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SOME HYDROGRAPHIC OBSERVATIONS IN THE NORTHWESTERN INDIAN OCEAN DURING THE EARLY SW-MONSOON, 1983

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ABSTRACT

Temperature profile measurements along sections in the northwestern Indian Ocean shortly after the onset of the SW-monsoon 1983 reveal a hydrographic structure typical of pre-monsoon conditions. Thus, away from the coasts the oceans response to windforcing is much less dramatic than in coastal regimes where a reaction within a few days has been observed previously. Strong interleaving of watermasses was observed across a salinity front at intermediate depths in the Northern Somali Basin. The vertical length scale of the layers was found to be proportional to the ratio between the mean salinity gradient and the vertical stability which compares well with theoretical predictions of the characteristics of double diffusive intrusions.

Key-words : Hydrography, Temperature profile, SW Monsoon, Indian Ocean.

During her maiden cruise the RV *Sagar Kanya* conducted a geological/geophysical survey in the northwestern Indian Ocean. Although the routing was less than ideal from a physical oceanographers point of view, a chance was taken to carry out hydrographic measurements whenever time permitted. In this note we report temperature profile measurements made enroute between geophysical survey sites and CTD-measurements carried out in the northern Somali Basin. The location of the sections and stations covered between 4 and 23 June 1983 are shown in Figure 1.

Development of the windfield

Standard synoptic meteorological observations were taken on board at 3 hourly intervals during the entire cruise. Figure 2 shows stickplots of the windvectors. During the first week of June they show southwesterly winds with moderate speeds around 5m/s. During this time the ship was located in the vicinity of the Findlater Jet where it leaves the coast and veers out into the Arabian Sea (Findlater, 1971). Thus by 7 June the SW-monsoon had not reached its final strength which is characterized through wind speeds of more than 20 m/s in this area.

On 8–9 June wind speeds increased rapidly from less than 7 m/s to more than 13 m/s. By this time the vessel had already completed half of the Somali coastal section (Fig. 1) and was located outside the immediate region of the Findlater Jet. So one can expect the wind speeds there to have increased even further. Of course, it is difficult to pin-down a signal in time

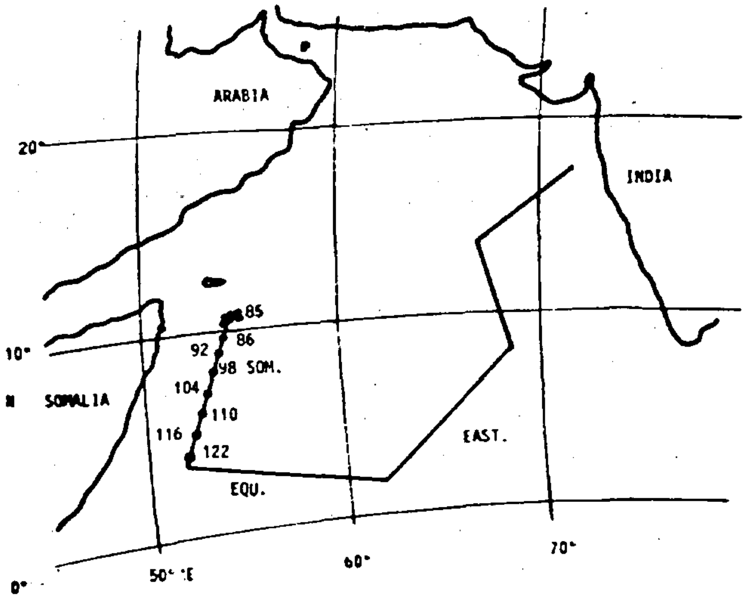

Fig. 1. Location of XBT sections in northwestern Indian Ocean, R V "Sagar Kanya", 6 — 23 June 1983. CTD stations along Somali section are indicated by heavy dots.

from a platform moving in a field of strong horizontal gradients. However, the increase of wind speed by a factor of two in a spatial gradient where it should decrease by a factor of two suggests that the onset of strong monsoon winds took place around 9 June. The remainder of the wind observations after 9 June in the eastern part of the Arabian Sea (Fig. 2) agree well with mean climatological data of the fully developed SW-monsoon (e.g. KMNI, 1952; Findlater, 1971). In summary, the observations suggest that the onset of the SW-monsoon in 1983 was around 9 June. This onset took place only a few days later than the mean climatological onset around 6 June (Fieux and Stommel, 1977).

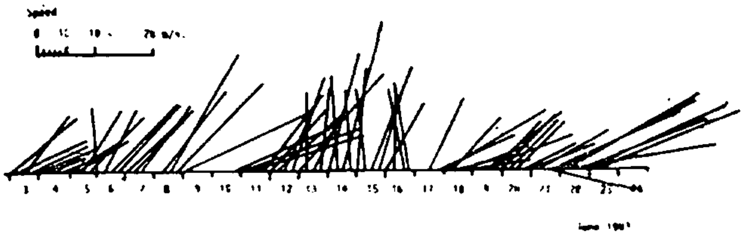

Fig. 2. Stickplots of windvectors as measured aboard R V "Sagar Kanya", 3 — 23 June 1984. Sticks are pointing into the direction towards which the wind is blowing. North is upwards.

Temperature sections

The temperature profile measurements were obtained by use of expendable bathythermographs (XBT's, Sippican 750 m and 1800 m probes). The distribution of temperature along the three sections, Somali, Equatorial and Eastern, is plotted in Figure 3. In general the temperature sections are typical of premonsoon conditions, exhibiting relatively little mesoscale variability.

Somali section: The sloping of isotherms indicates onshore flow near 5 °N and weak offshore flow north of this latitude, typical for the pre-monsoon situation when the northern Somali gyre has not spun up yet. The strong uplifting of isotherms near 4° N suggests the existence of a southern eddy as observed during the 1979 FGGE-INDEX survey (Swallow, Molinari, Bruce, Brown and Evans, 1983).

Equatorial section: The relatively shallow thermocline level (90–100 m) and high sea surface temperature (> 29°C) are again typical for premonsoon conditions when the eastward equatorial jet is still running (Wyrtki, 1973; Quadfasel, 1982a).

Eastern section: The boundary of the equatorial domain is clearly marked by the spreading of isotherms in the thermocline near 3° N. The thermocline topography is almost flat up to about 8°–9° N and slopes downward north of this region, indicating westerly flow. Near the Indian coast isotherms slope upward again in conjunction with a broad southward flow parallel to the coast.

Near the core of the Findlater Jet (here at about 14° N) sea surface temperatures are below 29 °C. Two weeks earlier, right after the second monsoon onset, SST in this region was 30.2 °C (data from standard ship observations, Huber, DHI, pers. com.). This cooling of 1.5 °C which corresponds to about one third of the total cooling during the SW-monsoon, is certainly due to local mixing effects and not caused by advection of cold upwelling water from the East African and Arabian coasts.

A comparison of mean climatological surface currents and surface currents derived from geostrophic estimates confirm that during this cruise the ocean had not reacted to the second monsoon onset yet. Plotted in Figure 4 are mean surface current vectors for May and June from the Dutch Atlas (KMNI, 1952) together with the cross section geostrophic surface current of June 1983. The latter was calculated using the depths of the 20 °C – isotherm which was found to be highly correlated with the dynamic height anomaly (0–1500 dbar) in the western Indian Ocean (Quadfasel, 1982b). Although deviations between vectors are large — which one expects as a single survey is compared with long term mean values and Ekman drift has been neglected — it is evident that the overrall resemblance of our data with the pre-monsoon data of May is better than with the June currents. In particular, the strong SW-monsoon current the equator and 12° N had not developed yet.

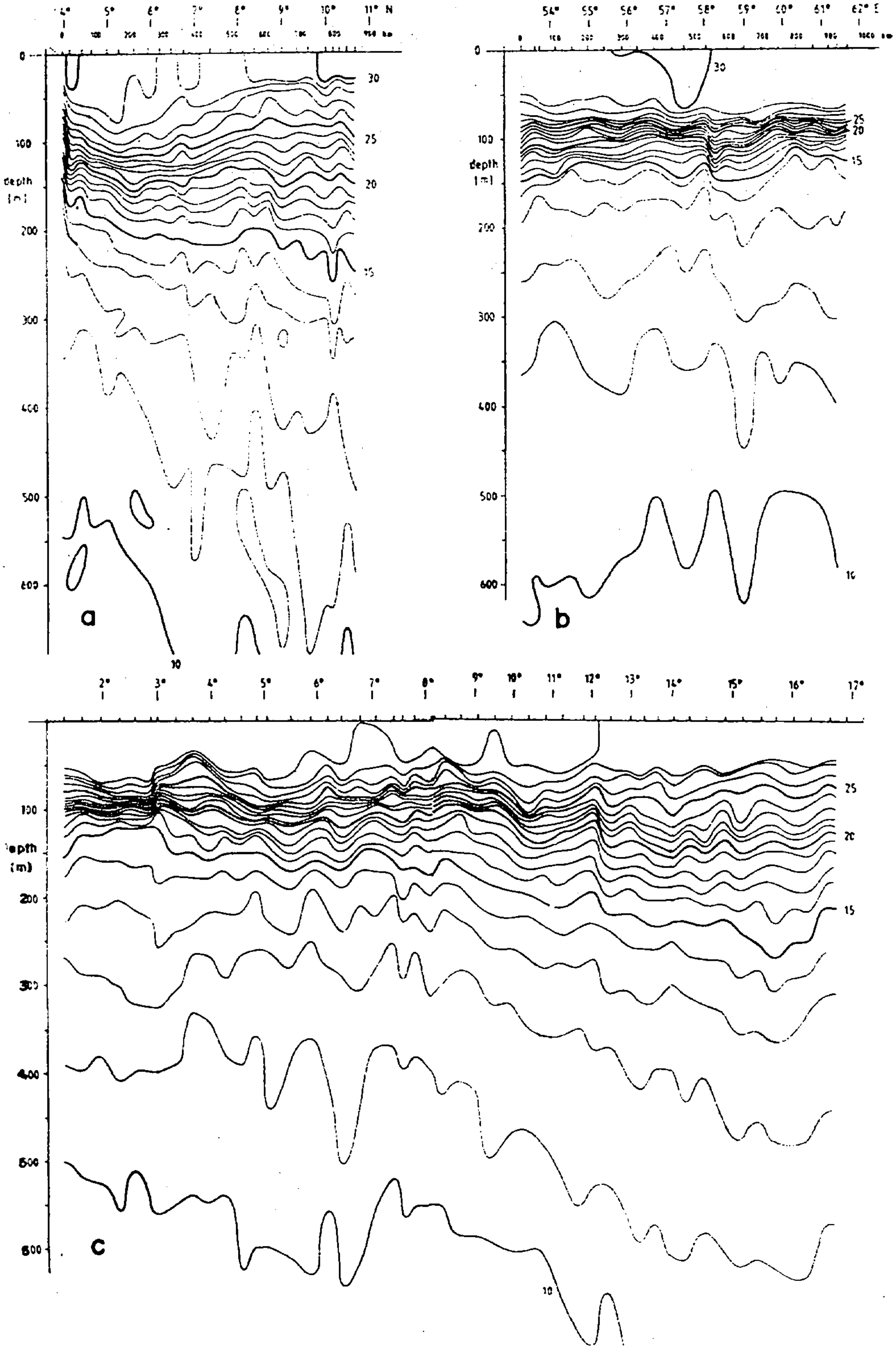

Fig. 3. Vertical distribution of temperature along XBT sections; (See Fig. 1 for

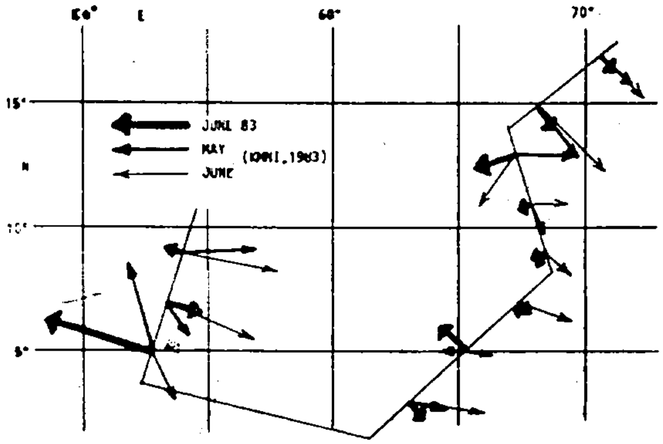

Fig. 4. Comparison of mean climatological surface currents of May and June (KMNI, 1982) with geostrophic surface flow derived from thermocline topography.

Fine structure observations

Vertical profiles of temparature and salinity down to a depth of 1500 m were measured in the northern Somali Basin (Stn. 85/1–11) and along the Somali coastal section (Stn 86–112, Fig. 1), employing a ME-Multisonde CTD. Accuracy of the measurement is ± 0.02°C for temperature and ± 0.01‰ for salinity. Here we will confine our attention to the observations in the intermediate depth layers (200 – 900 m) where intrusions of high salinity water originating in the Persian Gulf and in the Red Sea are most prominent signals.

The vertical salinity distribution within this layer has often been observed to contain strong fluctuations, especially in regions where large horizontal gradients in the water mass properties exists (Federov, 1978; Quadfasel and Schott 1982). These fluctuations which have vertical scales of meters to several hundred meters have been attributed to double diffusive processes generating interleaving layers across the front (Ruddick and Turner, 1979).

Such a front was observed in the northern Somali Basin near 9° N during June 1983 survey. Figure 5 shows mean salinity profiles from stations north of 9°30′N and south of 8°N. The horizontal variability within these groups of profiles is rather small, rms deviations do not exceed 0.05‰ in the 250 – 700 m depth range. The difference between the two mean profiles is about 0.20‰ increasing slightly with increasing depth. Thus the salinity difference is significantly different from zero for most of the intermediate depth layer.

In contrast to the smooth mean profiles the salinity profile at station 92 exhibits strong fluctuations with salinity values jumping between those of the two watertypes on either side of the front (Fig. 5). The vertical extent of these layers increases from about 30 m in the upper part to more than 100 m at greater depths.

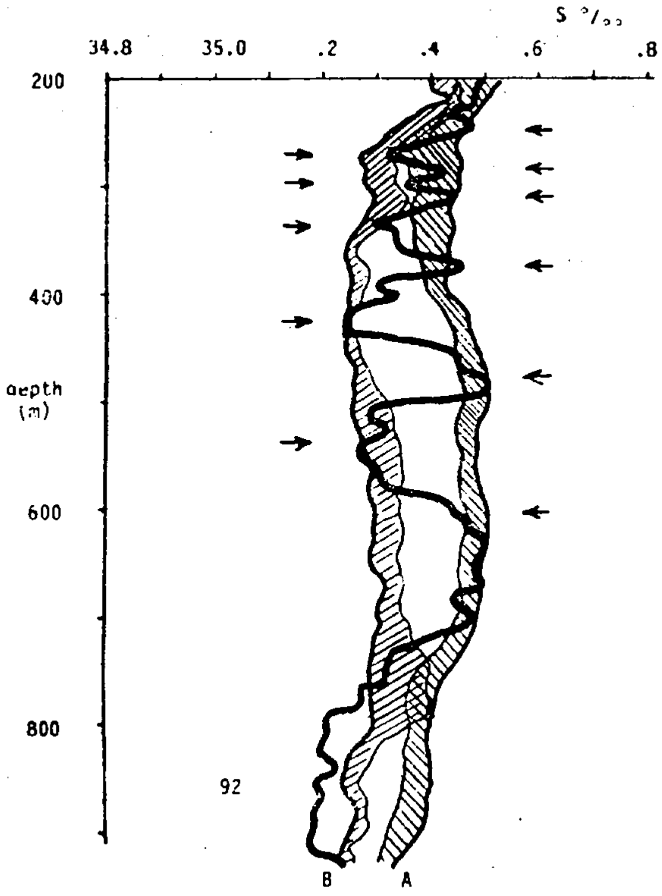

Fig. 5. Average salinity profiles in the intermediate depth layer from groups of stations north (A) and south (B) of the front near 9° N. Shading shows rms deviation of mean profiles, heavy line is the salinity profile at station 92. The arrows indicate boundaries of interleaving layers used for the fine structure calculations.

Based on energy considerations Ruddick and Turner (1979) have estimated the relation between the vertical scales (H) of such interleaving layers, the cross frontal mean salinity difference (Δs) and the stability:

$$H = \frac{3}{2} (1-n) \beta \Delta S \left(\frac{1}{\rho} \frac{d\rho}{dz} \right)^{-1} .$$

Here n is the flux ratio between heat and salt (∿ 0.56) and the saline contraction coefficient (0.78×10^{-3}). With a mean salinity difference $\Delta S = 0.20‰$ across the front and a value of stability of $10^{-6} m^{-1}$ the vertical fine structure scale H would be about 100 m, in good agreement with the layer thicknesses observed.

Between 250 and 800 m depth the actual stability decreases from $3 \times 10^{-6} m^{-1}$ to $1 \times 10^{-6} m^{-1}$. Also the mean salinity difference across the front varies between 0.15‰ and 0.25‰ with the maximum difference being reached above the core layer of the Red Sea water near 500 m depth. The effects of these variations on the layer thickness have been investigated in more detail. The results are listed in Table I. For the model calculations the actual values for stability and salinity differences derived from the two mean profiles have been taken. Over a range from 30 to 120 m, i.e. almost one order of magnitude, the agreement between observed and computed layer thicknesses is good to within 30%.

Table I. Comparison between observed and computed vertical length scale of interleaving layers.

Depth (m)	Type	$\overline{\Delta S}$ $^{0}/_{00}$	$\frac{1}{\varrho}\frac{d\varrho}{dz}$ $10^{-6}\,m^{-1}$	Layer Depth (m) computed	Layer Depth (m) observed
265	min	0.16	3.4	24	40
285	Max	0.18	3.0	31	30
300	min	0.17	2.8	31	25
320	max	0.16	2.5	33	35
345	min	0.17	2.1	41	65
385	max	0.19	1.6	63	95
430	min	0.22	1.2	95	110
490	max	0.24	1.0	117	120
550	min	0.22	1.1	107	125

These deviations are of the same magnitude as those of the laboratory experiments which Ruddick and Turner (1979) used when deriving their formula. Thus our results strongly suggest that the interleaving layers observed at the front are indeed caused by double diffusion processes.

Concerning the horizontal scales of these intrusions we have little information as the spacing of the CTD stations along the Somali section was more than 100 km. With a typical ratio of horizontal to vertical fine structure scales of 10^3 (Federov, 1978) the horizontal extent of the intrusions would be between 30 and 120 km and are therefore not resolved by our sampling. Thus one cannot expect that any coherent features to show in neighbouring profiles.

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