The International Indian Ocean Expedition: Australia's Contribution

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THE INTERNATIONAL INDIAN OCEAN EXPEDITION: AUSTRALIA'S CONTRIBUTION

By E. HIGHLEY*

Summary

During 1959–65 Australia made 35 cruises in the Indian Ocean and worked *c.* 1500 oceanographic stations. Samples were taken for hydrology, particulate carbon, primary production, pigments, and zooplankton. Other samples were taken for special studies. Six cruises, the Seasonal Biological Cruises, investigated seasonal variations along 110°E. On four cruises, aspects of energy interchange between ocean and atmosphere were studied. Australia's main contribution to the scientific results of IIOE was a systematic survey of the S.E. Indian Ocean. Also, Australia made facilities available so that Unesco's training and development roles in IIOE were met. A bibliography of Australian publications on Indian Ocean oceanography makes a significant contribution to the world literature on the subject.

I. INTRODUCTION

Over the past two decades international cooperation in science projects has increased markedly, and oceanography is a science that has been at the forefront of these international developments. This is not surprising when one considers the great extent of the world ocean, the expanse and multifarious problems associated with working in it, its common-property nature, and the fact that even now we know very little about it. Coupled with these factors has been an increasing awareness of the exponential increase in world population, the lag in agricultural production, and the consequent impending food shortages. Governments and international agencies are turning more to the sea for food and mineral resources. When Malthus made his gloomy predictions in the last century he could not account for increased agricultural production arising from advances in technology. It seems to-day that unless our methods of harvesting the living resources of the ocean are markedly improved Malthus' predictions might be belatedly upheld.

For other reasons too, interest in the oceans has increased. Priorities given to submarine weapon systems have meant that the defence departments of various countries have become more involved in oceanographic research. Many findings of general importance to oceanography have been the result of research sponsored by such agencies. Private institutions — oil companies and the like — have become more interested in the non-living resources trapped in the earth's crust on the continental shelf and at the bottom of the deep ocean.

This then is the climate in which international projects in oceanography have grown. The International Indian Ocean Expedition, 1959–65, was the first such major project.

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This paper gives an account of Australia's contribution to the Expedition. In many respects it is also a review of the development of Australian oceanography. Australia's first oceanographic observations were made in 1959 and in the Indian Ocean, and her geographic location made her peculiarly suited to contribute to the Expedition.

The Australian contribution was made up of work by the Royal Australian Navy and two CSIRO Divisions — Fisheries and Oceanography, and Meteorological Physics. *Section VIII of this paper is a bibliography of Australian publications resulting from Australian work during the Expedition.*

II. GENESIS OF THE EXPEDITION

The International Indian Ocean Expedition (IIOE) was conceived in 1957 by the Scientific Committee on Oceanic Research (SCOR), which was then a Special Committee of the International Council of Scientific Unions. IIOE was put forward as a coordinated project that would quickly overcome much of the then existing ignorance of oceanographic conditions in the Indian Ocean.

There was much interest in the proposed project and at the same time as SCOR was drafting preliminary plans a number of other significant and related developments were taking place on the international oceanography scene.

In March 1960, over 20 countries sent delegates to Paris for a Unesco-convened Preparatory Meeting to a proposed Intergovernmental Conference on Oceanographic Research (ICOR). At this meeting discussions centred around the utility of international cooperation in oceanography and the form that it should take. The importance of international surveys, exchange of data, and assistance to newly developing countries was recognized by all, and the utility of an intergovernmental body to deal with these aspects was discussed.

ICOR was held at Copenhagen in July 1960. Thirty-five countries, including Australia, attended, and the Conference recommended that Unesco establish an Intergovernmental Oceanographic Commission (IOC). The main aim of IOC would be to promote "scientific investigations of the oceans, with a view to learning more about their nature and their resources, through the concerted action of the Member States of the Commission".

In November 1960, following the recommendations of ICOR, Unesco established an Office of Oceanography and then the IOC itself, with SCOR scientific adviser to both.

After this, plans for IIOE proceeded more rapidly. However, the original plan for a highly coordinated survey with ports neatly apportioned between participants (Snider 1960; Wust 1960) had to be changed. There was some feeling against the original plan; many considered it impracticable. In any case, some laboratories elected to make extensive surveys, and others preferred to devote varying amounts of time to survey work but to concentrate on problems of particular interest to themselves. It is perhaps unfortunate that the latter occurred, because at the outset it tended to detract from the "expeditionary" concept of IIOE.

In 1961, Unesco became a co-sponsor, with SCOR, of IIOE. Scientific matters were SCOR's responsibility, while Unesco, through the IOC, assumed much of the responsibility for coordination and administration. In addition, Unesco brought wider aims to the Expedition in terms of training and assistance to the newly developing countries of the world, particularly those around the Indian Ocean. Unesco Shipboard Fellowships were created so that scientists from these countries could gain valuable experience in oceanography aboard the vessels of other participants.

It is difficult to give a precise date to the start of the Expedition — when planning ended and the project began — but cruises started in 1959 and Australia was one of the first countries to begin. Australia played an important role in the genesis of IIOE both as a Member State of IOC and in contributing to SCOR's efforts. The President of SCOR during the formative years of IIOE was an Australian, Dr G. F. Humphrey, who was also in charge of Australia's oceanographic laboratory.

TABLE 1

SPECIFICATIONS OF H.M.A.S. DIAMANTINA

Year built	1945	Range	3800 miles
Length overall	301 ft	Endurance	18 days
Beam	37 ft	Crew	140
Draft	14 ft	Scientists	6
Laden displacement	2100 tons	Engine	Triple expansion steam reciprocating
Speed: Cruising	13 kt		
Maximum	15 kt		
Minimum	2 kt		

The Expedition ended in December 1965, and by this time 12 countries (Australia, France, Germany, India, Indonesia, Japan, Pakistan, Portugal, South Africa, U.K., U.S.A., U.S.S.R.) had made IIOE cruises.

Any assessment of the worth of IIOE must take into account the degree of international cooperation it engendered and the utility of the data that were collected. As will be mentioned later, there was a great deal of cooperation between participants in intercalibration tests, in projects, and the like. Massive amounts of data were collected and lodged with the World Data Centres in Moscow and Washington. They are now being used to make biological, chemical, geological, and meteorological atlases of the Indian Ocean.

III. AUSTRALIAN OCEANOGRAPHIC FRIGATES

Australian IIOE cruises were made on board two frigates, H.M.A.S. *Diamantina* and H.M.A.S. *Gascoyne*. These ships were released from the Royal Australian Navy's reserve fleet in 1959, and extensively refitted for oceanographic research.

Table 1 gives specifications of H.M.A.S. *Diamantina* only, but *Gascoyne's* are similar. The low minimum speed is made possible by engine type and greatly facilitates handling on station.

Scientific facilities of H.M.A.S. *Diamantina* are shown in Figure 1. The biological winch is electrically powered and carries 200 m of wire. It is used to collect water samples for particulate carbon, primary production, pigment, and phytoplankton studies. The oceanographic winch is electrically powered, rated at 25 hp, and carries 10,000 m of wire. It is used to collect samples for chemical analysis, to make plankton net vertical hauls, and for light penetration measurements in connection with primary production studies. The steam winch is used in conjunction with the stern davit for plankton net towing and midwater trawling, and to take bottom samples.

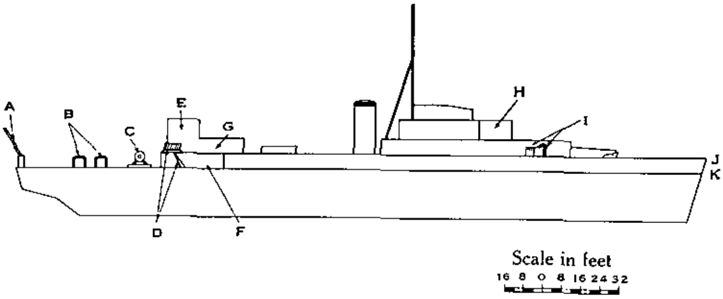

Fig. 1.—Scientific facilities on H.M.A.S. Diamantina. A, *plankton and dredging davit;* B, gimbal mounted light baths; C, steam winch; D, oceanographic winch and davit; E, balloon filling; F, laboratory; G, meteorological office; H, scientists' six-berth cabin; I, biological winch and davit; J, forecastle deck; K, upper deck.

The main entrance to the ship's laboratory (Fig. 2) is opposite the oceanographic winch davit. The laboratory has 378 sq ft of floor space, and is divided into two sections: a forward section, nearer the biological winch for biological work, and an aft section for physical and chemical work. Portable partitions can be used to separate sections of the laboratory for specific types of work, e.g. to make microscope cabinets.

In general, most of the analyses of samples are done while the ship is steaming between stations.

IV. Australian IIOE Cruises

Australia made 35 IIOE cruises, most of these aboard *Diamantina* in the eastern Indian Ocean. Figure 3 shows the number of oceanographic stations worked during Indian Ocean cruises between 1959 and 1965. Observations were made at about 1500 stations between 55° and 140°E. (mainly 100° and 120°E.), and 10°N. and 45°S.

Table 2 shows the work done during Australian IIOE cruises. Hydrology samples, which were usually collected from surface to bottom, were taken with standard aged metal Nansen bottles fitted with protected and unprotected thermometers. The samples were analysed for salinity, oxygen, inorganic phosphate, total phosphorus, and nitrate nitrogen. Particulate carbon, primary production, pigment, and phytoplankton samples were collected in the upper 150 m using plastic samplers. Zooplankton and midwater trawl organisms were collected in the upper 200 m. Benthic sampling was restricted to the continental shelf.

Details of sampling and analytical methods are given in the various Oceanographical Cruise Reports.

Meteorological observations on station, and continuous depth sounding, were undertaken by the Royal Australian Navy.

The Division of Meteorological Physics, CSIRO, made observations relating to energy exchange between atmosphere and ocean, in particular the radiant energy income of the ocean, on Cruises Dm1/62, G4/62, Dm2/63, and Dm3/63.

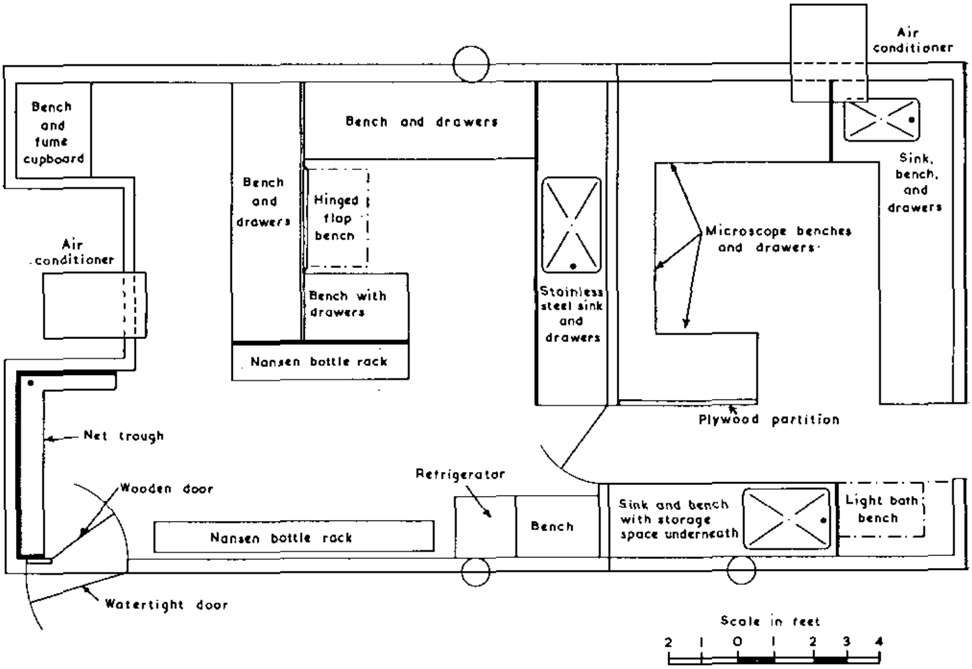

Fig. 2.—Laboratory arrangements on H.M.A.S. *Diamantina.*

Cruises between 1959 and 1962 were part of a general study of the oceanography of the eastern Indian Ocean, and were planned to cover the largest area possible. Data collected on these cruises allowed the formulation of specific problems investigated on subsequent cruises.

Cruises G4/62, Dm4/62, G1/63, Dm1/63, Dm2/63, and Dm3/63 were "Seasonal Biological Cruises" planned to investigate seasonal variations in hydrological and biological conditions along 110°E., between 32°S. and 10°N. In this programme, CSIRO collaborated with the Oceanographic Laboratory, Centre O.R.S.T.O.M., Noumea, New Caledonia, which planned and carried out midwater trawling.

V. COLLABORATION WITH OTHER PARTICIPANTS

Australia collaborated with other IIOE participants in a number of ways. Collaboration with French oceanographers from Noumea has already been mentioned.

IIOE was planned as a cooperative effort and to some extent the degree of collaboration between participants can perhaps be taken as one index of success of the project.

SCOR–Unesco Intercalibration Tests

One of the most important forms of collaboration during IIOE was the intercalibration of oceanographic techniques. There were considerable differences between participants in sampling and analytical methods. It was not known if the results of participants would be comparable. To throw light on this matter, four series of SCOR–Unesco Intercalibration Tests were held. Three series looked at the various chemical methods, and the other dealt with biological methods.

TABLE 2

WORK DONE ON AUSTRALIAN IIOE CRUISES

Cruise	Hydrology	Particulate Carbon	Pigments	Primary Production	Zooplankton Biomass	Phytoplankton	Meteorology	Benthos	Sediments	Midwater Trawl
Dm2/59	+		+	+	+	+				
Dm1/60	+		+	+		+				
Dm2/60	+		+	+	+	+				
Dm3/60	+									
Dm1/61	+		+	+	+	+				
Dm2/61	+		+	+	+	+				
G2/61	+		+	+						
Dm3/61	+		+	+	+	+				
Dm1/62	+		+	+	+	+	+			
Dm2/62	+		+	+	+					
G2 and G3/62	+				+			+		
G4/62*	+		+	+	+		+			+
Dm3/62	+		+	+	+					+
Dm4/62*	+		+	+	+					+
G1/63*	+	+	+	+	+					+
G2/63	+									
Dm1/63*	+	+	+	+	+					+
Dm2/63*	+	+	+	+	+		+			+
Dm3/63*	+	+	+	+	+		+			+
Dm4/63	+				+			+	+	+
Dm5/63	+	+	+	+	+					
Dm6/63	+							+	+	+
Dm1/64	+							+	+	+
G2/64	+				+					
Dm2/64	+									
Dm3/64	+									
Dm4/64	+				+				+	+
Dm5/64	+			+	+					
G5/64	+									
G2/65	+									
G5/65	+									
Dm1/65	+		+	+	+					+
Dm2/65	+				+					+
Dm3/65	+									+

* Seasonal Biological Cruises. Midwater trawling planned and carried out by the Oceanographic Laboratory Centre O.R.S.T.O.M., Noumea, New Caledonia.

The first chemical series was held at Honolulu in September 1961 aboard *Gascoyne* and the U.S.S.R.'s R.S. *Vityaz*, and in shore laboratories of the University of

Hawaii. Scientists from Australia, India, Indonesia, Japan, Pakistan, U.K., U.S.A., and U.S.S.R. collaborated in these tests, which showed much larger differences than expected between the phosphate and oxygen analyses of participants. It was found that in many cases these differences resulted from the use of unsuitable equipment.

The second series of SCOR–Unesco Chemical Intercalibration Tests, which was suggested by the Institute of Oceanology, Moscow, was held off Fremantle in August 1962 aboard R.S. *Vityaz.* Mr D. J. Rochford, the Australian hydrologist, was in charge of the work at these tests. Oceanographers from Australia, Japan, U.S.A., and U.S.S.R. collaborated.

The main aim of the second chemical series was to elucidate further some of the differences in results found during the first series. During the second series it was found that when different types of Nansen bottles were used to collect samples there were liable to be large differences in oxygen determinations made on samples from these bottles. Plastic lined, all plastic, and aged metal Nansen bottles were the most reliable. As sampling depth increased, samples from unaged metal Nansen bottles tended to give lower oxygen values than samples from other types of Nansen bottle (Rochford 1963).

The third series of chemical tests was held in May–June 1964 aboard U.K.'s R.R.S. *Discovery* in the Indian Ocean (Rochford 1964*a*). These tests were basically an extension of the first two series but were held during a long sea voyage. Australian and U.K. methods of inorganic phosphate, total phosphorus, oxygen, and salinity analysis were compared.

SCOR–Unesco Zooplankton Intercalibration Tests were held aboard R.S. *Vityaz* at the same time as the second chemical series. Mr D. J. Tranter, the Australian zooplanktologist, was in charge of the work which compared the catches of three types of zooplankton net. The nets compared were the Indian Ocean Standard Net (IOSN), the Soviet Juday net, and the Australian Clarke–Bumpus Sampler (CBS). The IOSN, of which more will be said later, was designed specially to take standard zooplankton samples during IIOE. The net tests showed that, despite great differences in size and construction, the three nets give comparable estimates of zooplankton biomass (Tranter 1963).

Methods of estimating primary production were compared aboard *Vityaz* and *Gascoyne* in 1961 and aboard *Vityaz* in 1962 (Doty *et al.* 1965) by a working group of which the Australian scientist Mr H. Jitts was a member. There were significant differences between the results of participants and these were interpreted to arise from variations in incubation conditions, sampling depths, and the methods used to standardize the amount of ^{14}C added.

SCOR–Unesco Reference Stations

To supplement the findings of the Intercalibration Tests, and also to monitor long-term changes in the deep ocean, 15 SCOR–Unesco Reference Stations were nominated (see Fig. 14). Ships participating in IIOE were requested to sample to the bottom at these stations as often as possible.

It was assumed that, at the great depths sampled at the Reference Stations, properties would change very slowly. Hence, larger than expected differences in the results of countries working these stations would tend to indicate faults in methodology rather than real property changes. As it turned out significant changes were noted, and more will be said about this in Section VI.

SCOR–Unesco Reference Station 1 is at 32°S., 111°50′E. in 5000 m of water off Fremantle, and Reference Station 2 is at 9°S., 105°E. in about 6000 m of water south of Java. During Australian IIOE cruises, No. 1 was sampled to the bottom 29 times, and No. 2 18 times.

Indian Ocean Standard Net

The IOSN was designed to undertake the minimum sampling necessary for an initial survey of zooplankton in the Indian Ocean. Many ships undertook more detailed and extensive collections for special studies but it was hoped that each vessel participating would make at least one IOSN haul at each station occupied. On most Australian cruises both the IOSN and Clarke–Bumpus Sampler were used at each station.

TABLE 3

IOSN SAMPLES RECEIVED BY IOBC

(February 1966)

Country	No. of Samples	Country	No. of Samples
Australia	206	South Africa	360
France	0	Thailand	0
India	436	U.K.	206
Indonesia	0	U.S.A.	457
Japan	180	U.S.S.R.	79
Pakistan	22	West Germany	122
Portugal	0		
		Total	2,068

The IOSN is a simple conical net devoid of opening and closing devices and was designed taking into account the requirements of several nations and of different gear and working conditions. In these respects its design is to some degree a compromise. The standard IOSN haul is vertical, from 200 m to the surface, at a speed of 1 m/sec.

Not only standard IOSN samples, but also as many other zooplankton samples as possible collected during IIOE were sent to the Indian Ocean Biological Centre (IOBC) at Cochin, in southern India. However, the main function of IOBC is to sort IOSN samples. IOBC is financed by Unesco and the Indian Council for Scientific and Industrial Research, and staffed by Indian scientists, and the Curator of the International Collection held there is appointed by Unesco. IOBC is advised by an International Consultative Committee of which the Australian zooplanktologist, Mr D. J. Tranter, is a member. Mr Tranter is also working as Curator for 1968–69. Under the guidance of the Committee, IOBC holds promise of developing into an active centre of research and its work is important of course to the biological atlas of the Indian Ocean now being produced.

Table 3 shows that Australia contributed 10% of the IOSN samples received by IOBC from IIOE participants. Many non-standard samples taken with other nets have also been received.

Facilities Available to Overseas Personnel

During IIOE, Australia made facilities available to contribute to Unesco's training and development roles in IIOE. In addition, other overseas personnel were present on Australian cruises during collaborative efforts. Table 4 lists the names of overseas scientists present during Australian cruises.

TABLE 4

OVERSEAS SCIENTISTS ON AUSTRALIAN IIOE CRUISES

Cruise	Scientist	Affiliation
Dm3/61	E. Hagmeier U. Rabsch	Institute for Marine Research, Kiel
G4/62	M. El-Hehyawi	Unesco Shipboard Fellow from U.A.R.
	M. Legand	Oceanographic Laboratory, Centre O.R.S.T.O.M., Noumea
Dm3/62	T. Khan	Pakistan Council for Scientific and Industrial Research
Dm4/62	Chan Kwan-Ming	Unesco Fellow, Cooperative Development and Fisheries Department, Hong Kong
	B. Wauthy	Oceanographic Laboratory, Centre O.R.S.T.O.M., Noumea
G1/62	C. Ho	University of Malaysia
	T. Khan	Pakistan Council for Scientific and Industrial Research
	A. Magnier	Oceanographic Laboratory, Centre O.R.S.T.O.M., Noumea
Dm1/63	J. Faget	Oceanographic Laboratory, Centre O.R.S.T.O.M., Noumea
Dm2/63	R. Desrosieres	Oceanographic Laboratory, Centre O.R.S.T.O.M., Noumea
	C. Ho	University of Malaysia
Dm3/63	J. Faget	Oceanographic Laboratory, Centre O.R.S.T.O.M., Noumea
Dm3/64	P. N. A. Nirun	Royal Thai Navy
	D. V. Subba Rao	Unesco Fellow from India, working at the Division of Fisheries and Oceanography

VI. AUSTRALIAN SCIENTIFIC RESULTS

(*a*) *Physical Oceanography*

(i) *Temperature–Salinity Structure in the Western Indian Ocean*

In May and June 1964 an Australian-designed Temperature–Salinity–Depth (TSD) Recorder was used during a cruise of R.R.S. *Discovery* to investigate temperature–salinity structure in the upper 1500 m in the western Indian Ocean (Hamon 1967). In this work Australian scientists and scientists from the U.K. National Institute of Oceanography collaborated.

The TSD Recorder measures temperature, salinity, and depth by electrical means as it is lowered through the water and the results are transmitted to the surface vessel by an acoustic link.

The TSD records revealed a number of interesting features of vertical structure in the Indian Ocean that would not have been revealed by conventional, standard-depth, sampling techniques.

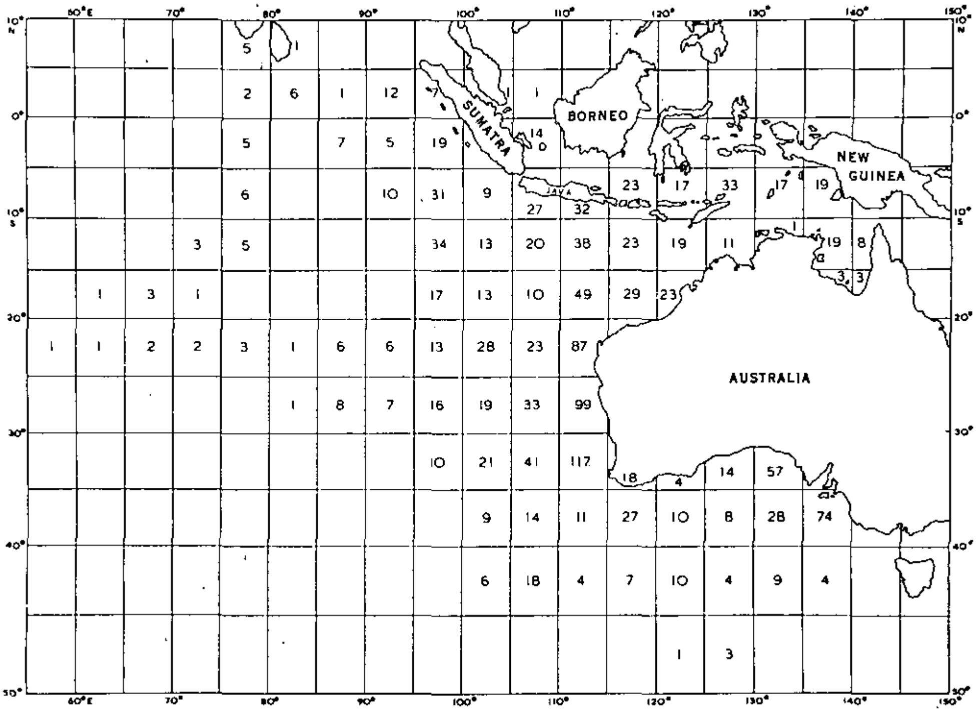

Fig. 3.—Number of oceanographic stations worked during Australian IIOE cruises (in 5° squares).

In the Red Sea and Persian Gulf, high temperatures and low precipitation produce high-salinity water which sinks and moves into the Indian Ocean at sub-surface depths. Migration and mixing of this water produce a complex vertical distribution of properties and this complexity was noted at many of the TSD stations (Fig. 4) in this study.

Figure 5 shows salinity–depth curves for six stations near the Arabian coast. A complex vertical structure was evident at each of these. Salinity changed appreciably within a few metres near the surface, and within a few tens of metres at greater depths. For example, at Station 5392, salinity changed from *c.* 36·10 to 35·70‰ within 20 m near the surface and rose again to *c.* 35·95‰ within another 20 m. At Station 5396, salinity at 150 m was *c.* 35·70‰. It then increased to *c.* 36·10‰ at 200 m, then fell again to *c.* 35·70‰ at 300 m. The six curves in Figure 5 suggest a tongue of higher salinity water moving through between 200 and 300 m.

In many cases salinity changes were so rapid that they could be classed as discontinuities, e.g. Stations 5393 and 5394 at *c.* 1100 m (Fig. 5). Many of the larger salinity changes were accompanied by temperature inversions, i.e. increases in temperature with increasing depth. Inversions were more frequent north of the equator, and half of them occurred between 500 and 800 m. They probably resulted from the spread of Red Sea water. The largest temperature inversion found was at Station 5401 (Fig. 4, 12°42′N., 56°51′E.) where temperature rose from 8·50° at 995 to 9·24°C at 1023 m.

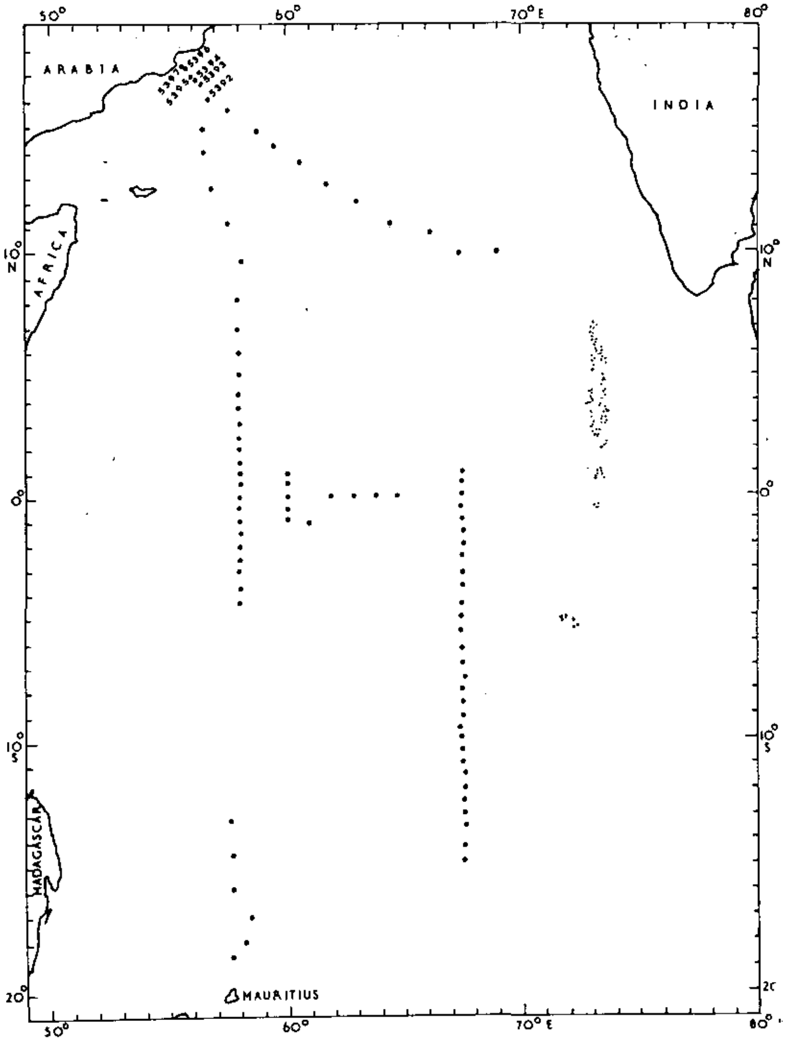

Fig. 4.—Stations at which Australian TSD Recorder was used during R.R.S. *Discovery* cruise in May–June 1964 (after Hamon 1967).

An examination of all TSD records showed that vertical structure in the deepest layers was most marked when the density (σ_t) of the water was within the range

(σ_t 27·0–27·4) shown by Rochford (1964*b*) to be characteristic of water of Red Sea origin. Rochford (1964*b*) showed also that water whose origin is presumed to be the Persian Gulf appears as a salinity maximum in the σ_t range 26·2–26·9. A marked salinity maximum in this range was found at Station 5394, near the Arabian coast.

(ii) *Geostrophic Currents in the South-East Indian Ocean*

Hamon (1965) determined currents in the upper 1750 m by the dynamic method (see Hamon 1962). Data from 13 Australian cruises, including Seasonal Biological Cruises, were used.

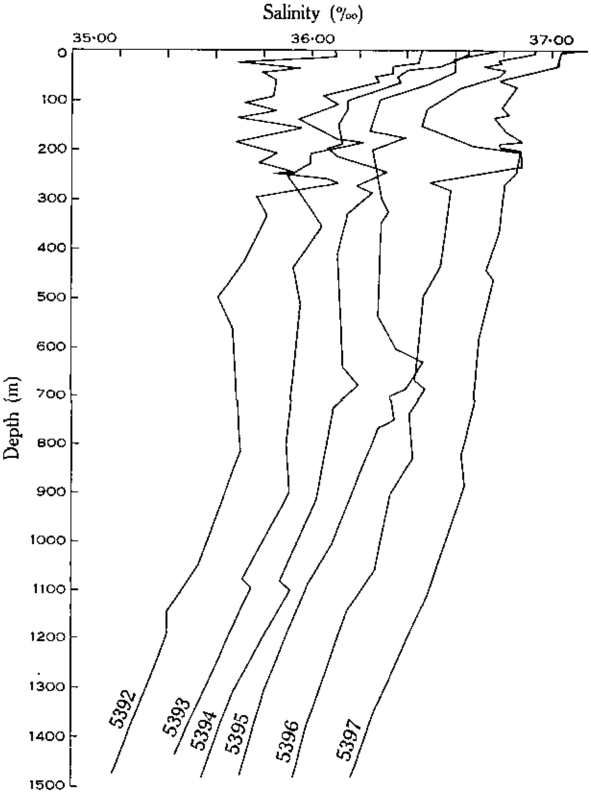

Fig. 5.—TSD Recorder (salinity–depth curves for six stations near the Arabian coast. The graphs for successive stations have been moved 0·2‰ to the right after Hamon 1967).

Figure 6 shows currents on the sea surface during July–September 1962. The most prominent feature is the narrow, west-flowing South Equatorial Current at around 12°S. on the 100, 105, and 110°E. meridians. At 105 and 110°E., there were appreciable eastward currents south of the South Equatorial Current. Figure 7 shows zonal currents across 110°E. in August–September 1962. The narrow South Equatorial Current around 10–12°S. is again the most prominent feature. Table 5 shows variations in the position and surface velocity of the South Equatorial Current across 110°E. during the Seasonal Biological Cruises. The Current is relatively constant throughout the year with no evident pattern in the small variations that do occur in its position and strength. The current is about 90 miles wide.

Perhaps the most interesting finding of this study on the south-east Indian Ocean was a suggested double eddy system off Fremantle in November 1959 (Fig. 8). However, available data indicate that such a system would be a rare occurrence.

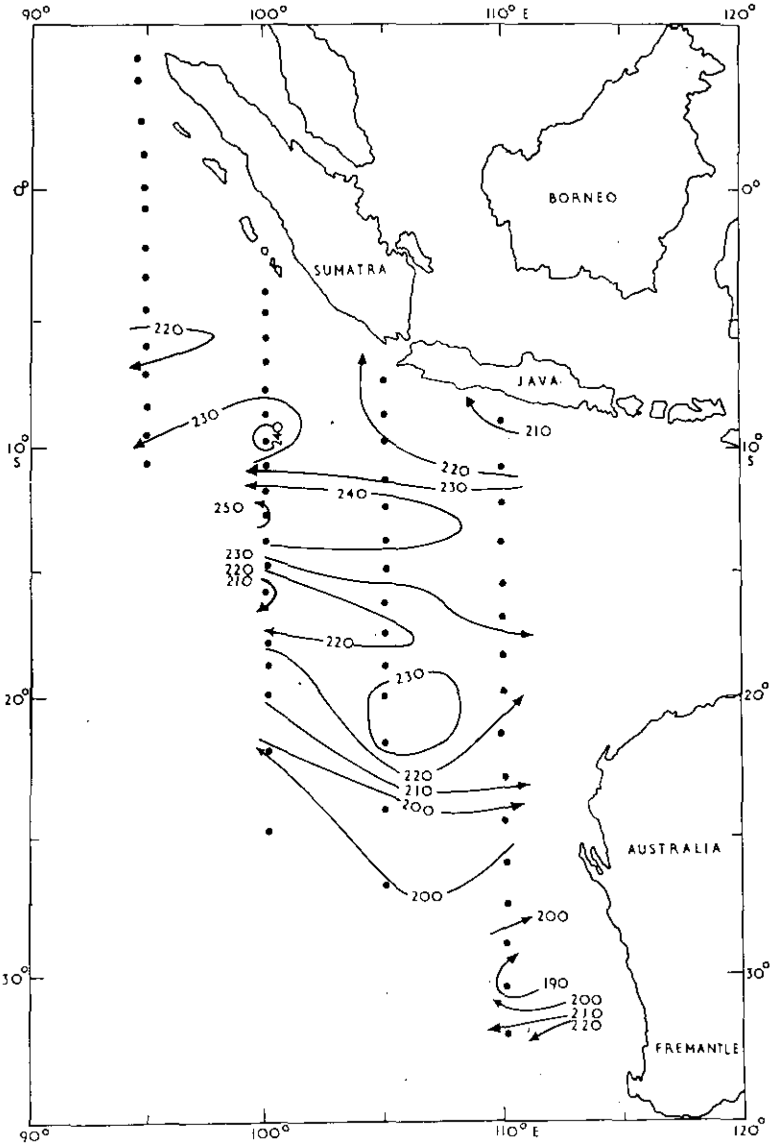

Fig. 6.—Sea-surface currents in the south-east Indian Ocean during July–September 1962 (after Hamon 1965). The values are sea surface heights in centimetres (see Hamon 1962 for explanation). ● *Station positions.*

In general, this study showed that, apart from the South Equatorial Current, circulation in the region can be very variable.

(b) *Chemical Oceanography*

Australian IIOE work in chemical oceanography was concerned with the distribution and circulation of various water masses in the Indian Ocean.

TABLE 5

MEAN LATITUDE AND SURFACE VELOCITY OF THE SOUTH EQUATORIAL CURRENT ON 110°E.

Cruise Dates	Surface Current (cm/sec)	Mean Position of Current (°S.)
19.viii–16.ix.62	50	11°45′
15.x–13.xi.62	64	11°45′
17.i–17.ii.63	34	13°15′
28.iii–27.iv.63	75	11°45′
6.v–3.vi.63	35	10°15′
9.vii–11.viii.63	96	10°15′

(i) *Banda Sea Water*

Rochford (1961) traced water from intermediate depths (1000 m) of the Banda Sea as far west as 95°E. Rochford (1966*a*) analysed more recent data on the movement of Banda Intermediate water collected on cruises by *Atlantis*, *Diamantina*, *Discovery*, *Umitaka Maru*, and *Vityaz*, west of 95°E. In addition, data collected during Seasonal Biological Cruises allowed investigation of seasonal changes in the drift of Banda Intermediate water across 110°E.

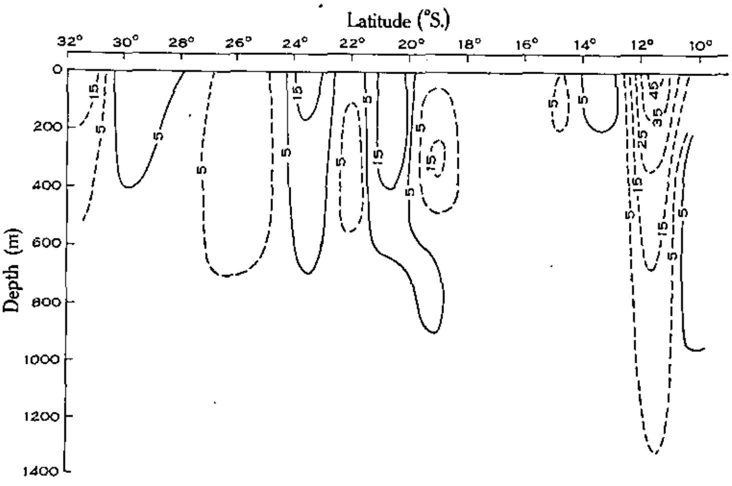

Fig. 7.—Zonal currents across 110°E. in August–September 1962 (after Hamon 1965). ------ West-flowing; ——— east-flowing. Numbers are current velocities (cm/sec).

Rochford (1966*a*) identified Banda Intermediate water in the Indian Ocean as a salinity minimum on about the 27·40σ_t (density) surface, mostly at depths between 900 and 1100 m, within latitudes 0–20°S., and always lying below an oxygen minimum shown by salinity characteristics to be of Red Sea origin.

Figure 9 shows the distribution in the Indian Ocean of water having Banda Sea salinity characteristics and the directions of drift of this Banda Intermediate water as far west as Madagascar within latitudes 0–20°S. There is appreciable southward diversion of flow but little to the north.

Figure 10 shows the depths at which spreading of Banda Intermediate water occurs. It leaves the Banda Sea at 1000 m and steadily deepens to 1400 m during its westward flow.

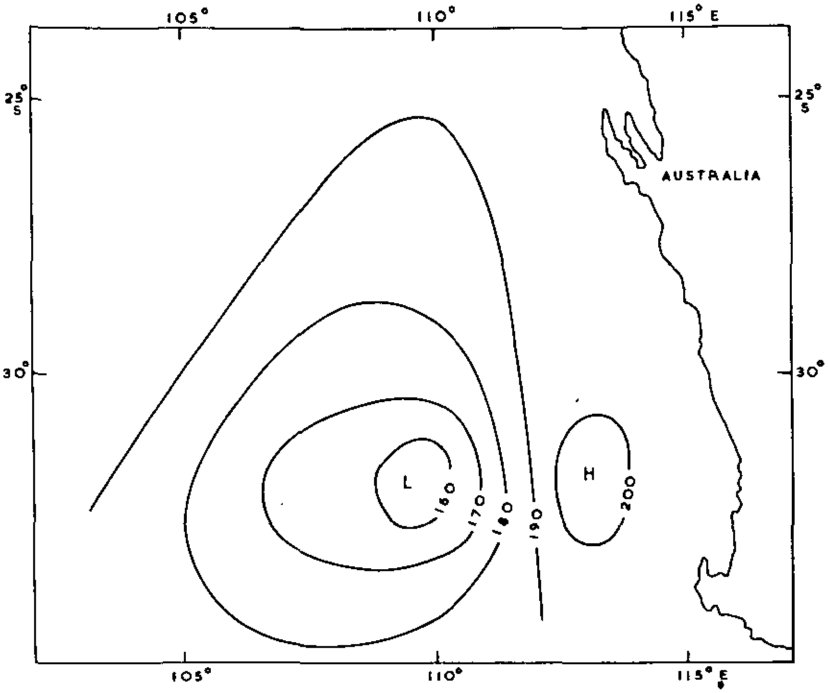

Fig. 8.—Double eddy system off Fremantle in November 1959 (after Hamon 1965).

It seems likely that Banda water is diverted south by a south-easterly flow of water of Red Sea origin. In May 1964, during a cruise by R.R.S. *Discovery* an exceptionally strong current (22 cm/sec) to the east was found at about 1000 m near the Chagos Is. Figure 11 shows other water masses in the Indian Ocean that affect the westward flow of Banda water.

Data collected during the Seasonal Biological Cruises showed that in August–December the region of maximum concentration of Banda water through 110°E. (11–12°S.) was within the South Equatorial Current (see Fig. 7) with westward velocities of 7–11 cm/sec. However, at other times of the year westward currents in the region of maximum concentration of Banda water were absent. A weakening of westward transport across 110°E. in March–July might be due to its seasonal absorption into east-flowing water of Red Sea origin — the same water as causes southerly diversion of Banda water further west.

Apart from being of intrinsic interest in Indian Ocean oceanography, the westward flow of Banda Intermediate water is interesting in so far as it has no known circulation counterpart in either the Atlantic or Pacific Oceans.

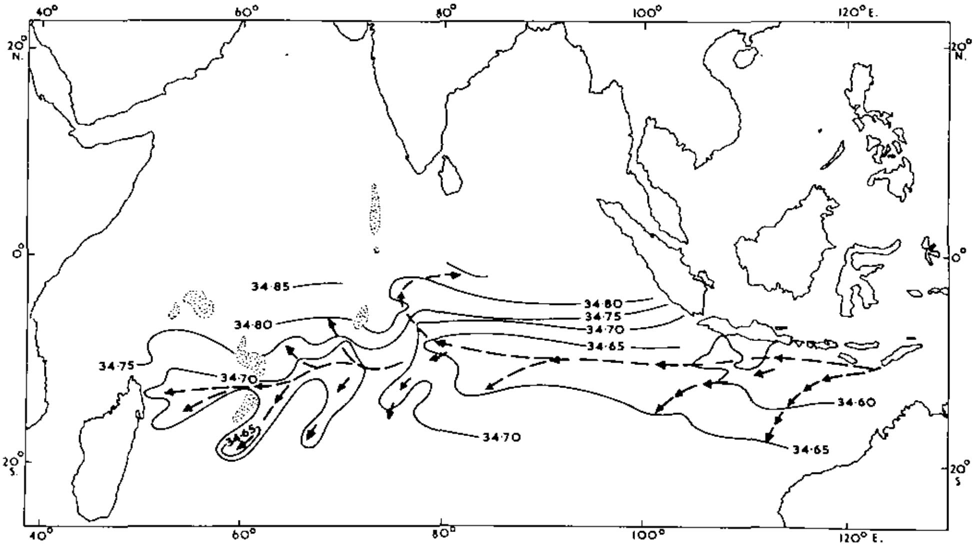

Fig. 9.—Distribution of Banda Intermediate water in the Indian Ocean (after Rochford 1966*a*). Values are salinity in ‰.

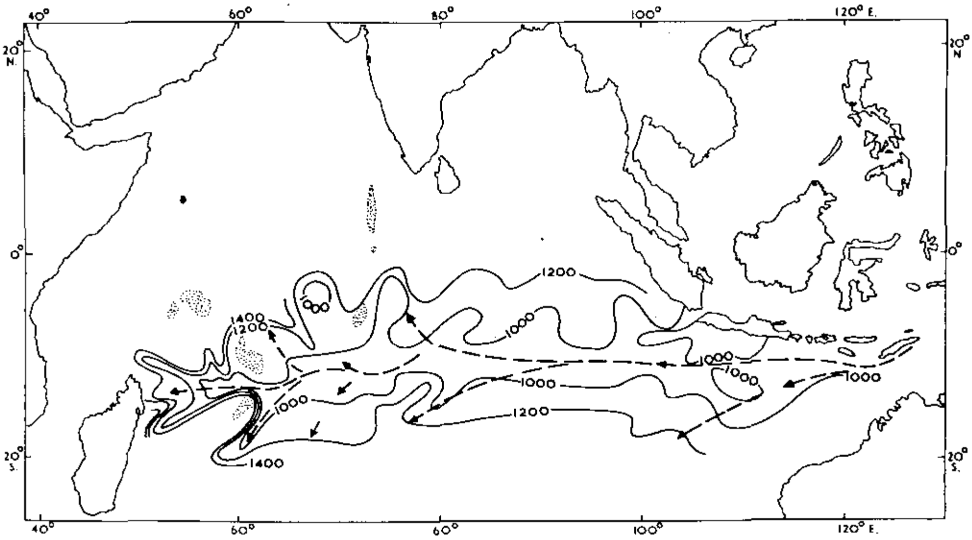

Fig. 10.—Depth (m) of Banda Intermediate water in the Indian Ocean (after Rochford 1966*a*).

(ii) *Movement of Oxygen-Rich Waters into the Arabian Sea*

Waters at mid-depths (200–400 m) in the Arabian Sea are generally very poor in oxygen. However, Rochford (1966*b*) showed that layers rich in oxygen occur and that these are formed by movement into the Arabian Sea of oxygen-rich water from outside sources. Data used in this investigation were collected during cruises by *Atlantis II*, *Diamantina*, *Discovery*, *Gascoyne*, *Ob*, and *Vityaz*.

Figure 12 shows oxygen concentration along a section from 15°N. to 6°S. in the Arabian Sea. South of 4°N. pockets of oxygen-rich water are present. These are formed by migrations of the subtropical oxygen maximum. Figure 13 shows the path of this and other oxygen-rich water masses into the Arabian Sea. The principal features of circulation are Equatorial Frontal water associated with the South Equatorial Current, water from the centre of the south Indian Ocean spreading northward, Antarctic Intermediate water moving beneath the South Equatorial Current to *c*. 15°N. off the Arabian coast, and subtropical water spreading north to *c*. 10°S. and then either joining the South Equatorial Current or continuing to north of the equator. Figure 13 shows also that the South Equatorial Current is an important factor in the transport of these oxygen-rich waters.

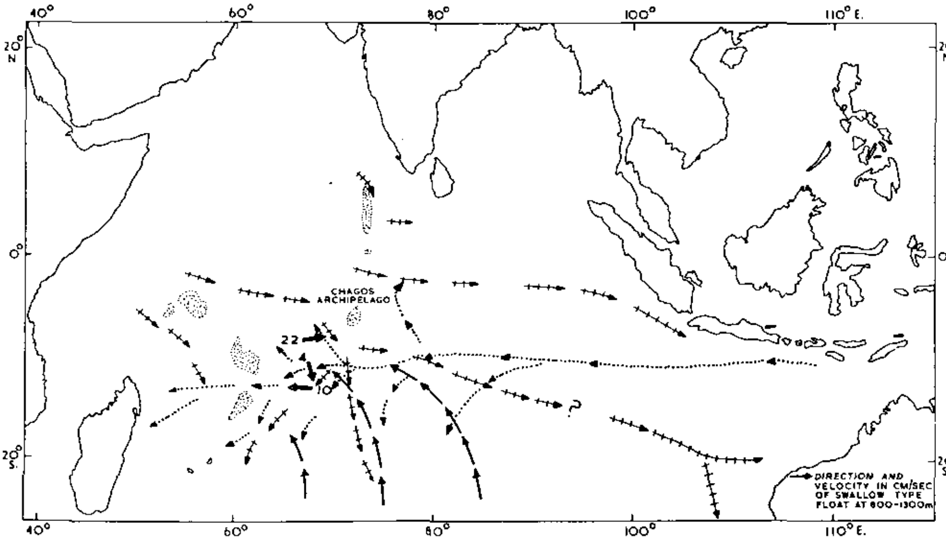

Fig. 11.—Water masses in the Indian Ocean affecting the westward flow of Banda Intermediate water (after Rochford (1966*a*). ······· Banda Intermediate. ++++++ Red Sea. ——— Antarctic Intermediate.

(iii) *Rapid Changes in Deep Properties at SCOR–Unesco Reference Stations*

As was mentioned earlier in this paper, SCOR–Unesco Reference Stations (Fig. 14) were created to aid intercalibration of oceanographic techniques used by IIOE participants. On Australian cruises, SCOR–Unesco Reference Stations 1 and 2 have been sampled to depths greater than 4000 m since 1959 and 1962, respectively. Rochford (1965) showed that large changes occurring in deep properties at these two stations made them unsuitable for intercalibration. Moreover, it was shown that large changes were liable to occur at some other SCOR–Unesco Reference Stations.

During 1959–62 and 1962–63 the salinity of the deep salinity maximum at Reference Station 1 varied ±0·01‰ about the mean. At Reference Station 2 during 1962–63 changes of the order of ±0·03‰ occurred. These variations are much greater than the experimental error for salinity determinations. In contrast, during 1962–63, changes in the salinity of the deep salinity maximum at the CSIRO Reference Station off Sydney (Fig. 14) were only ±0·004‰ about the mean.

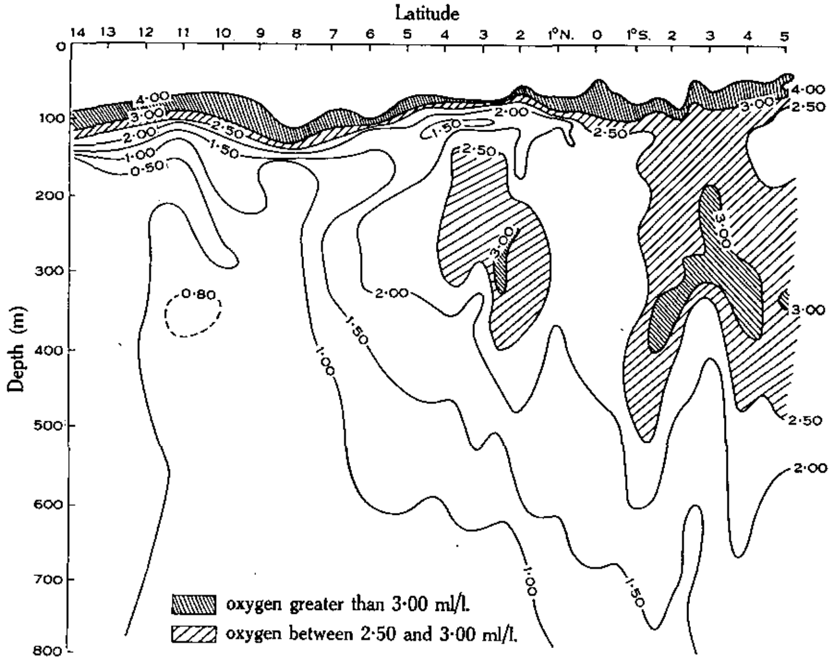

Fig. 12.—Oxygen concentration along a 15°N. to 6°S. section in the Arabian Sea (after Rochford 1966*b*).

It was obvious that real changes in salinity were occurring at Reference Stations 1 and 2, and in fact when salinity changes at these stations were plotted on an annual scale there was evidence of a repeated annual cycle (Fig. 15).

Rochford (1965, p. 148) notes: "For a deep reference station to be used to compare analytical accuracies it must have deep water with chemical characteristics that are stable for several years and longer if possible. SCOR–Unesco Reference Stations 1 and 2 have large seasonal changes in their deep chemical properties, principally caused by advection of north Indian deep water ... and are not suitable for comparison of analytical accuracies."

From Figure 14 it can be seen that SCOR–Unesco Reference Stations 5, 7, 8, 10, 11, and 13 also lie within the influence of north Indian deep water and their utility as comparison stations was also dubious.

(iv) *Phosphate Levels of Indian Ocean Surface Currents*

Rochford (1962) found that winter concentrations of phosphate (a phytoplankton nutrient) in the south-east Indian Ocean were often very low (less than 0·10 μg-atom/l.).

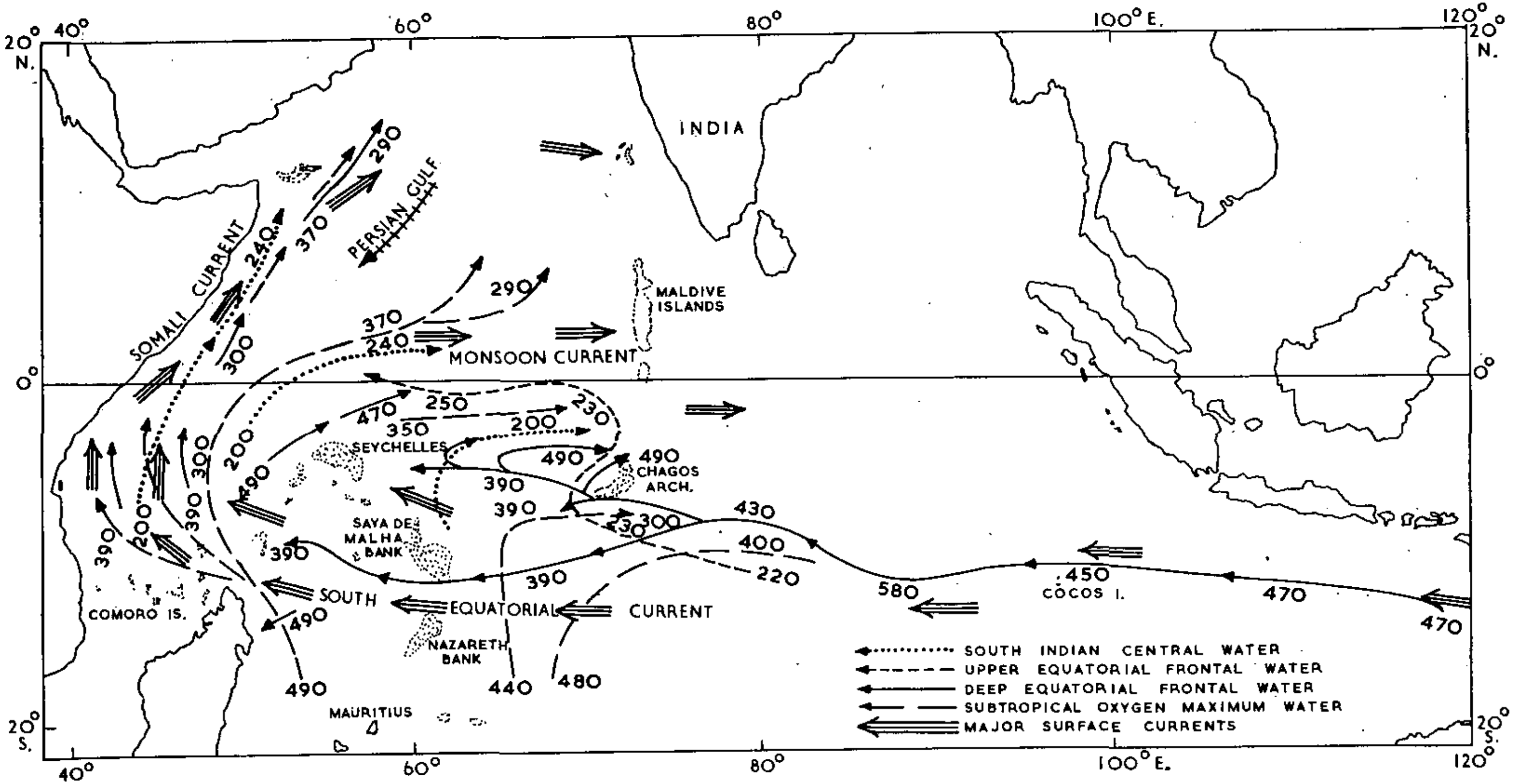

Fig. 13.—Paths and depths (m) of oxygen-rich water carried into the Arabian Sea (after Rochford 1966*b*).

Wood (1964), on finding that the region between 10° and 30°S. was very poor in phytoplankton, classified it as desert. Subsequently, Rochford (1967) investigated phosphate levels in the major surface currents of the Indian Ocean to determine the cause of these low values.

Figure 16 shows surface phosphate levels in the Indian Ocean in summer (Feb.–May; north-west monsoon). Values north of the equator are generally a little higher than those to the south. A belt of very low phosphate (less than 0·01 μg-atom/l.) occurs in the eastern Indian Ocean both north and south of the equator. Figure 17 gives winter (July–Sept.; south-east trade winds) surface phosphate. Again values north of the equator are higher but low-phosphate areas are much reduced.

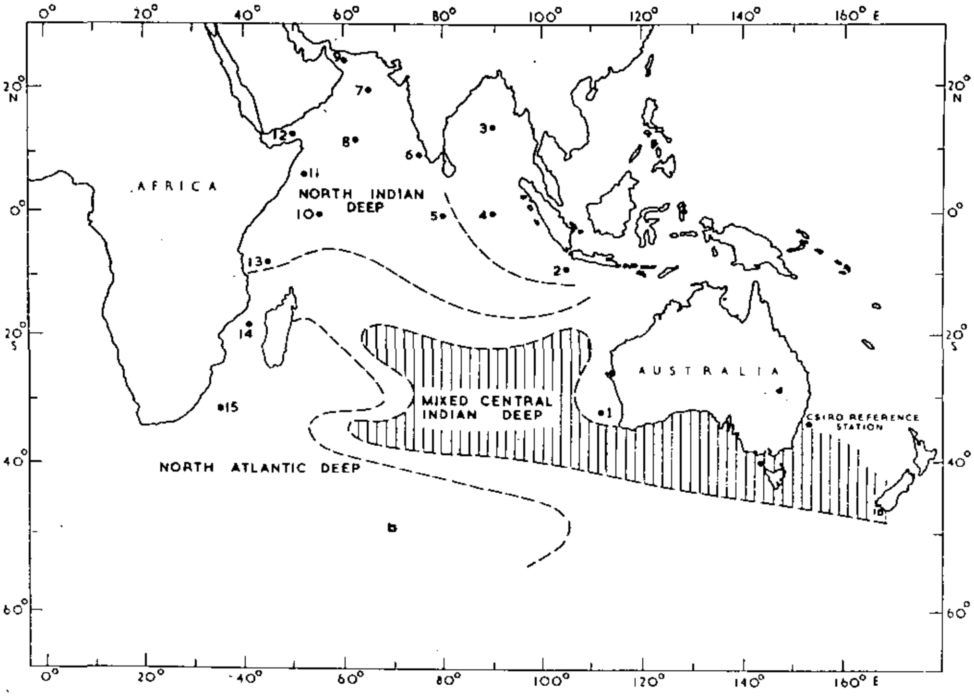

Fig. 14.—Positions of SCOR–Unesco Reference Stations and the extent of North Indian Deep Water (after Rochford 1965).

Low phosphate in the eastern Indian Ocean in summer is the result of an accumulation of low-phosphate water carried north by the West Australian Current, and low-phosphate water from the South Equatorial Current. Both these water masses have phosphate levels of less than 0·15 μg-atom/l. and Figure 18 shows their circulation in summer.

Indian Ocean surface currents in winter are shown in Figure 19. The south-west monsoon current and the countercurrent of the northern Indian Ocean carry eastward water of upwelled origin from the Arabian Sea and off the African coast. This water always has phosphate levels greater than 0·20 μg-atom/l., even as far west as Sumatra, and probably contributes to the increase in winter phosphate in the eastern Indian Ocean. In addition, in the south-east Indian Ocean, regions of upwelling or deep mixing are found within the South Equatorial Current north of 20°S. Such an area occurs around 110°E., to the south of Java (see Fig. 24), and results in an influx of phosphate-rich water into the region.

(c) *Biological Oceanography*

(i) *Primary Production*

Primary production measurements attempt to estimate the rate at which phytoplankton convert inorganic matter into living matter (organic carbon).

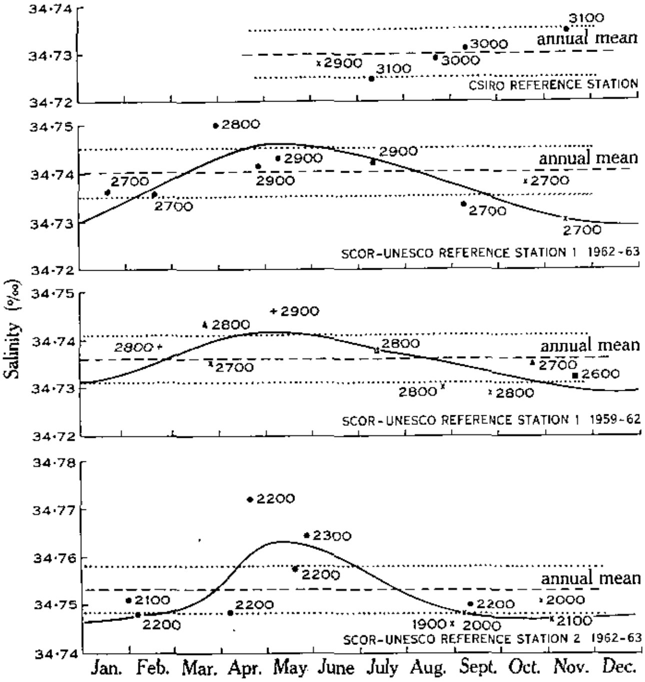

Fig. 15.—Salinity changes at SCOR–Unesco Reference Stations 1 and 2 (from Rochford 1965).

Jitts (unpublished data) surveyed primary production in the Indian Ocean east of 95°E., and south to 50°S. Data from 344 Australian oceanographic stations were used, and divided into summer (Oct.–Mar.) and winter (Apr.–Sept.). Figure 20 summarizes productivity characteristics in the region in summer and Figure 21 in winter.

In winter, productivity of the region as a whole is higher than in summer. In summer, most of the region is dominated by water of low productivity (11 mg C/(hr m^2)) from the centre of the Indian Ocean. In summer, mean productivity of the whole region is 21 mg C/(hr m^2).

In winter, mean productivity is 45 mg C/(hr m^2). This increase is a result of transport into the region of higher productivity waters and upwelling in the South Equatorial Current. Just south of Java, productivity is very high (79 mg C/(hr m^2)), indicating a major area of upwelling.

(ii) *Pigments*

Humphrey (1966) surveyed chlorophylls *a* and *c*, two phytoplankton photosynthetic pigments, in the south-east Indian Ocean, using data collected on Australian cruises between 1959 and 1962.

Data were assembled in 5° latitude–longitude squares and mean monthly concentration of chlorophyll *a* at the surface for these was between 0·01 and 0·50 µg/l. Chlorophyll *c* was between 0·01 and 0·66 µg/l. Concentration of both chlorophylls was nearly always higher in winter and for 5° squares which were sampled in both summer and winter mean concentration of chlorophyll *a* in summer was 0·08 µg/l. and in winter was 0·12 µg/l. The corresponding values for chlorophyll *c* were 0·17 and 0·21 µg/l., respectively.

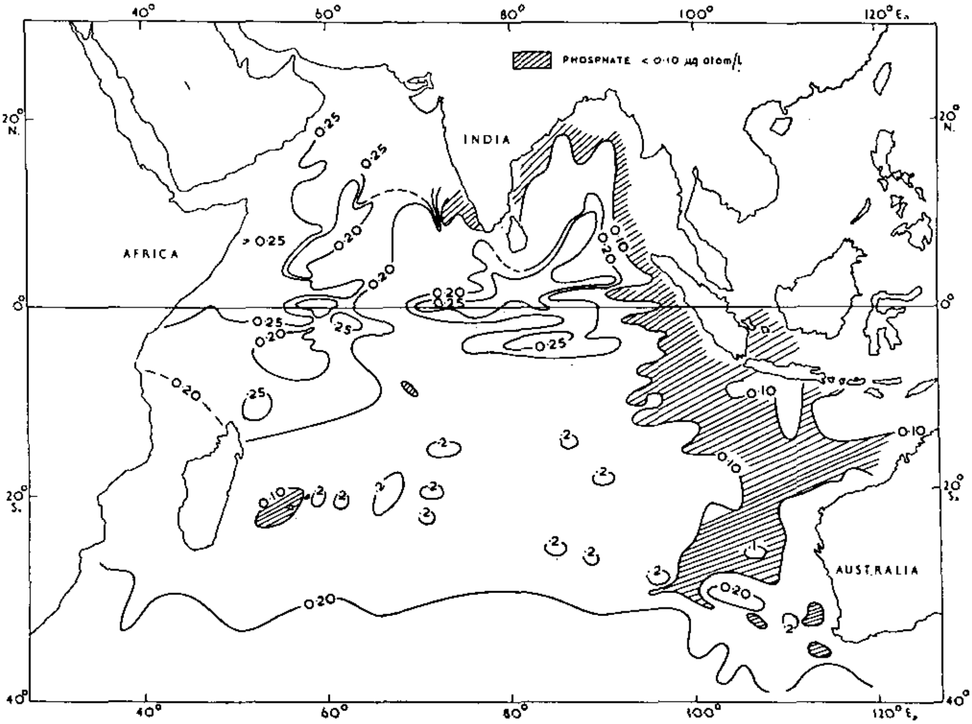

Fig. 16.—Surface phosphate (µg-atom/l.) in the Indian Ocean in February–May (after Rochford 1967).

For the whole of the year the surface of the south-eastern and southern parts of the Indian Ocean was characterized by low levels of both chlorophylls, i.e. usually less than 0·2 µg/l. (Fig. 22). This complements Jitts's finding of low primary production in the region and mentioned earlier. However, a few areas have higher values, e.g. near the upwelling area south of Java in winter.

The chlorophyll concentrations found by Humphrey (1966) were similar to those found in other oceans by other workers. However, in the south-east Indian Ocean the concentration of chlorophylls per litre does not reach the highest values found in the Atlantic and Pacific Oceans.

(iii) *Zooplankton*

Tranter (1962) showed that zooplankton biomass in the Indian Ocean near Australia was relatively low, in most parts no greater than 50 mg/m^3 and usually less than 25 mg/m^3.

Figure 23 shows zooplankton biomass in the upper 200 m in the south-east Indian Ocean in July–October (winter). It shows an area of greater abundance between the north-west coast of Australia and Indonesia. Maximum biomass was just south of Java and islands to the east, where values greater than 100 mg/m^3 were common. This is the area where upwelling associated with the South Equatorial Current occurs during the south-east monsoon. Figure 24 shows changes in biomass during the year in the region of upwelling.

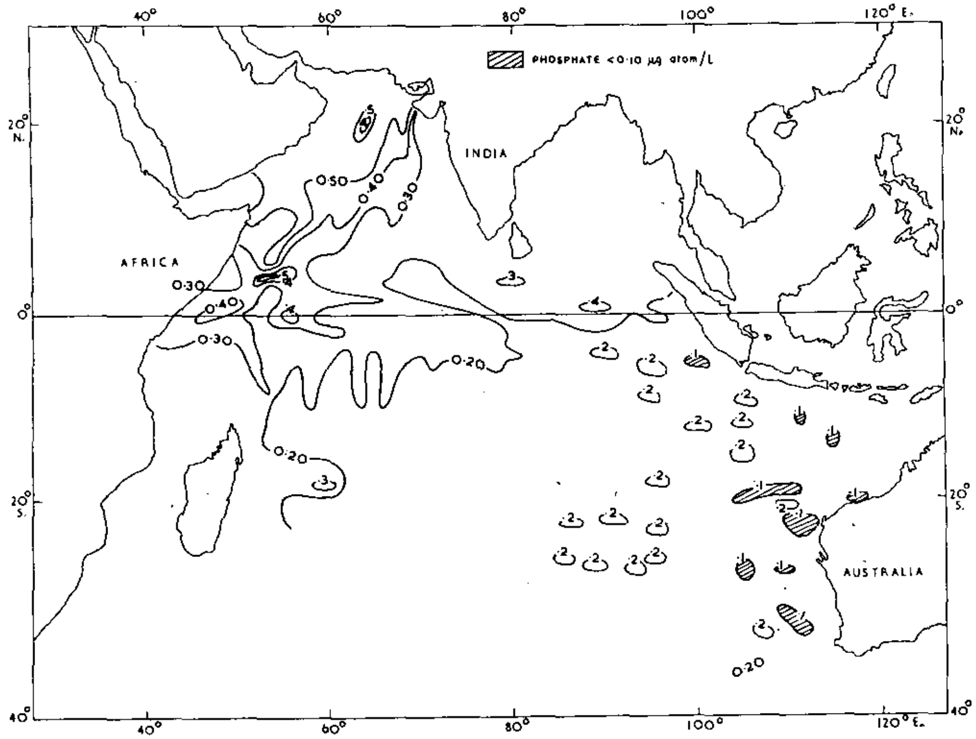

Fig. 17.—Surface phosphate (µg-atom/l.) in the Indian Ocean in July–September (after Rochford 1967).

(iv) *Phytoplankton*

On seven cruises (see Table 2), water samples were collected for phytoplankton counts. The species of diatoms and dinoflagellates present in the samples were determined, and in some cases counts of the numbers of particles with and without chlorophyll made. The results of these studies are given in the relevant Oceanographical Cruise Reports and in Wood (1963*a*, 1963*b*, 1963*c*, 1963*d*), and are discussed in Wood (1964).

(*d*) *Seasonal Biological Cruises*

Figure 25 shows the track chart and station positions for the six Seasonal Biological Cruises. Stations were *c.* 90 miles apart and the inter-cruise interval was two months. Table 2 showed what analyses were made and the results have been published in Oceanographical Cruise Reports (CSIRO Aust. 1965*a*, 1965*b*, 1965*c*, 1965*d*, 1966*a*, 1966*b*), and discussed in a series of scientific papers (Humphrey and Kerr 1968; Jitts 1968; Newell 1968; Rochford 1968; Tranter and Kerr 1968).

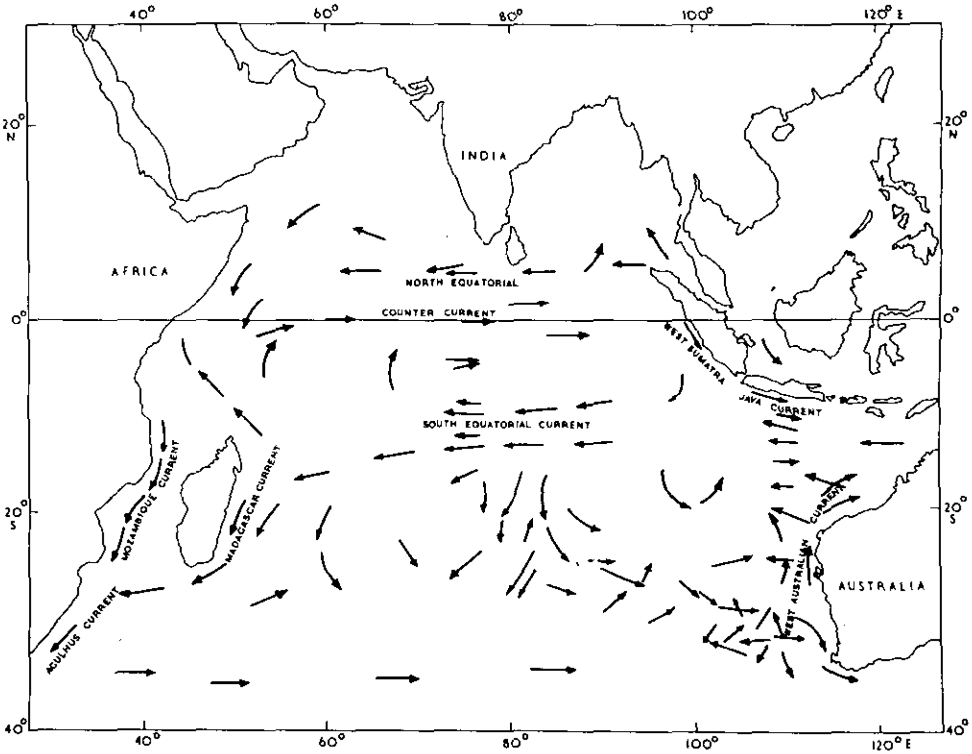

Fig. 18.—Surface circulation in the Indian Ocean in summer (after Rochford 1967).

(i) *Seasonal Changes in Hydrological Structure*

Changes in hydrological structure of the upper layers along 110°E. were very small and were also much smaller than those encountered in the other oceans which have been investigated. In fact, Rochford (1968) concluded that advection and mixing must have been less important in the genesis of these changes than local climatic changes.

Seasonal changes in nutrients at the surface were barely significant, confirming earlier findings (Rochford 1967). Changes in phosphate at the surface rarely exceeded 0·20 μg-atom/l. In general, both phosphate and nitrate decreased slightly to the north, except near 12°S. in winter where upwelling occurs.

The range of phosphate values was 0·07–0·30 μg-atom/l., with lowest values occurring in April–May, south of 15°S., and in July, from 11° to 17°S. Highest values were found in October–November. Around 12°S., inorganic phosphate increased in August because of upwelling.

Nitrate ranged between 0 and 2·1 μg-atom/l. Values greater than 0·5 μg-atom/l. were found only in January–May, south of 12°S. Nitrate did not increase in August when phosphate did. Perhaps nitrate was being utilized more quickly than phosphate. In any case, nitrate variations might have been within the limits of sensivitity of the analytical method used.

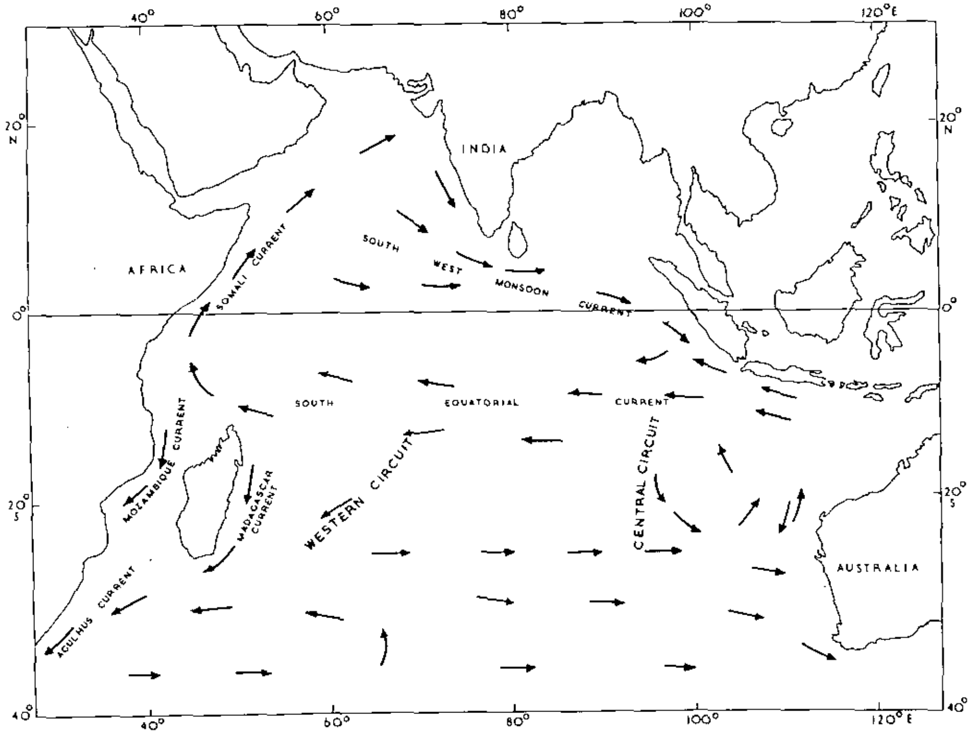

Fig. 19.—Surface circulation in the Indian Ocean in winter (after Rochford 1967).

Column averages of nutrients in the mixed layer did not vary significantly along the section. Seasonal variations in the mixed colomn averages of inorganic phosphate indicated that there was slightly more phosphate in the column in winter and spring than in summer or autumn. The range of column variation was, however, quite small; from less than 0·15 in summer and autumn, to more than 0·20 μg-atom/l. in winter and spring.

(ii) *Particulate Carbon*

The results of particulate carbon measurements made during the programme are discussed by Newell (1968). Like primary production and chlorophyll measurements, particulate carbon measurements are an estimate of primary biomass.

Figure 26 shows the average monthly particulate carbon at each depth for all stations sampled, regardless of latitude. Lowest values were in March, and values decreased with depth.

In general, particulate carbon values were highest in the south and least in mid-latitudes at all depths.

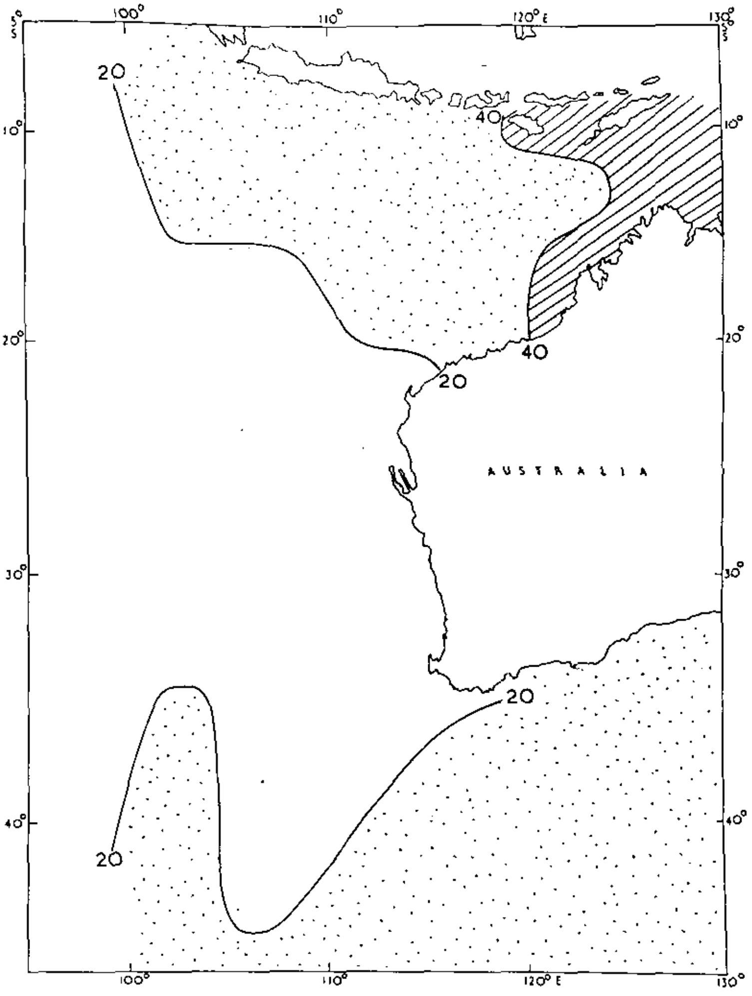

Fig. 20.—Primary production (mg C/(hr m^2)) in the south-east Indian Ocean in summer (Jitts, unpublished data).

(iii) *Pigments*

The highest concentrations of chlorophylls *a* and *c* found during these cruises were in June–August (Humphrey and Kerr 1968). This agreed with the previously discussed results of Humphrey in the south-east Indian Ocean. The highest concentration of both chlorophylls was 1·1 μg/l. These values are twice as great as those previously recorded in the south-east Indian Ocean.

In the 0–150 m water column chlorophyll *a* was between 10 and 30 mg/m^2 and *c* was between 15 and 40 mg/m^3. These results are higher than those found by the earlier study of Humphrey (1966).

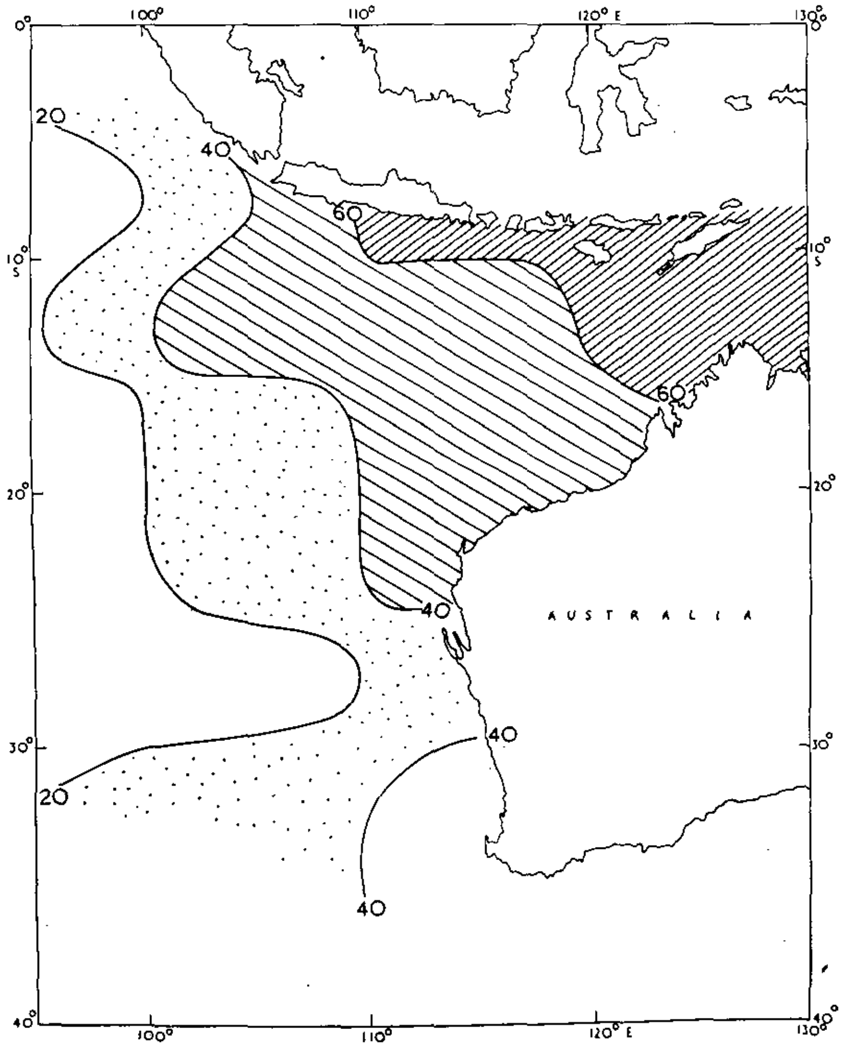

Fig. 21.—Primary production (mg C/(hr m^2)) in the south-east Indian Ocean in winter (Jitts, unpublished data).

(iv) *Primary Production*

Primary production along the meridian as a whole was highest in October and lowest in January (Jitts 1968). From June to December the meridian could be divided into four latitudinal intervals with definite productivity characteristics as summarized in Figure 27.

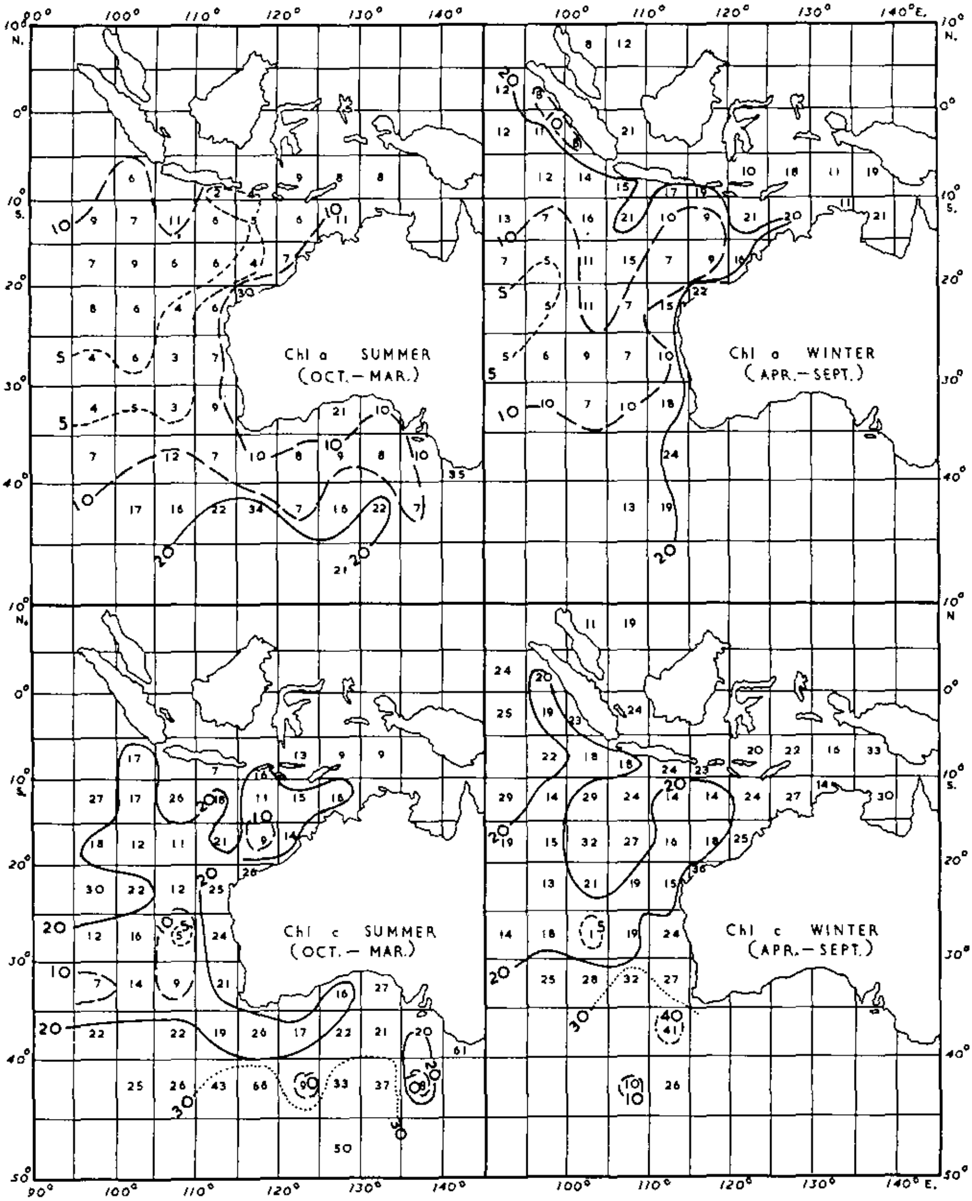

Fig. 22.—Seasonal contours of surface chlorophylls in the south-east Indian Ocean (from Humphrey 1966).

(v) *Zooplankton Biomass*

Zooplankton biomass along 110°E. (Tranter and Kerr 1968) varied between less than 25 and more than 100 mg/m^2 (Fig. 28). Values at night were always greater than day values.

The biomass of the section was greatest in August–September and February–March, and least in December–January and May–June (Fig. 29). Biomass was fairly uniform over a wide central region (16–27°S.), increasing to the north, and decreasing to the south. A conspicuous feature was a tongue of low values which in May–June invaded the section as far north as 14°S. (Fig. 29).

(vi) *Summation*

In general, Seasonal Biological Cruises showed that the hydrological regime along 110°E. was relatively constant. The most marked seasonal variations occurred around 12°S., where in winter during the south-east monsoon upwelling occurs at the edge of the South Equatorial Current.

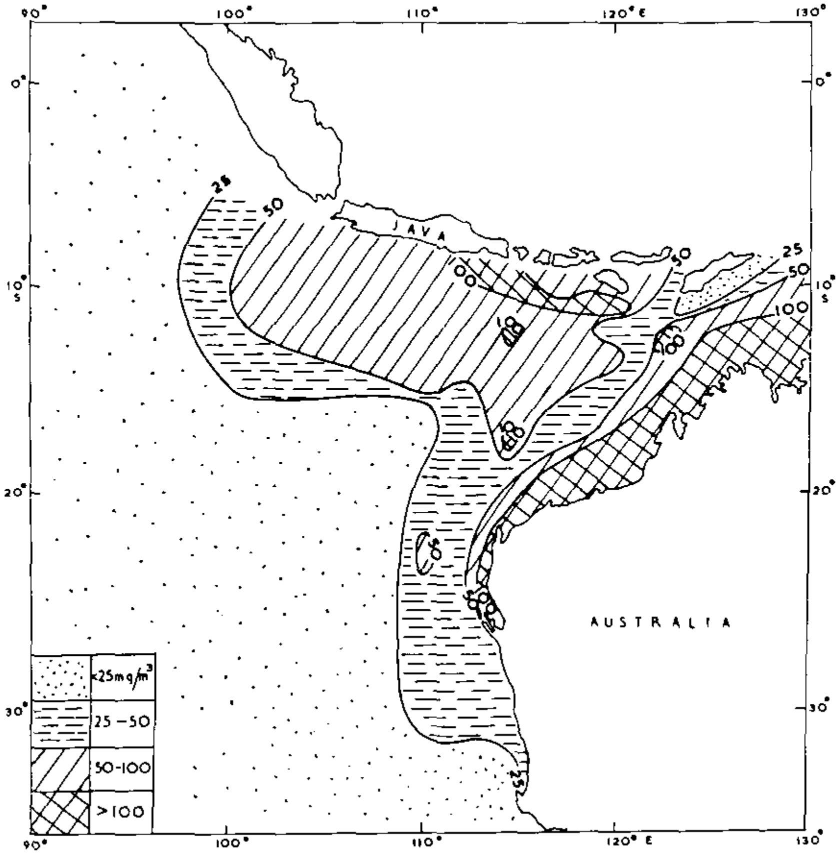

Fig. 23.—Zooplankton biomass in the upper 200 m in the south-east Indian Ocean (after Tranter 1962).

Biomass at various trophic levels paralleled changes in hydrological structure. Biomass at all trophic levels was highest in winter and increases were greatest around the area of upwelling. In other parts of the section biomass changes followed the weakening of the thermocline in winter and when water masses richer in nutrients invaded the section during this season.

The pattern of seasonal variations will be discussed more fully in later publications by the oceanographers involved.

(*e*) *Meteorology*

Australian meteorological observations during the International Indian Ocean Expedition were made to gather data for studies of energy interchange between ocean and atmosphere. Stevenson (1964, p. 132) notes: "The Indian Ocean could be compared to a large boiler-room or evaporator as it supplies the motive power for the great atmospheric circulations in this area, and at the same time is the source of the rainfall of some of the most highly populated regions of the world. To obtain a better understanding of the mechanics of monsoons and their variations from year to year it is an obvious first requirement to study the energy budget of the Indian Ocean and its seasonal variations."

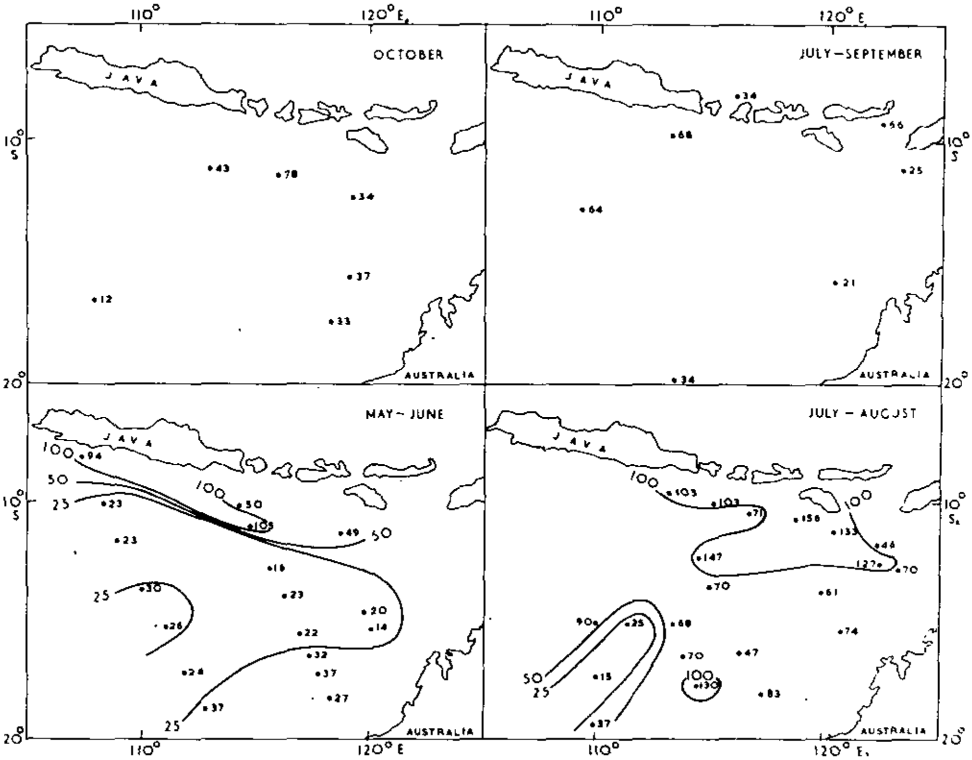

Fig. 24.—Seasonal changes in zooplankton biomass near the area of upwelling south of Java (after Tranter 1962).

In the Australian studies, radiation measurements were made using two instruments. The readings of these were recorded continuously on a chart recorder. The first instrument is a "Solarimeter". It measures incident radiation from the Sun, together with that scattered by the air and clouds. This is short-wave radiation with wavelengths of 0·3–4 μ. The second instrument is a radiometer and is similar to the solarimeter except that it is modified to measure longwave radiation (4–100 μ). This instrument measures heat radiated downwards by the atmosphere and clouds. Figure 30 shows the solarimeter and radiometer in place aboard H.M.A.S. *Gascoyne*.

The sea surface radiates heat, the rate being dependent on sea surface temperature. Sea surface temperature was measured continuously using a thermistor towed from a boom on the ship's side.

Net radiation income is dependent to a large extent on sky condition. Radiation income is low in overcast conditions. Photographs of the sky were taken automatically, every 4 min.

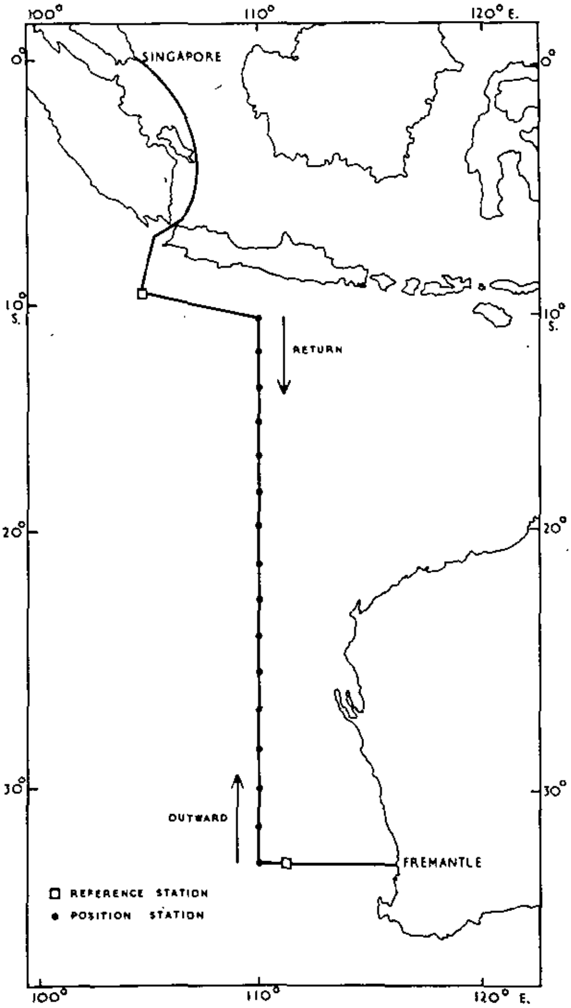

Fig. 25.—Track chart and station positions of Seasonal Biological Cruises.

Recorded information was supplemented by 2-hourly standard meteorological observations of pressure, wet and dry temperature, wind speed and direction, and wave height.

The results of Australian meteorological investigations during IIOE will be published as a Technical Paper of the CSIRO Division of Meteorological Physics. The Australian data will be a useful supplement to the other meteorological data collected during the Expedition, including that collected using fixed ocean buoys.

With the establishment of the International Meteorological Centre in India during IIOE, recognition was made of the importance of meteorological data, particularly data that would throw light on the dynamics of the monsoons, which have a profound effect on the lives of the peoples of the region.

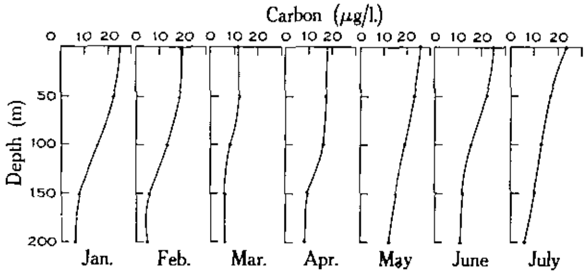

Fig. 26.—Average monthly particulate carbon at each depth for all stations sampled during the Seasonal Biological Cruises, regardless of latitude (from Newell 1968).

(*f*) *Other Studies*

On various Australian IIOE cruises, other samples were collected in connection with more specific research projects. The midwater trawl was used by CSIRO scientists on seven cruises, and a bottom trawl on three cruises, to collect crayfish larvae as part of a study of the larval distribution of the Western Australian crayfish. The results of this work are given in the relevant Oceanographical Cruise Reports. The midwater and bottom trawl samples from two of these cruises were also examined for deep-sea prawn species by officers of the Western Australian Department of Fisheries and Fauna, but results of this work are not yet published.

Latitude Interval	Mean Productivity Characteristics												
9°S. TO 15°S.	high productivity mean 69					low productivity mean 4			moderate productivity mean 24		high productivity mean 69		
15°S. TO 24°S.			high productivity mean 60			as above			as above		moderate productivity mean 32		
24°S. TO 30°S.	moderate productivity mean 42					as above			as above		high productivity mean 58		
30°S. TO 32°S.		moderate productivity mean 42				as above			as above			high productivity mean 70	
Period	AUG.	SEPT.	OCT.	NOV.	DEC.	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.
	1962					1963							

Fig. 27.—Schematic presentation of the seasonal variation of productivity characteristics in selected periods in four latitudinal intervals along the 110°E. meridian (after Jitts 1968). Mean productivity values in mg C/(hr m²).

Bottom samples were collected by the University of Western Australia on three cruises, by the Division of Fisheries and Oceanography on two cruises, and by the Western Australian Museum and the Division of Applied Mineralogy, CSIRO, on one cruise. The results of work by the University of Western Australia and the Western Australian Museum are not yet published. Results of work by the Division of Fisheries and Oceanography, on benthic fauna, are given in CSIRO Aust. (1967).

Sediment samples taken by the Division of Applied Mineralogy on Cruise Dm6/63 were analysed for phosphate and the results are given by Farrand (1964).

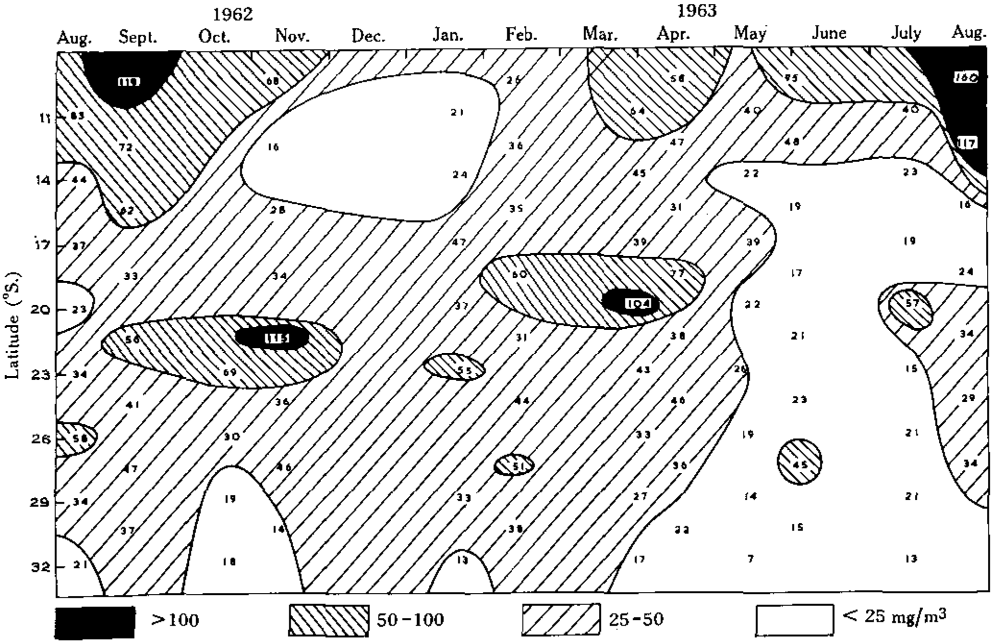

Fig. 28.—Zooplankton biomass along 110°E. (from Tranter and Kerr 1968).

No phosphate concentrations of economic importance were found in the samples taken. However, phosphate concentration tended to be higher in sediments of sand grain size, such sediments occurring mainly north of 25°S. on the continental shelf of Western Australia at depths of 50–165 fm. Farrand (1964) considered that the generally low phosphate concentrations on the Western Australian shelf were the result of the comparatively great width of the shelf in this area and the occurrence of strong tidal currents parallel to the coast which might prevent the influx onto the shelf of waters richer in phosphate from greater depths.

VII. Assessment of Australia's Contribution

Australia's contribution to the scientific results of IIOE was a systematic survey of the south-east Indian Ocean, a region about which, in common with the rest of the Indian Ocean, very little was known before 1959. Moreover, this survey included many of the several disciplines of oceanography, and its results have enabled scientists to map the main features of biological productivity and water mass composition and movement in the region. In addition, the Seasonal Biological Cruises, a programme more comprehensive in its approach to seasonal changes than any previous study, provided new insight into seasonal variability in the oceans. A comparison of the contributions of all IIOE partipants (Anon. 1967) shows that in terms of data collected Australia's was the second in order of magnitude.

Australia was peculiarly suited to contribute to IIOE; her efforts were intrinsically expeditionary, Australian deep-sea investigations starting at about the same time as IIOE. Australia supported the Expedition in ways, which though less tangible, were in many respects as important as scientific results. These arose out of Unesco's aims in co-sponsoring IIOE, and Australia made facilities available so that these aims would be met. Geographically, Australia was suited to do this, by virtue of bordering the Indian Ocean, and being close to many of the newly developing countries of the world.

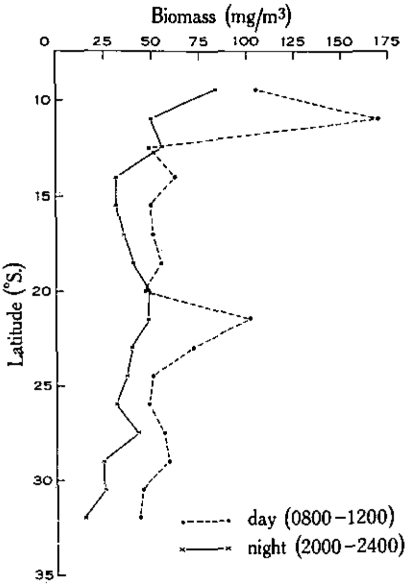

Fig. 29.—Seasonal changes in zooplankton biomass along 110°E. (after Tranter and Kerr 1968).

By participation in intercalibration tests, by working Reference Stations as often as possible, and in other ways, Australia sought to ensure that the scientific results of the Expedition would have maximum utility. By routine transmission of cruise data to the World Data Centres in Moscow and Washington, the stipulated IIOE data exchange centres, Australian data were made freely available to all interested scientists and countries.

The Australian IIOE Bibliography given in Section VIII of this paper makes a significant contribution to the world literature. A complete bibliography cannot be given at this stage because Australian scientists are still working on the many, more complex problems suggested by the data that they collected.

Considering IIOE in general, it is perhaps too early to make a valid assessment of its worth. It could be argued that greater amounts of useful data would have been collected if SCOR's original plan for a systematic survey had been agreed upon by all participants. At the First International Oceanographic Congress in 1959, the American oceanographer, Henry Stommel, noted (Wust 1960): "There is . . . one aspect of knowledge about the ocean which has been developed during the last fifty years and in which some of the best work is still being done: the systematic surveying and mapping of certain scalar quantities in the ocean: temperature, salinity, and density of the water. This difficult, painstaking, and sometimes tedious work is the very foundation upon which all other study of the ocean must be built. There are still areas of the world ocean where the available data are incomplete." Despite the fact that IIOE did not develop into a purely systematic survey, there can be little doubt that it went a long way towards remedying the great deficiency of data on the Indian Ocean.

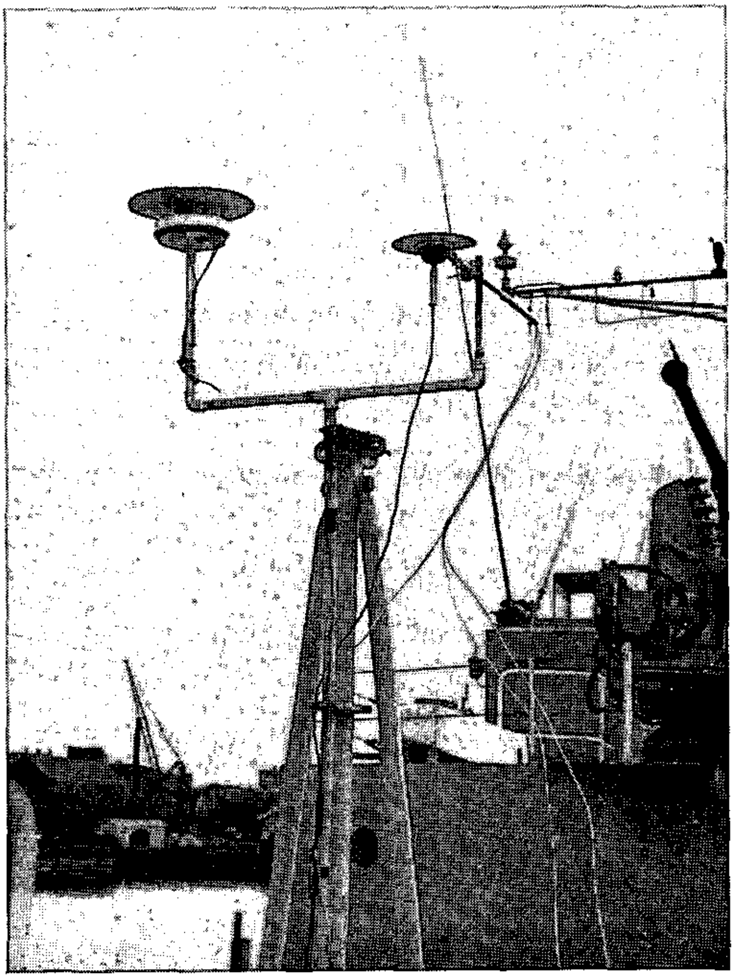

Fig. 30.—The solarimeter and radiometer, devices for measuring solar radiation, aboard H.M.A.S. *Gascoyne*.

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