Variability of water masses in the western Indian Ocean

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Abstract. In 1987, conductivity-temperature-depth and current data were collected in two oceanographic surveys carried out around the Indian Ocean coral atolls of Aldabra (46° 20' E, 9° 25' S) and Cosmoledo (47° 30' E, 9° 45' S) between April and July. During the surveys, significant changes were observed in the temperature and salinity of the upper layers. From temperature-salinity analysis, the dominant water masses in the upper layers (0–400 m) were categorized and their origin determined. During the first cruise, TS characteristics changed only slightly. Low salinity waters ($S = 34.5$ – 34.6 and $T = 28^\circ$ – 30°C), brought from the east by the South Equatorial Current, were dominant in the surface layers. During the second cruise, the surface waters were saltier and cooler ($S = 35.1$ and $T = 25^\circ$ – 26°C) and more homogeneous in the upper 200 m as a result of a greater admixture of a southern water mass. Seasonal cooling at this time was responsible for a deeper surface mixed layer. Near the end of the cruise, TS conditions changed suddenly due to an invasion of southern subtropical water masses in the layers above 200 m. Current meter records were dominated by the regional 50-day oscillation and higher-frequency variability and did not show the expected increase in strength of the South Equatorial Current to indicate onset of the southwest monsoon. The water mass changes were not correlated with changes in the local currents and were probably caused by advection of patches by the large-scale flow.

1. Introduction

The western Indian Ocean is an area of great interest because of the seasonal monsoon which provokes dramatic reversals in winds and currents along the Somali and Arabian coasts [Luther and O'Brien, 1985] and at the equator [Wyrki, 1973a; Knox, 1976]. The water masses in the western Indian Ocean have been studied by Warren *et al.* [1966], Wyrki [1971], Magnier and Piton [1974], and, more recently, You and Tomczak [1993]. In the northwest Indian Ocean, high-salinity waters occur as a result of excess evaporation over precipitation in the Red Sea, Arabian Sea, and Persian Gulf. They can be traced as they sink and spread out from their source regions [Quadfasel and Schott, 1982; Swallow *et al.*, 1983]. The low-salinity waters in the western Indian Ocean are brought from the eastern Indian Ocean by the South Equatorial Current and from the southern hemisphere by sinking in the subtropical convergence near 40°S [Warren *et al.*, 1966; Wyrki, 1971]. Between 5 and 12°S, a front separating the northern and southern water masses marks the separation between the influence of the monsoon system and the subtropical gyre [Wyrki, 1973b]. The predominantly zonal currents along the equator prevent any general

meridional exchange in the upper layers between the northern and southern regimes, except at the eastern and western boundaries.

In 1987, two oceanographic surveys were carried out in the South Equatorial Current in the area 7° to 10°S and 45° to 54°E (Figure 1). The coral atolls of Aldabra and Cosmoledo were investigated as case studies of the island mass effect [Heywood *et al.*, 1990]. It was evident that the area was affected by a 50-day oscillation in currents [Heywood *et al.*, 1994]. During the course of the two surveys (April–May and June–July), significant changes occurred in the water mass structure of the upper layers. The two cruises took place at the time of transition from the northeast to southwest monsoon circulations (Figures 1a and 1b), when a significant strengthening of the South Equatorial Current is expected. In this paper, the dominant water masses in the upper 400 m are categorized, their changes in time are documented, and the causes of the changes are investigated.

2. Observations

Hydrographic data were obtained during RRS *Charles Darwin* cruises 22 and 24 in the area around Aldabra (9° 25' S, 46° 20' E) and Cosmoledo (9° 45' S, 47° 30' E) (Figures 1a and 1b). Physical and chemical properties of the water column were measured to a maximum depth of 400 m using Neil Brown Mark III conductivity-temperature-depth probe (CTD) and General Oceanic rosette sampler. During cruise 22 (April 18 to May 3, 1987), 131 CTD stations were occupied around the islands (Figure 1c). An Aanderaa current meter array, W2,

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Figure 1. Study area in the western tropical Indian Ocean and schematic representation of the circulation during (a) the northeast monsoon and (b) the southwest monsoon. Hydrographic station positions are marked by plusses for (c) cruise 22 and (d) cruise 24. The position of the mooring W2 is shown by solid squares.

was deployed with six current meters in deep water (4000 m) to the west of Aldabra (Figure 1c and 1d). The upper three current meter levels were 80, 130, and 330 m. Current data in this paper have been low-pass filtered to remove the relatively small tidal component and decimated to 6-hour intervals.

The cruise 24 survey (June 19 to July 12, 1987) comprised 144 stations around Aldabra, at which 189 CTD casts were made (Figure 1d). The current meter moorings deployed during cruise 22 were recovered. During both cruises acoustic doppler current profiler (ADCP) data were obtained with an RD Instruments 150-kHz ship mounted system. Data were checked for erroneous values due to ship's gyro oscillations following turns, corrected for misorientation of the ADCP transducer and amplification factor, and averaged over 10-min intervals as described by Heywood *et al.* [1990]. Data from the first bin were rejected so that current maps shown correspond to 19 m depth.

CTD performance was checked against water bottle salinity samples (one or two on each cast), using an Autosol salinometer to an accuracy 0.005 on the practical salinity scale, and temperature, using reversing thermometer (at two levels on each cast) to an accuracy of 0.02°C. The comparisons indicated that the CTD system functioned well.

3. Water Masses of Aldabra

Aldabra is situated in the transitional zone separating the Indian Ocean into distinct northern and southern regimes. In this region, highly saline water masses originating in the north interact with water masses of lower salinity, from the southern and eastern part of the Indian Ocean. The resulting mixture of these water masses, identified as Western Equatorial Indian

Ocean Water [Wyrtki, 1971] (although now recognized not to form in the western equatorial Indian Ocean), acts as a boundary between water masses from the northern and southern hemispheres throughout the depth range of 100 to 1000 m.

Temperature and salinity data for all the stations of cruises 22 and 24 are shown in Figure 2 with the recognized water masses of the Indian Ocean superimposed [Warren *et al.*, 1966; Wyrtki, 1971]. The water properties ranged from 30°C and 34.5 at the surface to 10°C and 34.8 at 400 m. At any particular depth, there was considerable variability in the characteristics. The salinity maximum of 35.4 observed at the density anomaly surface $\gamma = 25.7 \text{ kg m}^{-3}$ is compatible with the influence of subtropical water. The overall characteristics in the upper 300 m layer around Aldabra correspond to Western Equatorial Indian Ocean Water diluted by lower-salinity eastern waters. While the historical TS curves provide a general context in which to examine the present data, they were sampled with water bottles generally at standard depths, and they clearly therefore cannot be used to make detailed comparisons with our high vertical resolution CTD data. Some of the salinity extrema found around Aldabra and discussed below are of small enough vertical extent to be undetectable with bottle sampling.

3.1. Water Masses Cruise 22

3.1.1. Near-surface layer. The TS data for cruise 22 are plotted in Figure 3 with an expanded salinity scale. The scatter in the data was largely due to spatial variability, but five water masses can be recognized in the upper 350 m layer. A surface water mass of low salinities (34.5–34.6) and high temperatures (29°–30°C) is observed (Figure 3). These low salinities derive from at least two circumstances. One is the influx through the

Figure 1. (continued)

Indonesian Archipelago of low-salinity water which is then carried westward by the South Equatorial Current. The other is the excess of precipitation over evaporation, which characterizes the northeastern part of the Indian Ocean (Bay of Bengal) and the zone 0° to 10° S, from 50° to 110° E. Water from the Bay of Bengal can be advected southward then westward in the South Equatorial Current where it mixes with water of Indonesian origin.

3.1.2. Subsurface layer. Beneath the low-salinity surface water, remnants of two water masses form the shallow salinity maximum: Arabian Sea Water (ASW) and Subtropical Surface Water (SSW) of the southern subtropical gyre seen in Figure 3. From the northern part of the Arabian Sea, where salinities are higher than 36.5, the core layer of the shallow salinity maximum spreads south and later east and can be traced to 10° S [Wyrki, 1971]. In the TS composite, traces of this core occur between the temperatures 21° – 24° C and salinities 35.0–35.1 ($\gamma = 24.0$ – 24.5 kg m^{-3}) but are obscured by the scatter of points.

The weak maxima are evident in individual profiles, e.g., station 72 (Figures 4a and 4c).

SSW is formed in the austral subtropical anticyclonic gyre under the influence of an excess of evaporation over precipitation. The highest surface salinities (~ 35.8), which are found in a belt between 25° and 35° S, extend northward near $\gamma = 26.0 \text{ kg m}^{-3}$, below the surface water into latitudes 10° to 15° S. The eroded core of SSW can be seen clearly in the scatter diagram ($\gamma = 26.0 \text{ kg m}^{-3}$). The maximum salinities correspond to 35.1–35.2, about 0.5 less than in the area of origin, with temperature close to 15° C.

3.1.3. Central water. Below the SSW, an isolated salinity maximum (SM in Figure 3) appears near the $\gamma = 26.4 \text{ kg m}^{-3}$ surface, close to the properties of Persian Gulf Water (PGW), which spreads chiefly along the west coast of India to the south. It is also found along the Somali coast, where it might spread during the northeast monsoon [Wyrki, 1971], though Currie [1992] suggested that its spread to the southwest is inhibited

Figure 2. TS diagram for all the stations of cruises 22 and 24 with Indian Ocean water masses superimposed (based on Wyrtki, [1971]). Abbreviations are SSW, Subtropical Surface Water; EW, Equatorial Water; SICW, South Indian Central Water; AIW, Antarctic Intermediate Water. Dotted curves show density anomaly in kilograms per cubic meter.

during the southwest monsoon. To find traces of PGW so far removed south of its source would be remarkable. The isolated salinity maximum was observed only at a few westernmost stations (108 to 113, Figures 4a and 4b) and had not been evident in the same location a week earlier in the cruise

Figure 3 TS diagram for all the stations of cruise 22 (April 18 to May 3, 1987). Abbreviations are ASW, Arabian Sea Water; SSW, Subtropical Surface Water; SM, salinity maximum, see text for discussion; SICW, South Indian Central Water; AIW, Antarctic Intermediate Water; RSW, Red Sea Water. Dotted curves show density anomaly in kilograms per cubic meter.

Figure 4. (a) Location of selected stations downstream of Aldabra during cruise 22 and their TS diagrams showing (b) the isolated salinity maximum (SM) and (c) the intermediate water masses AIW and RSW.

(stations 72 and 73, Figures 4a and 4c). The maximum salinities in the feature are 35.17–35.27 with temperatures of 13°–14°C at depths near 230 m.

Although advection by the Somali Current during the northeast monsoon could be responsible for its occurrence, the density anomaly ($\gamma = 26.4$ – 26.5 kg m^{-3}) of the salinity maximum at stations 108–113 seems rather low for Persian Gulf Water (26.6 kg m^{-3}). Its depth of occurrence at 230 m is also shallower than the 340 m which might be expected. An alternative interpretation is that this salinity maximum originates in the tongue of high salinities extending northward along the east coast of Madagascar. *Magnier and Piton* [1974] showed the tongue extends westward beyond the tip of Madagascar as a narrow ribbon of high salinity, low nitrate, and high oxygen. This water forms part of the upper South Indian Central Water (SICW in Figure 3), but its salinity is higher than found further east. High values of oxygen were found in the salinity maximum layer in a number of uncalibrated oxygen profiles made at stations 108–113. The most likely explanation therefore is that the maximum is due simply to the intrusion of the relatively high salinity and oxygen SICW beneath the lower salinity and oxygen waters in the shallower layers.

The SICW is found generally at levels below ~200 m and is characterized by salinity decreasing linearly with depth. It corresponds to the Indian Ocean Central Water [*Sverdrup et al.*, 1942], but was named South Indian Central Water by *Gordon*

et al. [1987]. This water originates at the subtropical convergence near 40°S and represents the body of water of which the SSW is the upper limit (Figure 3). In the diagram, this water spans the interval in a straight line from the SSW to the intermediate salinity minimum, with temperatures between 8° and 15°C and salinities between 34.7 and 35.2, with a density range from $\gamma = 26.5$ to 27.0 kg m^{-3} (300 to 400 m). SICW (most clearly shown on the 26.7 kg m^{-3} density anomaly surface [You and Tomczak, 1993]) is dominant south of the front at 10°S, where it recirculates in the subtropical gyre, traveling to the west south of 10°S. Some extends north around the tip of Madagascar, as described above, and a small part enters the northern Indian Ocean via the western boundary current during the southwest monsoon. There is no evidence in our data of the less saline Australasian Mediterranean water (formed from Pacific waters in the far east of the Indian Ocean [You and Tomczak, 1993]) influencing or displacing SICW.

3.1.4. Intermediate layer. CTD stations 72, 73, and 93, made to ~1000 m (Figures 4a and 4c), show traces of the Antarctic Intermediate Water salinity minimum and the Red Sea Water salinity maximum (also seen in Figure 3). Antarctic Intermediate Water (AIW), formed at the Antarctic Convergence near 50°S, sinks and spreads north near the $\gamma = 27.3 \text{ kg m}^{-3}$ surface, which lies near 10°S in the depth range of 700–800 m. This salinity minimum is observed at two stations (73 and 93), which are located around 30 km to the northwest of Aldabra. In the TS diagram (Figure 3), the core layer of this minimum lies at $\gamma = 27.25 \text{ kg m}^{-3}$ (740 m) with temperatures of 6.3°C and salinity of 34.764. However, AIW is not observed in the TS diagram of station 72, only ~50 km northwest of stations 73 and 93, indicative of horizontal inhomogeneity at these depths.

A feature common to the deeper stations 72 and 73 is the presence of traces of more saline water from the Red Sea Water (RSW). Station 93 was not deep enough to reveal any RSW influence. Clearly, intrusions or lenses of RSW are displacing and/or overriding AIW. RSW and AIW occur on the same density surface and mix isopycnically to form a water mass that is denser than either of the constituents [Premchand *et al.*, 1986], forming an isohaline layer. On leaving the Gulf of Aden, the main branch of RSW flows south along the Somali coast as a narrow band 100–350 km wide [Quadfasel and Schott, 1982]. Shapiro and Meschanov [1991] suggest that isolated lenses of RSW (Reddies) may be shed from the narrow streams of RSW, so it is possible that we encountered one of these. In the western Indian Ocean the salinity maximum related to the RSW is normally traceable to 25°S, concentrated along the western boundary, its core salinity decreasing from 38 in the Red Sea to about 34.7 in the Mozambique Channel [Wyrki, 1971]. Gründlingh [1985] observed that RSW is clearly present south of the Mozambique Channel, a tongue of order 50 km wide and a few hundred meters thick, at depths below 1000 m, to at least 30°S. Southward penetration is likely to be seasonal. He also showed that RSW must leave the southward flowing core and penetrate to the east, since total quantities of RSW decrease southward. In the region downstream of Aldabra the depth of the core layer ($\gamma = 27.35 \text{ kg m}^{-3}$) increases from 840 m in the westernmost station to 900 m in the more eastern station 73. The temperature and salinity in the core decrease from station 72 ($T = 6.85^\circ\text{C}$ and $S = 34.85$) to station 73 ($T = 6.36^\circ\text{C}$ and $S = 34.82$), which indicates how the core weakens with distance from the African coast.

3.1.5. Regional water masses. The TS properties for cruise 22 are compared with TS curves of stations distributed meridi-

Figure 5. Comparison between the TS diagram for cruise 22 and stations distributed (a) zonally to the east of Aldabra and (b) meridionally in the western Indian Ocean basins. The historical stations are from the Levitus data set as used by Gordon [1986].

onally in the western Indian Ocean basins and zonally to the east of Aldabra along 10°S taken from the Levitus data set as used by Gordon [1986]. The comparison with the stations along 10°S (Figure 5a) shows that the TS characteristics fall in between those of the eastern and western water masses which increase in salinity from east to west. The cruise 22 waters are most similar to those of the Somali Basin but are considerably less saline at all levels except in the SICW range. The characteristics below 10°C fall within the range of all the comparison stations and correspond to mixing of Red Sea and Antarctic Intermediate Waters.

3.2 Water Masses Cruise 24

3.2.1. Near-surface layers. The cruise 24 TS diagram (Figure 6) shows marked changes from the earlier situation (Figure 3). In the surface waters, the temperature has decreased by more than 4°C as the onset of austral winter has cooled the surface layers. The mixed layer depth increased from typical values of 0 to 30 m during the first cruise to 50 to 90 m during the second. Two characteristic TS profiles, both different to those observed previously, can be delineated for this cruise. The first, which was observed during most of the period, presents a weak salinity gradient with salinities (higher than in the earlier cruise) increasing from 35.1 to 35.2 between the surface and 200 m. Later in the cruise, a second characteristic profile emerged, which shows salinity increasing rapidly from about 34.8 at the surface to a sharp maximum of 35.4 at 120 m depth ($\gamma = 25.7 \text{ kg m}^{-3}$) and an equally rapid decrease at deeper levels. During the first part of the cruise, before June 25, the TS diagrams (Figure 7a) were broadly similar all around Aldabra, with only slight variations. Some eastern stations showed a low-salinity water at the surface (e.g., stations 19 and 35) which later appeared at many western stations (e.g., stations 93 and 98, Figure 7b). This thin layer of low-salinity water,

Figure 6. TS diagram for all cruise 24 conductivity-temperature-depth stations (June 19 to July 12, 1987). Abbreviations are SSW, Subtropical Surface Water; SICW, South Indian Central Water. Dotted curves show density anomaly in kilograms per cubic meter.

which must be due to recent local rainfall, produces the flat top on the TS curves which is clearly seen in the composite diagram for this cruise. In the stations northwest of Aldabra, the salinity increased gradually from 35.05 at the surface to a maximum of 35.27 at 200 m (Figure 7a, stations 12, 22, and 25). These salinity maxima are greater than those observed in cruise 22.

On and shortly after June 30, stations 57 and 61, north of Aldabra (Figure 7b), showed the same weakly stratified salinity gradient as earlier and stations west of Aldabra (e.g., station 98) still showed the sea surface temperature salinity maximum (~ 35.2) around 15°C observed there earlier in the cruise. However, marked changes can be observed south and east of the atoll. The TS curves in that area show lower surface salinities (34.9) and higher values (35.1) in the salinity maximum than the more homogeneous layer (Figure 7a) which previously occupied the upper 200 m.

All stations subsequent to July 8 around Aldabra present this second characteristic TS profile, initially observed only in the southeast. In later profiles, the highly saline SSW dominating the TS profiles in the depths from 60 to 160 m (Figure 7b, 128 and 137) was even more pronounced. The core layer lies at $\gamma = 25.7 \text{ kg m}^{-3}$ with salinities around 35.35 to 35.4 and temperatures around 14° to 20°C.

At the end of the cruise, a section was carried out northwest of Aldabra (Figure 8, stations 142 to 148) which together with stations 128, 138, and 141 shows the complexity of the spreading of the southern water mass in the locality. At the eastern stations (128, 141, 145, and 146), the TS properties are characteristic of SSW, but the most southwestern stations (142 and 143) still exhibit little salinity gradient. It seems likely that the SSW is carried by the southern branch of the South Equatorial Current diverted northward by Madagascar. After crossing the northern tip of Madagascar, these waters spread as a tongue westward into the surrounding body of more northern characteristic waters. Consequently, the spatial distribution pattern of the masses is complicated. A vertical salinity section of the stations 142 to 146 shows clearly the presence, more pronounced in the north, of SSW at 100-125 m (Figure 9). The shallow salinity maximum is more saline and colder than during the International Indian Ocean Expedition, which implies a northward shift of the current system during Cruise 24. However, it may simply be that maximum was less well defined by the relatively sparse vertical and horizontal sampling of the earlier data.

3.2.2. Regional water masses. The cruise 24 TS scatter diagram is superimposed onto data from stations from the western Indian Ocean (Figure 10b) and to the east of Aldabra along 10°S (Figure 10a). Along 10° (Figure 10a) the TS data lie mostly between the Somali Basin profile and the profiles further east. The exception to this is the unusually pure core of SSW ($\gamma = 25.5 \text{ kg m}^{-3}$) which is significantly more saline than any of the other profiles. The example profiles from the western Indian Ocean (Figure 10b) show that this saline water may be found in the Mozambique and Madagascar Basins. Most of the earlier TS data from cruise 24 are less saline than any of the western Indian Ocean Basins, implying that fresher waters were being brought to the area from further east.

4. Currents and Wind

Detided current meter records at the upper three levels on the mooring some 80 km northwest of Aldabra from the period during and between the cruises showed the presence of the 50-

Figure 7. TS diagrams for selected stations during two cruise 24 surveys (a) June 23 - 27 (b) June 29 - July 2.

Figure 8. TS diagrams for stations northwest of Aldabra showing the restricted spread of southern SSW salinity maximum through the area.

day oscillation with higher frequency variability, stronger at the uppermost level, superimposed (Figure 11). The oscillation, also observed on deeper current meters at the same mooring and on a second mooring, was identified as a baroclinic Rossby wave by Heywood *et al.* [1994]. Examination of the variability of temperature and salinity at the current meters demonstrated no correlation between the currents and the water masses present. The nature of the variability of the water masses is more indicative of advection of horizontal inhomogeneities past the mooring than of a TS field fluctuating back and forth with a 50-day or other periodicity.

Overall, the currents were westward on average. The mean and standard deviation of the zonal component decreased from

Figure 9. Vertical salinity section northwest of Aldabra during cruise 24 showing stronger SSW maximum to the north. Station positions and TS curves are shown in Figure 8.

Indian Ocean 10 °S
 — 02 °S, 50 °E Somali Basin
 — 10 °S, 66 °E
 — 10 °S, 80 °E
 — 10 °S, 96 °E

Western Indian Ocean
 — 02 °S, 50 °E Somali Basin
 — 20 °S, 42 °E Mozambique Channel
 — 25 °S, 52 °E Madagascar Basin
 — 13 °S, 56 °E Mascarene Basin

Figure 10. Comparison between the TS diagram for cruise 24 and stations distributed (a) zonally to the east of Aldabra and (b) meridionally in the western Indian Ocean basins. The historical stations are from the Levitus data set as used by Gordon [1986].

Figure 11. Wind measured on Aldabra Atoll and currents at 80, 130, and 330 m depth on W1 mooring 80 km west of the island. The periods of the two cruises are indicated. The vectors are drawn so that north is vertically up the page.

$16(\pm 17) \text{ cm s}^{-1}$ at 80 m to $2(\pm 15) \text{ cm s}^{-1}$ at 330 m, while the mean meridional components were less than $1(\pm 15) \text{ cm s}^{-1}$. The prevailing currents during the cruise periods were quite different. The mooring was not deployed until near the end of the first cruise (days 108–123), at which time flow in the upper layers was predominantly northward. During the second (days 170–193), the flow at 80 m was predominantly toward the west with several days of northward flow prior to July 4 (Day 185). At 130 and 330 m, there was little or no indication of the northward episode, and the flow changed from slightly north of westward to southwestward around June 30 (Day 180). None of the current meters was above the pycnocline, so surface motion was not sampled.

The current records did not show the increase in zonal transport of the South Equatorial Current suggested by the historical ships' drift analysis of Cutler and Swallow [1984] at this time of year, normally the onset of the southwest monsoon. Although there was a temporary enhancement of northwestward flow in mid-June (around day 160), there was no clear trend apparent. The wind recorded on Aldabra (Figure 11, top) was weak prior to the first cruise, then relatively constant towards the northwest until the second cruise, when two northward wind pulses occurred, the later one associated with northward flow

Figure 12. Surface temperature in degrees Celsius, salinity, and current velocity in centimeters per second during four surveys around Aldabra: (a-c) June 23 - 27, (d-f) June 27 - 29, (g-i) June 2 - 4, (j-l) July 4 - 6. Near-surface currents.

Figure 12. (continued)

at the uppermost current meter. Again, there was no clear trend apparent during the observation period including the cruises, and the observed increase in mixed layer depth between cruises was more due to convective overturn than direct wind action. The South Equatorial Current may have therefore been weaker than average during 1987, an El Niño year. *Anderson and Carrington* [1993] report anomalously weak flow of the South Equatorial Current until July 1987 in their results from a numerical model driven by observed winds.

5. Surface Characteristics: Cruise 24

Surface temperature and salinity were monitored continuously during the later cruise, together with near-surface (19 m) currents from the shipmounted acoustic doppler current profiler. These show clearly the temporal changes of water mass as fronts are advected past Aldabra. Initially (Figures 12a, 12b, and 12c; June 23–27) the current is weak and generally from the east or southeast. Warmer ($>25.5^{\circ}\text{C}$), fresher (<35.10) water is found around Aldabra, while cooler, more saline (>35.14) waters are seen at the eastern end of the area mapped.

By the time of the following survey, June 27–29 (Figures 12d, 12e, and 12f), a north-south band (salinity >35.14) is seen around the island: to the west, a front marks the boundary with fresher, warm water, while to the east, another front marks the boundary with fresher, cooler ($<25.0^{\circ}\text{C}$) water. The current flows more strongly to the north, parallel to these fronts, as seen in the 80-m current meter record at this time. The stronger northward wind at this time has mixed down the thin layer of low-salinity waters into the mixed layer beneath. This is also indicated by the general decrease in surface temperature between the surveys.

In the next sequence (Figures 12g, 12h, and 12i; June 29 – July 2), a particularly sharp front in salinity (34.92–35.06) is situated east-west across the island, as saline surface waters are replaced by water much fresher (<35.0) than any seen before. There is little gradient in surface temperature. The currents appear transitional, during the several days taken to complete the survey, between the earlier northward episode and a return to westward flow. Strong currents flow to the west along the salinity front. By the time of the final survey (Figures 12j, 12k, and 12l; July 4–6) the fresh (34.81–34.90) surface water from the south has almost completely replaced the saline water initially seen in the area, and the currents have returned to their original westward direction. This invasion of slightly cooler, low-salinity surface water clearly corresponds to the major change in the form of the TS curves observed late in the cruise and described above. Although this change coincided roughly with a northward pulse of wind, it could not be ascribed to wind mixing. The surface mixed layer did deepen at this time, but the layers down to almost 300 m were affected by the changes in TS characteristics.

The sequence of near-surface ADCP current maps shows essentially the same variation as observed at the 80-m current meter mooring west of Aldabra. The greater spatial inhomogeneity of currents seen in the first and third maps reflects the longer sampling period needed to make CTD surveys in contrast to the rapid underway surveys.

6. Conclusions

The present data set, one of the most detailed surveys in the central Indian Ocean, shows that

1. Waters in the region are a mixture of the major recognized water masses of the North and South Indian Ocean but are subject to rapid and major fluctuations.

2. During April 1987 the near-surface layers were occupied by water less saline than expected of the western region.

3. In July of the same year, similar conditions were, within a few days, disrupted by the sudden entry into the region of characteristics more typical of the Southern Subtropical Water originating further to the south.

4. These and other less dramatic changes in the dominant water masses were unrelated to the 50 day oscillation of currents observed during this study and known to be common in the area.

Although this study was conceived to investigate the effect of flow past an island obstacle, it has also demonstrated the inherent complexity of open ocean conditions in the region. The major fluctuations of currents, governed partly by the widespread 50-day oscillation but also occurring on shorter timescales, obscure any determination of the supposed background South Equatorial Current. Moreover, the strong changes in water masses occur rapidly and without any clear relation to local dynamic features. Although 1987 may have been an anomalous year, which would explain the apparent weakness of the westward flow of the South Equatorial Current, the shifts in water mass appear more likely due to advection of large scale patches rather than to anomalous currents.

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