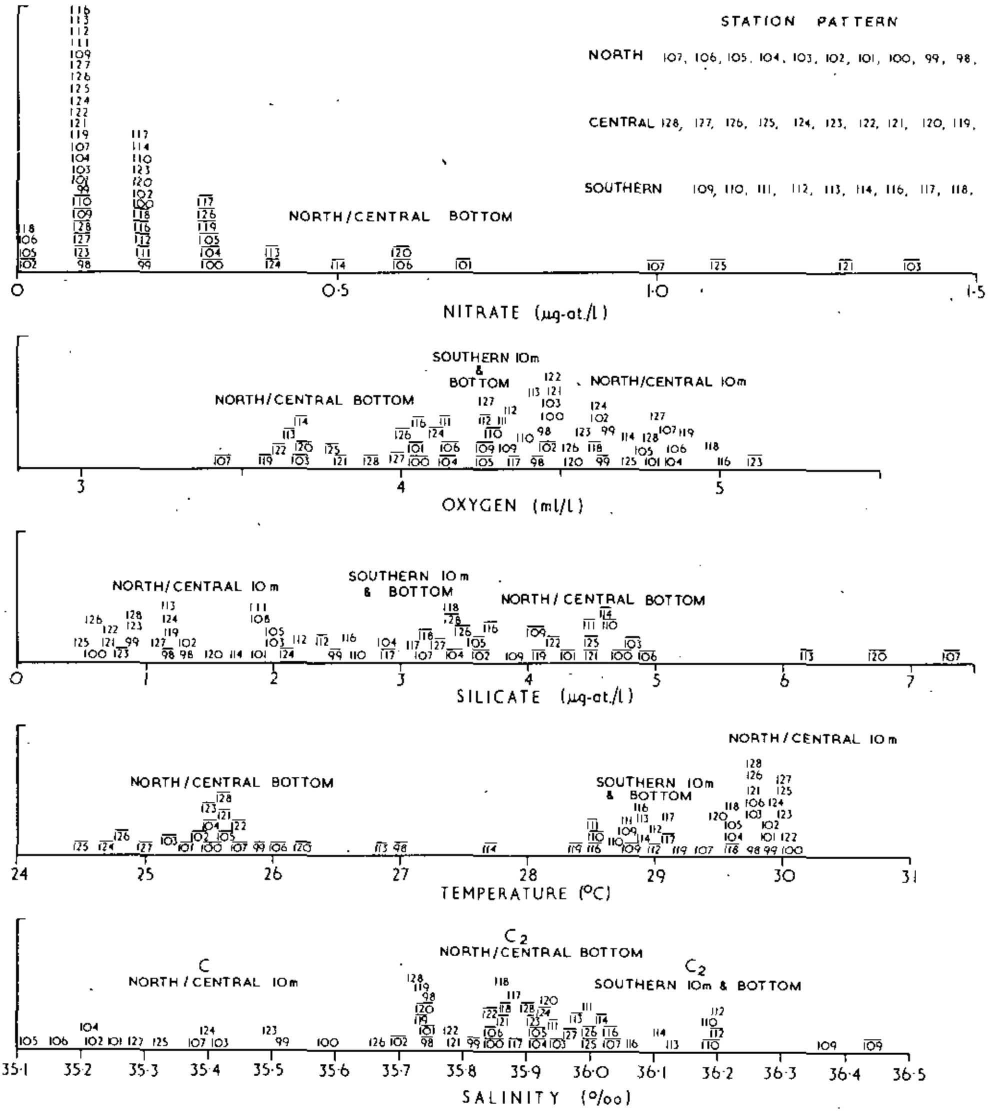

Fig. 5.—Frequency distribution of salinities, temperatures, dissolved oxygen, silicates, and nitrates in November 1970. Numerals refer to stations. Barred numerals 40-m (bottom), plain numerals 10-m depth.

TABLE 2

RANGES OF PROPERTIES FOR THE FOUR WATER TYPES ENCOUNTERED FROM MAY 1970 TO MARCH 1971

Month	Water type	Property				
		Salinity ($^{0}/_{00}$)	Temp. (°C)	Oxygen (ml/l)	Silicate (μg-atom/l)	Nitrate (μg-atom/l)
May	C	34.33–35.50	26.0–28.0	4.4–4.7	1.0–4.0	0.0–0.1
	C2	35.50–36.70	26.0–28.0	4.4–4.6	0.0–2.0	0.0–0.1
	D	36.50–36.66	28.8–29.2	3.6–3.8	5.4–7.0	0.7–2.2
July	C	34.91–35.50	24.0–26.0 (N.) 22.5–24.0 (S.)	4.4–4.7	1.0–5.0	0.0–0.1
	C2	35.50–36.26	24.0–25.0 (N.) 22.0–24.0 (S.)	4.6–5.2	0.0–3.0	0.0–0.1
Sept.	C	35.08–35.50	27.0–27.6	4.6–5.0	No clear mode	0.0–0.1
	C2	35.50–36.07	23.0–26.0 (bottom)	3.8–4.6 (NE. bottom)	1.0–3.0	0.0–0.1
			25.0–27.0 (surface)	4.6–5.0		
Nov.	C	35.10–35.50	29.5–30.9	4.6–5.0	0.5–2.0	0.0–0.2
	C2	35.50–36.44	25.5–27.0 (N. bottom)	3.4–4.6 (N. bottom)	2.0–5.0 (N. bottom)	0.7–2.2 (N. bottom)
			28.5–29.5	4.0–5.0	1.2–4.6	0–0.2
Mar.	B	28.40–35.50	28.5–29.8	4.0–5.0	2.0–6.0	0.1–0.4
	C2	35.50–36.12	27.4–29.5	2.5–4.0 (bottom)	6.0–10.4 (bottom)	0.9–4.4 (bottom)
				4.6–4.8 (surface)	1.8–3.3 (surface)	0.3–0.6 (surface)

Figures 6 and 7 show the mean monthly surface salinities and temperatures by one-degree squares for the period 1966–70 calculated from the observations taken under this Division's merchant ship sampling programme. Water of the required salinity and temperature is present in the eastern approaches of Torres Strait during April and May, so that the May medium-salinity water is most likely to represent the winter movement of type C into the Gulf.

The remaining water type detected by frequency mode (type D) was found only at the bottom in May. This water had distinctively high salinity and temperature values, whilst the oxygen content was low and silicate and nitrate content high (Table 2). Figures 6 and 7 show that whilst temperatures in the eastern approaches of Torres Strait during April were almost as high as those associated with type D ($>28°$), salinities were far too low in either April or May to provide an origin for type D east of the Strait. Type D was also much too saline to have an origin in the Arafura Sea. It therefore must be formed within the Gulf and a suggested origin is given in subsection (*h*).

(*f*) *Horizontal Distribution of Salinity and Temperature*

Table 2 shows that the distribution of water type may be approximated by charts of isohaline distribution, provided that the difference in origins of low-salinity

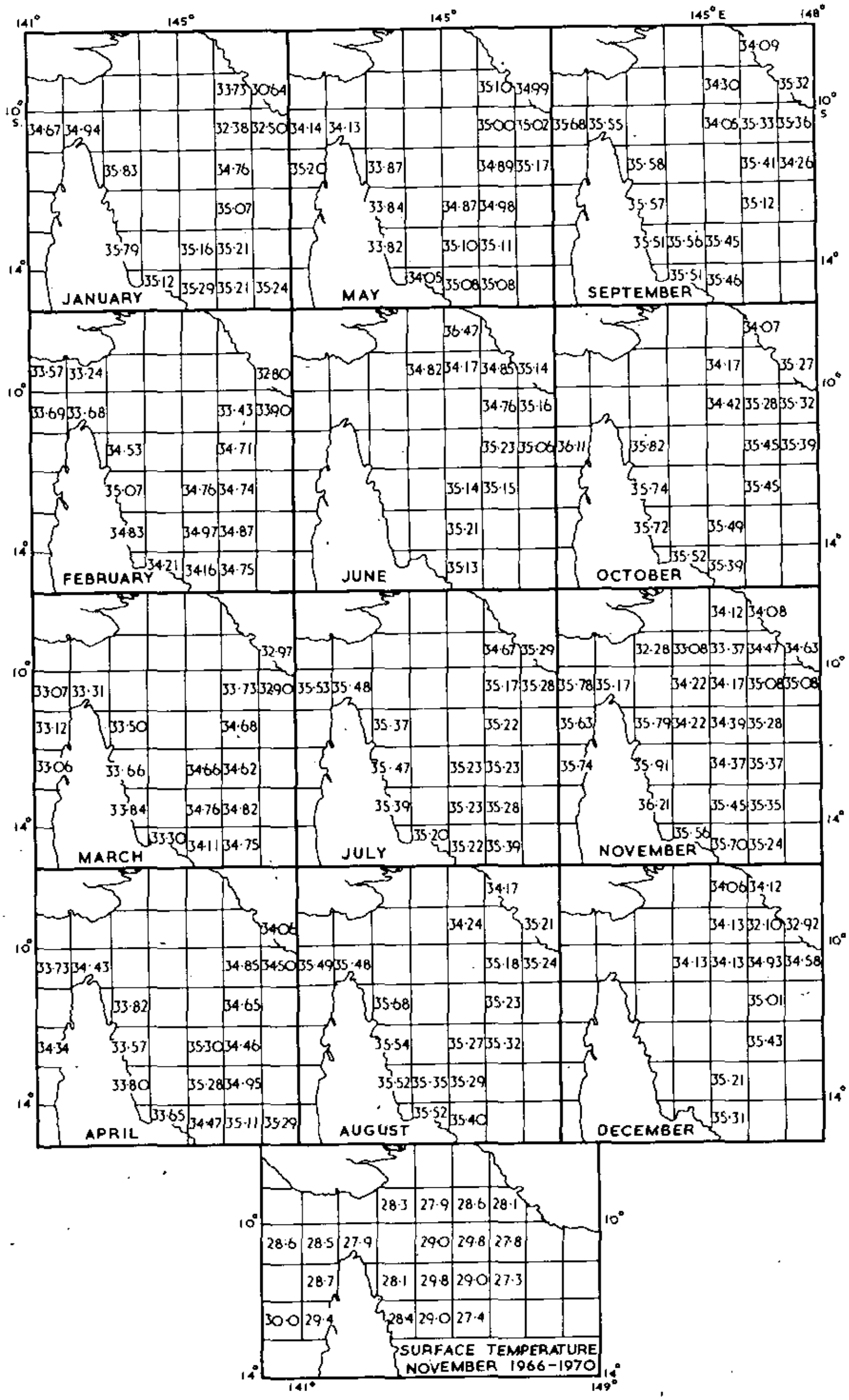

Fig. 6.–Surface salinities in the north-west Coral Sea. Monthly means by 1-degree squares for 1966–70.

water in March and May is borne in mind. Such charts have been prepared for 10-m and 30-m depth in May 1970 and for 10-m and 40-m depth in the other 4 months

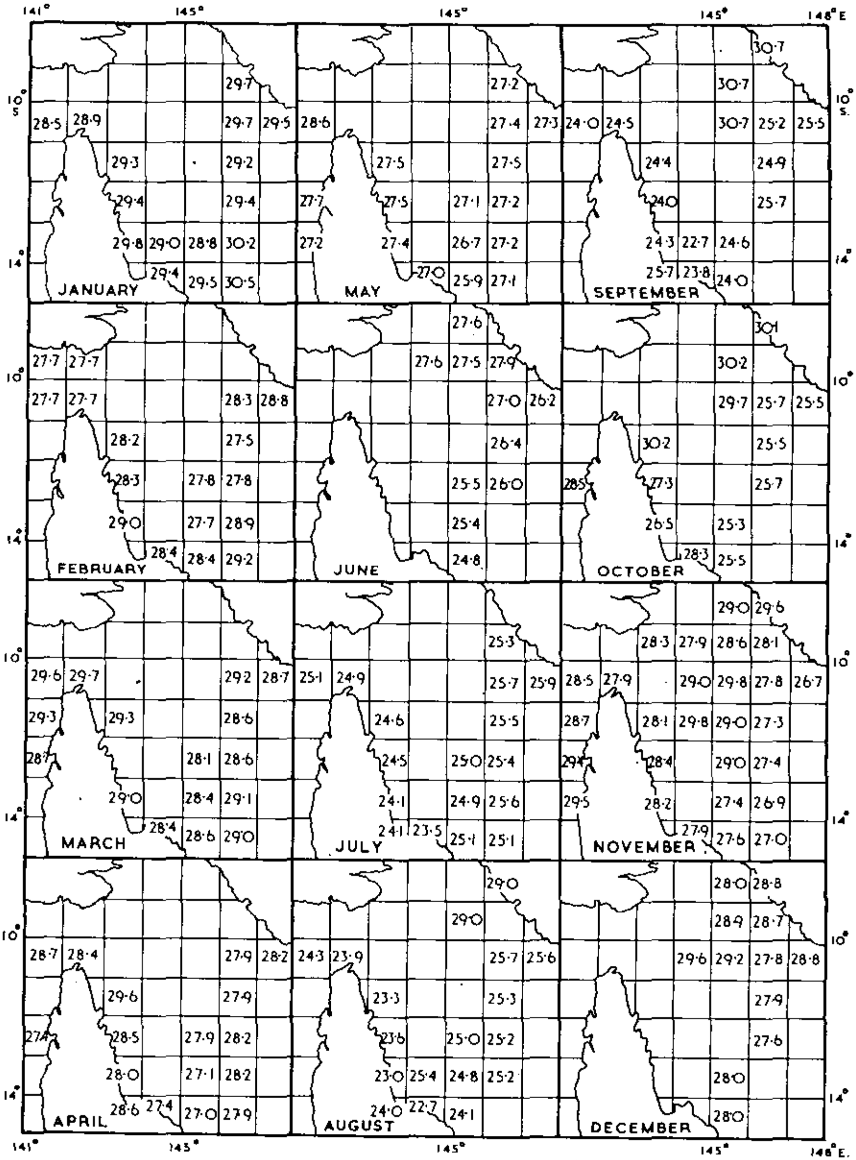

Fig. 7.–Surface temperatures in the north-west Coral Sea. Monthly means by 1-degree squares for 1966–70.

(Figs. 8–13). Included on these charts are the isotherm distributions which are necessary for any discussion of advective *versus in-situ* changes.

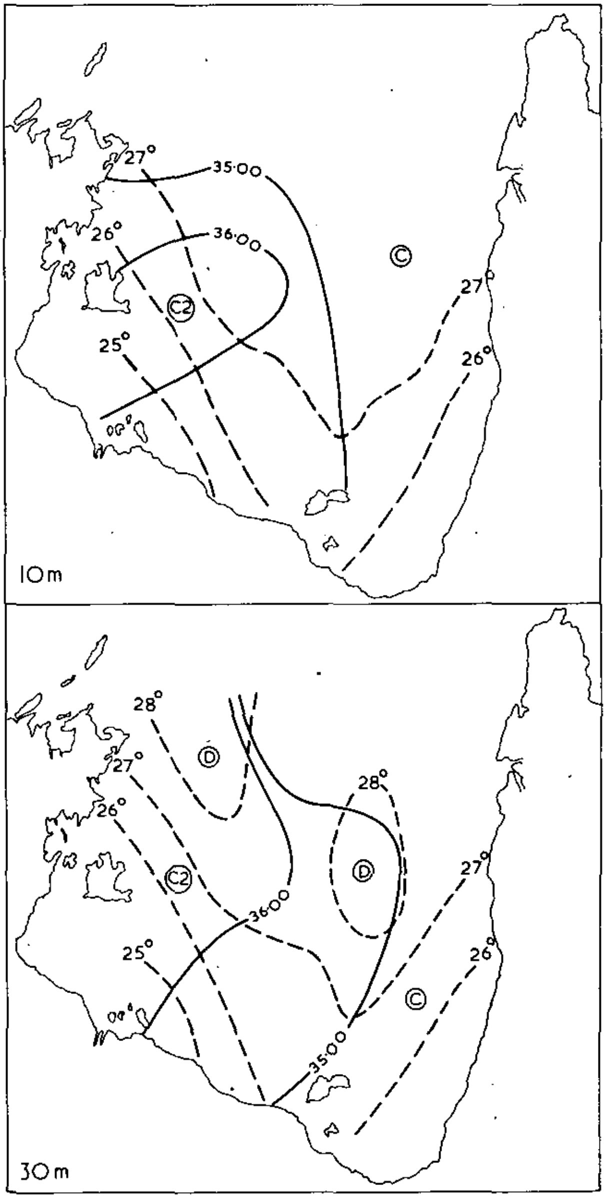

Fig. 8.—Distribution of temperature (---) and salinity (—) in May 1970 at 10-m and 30-m depth.

In May (Fig. 8) the Gulf contained western high-salinity and eastern low-salinity regions, with the high-salinity water extending eastwards under the lower-salinity water. The isotherm configuration suggests a movement of warm water into the Gulf in the east. Such a movement, if active during the cruise, should have produced a compensating flow of water out, the most probable mechanism being an exit of high-salinity low-temperature water (C2) along the bottom. However, any such exit could only occur in the north-west and was effectively blocked by the presence of type D water. Temperatures rose by 3 degC in a northerly direction along the bottom, and C2 water was confined in the south-western region. The movement of warmer, less saline type C water into the Gulf therefore presumably occurred earlier, and the situation found in May was more or less static.

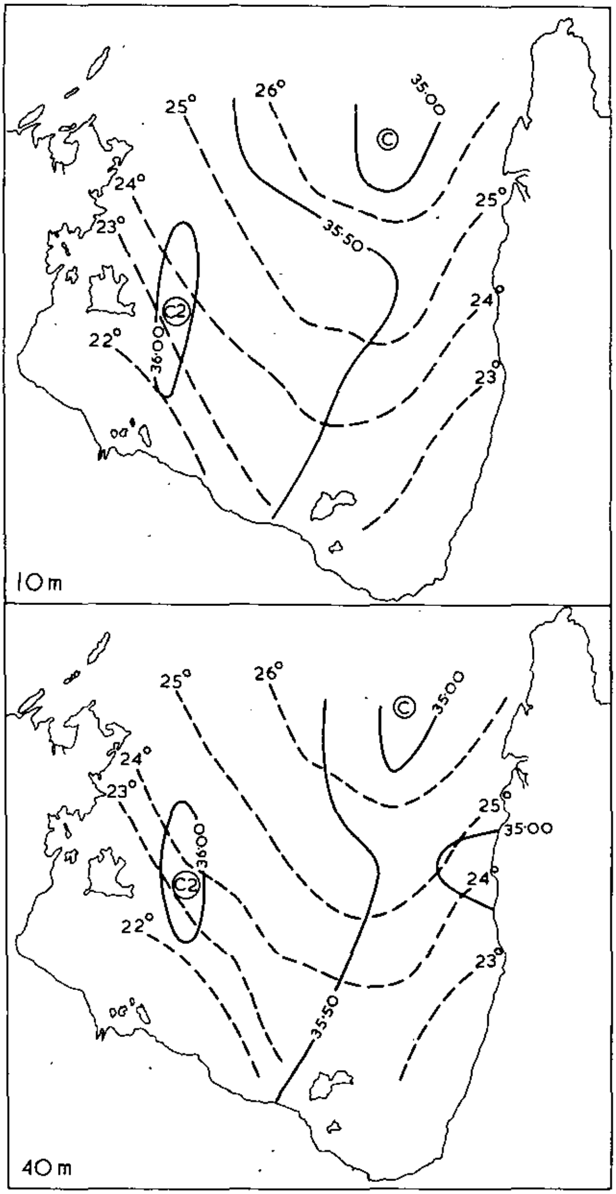

Fig. 9.–Distribution of temperature (---) and salinity (—) in July 1970 at 10-m and 40-m depth.

The situation in July (Fig. 9) at first sight presents an apparent paradox. Salinities rose generally by about 0.5‰ over the eastern and north-eastern region. At least half this rise may be attributed to evaporation (see subsection (*d*)), whilst it is also apparent that the area of high-salinity water in the west greatly contracted. At the same time both salinity and temperature show near-uniform vertical distribution. Such a situation argues for vertical mixing and some horizontal exchange of salt and heat but no decrease in horizontal temperature gradient comparable to that in salinity occurred. In fact the reverse is the case, the gradient across the Gulf from south-west to north-east increased from about 3 degC in May to about 4 degC in July. However, the increased gradient can be explained by differential cooling. Evaporative heat loss would produce more intensive cooling in the shallower south-west. Assuming a mean depth of 30 m in the south-west (Fig. 1), the heat loss of 91×10^{6} g cal m^{-2} (subsection (*d*)) can account for the fall of 3°C in that region. In the north-east and east, where the mean depth is about 50 m, a fall of only about 1.8 degC should have occurred. Temperatures in fact fell by about 2 degC in that region. Hence the changes between May and July can be explained by *in-situ* effects, and no appreciable advection occurred.

In September (Fig. 10) the high-salinity C2 water remained fairly constant in extent though changing slightly in position. On the other hand, the north-east and east of the Gulf increased again in salinity by about 0.5‰ at both 10 m and 40 m. However, Figure 10 shows that by September stratification had developed, with colder saline C2 water extending northwards underneath type C. The configuration of the isotherms suggests sinking in the south-west. Hence an *in-situ* explanation of the changes observed can once again be advanced, with minimal advection. The increase of salinity at 40 m in the north-east arose by gradual movement north-eastwards of C2 water subjected to evaporation in the shallow south-west. Again, assuming a mean depth of about 30 m, an increase of nearly 0.30‰ would have occurred (subsection (*d*)), maintaining salinities of *c.* 36.00‰ in the south-west as C2 water moved down and then north-eastward and was replaced by water of 35.50-36.00‰ original salinity. The rise of about 0.50‰ at 10 m in the north-east could be accounted for mainly by the effect of evaporation on the upper part of the water column.

The changes in temperature distribution conform with this suggested mechanism. The temperature gradient from south to north decreased from about 4 degC (July) to about 2 degC. The rise in temperature of some 3 degC in the south at 10 m and 1 degC at 40 m, giving a mean rise of 2 degC, was caused by the excess of 58×10^{6} g cal m^{-2} (subsection (*d*)) acting on the mean depth water column of 30 m. The rise of about 2 degC in the upper part of the water column in the north-east was similarly produced. Stratification presumably impeded heat transfer to the lower layers which remained at 25-26°C.

Some advection of water into the Gulf at upper levels may have occurred to compensate for the movement of C2 water northwards.

Figure 6 shows that in August and September salinities in the region of Torres Strait were around 35.50‰, so that movement of type C water into the Gulf at upper levels would have produced salinities similar to those observed, assisting the general increase due to evaporation.

By November (Fig. 11) the change of wind pattern had produced a shift in isohalines and isotherms. The areas of high salinity (>36.00‰) had moved to the south-west and south and an increase in extent of such waters had occurred. The rise in salinities from 35.50-36.00‰ to just over 36.00‰ is commensurate with the evaporation rate (subsection (*d*)) operating in the shallow south-west region. Sinking of type C2 in the south and its extension northwards at 40 m are indicated by isohaline distribution and confirmed by isotherm distribution. The north–south temperature gradient at 40 m is now reversed, and the water of temperature 26°C at 10 m in the central Gulf in September has moved south, down, and then northward along the bottom. The former cold (24°C) bottom water has moved out completely.

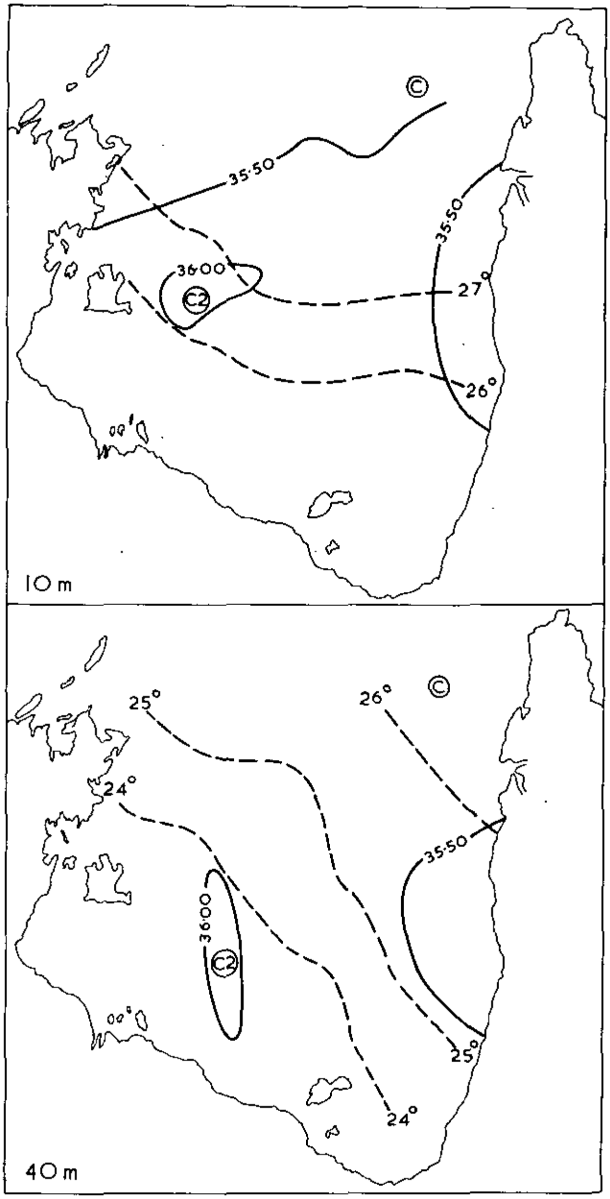

Fig. 10.–Distribution of temperature (- - -) and salinity (—) in September 1970 at 10-m and 40-m depth.

The large increase in temperatures at 10 m (*c.* 3 degC) tends to confirm movement of water into the Gulf in the upper layers. In subsection (*d*) it was calculated that little temperature change should have occurred between September and November. Similarly, evaporative effects should have produced an increase in salinities of *c.* 0.20-0.40‰ in these upper layers, depending on the depth of water column affected, yet the northern region shows slightly lowered salinities.

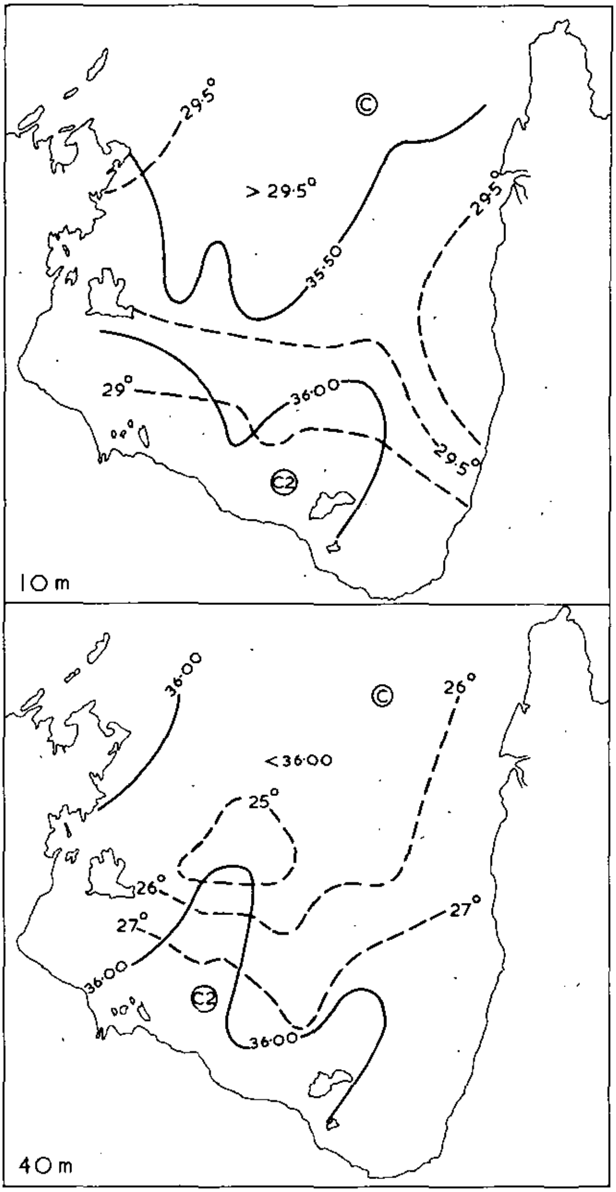

Fig. 11.–Distribution of temperature (- - -) and salinity (—) in November 1970 at 10-m and 40-m depth.

Figures 6 and 7 indicate that water in the vicinity of Torres Strait was too saline (>35.50‰) and too cold (28–29°C) in November to be a source for such advected water in the Gulf. However, Figure 12 shows the distribution of temperature and salinity in the northern half of the Gulf and the area to the north, drawn from data collected by R.V. *Oshoro Maru* in December 1968. From Figure 12 it seems that the source of the warm (>29°C) and moderately saline (35.00–35.50‰) water moving into the upper layers of the Gulf in November lies to the north-west. Hence November was a transition period between the winter influence of type C in the Gulf and the summer invasion of type B.

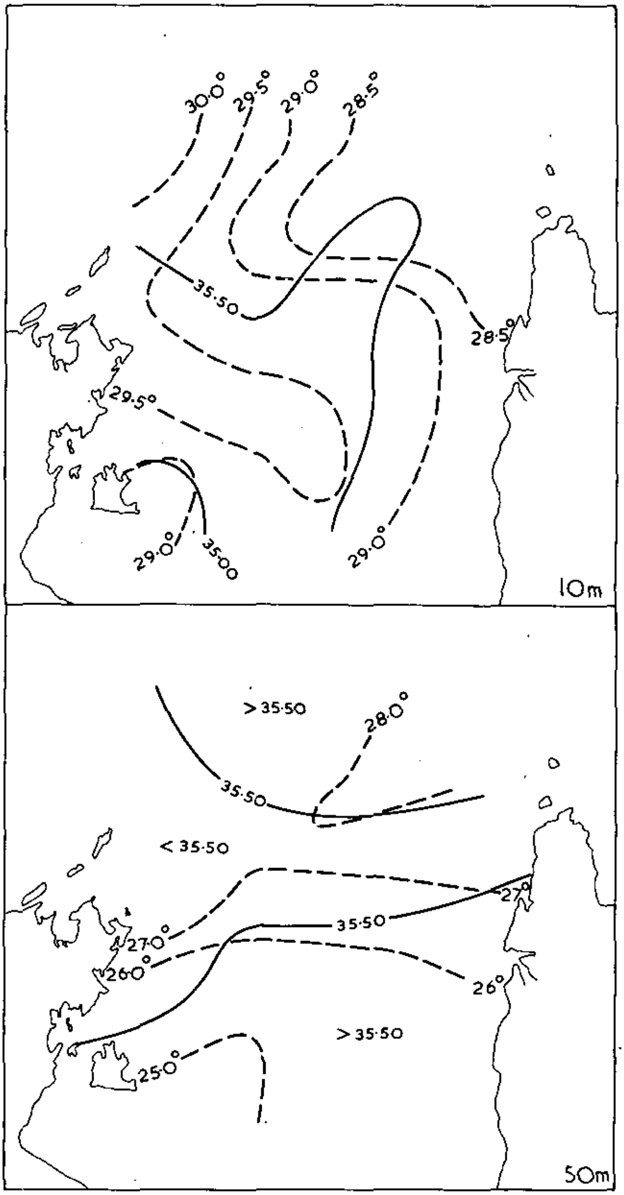

Fig. 12.–Distribution of temperature (---) and salinity (—) in the northern Gulf area at 10-m and 50-m depth (*Oshoro Maru*, December 1968).

The situation in March 1971 (Fig. 13) indicated a drastic change in regime. Type C2 water was present only at the bottom in the north-west and west, and the configuration of isotherms and isohalines suggests an escape of C2 to the north-west along the bottom. Whilst there is some effect of Gulf river outflow on salinities at 10 m in the east, the decrease in salinities generally is much greater than can be accounted for by local run-off (subsection (*d*)), so that the large area of low-salinity water must represent an invasion of type B water from the Arafura Sea. It would seem, in fact, that the Gulf is almost completely flushed out by type B water during the summer. This produces a problem in explaining the quite extensive distribution of type C2 water in the Gulf in May (Fig. 8). Water of such high salinity is not available from the north-west Coral Sea at this time of year (Fig. 6), so that

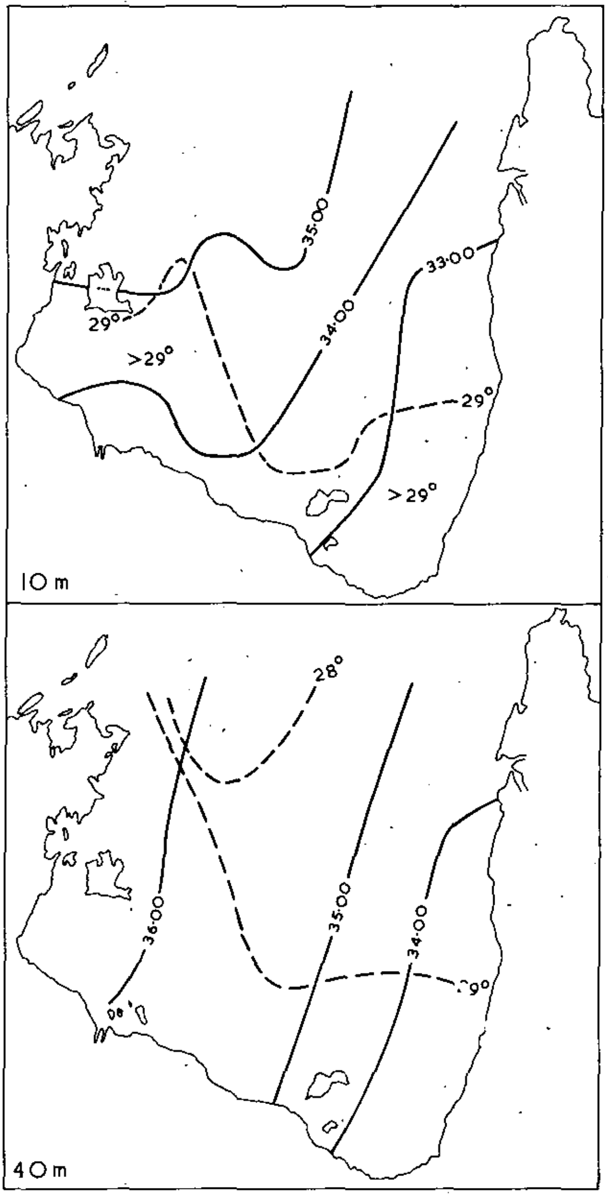

Fig. 13.–Distribution of temperature (---) and salinity (—) in March 1971 at 10-m and 40-m depth.

considerable evaporation must take place after the reversal of the wind system. The evaporation rate in May (subsection (*d*)) could not have transformed the low salinities of Figure 13 into the high salinities of Figure 8, so that considerable variation in timing and volume of the type B summer invasion must occur from year to year, that of 1969–70 being earlier and/or less extensive than that of 1970–71.

(*g*) *Vertical Distribution of Salinity and Temperature*

The vertical distribution of isohalines and isotherms for each section on each cruise is shown in Figures 14–18.

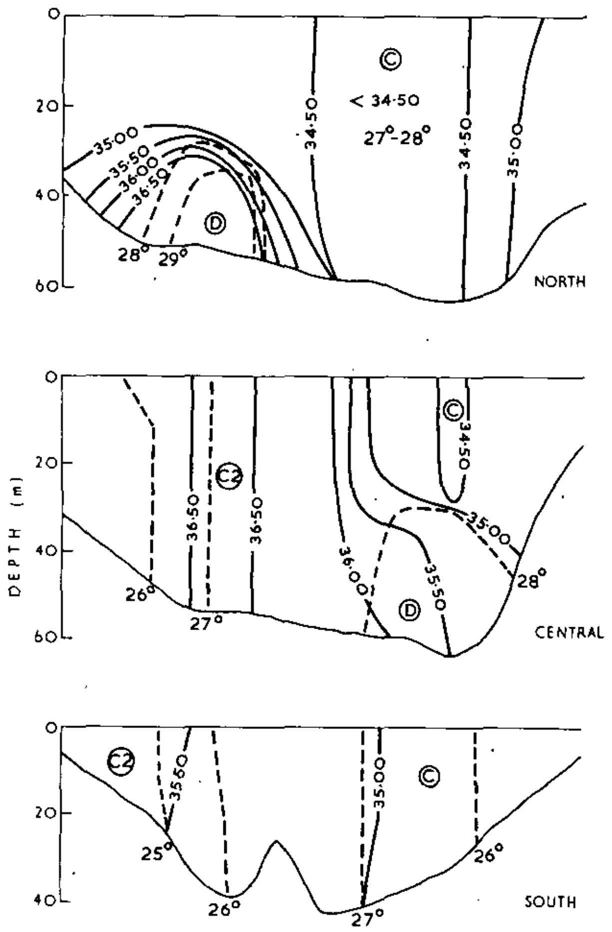

Fig. 14.—Vertical distribution of temperature (- - -) and salinity (—) along the three Gulf sections (Fig. 1) in May 1970.

Figure 14 emphasizes the vertical uniformity mentioned in subsection (*f*), except where type D water intrudes along the bottom in the north-west and extends to the east in the central section.

In Figure 15 the beginning of stratification through sinking of C2 water in the south-west is shown. This stratification has become well developed by September (Fig. 16), although some divergence and uplift of isotherms is apparent in the east, so that some of the slow movement of C2 water northward along the bottom may

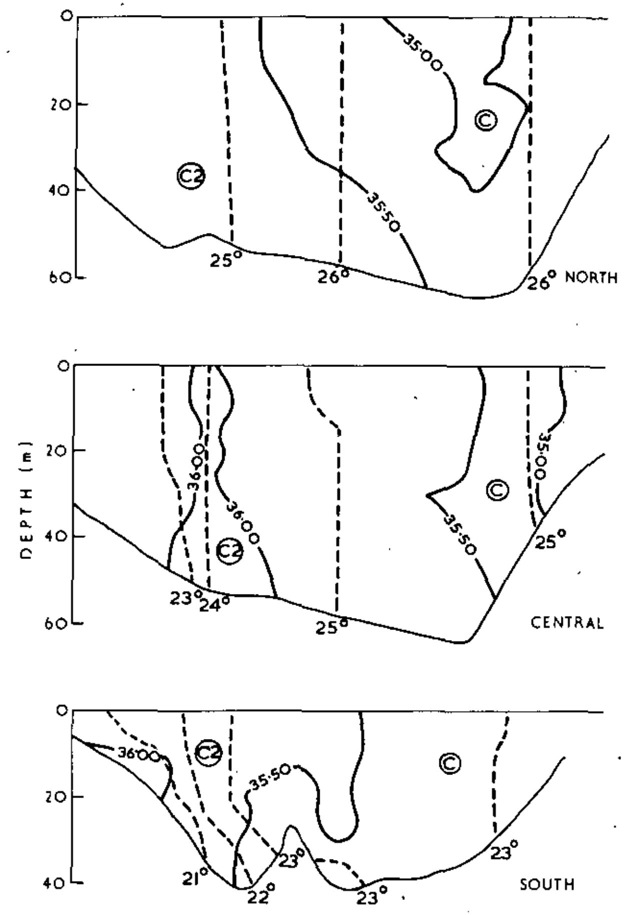

Fig. 15.–Vertical distribution of temperature (---) and salinity (—) along the three Gulf sections (Fig. 1) in July 1970.

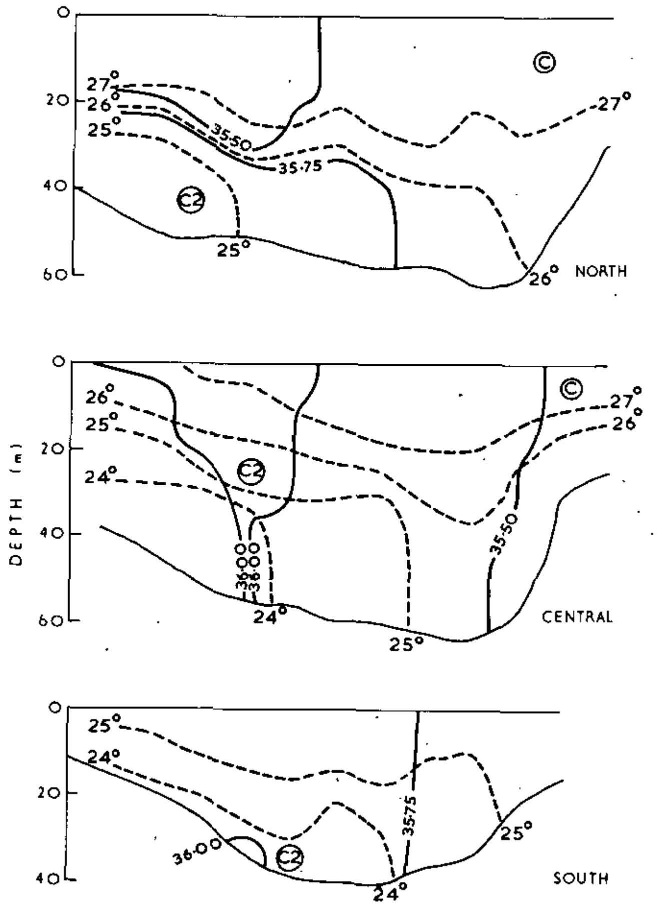

Fig. 16.–Vertical distribution of temperature (---) and salinity (—) along the three Gulf sections (Fig. 1) in September 1970.

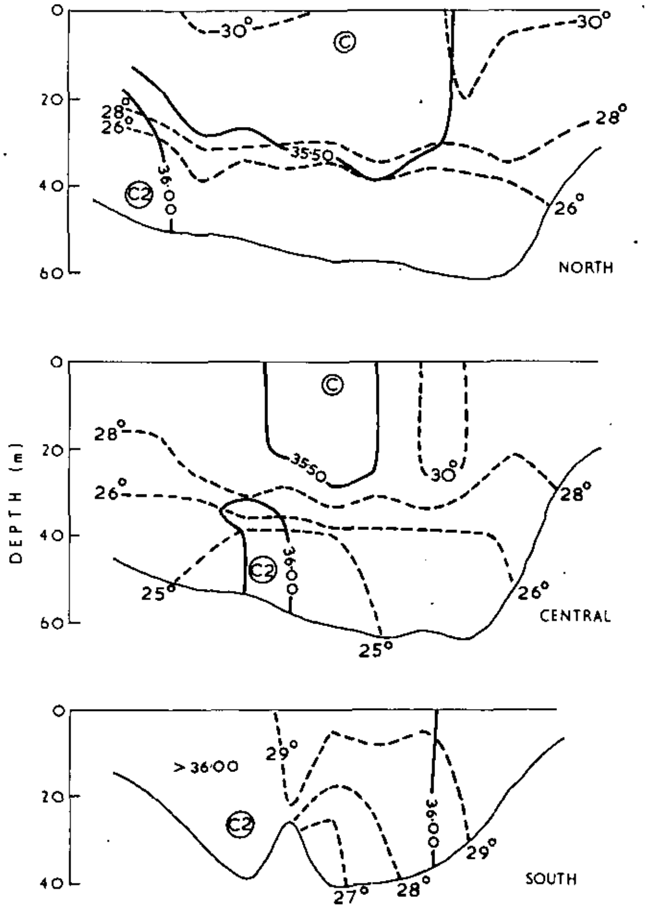

Fig. 17.–Vertical distribution of temperature (---) and salinity (—) along the three Gulf sections (Fig. 1) in November 1970.

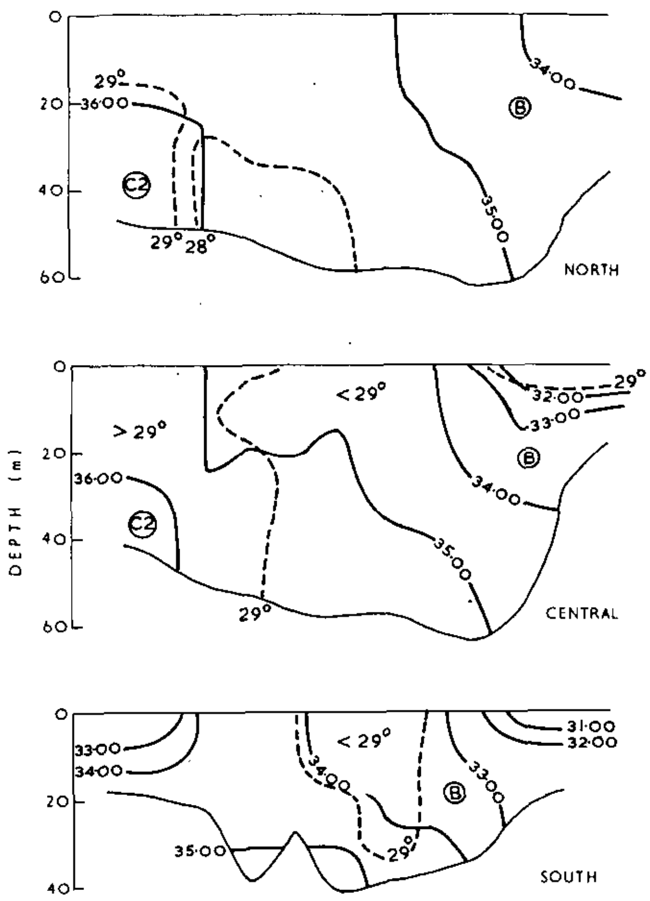

Fig. 18.–Vertical distribution of temperature (---) and salinity (—) along the three Gulf sections (Fig. 1) in March 1971.

be compensated for by vertical movement along the eastern edge of the Gulf. The same phenomenon is apparent in November (Fig. 17). Vertical stratification is now very pronounced, and it is the bottom water thus isolated that shows the trend to low oxygen and high silicate and nitrate values listed in Table 2. The sinking of C2 water has shifted from the west (Fig. 16) to the south.

Figure 18 illustrates the clockwise sweep of type B water around the Gulf and the suppression of type C2. Local river outflow produced salinities of 31.00‰, but only in the uppermost layers.

(*h*) *Origin of Type D Water*

In subsection (*e*) it was concluded that the high-salinity high-temperature water provisionally named type D must have originated within the Gulf. Examination of Figures 11 and 12 and Table 2 suggests a possible origin. In November 1970, water of high salinity (35.50-36.44‰) and high temperature (28.5-29.5°C) occupied most of the upper layers of the Gulf. In December 1968, water of similar properties was present but crowded into the north-eastern corner, with a tendency to sink to deeper levels (Fig. 12). Although the two situations are from different years, it may plausibly be claimed that the December 1968 pattern represents the beginning of the summer invasion of high-temperature low-salinity type B water from the Arafura Sea. This water moves south-eastwards into the Gulf, displacing some type C2 to the north-east and thence downwards. The lower levels of oxygen in type D compared to those of 10 m type C2 in November (3.6-3.8 ml/l *v.* 4.0-5.0 ml/l) can be accounted for by the effects of isolation at the bottom. A similar effect was observed earlier in the year in type C2 itself (subsection (*e*); Table 2). The higher levels of silicate (5.4-7.0 μg-atom/l *v.* 1.2-4.6 μg-atom/l) and of nitrate (0.7-2.2 μg-atom/l *v.* 0.0-0.2 μg-atom/l) are compatible with this. The slightly higher salinities (maximum 36.66‰ *v.* 36.44‰) are more difficult to explain in that the December to March period was one in which precipitation exceeded evaporation (Table 1), whilst some mixing with lower-salinity water to the south would be expected to occur. Furthermore, it is remarkable that such high temperatures (28.8-29.2°C) should have been retained in type D at the bottom as late as May, when temperatures generally in May were less than 28°C (Fig. 8). However, these anomalies may be a result of comparing the situations in May 1970 with the characteristics of the 1970/71 summer. If the 1969/70 summer was hotter and drier some of the anomaly could be explained. As was mentioned at the end of subsection (*f*), some difference in summer rainfall magnitude and timing must have occurred to explain the generally high salinities in May 1970.

In summary, type D therefore represents one part of the previous winter type C2, isolated to the north-east by the summer type B invasion.

(*i*) *Exit Path of Type C Water from the Gulf*

It has been stated (subsection (*f*)) that high-salinity type C2 water appears to escape from the Gulf along the bottom from November onwards. A search was made of data from all five available cruises in the area north and west of the Gulf for evidence of high-salinity water at intermediate depths. Only one cruise (Wood 1969) showed such evidence, and then only at three stations. The distributions of isotherms, isohalines, and isopycnals in a vertical section through four stations on this cruise are given in Figure 19. The latitude and longitude of each station are also shown in Figure 19. The stations lie on a shallow arc running north-west from the mid-north area of the Gulf and extending over a distance of about 280 nautical miles. All were occupied in May 1969.

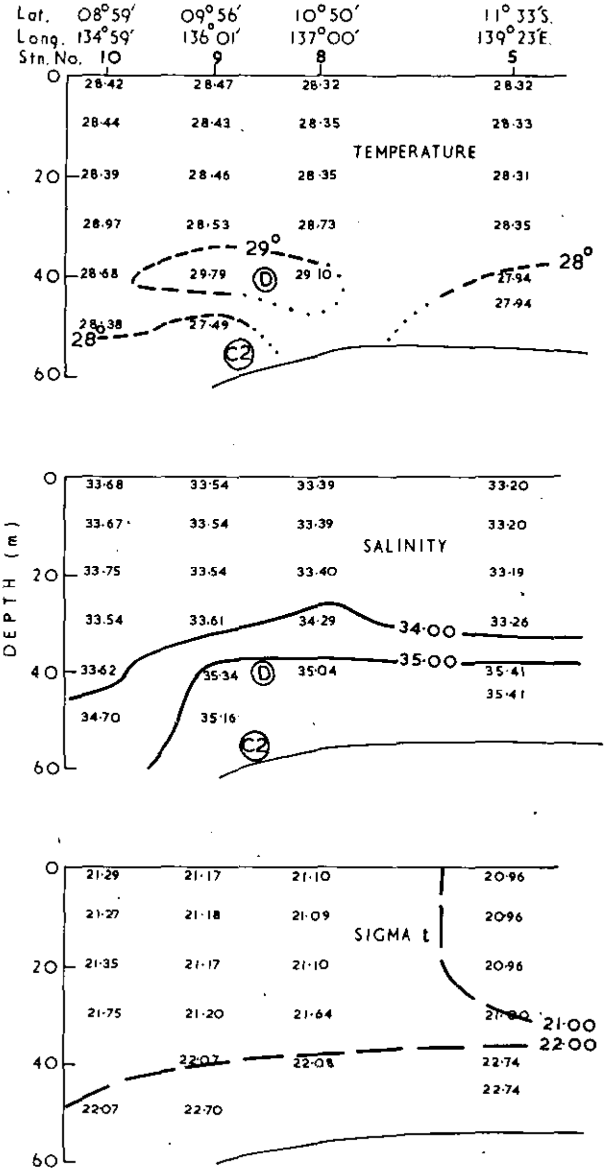

Fig. 19.—Escape path of water types C2 and D from the Gulf in May 1969.

At stations 5, 8, and 9 there is evidence of high-salinity (>35.00‰) water from about 40-m depth to the bottom and extending out from the Gulf.

Two samples (station 9, 40-m depth and station 8, 40-m depth) not only had high salinities (>35.00‰) but also a high temperature (>29°C) and are therefore likely to be traces of type D water. The remaining high-salinity water has temperature/salinity characteristics similar to type C2 water in May 1970 (Table 2). Though the salinities are slightly lower than for type C2, and the temperatures are slightly high, both departures could have resulted from mixing with the overlying water. In fact, there is a gradient of diminishing salinity westwards from station 5 below 40 m.

Since traces of type C2 could only be found at three out of ten stations in the region on this cruise (and on no other cruise examined), the volume of type C2 water escaping from the Gulf is presumably small and its rate and path of escape highly variable. The configuration of isopycnals in Figure 19 shows that the escape occurs *isentropically*.

(j) Direct Measurements of Water Movement in the Gulf

On four cruises of the *Islander VI*, Lerici current meters were laid at various locations in the Gulf. The results have been described by Cresswell (1971) and are summarized in Figure 20. All meters were suspended at 26-m depth except at Mornington Island in November, which was at 22 m. Tidal motion has been eliminated and only residual drift shown.

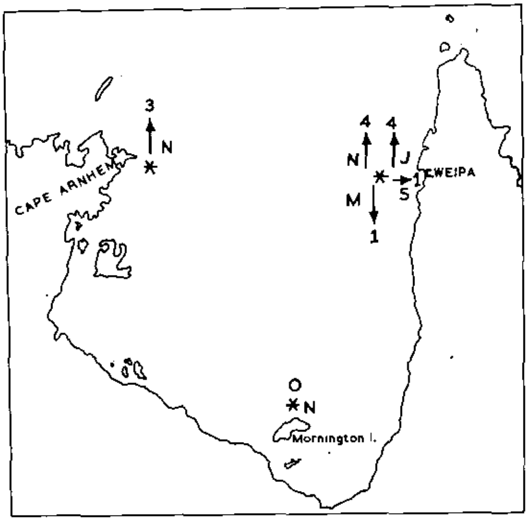

Fig. 20.—Residual (non-tidal) water movement in the Gulf as measured by Lerici current meters. Arrows denote direction, numerals the magnitude (miles/day) of drift. Letters denote month of observation (July, September, November, and March).

The most striking feature to emerge from the results is the low magnitude of non-tidal current velocities observed (from zero to 4 miles per day). The meters were set deep enough to lie either in or slightly below the shear zone between upper and lower layers in September and November (Figs. 16 and 17), and hence might be expected to register the movements of the lower layers postulated in subsection (*f*).

The direction of currents measured certainly does not correspond to any likely wind drift of the upper layers (Fig. 2). The slight eastward drift off Weipa in September may illustrate the onshore and upward movement of deeper water suggested for that month. The clear northward drift off both Cape Arnhem and Weipa in November corresponds well with the suggested northward movement of type C2 along the bottom in that month, whilst the zero motion at Mornington Island would be expected if convergence and sinking were occurring in the south in November. The shift of the 26°C isotherm between September and November (Figs. 10 and 11) amounted to about 100 miles in two months, if the isotherm is assumed to have moved south, sunk, and then moved north along the bottom. This corresponds to a velocity of 1.7 miles/day which is of similar magnitude to the measured current (4 miles/day) and may represent an average velocity as water movement increased from September to November (subsection (*f*)).

The southward current off Weipa in March is readily explained by the movement of type B water into the Gulf (Fig. 13). The northward movement off Weipa in July, however, cannot be explained from our data; in fact, July was considered to be a period of minimal advection (subsection (*f*)).

(*k*) *Chlorophyll* a *Levels in the Gulf*

Figure 21 shows the values of chlorophyll *a* found at each station. For July 1970 values are at 10-m depth, and for the other three months are the mean of all (2-3) depths sampled.

Chlorophyll was generally extremely low (<1.0 μg/l) throughout July and September. In November, slightly higher values (1.0-1.7 μg/l) occurred in the south-east, which may reflect convergence of surface water towards the south. In March, higher values (1.0-1.3 μg/l) were found in the north-west. No explanation can be offered for this phenomenon except to point out (Table 2) that bottom values of silicate were generally high (6.0-10.4 μg-atom/l) in this month, whilst the 40-m values of nitrate for the three westernmost stations in the northern section were unusually high (2.2, 4.0, and 4.4 μg-atom/l). Some enrichment of the water column may have resulted with consequent stimulation of algal growth.

IV. CONCLUSIONS

The results of this survey lead to the following conclusions (see also Fig. 22).

(1) During summer (the north-west monsoon) water from the northern Arafura Sea is driven east and south and fills the Gulf.

(2) In winter (the south-east monsoon) water from the north-west Coral Sea is driven westwards through Torres Strait and displaces Arafura water from the Gulf.

(3) In summer water moves southwards in the upper layers, displacing high-salinity water which flows out of the Gulf along the bottom.

(4) The Coral Sea water entering the Gulf during winter is subjected to high evaporation rates and intense heating and cooling which produce a high-salinity derived water type.

(5) In spring and early summer increased heating, decreased evaporative cooling, and advection result in a stratification of the Gulf. The water isolated at the bottom decreases in oxygen content and increases in nitrate and silicate content.

(6) The annual evaporation/precipitation budget of the Gulf forms a very small part of the total water exchange but is of great importance in influencing water movement.

(7) In autumn and early winter the Gulf is vertically homogeneous but develops large horizontal gradients in salinity and temperature, even though some horizontal exchange of salt occurs.

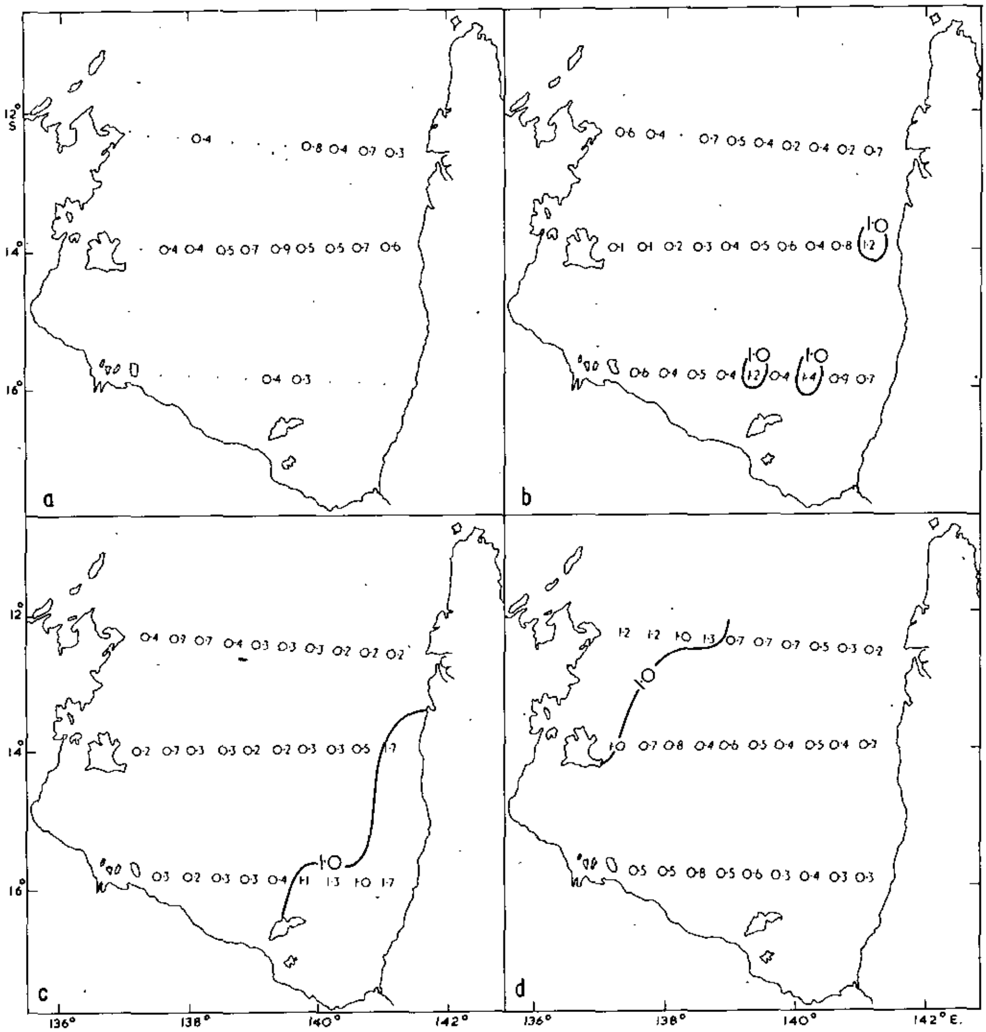

Fig. 21.–Values of chlorophyll *a* in the Gulf (μg/l).

(*a*) 10 m, July 1970.
(*b*) Mean all depths, September 1970.
(*c*) Mean all depths, November 1970.
(*d*) Mean all depths, March 1971.

(8) Levels of chlorophyll *a* are low throughout the year. Slightly higher values occurred in the south-east in November and in the north-west in March.

(9) The regime in the Gulf is a result of both *in-situ* climatic effects and the alternating wind system.

(10) The levels of the non-conservative properties (dissolved oxygen, silicate, nitrate, and total iron) show great variability throughout the Gulf, but all except total iron tend to occupy a characteristic range of values for a given water type.

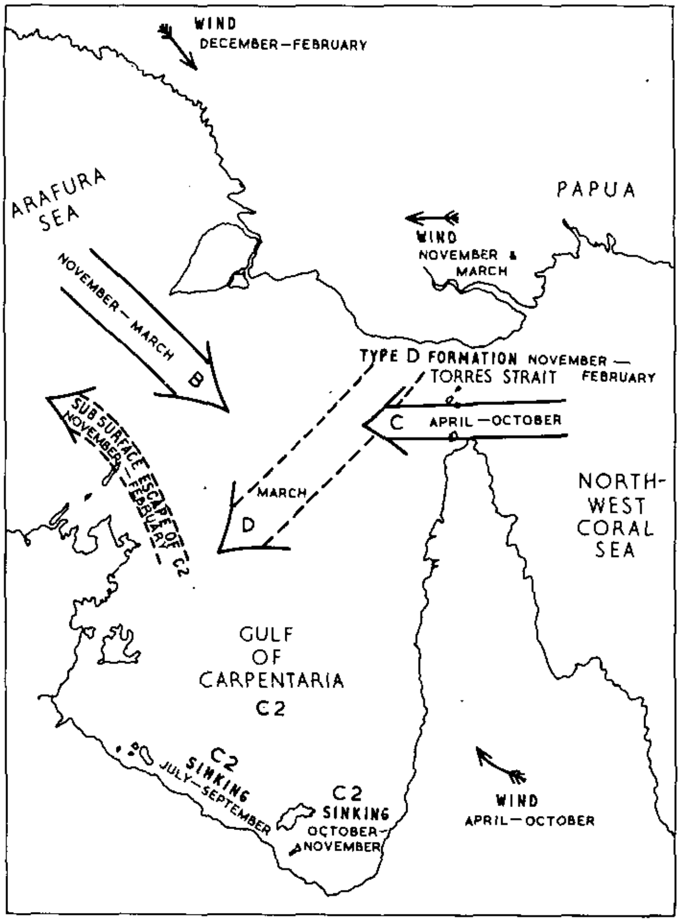

Fig. 22.–Summary of seasonal water movements in the Gulf in diagrammatic form.

V. ACKNOWLEDGMENT

Acknowledgment is made to Professor S. Nishizawa, Hokkaido University, for the data of M.V. *Oshono Maru* cruise of December 1968.

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