

4. Price, J. F., Sanford, T. B. and Forristall, G. Z., Forced stage response to a moving hurricane. *J. Phys. Oceanogr.*, 1994, **24**, 233–260.
5. Saji, P. K., Shenoi, S. C., Almeida, A. and Rao, G., Inertial currents in the Indian Ocean derived from satellite tracked surface drifters. *Oceanol. Acta*, 2000, **23**, 635–640.
6. Shay, L. K. and Chang, S. W., Free surface effects on the near-inertial ocean current response to a hurricane: A revisit. *J. Phys. Oceanogr.*, 1997, **27**, 23–39.
7. Webster, F., Observations of inertial period motions in the deep sea. *Rev. Geophys.*, 1968, **6**, 473–490.
8. Gill, A. E., *Atmospheric–Ocean Dynamics*, Academic Press, San Diego, California, 1982, p. 662.
9. Pollard, R. T., On the generation by winds of inertial waves in the ocean. *Deep-Sea Res.*, 1970, **17**, 795–812.
10. Pollard, R. T. and Millard Jr., R. C., Comparison between observed and simulated wind-generated inertial oscillations. *Deep-Sea Res.*, 1970, **17**, 813–821.
11. Weller, R. A., The relation of near-inertial motions observed in the mixed layer during the JASIN (1978) experiment to the local wind stress and to the quasi-geostrophic flow field. *J. Phys. Oceanogr.*, 1982, **12**, 1122–1136.
12. Gonella, J., A local study of inertial oscillations in the upper layers of the ocean. *Deep-Sea Res.*, 1971, **18**, 775–788.
13. Pond, S. and Pickard, G. L., *Introductory Dynamical Oceanography*, Pergamon Press, 1983, p. 64.
14. Shenoi, S. C. and Antony, M. K., Current measurements over the western continental shelf of India. *Continent. Shelf Res.*, 1991, **11**, 81–93.
15. Rao, R. R., Sanilkumar, K. V. and Mathew, B., Observed variability in the current field during summer monsoon experiments. I: Northern Bay of Bengal. *Mausam*, 1991, **42**, 17–24.
16. Rao, R. R., Kumar, K. V. S. and Mathew, B., Observed variability in the current field during summer monsoon experiments: Arabian Sea. *Mausam*, 1996, **47**, 355–368.
17. Yelland, M. and Taylor, P. K., Wind stress measurements from the open ocean. *J. Phys. Oceanogr.*, 1996, **26**, 541–558.
18. Price, J. F., Upper ocean response to a hurricane. *J. Phys. Oceanogr.*, 1981, **11**, 153–175.
19. Gonella, J., A rotary-component method for analyzing meteorological and oceanographic vector time series. *Deep-Sea Res.*, 1972, **19**, 833–846.
20. Emery, W. J. and Thomson, R. E., *Data Analysis Methods in Physical Oceanography*, Elsevier Science, 1998, p. 431.
21. Torrence, C. and Compo, G. P., A practical guide to wavelet analysis. *Bull. Am. Meteorol. Soc.*, 1998, **79**, 61–78.

ACKNOWLEDGEMENTS. We thank the Secretary, Ministry of Earth Sciences (MES), Government of India; Director, National Institute of Ocean Technology (NIOT) and the National Data Buoy Programme (NDBP) team for providing support and encouragement. India Meteorological Department (IMD) is acknowledged for cyclone report and Cochin University of Science and Technology (CUSAT), Cochin for facilities. The wavelet software was accessed from URL: paos.colorado.edu/research/wavelets. Comments by unknown referees improved the manuscript.

Received 1 May 2006; revised accepted 18 October 2006

## On the plausible reasons for the formation of onset vortex in the presence of Arabian Sea mini warm pool

R. Deepa, P. Seetaramayya, S. G. Nagar and C. Gnanaseelan\*

Indian Institute of Tropical Meteorology, Dr Homi Bhabha Road, Pashan, Pune 411 008, India

**It has been established through a numerical model that the onset vortex (OV) was formed dramatically in the shear line on the northern flank of a low level jet (LLJ) at 850 hPa over the mini warm pool (MWP) in the East Central Arabian Sea with the aid of sea surface temperature (SST) anomalies using MONEX-79 data. This study has led to serious investigation of MWP over the ECAS, but little attention has been given to its counterpart, i.e. the atmospheric pattern at 850 hPa, the level at which OV generally forms and extends on either side during the course of development. The present study examines the SST distribution over the Arabian Sea and circulation at 850 hPa to identify the MWP and the LLJ positions for five consecutive days with onset day as its centre and for six consecutive years 2000–05. The study has revealed that OV had formed only in 2001 under the influence of MWP on the northern flank of LLJ. During other years it seldom formed due to (i) absence of MWP, (ii) lack of sufficient strength of LLJ, and (iii) absence of the location of shear line (over the northern flank of LLJ) over MWP. The air–sea flux transfer processes for the OV year 2001 and a non-OV year 2002 are studied and compared for better understanding of the above process in relation to the OV and non-OV weather conditions over the study area.**

**Keywords:** Low level jet, mini warm pool, onset vortex, shear line.

It is well known that tropical cyclones form over warm waters. Usually, the onset of monsoon over Kerala (MOK) is ushered in by a storm of moderate intensity called onset vortex (OV) over the mini warm pool region (MWP, sea surface temperature (SST)  $\geq 30.5^\circ\text{C}$ ) in the East Central Arabian Sea (ECAS). Kershaw<sup>1</sup> hypothesized that the MWP has a great bearing on the genesis of OV of summer monsoon (OVSM) at 850 hPa. Subsequently, Kershaw<sup>2</sup> further emphasized that the warm anomaly of SST (real SST-climatology) in the ECAS did affect the onset of the monsoon and increased the rate of generation of kinetic energy, speeding up the onset. It caused rapid northward progression of the monsoon and promoted the formation of OVSM by enhancing the release of latent heat, perhaps

\*For correspondence. (e-mail: seelan@tropmet.res.in)

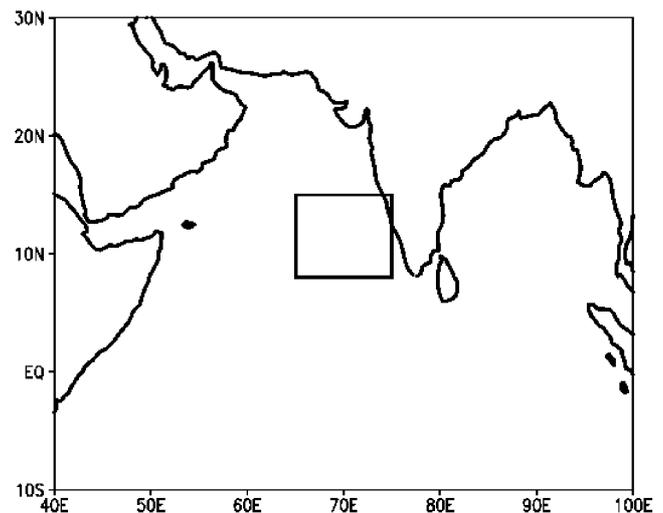
by promoting barotropic instability. The real-time SST used by Kershaw is taken from SST charts published by Seetaramayya and Master<sup>3</sup>. Further, Nyenzi<sup>4</sup> has also studied the synoptic weather conditions prevailing over the Indian region using MONEX-79 datasets (850 and 700 hPa circulation patterns). His study revealed that there existed a systematic sequential movement of the 850 hPa trough line (oriented in north-south direction) in the westerlies which lay over West Bengal and adjoining Bihar on 11 June, which gradually shifted south-southwestward on 12 and 13 June 1979. Finally it became zonal along 10°N and moved to the warm water pool over the ECAS on 14 June 1979, as reported by Seetaramayya and Master<sup>3</sup>. An incipient vortex formation at 850 hPa associated with the above trough line was clearly visualized by Hui<sup>5</sup>. Utilizing the daily wind data at 850 hPa, Krishnamurti *et al.*<sup>6</sup> have found that the OVSM of 1979 formed on the northern flank of a low level jet (LLJ) when the jet axis approached the southern tip of India just prior to the onset of the monsoon. They have shown that strong horizontal shear flow in the low levels (850–900 hPa) provided energy for the maintenance of this OV and the associated baroclinic instability in these levels was also triggered by the gradual descent of mid-tropospheric cyclonic circulation.

Seetaramayya and Master<sup>7</sup> have suggested that the combination of a variety of exchange processes of fluxes of latent heat, sensible heat and momentum at the air–sea interface, may play an important role in the initial establishment of large-scale low level convergence and convective instability, which facilitates a necessary condition favourable for penetrating large-scale convection over an active cyclogenesis area. Rao and Sivakumar<sup>8</sup> have studied the geographical coincidence of MWP and OV for a period of 30 years (1961–90). They have probed why OV does not form every year, even though MWP (SST  $\geq 30^{\circ}\text{C}$ ) forms almost every year. They could not find any comprehensive answer for this except specifying an unknown phenomenon of a remotely controlled atmospheric process responsible for OV formation. Thadathil and Gosh<sup>9</sup> have reported the presence of temperature inversions (due to the advection of cold and less saline water with Bay of Bengal origin over warm and highly saline water in the Arabian Sea along the west coast of India) below the mixed layer during the winter monsoon. Subsequent studies<sup>10,11</sup> have shown that these inversions form in the barrier layer and heat up the surface layer above, contributing to a 1.1°C increase in SST during November–March. These inversions disappear in April, when the Tropical Convergence Zone (TCZ) moves over the South East Arabian Sea (SEAS) and the warm pool engulfs the region. The evolving stage of this warm pool is believed to start partly with the formation of Lakshadweep High resulting from the incoming Rossby waves during November/December. This SST high in the Lakshadweep Sea and the warm pool in the SEAS satisfy a necessary, though not sufficient condition for the formation of OV, as suggested by Shenoi *et al.*<sup>12</sup>. This study offers relevant

observational evidence for the genesis of OVSM over the Arabian Sea by analysing the SST and 850 hPa wind field over the Arabian Sea and its associated air–sea interface processes (Figure 1).

The NOAA OIV2 weekly SST of Reynolds and Smith<sup>13</sup> for one week prior to and during MOK has been considered for identifying the MWP over the domain (0–24°N, 40–80°E). The NCEP–NCAR reanalysis daily 850 hPa wind data for the domain 10°S–30°N, 40–100°E have been used to understand the genesis of OVSM. To examine the air–sea interface processes associated with OV formation, the daily WHOI OA (Woods Hole Oceanographic Institution Objectively Analysed) fluxes averaged over the area 8–15°N, 65–75°E are used. These fluxes are computed using state-of-the-art bulk flux algorithm 3.0, developed from the Coupled Ocean–Atmosphere Response Experiment (COARE) by Fairall *et al.*<sup>14</sup>.

Table 1 gives the onset dates of MOK as reported by India Meteorological Department (IMD) for 2000–05 taken from Indian Daily Weather Reports<sup>15</sup>. The normal date of MOK is 1 June, with a standard deviation of eight days<sup>16</sup>. It can be seen from Table 1 that the onset was normal during



**Figure 1.** Areal map of the present study. Square box inside represents the area used for computation of fluxes.

**Table 1.** Dates of onset of monsoon over Kerala

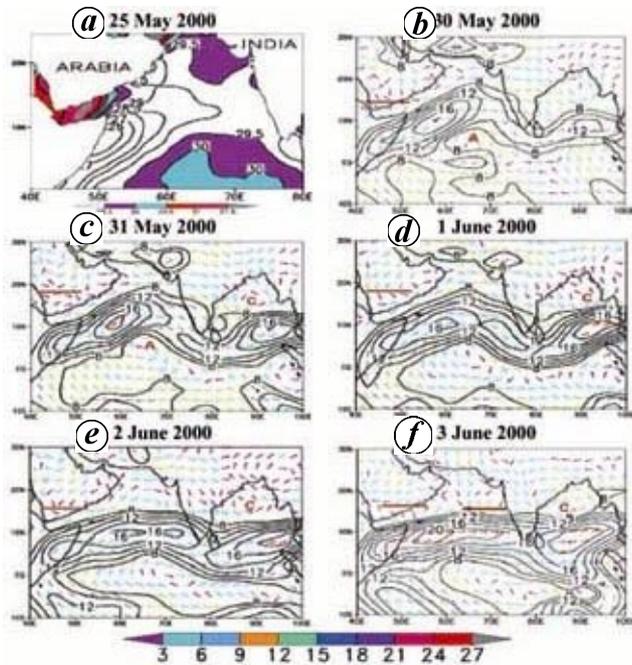
Year	Onset date
2000	1 June
2001	23 May
	21 May*
	27 May**
2002	29 May
2003	8 June
2004	18 May
2005	5 June

\*Date of incipient formation of OV.

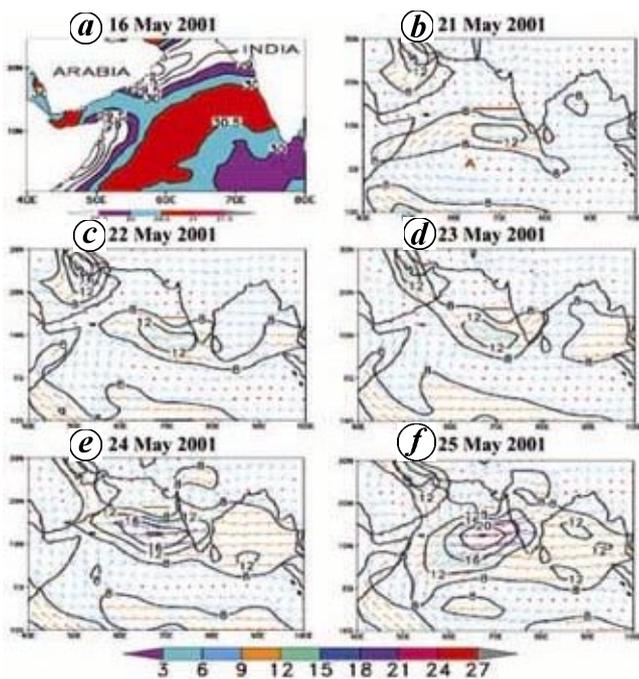
\*\*Date of intensification of OV.

RESEARCH COMMUNICATIONS

2000, 2002 and 2005. It was early in 2001 and 2004, whereas during 2003, it was delayed by seven days from its normal date. From the daily synoptic charts, it is observed that OV formed only during 2001 and its incipient formation is observed two days before the date of MOK.



**Figure 2.** a, SST distribution exactly one week prior to MOK for the year 2000. b-f, 850 hPa flow patterns for five consecutive days. Thick brown lines (b-f) represent shear lines. A, Anticyclonic circulation, C, Cyclonic circulation.

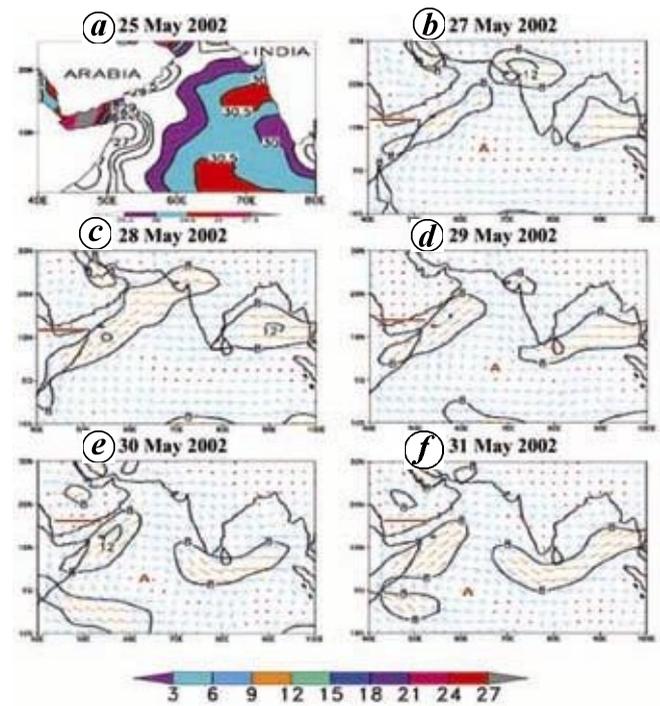


**Figure 3.** Same as Figure 2, but for the year 2001.

A low pressure area formed over southern parts of the central Arabian Sea over the MWP on 21 May. It intensified into a depression and then into a deep depression on 22 May. It further intensified into a cyclonic storm (CS) and lay centred at 14°N, 71°E on the same day. The CS over ECAS intensified into a severe cyclonic storm (SCS) and then into a very severe cyclonic storm (VSCS) with its centre at 15°N, 71°E on 23 May. The VSCS (central pressure, 994 hPa) moved northwestwards and lay centred at 16.5°N, 69.5°E by 24 May. On 25 May, the VSCS remained practically stationary and lay centred at 17°N, 68°E, but its central pressure decreased to 992 hPa. The VSCS moved slightly northwestwards and weakened into a SCS with its centre at 17.5°N, 67.5°E. By 27 May, the SCS had moved northwestwards and lay centred at 18°N, 67.5°E.

Figures 2 to 7 show SST distribution for a week centred exactly seven days prior to the onset of MOK for the years 2000 to 2005 respectively. To understand the dynamics of low-level flow during the onset process, 850 hPa flow patterns for five consecutive days, i.e. two days prior, during and two days after the onset are shown in Figures 2-7.

It can be seen from Figure 2 a that in 2000, MWP had not formed one week prior to MOK. A well-established LLJ is seen extending from the Somali coast to the eastern Bay of Bengal (Figure 2 b). An east-west shear line (marked by a thick brown line) over Saudi Arabia and a near equatorial anticyclonic circulation (marked by A) are observed over the Arabian Sea. A cyclonic circulation is



**Figure 4.** Same as Figure 2, but for the year 2002.

present over the Bay of Bengal centred at 12°N, 90°E one day prior to the onset (Figure 2 *c*). On the day of onset, i.e. 1 June, the LLJ had intensified over the Bay of Bengal, but had decreased in intensity over the Arabian Sea (Figure 2 *d*). On 2 June, the core of the LLJ had extended eastwards and a cyclonic shear line is seen over Arabia near 15°N, 55°E (Figure 2 *e*). The next day (Figure 2 *f*), the core of LLJ over the Arabian Sea was centred at 9°N, 56°E with intensity of 20 m/s, while in the Bay of Bengal it was centred at 9°N, 88°E. The shear line is seen on the northern flank of LLJ at 15°N in ECAS and over Arabia. A strong anticyclonic circulation is seen over the Bay of Bengal with its centre at 15°N, 87°E, which inhibited the formation of OV over the Arabian Sea.

In 2001 (Figure 3 *a*), the MWP is seen as a tongue extending westwards covering the ECAS. The LLJ (12 m/s) had touched the southern tip of India, two days before the onset with a shear line on its northern flank on 21 May (Figure 3 *b*). This shear line in association with the MWP helped in its subsequent development into a cyclonic storm on 22 May (Figure 3 *c*). On 23 May (MOK), the LLJ had oriented in a northwest-northeast direction with further intensification of the system (Figure 3 *d*). The system again intensified on 24 May and moved northward with intensification of LLJ (16 m/s; Figure 3 *e*). It further intensified and the LLJ core was more concentric with its centre at 12°N, 69°E (Figure 3 *f*). Thus the northward progression of the shear line due to subsequent intensification of the system is noticeable (Figure 3 *b–f*).

The MWP is seen as a small blob north of 10°N and between 60 and 70°E during 2002 (Figure 4 *a*). The LLJ

(12 m/s) appeared over the Bay of Bengal two days before the onset (Figure 4 *b*). The cross-equatorial flow made its way directly to Gujarat without touching the southern tip of India (Figure 4 *c*). On 29 May (the onset), the LLJ (8 m/s) was seen near the southern tip of India (Figure 4 *d*). On 30 May, the LLJ near the Somali coast intensified (12 m/s), but still did not touch the southern tip of India due to the presence of an anticyclonic circulation over the Arabian Sea (Figure 4 *e*). This anticyclonic circulation shifted further westward on 31 May (Figure 4 *f*). The LLJ over the Somali basin weakened (8 m/s) leading to a weak monsoon current.

A well-marked concentric region of MWP with its core (SST  $\geq 31^\circ\text{C}$ ) at 12°N, 65°E had occupied the ECAS in 2003 (Figure 5 *a*). The Somali coast and the southern tip of India started cooling one week before the onset in 2003. The 850 hPa wind field shows that the LLJ core seen over 9°N, 70°E on 6 June (Figure 5 *b*) shifted westward over the Somali coast just one day before the onset (Figure 5 *c*). A cyclonic shear line can be seen just ahead of the jet core between 50 and 60°E in the Gulf of Aden from 7 June onwards in 2003. The LLJ strengthened (20 m/s) on 8 June (Figure 5 *d*). It moved slightly northwards over Arabia on 9 and 10 June (Figure 5 *f*), i.e. far away from the west coast of India.

In 2004, the whole Arabian Sea was engrossed by SST  $< 30^\circ\text{C}$ , particularly SEAS, SST  $< 29.5^\circ\text{C}$  (Figure 6 *a*). A small blob of SST  $> 30^\circ\text{C}$  region is seen at 5°N, 62°E. The LLJ over the Arabian Sea had not developed two days prior to MOK (Figure 6 *b*) whereas strong winds (16 m/s) with core at 3°N, 88°E in the Bay of Bengal are clearly

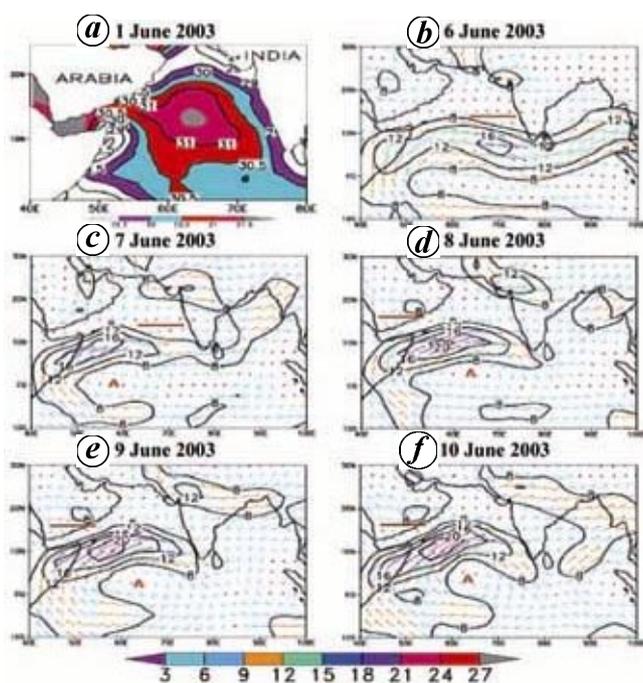


Figure 5. Same as Figure 2, but for the year 2003.

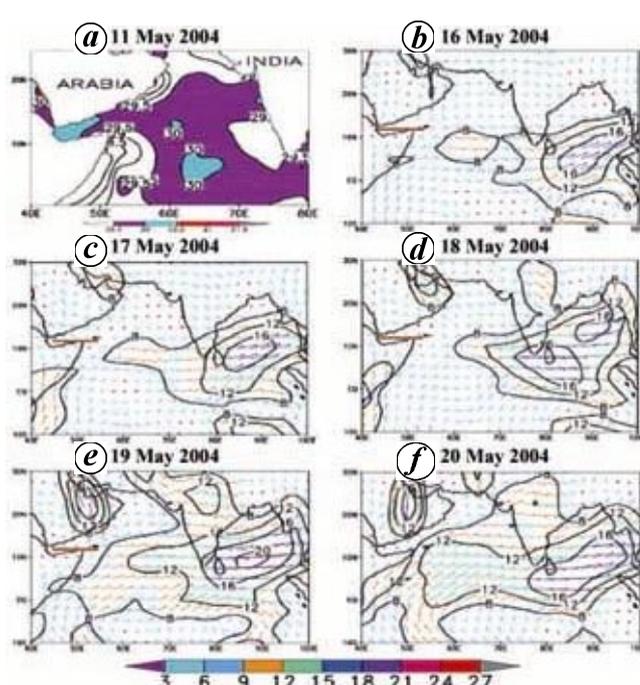


Figure 6. Same as Figure 2, but for the year 2004.

seen (Figure 6 *b* and *c*). On the following days (18 and 19 May), the LLJ slowly extended westwards over the Arabian Sea with intensity of 12 m/s (Figure 6 *d* and *e*) and the whole Arabian Sea was dominated by westerly flow. The areal extent of strong winds elongated westward on 20 May (Figure 6 *f*).

The SST pattern for the year 2005 shows a concentric warm pool region having core (SST > 31°C) at 10°N, 62°E surrounded by 30.5°C isotherm (Figure 7 *a*). The LLJ cores can be seen over the Somali coast (12 m/s) and south of Sri Lanka (16 m/s) two days and one day prior to MOK (Figure 7 *b* and *c*). On the following day, the core over the Somali coast extended eastwards and merged with that over the Bay of Bengal (Figure 7 *d*). On 6 June, the LLJ again split into two cores similar to what happened on 4 June, but the intensity of the core was greater (16 ms<sup>-1</sup>) over the Somali coast than over the Bay of Bengal (12 m/s). The two cores again merged on 7 June (Figure 7 *f*) as an elongated LLJ extending from the Somali coast to eastern Bay of Bengal.

Thus it is clear from Figures 2–7 *a* that the MWP shows variability in its location as well as its areal extent. Table 2 delineates this variability from 2000 to 2005. It shows that MWP covers the largest area (2.58 × 10<sup>12</sup> m<sup>2</sup>) during 2003 and the lowest (0.07 × 10<sup>12</sup> m<sup>2</sup>) in 2002. MWP is absent in 2000 and 2004 as discussed above.

Figure 8 depicts the change in SST field after and before the formation of the OV. The tracks of the OV along with its intensity are also shown in Figure 8. It is seen that the OV first moved eastwards and deepened into a SCS, then moved north-northwestwards during its intensification

phase and finally northwards during the weakening phase. It is also noticed that the SST decreased considerably in the ECAS (>1°C decrease) due to the passage of the OV.

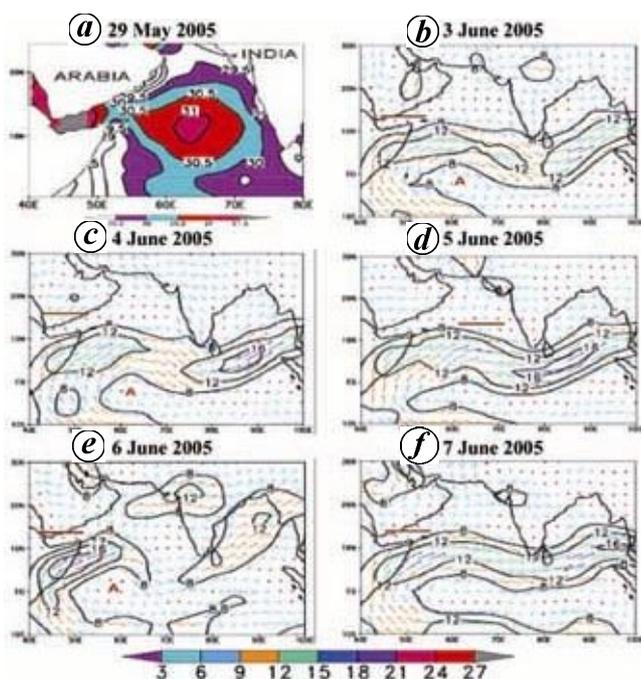
In general, during almost all the other five years (figures not shown), a 0.5°C decrease in SST was observed one week before and during the week of onset. This is due to monsoonal circulation.

The WHOI OA flux data are available up to 2002. The non-OV year 2002 was an El-Nino year and an extreme drought year for India. For the last five years in the last decade (i.e. 1995–99), 1998 was an OV year and 1997 an El-Nino year. MWP was absent during 1996 and 2000. So we have considered 1995 a non-OV year in which the MWP was present and El-Nino was absent.

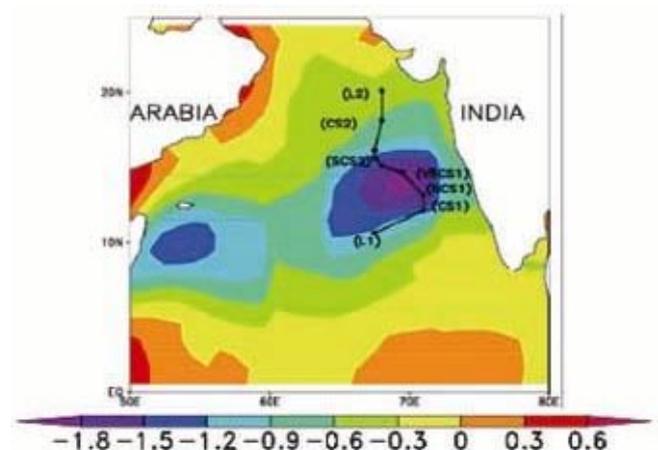
Figure 9 *a–d* shows respectively, the time series of heat fluxes (sensible and latent heat), Bowen ratio and momentum flux for 2001, 2002 and 1995. Dashed arrow represents the date of OV formation, solid arrow represents the date of MOK and double-headed arrow represents the date of intensification phase of OV. The sensible heat flux showed more or less constant values ranging from 14 to 16 Wm<sup>-2</sup> up to 25 May. Thereafter it decreased considerably in 2001 (6 Wm<sup>-2</sup>) on 26 May. In 2002, it oscillated between 5 and 16 Wm<sup>-2</sup> with 12 Wm<sup>-2</sup> on the day of

**Table 2.** Area of the mini warm pool (SST ≥ 30.5°C) over the Arabian Sea

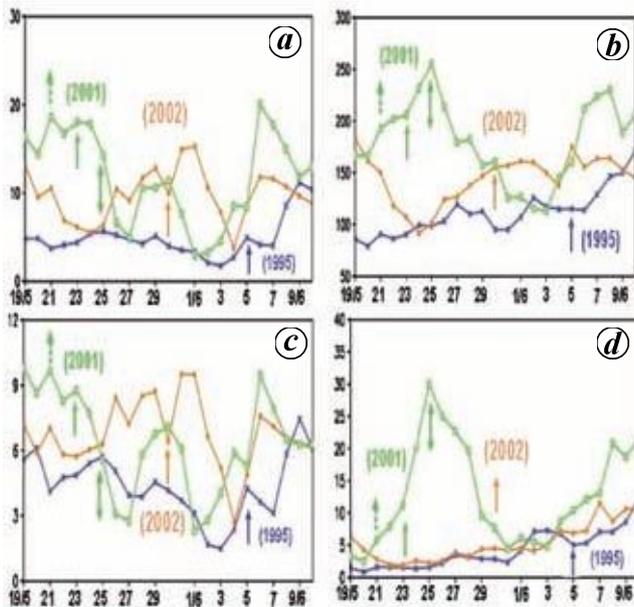
Year	Area (m <sup>2</sup> )
2000	MWP absent
2001	2.24 × 10 <sup>12</sup>
2002	0.07 × 10 <sup>12</sup>
2003	2.58 × 10 <sup>12</sup>
2004	MWP absent
2005	1.485 × 10 <sup>12</sup>



**Figure 7.** Same as Figure 2, but for the year 2005.



**Figure 8.** Change in SST field after and before formation of OV along with track of OV during 2001. L, Low pressure area – L1 on 21 May, L2 on 28 May; CS, Cyclonic storm – CS1 on 22 May, CS2 on 27 May; SCS, Severe cyclonic storm – SCS1 on 24 May, SCS2 on 26 May VSCS, Very severe cyclonic storm – VSCS on 25 May.



**Figure 9.** Time series of *a*, sensible heat flux ( $\text{Wm}^{-2}$ ); *b*, latent heat flux ( $\text{Wm}^{-2}$ ); *c*, Bowen ratio ( $\times 10^{-2}$ ) and *d*, momentum flux ( $\times 10^{-2} \text{Nm}^{-2}$ ) during 2001 (open green circles), 2002 (solid brown circles) and 1995 (blue crosses). Dashed arrow represents date of OV formation. Solid arrow represents date of MOK. Double-headed arrow represents date of intensification of OV.

MOK. During 1995, the sensible heat flux was quite low ( $\leq 6 \text{Wm}^{-2}$ ) prior to MOK and it increased to  $11 \text{Wm}^{-2}$  after four days (Figure 9 *a*). The latent heat flux showed a sudden increase from  $231 \text{Wm}^{-2}$  on 24 May to  $254 \text{Wm}^{-2}$  on 25 May (i.e. the day of OV intensification) during 2001, while it was  $146 \text{Wm}^{-2}$  in 2002 and  $100 \text{Wm}^{-2}$  in 1995, on the day of MOK.

The Bowen ratio showed maximum value 0.1 on 21 May (two days before the onset) during 2001 (Figure 9 *c*). After 25 May, it started decreasing slowly with a value of 0.03 on 26 May. It decreased considerably afterwards as the OV moved away from the area. In 2002 on the date of MOK (29 May), the Bowen ratio showed a low value of 0.08. After that it increased to 0.09 and had remained more or less constant from 31 May to 1 June. During 1995, the Bowen ratio showed a low value 0.04 on the day of MOK and decreased afterwards. During 2001, on the day of incipient development, the value of momentum flux was  $5.8 \times 10^{-2} \text{Nm}^{-2}$ . After that it started increasing rapidly and attained a value of  $30 \times 10^{-2} \text{Nm}^{-2}$  on 25 May. In 2002 and 1995, however, the 850 hPa circulation did not strengthen and the momentum flux did not show such drastic change. It was more or less uniform ( $5 \times 10^{-2} \text{Nm}^{-2}$ ) during the onset period.

In the present study, observations have shown that MWP formed during four years (2001, 2002, 2003 and 2005) with different intensities. However, the OV did not form in all these years, except during 2001. A close examination of SST distribution over the Arabian Sea and 850 hPa circulation patterns revealed that with the onset, or a few

days before the onset, a shear line had formed at 850 hPa and tended to extend over the MWP region. A comparison of Figure 3 *a* and *b* (by superimposing the latter on the former) shows that the positions of 850 hPa shear line and MWP are exactly coincident with each other during 2001. This shear line helped in the initial low-level vorticity and convergence, which in turn enhanced the surface wind speed leading to more moisture convergence, convection and precipitation. This led to further release of latent heat in the lower troposphere and hence further ascent of air. This type of mechanism of OV formation is similar to that of a 'providing cycle' discussed by Laevastu *et al.*<sup>17</sup> and Kershaw<sup>2</sup>.

Absence of MWP in 2000 (Figure 2 *a*) and 2004 (Figure 6 *a*) may be attributed to formation of cyclonic systems which formed one or two weeks before onset<sup>15</sup>. A well-defined concentric circular isothermal region of warm pool evolved during 2003 and 2005, but the 850 hPa circulation pattern over this region was not conducive to the development of OV due to the absence of shear line over the ECAS. In 2003, a cyclonic circulation or shear line formed over Arabia just ahead of the LLJ core over the Somali basin (Figure 5 *d*), which lies to the west of the MWP region. In 2005, the LLJ was not strong enough to induce the shear line (Figure 7) and hence there was no OV formation. Moreover, with the onset and advance of the monsoon northwards, the warm water pool moved northwards during 2003 (figure not shown).

Distribution of fluxes of sensible heat, latent heat and momentum has shown an increasing tendency with the deepening of the system. These diabatic heat fluxes are important in the boundary layer for storm formation<sup>7</sup>. The transfer of sensible heat from an infinite source of the warm ocean heats up the air in contact with it, and generates and produces buoyancy. The transfer of latent heat on the other hand, continuously supplies moisture to the air in contact with the surface. The Bowen ratio also shows a high value ( $9 \times 10^{-2}$ ) on the day of formation of OV, which denotes high sensible heat and moisture transfer from the ocean surface. Gray<sup>18</sup> has defined six genesis parameters for cyclone development: (i) low-level relative vorticity (850 hPa), (ii) Coriolis parameter, (iii) inverse of vertical shear of the horizontal wind between the lower and upper troposphere, (iv) ocean thermal energy excess above  $26^\circ\text{C}$  to a depth of 60 m, (v) vertical gradient of  $\Theta_e$  between the surface and 500 hPa, and (vi) middle tropospheric relative humidity. For a given SST ( $\geq 30.5^\circ\text{C}$ ) and 850 hPa circulation with LLJ and shear line keeping the other four parameters constant, one can easily understand that the OV develops only when the MWP and 850 hPa coexist along the west coast of India. Note that according to Gray<sup>18</sup>, the threshold of SST favourable for the formation of a tropical storm is  $26^\circ\text{C}$  and an ocean thermal energy excess above  $26^\circ\text{C}$  to a depth of 60 m. In the present study, we have noticed that a warm pool of SST  $\geq 30.5^\circ\text{C}$ , which is above  $3.5^\circ\text{C}$  higher than the threshold value, was necessary for OV to form

over the Arabian Sea in May 2001. The above threshold value of SST ( $26^{\circ}\text{C}$ ) does not hold good in the Arabian Sea in the hot season of May to form a tropical cyclone.

Examination of weekly SST distribution over the Arabian Sea revealed that MWP (SST  $\geq 30.5^{\circ}\text{C}$ ) existed over the Arabian Sea during 2001, 2002, 2003 and 2005. The OV developed over the northern flank of LLJ<sup>1,2,6</sup> under the influence of MWP with the aid of a 'providing cycle' during 2001 only. Nevertheless, the LLJ must be strong enough ( $\geq 10 \text{ ms}^{-1}$ ) and lie close to the southern tip of India. Even though MWP existed in 2003 and 2005, the features relating to the LLJ at 850 hPa were absent. A strong anti-cyclonic circulation to the south of the LLJ axis inhibited the formation of OV. In brief, though the ocean is fully cooperative with high thermal energy in the upper part, the OVSM does not form over the MWP unless the shear line forms along the northern flank of the LLJ at 850 hPa near the west coast of India, which is a necessary condition.

1. Kershaw, R., Onset of the southwest monsoon and SST anomalies in the Arabian Sea. *Nature*, 1985, **315**, 561–563.
2. Kershaw, R., Effect of a sea surface temperature anomaly on a prediction of the onset of the southwest monsoon over India. *Q. J. R. Meteorol. Soc.*, 1988, **114**, 325–345.
3. Seetaramayya, P. and Master, A., Observed air–sea interface conditions and a monsoon depression during MONEX-79. *Arch. Meteorol. Geophys. Bioklimatol.*, 1984, **A33**, 61–67.
4. Nyenzi, B. S., The influence of lower tropospheric flow on the onset of the summer monsoon over India in June 1979. *FGGE Operations Report A*, 1980, vol. 9, pp. 68–80.
5. Hui, D. Y., A case study of the formation and structure of a monsoon depression over the Arabian Sea. *FGGE Operations Report A*, 1980, vol. 9, pp. 92–113.
6. Krishnamurti, T. N., Ardanuy, P., Ramanathan, Y. and Pasch, R., On the onset vortex of the summer monsoon. *Mon. Weather Rev.*, 1981, **109**, 344–363.
7. Seetaramayya, P. and Master, A. H., Exchange of heat and momentum between ocean and atmosphere in relation to monsoon depression during MONEX-79. *Meteorol. Atmos. Phys.*, 1986, **35**, 59–63.
8. Rao, R. R. and Sivakumar, R., On the possible mechanisms of the evolution of the mini warm pool during the pre-summer monsoon season and the onset vortex in the southeastern Arabian Sea. *Q. J. R. Meteorol. Soc.*, 1999, **125**, 787–809.
9. Thadathil, P. and Gosh, K., Surface layer temperature inversion in the Arabian Sea during winter. *J. Oceanogr.*, 1992, **48**, 293–304.
10. Durand, F., Shetye, S. R., Vialard, J., Shankar, D., Shenoi, S. S. C., Ethe, C. and Cadec, G., Impact of temperature inversions on SST evolution in the south-eastern Arabian Sea during the pre-summer monsoon season. *Geophys. Res. Lett.*, 2004, **31**, L08305.
11. Shankar, D. *et al.*, Observational evidence for westward propagation of temperature inversions in the southeastern Arabian Sea. *Geophys. Res. Lett.*, 2004, **31**, L01305.
12. Shenoi, S. S. C., Shankar, D. and Shetye, S. R., On the sea surface temperature high in the Lakshadweep Sea before the onset of the southwest monsoon. *J. Geophys. Res.*, 1999, **104**, 15703–15712.
13. Reynolds, R. W. and Smith, T. M., Improved global SST analyses. *J. Climate*, 1994, **7**, 929–948.
14. Fairall, C. W., Bradley, E. F., Hare, J. E., Grachev, A. A. and Edson, J. B., Bulk parameterization on air–sea fluxes: Updates and verification for the COARE algorithm. *J. Climate*, 2003, **16**, 571–591.
15. Indian Daily Weather Reports (May 2000 and 2004), India Meteorological Department, Pune.

16. Ananthkrishnan, R., Pathan, J. M. and Aralikatti, S. S., The onset phase of southwest monsoon. *Curr. Sci.*, 1983, **52**, 155–164.
17. Laevastu, T., Rabe, M. K. and Hamilton, G. D., Mesoscale feedback from the ocean to the atmosphere in coastal and oceanic frontal regions. Environmental Prediction Research Facility (Navy) Monterey, California, 1972, pp. 7–8.
18. Gray, W. M., Hurricanes: Their formation, structure and likely role in the tropical circulation. In *Meteorology over the Tropical Oceans* (ed. Shaw, D. B.), Royal Meteorological Society, 1979, pp. 155–218.

ACKNOWLEDGEMENTS. R.D. thanks CSIR, New Delhi for JRF/SRF fellowship. We thank the Director, IITM, Pune for encouragement and support. We also thank NCEP/NCAR and IMD, Pune for data and DOD, Govt of India for financial support.

Received 25 May 2006; revised accepted 30 October 2006

## Genetic variability of *Helicoverpa armigera* (Hübner) attributable to cadherin gene-specific molecular markers

G. T. Gujar\*, R. N. Khawale and V. Kalia

Insect Biotechnology Laboratory, Division of Entomology, Indian Agricultural Research Institute, New Delhi 110 012, India

**Cry1Ac resistance in the American bollworm, *Helicoverpa armigera* is associated with alteration in midgut cell adhesion protein, cadherin. Genetic diversity of cadherin gene was studied using molecular markers developed from cDNA sequences of *H. armigera*. Six out of eight pairs of molecular markers were able to amplify the cadherin gene in eighteen insect populations collected from different locations in India and produce a total of 218 amplicons. The maximum similarity (96%) was found for three pairs of insect populations from Rajkot and Sirsa, Akola and Bhatinda, and Faridkot and Karnal; while the minimum similarity (82%) was for the pair of insect populations from Nanded and Hyderabad. The study showed 4–18% genetic diversity in cadherin-specific gene of *H. armigera* populations which differed at least 100-fold in their susceptibility to Cry1Ac.**

**Keywords:** American bollworm, cadherin, genetic variability, *Helicoverpa armigera*, molecular markers.

AMERICAN bollworm, *Helicoverpa armigera* (Hübner) (Lepidoptera: Noctuidae) is the most serious pest of cotton, pulses and many other agriculturally important crops in India and abroad. Indiscriminate use of pesticides for control of *H. armigera* has resulted in the development of resistance against almost all groups of conventional in-

\*For correspondence. (e-mail: gtgujar@iari.res.in)