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Water Characteristics and Current Structure at 65°E during the Southwest Monsoon*

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Abstract: Hydrographic data collected aboard R. V. Anton Bruun along 65°E between 18°N and 42°S from 17 May to 4 July 1964 are used to investigate water characteristics and current structure in the upper 500 m in the Indian Ocean. The water characteristics indicate the occurrence of three main water masses, *viz.*, warm, saltier, low-oxyty and nutrient-rich Arabian Sea Surface Water, relatively fresh and high-oxyty Equatorial Indian Ocean Water, and more saline, high-oxyty and nutrient-poor Tropical Water of the South Indian Ocean. The recently discovered South Equatorial Countercurrent and Subtropical Countercurrent (renamed Tropical Countercurrent, at the suggestion of Dr. R. B. MONTGOMERY) are observed in the current structure at 13°S and 22°-26°S respectively, and these could also be identified on the vertical sections of temperature, thermosteric anomaly and salinity. Contrary to the existing concept, the North Equatorial Current continues to be present even after the onset of the southwest monsoon. The Equatorial Undercurrent could not be traced in the Indian Ocean during this period.

1. Introduction

Unlike that over the Pacific and the Atlantic, the atmospheric circulation over the North Indian Ocean reverses semiannually, whereas, in the South Indian Ocean no such reversal occurs. The monsoon wind reversal creates seasonal currents, which, in turn, affect the entire oceanic circulation and water characteristics. During the southwest monsoon, the sea surface slopes up towards the east with a magnitude of the slope comparable to that of the sea surface in the Pacific and the Atlantic, but it is of opposite sign (TAFT and KNAUSS, 1967). The conditions in the North Indian Ocean differ much from the other oceans during the southwest monsoon. The Equatorial Undercurrent, which is present all through the year in the Pacific and the Atlantic, is present only during the northeast monsoon in the Indian Ocean (TAFT, 1967; TAFT and KNAUSS, 1967; SWALLOW, 1967; SHARMA, 1968).

The presence of the South Equatorial Countercurrent in the Pacific was first brought to attention by REID (1959), and a further evidence was presented by REID (1961, 1965), WOOSTER (1961) and TSUCHIYA (1968). A similar feature in the Atlantic was also reported by REID (1964a, 1967b). YOSHIDA (1961) pointed out that this eastward current could be expected dynamically from the calculation of wind-driven transport.

Recently, YOSHIDA and KIDOKORO (1967a, 1967b) have predicted theoretically the existence of the Subtropical Countercurrent (Tropical Countercurrent). UDA and HASUNUMA (1969) reported the eastward current in their charts of geostrophic current in the North Pacific, prepared from various hydrographic data, at latitudes 20°-25°N, and it was associated with a thermal front. Similar eastward current and a thermal front were found by VOORHIS and HERSEY (1964) in the Atlantic.

It is not yet fully realized if the current structure in the Indian Ocean shows the existence of the South Equatorial Countercurrent and the Tropical Countercurrent, although YOSHIDA and KIDOKORO (1967a, 1967b) remarked that the charts of WELANDER (1959) reveal features in the South Indian Ocean that are somewhat similar to those of the Tropical Countercurrent. The present paper is an attempt to study the current structure and water

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characteristics of the Indian Ocean during the southwest monsoon in order to learn whether the South Equatorial Countercurrent and the Tropical Countercurrent are present when the atmospheric circulation over the North Indian Ocean differs from that over the Pacific and the Atlantic.

2. Treatment of the material

To illustrate the meridional distributions of properties, vertical sections of temperature, thermosteric anomaly, salinity, oxyty and phosphate-phosphorous have been drawn from R.V. Anton Bruun stations along 65°E from 18°N to 42°S during the period 17 May to 4 July 1964 (Fig. 1). The preparation of the vertical sections of water properties follows the method indicated by REID (1965).

The geostrophic flow at an isanosteric surface can be computed from the gradient of the acceleration potential (MONTGOMERY, 1937; MONTGOMERY and SPILHAUS, 1941; MONTGOMERY, 1954; MONTGOMERY and STROUP, 1962) or MONTGOMERY function as it has been variously called (REID, 1965). The expression for acceleration potential used here is

$$\int_{\delta_{TO}}^{\delta_T} P d\delta_T + P_0 \delta_{TO}$$

where δ_{TO} is the thermosteric anomaly at the

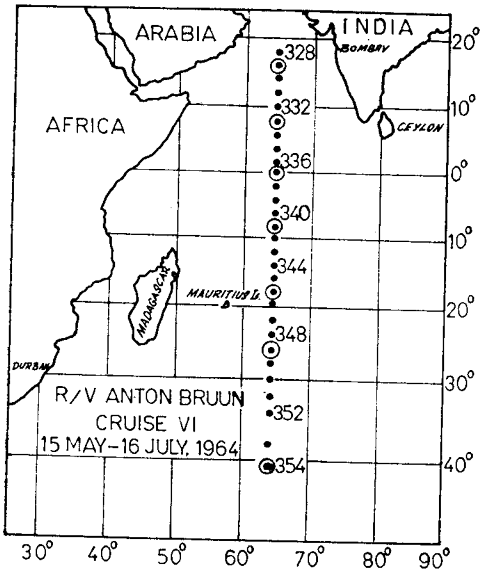


Fig. 1. Station positions (Station curves are drawn in Fig. 2 for those circled).

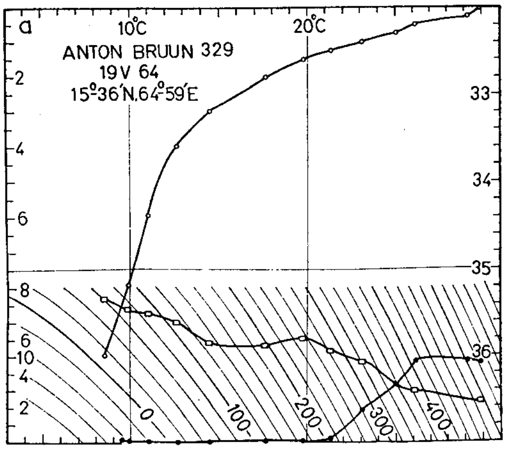
reference pressure (P_0). This use of thermosteric anomaly in place of the more general steric anomaly is justified by MONTGOMERY and WOOSTER (1954), who demonstrated that in the eastern Pacific the steric anomaly can be replaced by thermosteric anomaly in deducing the geostrophic velocities while retaining sufficient accuracy. The reference pressure for this integration has been chosen to be 1,000 db and the numerical integration has been carried out at each station at an interval of 10 to 40 cl t^{-1}. The computation of meridional component of the pressure-gradient force and the zonal component of geostrophic velocity have been carried out after the method adopted by MONTGOMERY and STROUP (1962). They proposed a novel method for representing the distribution of the pressure-gradient force per unit mass and the geostrophic flow through a vertical section. In view of the advantages of such a presentation, the same method is used in the present paper. The width of the band represents the magnitude, and the sign is represented by shaded and stippled bands.

3. Distribution of properties

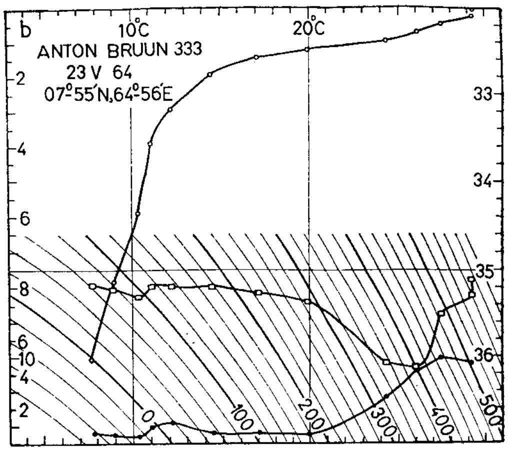
3.1. Temperature and thermosteric anomaly

Either the temperature or the thermosteric anomaly distribution could be used to describe the structure of the thermocline. The following discussion refers to temperature with an understanding that most of the remarks apply to thermosteric anomaly also.

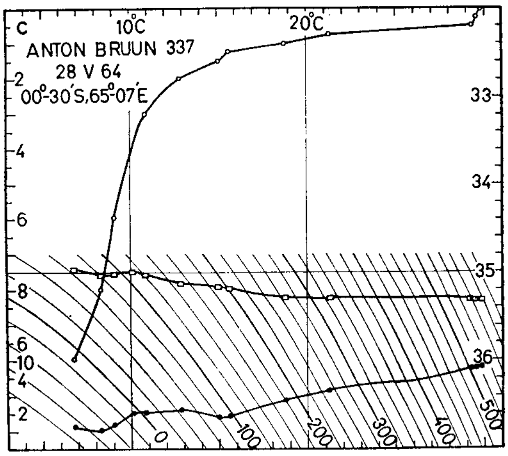
The surface temperature increases steadily (from 12.9°C at 41°S to 25.0°C at 19°S) with an average increase of 0.55°C per degree latitude (Fig. 3a). Thereafter, the increase is much less, and between 14°S and 16°S even a decrease in surface temperature is noticed. The warmest water, with temperature higher than 30.0°C at the surface, is encountered in the Arabian Sea at 8°-14°N, and this is evidently due to the enormous radiation balance in the Arabian Sea: 1.2×10^5 to more than 1.4×10^5 cal cm^{-2} annually, the largest values shown anywhere on the earth's surface in the Morskoi Atlas (WARREN *et al.*, 1966). The sudden increase in temperature around 25°S at all depths and a decrease around 15°S are associated with two thermal fronts. Between these two fronts, practically there is no horizontal variation in a


a
10°C
20°C
ANTON BRUUN 329
19 V 64
15°36'N, 64°59'E
33
34
35
36
0
100
200
300
400

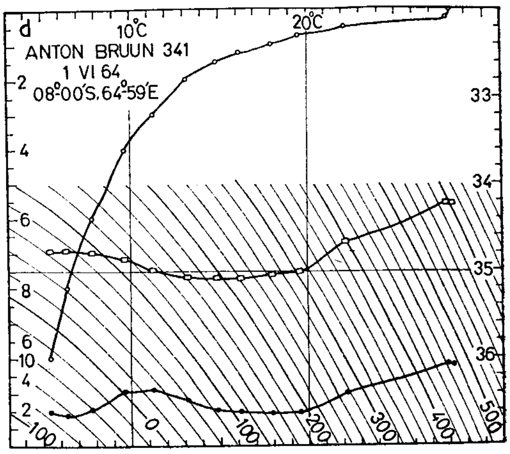
b


b
10°C
20°C
ANTON BRUUN 333
23 V 64
07°55'N, 64°56'E
33
34
35
36
0
100
200
300
400
500

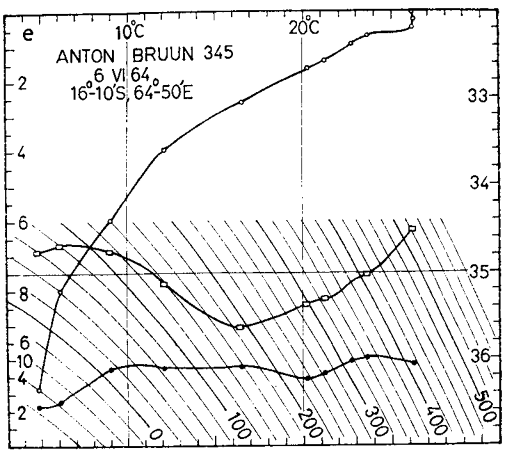
c


c
10°C
20°C
ANTON BRUUN 337
28 V 64
00°30'S, 65°07'E
33
34
35
36
0
100
200
300
400
500

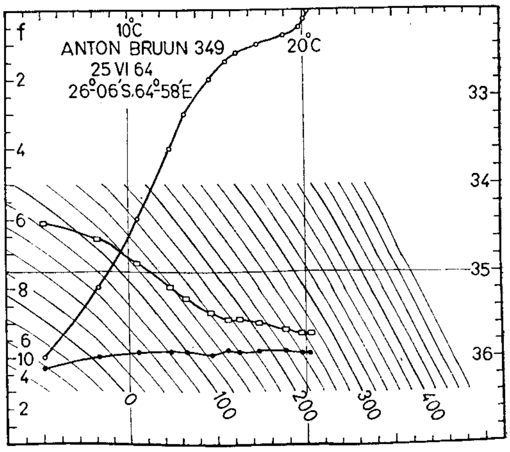
d


d
10°C
20°C
ANTON BRUUN 341
1 VI 64
08°00'S, 64°59'E
33
34
35
36
-100
0
100
200
300
400
500

e


e
10°C
20°C
ANTON BRUUN 345
6 VI 64
16°10'S, 64°50'E
33
34
35
36
0
100
200
300
400
500

f


f
10°C
20°C
ANTON BRUUN 349
25 VI 64
26°06'S, 64°58'E
33
34
35
36
0
100
200
300
400

g

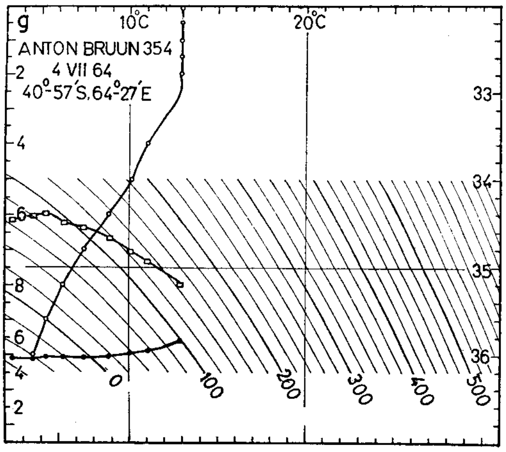


Fig. 2a-g. Station curves for stations shown in Fig. 1 as circled. The common abscissa is temperature in °C. In each graph, the upper curve shows depth in hectometers (scale at left); the middle curve shows salinity in per mil (scale at right); and the lower curve shows oxyty in milliliters per liter (scale at left).

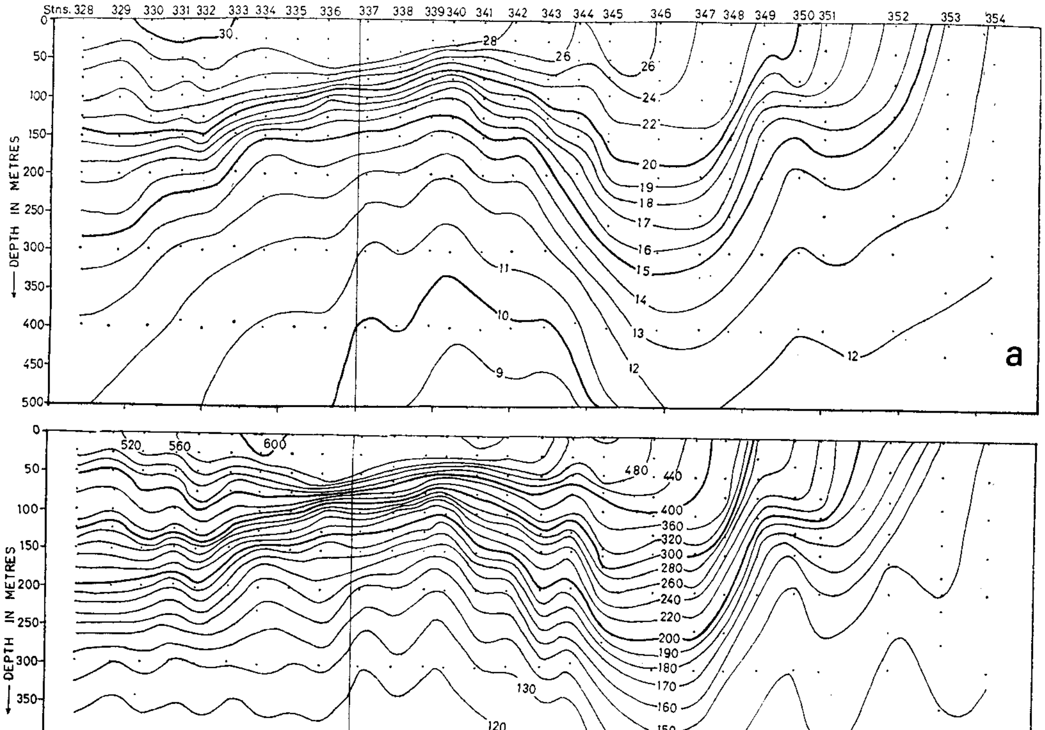


Fig. 3. Meridional distribution of a) temperature in °C b) thermosteric anomaly in cl t^{-1} at 65°E, 17 May to 4 July 1964 (Vertical exaggeration on all the vertical sections is 5.55×10^3).

Table 1. Thickness in meters between 16°C and 26°C.

Latitude	18°N	15°N	13°N	10°N	8°N	5°N	2°N	0°	2°S	5°S	8°S	10°S	13°S	15°S
Thickness	184	187	114	106	79	72	60	63	65	58	95	94	139	228

temperature. Even the vertical variation is much less and the thermocline is less well defined. These two fronts represent the strong pressure-gradient force towards the equator and pole respectively (Fig. 5a), and are located where the components of westward and eastward flows are maximum (Fig. 5b). A trough of the thermocline seems to be the characteristic feature of the Indian Ocean at these latitudes all through the year, as noticed in the various vertical sections of the International Indian Ocean Expedition Atlas (WYRTKI, 1971, pp. 399, 405, 411, 462, 464, 481, 491, 501, 509). The region where the thermocline is deepest (17°–22°S) seems to be the southern boundary of the South Equatorial Current and the northern boundary of the east flowing Tropical Countercurrent. The same inference was drawn by SHARMA (1972) from the depth contours of the 200-cl t^{-1} isanosteric surface where a trough is centered between 17°S and 22°S.

In order to arrive at a number characterizing the spreading of the thermocline at different latitudes, the vertical separation between 26°C and 16°C is taken as an arbitrary indication of the thickness of the thermocline. This information is listed in Table 1. The thermocline slopes down continuously from 6°S to 10°N with a minimum thickness of less than 65 m between 5°S and 2°N (Table 1). Between 8°S and 16°S the thermocline slopes down steeply from north to south. The smaller feature of contraction of the thermocline at 2°N and its spreading on either side is a characteristic feature of thermal field in the Indian Ocean during the southwest monsoon (SHARMA, 1968, Figs. 5–8; WYRTKI, 1971, pp. 405, 491, 501, 508).

The upper isanostere of 560 cl t^{-1} crops out into the naviface at about 11°30′N and 13°S. The water above 400 cl t^{-1} is characterized by an increase of specific volume towards 2°N from south as well as from north. The lower water (below 400 cl t^{-1}) is characterized by a decrease of specific volume towards 2°N from north. On this section, between Stns. 334 and 336 (6°–2°N), the 400 cl t^{-1} surface is mostly level, placing the core at 80 m. This isanostere coincides with either the maximum eastward pressure gradient or the minimum poleward pressure gradient (Fig. 5a). In the zone between 0° and 2°N the specific volume of water above 280 cl t^{-1} isanosteric surface decreases northward, whereas the specific volume of the water below this surface increases northward. Although the temperature distribution (Fig. 3a) is not quite parallel to that of the thermosteric anomaly (Fig. 3b), particularly at 13°S where the South Equatorial Countercurrent is located, because of salinity gradients, still both show almost similar features.

3.2. Salinity

Surface salinity decreases abruptly from 36.5‰ at Stn. 329 (15°36′N) to 35.2‰ Stn. 332 (10°04′N). Relatively intense horizontal gradients in salinity prevail at all depths between these stations. The highest salinity occurs near the surface in the north, which is due to excess of evaporation over precipitation in the Arabian Sea (WARREN *et al.*, 1966). The high-salinity water originating in the Arabian Sea surface sinks to subsurface layers and spreads southward to 5°N. From the station curves (Fig. 2a-g) (all are not shown in the paper), it is obvious that the salinity maximum at all stations north of 5°N (Stn. 335) centers between 320 and 400 cl t^{-1} isanosteres (Fig. 2b). The lowest salinity in the northern hemisphere, on this section, is observed in the surface layer near 5°N, and this water seems to be from the Bay of Bengal. In the latitudinal belt of 5°N to 5°S the salinity variation in the depth range of 100–1,000 m is less than 0.3‰ (Fig. 2c). Such a salinity distribution is a normal feature of the Indian Ocean during the southwest monsoon when the Equatorial Undercurrent is absent (SHARMA, 1968, 1972). But during the northeast monsoon when the Equatorial Undercurrent is present in the Indian Ocean, the high-salinity core is prominent along the equator at about 100–150 m (TAFT, 1967; TAFT and KNAUSS, 1967; SWALLOW, 1967; SHARMA, 1968). The less saline Equatorial Indian Ocean Water separates the two water masses originating in the surface of the Arabian Sea and the tropical region of the South Indian Ocean, in the depth range of 150–1,000 m and this water appears to act as a barrier for the transequatorial flow of the two water masses.

In the southern hemisphere, the salinity maximum centers between 160 and 260 cl t^{-1} isanosteres (Figs. 2d, 4a). The 160 cl t^{-1} surface outcrops the naviface at about 38°S, south of

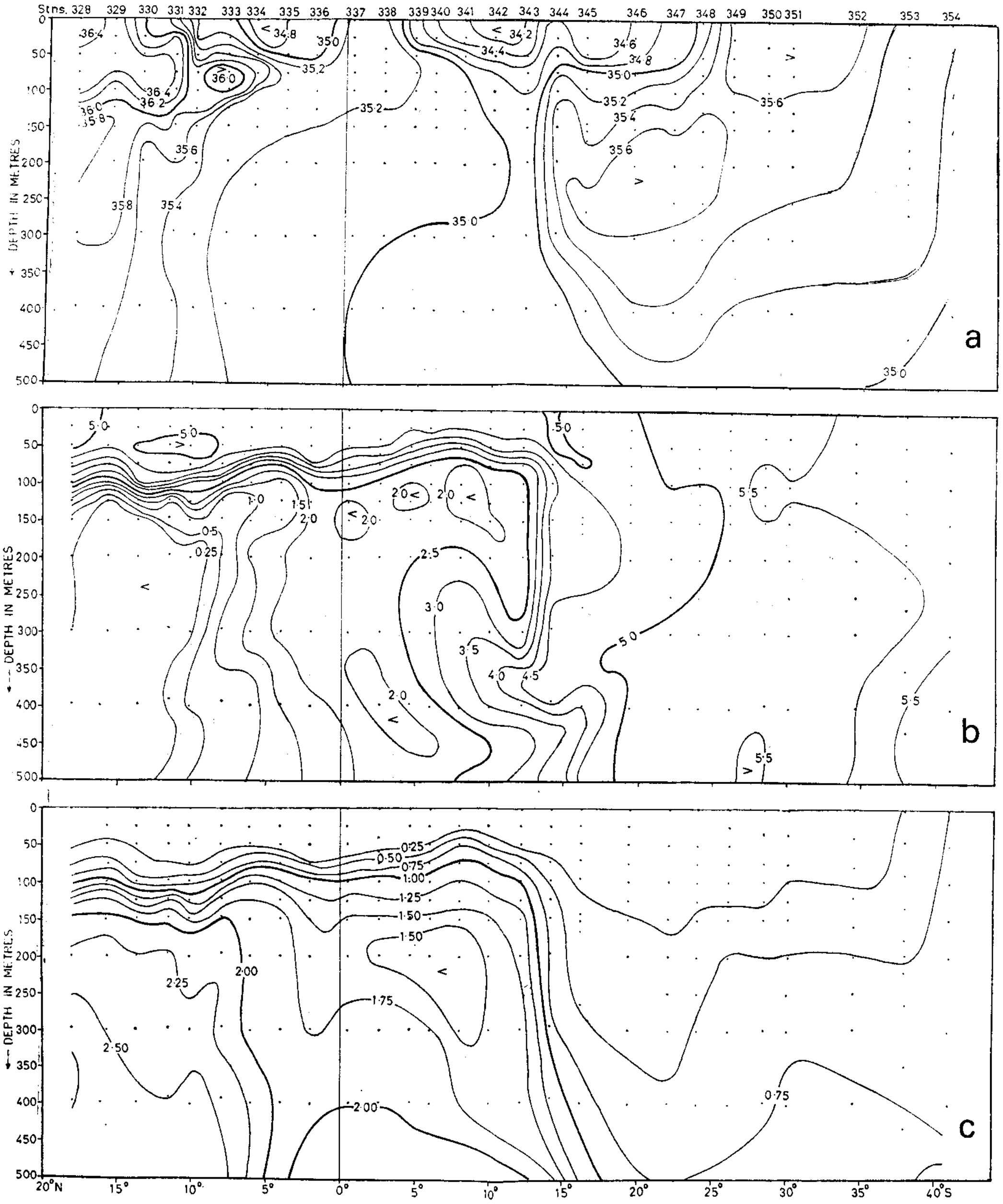


Fig. 4. Meridional distribution of a) salinity in per mil b) oxyty in milliliters per liter c) phosphate-phosphorous in microgram atom per liter at 65°E, 17 May to 4 July 1964.

which the salinity maximum is confined to the surface layers and the salinity decreases southward horizontally in the upper 500 m. At these latitudes, salinity decreases with lower thermosteric anomaly. The lowest salinity is encountered in the upper 100 m layer between 4°S and 20°S, and the halocline there, is more pronounced. The low-salinity water seems to be an incursion from the Pacific through the Banda and Timor seas. The South Equatorial Current carries this water westward. The distribution of salinity, on various isanosteric surfaces and sigma-θ surfaces, indicates the flow of the low-salinity water by a tongue structure (TAFT, 1963; WYRTKI, 1971; SHARMA, 1972). The high-salinity water, originating in the tropical surface of the South Indian Ocean, sinks and extends progressively to the north with increasing depth. The abrupt termination of the extension of this water at 13°S (Fig. 4a) is a conspicuous feature.

North of 14°S up to 8°N, the salinity in the depth range 150–500 m varies very little. This vertical homogeneous water forms a part of the Equatorial Frontal Zone, extending across the South Indian Ocean as a structural feature of the South Equatorial Current (ROCHFORD, 1969), and this water is of higher salinity than the one between 5°N and 5°S. Vertical sections in the International Indian Ocean Expedition Atlas (WYRTKI, 1971) indicate, below the tropical low-salinity water, a decisive front in the hydrographic structure, extending to several hundred meters down. Within the upper thermocline, this front is marked by a horizontal salinity minimum, separating the salinity maximum of the Tropical Water. The waters from the Persian Gulf and the Red Sea enter the Arabian Sea at about 50 and 100 m (the sill depths being 50 and 100 m; WYRTKI, 1971, sections 10, 11), and sink to deeper layers along the potential density surfaces of 26.6 and 27.0 g l^{-1} respectively. On these sections, 35.4 ‰ isohaline seems to be the southern limit of these waters, and it is doubtful if they ever cross the latitude of 5°N at 65°E in the upper 500 m. These waters can be traced only below the 200 cl t^{-1} isanosteric surface (SHARMA, 1972). Thermal structure in the meridional sections in the western Indian Ocean confirms this conclusion showing warm, high-salinity water of the Persian Gulf and the Red Sea origin at sigma-θ 26.6 and 27.0 g l^{-1} surfaces respectively (WYRTKI, 1971). The salinity maximum of the Persian Gulf Water is shown to be present in the depth range of 200–300 m (WYRTKI, 1971, Fig. 7) at different locations in the Arabian Sea, but it could not be identified near the equator. The Red Sea Water could not be traced in the upper 500 m, however, its presence can be identified in the station curve (Fig. 2b) at about 100 cl t^{-1} isanosteric surface by a salinity maximum at a depth of 550 m.

According to WYRTKI (1971), the Arabian Sea Water extends to 10°S as a core layer. But the present section as well as many of the sections in his atlas, taken during the southwest monsoon, show that the salinity in the layer between 150 and 1,000 m depths, is essentially homogeneous between the latitudes 5°N and 5°S. This water mass distinguishes from either of the water masses from the northern or southern hemispheres. Perhaps, it may be an admixture of various water masses showing its own identity. This may, preferably be called the Equatorial Indian Ocean Water.

3.3. *Oxyty*

South of 15°S, oxyty is uniformly high at all depths, occasionally increasing with depth, forming an upper oxyty maximum. At the transition zone, around 13°S, oxyty decreases rapidly northward in the depth range 80–300 m, and is associated with one of thermal fronts. This front is formed between the high-oxyty water of the tropical oxyty maximum of the South Indian Ocean, and less-oxyty water of the Equatorial Frontal Zone (ROCHFORD, 1969). Below the depth of thermocline (100–150 m), oxyty values, north of 12°S, are less than 2.5 ml l^{-1}, except in the tongue of oxyty maximum which protrudes from a depth of 380 m at 15°S to a depth of 200 m at 4°S. Similar to salinity, oxyty also shows a complex distribution in the low latitudes.

Oxyty in the Indian Ocean, in general, decreases from south towards the equator. An oxyty minimum at about 150 m protrudes as a tongue from the Arabian Sea towards the equator, consequent to the spreading of the Arabian Sea Water to the south (Fig. 4b). A similar feature of salinity maximum in the salinity distribution is also noticed (Fig. 4a). At these latitudes, oxyty decreases drastically within the thermocline.

A noteworthy feature of the oxyty distribution is a zone of very low oxyty in the northernmost part of the section where the circulation is anticyclonic (VARADACHARI and SHARMA, 1967). The waters of Somali Current that reach the 15°N might have already lost a substantial part of oxyty as they have gained temperature and salinity. Processes of respiration and biological decay are likely to be more effective in reducing the oxyty at those levels where the replenishment by diffusion and lateral advection is least. At such levels, a steady state is reached only when the oxyty has been drastically reduced, and a vertical gradient which is so strong that the vertical replenishment, if any, balances respiration and decay, is established (REID 1965). The vertical replenishment is limited because of the sharp stericline in the central Arabian Sea. The very low oxyty in the central Arabian Sea seems to be the result of a similar condition.

The area of minimum oxyty in the Arabian Sea is also the zone of higher inorganic phosphate-phosphorous. Perhaps, the higher productivity and the stratification of the waters in the Arabian Sea resulted in the formation of oxyty minimum (RYTHER *et al.*, 1966). REID (1965) offered an explanation for the depletion of oxyty in areas where the productivity is high.

Between 10°N and 5°N, oxyty abruptly in creases southward below the thermocline. In the region between 3°N and 5°S, vertical variation in oxyty beneath the discontinuity layer is relatively less. Such a distribution in the equatorial Indian Ocean is normal all through the year (SHARMA, 1968; WYRTKI, 1971). In this part of the ocean, the main source of oxyty replenishment, below the thermocline, is through the tropical water of the South Indian Ocean.

Oxyty distribution, in the equatorial region and in the north, has a close relationship with the zonal component of the current vector (Figs. 4b, 5b), particularly in the subsurface depths where replenishment of oxyty takes place only through advection and diffusion. In the region of westerly component, the oxyty is relatively higher laterally, perhaps, because of the advection with the higher oxyty water present in the east and south, and in the zone of easterly component, the oxyty is low due to a similar reason. The abrupt latitudinal variation in the oxyty between Stns. 332 and 334 (11°-6°N) is associated with the westerly component of the geostrophic current vector. Similarly, in the equatorial region where the oxyty is uniformly high, the zonal component of the current vector is westerly (Stns. 336-338). Such a variation is observed in the salinity distribution also. The effect of westerly component on salinity distribution is that the salinity decreases, and it increases with the easterly component, which can be attributed to the lateral mixing with the lower and higher salinity waters respectively.

The salinity and oxyty distributions indicate 13°S as the northern limit of the tropical water flow towards the equator in the depth range 100-500 m, and the Arabian Sea Water in the depth range 50-200 m spreads up to 5°N only (Figs. 4a, 4b). The homogeneous nature of the Equatorial Indian Ocean Water may be the consequence of these limits.

3.4. *Phosphate-phosphorous*

The phosphate-phosphorous distribution (Fig. 4c) along 65°E is almost similar to those of salinity and oxyty with the higher concentration of phosphate-phosphorous corresponding to the higher salinity and lower oxyty, except in the region south of 20°S. Above the thermocline, the lowest values (less than 0.1 μg-at l^{-1}) are found in the surface between the two thermal fronts in the southern hemisphere. The maximum concentration at the surface is observed at Stn. 329 (15°N), with a value 0.24 μg-at l^{-1}. Below the discontinuity layer, phosphate-phosphorous continuously increases northward from 20°S.

Strong vertical gradients in the thermocline separate the high concentrations below, from the nutrient depleted surface layers. Where there is a well defined stericline, the isopleths of phosphate-phosphorous follow the isanosteric lines. In the latitudinal belt of 5°N to 13°S, the phosphate-phosphorous distribution below the thermocline is, in general, uniform, similar to that of salinity and oxyty.

4. Current structure

The meridional component of the pressure-gradient force and the zonal component of the geostrophic current are presented in Figs. 5a and 5b respectively. The former is simply related to the observed conditions, while the latter incorporates the highly variable divisor $\sin\phi$ near the equator. The zonal component of the current vector appears to be fictitious near the equator.

The easterly component between 10°N and 15°N varies from 10 to 20 cm s^{-1} with a minimum value midway between these limits. The westerly flow at 6°-10°N may be due to the anticyclonic circulation in the Arabian Sea in the early months of the southwest monsoon (VARADACHARI and SHARMA, 1967). South of this westerly flow, the Southwest Monsoon Current appears with a very weak easterly flow. The intense westerly component of 120 cm s^{-1} near 1°N may be the result of the divisor $\sin\phi$, and

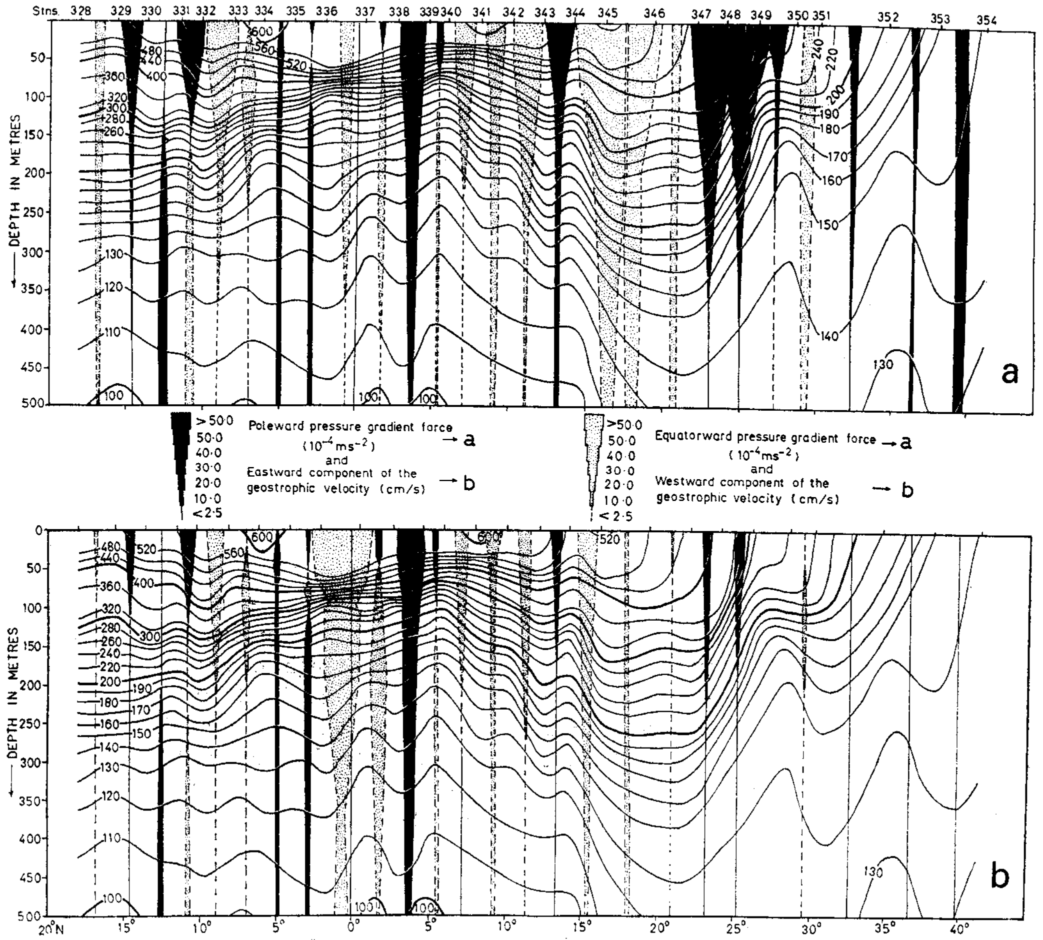


Fig. 5. Vertical sections at 65°E, 17 May to 4 July 1964. a) The average between-stations meridional component of pressure-gradient force per unit mass, based on 1,000 db surface. b) The average between-stations zonal component of geostrophic velocity based on 1,000 db surface. (Thermosteric anomaly is shown by isopleths numbered in cl t^{-1}).

t may not be of real nature. In the Pacific and the Atlantic, the geostrophic balance to as low as one half degree has been presented by KNAUSS (1960, 1963), MONTGOMERY and STROUP (1962) and METCALF *et al.* (1962). But the present study indicates the absence of the geostrophic balance to such a low latitude as that in the Pacific and Atlantic, probably, because the circulation in the North Indian Ocean is controlled by the monsoons. However, the equatorward pressure-gradient force confirms the presence of the North Equatorial Current till the end of May when the observations were made near the equator. The conventional climatological current data from the atlases show the absence of the North Equatorial Current by the end of April, and in its place the Southwest Monsoon Current which merges with the Equatorial Countercurrent appears (SVERDRUP *et al.*, 1942; DEFANT, 1961; VARADACHARI and SHARMA, 1967; SHARMA, 1971). The reversal of wind direction in the equatorial region of the Indian Ocean in 1964 took place by April, indicating the onset of the southwest monsoon (SWALLOW, 1967). Contrary to the existing cencept that the North Equatorial Current is replaced by the Southwest Monsoon Current in April, the present investigation indicates the presence of the North Equatorial Current till the end of May, even after the onset of the southwest monsoon. As a consequence of the presence of the North Equatorial

Current, the North Equatorial Countercurrent which merges subsequently with the Southwest Monsoon Current, could be well distinguished with a zonal component of 40 cm s^{-1}. The South Equatorial Current, with its northern boundary, usually, at 10°S in winter, shifted to 5°S. Its maximum zonal component is about 30 cm s^{-1} at 9°S near the surface.

The recently discovered South Equatorial Countercurrent in the South Equatorial Current system is well depicted in the Indian Ocean at 13°S as a narrow, weak easterly flow with a magnitude of about 20 cm s^{-1}. Because this latitude is dominated by strong southeast trades, the actual surface current should have been westerly, if the current structure is to be governed by winds alone. This narrow eastward geostrophic flow is clearly associated with the strong meridional gradient of salinity, developed between high-salinity tropical water of the South Indian Ocean and low-salinity water of the Pacific origin. The salinity gradient is so intense that it determines the sense of thermosteric anomaly gradient; if only the temperature gradient is present, a westward geostrophic flow would result, slightly higher surface salinity at Stn. 344 is consistent with the eastward transport of high-salinity water from the west.

The South Equatorial Countercurrent appears to be a small strip of easterly flow in the broad South Equatorial Current and its existence may be the consequence of a gradient current developed at the discontinuity (13°S). Other than this narrow band of easterly component, confining to less than 2° latitude, the flow between 6°S and 20°S is essentially westerly, representing the South Equatorial Current whose maximum zonal component occurs in the surface layers and exceeds 60 cm s^{-1}.

Vertical sections in the Indian Ocean Atlas (WYRTKI, 1971) also indicate that the meridional salinity gradient tends to produce a narrow band of eastward geostrophic flow. The surface geopotential maps in this atlas do not show any conclusive evidence of this current. Probably, this feature is masked in the averaging over 300 miles squares. Nevertheless, the surface dynamic topography, on the vertical sections, defines this narrow, weak, eastward flow between 8°S and 15°S at various meridians, with a southward inclination towards the east. A close examination of the climatological drift charts (K. Ned. Met. Inst., 1952) which give monthly mean surface current vectors for each 2° latitude-longitude quadrangle, reveals the occasional occurrence of an easterly drift at different meridians in the latitudinal belt of 10°–14°S.

The magnitude of the South Equatorial Countercurrent in the Pacific and Atlantic is of the order of 8–25 cm s^{-1} (REID, 1959, 1964; WOOSTER, 1961). According to REID (1959), this current is confined to 2°–5°S at 165°E and 10°–14°S at 95°W in the Pacific. The distributions of hydrographical properties associated with this current in the Indian Ocean are not exactly similar to those of the Pacific and Atlantic. In the Indian Ocean, where the South Equatorial Countercurrent is located, the salinity and oxyty drastically vary horizontally.

South of the South Equatorial Current (Fig. 5b), the zonal flow is again easterly at 22°–26°S where the thermal front associated with the Tropical Convergence Zone is situated. Across this thermal front, temperature increases northward so that an eastward geostrophic current, flanked by westward current on either side is expected to exist along the front. This Tropical Countercurrent is wider and stronger than the South Equatorial Countercurrent. It is interesting that the region of this relatively strong eastward flow is dominated by the southeast trades; of course, not so strong as they are at 13°S during the southwest monsoon (K. Ned. Met. Inst., 1952). This geostrophic current flows against the winds just like the South Equatorial Countercurrent. But in this case, temperature gradient is the main factor in determing the sense of thermosteric anomaly gradient. The Tropical Countercurrent is separated from the west wind drift associated with the Antarctic Circumpolar Current by a weak westerly flow at 29°S.

In the zone south of 20°S, the depth chart of 200 cl t^{-1} isanosteric surface shows a continuous easterly flow all along the width of the Indian Ocean during the southwest monsoon (SHARMA, 1972). The meridional sections, drawn along various meridians and for different months, reveal the features of a permanent thermal front between 20°S and 25°S, indicating the possibility of the Tropical Countercurrent round the year, along the total width of the Indian Ocean (WYRTKI, 1971). This geostrophic current is evident on all the bimonthly surface geopotential charts in the Indian Ocean Atlas (WYRTKI, 1971). These charts show a maximum of geopotential along about 20°S or slightly to the north, and the eastward current flows on the southern side of the maximum from Malagasy as far east as Australia. Between this eastward flow and the eastward Antarctic Circumpolar Current, the surface current is also eastward but very weak. The westerly flow, shown in the present section is, probably masked in the charts of the atlas because of averaging over 300 miles squares. However, the vertical sections in this atlas reveal the features of westerly flow, south of the thermal front.

The monthly surface current charts (K. Ned. Met. Inst., 1952) indicate the existence of a continuous eastward current at about 20°-28°S on all the charts, *i.e.*, throughout the year. These charts show a north to south shift of the eastward current from season to season, with a southward shift during the northeast monsoon, and northward during the southwest monsoon.

The Tropical Countercurrent, identified in the Indian Ocean, is synonymous to the Subtropical Countercurrent discovered theoretically by YOSHIDA and KIDOKORO (1967a, 1967b), and the observational evidence was put forth by UDA and HASUNUMA (1969) in the North Pacific at 20°-25°N. The associated thermal feature of this current in both the oceans is a thermal front in the tropical latitudes. UDA and HASUNUMA (1969) pointed out "North of the Countercurrent, the thermocline is entirely separated into the main thermocline and the seasonal thermocline. Between these thermoclines, a homogeneous layer, not only temperature but in salinity, is found at 100-400 m depths. This homogeneous water-mass, which corresponds to the 18°C Water pointed out by WORTHINGTON (1959) in the North Atlantic, is named the Subtropical Mode Water by MASUZAWA (1967). Therefore, the Subtropical Countercurrent is located near the southern boundary of the Subtropical Mode Water. In the Indian Ocean, all the thermal features associated with the Tropical Countercurrent are similar to those in the Pacific, but the particular feature of separation of the thermocline into two, and the 18°C Water Mass south of the Tropical Countercurrent are unnoticed. Nevertheless, a thermostad with temperatures at 12-13°C developed just south of the thermal front associated with the eastward flow, and the homogeneous nature of salinity distribution upto 400 m depth in the same region are noticed in the Indian Ocean.

During the southwest monsoon the current structure in the North Indian Ocean differs from the Pacific and the Atlantic. This difference is characteristically depicted in the distribution of temperature, salinity and thermosteric anomaly. Unlike in the equatorial regions of the Pacific and the Atlantic, where relatively cooler, saltier water with lower thermosteric anomaly associated with the Equatorial Undercurrent is present (KNAUSS, 1960; MONTGOMERY and STROUP, 1962; METCALF *et al.*, 1962; REID, 1965; TSUCHIYA, 1968); in the Equatorial Indian Ocean relatively warm, less saline water with higher thermosteric anomaly, without the indication of the Equatorial Undercurrent is predominant. The current structure also supports the inference drawn from water properties.

5. Conclusion

The water characteristics and current structure at 65°E in the upper 500 m, discussed in this paper suggest the following conclusions:

The three water masses encountered are 1) most saline, low-oxyty and nutrient-rich Arabian Sea Surface Water, 2) homogeneous and high-oxyty Equatorial Indian Ocean Water, and 3) saltier, high-oxyty and nutrient-poor Tropical Water of the South Indian Ocean.

No transport across the equator occurs in the upper 500 m at 65°E during the southwest monsoon.

The southward movement of the Arabian Sea Water, and the northward flow of the Tropical Water of the South Indian Ocean in the depth range of 100-500 m are confined to 5°N and 13°S respectively.

The narrow, weak South Equatorial Countercurrent is observed at 13°S in the broad South Equatorial Current system at 65°E.

The Tropical Countercurrent is present in the Indian Ocean round the year at 22°-26°S.

In contrast to the existing concept, the North

Equatorial Current is noticed even after the onset of the southwest monsoon.

The Equatorial Undercurrent could be traced neither in the water properties nor in the current structure during the southwest monsoon.

An interesting relationship exists between the zonal component, and the distribution of salinity and oxyty at 65°E. In the region of westerly component the distributions are characterized by lower salinity and higher oxyty, whereas in the zone of easterly component, it is of higher salinity and lower oxyty.

References

DEFANT, A. (1961): Physical Oceanography. Pergamon, Oxford, **1**, 745 pp.

KNAUSS, J. A. (1960): Measurements of the Cromwell Current. Deep-Sea Res., **6**, 265-286.

KNAUSS, J. A. (1963): Equatorial currents. Trans. Am. Geophys. Union, **44**, 477-478.

Koninklijk Nederlands Meteorologisch Instituut (1952): Indische Oceaan. Oceanografische en Meteorologische gegevens. 2nd Edition, Publ. No. 135, **1**, Text 31 pp., **2**, 24 charts.

MASUZAWA, J. (1967): An oceanographic section from Japan to New Guinea at 137°E in January 1967. Oceanogr. Mag., **19**, 95-118.

METCALF, W.G., A.D. VOORHIS and M.C. STALCUP (1962): The Atlantic Equatorial Undercurrent. J. Geophys. Res., **67**, 2499-2508.

MONTGOMERY, R. B. (1937): A suggested method for representing gradient flow in isentropic surface. Bull. Am. Met. Soc. **18**, 210-212.

MONTGOMERY, R. B. (1954): Analysis of Hugh M· Smith oceanographic section from Honolulu southward across the equator. J. Mar. Res., **13**, 67-75.

MONTGOMERY, R. B. and A. F. SPILHAUS (1941): Examples and outline of certain modifications in upper-air analysis. J. Aero. Sci., **8**, 276-283·

MONTGOMERY, R. B. and E. D. STROUP (1962): Equatorial waters and currents at 150°W in July-August 1952. Johns Hopk. Oceanogr. Stud., **1**, 68 pp.

MONTGOMERY, R. B. and W. S. WOOSTER (1954): Thermosteric anomaly and the analysis of serial oceanographic data. Deep-Sea Res., **2**, 63-70.

REID, J. L. (1959): Evidence of a South Eqatorial Countercurrent in the Pacific Ocean. Nature, **184**, 209-210.

REID, J. L. (1961): On the geostrophic flow at the surface of the Pacific Ocean with respect to the 1,000-decibar surface. Tellus, **13**, 489-502.

REID, J. L. (1964a): Evidence of a South Equatorial Countercurrent in the Atlantic in July 1963. Nature, **203**, 182.

REID, J. L. (1964b): A transequatorial Atlantic oceanographic section in July 1963 compared with other Atlantic and Pacific sections. J. Geophys. Res., **69**, 5205-5215.

REID, J. L. (1965): Intermediate waters of the Pacific Ocean. Johns Hopk. Oceanogr, Stud., **2**, 85 pp.

ROCHFORD, D. J. (1969): Seasonal variation in the Indian Ocean along 110°E. I. Hydrological structure of the upper 500 m. Aust. J. Freshwat. Res., **20**, 1-50.

RYTHER, J.H., J.R. HALL, A.K. PEASE, A. BAKUN and M. M. JONES (1966): Primary organic prodution in relation to the chemistry and hydrography of the western Indian Ocean. Limnol. Oceanogr., **11**, 371-380.

SHARMA, G. S. (1968): Some inferences on the Equatorial Undercurrent in the Indian Ocean based on the physical properties of the waters. J. Mar. Biol. Assoc. India., **10**, 224-236.

SHARMA, G. S. (1971): Studies on divergence of the surface waters in the North Indian Ocean. Ph. D. thesis, Andhra University, Waltair, 102 pp.

SHARMA, G. S. (1972): Water characteristics at 200 cl t^{-1} in the intertropical Indian Ocean during the southwest monsoon. J. Mar. Res., **30**, 102-111.

SVERDRUP, H.U., M.W. JOHNSON and R.H. FLEMING (1942): The Oceans: Their physics, chemistry and general biology. Prentice-Hall, New York, 1087 pp.

SWALLOW, J.C. (1967): The Equatorial Undercurrent in the western Indian Ocean in 1964. Stud. Trop. Oceanogr. Miami, **5**, 15-36.

TAFT, B. A. (1963): Distribution of salinity and dissolved oxygen on the surface of uniform potential specific volume in the South Atlantic, South Pacific, and the Indian Ocean. J. Mar. Res., **21**, 129-146.

TAFT, B. A. (1967): Equatorial Undercurrent in the Indian Ocean, 1963. Stud. Trop. Oceanogr. Miami, **5**, 3-14.

TAFT, B. A. and J. A. KNAUSS (1967): Equatorial Undercurrent of the Indian Ocean as observed by the Lusiad Expedition. Bull. Scripps Inst. Oceanogr., **9**, 163 pp.

TSUCHIYA, M. (1968): Upper waters of the intertropical Pacific Ocean. Johns Hopk. Oceanogr. Stud., **4**, 50 pp.

UDA, M. and K. HASUNUMA (1969): The eastward Subtropical Countercurrent in the western North Pacific Ocean. J. Oceanogr. Soc. Japan, **25**, 201-210.

VARADACHARI, V. V. R. and G. S. SHARMA (1967): Circulation of the surface waters in the North Indian Ocean. J. Indian Geophys. Union, **4**, 61-73.

VOORHIS, A. D. and J. B. HERSEY (1964): Oceanic thermal fronts in the Sargasso Sea. J. Geophys. Res., 69, 3809-3814.
WARREN, B., H. STOMMEL and J. C. SWALLOW (1966): Water masses and patterns of flow in the Somali Basin during the southwest monsoon of 1964. Deep-Sea Res., 13, 825-860.
WELANDER, P. (1959): On the vertically integrated mass transport in the oceans. The Atmosphere and the Sea in Motion, The Rossby Memorial Volume, pp. 95-101.
WOOSTER, W. S. (1961): Further evidence of a Pacific South Equatorial Countercurrent. Deep-Sea Res., 8, 294-297.
WORTHINGTON, L. V. (1959): The 18°C Water in the Sargasso Sea. Deep-Sea Res., 5, 297-307.
WYRTKI, K. (1971): Oceanographic Atlas of the International Indian Ocean Expedition. National Science Foundation, Washington, D. C., 531 pp.
YOSHIDA, K. (1961): Some calculations on the equatorial circulation. Rec. Oceanogr. Wks. Japan, New Series, 6, 101-105.
YOSHIDA, K. and T. KIDOKORO (1967a): A Subtropical Countercurrent in the North Pacific—An eastward flow near the Subtropical Convergence. J. Oceanogr. Soc. Japan, 23, 88-91.
YOSHIDA, K. and T. KIDOKORO (1967b): A Subtropical Countercurrent (II)—A prediction of eastward flow at lower subtropical latitudes. J. Oceanogr. Soc. Japan, 23, 231-246.

南西モンスーン時期における 65°E の海水の性質と海流構造

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1964年5月17日から7月4日にかけて行なわれたアントンブルーン号の，65°E に沿った海域でえられた海洋観測資料を用い，インド洋表層 500 m における，海水の性質と，海流構造を研究した．この海域の海水は，次のように3つに分けられる：(1) 温暖で，高塩分，低酸素量で，栄養塩含量の高いアラビア海表面水，(2) 比較的新らしく，酸素含量の高い赤道インド洋海水，(3) 更に高塩分で，酸素含量が高く，栄養塩含量に乏しい南インド洋の熱帯水．最近見出された南赤道反流と亜熱帯反流(MONTGOMERY の意見により熱帯反流と改名)が，13°S と 22～26°S の海流構造に夫々見出され，また，水温，サーモステリックアノマリーおよび塩分の断面でも確認された．従来の定説に反し，北赤道海流は南西モンスーン時期終了後もつづけて存在する．赤道潜流は，この時期のインド洋においてみられなかった．