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Off shore trough and very heavy rainfall events along the West Coast of India during ARMEX-2002

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सार – इस शोध पत्र में अपतटीय द्रोणी (ओ. एस. टी.) की विद्यमानता तथा निहित भ्रमिलताओं का अध्ययन करने के लिए मध्य जून से लेकर मध्य अगस्त तक अरब सागर मानसून प्रयोग (आरमेक्स) 2002 किया गया। भारत के पश्चिमी तट के साथ–साथ भारी वर्षा (24 घंटे में 12 सें. मी. से अधिक वर्षा) के चार मामले 14–16 जून, 20–22 जून, 26–28 जून और 7–10 अगस्त 2002 को रिकार्ड किए गए। 26–28 जून को हुई भारी वर्षा की घटना निम्नदाब तंत्र के कारण हुई थी जिसने बंगाल की खाड़ी से होते हुए मध्य प्रदेश से गुजरात और समीपवर्ती राजस्थान को पार किया। भारी वर्षा की अन्य तीन घटनाएं अपतटीय द्रोणी तथा अपतटीय भ्रमिलताओं से संबद्ध थीं।

अरब सागर में लगाए गए अनेक समुद्री प्लवों में से केवल एक प्लव का गोआ में पता लगा जिससे प्रबल और मंद पवन की दोनों स्थितियों में अपतटीय द्रोणी का संकेत मिला है। तथापि अन्य प्लवों से प्राप्त सतह पवन आँकड़ें और क्यू. एस. सी. ए. टी. सतह पवनों अपतटीय द्रोणी की विद्यमानता को सदैव प्रमाणित नहीं करती हैं। ये संकेत अत्यंत सूक्ष्म प्रकार के थे और इन्हे राष्ट्रीय मध्यम अवधि मौसम पूर्वानुमान केन्द्र द्वारा किए विश्लेषण अथवा पूर्वानुमान चार्टों पर प्रेक्षित करना कठिन था। इस अध्ययन में यह ज्ञात किया गया कि कमजोर और प्रबल मानसून की स्थितियों में अपतटीय द्रोणी पाई जा सकती है। तथापि जब मानसून की धारा कुछ सिनॉप्टिक तरंग के साथ संबंद्ध अरब सागर और बंगाल की खाड़ी दोनों में ही प्रबल होती है तभी भारी वर्षा की घटनाएं देखी जा सकती है। इसके अलावा, भारी वर्षा की घटनाओं के सभी मामलों में अरब सागर और बंगाल की खाड़ी में परिसंचरण विशेषताओं को साथ में देखते हुए और निम्न से मध्यम अथवा ऊपरी क्षोभमंडलीय स्तरों से पवन के प्रवाह के पैटर्न में पूर्वी पश्चिमी अपरूपण रेखा बढ़ती हुई देखी गई है। उपग्रह के चित्रों में पाई गई मेघ विशेषताओं और टी. आर. एम. एम. वर्षा दर पैटर्न के आधार पर भारी वर्षा की घटनाओं के दौरान मेसोस्केल भ्रमिलताओं/सुनियोजित सवंहनी तंत्र का भी पता चला है।

ABSTRACT. Arabian Sea Monsoon Experiment (ARMEX) 2O02 was carried out from mid June to mid August to study the presence of off-shore trough (OST) and embedded vortices. Four cases of heavy rainfall along the west coast (rainfall exceeding 12 cm in 24 hour) of India were recorded on 14-16 June, 20-22 June, 26-28 June and 7-10 August 2002. The heavy rainfal1 event of 26-28 June was due to a low pressure system that moved from Bay of Bengal across Madhya Pradesh to Gujarat and adjoining Rajasthan. The other three heavy rainfall events were associated with the off shore trough and /or off shore vortices.

Of the various sea buoys deployed in the Arabian Sea, only one buoy located off Goa, did give hint of an OST both in strong and weak wind conditions. However, surface wind data from other buoys and QSCAT surface wind did not always support the presence of OST. The indications were very subtle and it was found difficult to observe them on the NCMRWF (National Centre for Medium Range Weather Forecasting) analysis or forecast charts. In the present study it has been observed that off shore trough may be observed in weak as well as strong monsoon conditions. However, heavy rainfall events were noticed only when the monsoon current is strong both in the Arabian Sea as well as Bay of Bengal in association with some synoptic systems. In addition, an east-west shear line in wind flow pattern extending from lower to middle or upper tropospheric levels and joining the circulation features in the Arabian Sea and Bay of Bengal has been noticed in all cases of heavy rainfall events. Meso-scale vortices/organized convection systems were also identified during heavy rainfall events on the basis of cloud features noticed in the satellite pictures and TRMM rain rate patterns.

Key words – ARMEX, Off shore trough, Heavy rainfall, Off shore vortex.

1. Introduction

Seasonal monsoon rainfall from June to September along the west coast of India, varies between 250 & 350 cm. The months of June and July usually receive more than half of the seasonal precipitation. Precipitation amounts of 5-10 cm in 24 hours are not uncommon. India Meteorological Department has laid down rainfall exceeding 12 cm in 24 hours as very heavy precipitation. On some occasions, 24 hourly accumulated rainfall amounts may exceed 15 to 20 cm and such events may last for 1-2 days along different sectors of the west coast. These high intensity rainfall events that occur along Kerala, Karnataka, Goa-Konkan, Maharashtra and south Gujarat coasts are known to be associated with synoptic features such as pressure trough on the sea level surface chart commonly known as Off Shore Trough (OST). Associated with the OST are sometimes meso-scale cyclonic vortices, with dimensions of 100-200 km across. These vortices can be observed through satellite cloud imagery or through subtle changes in surface wind at stations located along the coast. The satellite imagery clearly indicates intense convective features and its movement northwards along the coast. The collective contribution of such intensive precipitation episodes, numbering 4-5 in the monsoon season, may contribute upto 50% of the total rainfall for the monsoon season over different stations along the west coast. The problem of understanding the onset of such intensive meso-scale convective episodes and their prediction has been one of the objectives of Arabian Sea Monsoon Experiment - I (ARMEX-I).

ARMEX-I field phase experiment was conducted from mid June to mid August 2002 in the Arabian Sea. Intensive meteorological observations were taken by observatories within 200 km of the coast line. Routine and special observations were taken by setting up some meso-net of observations over land as well as ship and aircraft observations. The details of the experimental set up are given in the document issued by Department of Science and Technology, Govt. of India.

1.1. *Earlier studies*

George (1956) examined the formation and dissipation of small scale circulation and vortices along the west coast of India during the monsoon season. Some of the vortices were found to develop into significant size and shape and made noteworthy contributions towards rainfall along the west coast. The vortices were found to be of the order of 30 to 100 miles in horizontal extent and generally moved northwards parallel to the Ghats. He also concluded that the rainfall associated with the vortex was usually heaviest between the 'core' region and the 'confluent' region of the vortex. Rao (1976) stated that nothing much is known about the life period of such vortices and it is not possible to be sure of its features on the basis of which they have been identified. Discussing about the trough off the west coast of peninsula, he stated that such type of systems quite frequently develop off the west coast of India, anywhere from north Kerala to south Gujarat and are responsible for the strengthening of the monsoon in terms of rainfall in the adjacent coastal belt. The development of the trough is seen as a weakening of the usual pressure gradient and southerly/easterly surface winds in some belt as against the normal westerlies. A small closed circulation may be embedded in some troughs. The troughs form more near coastal Karnataka and slowly shift 2° latitude per day northward, though they may appear and disappear *in situ* over any area. Pressure gradient increases to the south of the trough particularly as it shifts to north. Upper winds are affected only in the lower troposphere and that too below 1 km. Cyclonic vorticity may still be present above the surface trough, as wind shear. As the troughs move to Maharashtra coast, upper winds are drawn into the circulation to a greater depth. Mukherjee *et al*. (1978) also examined these off shore vortices and observed them to be most prominent in July. Heavy rainfall associated with them was confined to coastal stations rather than the Ghats. There was association between the formation of off shore vortices and existence of upper air cyclonic circulation between 2.1 and 3.6 km over Gujarat region and neighbourhood. Kalsi *et al*. (2004) observed shallow off shore trough along different parts of west coast and stated that it persisted on most of the days from 20 May to 17 September 2002. ARMEX-I experiment offered a unique opportunity to examine the synoptic features conducive to the formation of an off shore trough, development of meso vortices and associated heavy rainfall events.

2. Data

In order to examine the meteorological processes of very heavy rainfall events, meteorological data pertaining to very heavy rainfall episodes was collected. A very heavy rainfall event is defined when a station records 12 cm or more of precipitation in 24 hours. In the present context it is implied that a few stations along the west coast would record the stated amount of precipitation in 24 hours time. During June to mid August 2002, four very heavy rainfall events along the west coast of India were recorded *viz*., (*i*) 14-16 June 2002; (*ii*) 20-22 June 2002; (*iii*) 26-28 June 2002 and (*iv*) 7-10 August 2002. In the month of July, no heavy rainfall event was observed. In fact scanty rainfall in July, lead to drought conditions over many parts of the country.

The heavy rainfall event of 26-28 June 2002, was due to low pressure system that moved from Bay of Bengal and when over west Madhya Pradesh and

adjoining Gujarat and Rajasthan, an off shore trough also developed along Konkan-Goa coast. Heavy to very heavy precipitation took place over coastal Gujarat well as interior parts at and some parts of Maharashtra. The other three heavy rainfall events were associated with intense convection, possibly meso vortices. However, the association of the OST was rather subtle.

The weather charts pertaining to these dates from Northern Hemisphere Analysis Centre of India Met. Department, METEOSAT cloud imageries, NWP analysis using T-80 model analysis and forecast system of National Centre for Medium Range Weather Forecasting (NCMRWF) were used. Other weather information such as weather radar reports, Q-SCAT data, TRMM data, AWS data, Rawin/radiosonde data, Digicora data from Goa and Sagar Kanya etc. where available were also utilized. The ORV Sagar Kanya sailed into the observational area on 20 June 2002.

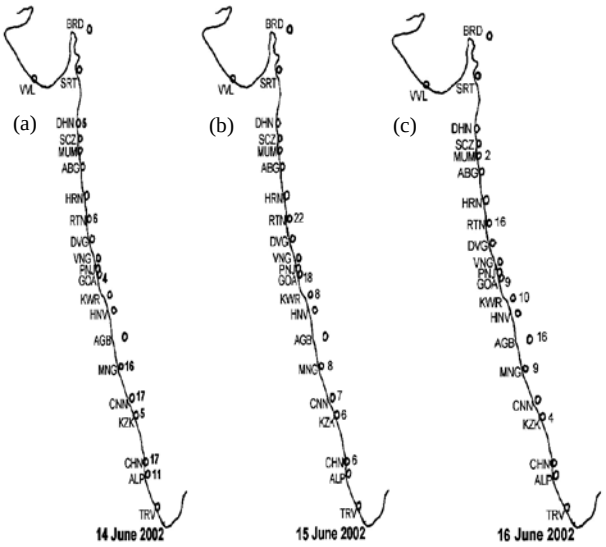
3. Description of weather features during very heavy rainfall events

The monsoon hit Kerala coast on 29 May and its progress northwards along the west coast was nearly normal till about 25 June 2002. The first two heavy rainfall events *viz*., 14 to 16 June and 20 to 22 June were similar in nature and occurred during the advancing phase of the monsoon along the west coast. The third rainfall event of 26-28 June 2002 was the heaviest. However, it affected more the interior parts of Gujarat and Maharastra as well as the coastal regions and the event occurred as a result of low pressure area that moved from Bay of Bengal to Gujarat and adjoining parts of Rajasthan, Madhya Pradesh and Maharashtra. The fourth rainfall event of 7-10 August 2002, took place after a relatively long dry spell because in July 2002 monsoon was continuously weak over the entire country and no heavy rainfall was observed along the west coast stations. In the following sections, first, second and fourth very heavy rainfall events have been examined synoptically and through other special observations. A case of weak precipitation in July 2002 has also been examined for comparison purposes.

3.1. *Very heavy rainfall event of 14-16 June 2002*

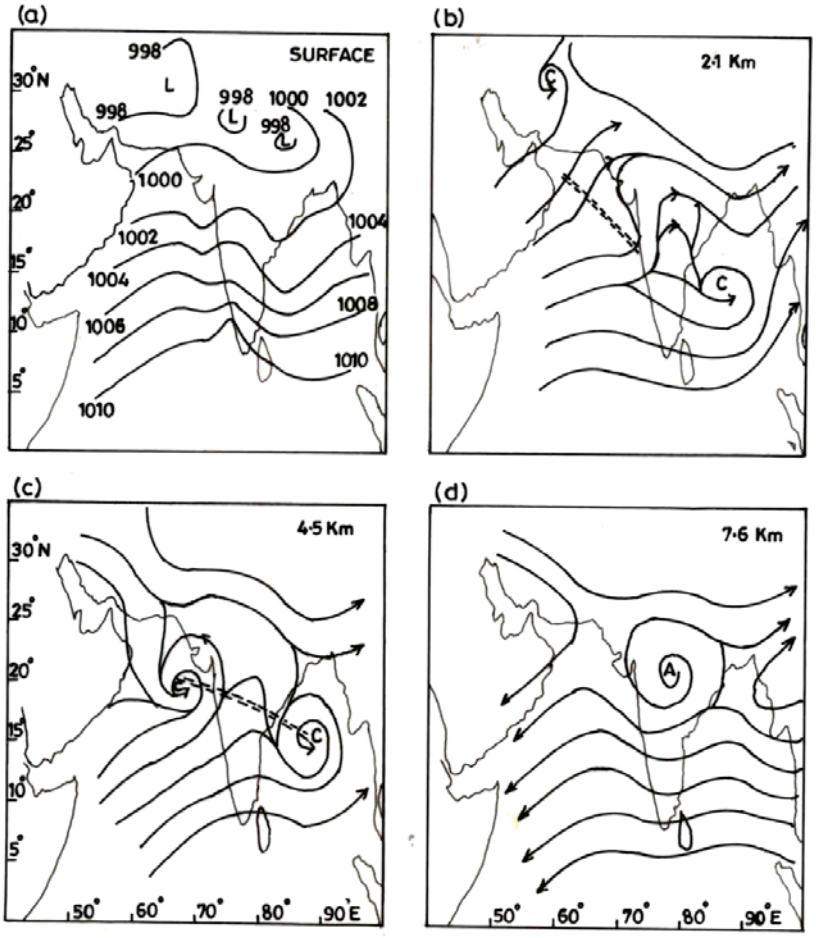
(a) *Brief details of observed precipitation and synoptic situation*

The past 24 hourly precipitation observed at 0830 hr (IST) from 14 to 16 June 2002 along the west coast stations are shown in Fig. 1. Heavy rainfall was observed at stations between Mangalore and Cochin on 14 June. The heavy rainfall region moved northward and became more intense on 15 June. On this day, it was confined to stations between Ratnagiri and Goa. On 16 June, the region of heavy rainfall remained practically stationary



Figs. 1(a-c). 24 hourly accumulated precipitations (cm) recorded at 0300 UTC along the west coast stations of India on (a) 14 June 2002, (b) 15 June 2002 and (c) 16 June 2002

but the intensity decreased. Thus, the heaviest rainfall was noticed on 15 June 2002. Examination of surface weather charts indicated an off shore trough or low was present on the sea level chart extending from Konkan – Goa to Kerala coast on all the days. The trough was marked on the basis of surface wind of coastal stations that were light and varied between easterly & southerly. The buoy (index no. 23094) located at 12.9° N, 74.7° E, very close to the coastline (Fig. 5) indicated light surface wind varying between northwesterly to southwesterly direction, speed 1 to 5 ms^{-1} between the nights of 13 June to the morning of 16 June. The wind direction does support the presence of a tough close to the coast. The upper level wind at 0.9 km on 14 June 2002 indicated the presence of a circulation or shear line between Mumbai and Goa. A cyclonic circulation between 1.5 km & 4.5 km was observed in the Arabian Sea lying off Gujarat coast. Another cyclonic circulation was noticed in the Bay. A WNW-ESE oriented shear line running across the peninsula joined the two circulations. The shear line particularly at 4.5 km, slowly moved northwards from 14 to 16 June 2002. The surface and the associated upper air charts at selected levels for 15 June, copied from NHAC weather charts, are shown in Figs. 2(a-d). An east west shear line at 4.5 km joining the circulation features in the Arabian Sea and Bay of Bengal is prominent. The monsoon current was strong both in the Arabian Sea and Bay of Bengal. The low level jet (LLJ) wind speed reaching 28-30 kts (14-15 ms^{-1}) was noticed at Goa. Since the monsoon was advancing, the presence of shear zone between the advancing strong westerly monsoon current and the relatively dry and weaker wind to the north was clearly discernible.



Figs. 2(a-d). The surface and associated upper air stream line analysis weather charts at 0000 UTC on 15 June 2002 [*Source* : Northern Hemispherical Analysis Centre, India Met. Department]. (a) Surface, (b) 2.1 km, (c) 4.5 km and (d) 7.6 km

(b) *Satellite pictures*

The METEOSAT cloud imagery of visible channel of 14, 15 and 16 June 2002 at 0600 UTC is shown in Figs. 3(a-c).

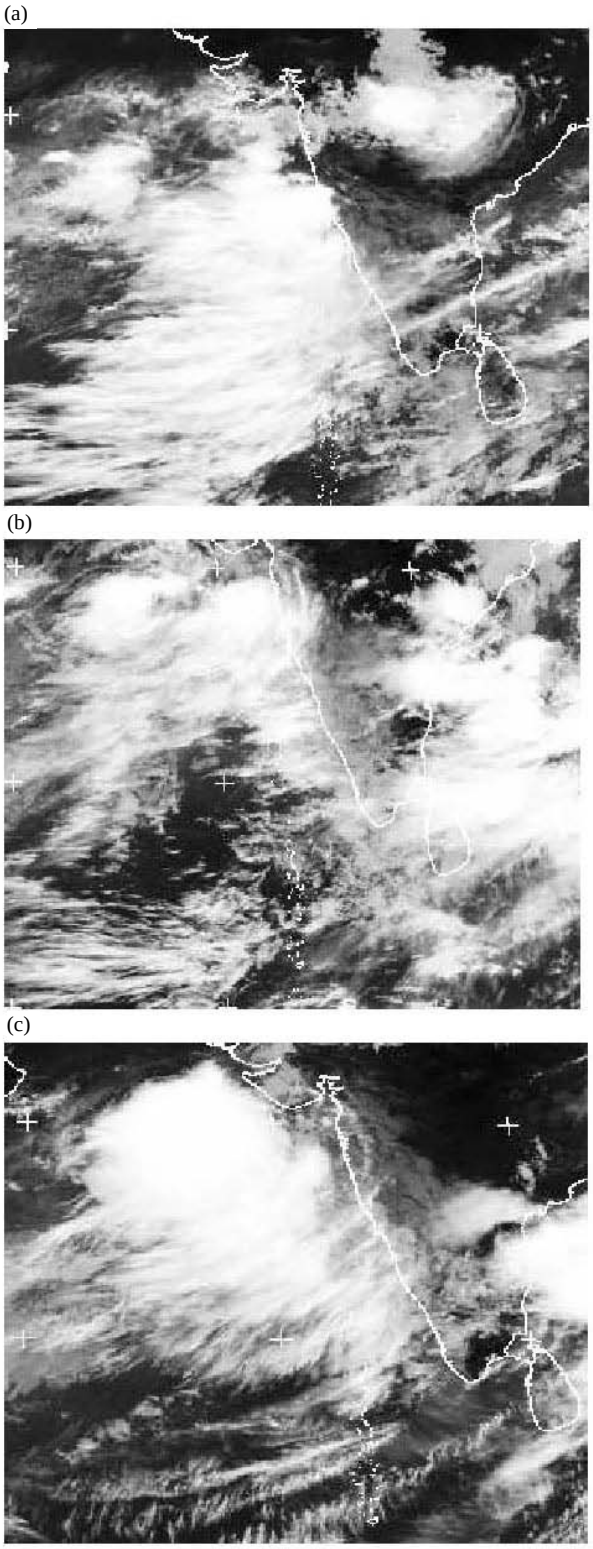
0600 UTC, 14 June 2002 − Broken intense convection is observed off the coasts of Kerala, Karnataka and Konkan-Goa between 5° N - 17° N, 65° E - 75° E. Intense circular masses over and off Goa and another at about 16° N, 65° E with converging and spiraling cloud lines are clearly noticeable and indicate the presence of meso vortices. The location of the vortices was very close but to the north of the low level jet location. Broken intense convection is also observed in the north east to east central Bay.

0600 UTC, 15 June 2002 − Very intense broken to solid convection is observed off Konkan – Goa coast between 15° N - 20° N, 63° E - 75° E. Broken very intense convection is also noticed off Karnataka and Kerala coasts between 10° N - 15° N, 70° E - 75° E. Two vortices one located at about 18° N, 72° E and the other at 18° N, 65° E each of about 3° diameter are clearly identified. As compared to the previous day, the cloud systems have moved northwards.

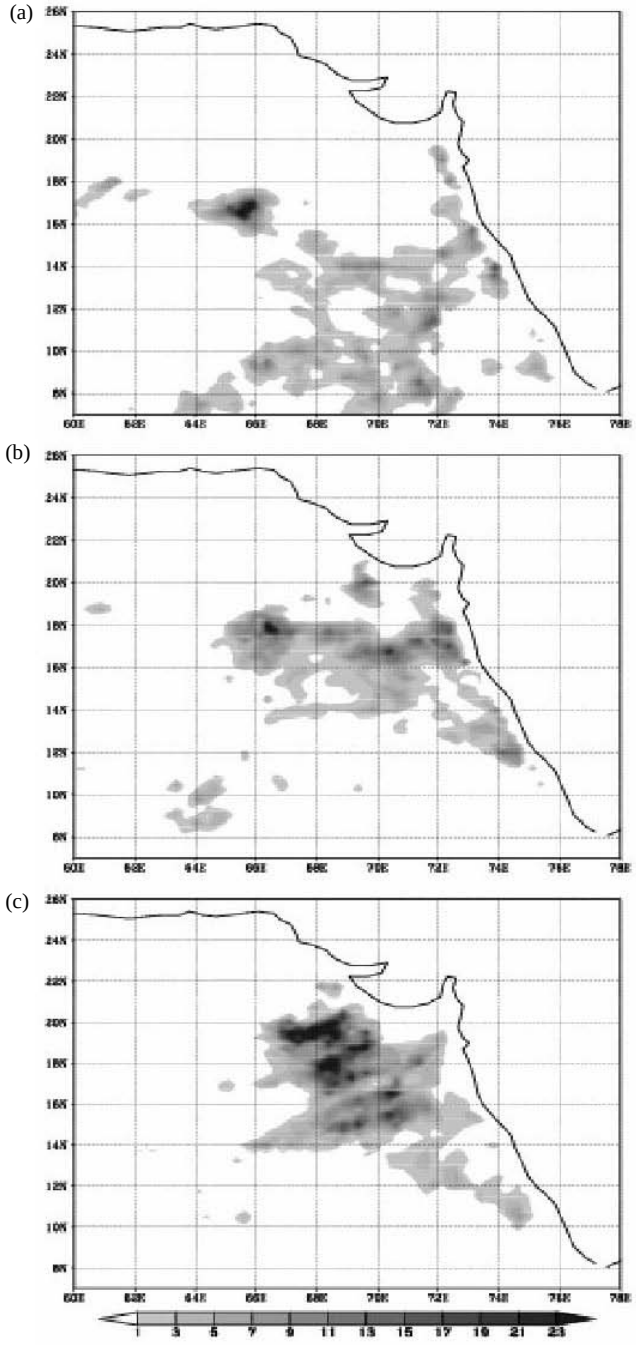
0600 UTC, 16 June 2002 − Solid, very intense circular mass of 4 to 5° diameter is noticed off Gujarat and Konkan-Goa coasts between 15° N - 22° N, 65° E-72° E. The centre of the circular mass appears to be close to 20° N, 65° E. The two vortices noticed on 15 June, appear to have merged to form a single vortex. The vortex propagated northwards within the region of off shore trough.

(c) *SSMI, Q-SCAT and upper air observations*

The SSMI rain rate (mm/hr) on 14, 15 and 16 June is shown in Figs. 4(a-c). Intense rain rate areas, some of them nearly circular, gradually shifting north or north



Figs. 3(a-c). METEOSAT Satellite cloud imagery in the visible channel at 0600 UTC. (a) 14 June 2002, (b) 15 June 2002 and (c) 16 June 2002



Figs. 4(a-c). SSMI rain rate in mm/hr. (a) 14 June 2002, (b) 15 June 2002 and (c) 16 June 2002

northwest wards and nearly coinciding with the intense circular cloud masses in satellite picture of Figs. 3(a-c), indicate the presence of meso-scale cloud system vortices. They are located at the interface of the moist southwesterly moist current to the south and relatively dry air to the north or on the leading edge of the advancing monsoon rains. The Q-SCAT data of 16 June at selected few points is shown in Fig. 5. Buoy data at or close to 0300 UTC along with the coastal stations surface wind is also indicated. It clearly indicates a trough between

coastal Saurashtra and north Konkan coast with possibly an embedded circulation and considerable shear.

The digicora data of 15th morning from Goa (obtained from Indian Navy) indicated the presence of a trough to the west in the lower levels upto about 0.3 km. Strong vertical wind shear was also noticed in the lower troposphere. The atmosphere was nearly saturated from surface upto 400 hPa. Similarly Mumbai RS/RW observations on 16 June, both at 0000 and 1200 UTC indicated southerly or southwesterly winds upto 500 hPa and very moist atmosphere. This indicated the presence of trough or circulation in the Arabian Sea, west or northwest of Mumbai.

(d) *Cross section along 72° E based on NCMRWF analysis*

Based on the NCMRWF analysis at 0000 UTC on 15 June 2002, cross section along 72° E was prepared consisting of zonal wind, meridional wind, omega and specific humidity and is shown in Figs. 6(a-d). Inspite of low – resolution of the NCMRWF model (T-80), the fields shown in Figs. 6(a-d) indicate the presence of trough with upward vertical motion and the depth of moist layer increases north of 10° N.

3.2. *Heavy rainfall event of 20-22 June 2002*

(a) *Brief details of observed precipitation and synoptic situation*

The past 24 hourly precipitation observed at 0830 hrs from 20 to 22 June is shown in Figs. 7(a-c). In this case the heavy rainfall was observed only on 21 June 2002 between the stations Honavar and Dhanu. The movement of the rainfall belt northwards is not clearly noticed. Probably the system had a shorter life span of a day only. Examination of surface and upper air weather charts indicated an off shore trough on the sea level chart extending from south-Gujarat to Kerala on all the days. The trough was marked on the basis of surface wind at the coastal stations. Other more significant synoptic features indicated that on 20 June 2002, a low pressure area lay over northwest Bay with cyclonic circulation extending upto mid tropospheric levels. A cyclonic circulation between 0.9 km & 7.5 km also lay over south Gujarat, tilting southwards with height. A shear line across the peninsula joining the two circulations was noticed between 4.5 & 7.5 km. On 21 June 2002 the shear line weakened and on 22nd June 2002 it further weakened. The corresponding surface and upper air charts have not been presented, but it may be noticed that monsoon current was strong both in the Arabian Sea and Bay of Bengal. This feature has been noticed in the earlier case too.

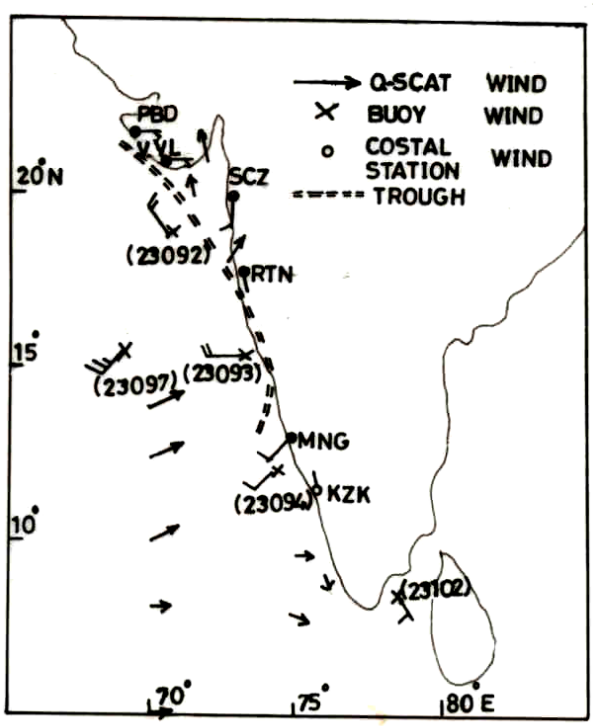


Fig. 5. Q-SCAT data of surface wind at selected points, Buoy and coastal stations surface wind at 0300 UTC on 16 June 2002

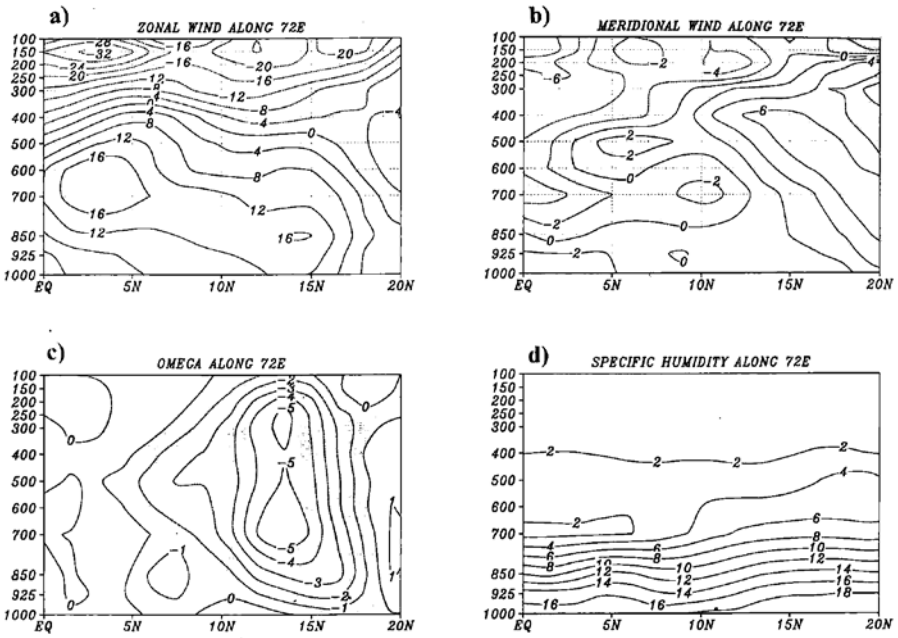
(b) *Satellite picture*

The METEOSAT cloud imagery of visible channel on 20, 21 and 22 June 2002 is shown in Figs. 8(a-c).

0600 UTC, 20 June 2002 − Broken intense convection is observed over and off Konkan-Goa and Karnataka coasts. Cloud motion vectors indicated a circulation between 800 to 600 hPa but cloud imagery does not indicate any vortex. Broken intense convection is also observed off Orissa coast and central Bay between 10° N - 20° N, 80° N - 95° E, indicating strong monsoon conditions.

0600 UTC, 21 June, 2002 − Broken intense convection observed off the coasts of Konkan-Goa and Karnataka between 14° N - 21° N east of 70° E extending upto the coast. A weak vortex can be noticed close to 17° N, 70° E. It is about 200 km in diameter. This vortex is located slightly to the north of low level jet. Probably the vortex developed between 0600 UTC on 20 June & 0600 UTC on 21 June 2002 and gave heavy precipitation, as is evident by the 24 hourly precipitation recorded at 0300 UTC on 21 June 2002. Broken to solid very intense convection observed over north and central Bay indicated strong monsoon conditions in the Bay of Bengal.

0600 UTC, 22 June 2002 − Broken intense convection was observed off Konkan-Goa and Gujarat



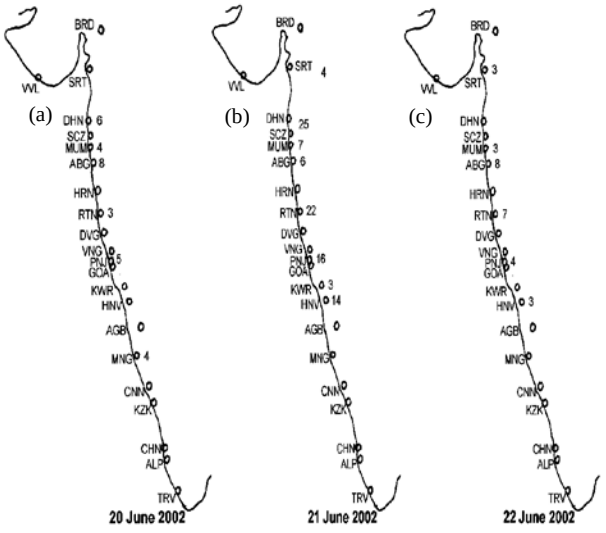
Figs. 6(a-d). North-South cross section along 72° E on 15 June 2002 based on NCMRWF analysis at 0000 UTC. (a) Zonal wind, (b) Meridional wind (c) Omega field and (d) Specific humidity

coast. A weak vortex at 19° N, 68° E appears to be embedded in the cloud mass, as noticed by curved cloud lines. It is about 300 km in diameter. The vortex had moved in NNW direction from its previous position and moved away from the coast line. The 24 hourly precipitation reduced considerably on the coastal stations. Broken to solid, very intense convection continued in the Bay of Bengal indicating strong monsoon condition.

(c) *SSMI, Q-SCAT and upper air observations*

The SSMI rain rate of 20, 21 and 22 June (figures not presented) indicate the presence of enclosed intense rain rate areas close to the coast when viewed in combination with the satellite picture of Figs. 8(a-c). The presence of vortex/intense convection can be anticipated. The Q-SCAT and buoy surface wind however do not clearly indicate the presence of an off shore trough in the region of the heavy precipitation.

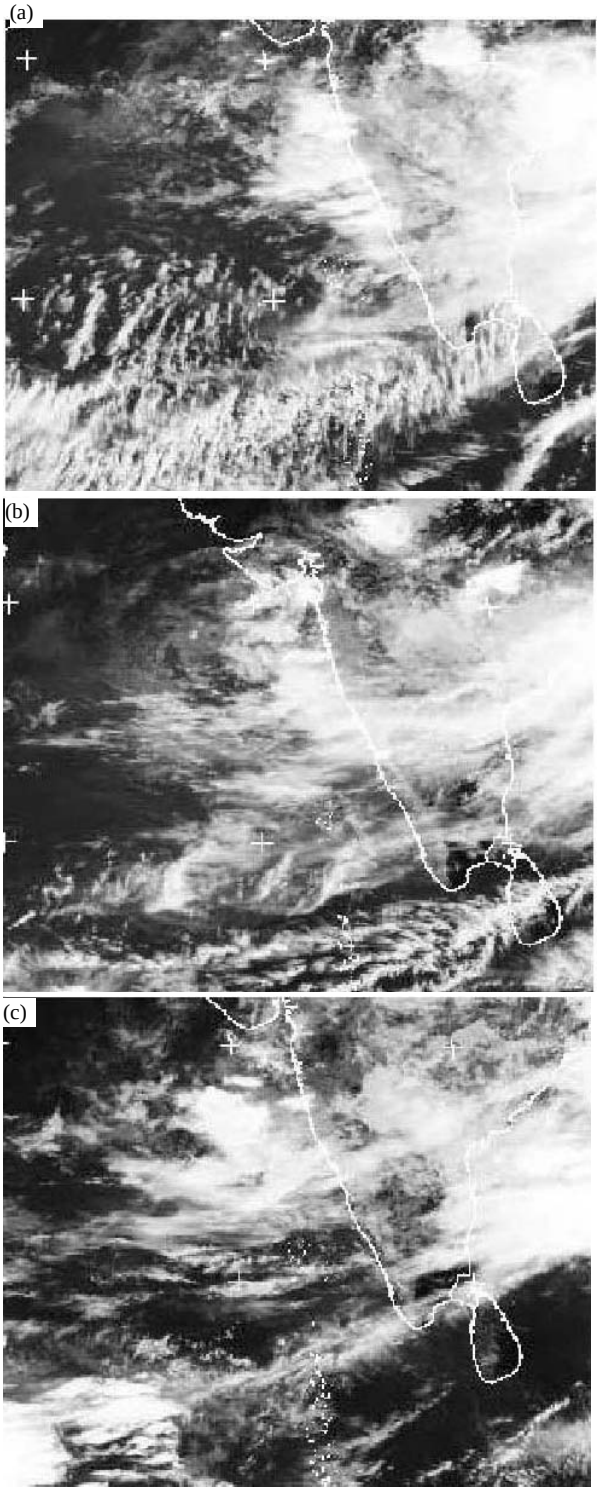
The wind observations based on digicora data of Goa on 21 June 2003, indicate that in the morning the winds are southeasterlies to south southwesterlies upto 0.3 km with speed ranging between calm & 7 kts (3 ms^{-1}). They indicate light wind conditions and the presence of a trough off Goa under such conditions cannot be ruled out. Aloft they become southwesterlies and the maximum wind of 27 kts (13 ms^{-1}) in the lower troposphere is observed at 900 hPa. The atmosphere is moist upto 600 hPa. By evening the winds upto 0.3 km have become westerlies 10-20 kts. The OST can not be anticipated. The



Figs. 7(a-c). 24 hourly accumulated precipitation (cm) recorded at 0300 UTC along the west coast stations of India on (a) 20 June 2002, (b) 21 June 2002 and (c) 22 June 2002

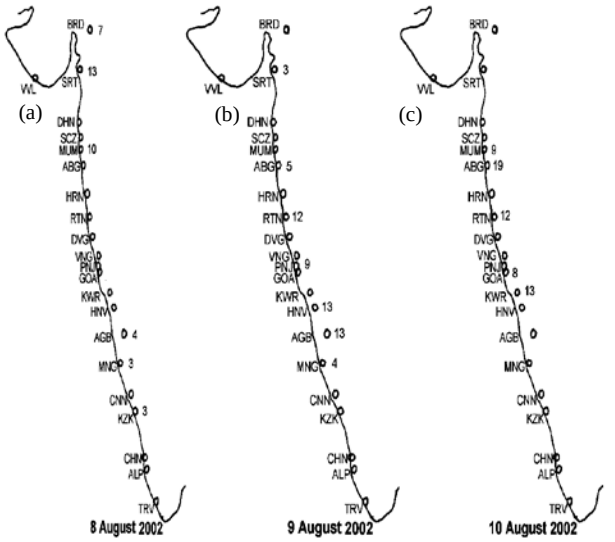
maximum wind of 22 kts (11 ms^{-1}) is noticed at 840 hPa. The atmosphere has 70-85% relative humidity till 700 hPa.

On 22 June 2002, the morning winds were south easterly to south south westerly upto about 0.3 km with a speed of 6-18 kts (3-9 ms^{-1}). The south easterly wind indicates the presence of trough close to Goa in the Arabian Sea. The maximum wind is 21 kts (10 ms^{-1}) at



Figs. 8(a-c). METEOSAT Satellite cloud imagery in the visible channel at 0600 UTC (a) 20 June 2002, (b) 21 June 2002 and (c) 22 June 2002

925 hPa. No heavy precipitation has been reported. The relative humidity is 75% or more upto 700 hPa. By evening the winds upto 0.3 km have changed to westerly to southwesterly and the maximum speed of 23 kts is



Figs. 9(a-c). 24 hourly accumulated precipitations (cm) recorded at 0300 UTC along the west coast stations of India on (a) 08 August 2002, (b) 09 August and (c) 10 August 2002

observed at 860 hPa. The atmosphere is moist upto 400 hPa.

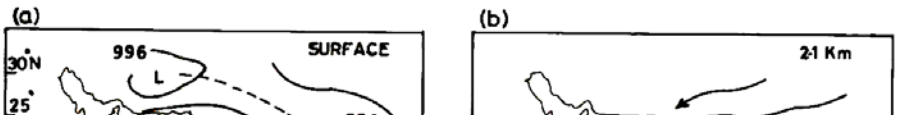
The morning to evening wind in the lower levels indicates that the trough is more marked and probably closer to the coast in the morning. By evening the trough appears to have either weakened or totally wiped out.

The RS/RW data of Mumbai from 20-22 June 2002, indicated very moist atmosphere till 500 hPa on all days. On 22 June the wind in the lower levels become south southwesterly indicating the presence of a trough off the west coast.

Thus, it appears that it is only the coastal stations surface wind direction or very low level upper atmospheric wind direction that point towards the presence of a trough in the Arabian Sea, but it is not usually supported by the buoy data or ship observations in the Arabian Sea as these observing systems were quite far off from the Goa coast where the trough could have been present.

Cross section chart along 72° E based on NCMRWF analysis of 0000 UTC on 21 June 2002 (Figure not presented) also indicated strong cyclonic wind shear slightly north of 15° N in the lower level with upward vertical motion close to 16° N and moisture–rich air upto 700 hPa.

Thus, from the analysis of different weather charts and other observations, it can be stated that the vortex formed close to 17° N, 70° E, in the region of strong cyclonic wind shear to the north of the low level jet. This region coincides with the heavy rainfall reported on 21 June 2002. The monsoon was strong both in the



Figs. 10(a-d). The surface and associated upper air streamline weather charts at 0000 UTC on 9 August 2002 [*Source* : Northern Hemispherical Analysis Centre, India Met. Department]. (a) Surface, (b) 2.1 km, (c) 4.5 km and (d) 7.6 km

Arabian Sea and Bay of Bengal due to the presence of synoptic systems both in the Bay of Bengal and Arabian Sea. An east-west shear line in the middle and upper troposphere extended from Arabian Sea to Bay of Bengal. The synoptic situation was nearly similar to the situation as on 14-16 June 2002.

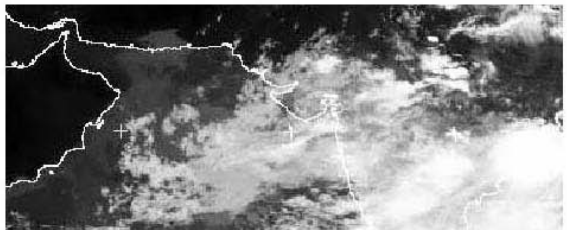
3.3. *Very heavy rainfall event 8, 9 and 10 August 2002*

(a) *Brief details of observed precipitation and synoptic situation*

The 24 hourly precipitation at 0830 hr (IST), from 8 August to 10 August is shown in Figs. 9(a-c). It is noticed that heavy rainfall started in the region between the stations Agumbe and Ratnagiri on 9 August and it moved northwards on 10 August. An off shore trough in the Arabian Sea lay extending from Maharashtra coast to Kerala coast and is marked on all days on the surface charts of NHAC. The trough is marked on the basis of surface wind of coastal stations and mean sea level pressure. The buoy (index no. 23094), located at 12.9° N, 74.7° E indicated light wind varying between southerly & westerly between 7 & 10th August 2002. Buoys located away from the coast usually showed southwesterly wind with speed varying between 5 & 15 ms^{-1}. Thus, the buoy located close to the coast behaves like a coastal station and indicates similar type of fluctuations in the surface wind. Under weak surface wind conditions over coastal stations, when the direction varies between north & south through east, one tends to believe the presence of a trough close to the surface. Buoy data or ship data may not support its presence. In the present case also, large scale synoptic features were common as in the earlier two cases. A cyclonic circulation between 2.1 km & 7.6 km was observed over Saurashtra, Kutch and neighbourhood. A low pressure area from Bay had moved inland into Gangetic West Bengal and neighbourhood with the associated cyclonic circulation extending upto 7.6 km. The circulation tilted ESE wards with height. A shear line joining the circulation over Saurashtra to the north west Bay was noticed between 2.1 & 7.6 km. The associated surface and upper air charts of 9 August 2002 (copied from NHAC charts) are shown in Figs. 10(a-d). An east-west shear line connecting the circulation features and extending from Arabian Sea to Bay of Bengal across the Indian peninsula is very prominent. The monsoon current is strong both in the Arabian Sea and Bay of Bengal due to the presence of synoptic systems both in the Bay of Bengal and Arabian Sea. Thus, strong monsoon conditions is the most common features in all cases of heavy rainfall along the west coast.

(b) *Satellite pictures*

The METEOSAT Cloud Imagery on 8, 9 and 10 August 2002 at 0600 UTC is shown in Figs. 11(a-c) and



(a)

(b)

(c)

Figs. 11(a-c). METEOSAT Satellite cloud imagery in the visible channel at 0600 UTC. (a) 08 August 2002, (b) 09 August 2002 and (c) 10 August 2002

clearly show broken low/medium clouds with isolated convection over NE Arabian Sea and along the coastal belt on 8 August. A circular convective cloud mass is observed off Goa-Karnataka coasts on 9 August. The curved convective lines suggest possibly a weak circulation or vortex off Goa of about 200 km in diameter. On 10 August also broken low/medium clouds with scattered convection were observed over NE Arabian Sea, coastal Maharashtra and Karnataka. The convection appears to have slightly weakened and shifted northward. On all the three days (8, 9 & 10 August) broken intense convection was also observed in the east and central Bay indicating strong monsoon in the Bay also.

(c) *SSMI, Q-SCAT and upper air observations*

The SSMI rain rate data of 8 and 9 August 2002, indicate intense circular rainfall areas close to Goa and north of it. The Q-SCAT plot along with buoy data and coastal stations surface wind at 0300 UTC (Fig. 12) does not indicate the presence of an off shore trough. *T*-ϕ gram analysis of TEMP stations at Trivandrum, Goa and Mumbai indicated weakly unstable but very moist atmosphere upto upper tropospheric levels. Trivandrum was driest and Goa the most moist amongst the three stations. The low level jet as usual was located in the latitudinal belt close to Goa.

Digicora observations aboard Sagar Kanya located at 14.99° N and 71.03° E in the Arabian Sea on 9 August 2002 at 1200 UTC are compared with the digicora observations of Goa (15.52° N, 73.47° E). The atmosphere is very moist upto 400 hPa. The relative humidity observed on board the ship is higher upto 700 hPa. The dry bulb temperatures show no contrast. The wind speed also is higher at the ship location, upto about 700 hPa, indicating speed convergence closer to the coast. The presence of an off shore trough even in the lower troposphere is not noticed in this case from the wind direction analysis. It is felt that due to speed convergence close to the west coast, possibly due to western Ghat hill features, the wind slows down considerably to nearly calm or variable state on approaching the coast. It may flow northwards or southwards along the hill ranges, close to the surface or lower/levels of the atmosphere and vertically upwards. Under favourable conditions of upper level divergence, which is quite frequent, the trough on the sea level chart may be observed oftenly. In the region where cyclonic wind shear is present, which is usually close to or the north of Goa latitude, the surface or lower level wind may flow northwards. This may frequently give rise to the indication of an off shore trough on the surface chart or very low level flow field particularly between Konkan-Goa coast to north Maharastra or Gujarat coast. The off shore trough oftenly may not be supported by the buoy data, Q-SCAT winds or even ship data located away from the coast.

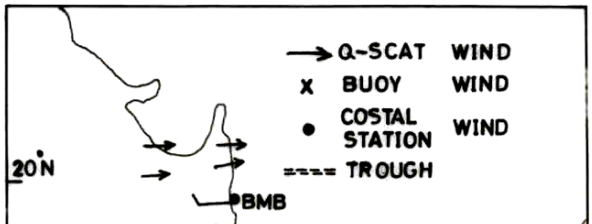


Fig. 12. Q-SCAT data of surface wind at selected points, Buoy and coastal stations surface wind at 0300 UTC on 09 August 2002

Cross section chart along 72° E, based on NCMWRF analysis of 0000 UTC on 9 August 2002 (Fig. not shown) also indicate a strong upward motion close to 18° N and relative strong cyclonic wind shear in association with the LLJ close to 15-16° N between 600 & 700 hPa. This heavy rainfall event was much less intense though it occurred after the monsoon had remained rather very weak during the whole of July. The monsoon current in this case was comparatively less strong as compared to the earlier cases. The meso-scale cloud complex, possibly a meso vortex on 8 August and subsequent days developed close to Goa, in the vicinity of strong cyclonic wind shear associated with the low level jet.

4. Features observed during heavy rainfall events, OST and off shore vortex

In all the cases of heavy rainfall observed along the west coast of India during ARMEX-2002, though NHAC surface charts indicated the presence of an off shore trough but buoy, Q-SACT surface wind and ship data supported it distinctly only in one case. Off shore vortices were identified from satellite imagery and supported by TRMM heavy rain rate enclosed areas in the vicinity of satellite observed vortices. The vortex formed, on the cyclonic wind shear side of the low level jet and in its close proximity. The buoys or the ORV Sagar Kanya were not directly affected by any meso vortex. There was a synoptic system both in the Arabian Sea and Bay of Bengal in the form of a low-pressure area/depression or cyclonic circulation. The east-west oriented shear zone joining circulation features in Arabian Sea and Bay of Bengal extended upto middle and upper tropospheric levels. The monsoon current was thus strong in both Arabian Sea and Bay of Bengal. The pressure gradient along the west coast was steep (about 8-10 hPa between Dahanu and Trivandrum). The vortex usually moved northwards along the coast. The life span was usually a day or two. The vortex usually developed in the cyclonic wind shear zone to the north of the low level jet. The area of genesis of the vortex need not necessarily be the OST zone. Off shore vortex has been observed even quite far away from the OST. However, whenever the vortex is very close to the coast, heavy rainfall has been reported from the coastal stations. The vortices observed have been 2° to 3° in diameter. No vortex was directly penetrated by any of the buoys or research ships or the Indian Air Force aircraft. It was inferred on the basis of satellite picture, TRMM data, and some of the RS/RW data of TEMP stations located on the coast. Thus, it may be said, that off shore vortices associated with intense heavy rainfall were observed, as meso-scale systems, in the large scale cloud field during the advancing phase of the monsoon and whenever the monsoon current was strong. The monsoon current is usually strong when large scale synoptic systems are present in the Arabian Sea or Bay of Bengal or both. Aided by orography of the western ghats, the strong cyclonic wind shear, enhanced air-sea fluxes, the evolution of deep convection takes place off the west coast of India, usually in combination with an off shore trough. The OST can also help in the development of meso vortices.

5. Light rainfall and OST in July 2002

July 2002 reported scanty precipitation along the west coast of India. Monsoon current was generally weak both in the Arabian Sea and western Bay of Bengal. Weather charts from 5 - 8 July and buoy data were also examined. Based on buoy data, coastal stations surface winds and Q-SCAT data, a feeble off shore trough was noticed on 6 July 2002 (Fig. 13). No significant convective activity was observed either on the satellite imagery or SSMI rain rate in Arabian Sea. The ORV Sagar Kanya and Goa, upper air data indicated inversion layers close to 800 and 500 hPa and extremely dry air between these two levels. The relative humidity was close to 20-30% in this layer, though it was fairly moist between surface & 800 hPa. The deep inversion layer coupled with very dry atmosphere in the mid tropospheric levels did not permit the deep convective clouds to develop and hence negligible precipitation. The wind direction however, does indicate the presence of weak trough between Goa and the location of ORV Sagar Kanya. The wind speed was considerably weaker as compared to the strong monsoon

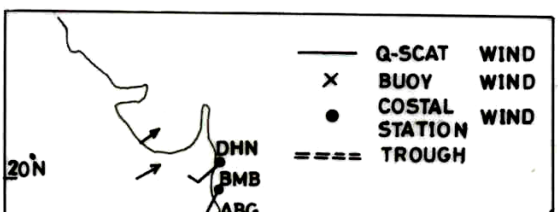


Fig. 13. Q-SCAT data of surface wind at selected points, Buoy and coastal stations surface wind at 0300 UTC on 06 July 2002

situation. Thus, one comes across, that OST can be observed even during weak monsoon conditions and it need not be associated with heavy precipitation.

6. Conclusions

(*i*) Off shore trough (OST) in the Arabian Sea during southwest monsoon season (June-September 2002) has been observed both during strong monsoon as well as weak monsoon conditions. The OST is located very close to the coastline and is usually inferred on the basis of surface wind at the coastal stations or very close by off shore observations of a Buoy. The surface wind at the coastal stations though indicative of the OST, is usually light. The OST is usually located on the surface chart and rarely extends in the upper levels beyond 0.3 to 0.6 km. The buoys located slightly away from the coast or Q-SCAT and even Sagar Kanya surface data do not always support its existence.

(*ii*) Heavy rainfall events along the west coast stations of India are observed, when the monsoon current is strong both in the Arabian Sea as well as Bay of Bengal under the influence of synoptic systems. An east west shear line joining the circulation features in the Arabian Sea and Bay of Bengal extended upto middle or upper tropospheric levels. Such a situation may be associated with the off shore trough off west coast of India in the lower levels of the atmosphere but is not essential.

(*iii*) Meso-scale vortices/organized convective systems were observed during June and first half of August 2002. Off shore trough may be associated with the heavy rainfall event under strong monsoon conditions both in the Arabian Sea and Bay of Bengal. The location of formation of the vortices had been on the cyclonic wind shear region of the low level jet. The vortices may develop close to the coast in the OST region or even away from it. The favourable region of development of vortices close to coast is 12-13° N, where the low level jet impinges the coast. The vortices have been observed on the basis of satellite cloud imagery and SSMI rain rates. The vortices located close to the coast usually lead to the development of heavy rainfall events. However, some vortices were quite far away from the coast. They usually moved north or north-northwest wards. The life span was one to two days. The diameter varied between 200 & 300 km. The vortex formation can also be aided by the orography of the western ghats and OST. The deep convection may be induced by enhanced air-sea fluxes as a result of strong monsoon current. During July 2002, the monsoon was very weak in the Arabian Sea and no heavy rainfall event and hence vortex was observed.

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