

Air-sea interaction properties in the eastern Arabian Sea during active phase of off-shore trough (IOP 7-9 August ARMEX-2002)

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सार –दक्षिणी पश्चिमी मानसून ऋतु के दौरान, भारत के पश्चिमी तट के साथ साथ अपतटीय द्रोणियाँ अभिसरण के उथले क्षेत्र में बनीं रहती हैं। उत्तरी केरल से लेकर दक्षिणी गुजरात तक फैले भारत के पश्चिमी तट पर ये द्रोणियाँ प्रायः विकसित और कम होती रहती हैं। आकार में ये द्रोणियाँ विशिष्ट प्रकार की होती हैं जिसका क्षेत्रीय विस्तार 100 कि.मी. के क्रम में तथा लगभग 900 हैक्टापास्कल से परिसीमा स्तर के एकदम ऊपर तक देखा जाता है। मानसून की सक्रिय अवस्था के दौरान और इसी प्रकार कमजोर अवस्था के दौरान तटीय स्थानों में ये भारी वर्षा करती हैं।

इस शोध-पत्र में पूर्वी अरब सागर पर वायु-समुद्र इंटरफेस के पार धरातलीय फलक्सों के अंतरण के पश्चात् तीव्र अपतटीय द्रोणी के अनुसरण की जाँच की गई है। यह द्रोणी 7-9 अगस्त 2002 के दौरान पश्चिमी तट से दूर विकसित हुई। समुद्री स्तर चार्ट पर इस अपतटीय द्रोणी के सिनॉप्टिक संचालन के संबंध में प्राप्त हुए परिणामों की चर्चा की गई।

ABSTRACT. During southwest monsoon season, the off-shore troughs along the west coast (WC) of India occupy shallow zones of convergence. These troughs frequently develop and decay off the WC extending from North Kerala to South Gujarat. They are typical in size, horizontal extent being of the order of 100 km and are discernible from just above the boundary level to about 900 hPa. They produce heavy rainfall over the coastal stations during active phase of the monsoon and *vice-versa* in weak phase.

In the present study the transfer of surface fluxes across the air-sea interface over eastern Arabian Sea following an intense off-shore trough is examined. This trough has developed off the WC during 7-9 August 2002. The results are discussed in relation to synoptic movement of this off-shore trough on the sea level chart.

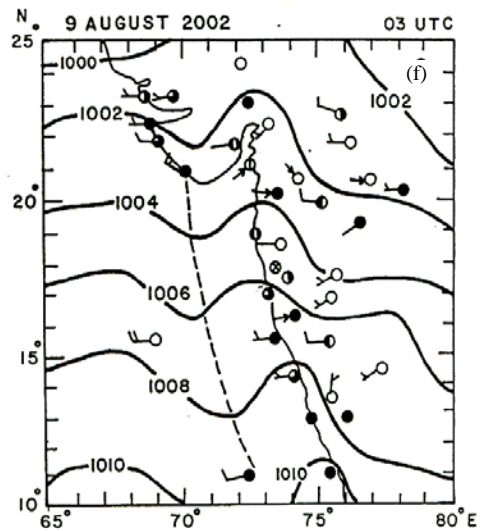
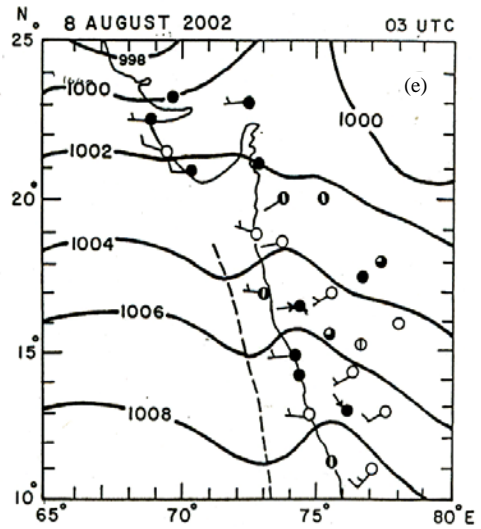
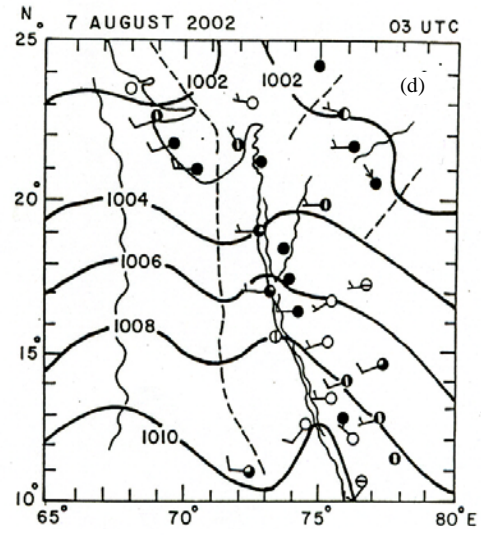
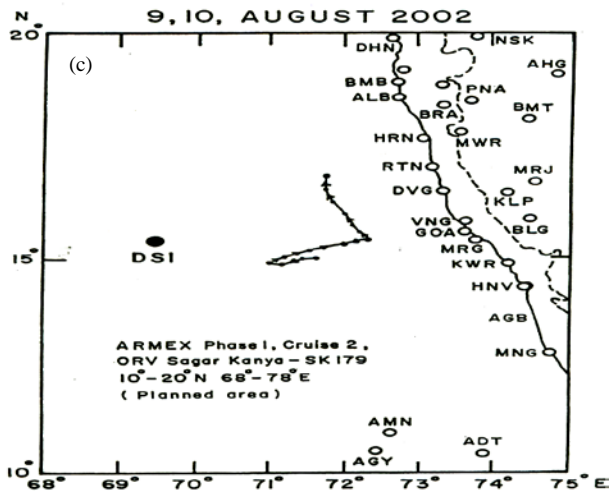
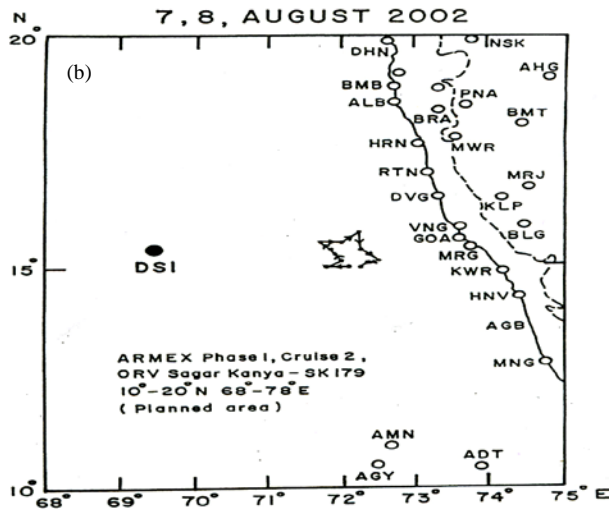
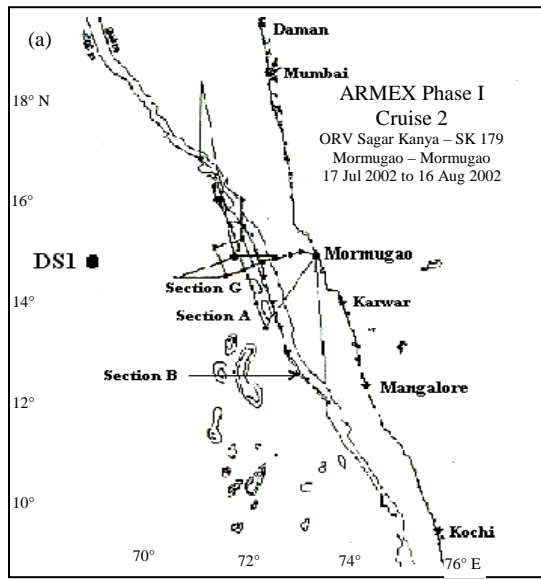
Key words – ARMEX, Arabian Sea, Southwest Monsoon, Off-shore trough.

1. Introduction

The southwest monsoon, which gives 80 % of the annual rainfall of India during four months June to September, is the most outstanding feature of Indian meteorology (Ananthakrishnan *et al.* 1983). The northward advance of south west monsoon is usually associated with some synoptic weather disturbances. In June and July a trough of low pressure off the west coast of India, running north to south is often seen in the surface charts, which is called as off-shore trough (Raj 2003). Ananthakrishnan *et al.* (1968) have found that about 75% of occasions the advance of monsoon is associated with some synoptic scale systems, feeble troughs (off-shore

troughs) on the low level charts (surface and 850 hPa) accounting for about 50% and depressions and storms for about 25%. The frequency of the off-shore troughs is observed to have decreased in August and September as compared with June and July. The associated rainfall along the west coast becomes less in August and September.

The west coast trough frequently develops and decays off the WC extending from North Kerala to South Gujarat. Small vortices develop within this trough. George (1956) has named these vortices as off-shore vortices. Mukherjee *et al.* (1978) have documented the off-shore vortices for the month of July for the period 1974 to 1976.



Figs. 1(a-c). ARDEX Phase-I Cruise track ORV Sagar Kanya SK-179, (a) during 17 July to 18 August 2002, *in situ* cruise track during (b) 7 & 8 August and (c) 9 & 10 August 2002

Figs. 1 (d-f). Synoptic charts at 0300 UTC during, (a) 7 August (b) 8 August and (c) 9 August 2002

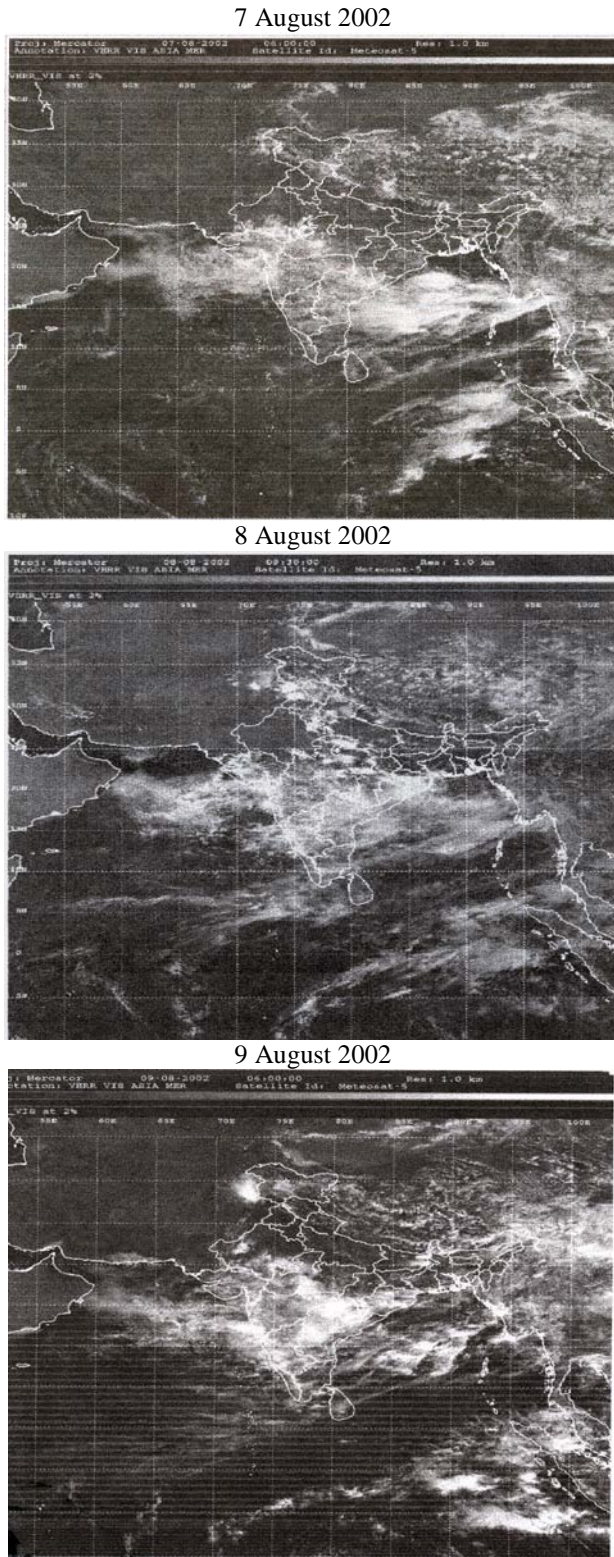


Fig. 2. Meteosat-5 satellite imagery during active Phase of off-shore trough

They concluded that these vortices form just south of 15° N, prominent in July and have a tendency to form in series. Heavy rainfall over the coastal stations is associated with these vortices. Shah (1978) noticed that these vortices are associated with normal or active monsoon conditions and not seen with weak monsoon conditions over the Arabian Sea. By analyzing the dropsonde wind data during MONEX 1979, Mukherjee (1980) found that the off-shore vortices have diameter of about 150 km and height about 1 km from the surface. These systems are typical in size and occupy shallow zones of convergence. They produce heavy rainfall activity over the coastal stations. De (1991) has studied the dynamical properties of the off-shore vortices over the western India.

In the present study an opportunity has arisen to examine the transfer of surface fluxes across the air-sea interface over eastern Arabian Sea following an intense sea level trough. This intense sea level trough has developed off the WC during the period from 7 - 9 August 2002 while during the same period the Arabian Sea Monsoon Experiment (ARMEX) was under progress. The results are presented and discussed in relation to synoptic movement of the off-shore trough.

2. Methodology

The fluxes of momentum (τ), sensible heat (Q_H) and latent heat (Q_E) and Bowen ratio (BR) have been computed using the standard bulk aerodynamic formulae (Seetaramayya and Master 1986) as follows :

$$\tau = \rho C_d U^2 \quad (1)$$

$$Q_H = \rho C_p C_H (T_s - T_a) U \quad (2)$$

$$Q_E = \rho LCE [q_s(T_s) - q(T_a)] U \quad (3)$$

$$BR = Q_H / Q_E \quad (4)$$

The height of the lifting condensational level (H_{LCL}) has been computed following Hsu (1998) as :

$$H_{LCL} = 125(T_a - T_d) \quad (5)$$

where ρ is the density of air ($= 1.23 \text{ kg.m}^{-3}$), C_p specific heat at constant pressure [$= 1005 \text{ J.kg}^{-1}(\text{K})^{-1}$],

TABLE 1

Rainfall in (cm) along the west coast of India during August 2002

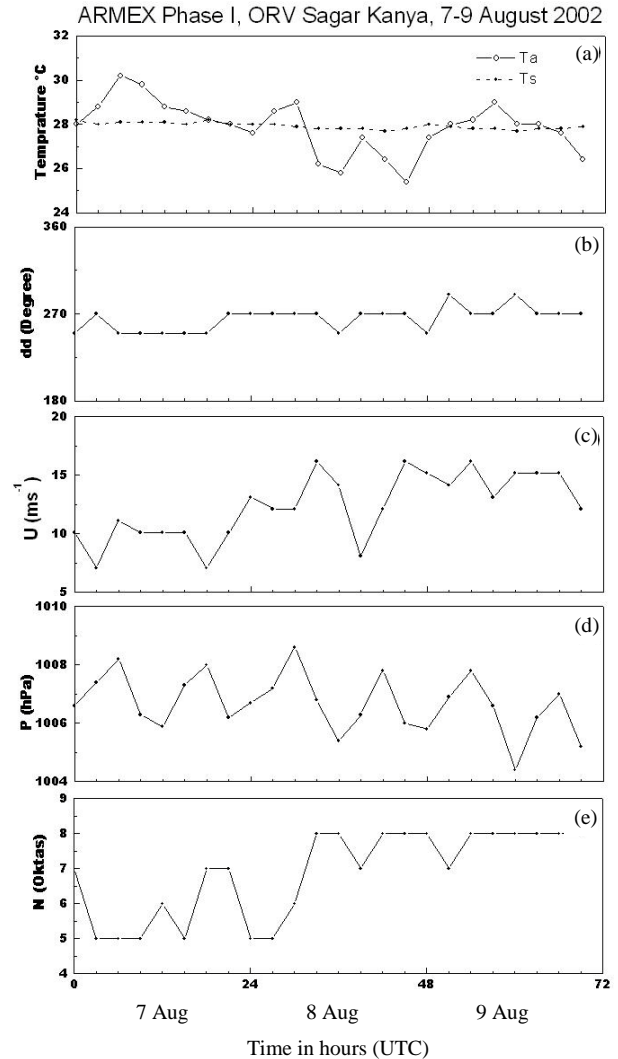
Station	Lat. (°N)	Long.(°E)	August		
			07	08	09
DHN	19.58	72.43	-	18	3
BMB(S)	19.07	72.51	19	-	-
BMB(C)	18.54	72.49	-	10	-
ALB	18.38	72.53	2	-	5
MWR	17.56	73.40	28	-	12
HRN	17.49	73.06	-	-	-
RTN	16.59	73.20	-	-	12
GOA	15.25	73.47	-	-	9
KWR	14.54	74.18	-	1	-
HNV	14.17	74.27	-	-	13
AGB	13.35	75.00	3	4	13
MNG	12.52	74.51	-	3	4

Dhanu-(DHN); Mumbai (Santacruz)-(BMB) (S); Mumbai (Colaba)-BMB (C); Alibag-(ALB); Mahableshwar-(MWR); Harnai-(HRN); Ratanagiri-(RTN); Panaji-(GOA); Karwar-(KWR); Honawar-(HRV); Agumbe-(AGB); Mangalore-(MNG);
Note : (-) Rainfall not reported at particular station

L is the latent heat of evaporation ($= 2.45 \times 10^6 \text{ J.kg}^{-1}$), C_d , C_H and C_E ($= 1.45 \times 10^{-3}$) are the exchange coefficients for momentum, heat and moisture respectively, $q_s(T_s)$ and $q(T_a)$ are saturation specific humidity at sea surface temperature (T_s) and specific humidity of air temperature (T_a) at 10 m height respectively. Hsu (1998) has derived H_{LCL} to the present form based on some thermodynamic considerations such as dry adiabatic lapse rate and dew point lapse rate (McIlveen 1986).

3. Data

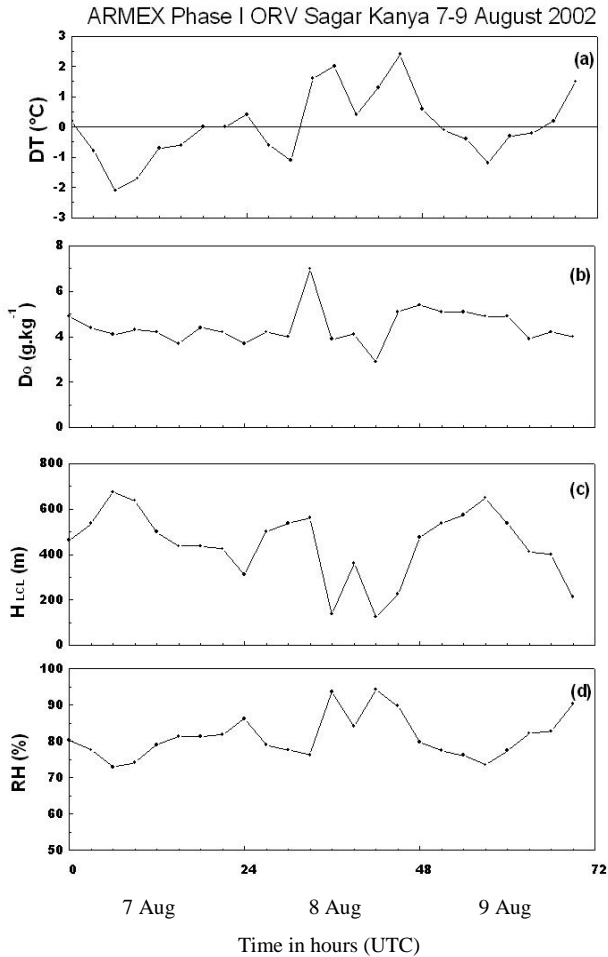
We have used three hourly marine meteorological observations collected onboard ORV Sagar Kanya, by the Indian Meteorological Department (IMD), New Delhi for the period 7 - 9 August, ARMEX-2002. This period has been declared as an intensive observation period (IOP) during the ARMEX. The parameters such as sea surface temperature (T_s), air temperature (T_a), dew point temperature (T_d), wind speed (U), mean sea level pressure (P) are used to compute the fluxes of heat, moisture and momentum.



FIGS. 3(a-e). Time series of (a) Sea surface T_s and air temperature T_a , (b) Wind direction dd , (c) Wind speed U , (d) Pressure P and (e) Total cloud amount N during 7-9 August 2002

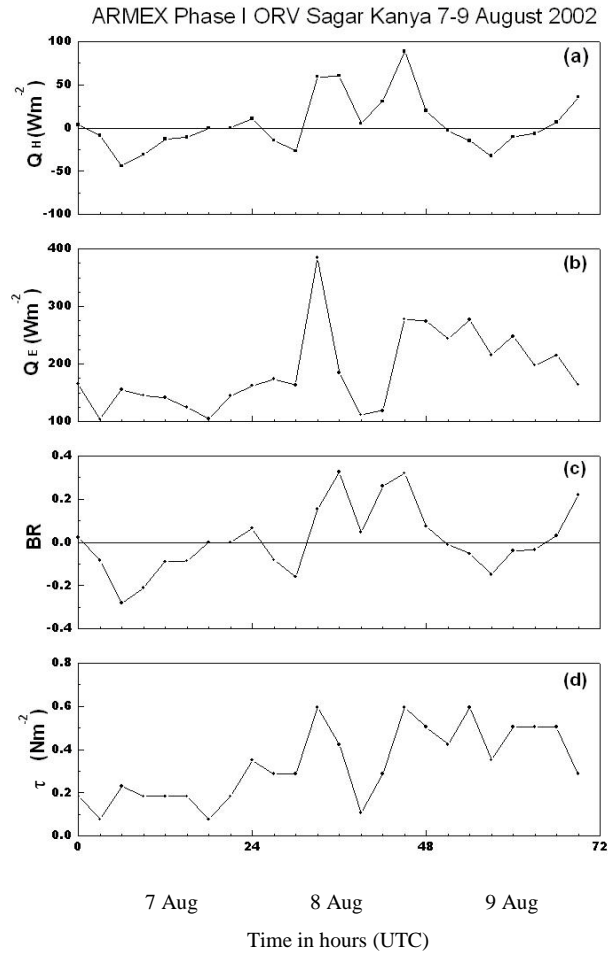
4. Results and discussion

The tracks of the ORV Sagar Kanya research ship are presented in Figs. 1 (a-c). Fig. 1(a) shows the movement of cruise for the whole period of ARMEX - 2002, Phase I, field experiment in the Eastern Arabian Sea, Figs. 1(b&c) shows *in situ* tracks taken on 7 - 8 August and 9 - 10 August respectively. The surface synoptic weather charts are consulted in this study to identify the off-shore trough and the off-shore vortices. Figs. 1(d-f) shows the three consecutive surface synoptic charts showing the existence of off-shore trough in the Arabian Sea off WC during 7-9 August. The trough line



Figs. 4(a-d). Same as Figure 3 but for (a) Temperature difference $DT (=T_s - T_a)$, (b) Specific humidity difference $Dq [= q_s(T_s) - q(T_a)]$ and (c) Height of lifting condensation level H_{LCL} and (d) Relative humidity RH

which had initially aligned along the longitude $72.5^\circ E$ on 7 August 2002 exhibits to and fro oscillation on either side of this longitude during next two days. It extends from Kerala to Gujarat on 7 and 9 August whereas, it has shifted further southward on 8 August. From the comparison of the day to day trough positions with the corresponding ship movements, it has been observed that the ship has always moved close to the trough and followed the trough oscillations as revealed by the tracks of the ship [Figs. 1(b&c)]. Fig. 2 shows the daily Meteosat-5 satellite imagery for the period 7 to 9 August 2002. It is seen from this figure that cloud coverage on 7 August is less as compared to that on 8 and 9 August, which show the intense active phase of the off-shore trough. Table 1 shows the rainfall amount received over some of the coastal stations during this active phase of the



Figs. 5(a-d). Same as Figure 3 but for (a) Sensible heat flux Q_H , (b) Latent heat flux Q_E , (c) Bowen ratio BR and (d) Momentum flux τ

off-shore trough. Remarkable increase in amount of rainfall along the west coast is clearly seen from this Table. On 7 August only few stations reported rainfall, whereas, on 8 and 9 August number of stations and the amount of rainfall is increased.

Figs. 3 (a-e) shows the time series of T_a and T_s , dd , U , P and N . It is observed that [Fig. 3(a)] T_s remains more or less constant at $28^\circ C$ whereas, T_a tends to meander over T_s with warm air during day time and cold air during night time. Wind speed [Fig. 3(b)] shows prominent oscillations on 8 August. From Fig. 3(c) it is clear that wind is blowing nearly westerly throughout the study period. Apart from the semidiurnal oscillations, the surface pressure [Fig. 3(d)] shows a decreasing trend. The

TABLE 2

Daily mean values of DT, D_Q , Q_H , Q_E , BR, and τ

Date	DT (°C)	D_Q (g.kg ⁻¹)	Q_H (Wm ⁻²)	Q_E (Wm ⁻²)	BR	τ (Nm ⁻²)
7 Aug	-0.71	4.25	-12.95	135.86	-0.095	0.162
8 Aug	0.80	4.36	26.81	197.01	0.136	0.366
9 Aug	0.01	4.68	-0.54	229.46	-0.002	0.459
Mean	0.03	4.43	4.44	187.44	0.013	0.329

TABLE 3

Climatological values of, Q_H , Q_E and BR

Month	Parameter		
	Q_H (Wm ⁻²)	Q_E (Wm ⁻²)	BR
July	0	160	0
August	-2	110	-0.018

cloud amount [Fig. 3(e)] increases to 8 oktas from 0900 UTC of 8 August onwards. On 8 August T_s remains constant at 28° C whereas, all other parameters show remarkable changes from 1200 UTC to 2100 UTC through 1500 UTC. T_a shows minimum value of 26° C at 1200 UTC; suddenly increases to 27.4°C at 1500 UTC and again decreases to 25.4° C at 2100 UTC (second minimum value). Wind veers from 260° to 270°, wind speed decreases from 15 ms⁻¹ at 1200 UTC to 7 ms⁻¹ at 1500 UTC and again suddenly increases to 16 ms⁻¹. The surface pressure (P) has increased from 1005.2 hPa at 1200 UTC to 1006.2 hPa at 1500 UTC. On 9 August T_s remains constant around 28° C. The air temperature shows a decreasing trend with an increase at 0900 UTC, wind speed remains more or less constant with a slight decrease at 0900 UTC. The surface pressure decreases from 1007.8 hPa at 0600 UTC to 1004.2 hPa at 1200 UTC. These sudden changes in the above parameters from 1200 to 1500 UTC on 8 August and from 0600 UTC to 0900 UTC on 9 August may be attributed to change in the trough's position.

Figs. 4(a-d) shows the time series of the DT ($= T_s - T_a$), difference between sea surface and air temperature, $D_Q = q_s(T_s) - q(T_a)$, difference between saturation specific humidity at sea surface temperature and specific humidity of air at 10 m height, H_{LCL} , height of lifting condensation level, and RH, relative humidity. It is seen

from Fig. 4(a), that DT , values are negative on 7 August (0 to -2° C) and on 9 August (0 to 1° C), and tends to +ve values (0 to 2.5° C) on 8 August. In Fig. 4(b) D_Q varies between 3 & 7 gkg⁻¹. Figs. 4(c&d) show opposite trend in height of lifting condensation level (H_{LCL}) and (RH) which suggests that as RH increases the (H_{LCL}) falls down, implying formation of clouds in the boundary layer during active phase of the off-shore trough. The values of H_{LCL} [Fig. 4(c)] vary from 125 m to 675 m and RH [Fig. 4(d)] varies between 70 & 95 %. The low values of H_{LCL} coincide with high RH ($\geq 90\%$) and the high values coincide with low RH ($=60\%$).

Figs. 5(a-d) shows the time series of sensible heat (Q_H), latent heat (Q_E), Bowen ratio (BR) and momentum flux (τ). It is seen from Fig. 5(a) that Q_H varies between -44 & 89 Wm⁻². Two epochs ($Q_H < 0$) on 7 and 9 August are separated by a cooler epoch ($Q_H > 0$) on 8 August in the trough. In general Q_E [Fig. 5(b)] varies between 104 & 384 Wm⁻² with mean value 185 Wm⁻². The lowest value (104 Wm⁻²) observed on 7 August at 0300 UTC is associated with warmer air temperature (28.8° C), with wind speed 6 ms⁻¹ and the highest value (380 Wm⁻²) is observed at the time of coldest air temperature (25.4° C) with high wind speed (16 ms⁻¹). It is seen from Fig. 5(c) the range of BR is -0.034 to 0.32. The momentum flux [Fig. 5(d)] shows maximum on 8 August (0.595 Nm⁻²) and minimum on 7 August (0.077

Nm^{-2}). Vinaychandran *et al.* 1989 have studied the latent and sensible heat fluxes over the Arabian Sea during active and break phases of monsoon 1986. They have found high values of latent heat flux ($\approx 260 \text{ Wm}^{-2}$) with active monsoon similar to this study, whereas they reported sensible heat flux in the range between 10 & 15 Wm^{-2} which is comparatively lower than that of the present study.

Table 2 shows the daily mean values (7 - 9 August), of DT, D_Q , Q_H , Q_E and τ . Table 3 shows the monthly mean climatological values of Q_H , Q_E and BR for July and August, over the study region reported by (Hastenrath, & Lamb, 1979). The negative values of DT are reflected in Q_H and BR on 7 and 9 August. The high values of BR on 8 August shows the stability of the atmosphere. The strong winds on 9 August lead to high value of τ . It is seen from Tables 2 & 3 that Q_H , and Q_E , values are larger than climatological value for August. The magnitude of mean Bowen ratio is quite comparable with climatology.

5. Conclusions and remarks

The off-shore trough and off-shore vortices are important monsoon systems, which contribute substantial amount of rainfall along the west coast and help in the revival of southwest monsoon. In this study we have examined three hourly time series of marine meteorological observations recorded during a very active phase of off-shore trough during 7 - 9 August 2002. We have analysed ARMEX-2002 Phase-I data, in consultations with the surface synoptic weather charts 0300 UTC and Meteosat-5 satellite imageries. The results of the preliminary analysis of above data reveal that there exists a well marked trough off the west coast of India during these days. However, no off-shore vortex was noticed. Considerable variations in the meteorological parameters and surface fluxes are observed with the intensification and oscillation of this off-shore trough. The trough shows oscillations on diurnal scale with regard to its intensity and position. These oscillations give rise to changes in the surface meteorological parameters which in turn impact on the air-sea exchanges of sensible heat and latent heat. The average latent flux is about 190 Wm^{-2} which is typical of active monsoon conditions.

Acknowledgements

The authors are thankful to Dr. G. B. Pant, Director IITM, Pune for his constant encouragement, and keen interest in the subject. We acknowledge India Meteorological Department, New Delhi, for availing their data products in the present study (ARMEX Phase I data, Indian daily weather Summary and Weekly Weather Reports etc). Shri. V. V. Devadhar, Draftsman, for his

help in drawing the synoptic charts. The authors are extremely grateful for the valuable comments and suggestions given by the referee.

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