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Structure of currents and hydrographic conditions in the western equatorial Indian Ocean during the summer monsoon

L. V. GANGADHARA RAO, V. RAMESH BABU
AND V.V.R. VARADACHARI

This chapter presents the results of studies on the currents and hydrography of the waters of the western equatorial Indian Ocean during the period 28 May to 3 June 1973. Studies of hydrographic conditions in the area after about one month (i.e. 25 June to 2 July 1973) are also discussed. Time-series data on horizontal currents were gathered by recording current meters attached to a buoy anchored at the Equator near 60° E during the Indo-Soviet Monsoon Experiment 1973. Hydrographic data were also obtained from repeated Nansen casts at 3-hourly intervals around the buoy. The time variation of currents (3-hour averages) at different depths (75 m, 100 m, 150 m, 200 m, 300 m, 500 m and 800 m) and the vertical time sections of temperature, salinity and density from the surface to 1000 m depth are presented and discussed.

The studies show a complex vertical structure of horizontal currents with predominant easterly components at 75 m and 100 m depth and predominant westerly components at 200 m, 300 m, 500 m and 800 m depth, and a zone of strong current shear between 100 m and 200 m depth. At 150 m depth, the current has been found to be oscillatory with a period of oscillation of about 2 hours. The currents are rather strong even at deeper levels, particularly at 200 m and 800 m depths where westward jets with speeds of the order of 0.35 m s^{-1} and 0.4 m s^{-1} respectively have been encountered.

Studies of the hydrographic conditions have revealed the presence of internal waves in the area. A significant fall in temperature (about 2 °C) and a slight decrease in salinity in the surface layer were noticed during the one-month interval between the two series of hydrographic observations (May/June–June/July).

30.1 Introduction

Important among the unique features of the Indian Ocean is its exposure to the seasonally reversing monsoon winds. As a result, the surface currents, especially in the equatorial part of the Indian Ocean, differ markedly from those in the other oceans. A study of the structure of currents in the equatorial region of the Indian Ocean therefore assumes special significance.

Some investigations of the structure of currents in the equatorial Indian Ocean, aimed at achieving a better understanding of the behaviour, driving mechanism and method of maintenance of currents in this region, were carried out during the International Indian Ocean Expedition (1960–5) which used direct measurement of currents together with measurement of water properties (temperature, salinity, density, etc.). Results of the current measurements made from RV *Argo* of the Scripps Institution of Oceanography, USA during 1962 and 1963 (reported by Knauss and Taft, 1963 and 1964, and Taft, 1967) and those conducted from RRS *Discovery* of the UK in 1964 (reported by Swallow, 1964 and 1967), established the presence of an undercurrent in the Indian Ocean. This undercurrent showed some characteristics different from those of the undercurrents present in the Atlantic and the Pacific Oceans. These current measurements were, however, mostly confined to the upper 400 m. Some measurements of currents at greater depths were made in the equatorial region of the Indian Ocean from RV *Vityaz* of the USSR, during the southwest monsoon period of 1962, when a strong westward flow was found in the deeper regions (Neyman, 1964).

A joint Indo-Soviet Monsoon Experiment (ISMEX) was carried out from May to July 1973. During this experiment a vast amount of meteorological and oceanographic data was collected. The data was used for a preliminary exercise in the investigation of the atmospheric and oceanic processes associated with various phases of the Indian summer monsoon in preparation for the detailed studies to be taken up during the International Monsoon Experiment (MONEX) planned for 1979. The programme of ISMEX included collection of time-series data on horizontal currents and water properties from a few current-meter

moorings and the associated research ships. Results of measurements made at a current-meter mooring positioned on the Equator in the western part of the equatorial Indian Ocean during the ISMEX are presented and discussed in this chapter.

30.2 Collection and treatment of data

During the ISMEX, *Okean*, a research vessel of the Hydro-meteorological Services of the USSR laid a current-meter mooring on the Equator at 60° E from 27 May to 4 June 1973 to gather information on the structure of currents during the early phase of the summer monsoon. Time-series data on horizontal currents at seven depths (75 m, 100 m, 150 m, 200 m, 300 m, 500 m and 800 m) were collected with *Alekseev* recording current meters attached to the moored buoy at the respective depths. The ship was allowed to drift in the area and manoeuvred to keep herself within 3 miles (4.8 km) distance from the buoy which she had laid and which she subsequently recovered. Nansen casts were made down to about 1200 m depth at 3-hourly intervals and data on hydrographic parameters were collected for a study of the water properties. The ship returned to the same area after about a month and the observations were repeated from 25 June to 2 July 1973, to identify any changes.

Data on currents sampled at 20-minute intervals for different depths were resolved into zonal and meridional components. Three-hourly averages of currents (zonal component, meridional component and current vector) for the period 28 May to 3 June 1973 were calculated and presented in a chart describing their variation with time at different depths. Arithmetic and vectoral averages of currents for the entire period were also computed for different depths to distinguish the oscillatory type of current from the steady type.

Using the processed hydrographic data, vertical time sections of temperature, salinity and density from the surface to 1000 m depth, were prepared for the periods 28 May to 3 June and 25 June to 2 July. In these sections, the vertical scale is reduced by half for the depth range 500 to 1000 m as the variations of the parameters at these depths are less marked. The vertical time sections of temperature, salinity and density have been presented with isotherms, isohalines and isopycnals drawn at intervals of 1 °C, 0.1‰ and 0.2 kg m⁻³ (grammes per litre) respectively. However, in the region of strong density gradients ($\sigma_t = 23$ to 25 kg m⁻³) the σ_t lines have been drawn at unit intervals.

30.3 Results and discussion

The western part of the equatorial Indian Ocean, with bathymetric contours of the region (shown in metres) and the location of the buoy station where the observations were taken, is shown in Fig. 30.1. It is seen that the station is located in an ideal deep-ocean environment free from any boundary effects of continents or islands. The water depth at the station was 4470 m.

Fig. 30.2 shows the time variation of currents (3-hourly averages) for the period 27 May to 4 June 1973 for different depths. Arithmetic and vectoral averages of the currents for the entire period are presented in Table 30.1. At 75 m depth, the current speeds vary between 0.3 m s^{-1} and 0.5 m s^{-1} with directions mostly between northeasterly and easterly exhibiting predominantly easterly components. The currents are rather weak at 100 m depth with speeds ranging between 0.2 m s^{-1} and 0.4 m s^{-1} and directions varying mostly between southeasterly and easterly. At 150 m depth, even though the individual values of speeds sampled at 20-minute intervals are of the order of 0.3 m s^{-1} , the vectorial averages over 3-hour periods are much less (less than 0.1 m s^{-1}) indicating that the currents at this depth are oscillatory. To depict the oscillatory nature of currents at this depth, a progressive vector diagram of currents for one day (28 May 1973) using 20-minute sampling has been prepared and presented in Fig. 30.3. It can be inferred from this diagram that the period of oscillation of currents at this depth is about 2 hours, and that

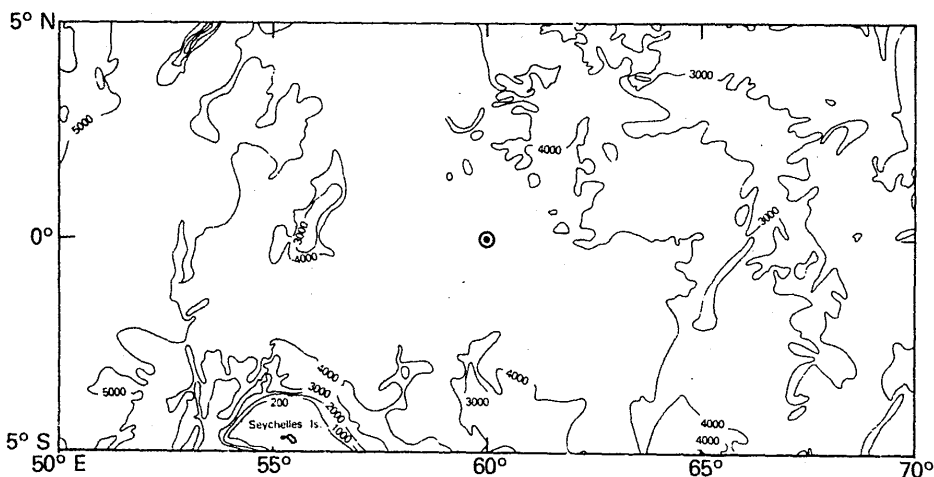


Fig. 30.1. Station location (at the centre of the region). The contours of ocean depth are labelled in metres.

TABLE 30.1. Average currents for the period 28 May to 3 June 1973.

Depth of sampling (m)	Average current (arithmetic mean) (m s^{-1})	Average zonal component, \bar{u} (m s^{-1})	Average meridional component, \bar{v} (m s^{-1})	Average current (vectoral mean), \bar{V}	
				Speed (m s^{-1})	Direction
75	0.41	0.36	0.09	0.37	76°
100	0.34	0.28	-0.13	0.31	115°
150	0.29	-0.03	-0.02	0.04	236°
200	0.37	-0.35	0.01	0.35	272°
300	0.33	-0.28	0.15	0.32	298°
500	0.37	-0.34	-0.01	0.34	268°
800	0.43	-0.32	-0.24	0.40	233°

there is a net southward movement at the rate of about 2.5 km per day. At 200 m depth, the current is again strong (speeds range from 0.3 m s^{-1} to 0.45 m s^{-1}) and the directions vary between west-southwest and west-northwest exhibiting predominantly westerly components. At 300 m depth, the current speeds are slightly less than those at 200 m (speed variation between 0.2 and 0.43 m s^{-1}) and the directions vary between west and northwest. The current speeds vary between 0.25 and 0.46 m s^{-1} at 500 m depth, and the directions vary between west-northwest and west-southwest, exhibiting predominantly westerly components. At 800 m depth, the current speeds and directions vary between 0.35 and 0.5 m s^{-1} and west-southwest and south-southwest respectively.

These features agree fairly well with the findings of the recent observations on currents (time series of vertical profiles of horizontal velocity extending from ocean surface to the bottom, employing an acoustic dropsonde, a free-fall acoustically self-navigating vehicle) carried out from RV *Atlantis II* of the Woods Hole Oceanographic Institution, USA in the western Indian Ocean (along 53° E meridian) during May-June 1976, during the Indian Ocean Experiment (INDEX), reported by Luyten and Swallow (1976).

A critical study of the values of average currents (Table 30.1) reveals that except at 150 m depth, the currents are rather steady as no significant difference between the arithmetic mean and the vectoral mean could be found at these depths. A clockwise shift in the direction of currents from 75 m to 300 m depth and a counter-clockwise shift further down to 800 m depth is encountered (Table 30.1) suggesting that the complex variations

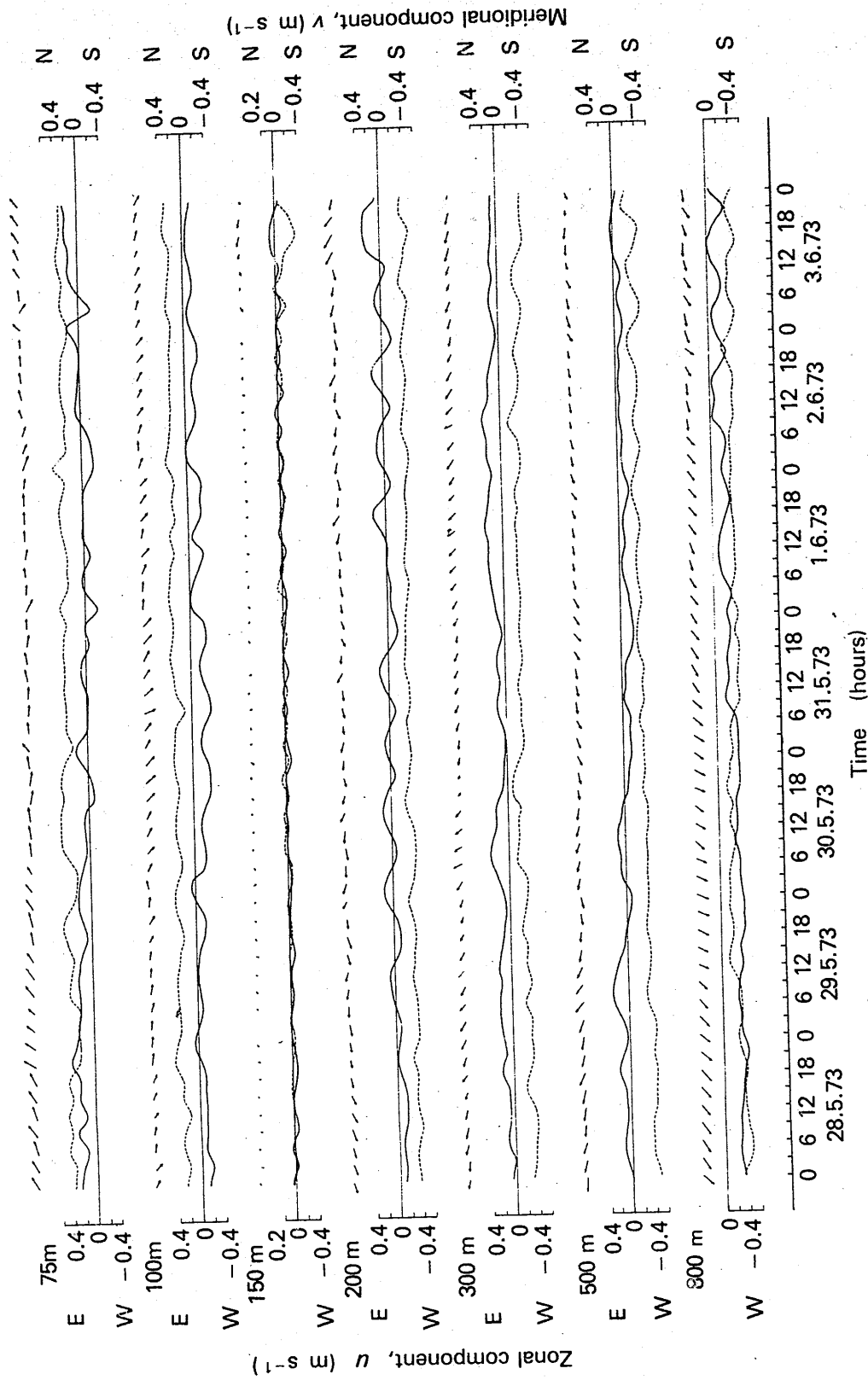


Fig. 30.2. Time variation of currents (3-hour averages) during the period 28 May to 3 June 1973. The arrows are current vectors. The zonal component u (E-W) is represented by a broken line. The meridional component v (N-S) is represented by a solid line.

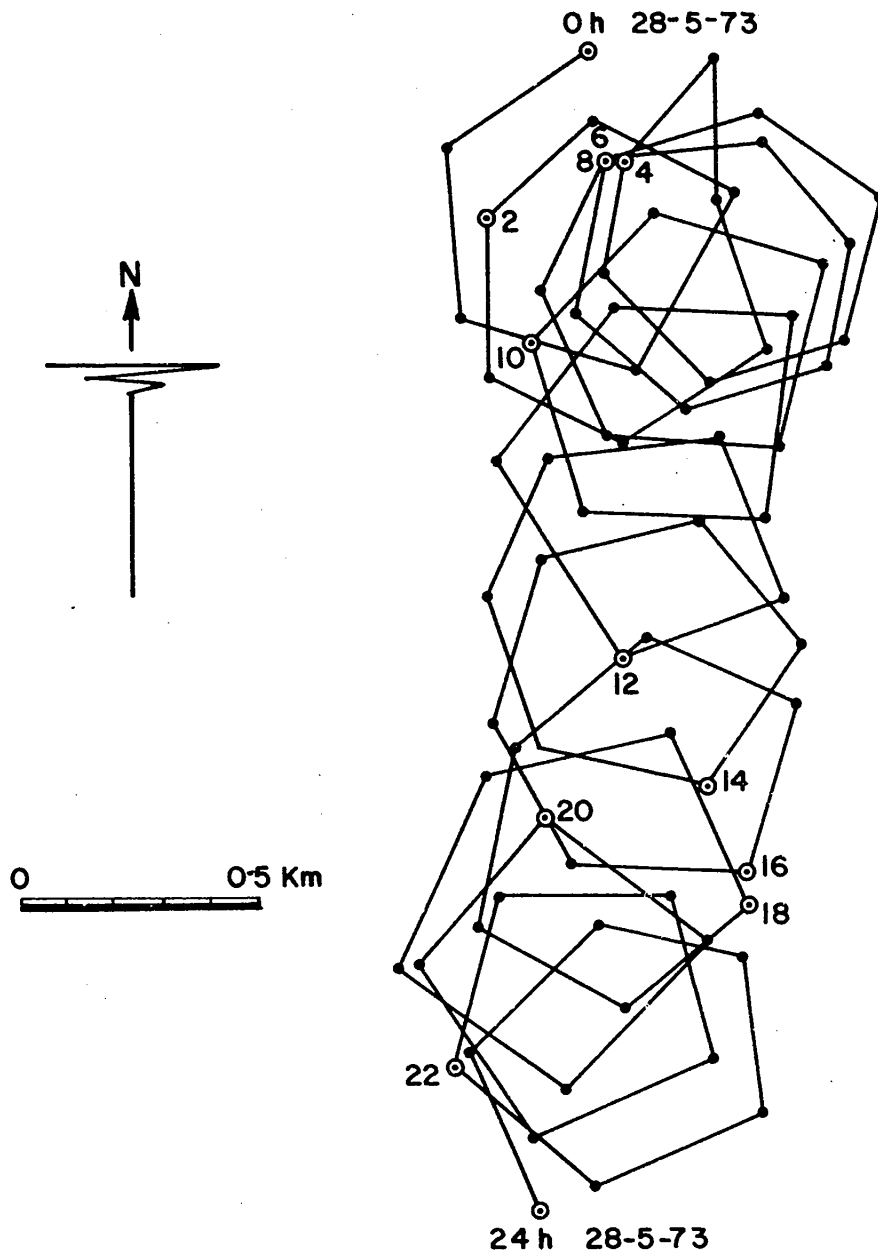


Fig. 30.3. Progressive vector diagram of currents at 150 m depth, using 20-minute sampling, for 28 May 1973.

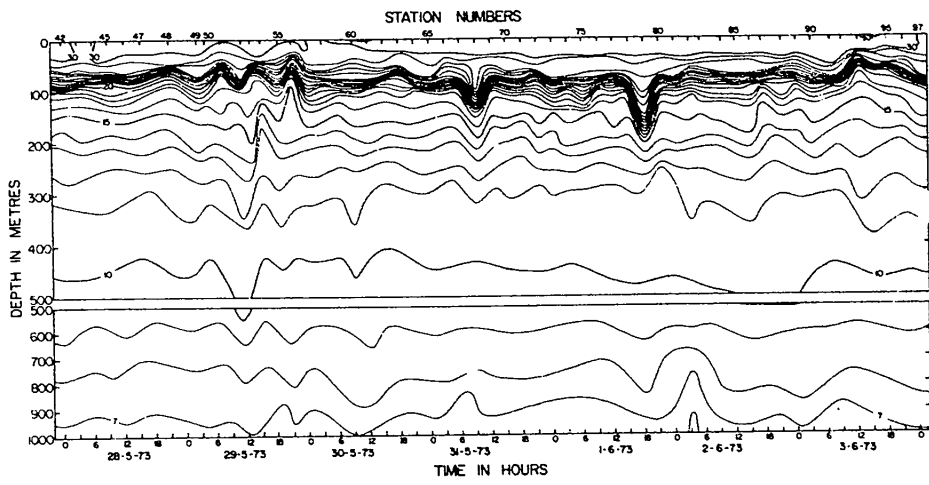
of currents with depth, and the shear zones, are not confined to the upper layers, but extend perhaps to depths greater than 800 m. Rather strong currents with average speeds of the order of 0.35 m s^{-1} and 0.4 m s^{-1} , with predominant westward components encountered at depths of 200 m and 800 m respectively, could be referred to as westward jets since currents with such high magnitudes are not common in deeper regions. These findings agree well with those reported recently by Luyten and Swallow (1976) based on the current measurements carried out from RV *Atlantis II*.

Vertical time sections of temperature, salinity and density for the periods 28 May to 3 June and 25 June to 2 July are presented in Figs. 30.4 and 30.5 respectively, depicting the hydrographic conditions prevailing in the area at the time of current-meter mooring and a month later. During the former period, the temperature of the surface layer is more than 30°C , the thermocline is very well developed with sharp vertical temperature gradients (10°C per 25 m) and the isotherms exhibit a regular wavy pattern indicating the presence of internal waves. Within a month, the temperature of the surface layer fell by about 2°C and the thermocline became slightly diffuse. (Fig. 30.5).

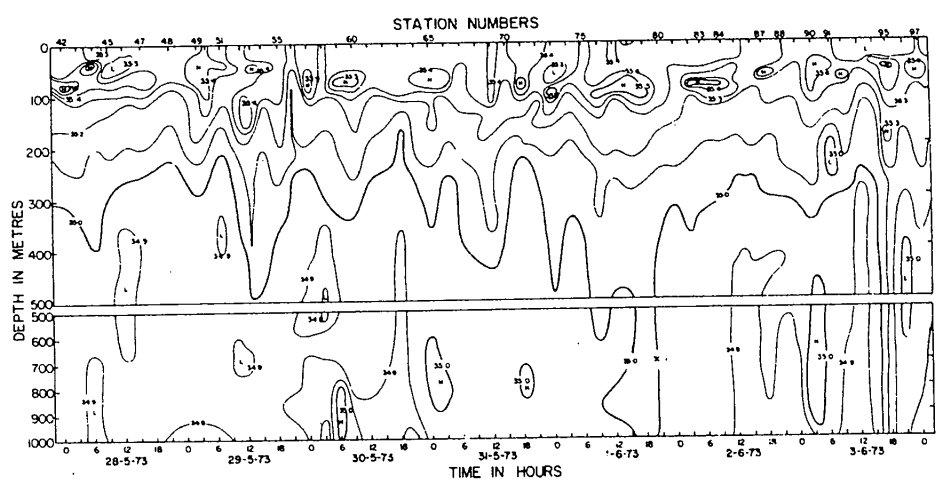
The density of surface waters is slightly higher during the latter period, periods, with slightly lower values being encountered during the latter period. An interesting feature of these sections is the presence of a series of cells of high and low salinity in the upper part of thermocline during the former period. This may be the result of local circulations associated with intense internal-wave activity (La Fond and Lee, 1962). The salinity structure during the latter period is comparatively simple with very few cells.

The density of surface waters is slightly higher during the latter period, reflecting the effect of relatively low surface temperatures encountered during this period. The presence of the strongly developed density discontinuity layer exhibiting a wavy pattern during the former period confirms the intense internal-wave activity revealed in the thermal structure.

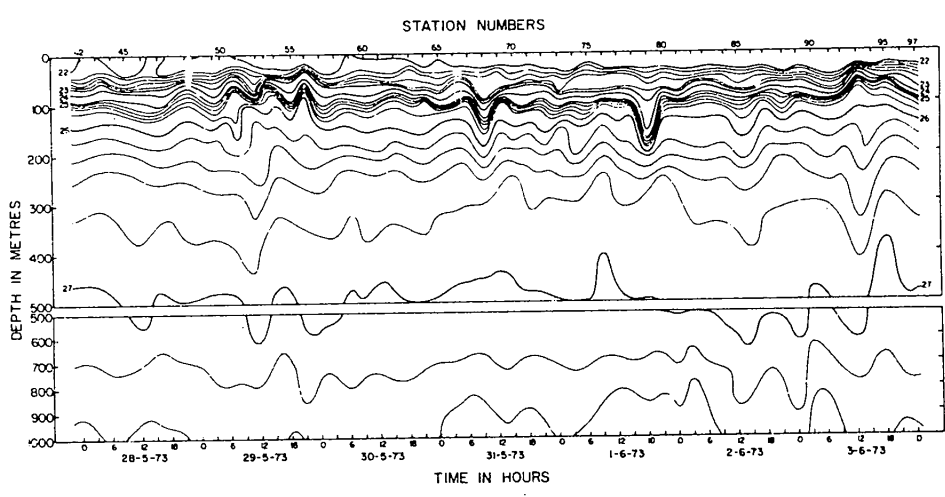
The effect of local circulations associated with internal waves can be seen in the currents at depths of 75 m and 100 m, where slight variations in velocity have been observed periodically during May–June (Fig. 30.2). The period of oscillation (of about 2 hours) of currents at 150 m depth may as well, perhaps, be related to that of internal gravity waves present in this region as this feature cannot be attributed either to inertial oscillations or to tidal motions. These findings are in agreement with the



(a)



(b)



(c)

Fig. 30.4. Vertical time sections of: (a) temperature (contours labelled in $^{\circ}\text{C}$); (b) salinity (contours labelled in ‰); and (c) density (contours labelled in kg m^{-3}) for the period 28 May to 3 June 1973.

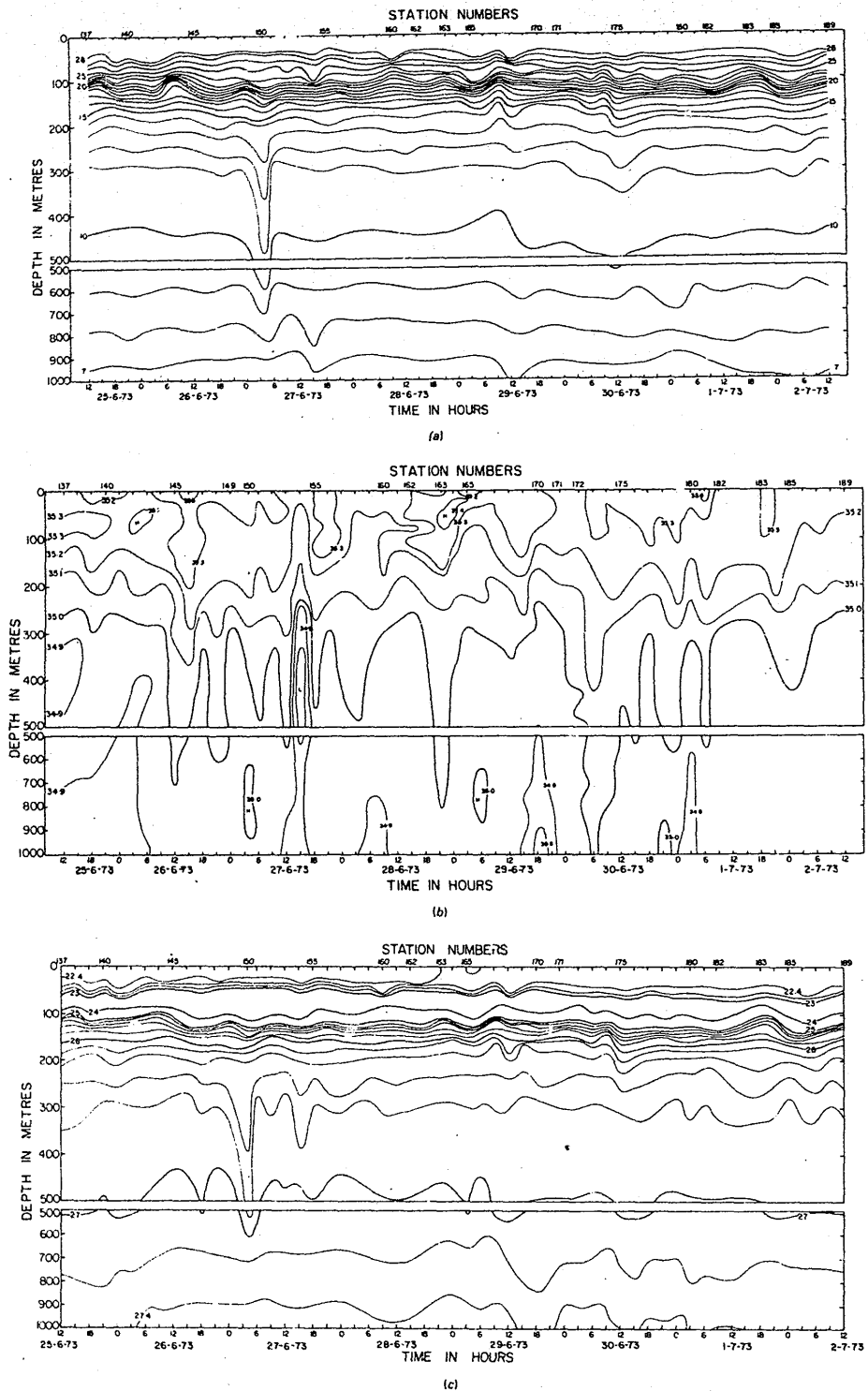


Fig. 30.5. Vertical time sections of: (a) temperature (contours labelled in $^{\circ}\text{C}$); (b) salinity (contours labelled in kg m^{-3}); and (c) density (contours labelled in kg m^{-3}) for the period 25 June to 2 July 1973.

complexity of vertical structure of the horizontal velocity field with periods of oscillation of appreciably longer timescales, as encountered during the recent observations in the equatorial Indian Ocean (Luyten and Swallow, 1976).

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