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Role of Heat, Moisture and Momentum Transport across the Air-sea Interface in the Off-shore Trough over the Eastern Arabian Sea during (IOP 22 July - 4 August) ARMEX - 2002.

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ABSTRACT
The day-to-day variability in the synoptic and sub-synoptic weather conditions is responsible for the development, intensification and dissipation of the offshore troughs. The evolutionary processes have been examined using recent surface meteorological data recorded onboard ORV Sagar Kanya, during an intensive observation period (IOP 22 July- 4 August) of ARMEX-2002. Indian daily weather summary (IDWS) have also been consulted. Bulk formulae have been used to compute surface fluxes. The parameter D_Q (= difference between saturation specific humidity at sea surface temperature and specific humidity of air at 10m height) is used to assess the moist spells. It is observed that the marine atmosphere near the sea level over the eastern Arabian Sea has become dry (D_Q>4 g.kg^{-1}) due to the weakening of the offshore trough and tends to become moist (D_Q<4 g.kg^{-1}) due to the intensification of this offshore trough.

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 summer monsoon is usually associated with some synoptic weather disturbances (Shrestha 1980). 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 offshore trough (Raj 2003). The frequency of the offshore troughs is observed to have decreased in August and September as compared with June-July and the associated rainfall along the west coast becomes less in August and September. The offshore trough is an important disturbance in causing active/weak monsoon conditions over the west coast of India. It extends normally only up to 10°N and the associated rainfall decreases south of 10°N over the west coast. The vertical extent of the offshore trough is generally confined up to 1 km height above mean sea level. Its presence can be detected from the winds of coastal stations and the Arabian Sea islands. Over Kerala 90 % of active monsoon conditions are associated with offshore troughs. Heavy rainfall is generally realized in the southern portion of trough (Raj 2003). Ananthakrishnan, Pathan, & Aralikatti (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% depressions and storms for about 25%.

In the present study an attempt is made to examine the air–sea interface processes based on the measurements made during ARMEX-2002. ARMEX (Arabian Sea Monsoon Experiment) is a national scientific program conducted by Department of Science and Technology, New Delhi, India with one of its objectives to understand and explain the processes that govern the genesis and intensification of offshore troughs and embedded vortices over the eastern Arabian Sea during the peak monsoon months. The variations in surface meteorological parameters and associated surface fluxes across the air-sea interface from 22 July to 4 August 2002 are examined in this study.

DATA AND METHODOLOGY

Three hourly routine surface marine meteorological parameters such as sea surface temperature (Ts), air temperature (Ta) and dew point temperature (Td) at reference height of 10m, mean sea level pressure (P),

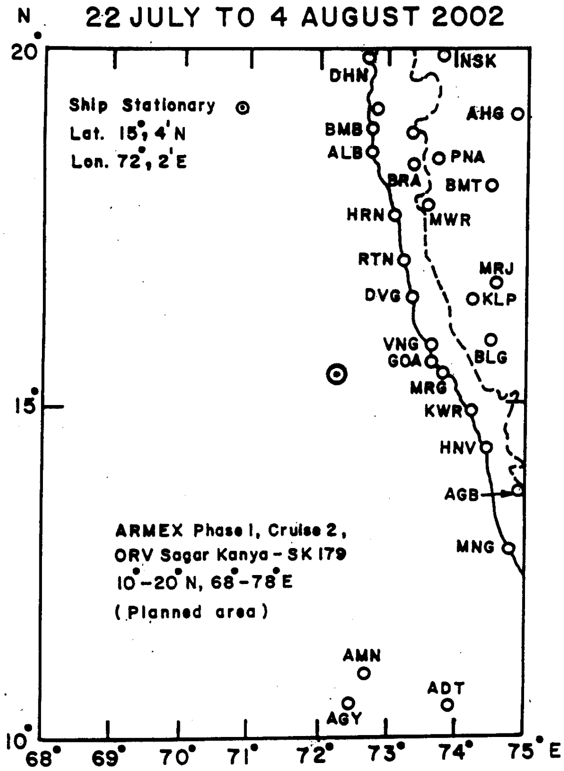

Figure 1. The location of ORV Sagar Kanya stationary at 15°4'N, 72°2'E (marked by circular dot) during 22 July to 4 August 2002.

wind speed (U) and wind direction (dd) at 10 m height and total cloud cover (N) collected on-board ORV Sagar Kanya (cruise No. SK179) by the India Meteorological Department, New Delhi is analysed. Fig.1 shows the stationary position of the ship at 15°4'N, 72°2'E (marked by circular dot) during the period from 22 July to 4 August 2002, ARMEX -2002, Phase I.

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

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

$$Q_H = \rho C_p C_H \,(Ts\text{-}Ta)\, U \quad (2)$$

$$Q_E = \rho L C_E (q_s\,(Ts)\text{-}q\,(Ta))\, U \quad (3)$$

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

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

$$H_{LCL} = 125(Ta\text{-}Td) \quad (5)$$

Where ρ is the density of air (=1.23 kg.m^{-3}), C_p specific heat at constant pressure (=1005 J.kg^{-1} (°K)$^{-1}$, L is the latent heat of evaporation (= 2.45X10^{6} J.kg^{-1}), C_d, C_H and C_E (=1.45X10^{-3}) are the exchange coefficients for momentum, heat and moisture respectively, q_s (Ts) and q (Ta) are saturation specific humidity at sea surface temperature (Ts) and specific humidity of air temperature (Ta) at 10m 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)

Synoptic Weather conditions

From a close examination of all India Daily Weather Summaries and Weekly Weather Reports, it is noticed that throughout the period of observations (i.e. 22 July to 4 August 2002) an offshore trough is always present along the west coast of India. This offshore trough is found to be quite weak up to 31 July 2002; therefore the Arabian Sea branch of summer monsoon has become weak. Due to this weakness a few isolated heavy spells of rainfall along the west coast. Consequently, continuous rainfall for 2-3 days has seldom been observed at any two consecutive stations along the west coast. However, some isolated heavy rainfall has been observed at Mahabaleshwar, viz. 15 cm on 23 July and 9 cm on 25 July. Similarly Augumbe has received heavy rainfall of 6 cm on 23 July and 18 cm on 28 July (vide Table 1). Fig. 2 shows the satellite imageries on some selective days (23, 26, 29 and 30 July 2002) during these feeble conditions of the offshore trough. It is seen from this Fig. that the Arabian sea seems to be nearly cloud free, especially, close to the west coast of India. The ship also has reported quite clear weather conditions with hazy sky during most of the time of observations that complement the above satellite imageries.

Fig.3 shows surface synoptic charts for last four days from 1 to 4 August 2002. During these days the offshore trough has intensified vigorously. An offshore trough in the eastern Arabian sea (marked by dashed line) is clearly seen in the Fig. It is confined to southeast Arabian Sea. The trough line is not continuous during 1 August to 3 August 2002. The isobaric spacing on 1 and 2 August appears to diverge with weak pressure gradients along the west coast of India. On 3rd August, the pressure gradient appears to increase between 15-20°N with a northward movement of trough line and on 4th August, this trough appears to be intensified and moved further northwards parallel to the west coast. It has further deepened and concentrated over an area between 13°N-18°N, and 71°E-73°E. Fig. 4 shows the satellite imageries for 1-4 August 2002. An increase in cloudy area near the south-west coast of India is clearly seen from the Fig. (vide picture on 1st August 2002). Dense cloud clusters along the coastline are visible on 2nd

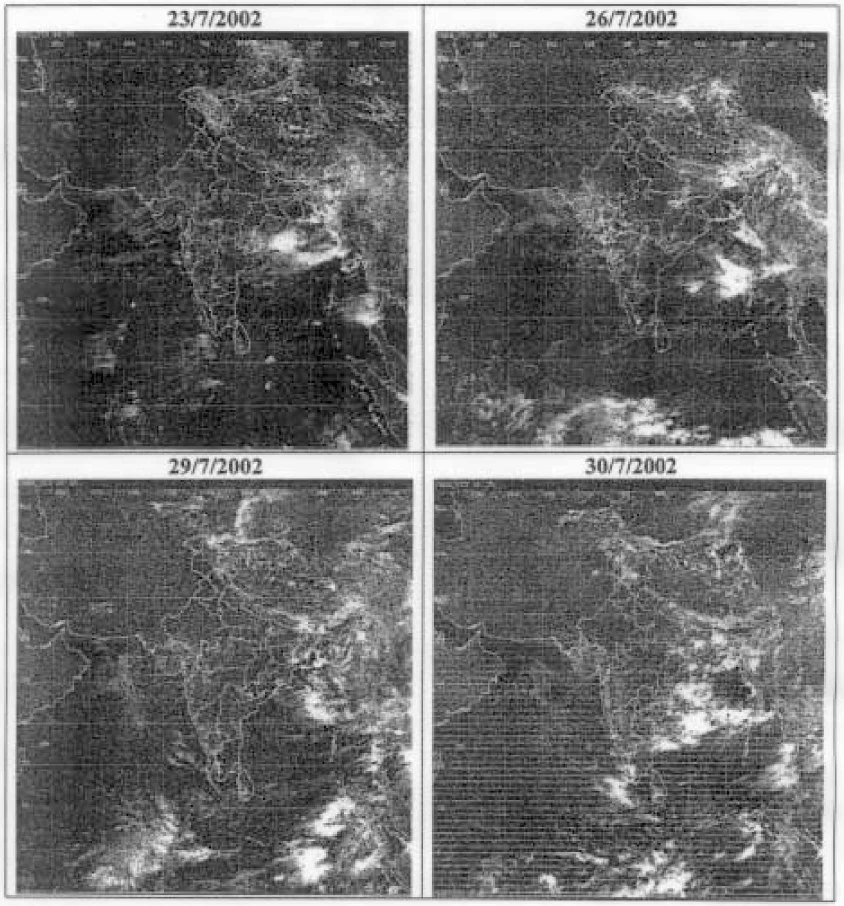

Figure 2. Meteosat-5 06 UTC,Visible imageries during weak conditions of the off-shore trough.

Table 1. Rainfall along the west coast of India during 22 July to 4 August 2002.

		← July									→	← August		→
STN/ DATE	LAT/LON °N / °E	22	23	24	25	26	27	28	29	30	31	01	02	03	04
DHN	19.58, 72.43	-	-	-	-	-	1	-	NA	-	NA	-	-	-	-
BMB(s)	19.07, 72.51	-	-	-	-	-	-	-	NA	-	NA	-	-	-	2
BMB(c)	18.54, 72.49	2	-	1	2	2	-	-	NA	-	NA	-	-	-	-
ALB	18.38, 72.52	-	2	-	-	-	-	-	NA	-	NA	-	-	-	6
MWR	17.56, 73.40	-	15	-	9	-	-	-	NA	-	NA	-	-	-	-
HRN	17.49, 73.06	-	-	7	-	-	-	-	NA	-	NA	-	-	-	-
RTN	16.59, 73.20	2	-	2	4	-	2	1	NA	-	NA	-	-	3	-
GOA	15.25, 73.47	-	-	-	-	-	-	-	NA	-	NA	-	-	-	9
KWR	14.54, 74.18	2	2	-	-	-	1	-	NA	-	NA	-	-	1	5
HNV	14.17, 74.27	3	-	-	-	2	1	-	NA	-	NA	6	-	-	-
AGB	13.35, 75.00	-	6	-	-	-	2	18	NA	-	NA	-	5	9	-
MNG	12.52, 74.51	-	4	1	-	2	-	6	NA	2	NA	-	-	1	3

Stations along West coast: Dahanu ; Mumbai (SCZ) ; Mumbai (Colaba) ; Alibag ; Mahableshwar ; Harnai;Ratanagiri; Goa ; Karwar ; Honawar ; Agumbe ; Mangalore.
These stations are marked with respective abbreviations in Fig. 1.
Note: (-) Rainfall not reported at the particular station
(NA) Data not available

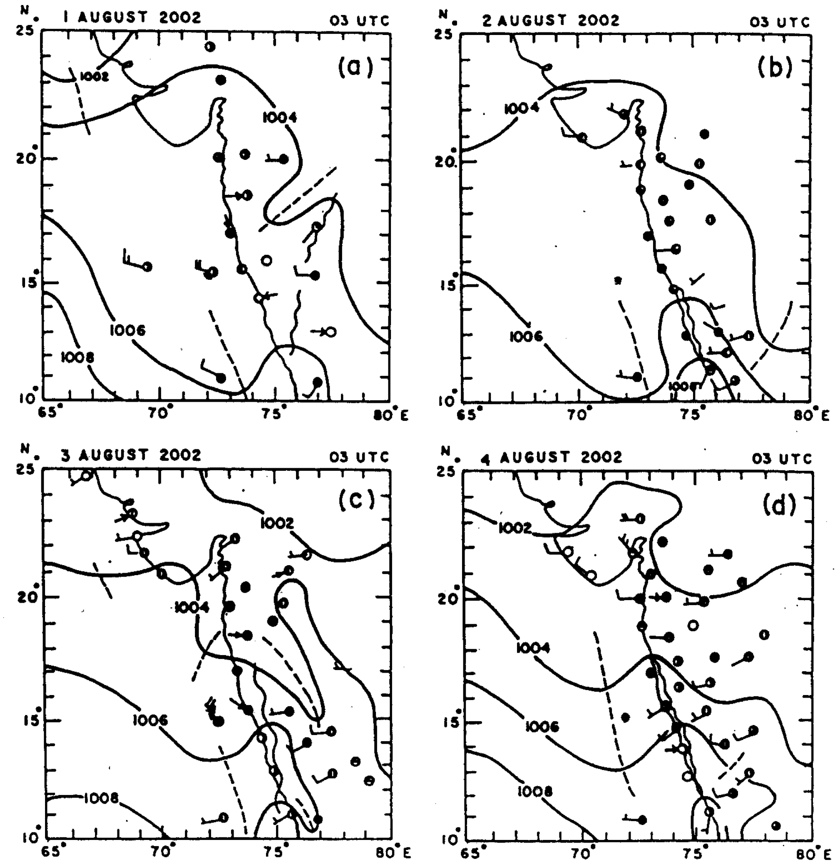

Figure 3. Synoptic charts at 03 UTC during 1-4 August 2002.

and 3rd August with this northward movement. This cloudy area further moves northward along with northward movement of the trough on 4th August 2002. Due to intensification of this offshore trough, the Arabian Sea branch of monsoon became active and there exists a spell of heavy rainfall at many stations along the west coast of India on 4 August. Table 1 gives the rainfall recorded at stations along the west coast of India on 4 August 2002. Alibag has recorded 9cm, whereas Panaji (Goa) has recorded 9cm of rainfall on 4 August. The ship also has recorded rainfall during 2-4 August 2002. Afterwards the sky again has become hazy and partly cloudy over the ship.

RESULTS AND DISCUSSION

Fig. 5(a-e) shows the distribution of Ts, Ta, dd, U, P, and N during the period 22 July to 4 August 2002 at the stationary position 15°4′N, 72°2′E. In this Fig. 00 hour on abscissa corresponds to 00 UTC of 22 July, 240 hour corresponds to 00 UTC of 1 August, 312 hour corresponds to 00 UTC of 4 August and finally the last hour corresponds to 21 UTC of 4 August 2002.

It is seen from Fig. 5a that Ts, starting with 27.0°C at 00 UTC on 22 July, has gradually increased to 28.5°C at 15 UTC on the same day. Thereafter it has remained more or less constant at 28°C with small fluctuations during night hours and this trend has continued till the last day of observations. However, Ta has shown systematic diurnal variations with a maximum around 09 UTC and minimum around 00 UTC every day from 22 to 31 July. Large fluctuations during 1 to 4 August in Ta are noticeable due to changing cloud cover and associated rain spells (Fig. 5e). During day time Ta tends to become higher than Ts and reduces to Ts during night time from 22 to 31 July, while Ta is always lower than Ts from 2 to 4 August 2002 except at 00 UTC of 4 August. During the period from 1 to 4 August Ta in general appears to fall below Ts due to the cloudy sky conditions. The steep decreases in Ta confine to rain spells on these occasions.

The wind direction (dd in Fig. 5b) has varied between 250°-340°, with its average value at 290° (i.e. westnorthwesterly). Fig. 5c shows that wind speed (U) has varied between 8 to 28 knots with an average value

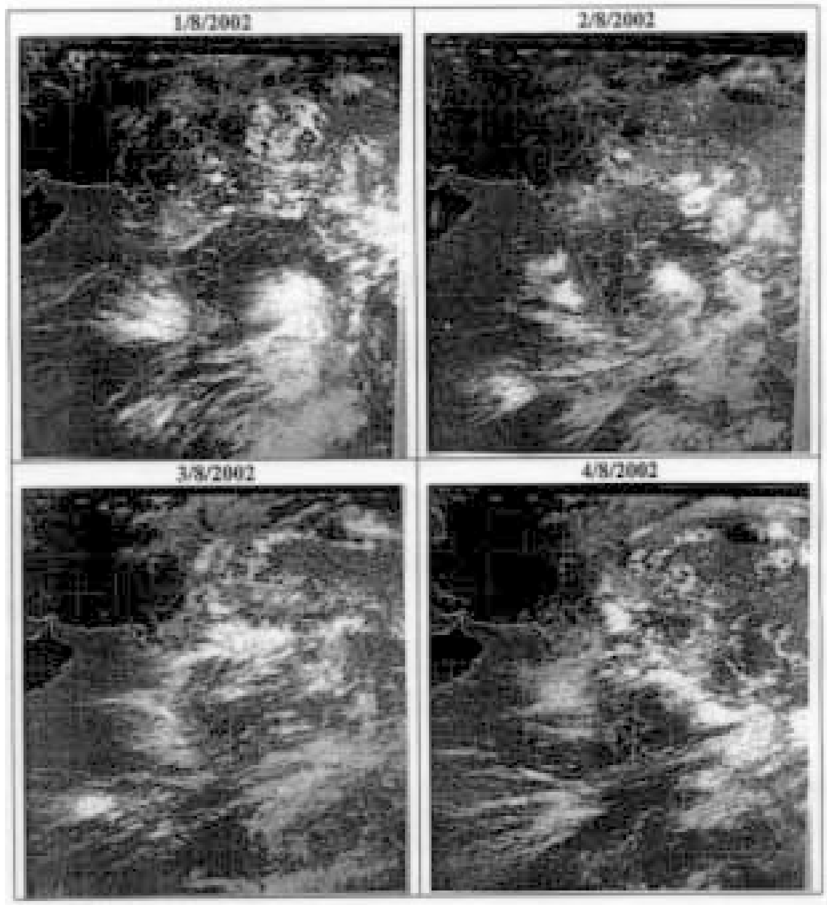

Figure 4. Meteosat-5 06 UTC, Visible imageries during developing stages of the off-shore trough.

Table 2. Daily mean Values at (15°4′N, 72°2′E) during 24 July-4 August 2002.

Date	DT(°C)	D_Q(g.kg^{-1})	Q_H(Wm^{-2})	Q_E(Wm^{-2})	BR	Tau (Nm^{-2})
22/7	-0.89	4.9	-20.80	179.62	-0.116	.225
23/7	-0.99	4.7	-21.63	167.70	-0.129	.203
24/7	-0.74	4.8	-10.84	138.57	-0.078	.125
25/7	-0.55	5.1	-6.51	154.13	-0.042	.158
26/7	-0.81	5.2	-12.69	155.79	-0.081	.138
27/7	-0.64	4.7	-8.93	123.68	-0.072	.111
28/7	-0.70	4.5	-10.97	127.48	-0.086	.120
29/7	-0.79	4.8	-12.61	137.74	-0.092	.127
30/7	-0.54	4.6	-7.09	124.71	-0.057	.112
31/7	-0.55	4.5	-7.58	123.30	-0.061	.114
1/8	-0.35	4.5	-7.57	149.09	-0.051	.177
2/8	1.36	4.6	27.06	148.56	0.182	.180
3/8	0.99	4.7	15.79	137.95	0.114	.134
4/8	0.31	3.1	5.25	106.11	0.049	.194
Mean	-0.34	4.6	-5.65	141.03	-0.037	.151

Table.3 Comparison with Climatology Hastenrath & Lamb (1979)

Month / Parameter	Q_H(Wm^{-2})	Q_E(Wm^{-2})	BR
July	0	160	0
August	-2	110	-0.018

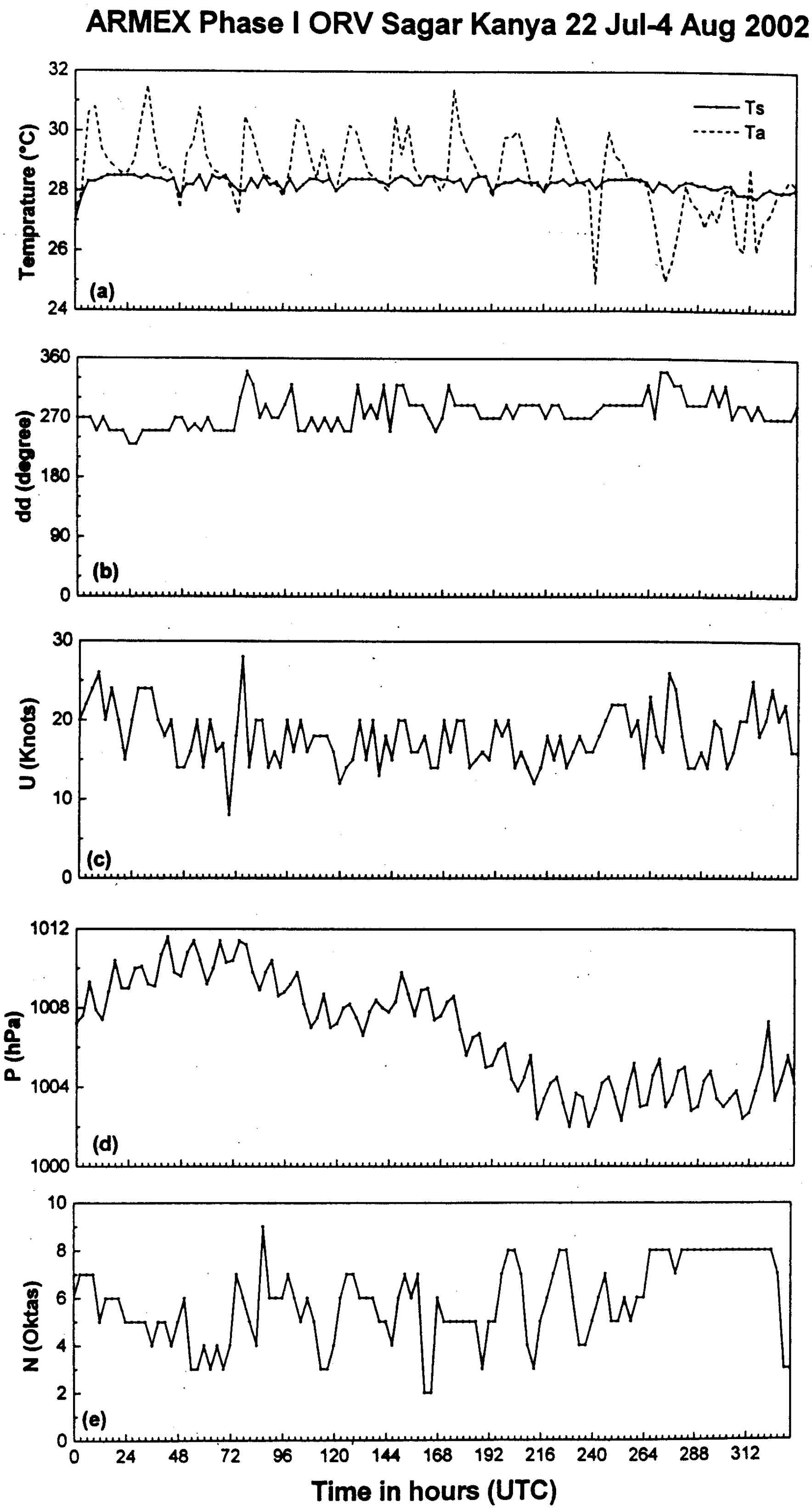

Figure 5. Time series of (a) Temperature Ts and Ta, (b) Wind direction dd,(c) Wind speed U (d) Pressure P and (e) Total cloud amount N during 22 July to 4 August 2002.

of 18 knots. It is observed that the wind speed is not uniform but appears to fluctuate frequently with amplitude of 2-5 knots with change in pressure (Fig.5d) and wind direction (Fig.5b). Its amplitude is 10 knots at late night on 23 July when minimum and maximum has been observed during two consecutive observations. Significant fluctuations both in U and dd are noticed between 1 to 4 August 2002 and these fluctuations are due to the growing cloud cover (vide Fig.5e) and pressure (Fig.5d).

From Figs 5d and 5e it is noted that in general the mean sea level pressure pressure (P) and total cloud amount (N) have maintained opposite trends to each other. This implies that the high values of P appear to coincide with low values of N and vice-versa. Even though both the parameters P and N have shown opposite trends to each other, the parameter P has systematic semi-diurnal as well as synoptic oscillations of 3-6 days while N has inhibited such trends on a diurnal scale. Between 22 and 25 July, though the average pressure attains a high value (P=1010 hPa), N has varied between 3 to 7 oktas. Thereafter the pressure has gradually decreased sinusoidally to a low value of 1002 hPa on 31 July 12 UTC. It has fluctuated around 1003 hPa during the rest of the period following the northward movement of the trough line. It has shown an increase on 4 August when the intensified offshore trough lies just to the western side of the ship (marked by circular dot in Fig. 3d). The associated cloud amount appears to vary from 6-8 oktas during 31 July to 2 August and 8 oktas afterwards. There is a rapid fall in N during the last few hours of observations, which might have occurred due to an increasing pressure tendency

Fig.6(a-d) shows the time series of relative humidity (RH), height of the lifting condensation level (H_{LCL}), sea-air temperature difference (DT=Ts-Ta) and specific humidity difference (D_Q= q_s(Ts)-q(Ta)). It is seen from Figs 6a and 6b that an increase in RH seems to have reflected in decrease in H_{LCL}. It implies that higher (lower) the RH, lower (higher) is the H_{LCL}. The H_{LCL} is seen to be very sensitive to RH over this region of study. The high RH favors the formation of the clouds in the boundary layer at lower levels in the moist environment and low RH leads to stratification of clouds in the upper layers of the atmosphere with the rise in the H_{LCL}. RH appears to vary from 60-85 % during 22 July to 31 July. The corresponding H_{LCL} has shown a variation from 300 to 950m. During 1-3 August when the trough was intensifying RH has varied from 80-100%. It is also noticed that when RH attains 100% at 03 UTC on 4 August, the H_{LCL} has reduced to very low value (20m or even less than that). From the variability in DT as shown in Fig.6c it is seen that the Arabian Sea was rather cooler than the air up to 1 August. Between 1-4 August DT shows a positive tendency. This implies that the air temperature has become cooler than the Ts (which remained constant at 28°C). The reason for the positive DT is mainly the cool air breeze spreading over the area due to developing clouds in the offshore trough (vide Fig. 3). The values of D_Q in Fig.6d are fluctuating between 4 to 6 g.kg^{-1} (implying dry spell) up to 31 July. It has varied between 4 and 5 g.kg^{-1} (fairly moist spell) from 1 August to 3 August. An abrupt drop in D_Q to 2 g.kg^{-1} (moist spell) is due to sudden decrease in Ta as seen in Fig. 5a. Though Ts was nearly constant around 28°C on 4 August, Ta has lowered by 2.8°C from 00 UTC to 03 UTC, which led DT to become positive, and a drop in D_Q i.e. a moist spell.

The variations of surface heat fluxes Q_H and Q_E (sensible and latent heat respectively), Bowen ratio (BR) and momentum flux (Tau) are shown in Fig.7 (a-d). It is seen from Fig. 7a that most of the time Q_H is negative up to 1 August due to DT<0 as seen in Fig. 6c. It varied between -71 Wm^{-2} (on 23 July, 09 UTC) to 86 Wm^{-2} (on 2 August 09 UTC). At the time of these extreme values of Q_H, the absolute value of DT is > 2°C and wind speed is above 20 knots. Fig.7b shows large fluctuations in Q_E in the range of 70 to 240 Wm^{-2}. High values of Q_E are associated with strong winds and high D_Q. During moist spell Q_E reduced to 70-100 Wm^{-2}. The time series of BR in Fig. 7c shows similar pattern as that of Q_H in Fig.7a. It varies between -0.31 to 0.44. With the intensification of the trough, BR shows positive values. The values of Tau in Fig. 7d are quite high (0.42 Nm^{-2}) on 25 July 03 UTC associated with strong winds of 28 knots. Other peaks of high values are observed on 2 August 09 UTC (0.35 Nm^{-2}) and 4 August 00 UTC (0.32 Nm^{-2}) when the wind speed was 26 and 25 knots respectively. It is below 0.2 Nm^{-2} when wind speed was below 20 knots during 25 July to 31 July 2002.

The daily mean values of DT, D_Q, Q_H, Q_E, BR and Tau are given in Table 2. It is seen from the Table that the sea surface over the Arabian Sea was colder than the atmosphere up to 1 August. It was warmer on 2 August i.e. prior to the intensification of the offshore trough. Thereafter Ts decreased but still it remained warmer than the overlying atmosphere. The atmosphere was moist on 4 August as revealed from the lowest value of D_Q. Negative values of Q_H and BR indicate that the atmosphere was stable up to 1 August and it became unstable afterwards. Overall very low negative mean value of BR clearly shows near

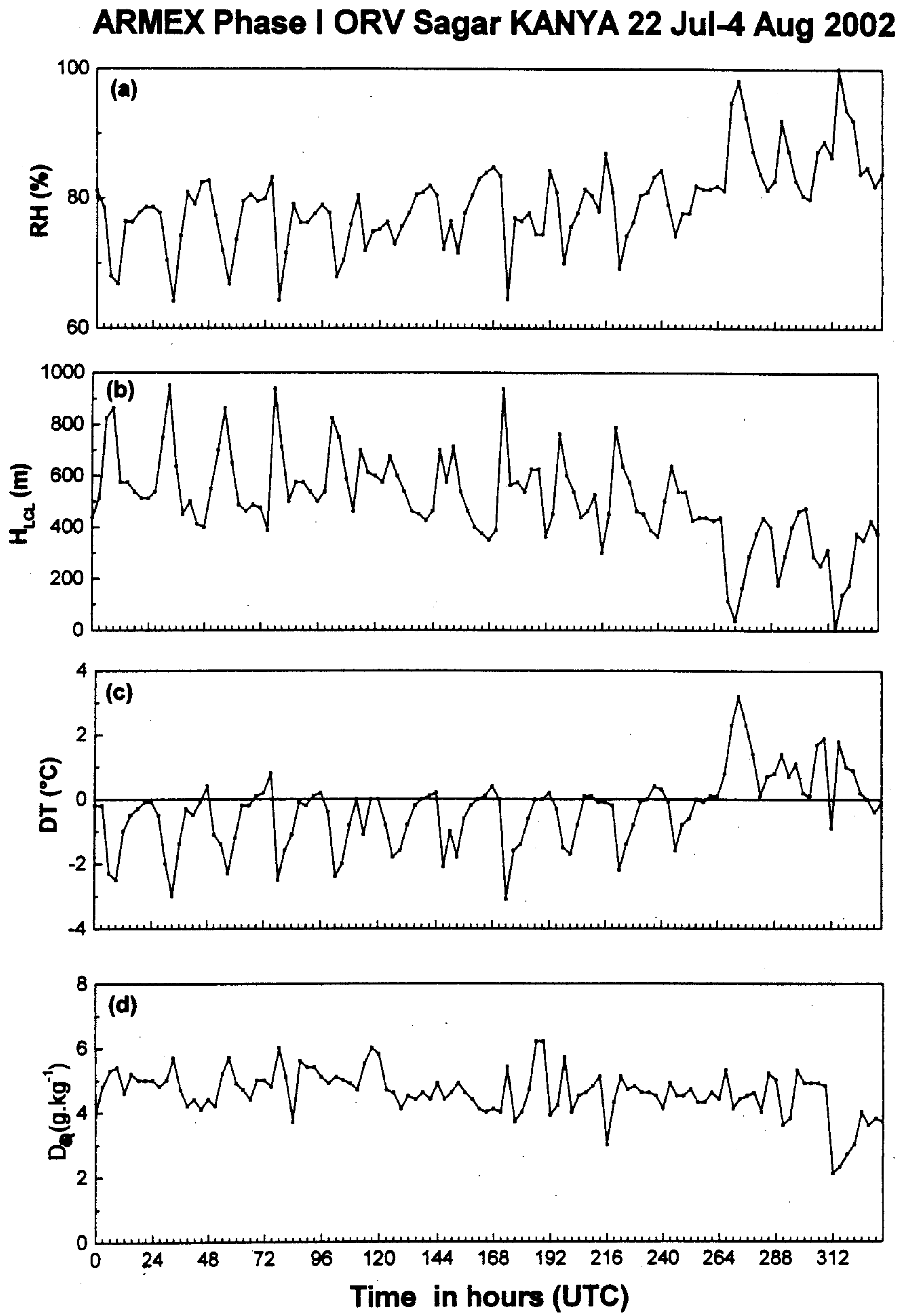

Figure 6. Same as Fig. 5 but for (a) Relative humidity RH, (b) Height of lifting condensation level H_{LCL}, (c) Temperature difference DT (=Ts-Ta) and (d) Specific humidity difference D_Q (=q_s(Ts)-q(Ta)).

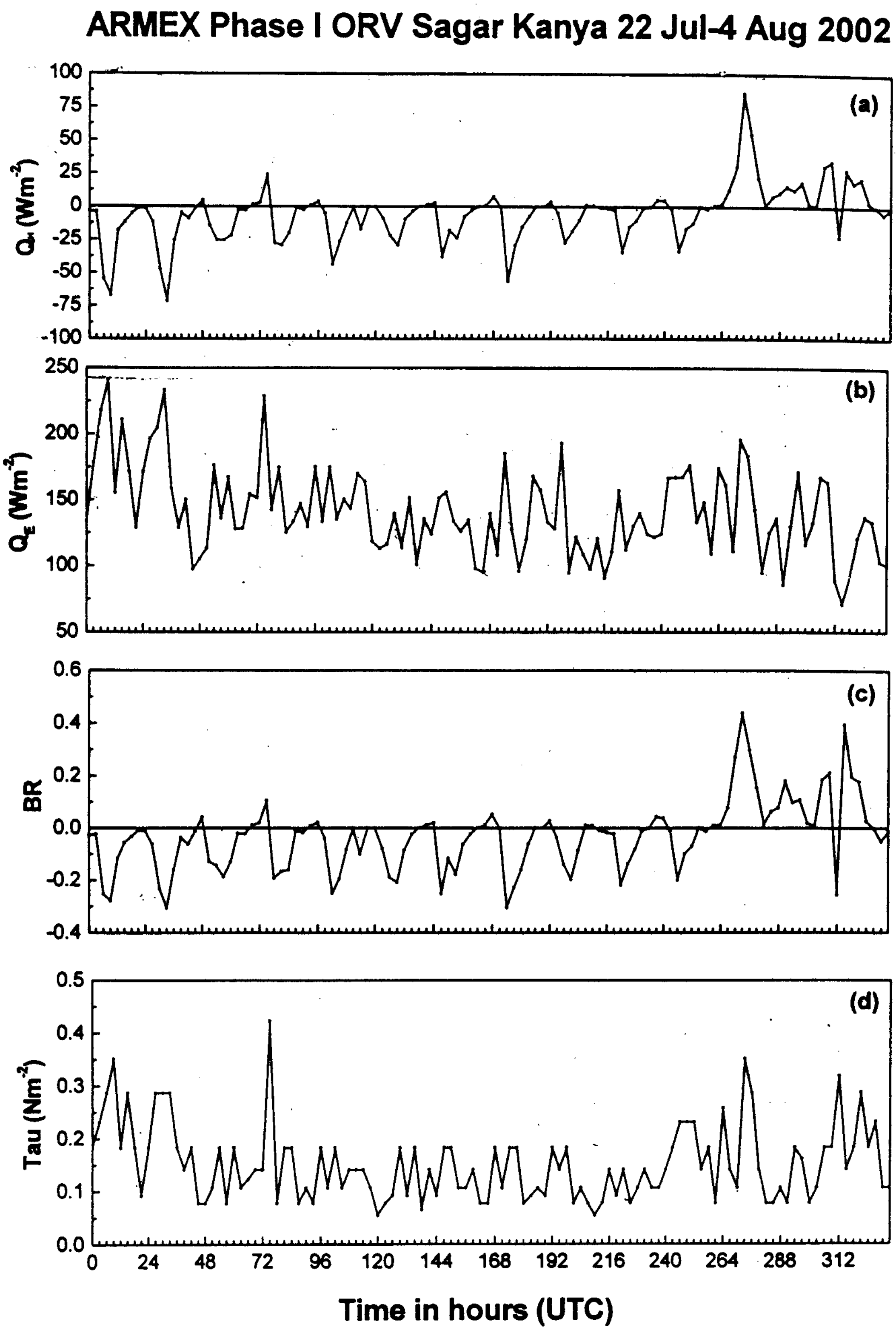

Figure 7. Same as Fig. 5 but for (a) Sensible heat flux Q_H, (b) Latent heat flux Q_E, (c) Bowen ratio BR and (d) Momentum flux Tau.

neutral conditions of the Arabian Sea during the study period. These mean values of Q_H, Q_E and BR when compared with the climatological monthly mean values (Hastenrath & Lamb 1979) over this region for the months of July and August, it is found that they are in agreement (Table 3).

CONCLUSIONS

The surface meteorological observations taken on-board ORV Sagar kanya during ARMEX-2002 (IOP: 22 July to 4 August 2002) have been used to study air-sea interface characteristics over Arabian Sea. During this period the ship was stationary at 15°4′N, 72°2′E. A weak and broken offshore trough extending from Maharashtra coast to Kerala coast was present throughout the period i.e. 22 July-4 August 2002. This offshore trough intensified and deepened on 4 August 2002. Due to the intensification of this trough, the Arabian Sea branch of southwest monsoon had become active and many of the stations along the west coast of India received heavy to very heavy rainfall.

In general the east Arabian Sea was colder than air at 10m height up to 31 July. The sea surface temperature was more or less constant at 28°C throughout the study period and air temperature at 10m height appears to meander on it. During the evolutionary stage of the trough, a marked drop in air temperature, an increase in wind speed and total cloud amount is noticed. During 2-4 August sensible heat flux had become positive, the air-sea interface was moist (RH>80 %, D_Q<4 g.kg^{-1}) and the Bowen ratio had attained high values (0.2-0.4). The distribution of the parameters H_{LCL} and RH have shown exactly opposite trend to each other. During dry periods (RH<70 %, D_Q= 4 to 6 g.kg^{-1}), the H_{LCL} rises as high as 990m on 23, 25 and 29 July whereas, during the period of moist spell (RH > 80% D_Q<4 g.kg^{-1}) from 2 to 4 August, the H_{LCL} has come down varying between 20-400m.

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