

# Mixed layer depth and thermocline climatology of the Arabian Sea and western equatorial Indian Ocean

T G Prasad & N Bahulayan

Physical Oceanography Division, National Institute of Oceanography, Goa 403 004, India

Received 8 December 1994; revised 9 February 1996

A band of zonally oriented ridge of mixed layer depth and thermocline base extending from African coast to the central Indian Ocean is observed between 5°S and 10°S throughout the year. Mixed layer depth and thermocline base deepen during February and March in the vicinity of equator, off Kenya due to the convergence of northward flowing East African Coastal Current and southward flowing Somali current. Power law has been used to calculate thermocline base. Characteristics of thermocline thickness resemble those of the thermocline base.

The western equatorial Indian Ocean including Arabian Sea is a region of intense air-sea interaction processes and plays a significant role in climate variability<sup>1,2</sup>. To model the ocean's climate and its interannual variability, reliable informations on the climatological space-time variability of mixed layer depths and thermocline parameters are required. Several climatological representations of SST, mixed layer depths and thermocline parameters<sup>3-5</sup> exist for the tropical Indian Ocean. Levitus<sup>6</sup> produced the climatology of sub-surface temperature and salinity structure including mixed layer depths for two months for the entire Indian Ocean as part of a global climatology. No effort has so far been made to prepare maps of mixed layer depth and thermocline climatology based on monthly mean data of temperature. Present study consists the climatological maps of monthly mean mixed layer depth and thermocline parameters using Levitus data sets for the western Indian Ocean (north of 20°S and west of 80°E). It is compared with climatology prepared by Hastenrath and Greischar<sup>4</sup>. Also a new mathematical relation (power law) is proposed for the computation of thermocline base.

## Materials and Methods

### Monthly mean data on temperature, mixed layer depth and thermocline base

Monthly mean data on temperature, mixed layer depth and thermocline base were extracted from the data sets compiled by Levitus<sup>6</sup> for the western Indian Ocean north of 20°S and west of 80°E (Fig. 1). All the data available at the National Oceanographic Data Centre (NODC), Washington upto the first quarter of 1978 were used to compile this data sets. Mixed layer depths were determined from monthly aver-

ages of temperature based on temperature criterion. The depth at which the temperature is 1°C lower than at the surface was chosen as the mixed layer depth<sup>2,7</sup>. A linear interpolation is performed between two consecutive subsurface levels where the temperature difference is 1°C. There is no universally accepted definition for the thermocline base<sup>4,7</sup>. If the vertical thermal structure profiles are not appropriately smoothed, the error of computation of thermocline base would be the length scale over which the variations is assumed. It is, therefore, always appropriate to assume a lower gradient over a smaller length scale for the thermocline base. In the present study, the base of the thermocline is defined as the depth at which gradient of temperature is less than 0.4°C over a 10 m depth interval which is equivalent to the definition given by Hastenrath and Greischar<sup>4</sup>. In

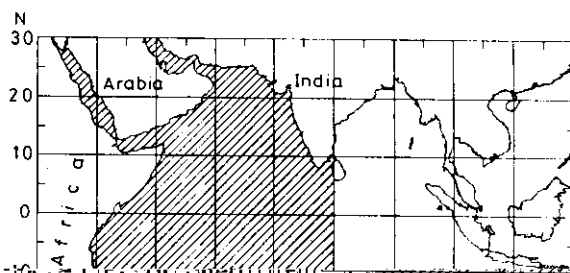


Fig. 1—Location map

order to determine the thermocline base more accurately, a power law of the form:

$$T = az^b$$

(where  $T$  is the temperature in degree centigrade,  $z$  is the depth in meters and 'a' and 'b' are constants) is proposed. This power law has been defined for the region 100 to 400 m depth where the thermocline is normally found. Temperature variability within 100 and 400 m depth has been fitted with power law and the thermocline base has been calculated with the criterion mentioned above ( $0.4^\circ\text{C}$  per 10 m). Constants  $a$  and  $b$  are determined by least square regression method. Observed profiles and fitted curves using the above power law for three selected profiles in the western Indian Ocean are presented in Fig. 2. Values of the constants 'a' and 'b' and the rms error of three profiles are given in Table 1. Thermocline thickness ( $\Delta Z = Z_b - Z_m$ , where  $Z_b$  and  $Z_m$  are the thermocline base and mixed layer depth respectively) is the vertical distance from the base to the top of the thermocline.

## Results and Discussion

### Mixed layer depth

Monthly mean mixed layer depth from January to December are presented in Fig. 3 (a-1). Throughout the year, mixed layer depth is found to be relatively shallow in the equatorial belt (between  $0^\circ$  and  $10^\circ\text{S}$ ) and deep in the southern ocean (south of  $10^\circ\text{S}$ ). However, seasonal variations in mixed layer depth are observed in the northern Indian Ocean due to seasonal variations in solar insolation and wind stress. A band of minimum mixed layer depth is located between the equator and  $10^\circ\text{S}$  during November to January. From February to April, this band shifted to around  $10^\circ\text{S}$ . Deepening of mixed layer noted along the African coast in the vicinity of equator during February-March is the manifestation of the convergence of southward flowing Somali current and northward flowing East African Coastal Current. Mixed layer depth increases gradually from equator to northern Arabian Sea during January and February.

During southwest monsoon season, mixed layer depth changes in accordance with the monsoon winds. From July to September, it shallows along the coast of Somalia, Arabia and northernmost extremity of Arabian Sea, while it grows very deep in the central Arabian Sea. The contrast between shallow mixed layer along the western boundary and the central Arabian Sea persists up to September, but vanishes by winter season.

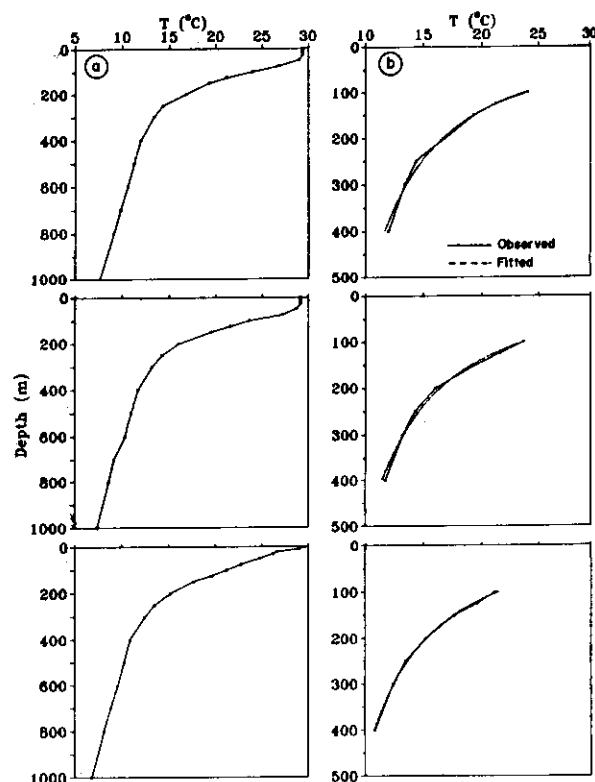


Fig. 2—Three selected profiles in the western Indian Ocean  
(a) observed profile (b) fitted curve

Table 1—Constants and rms error of three profiles

Profile No.	a	b	rms error
1	254.44	-0.5147	0.251978
2	273.77	-0.5306	0.318008
3	211.88	-0.4968	0.199597

### Thermocline base

Monthly mean maps of thermocline base from January to December are presented in Fig. 4 (a-1). Maps of thermocline base closely follow the mixed layer depth. Base of the thermocline south of  $10^\circ\text{S}$  does not show much gradient. Thermocline base is relatively shallow in a band of  $5-10^\circ\text{S}$  latitude in the western portion of basin. Further its depth increases southward and northward, and shallows in the northwestern extremity of the Arabian Sea. In winter (January to March), thermocline base deepens along the western boundary of the Arabian Sea and southwest coast of India.

During southwest monsoon (June to September) the base of the thermocline shallows along the coasts of Somalia, Arabia and west coast of India with concomitant deepening in the central Arabian Sea. This is mainly due to the development of intense upwelling along Somalia, Arabia and west coast of India. Central Arabian Sea is character-

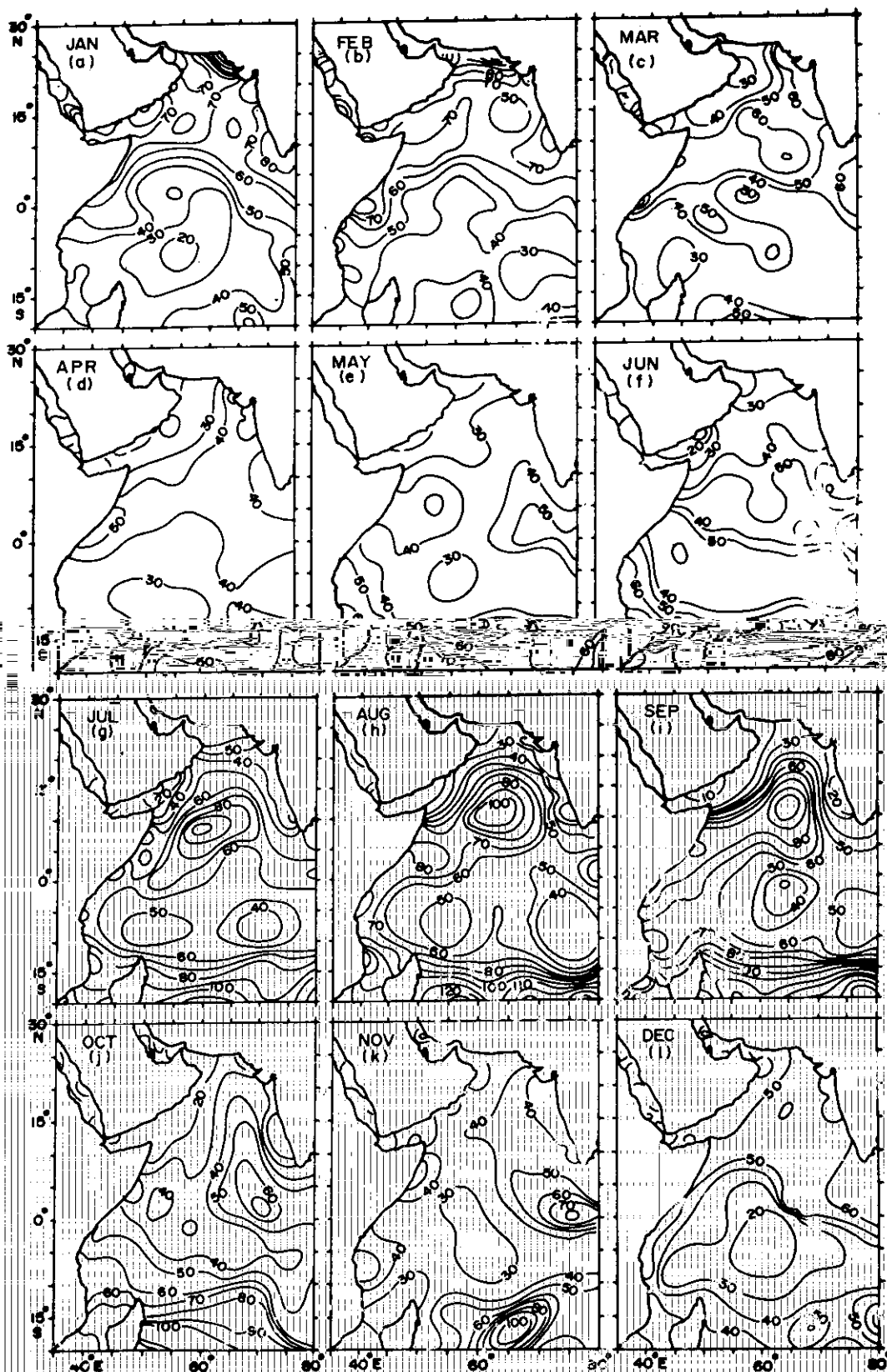


Fig. 3—Monthly maps of mixed layer depth (m)



Fig. 4—Monthly maps of base of thermocline (m)

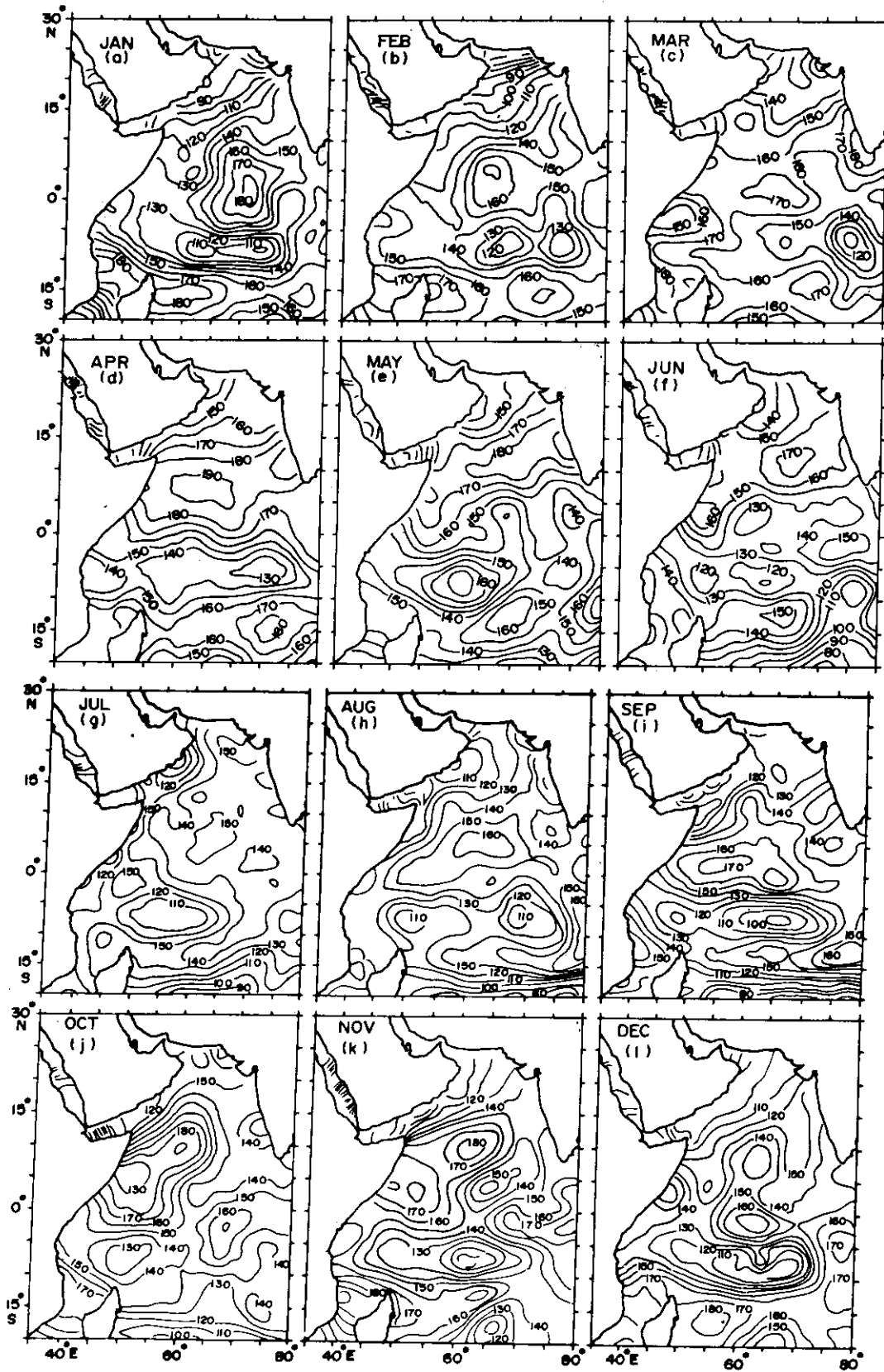


Fig. 5—Monthly maps of thermocline thickness (m)

ized by a zone of convergence with the deepest thermocline base.

#### *Thermocline thickness*

The thermocline thickness from January to December is presented in Fig. 5 (a-1). Characteristics of thermocline thickness resemble those of the depth of the thermocline base. During January and February, the thermocline thickness is thin in a band between 0-10°S, and at the northwestern boundary of the Arabian Sea. In March, a zone of large thermocline thickness is found off Kenya coast and it coincides with maximum mixed layer depth and thermocline base. During the southwest monsoon season, the thermocline is found to be thin south of 12°S. Shallowing of thermocline is also observed off the coast of Somalia, Arabia and off the west coast of India.

Mixed layer depth during November to January shows a near equatorial band of shallow values extending from African coast to central Indian Ocean. The magnitude of mixed layer depths along this shallow band between 0° and 10°S ranges from 20 to 30 m. In depth and thickness, these are comparable to estimates by Hastenrath & Greischar, who used original temperature profiles (MOODS) to calculate mixed layer depth. In the northernmost extremity of Arabian Sea, the

higher than that computed by Hastenrath & Greischar<sup>4</sup>. In Hastenrath's atlas very shallow thermocline base with magnitude as low as 40 m depth is observed in the northern Arabian Sea during May and June and these low values might be due to non-smoothing of original data sets (MOODS) and unrealistic criterion (2°C per 50 m depth) used for the computation of thermocline base. Normally, the thermocline base is always observed between 100 and 250 m depth. Present computed values range from 100 to 250 m depth and shows that the criterion (0.4°C per 10 m depth) and power law used to compute the thermocline base are quite appropriate.

Characteristics of thermocline thickness resemble those of the depth of the thermocline base. During January and February, thermocline is thin between 0-10°S where its values range from 100 to 120 m. In the northwestern Arabian Sea, the very shallow thermocline with thickness varying from 100 m to 200 m depths is noticed. During the southwest monsoon season, the thermocline is found to be thin south of 12°S off the coast of Somalia, Arabia and off the west coast of India.

#### **Acknowledgement**