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Mixed layer variability at selected locations in the Arabian Sea during pre and summer monsoon seasons : Observations and simulations

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सार – इस शोध–पत्र में मानसून ऋतु से पूर्व और ग्रीष्मकालीन मानसून ऋतु के दौरान अरब सागर में चुनिंदा स्थानों पर मिश्रित सतह गहराई (एम.एल.डी.) और तापमान (एम.एल.टी.) के लघु अवधि (कुछ दिनों से लेकर कुछ सप्ताह तक) देखी गई परिवर्तनशीलता के बारे में चर्चा की गई है। अरब सागर में मानसून से पूर्व की ऋतु में प्रायः कभी कभी आने वाले गर्ज भरे तूफान और वर्षा के साथ साफ मौसम की स्थितियाँ बताई गई है। अरब सागर के पूर्व में समुद्र सतह तापमान 30° से. से ऊपर है जो हिंद महासागर की उष्ण धारा के भाग के रूप में जाना जाता है और लगभग 1.5° से. के दैनिक परास के माध्यम से बताई गई है। मानसून ऋतु के दौरान आरंभ की अवस्था में अरब सागर के मध्य में मिश्रित सतह का अधिकतम शीतलन (>1°से.) और गहराई (5075 मी.) देखी गई है। इसके विपरीत जल के ऊपर तक आ जाने के कारण तटीय क्षेत्रों में मिश्रित सतह छिछली होती है। मिलर के एक आयामी मिश्रित सतह निदर्श का उपयोग प्रेक्षित मिश्रित सतह की परिवर्तनशीलता के अनुकरण के लिए किया जाता है। एम.एल.टी. और एम.एल.डी. की परिवर्तनशीलता को अनुकरित करने वाले मॉडल सिनॉप्टिक स्केल पर काफी अच्छे साबित हुए हैं। जब भी अभिवहित प्रक्रिया (क्षैतिजीय और उर्ध्वाधर) और बड़े आकार की तरंगे प्रबल होती हैं तो प्रेक्षित और अनुकरित मानों के बीच प्रत्यंतर महत्वपूर्ण पाए जाते हैं।

ABSTRACT. Observed short term (few days to few weeks) variability of mixed layer depth (MLD) and temperature (MLT) at selected locations in the Arabian Sea during pre and summer monsoon seasons is discussed. In the Arabian Sea, pre monsoon season is generally characterized by fair weather conditions with occasional thunder squalls. In the eastern Arabian Sea, SST is above 30° C, which is assumed to be the part of the Indian Ocean warm pool, and is characterized by the diurnal range of about 1.5° C. During the monsoon season, maximum cooling (>l° C) and deepening (5075 m) of the mixed layer is noticed in the central Arabian Sea during the onset phase. On the contrary, the mixed layer shoals in the coastal zones due to upwelling. Miller's one dimensional mixed layer model is used to simulate the observed mixed layer variability. The model simulated MLT and MLD variations reasonably well on a synoptic scale. Whenever advective processes (horizontal and vertical) and large amplitude waves dominate, significant departures are noticed between the observed and simulated values.

Key words – Arabian Sea, Mixed layer depth (MLD), Mixed layer temperature (MLT), Warm pool, One-dimensional model.

1. Introduction

Marked variations are noticed in the mixed layer characteristics of the Arabian Sea in association with the seasonally reversing summer and winter monsoons (Wyrtki, 1971). Generally, shallow mixed layers are noticed during pre monsoon season when surface layer warming occurs (Hastenrath and Lamb, 1979). During summer monsoon season, though mixed layer cools in the entire Arabian Sea, it deepens in the central regions and shoals in the coastal regions. The variability in mixed layer is closely related to surface energy exchange processes, surface wind stress, entrainment at the mixed layer base, horizontal/vertical advection etc. However, on shorter time scales (few days to few weeks), the one dimensional processes, *viz*. buoyancy flux and surface wind stress appear to control MLD and MLT in the regions of weak horizontal variability (Denman and Miyake, 1973).

Following the one dimensional numerical model of Kraus and Turner (1967), several attempts have been made to simulate MLD and MLT in the ocean (Denman, 1973; Miller, 1976; Niiler and Kraus, 1977; Price *et al*., 1986). In the Arabian Sea few studies were made to simulate the mixed layer characteristics on shorter time scales (Rao, 1986; Rao and Mathew, 1990; Joseph *et al*., 1990; Hareesh Kumar *et al*., 1990; Murthy and Hareesh Kumar, 1991; Sanil Kumar *et al*., 1993; Rao *et al*., 1993, 1994). In all these studies with the only exception of Rao *et al.* (1993) all simulations were carried out by tuning the coefficients γ (extinction coefficient) and m (fraction of wind energy used for mixing) to get the best result. Secchi disc measurements collected during MONSOON-77 and

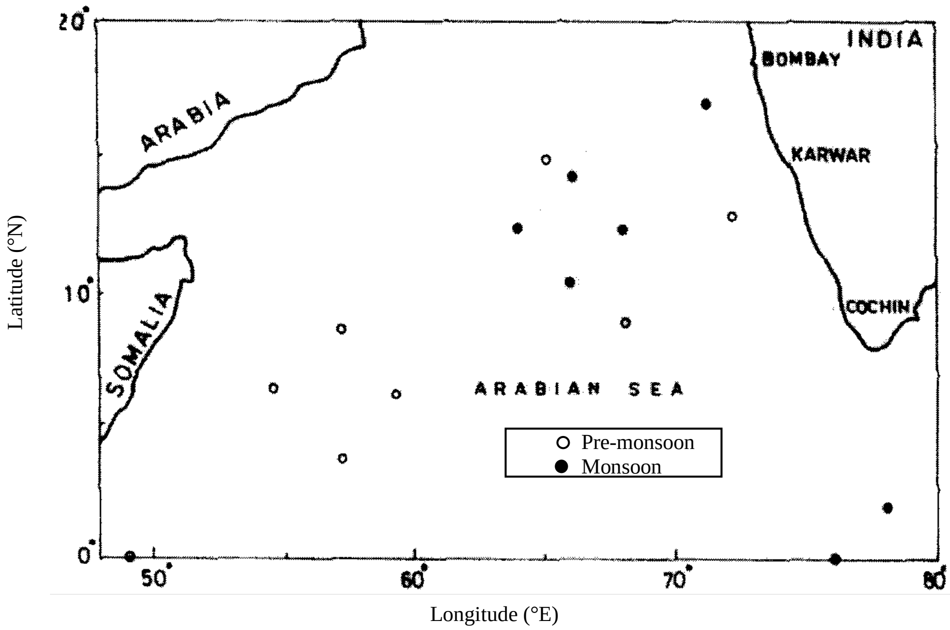


Fig. l. Station location map

MONEX-79 at some of these locations revealed that the extinction coefficient used in these simulations (0.002 cm^{-1}) are much higher than the observed values (0.0005 cm^{-1}) (Hareesh Kumar, 1994). In ihis paper, performance of Miller's (1976) model in simulating MLD and MLT at selected locations in the Arabian Sea is evaluated with the extinction coefficient derived from secchi disc measurements.

2. Observations

Data sets utilized in this study are collected at selected locations in the Arabian Sea during pre (April/May) and summer monsoon (June to August) seasons. Station locations (Fig. l), symbols and the observational periods are presented in Table 1. Stations are designated as N77, E77, S77, W77, N79, E79, S79 and W79 corresponding to the four corners of the polygons during 1977 (MONSOON-77) and 1979 (MONEX-79) respectively. EQ79, SR77, SH77 and PB77 are the four stations located around the equator. I177, I277, DK79 and DP79 designate the four Indian ship locations. Hourly surface meteorological data (solar radiation, albedo, wind speed and direction, visually observed cloudiness, atmospheric pressure, air temperature, wet bulb/dew point temperature) and three/six hourly vertical profiles of temperature and salinity collected from these locations were used. Wherever solar radiation measurements are not available, they are estimated following Lumb (1964).

2.1. *Surface meteorology and heat budget*

The sea surface temperature (SST) in the Arabian Sea exhibits a bimodal distribution in the annual cycle with cooling during winter and summer monsoon seasons and heating during the transition periods. To quantify the warming and cooling in the annual cycle, SST difference (ΔT) (between May and January and August and May are presented in Fig. 2. During pre monsoon maximum ΔT (>4.5° C) is observed in the northern Arabian Sea and minimum (<1° C) east of 65° E near the equator. Net oceanic heat gain during pre monsoon season contributed to large ΔT between January and May. In the southeastern Arabian Sea ΔT is minimum (<1° C) due to weak winter cooling and weak heat input in May (Hastemath and Lamb, 1979). Similar to pre-monsoon warming, summer cooling is also noticed in the entire Arabian Sea [Fig. 2(b)]. Regions of maximum cooling are off Somalia coast (~5.5° C), Arabia coast (~4° C) and southwest coast of India (~3.5° C), which are the well known regions of coastal upwelling. Cooling of the order of –2.5° to –3.5° C observed in the central Arabian Sea is mainly due to increased net heat loss, entrainment of colder water from thermo cline into the mixed layer and advection of cold water from coastal upwelling regions (Duing and Leetmaa, 1980). In the southeastern Arabian Sea the cooling is less than 0.5° C.

Though pre-monsoon season is generally characterized by fair weather conditions, occasional thunder squalls occur in the Arabian Sea causing

TABLE 1

Location	Symbol	Period	γ (cm^{-1})	RMS error	
				MLT (°C)	MLD (m)
		Pre-monsoon			
0° N, 49° E	EQ79	17-25 May 1979	0.0005	0.23	12.9
8° 48' N, 57° 03' E	N79	17-30 May 1979	0.0005	0.17	6.6
6° 15' N, 59° 08' E	E79	17-30 May 1979	0.0005	0.19	4.8
3° 56' N, 57° 10' E	S79	17-30 May 1979	0.0005	0.16	7.0
6° 25' N, 54° 38' E	W79	17-30 May 1979	0.0005	0.21	6.0
15° N, 65° E	DP79	20 May - 8 June 1979	0.0005	0.24	11.0
9° 48' N, 68° E	DK79	3-13 May 1979	0.0005	0.15	7.6
		26 May - 4 June 1979	0.0005	0.11	10.4
13° N, 72° E	I177	26 May -8 June 1977	0.0005	0.46	10.3
		Monsoon			
13° 30' N, 66° E	N77	7-20 June 1977	0.0006	0.40	6.8
		30 June - 16 July 1977	0.0006	0.32	11.8
12° 30' N, 68° E	E77	7-20 June 1977	0.0005	0.30	5.5
		30 June – 16 July 1977	0.0005	0.16	14.7
10° 30' N, 66° E	S77	7-20 June 1977	0.0005	0.12	7.7
		30 June - 16 July 1977	0.0005	0.13	20.4
12° 30' N, 64° E	W77	7-20 June 1977	0.0005	0.20	8.2
		30 June - 16 July 1977	0.0005	0.12	9.4
17° N, 71° E	I277	4-19 August 1977	0.0005	0.50	18.0
13° N, 72° E	I177	26 June - 15 July 1977	0.0006	0.35	10.0
0° N, 80° E	SR77	24-31 July 1977	0.0007	0.75	12.0
0° N, 76° E	SH77	24-31 July 1977	0.0007	0.50	15.0
0° N, 78° E	PB77	24-31 July 1977	0.0006	0.20	19.0

considerable variations in the meteorological and oceanographic conditions on a synoptic scale (Fig. 3). In general, all locations experienced high atmospheric pressure, weak winds (< 5m/s) and clear skies. In association with the formation of a low pressure system on 25 May 1979 (Krishnamurti, 1981), net heat loss occurred in the western equatorial Arabian Sea (N79, E79, S79 and W79). Except on these days, substantial heat gain (Q) was noticed at all the locations (average heat gain of 120, 68, 77, 101, 57, 126 and 169 Wm^{-2} at N79, E79, S79, W79, DK79 and DP79 respectively). SST was above 29° C at all the locations with large amplitudes of diurnal oscillation. During this period, mixed layers are generally shallow in the Arabian Sea (<30 m) except at EQ79 where advective processes play a significant role in controlling MLD (Joseph *et al*., 1990). Maximum SST (>30° C) and large diurnal range (>1.5° C) are observed in the eastern Arabian Sea (I177) in association with weak winds and

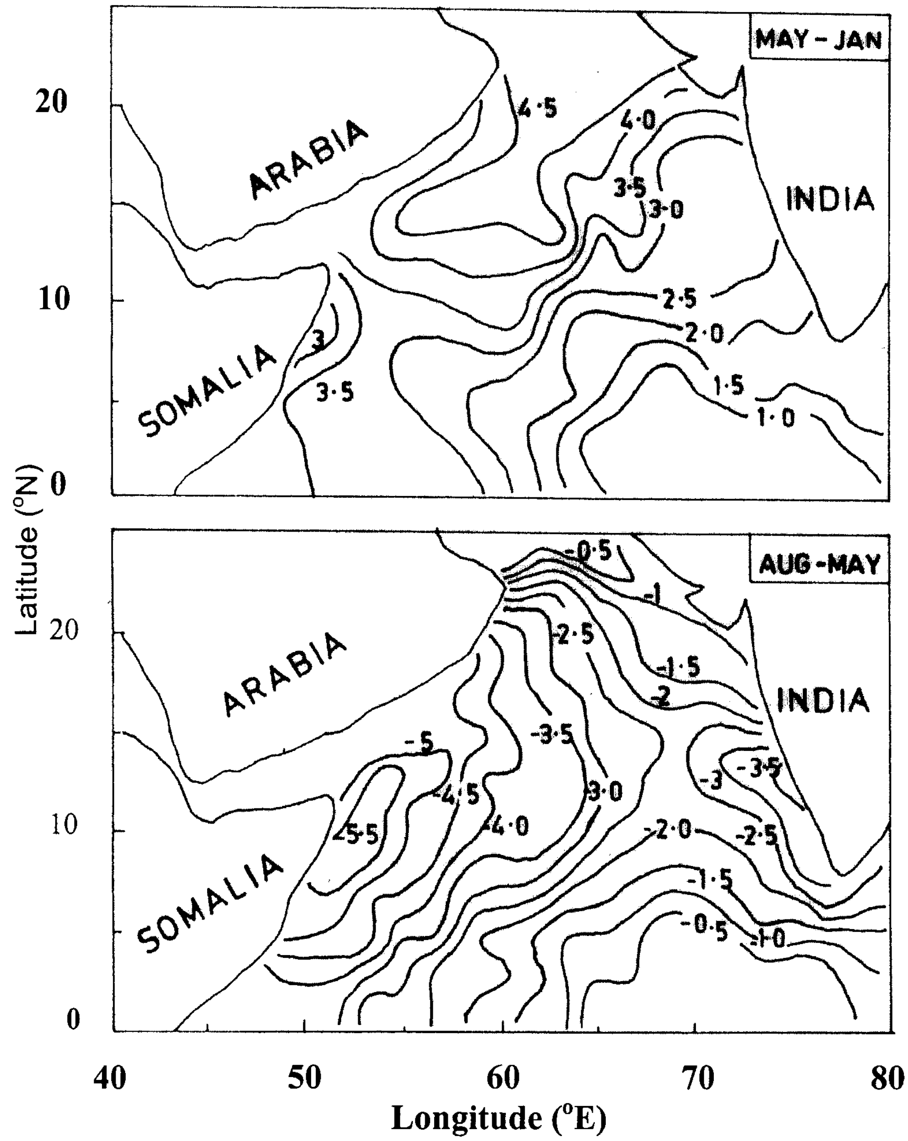


Fig. 2. Sea surface temperature difference between May and January (May-January) and August and May (August-May)

clear skies which aid the accumulation of heat (Rao and Hareesh Kumar, 1989). This resulted in shallow mixed layers in the eastern Arabian Sea (on an average less than 15 m). In the eastern Arabian Sea, the pre-monsoon season is characterised by a warm pool with SST greater than 30° C (Seetaramayya and Master, 1974). Hence, the zone of high SST noticed in the eastern Arabian Sea is assumed to be the part of the Arabian Sea warm pool.

During summer monsoon season, strong winds (>10 ms^{-1}), low atmospheric pressure (<1005 hPa) and overcast skies [Figs. 4 (a&b)] are noticed in the central Arabian Sea (N77, E77, S77 and W77). Though winds are strong (>10 ms^{-1}) during the onset (7-20 June 1977) and post onset (30 June - 15 July 1977) phases, substantial heat loss was noticed during the onset phase (–229, –262, –222 and –285 Wm^{-2} at N77, E77, S77 and W77 respectively) compared to the post onset period (–150, –153, –57 and –133 Wm^{-2} at N77, E77, S77 and W77 respectively). The onset phase is marked by a spurt in the convective activity in the boundary layer and release of large amount of latent heat which enhance the exchange processes (Pearce and Mohanty, 1984).

With the onset and progress of the monsoon, mixed layer cooled dramatically in the central Arabian Sea.

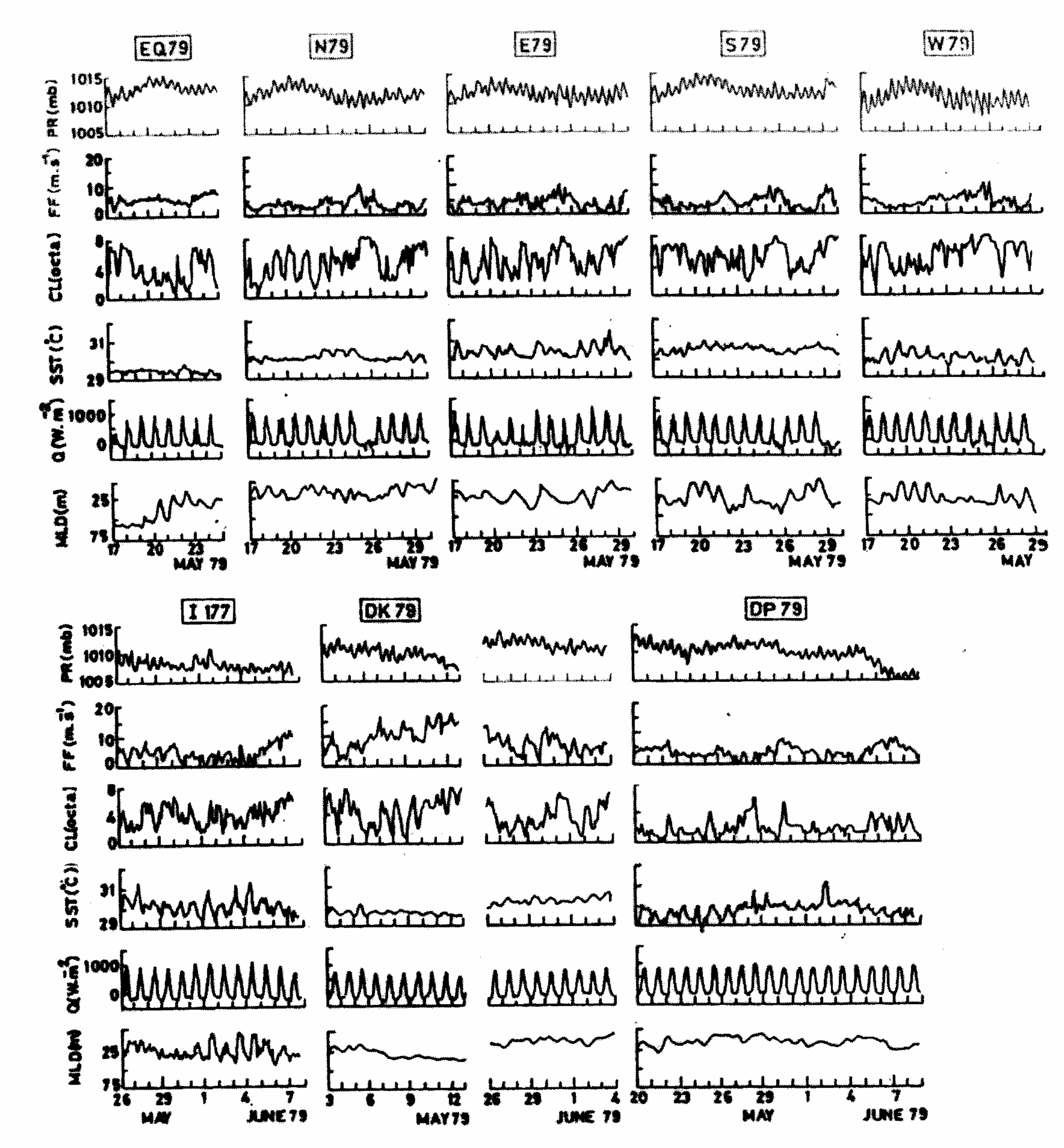
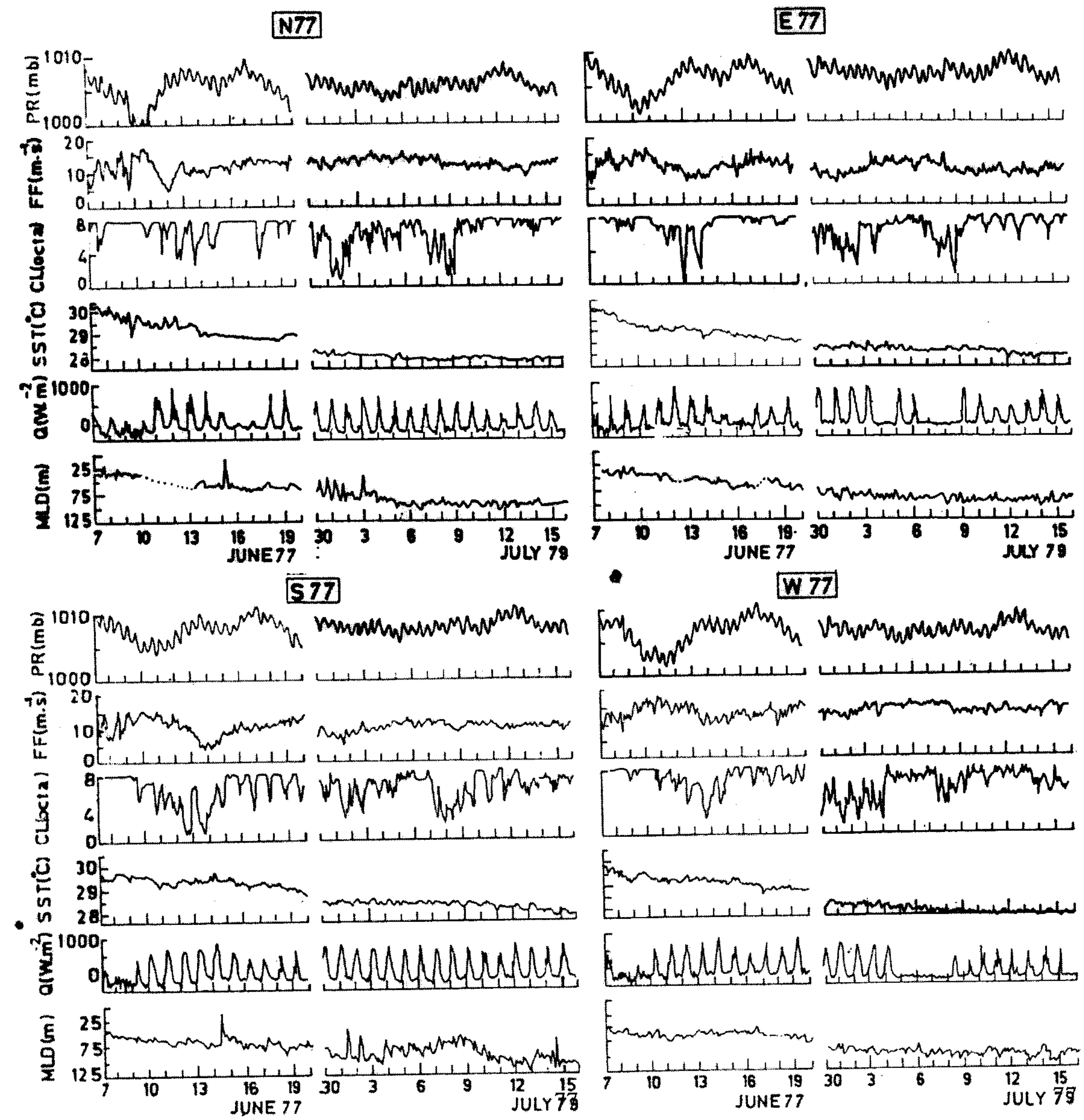


Fig. 3. Distribution of pressure (PR), wind speed (FF), cloud (CL) sea surface temperature (SST), net heat flux (Q) and mixed layer (MLD) at selected locations in the Arabian Sea during pre monsoon

Increased net oceanic heat loss (Hastenrath and Lamb, 1979; Rao *et al*., 1989), advection of cold upwelled water from the Somali/Arabia coasts (Duing and Leetmaa, 1980) are considered to be responsible for the cooling in this region. Cooling (1.3° C, 1.3° C, l° C and 1.l° C at N77, E77, S77 and W77 respectively over 14 days) and deepening (on an average 50 to 75 m) of the mixed layer was maximum during the onset phase than during the post onset phase (0.4° C, 0.2° C, 0.6° C and 0.5° C over 16 days and deepening of 25 to 30 m). In the central Arabian Sea, mixed layer deepened by more than 80 m (40 to 120 m) by mid July. Increased mixed layer depths and strong vertical mixing reduced the diurnal variation in SST to less than 0.2° C during the summer monsoon



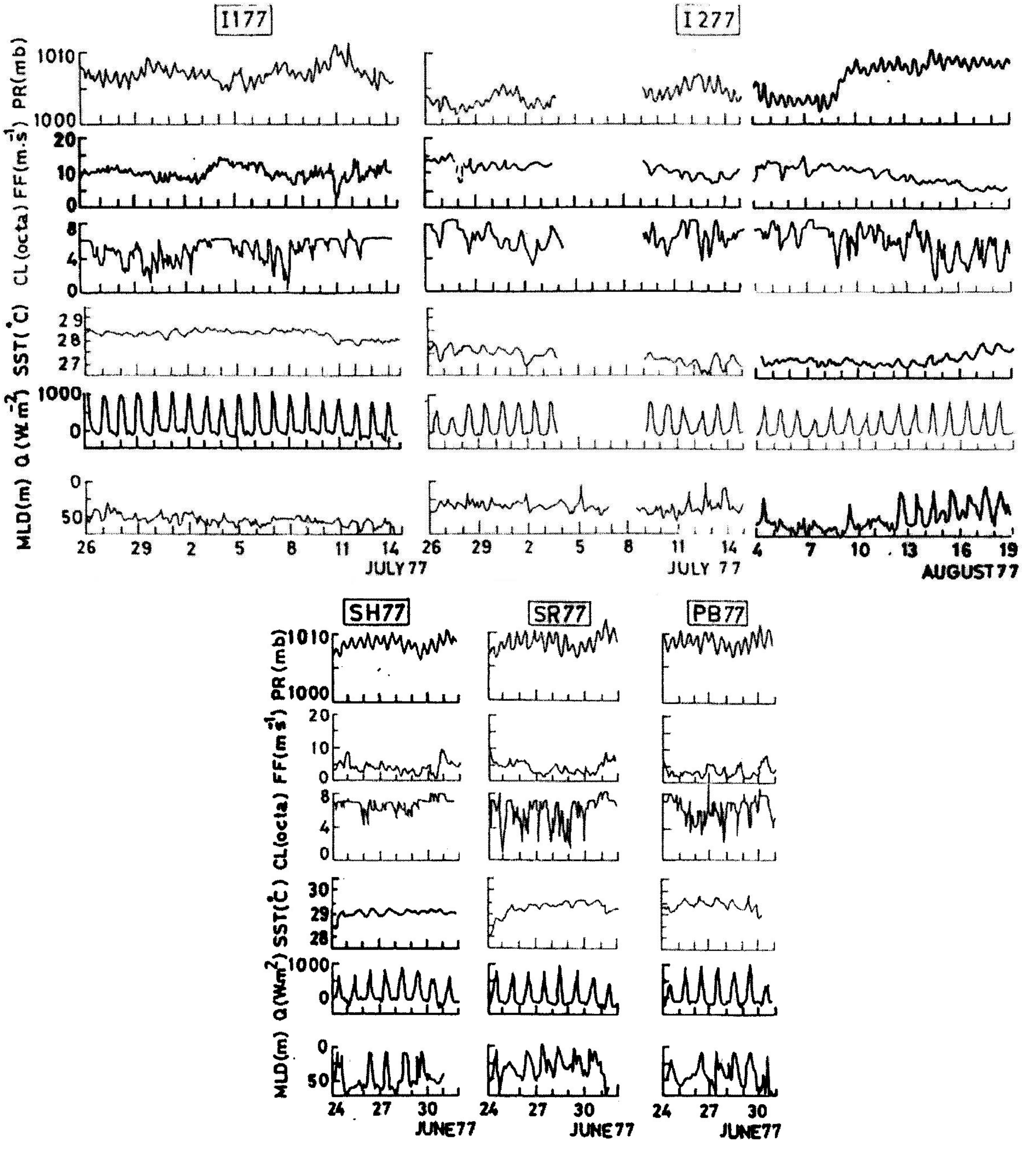
Figs. 4(a). Distribution of pressure (PR), wind speed (FF), cloud (CL) sea surface temperature (SST), net heat flux (Q) and mixed layer (MLD) at selected locations in the Arabian Sea during monsoon

season. In the equatorial Arabian Sea (SH77, SR77 and PB77) weak winds (~5 ms^{-1}), high atmospheric pressure (> 1008 hPa) and net oceanic heat gain favoured higher SST.

3. Modelling of the mixed layer characteristics

It is well known that during surface heating regime and under light wind conditions, mixed layer shoals and its temperature increases. Under strong winds even if there is net heating, surface layer thickness increases and its temperature decreases. These changes can be caused by turbulent entrainment of colder and denser water into the mixed layer from below. Net surface cooling can deepen the mixed layer through convective overturning.

The time dependent behaviour of the mixed layer at a stationary position is formulated from a set of differential equations based on conservation of thermal



Figs. 4(b). Distribution of pressure (PR), wind speed (FF), cloud (CL) sea surface temperature (SST), net heat flux (Q) and mixed layer (MLD) at selected locations in the Arabian Sea during monsoon

energy, salinity and mechanical energy with appropriate boundary conditions. The simplified one dimensional equations used in the mixed layer simulations are (Miller, 1976),

$$\frac{\mathrm{d}h}{\mathrm{d}t}=\frac{2\left[G-D+\gamma^{-1}Q_i\left(1-e^{-\gamma h}\right)\right]-h\left[Q_b+Q_e+Q_h+Q_i\left(1+e^{-\gamma h}\right)+\frac{\lambda}{\alpha}S\left(P-E\right)\right]}{h\left[T-T_h+\frac{\lambda}{\alpha}\left(S-S_h\right)\right]} \tag{1}$$

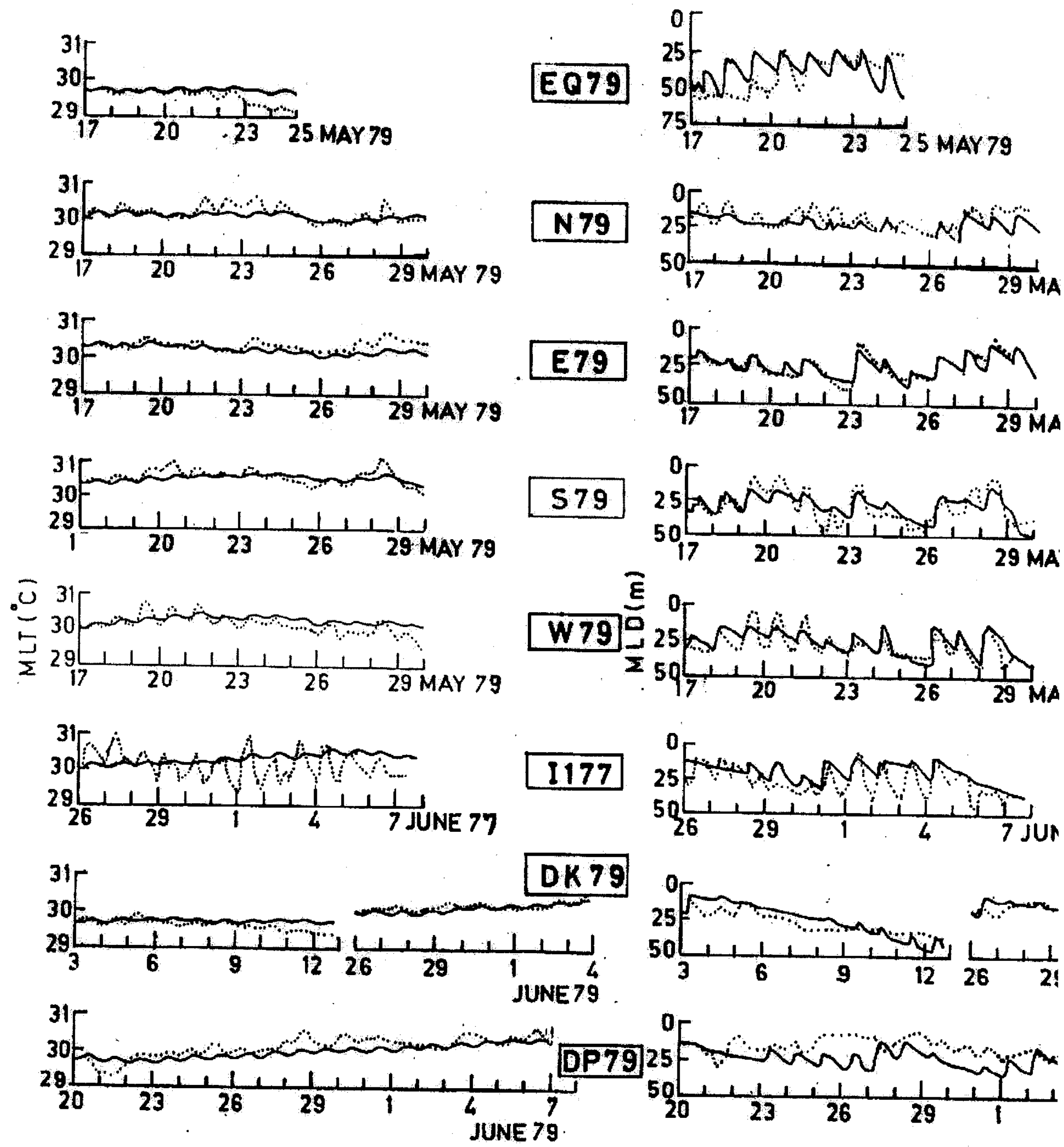


Fig. 5. Observed (dashed) and simulated (continuous) mixed layer depth (MLD) and temperature (MLT) at selected locations during pre monsoon

$$\frac{\mathrm{d}T}{\mathrm{d}t}=\frac{1}{h}\left[-\frac{\mathrm{d}h}{\mathrm{d}t}(T-T_h)+Q_b+Q_e+Q_h+Q_i\left(1-e^{-\gamma h}\right)\right] \quad (2)$$

$$\frac{\mathrm{d}S}{\mathrm{d}t}=\frac{1}{h}\left[-\frac{\mathrm{d}h}{\mathrm{d}t}(S-S_h)+S(P-E)\right] \quad (3)$$

$$\frac{\mathrm{d}T_{-h}}{\mathrm{d}t}=\gamma Q_i e^{-\gamma h}-\frac{\mathrm{d}h}{\mathrm{d}t}\left(\frac{\partial T}{\partial z}\right)_{-h} \quad (4)$$

$$\frac{\mathrm{d}S_{-h}}{\mathrm{d}t}=-\frac{\mathrm{d}h}{\mathrm{d}t}\left(\frac{\partial S}{\partial z}\right)_{-h} \quad (5)$$

where dh/dt is the rate of mixed layer deepening; G-D, fraction of the turbulent energy derived from wind ($-m\tau U/\alpha\rho g$); m, fraction of energy transferred from wind, τ - wind stress; g - acceleration due to gravity; ρ - mean density of mixed layer; α - extinction coefficient; Q_i - solar radiation incident on the sea surface, h - depth of mixed layer, Q_b - effective back radiation, Q_e - latent heat flux; Q_h - sensible heat flux; λ - coefficient of thermal expansion, α - coefficient of saline contraction, P - precipitation and E - evaporation.

For the wind dominated regime (dh/dt > 0), the cold water from below the mixed layer is entrained into the

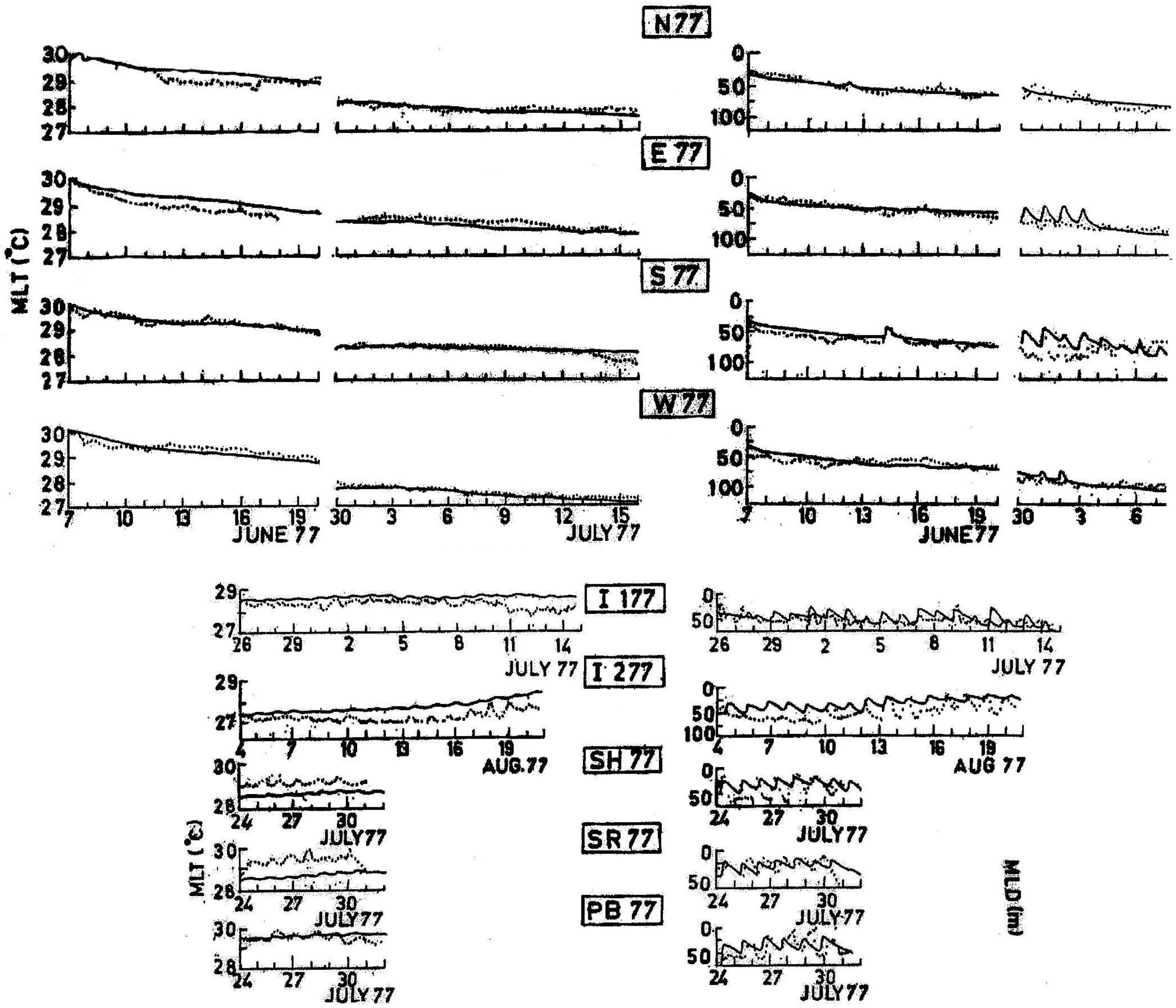


Fig. 6. Observed (dashed) and simulated (continuous) mixed layer depth (MLD) and temperature (MLT) at selected locations during monsoon

mixed layer as a result of work done by the turbulent eddies against the buoyancy forces. In such cases, equations 1-5 are solved using Runge-Kutta numerical integration scheme with a time step of 5 minutes. For the heat dominated regime ($dh/dt < 0$), entrainment mixing at the base of the mixed layer does not appear in the equations. In such cases, terms involving the below layer density gradient loses its significance and '*h*' is determined using Newton's iterative technique.

$$h = \frac{2\left(G - D + \gamma Q_i e^{-\gamma h}\right)}{Q_b + Q_e + Q_h + Q_i\left(1 + e^{-\gamma h}\right)} \tag{6}$$

$$\Delta T_s = \frac{\Delta t}{h}\left[Q_b + Q_e + Q_h + Q_i\left(1 - e^{-\gamma h}\right)\right] \tag{7}$$

The two unknown parameters used in this model are the fraction of wind mixing energy (m) which is used to increase the potential energy of upper layers and the extinction coefficient for solar radiation (γ) in sea water. In the absence of any information about the time variation of 'm', model calculations are made on the assumption that the rate of increase of potential energy due to mechanical mixing is constant. The laboratory experiments of Kato and Phillips (1969) suggested a value of 0.0015 for 'm' while Denman (1973) used 0.0012 on an idealized case of wind mixing and diurnal heating which are much lower than the values of 0.01 obtained by Turner (1969) in the laboratory experiment. After tuning the above values of 'm' with γ derived from the secchi disc measurements (γ = 1.7 / D, where D is the Secchi disc value), m = 0. 0009 was found to give best agreement with observations. The extinction coefficient (used in the model) and the Root Mean Square error (RMS error) for MLT and MLD are presented in Table 1. Comparison of the model results with observation is made difficult by the presence of short period internal waves (<12 hrs). Hence in the subsequent analysis, the model results are compared with a low pass filtered series of observed MLD and MLT.

3.1. *Pre monsoon season*

Simulations are carried out at five stations in the western equatorial Arabian Sea (N79, E79, S79 W79 and EQ79) and at three stations in the eastern Arabian Sea (DP79, DK79 and I177). Results of the simulations along with the observed values are presented in Fig. 5. In the western equatorial Arabian Sea (N79, E79, S79, W79 and EQ79) inclusion of entrainment in the model physics produced excessive cooling and consequently at these locations this term was not included in the model equations.

On a synoptic scale, the model reproduced the pattern of MLT variation very well at all the stations. On calm days, the model SST is higher because surface heating influences a shallow mixed layer. However, the simulated diurnal amplitude in MLT was very small compared to the observed. At I177, more than a three fold reduction is observed in the simulated diurnal variation in MLT (<0.5° C) when compared with observations (1.5 to 2° C). This may be due to the improper parameterization of the short wave irradiance as a function of depth. This term is very important when the winds are weak, as observed during the pre onset period. At EQ79 and W79, the model simulated a warmer surface layer after 21 May. From a detailed measurements of the flow pattern in the western equatorial Indian ocean, Swallow *et al*. (1983) found that the northward flowing/western boundary current, which brings cold and low saline water, turned offshore near 2-3° N by 20 May. Intrusion of this cold and low saline water into the observational site might have reduced the surface temperature after 21 May especially at EQ79 and W79. At EQ79, Joseph *et al*. (1990) obtained greater error both in MLD (17.8 m) and MLT (0.3° C) when they slightly increase the value of $\gamma(0.0015\ cm^{-1})$ even by including the correction for cold water advection. From this it can be inferred that local meteorological forcing cannot simulate the deeper mixed layers observed during the initial period, which is the result of internal ocean dynamics. The effect of this cold water advection was also evident at W79 while its effect was not noticed in the rest of the stations (N79 and E79). Among all the stations, maximum agreement between the observed and simulated MLT was observed in the eastern Arabian Sea (RMS errors of 0.11° C at DK79 during the latter period, *i.e*. after 26 May).

The simulation of MLD was not as good as that of temperature, which is evident from large RMS errors (>9 m). Maximum agreement was obtained at E79 (RMS error 4.8 m). At EQ79, agreement was good only after 21 May, when mixed layer shoaled due to the intrusion of cold and low saline water into the site. At I177 and DP79, though the model simulated the diurnal peaks both in MLT and MLD, marked deviations are noticed between the observed and simulated MLD (RMS error >10 m).

3.2. *Monsoon season*

Simulations were carried out at four stations in the central Arabian Sea (N77, E77, S77 and W77), at two stations in the eastern Arabian Sea (I177 and I277) and at three stations in the equatorial Arabian Sea (SR77, SH77 and PB7). Results are presented in Fig. 6.

During summer monsoon, the model simulated the cooling and deepening rates of the mixed layer reasonably well in the central Arabian Sea. However, the agreement was found to be the best during the onset phase (RMS errors for MLD is < 8 m during the onset phase and > 10m during the post onset phase). This may be due to the dominance of local meteorological forcing in the evolution of MLD variation during the onset phase. Rao and Mathew (1990) also noticed the same and further suggested that in the post onset period internal ocean dynamics appear to playa significant role in the MLD variation, which can lead to large error in the simulation. During the post onset period, *i.e*. when the Arabian Sea began to attain the steady state conditions, large difference is noticed between observed and simulated MLD when the internal ocean dynamics becomes more important. During this period, the model could not simulate the synoptic scale perturbations in MLD which are generated internally. During this period the simulated MLT is slightly overestimated. This may be due to the non inclusion of the correction for the lateral advection into the interior of the Arabian Sea.

4. Summary and conclusions

In the Arabian Sea, mixed layer depth and temperature show dramatic variations between pre and summer monsoon seasons. During the pre monsoon season, sea surface temperature is greater than 30° C in the eastern Arabian Sea with diurnal ranges of the order of 1° to 1.5° C. One of the notable feature is that though mixed layer cools in the entire Arabian Sea, it deepens in the central regions more prominently due to enhanced vertical mixing (both buoyant and mechanical) and sinking while it shoals in the eastern Arabian Sea as the season progresses due to coastal upwelling. Moreover, due to the spurt in the convective activity, cooling (> 1° C) and deepening (50 – 75 m) of the mixed layer is maximum in the central Arabian Sea during the onset phase. The one dimensional mixed layer model of Miller (1976) simulated the pattern of MLT and MLD variations reasonably well on a synoptic scale. However, the simulated amplitude in MLT and MLD are small compared to the observations due to improper parameterization of the penetration of solar irradiance. Whenever, processes such as horizontal and vertical advection, large amplitude waves etc. dominated, significant departures are noticed between the observed and simulated values.

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