Mausam, (1990), **41**, 3, 439-444

551.558.1 : 551.511 : 551.553.21 (267)

Observed variability in the thermal response of the upper north central Arabian Sea to the forcing of onset vortex during summer monsoon experiments

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(*Received 25 March 1987*)

सार — स्थिर पोतों से, तीन मानसून प्रयोगों ISMEX-73, MONSOON-77 और MONEX-79 के दौरान ग्रीष्म मानसून के आरम्भ के पहले व बाद में मध्य अरब सागर की ऊपरी सतहों में एकत्र किए गए तापमान आंकड़ों का प्रयोग, मानसून के आरम्भ सहित उपरि महासागर ऊष्मीय संरचना में प्रेक्षित विभिन्नता को प्रलेखित करने के लिए किया गया। इन तीन वर्षों के दौरान आरंभिक भ्रमिल के प्रभावस्वरूप, संमिश्र सतह के शीतलन और गहनता और सतह के नीचे ऊष्मन, असमान परिमाण में पाये गये। उर्ध्वाधर तापीय प्रवणता के प्रोफाइल में भी ऐसी ही विभिन्नताएं देखी गई। 1973 के दौरान उर्ध्वाधर तापीय प्रवणता में गौण महत्तम के प्रभाव से 1972 के दौरान क्षीण ग्रीष्म मानसूनी बल का पता चला। वर्ष 1972 को सार्वत्रिक रूप से सूखा वर्ष के रूप में देखा गया था। 1973 और 1979 के बीच संचयी तापमात्रा के परिवर्तन में काफी विभिन्नताएं देखी गई। जो कि क्रमश: अच्छ और खराब मानसून वर्ष थे।

ABSTRACT. Temperature data collected in the upper layers of the central Arabian Sea before and after the onset of the summer monsoon during the three monsoon experiments ISMEX-73 (1973), MONSOON-77 (1977) and MONEX-79 (1979) from stationary ships are made use of to document the observed variability in the upper ocean thermal structure with the onset of the monsoon. Cooling and deepening of the mixed layer and warming below the layer were found to be of unequal magnitudes under the influence of onset vortex during these three years. Similar differences were also noticed in the profiles of vertical thermal gradient. Absence of a secondary maximum in the vertical thermal gradient during 1973 suggests a weak summer monsoonal forcing during 1972 which was viewed as a global drought year. Large differences were noticed in the changes of accumulative heat content between 1973 and 1979 which were good and bad monsoon years respectively.

1. Introduction

A large body of literature exists documenting the observational evidence of the interannual variability of the monsoon circulation and rainfall and its possible relationship with other regional and global circulation features. One of the important scientific questions is to determine the mechanisms responsible for the interannual variability of monsoons. There is a growing body of observational and theoretical studies which suggest that slowly varying boundary forcings may be the primary cause for the monsoon variability. Parthasarathy and Mooley (1978) have shown large interannual variability in the observed summer monsoonal rainfall over India. This implies a corresponding variability in the monsoonal forcing over the Arabian Sea probably producing interannual variability in the sub-surface characteristics of the sea. However, there is very little information available on the interannual variability for the tropical oceans, in general and for Arabian Sea, in particular. On the annual cycle summer monsoon is the major wind system that interacts with the Arabian Sea in determining its heat budget and consequently the sub-surface thermal structure of the upper layers of the sea. This interaction is manifested over a wide range of space-time scales in a non-linear manner. The mode of the interaction (mostly through the fluxes of heat and momentum across the air-sea interface) is known to be stronger during disturbed weather associated with the onset and active phases of the monsoon. As the fluxes across the air-sea interface also influence the ocean upper layer characteristics, it is to be expected that significant changes occur in the characteristics of the sub-surface layers during disturbed weather.

Bunker compiled surface marine meteorological parameters and heat budget estimates for all the ten-degree squares of the Indian Ocean using all the available ship data for the period 1947 to 1972. During May, the surface temperature (Fig. 1) in the central Arabian Sea fluctuates around 29°C to 30°C and by August cools around 2°C to 3°C with the onset and sway of the summer monsoon. The magnitude of the interannual variation in SST appears to be relatively higher (~1 °C) in May

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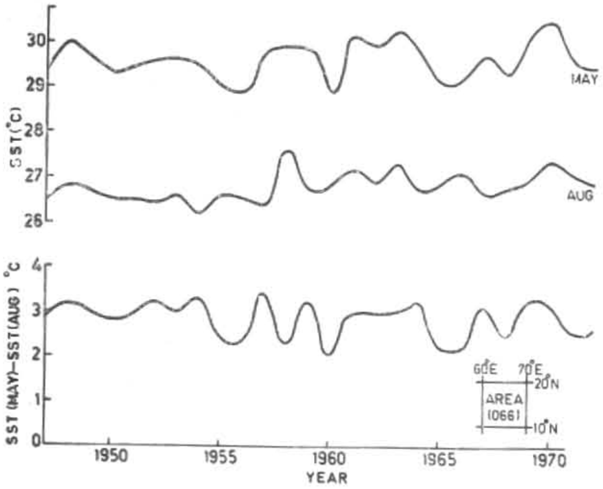

Fig. 1. Interannual variation of the summer monsoon cooling in the central Arabian Sea (Marsden Square No. 066)

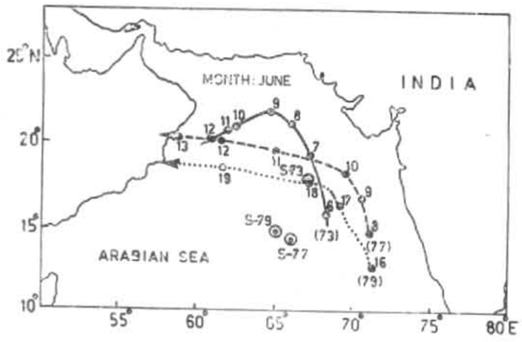

Fig. 2. Stationary positions and the analysed tracks of onset vortices during summer monsoon experiments

TABLE 1

Details of the onset vortices during summer monsoon experiments

Storm period	Date of maximum intensity	Estimated central pressure (mb) from satellite cloud pictures	Observed minimum pressure (mb) from a nearby ship/ station	Estimated maximum wind speed (kt) from sat. cloud pictures	Observed maximum wind speed (kt) from a nearby ship/ station	Dvorak's classi- fication from sat. cloud pictures	Approximate distance (km) between observing station and the centre of storm under most intense conditions
7-12 June 1973	10 June 1973	991	992	35	33	T 2/2	595
9-13 June 1977	12 June 1977	964	959	85-90	—	T 5/5	815
16-20 June 1979	19 June 1979	981	—	50-65	30-40 (ships 7-8° south of storm)	T 3.5/3.5	570

TABLE 2

Details of the periods of different regimes of the monsoon for the summer monsoon experiments

Year	Station	Pre-onset regime	Onset vortex regime	Post onset regime	Av. time difference between pre- and post onset regimes
1973	18°N ,67°E	29 May-5 Jun (8 days)	7-12 Jun, (6 days)	26 Jun-2 Jul (7 days)	28 days
1977	14.5°N, 66° E	7-9 Jun (3 days)	9-13 Jun (5 days)	30 Jun- 6 Jul (8 days)	26 days
1979	15°N, 65°E	1-8 Jun (8 days)	16-20 Jun (5 days)	21-24 Jun (4 days)	18 days

compared to that of in August (~ 0.5°C). In the Arabian Sea, the SST data are probably the only historical open ocean data sets with sufficient spatial and temporal density to examine the interannual variability. Brown and Evans (1981) and Duing and Leetmaa (1980) have examined the maximum seasonal amplitude (April-August) of the mean SST change in the Arabian Sea for selected years. It was found to vary from 0°C to 5°C dependent on the particular sub-region selected with large (1-3°C) interannual changes in the central Arabian Sea. Since SST change is highly correlated with average mixed layer temperature, this implies large interannual signals in the mixed layer heat content. Strong interannual variability is known to exist in the large scale wind field and sea surface temperatures in the Indian Ocean (Cadet & Diehl 1984). However the interannual variability in the thermal response of the upper central Arabian Sea to the forcing of the summer monsoonal onset vortex is not reported in the literature due to paucity of observed sub-surface data sets. The three monsoon experiments carried out over the Arabian Sea during the summer monsoon seasons of 1973 (ISMEX-73), 1977 (MONSOON-77) and 1979 (MONEX-79) provided a unique opportunity to look into this phenomenon in a limited sense. Despite the fact that no single common area was monitored before and after the onset of the monsoon during all the three experiments, an attempt is made here to make the optimum use of these data sets to address this problem of year to year variability in the observed thermal response of the upper layers of the north central Arabian Sea to the monsoonal forcing.

2. Data

Three hourly time series measurements of BT data at selected stations and periods were made during all the monsoon experiments. The onset vortices appeared in the monsoonal flow and the observational schedules were well coincided to collect data before and after the onset event during all these experiments. The best available stations (nearest to each other) in the north central Arabian Sea were selected for comparison. Fortunately onset vortices formed and traversed in the nearby vicinity of the observing stations during all these experiments.

Data are stratified in the time domain to give the best representation of upper ocean thermal conditions during pre- and post-onset regimes. Averaging is done for periods of three days or more to minimize the influence of inertial oscillations and to make the data sets more representative of the typical regimes (Table 2).

3. History of the onset vortices

The influence of the onset vortex on the upper ocean properties would also be determined by the storm characteristics as size, intensity, life (duration), translation speed and proximity to the observing station, etc. A brief summary on the life history for each of the storm is given to gain a comprehensive idea on some of the features of the storms (Table 1). During MONSOON-77, as there is some overlapping (9 June 1977) between the pre-onset regime and the storm period, the corresponding data of the pre-onset regime may show a mild bias towards that of the storm conditions.

4. Analysis and discussion

The analysed tracks of the onset vortices during ISMEX-73, MONSOON-77 and MONEX-79 experiments are shown in Fig. 2. The numbers along tracks indicate the dates in June corresponding to the analysed centres of the vortices. The observing stationary positions designated as S-73, S-77 and S-79 correspond to ISMEX-73, MONSOON-77 and MONEX-79 experiments respectively. Formation of the vortices in the southeastern Arabian Sea and eventual northnorthwestward movement during the initial days followed by westward movement stand out in all three cases. The life of the 1979 vortex was shorter than either of the 1973 and 1977 vortices over the sea. In general the track of the 1973 vortex was closest to the observing station out of all the three cases studied here.

The averaged vertical temperature profiles for pre- and post-onset regimes for the three experiments are shown in Fig. 3. During the pre-onset regime the near surface temperature was around 30°C and the year to year differences were within a range of 0.5°C. However, considerable differences were noticed in the upper thermocline. For instance, at 80 m depth the year to year

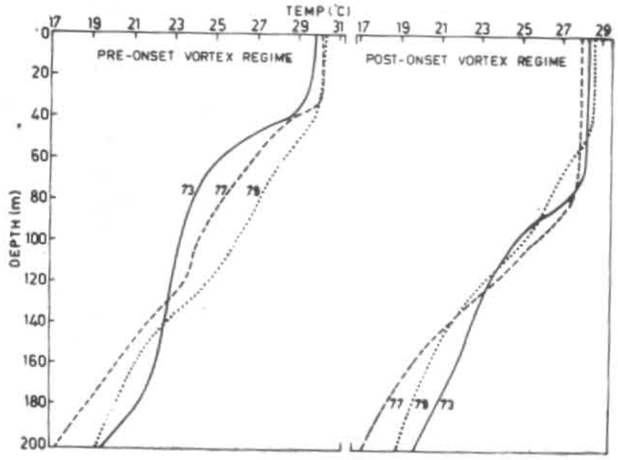

Fig. 3. Typical BT profiles for pre- and post-onset regimes during summer monsoon experiments

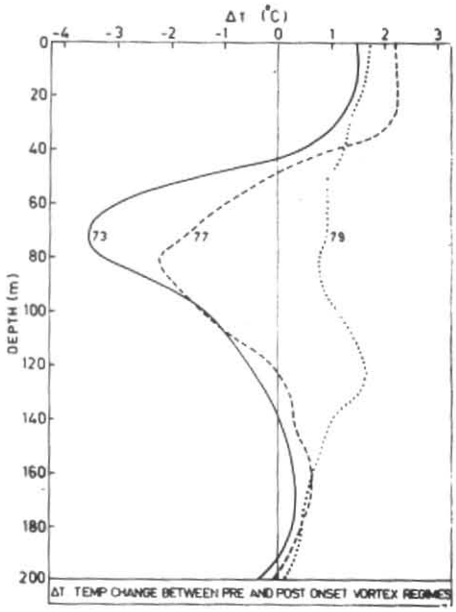

Fig. 4. Temperature changes in the vertical between pre- and post-onset regimes during summer monsoon experiments

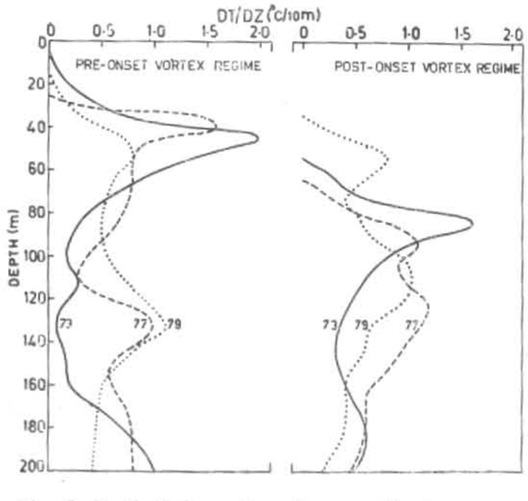

Fig. 5. Vertical thermal gradient profiles for pre- and post-onset regimes during summer monsoon experiments

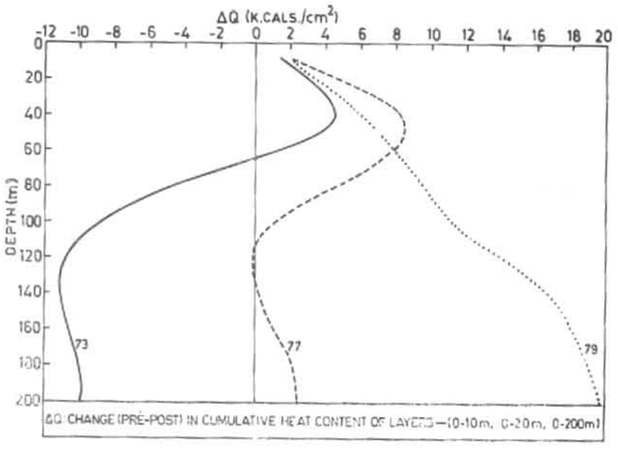

Fig. 6. Changes in the accumulative heat content between pre- and post-onset regimes during summer monsoon experiments

temperature differences were within a range of 3°C implying differences in the slopes of the thermocline.

With the onset of the monsoon, though cooling occurred during all the three years, significant differences were noticed in the depth of the mixed layer (MLD). During the post-onset regime the difference in MLD for 1979 from either of the other two years stands out very prominently. The layer deepening was approximately half of the corresponding of either of the other two years. Just below the mixed layer, the separation in the profiles was reduced from pre- to post-onset regime. The water column below 130 m depth appears almost unaffected by these onset vortices.

The extent of cooling/heating caused in the top 200 m water column by the onset vortices during these years is shown in Fig. 4. Cooling of the order of 1.5° to 2°C was evident in the top mixed layer and < 1°C below 140 m depth during all the years. However, warming below mixed layer caused by layer deepening and downwelling was seen only in the profiles of 1973 and 1977 but not in the profile of 1979. Instead, a uniform cooling of around 1°C probably caused due to weak deepening of the layer and upwelling below is noticed in 1979. The warming below mixed layer was more than 3°C during 1973 compared to that of 2°C during 1977.

The profiles of vertical thermal gradient are shown for pre- and post-onset regimes for all the years in Fig. 5,

TABLE 3

Thermal parameters of the upper ocean corresponding to the pre- and post-onset regimes during summer monsoon experiments

Parameter	Pre-onset vortex regime			Post-onset vortex regime		
	1973	1977	1979	1973	1977	1979
(1) Mixed layer mean temperature (°C)	29.7	30.1	30.2	28.3 (1.4)	27.9 (2.2)	28.6 (1.6)
(2) Mixed layer depth (m)	23.0	34.0	36.0	66.0 (—43.0)	76.0 (—42.0)	46.0 (—20.0)
(3) Bulk thermal gradient in the upper thermocline (°C/10 m) (mixed layer base to 200 m)	0.57	0.76	0.62	0.61 (—0.04)	0.82 (—0.06)	0.59 (0.03)
(4) Depth of 25°C (m)	64.0	86.0	116.0	97.0 (—33.0)	107.0 (—21.0)	101.0 (15.0)
(5) Depth of 20°C (m)	195.0	165.0	185.0	198.0 (—3.0)	156.0 (—9.0)	175.0 (10.0)
(6) Heat potential over 28°C (K cal/cm^2)	5.9	8.0	10.3	1.8 (4.1)	0.0 (8.0)	2.7 (7.6)
(7) Heat content of top 10 m (K cal/cm^2)	28.4	28.7	28.8	27.0 (1.4)	26.6 (2.1)	27.3 (1.5)
(8) Heat content of top 100 m (K cal/cm^2)	255.5	264.5	273.8	264.2 (—8.7)	263.2 (1.3)	262.9 (10.9)
(9) Heat content of top 200 m (K cal/cm^2)	466.4	465.3	486.2	476.3 (—9.9)	462.9 (2.4)	456.8 (19.4)

Note : Numbers in parentheses are the differences between pre- and post-onset regimes

All the profiles showed a double maxima with the primary maxima just below the mixed layer and the secondary maxima a little deeper. The only exception was that of 1973 which did not show any secondary maximum during both the regimes. The primary maximum might have been caused due to intense solar heating followed by wind mixing of the upper layers during the preceding summer season. The secondary maximum may be viewed as the remnant of the previous year's below layer gradient descending due to combined effect of mixed layer deepening and downwelling in the thermocline. The magnitude of the secondary maximum might give an indication of the strength of the summer monsoonal forcing of the preceding year. No secondary maximum in 1973 may imply a weak monsoonal forcing in 1972 which was a global drought year. Differences in the strength of primary and secondary maxima among these years can also be noticed. The secondary maxima were relatively weak.

During the pre-onset regime, the primary maximum of 1979 was very weak compared to those of 1973 and 1977. The secondary maxima of 1977 and 1979 were of comparable magnitude. With the onset of the monsoon, the primary maxima descended with differing magnitudes. The rate of descent was minimum in 1979 probably due to weak layer deepening and upwelling from below (Rao 1984). Further, the primary maxima were weakened from pre- to post-onset regime only during 1973 and 1977 but not during 1979. This may indicate that the forcing of the onset vortex was also not strong enough to weaken the primary maximum below mixed layer in 1979. The secondary maxima did not show any change in strength from pre- to post-onset regime. However, ascent of secondary maxima was noticed in 1977 and 1979, the latter with a higher value.

The accumulative values of heat content $(\rho\, c_p \int_0^D T\, dz)$ of the top layers, *viz.*, from surface to 10 m, 20 m, . . and 200 m depths are evaluated for both the regimes. The differences for both the regimes are shown in Fig. 6. Positive values indicate depletion in the heat content with respect to pre-onset regime. The profiles resembled with each other only in the top 40 m water column where mixed layer cooling occurred. In the top 40 m water column the depletion in 1977 was double that of 1973. Below 40 m, the patterns of 1973 and 1977 although appear to run parallel, large differences prevailed in their magnitudes. Below 75 m accumulation of heat was evident only in 1973 while depletion of heat was noticed in 1977 and 1979, the latter with a higher value. This abnormal depletion in 1979 might have resulted due to upwelling of colder waters in the thermocline. The salient thermal features of both the regimes for all the three years are summarized in Table 3.

5. Conclusions

During the three summer monsoon experiments with the formation and passage of onset vortex the year to year variation in the mixed layer cooling was 1.4° to 2.2°C and that of deepening was 20 to 43 m. Minimum deepening of the layer occurred in 1979.

Below layer warming due to deepening of the layer and downwelling below was highest during 1973 (~ 3°C) while mild cooling (~ 1°C) was noticed throughout the 200 m water column in 1979.

During the pre-onset regime primary below layer maximum gradient was weakest in 1979. Secondary maximum gradient was not seen in the profile of 1973 probably due to weak forcing of the summer monsoon during the preceding year in 1972 which was a drought year.

Though depletion of heat was noticed in the topmost layers during all three years, large differences were noticed in the changes of accumulative heat content between the years 1973 and 1979 which were good and bad monsoon years respectively.

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