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Interaction of a mesoscale low and diffused tropical depression during south Asian summer monsoon

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सार – इस शोध–पत्र में मरूस्थलीय जलवायु में निम्न मेसोस्केल के साथ बंगाल की खाड़ी पर बनने वाले उष्णकटिबंधीय विसरित अवदाब के परस्पर प्रभावित करने से दक्षिणी एशियाई ग्रीष्मकालीन मानसून की विशेष स्थिति के नैदानिक अध्ययन से प्राप्त हुए परिणाम प्रस्तुत किए गए हैं। इस अध्ययन प्रक्रिया में उपग्रह एवं रेडार बिम्बावलियों से प्राप्त किए गए सतह एवं एन. सी. ई. पी. पुनः विश्लेषित आँकडों को शामिल किया गया है। इसमें भारी वर्षा होने की प्रक्रिया और अधिक मात्रा में उसके परिसंचरणों की विधियों जैसे – पश्चिमी धारा, निम्न स्तरीय धारा, अभिसरण, भ्रमिलता एवं जलवाष्प के परिवहन जैसी स्थितियों के संबंधों की जाँच करके इसकी अन्य क्रिया को समझने का प्रयास किया गया है। यह पाया गया है कि उत्तरी अंक्षाशों के ऊपर से आने वाली ठंडी वायु के अभिवहन से निम्न मध्य मापक्रम विकसित हुआ और आद्रता अभिसरण उस क्षेत्र अर्थात राजस्थान में, 24 जुलाई 2003 को प्रबल अभिवहन पैदा हुआ। उसी दिन बंगाल की खाड़ी में निम्न दाब का क्षेत्र बना जो आगे चलकर मानसून अवदाब में विकसित हुआ। इसके बाद यह दक्षिण पश्चिम भारत में निम्न मेसोस्केल होने के कारण खाड़ी से पश्चिम की तरफ चला गया। यह निम्न मेसोस्केल लगभग दो दिनों तक स्थिर रहकर तीव्र होता रहा और बाद में अपेक्षाकृत धीमी गति से दक्षिण–पश्चिम दिशा की ओर बढ़ गया। इन दोनों प्रणालियों के परिणाम स्वरूप इनके प्रभाव क्षेत्र में कहीं सामान्य तो कहीं भारी वर्षा हुई। इनकी तीव्रता में अचानक वृद्धि से इनके परस्पर प्रभाव में काफी वृद्धि होने का पता चला है।

ABSTRACT. This paper presents the results of a diagnostic study of a typical case in south Asian summer monsoon when a meso-scale low in a desert climate interacted with a diffused tropical depression originated over the Bay of Bengal. Surface and NCEP reanalysis data supported by satellite and radar images were incorporated in diagnosis. The relationship between heavy precipitation process and large-scale circulations such as westerly jet, low level jet, convergence, vorticity and water vapor transport were investigated to further understand the mechanism of this peculiar interaction. It has been found that the meso-scale low developed as a result of cold air advection aloft from northern latitudes and strong convection over the region of humidity convergence, *i.e.*, Rajasthan (India) on 24th July 2003. On the same day, a low formed on the Bay of Bengal which further developed into monsoon depression. It moved westward from the Bay towards the meso-scale low over southwest India. Meso-scale low remained more or less stationery for two days gaining intensity and then moved relatively with slower speed in southwestward direction. Both the systems yielded moderate to heavy rain in areas under their influence. Interaction resulted into huge accentuation with an abrupt increase in intensity.

Key words – Monsoon depression, Convective instability, Cold air advection, Low level jet, Westerly jet, Summer monsoon, Mesoscale Convective System (MCS).

1. Introduction

Frequency of occurrence of heavy rains exceeding 60 mm in 24 hours is a common feature over foothills of Himalayas during southwest summer monsoon (June-September). Events of very heavy precipitation more than 120 mm per day are although less frequent but highly devastating. Torrential rains result in flash flooding downstream causing huge damage to soil, crops and infrastructure. Exceptionally heavy rain totaling 620 mm in only 10 hours in Islamabad-Rawalpindi (twin cities in Pakistan) on 23rd July 2001 is the recent example. Civic life was completely paralyzed and infrastructure suffered irreparable damage. Rasul *et al*., (2004) discussed the reasons of development of that meso-scale system in the sub-humid mountainous terrain under the combined effect of strong convection, moisture convergence and triggering action of westerly wave trough across northern latitudes of Pakistan. They have also analyzed the heavy rainfall over arid plains of India and Pakistan due to merger of a tropical depression and a meso-scale low (Rasul *et al*., 2005).

Number of heavy rain events sharply decreases towards south Pakistan following a relative fall in amounts of precipitation (Chaudhry, 1991). The climate of southern half of Pakistan (30° N - 24° N) is generally hot and dry except some patches of moderate climate in the west. The frequency of occurrence of rainfall in southern parts of Pakistan even in monsoon season is considerably lower that the northern half of the country. Asian summer monsoon is the main source of precipitation in most of the countries of south Asia including India and Pakistan. More than 50% of year's total rainfall in Pakistan is received during summer monsoon season from July to September (Chaudhry, 1991). Although Pakistan is situated nearer to the Arabian Sea than to the Bay of Bengal but it is interesting to note that until the easterly monsoon current from the Bay of Bengal penetrates into Pakistan, not much rain is experienced. This rain is generally associated with depressions and low pressure areas which form on the Bay of Bengal and move westward or northwestward sometimes reach Pakistan depending upon intensity (Ramage, 1963; Ding *et al*., 1984). Several scientists have developed some numerical techniques for prediction of heavy rainfall during summer monsoon and even high resolution meso-scale models are now available for prediction of heavy rainfall events.

Present study is focused on diagnosis of heavy downpour amounting 108.4 mm in Karachi (24° 54′ N, 67° 08′ E) on 28th July 2003. The rain amount of 108 mm in 24-hrs seems not to be devastating but the areas like Karachi, where such rains seldom occur, it becomes hazardous. Karachi is the largest city of Pakistan populated with over 10 million people, and is located at the north coast of the Arabian Sea. It receives some precipitation in summer during peak monsoon season only, therefore, experience arid and yet maritime climate.

TABLE 1

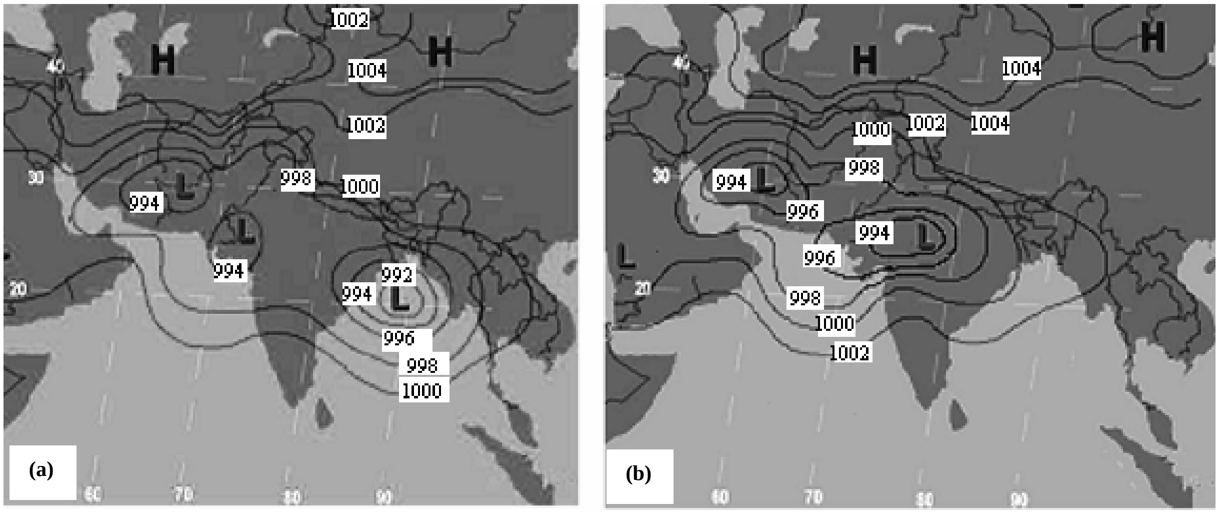
Heavy rainfall (> 60 mm) over Karachi

Date	Rain	Date	Rain
27 Aug 1961	98.8	01 Jul 1977	207.0
13 Jul 1964	69.3	18 Aug 1978	133.6
22 Jul 1965	65.5	07 Aug 1979	166.0
25 Jul 1967	120.4	07 Aug 1984	113.7
05 Jul 1970	97.0	13 Aug 1992	91.7
08 Jul 1973	104.6	14 Jan 1995	81.3
19 Jul 1976	122.4	29 Jul 2003	108.4

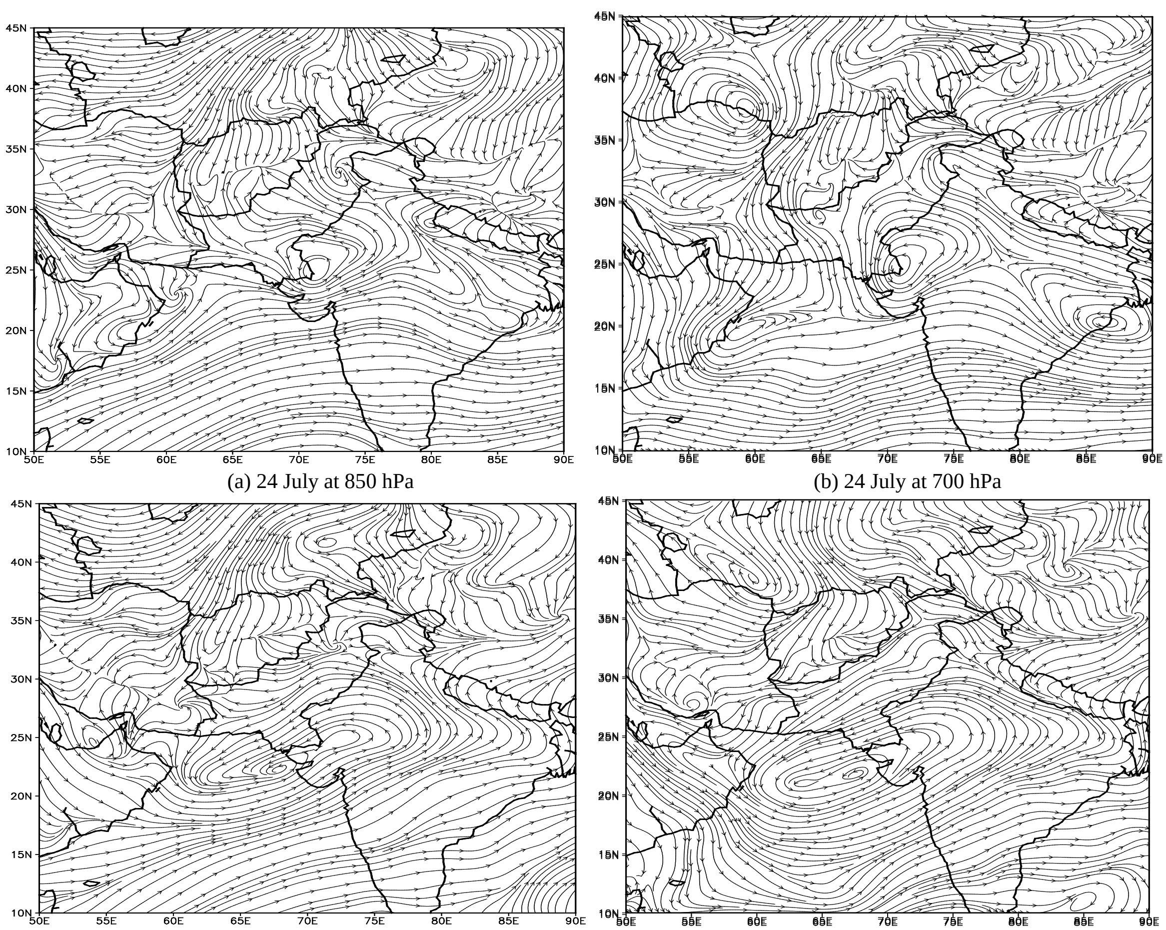
Very often whole year's supply is received within a day or two in the form of heavy showers during the monsoon season (Rao, *et al*., 1970; Rao, 1976). In 1944, the year's total rainfall in Karachi was recorded as 745.5 mm, whereas in 1931 it dropped down to 2.3 mm only. The highest amount of total rainfall in a month is 473.2 mm (July 1894) and 278.1 mm rainfall was recorded on 7th August 1953 in 24 hours (Shamshad 1986). Table 1 shows heavy rainfall (rainfall > 60 mm) events recorded in 24-hours over Karachi from 1961-2005.

2. Synoptic situation and rainfall distribution

On 23rd July 2003, a trough of low pressure in the mid troposphere appeared over west Rajasthan (India) and adjoining southeastern parts of Pakistan, which developed into a low pressure area. On the same day, a low pressure at the North Bay of Bengal developed into a depression. The low pressure over Rajasthan persisted over the area and further expanded to neighbouring regions westward. Prominent features regarding the position and intensity of both the systems on the surface can be seen in synoptic surface maps shown in Figs. 1(a&b) for 25th July and 28th July, respectively. A trough of westerly wave across north of Pakistan over mid latitudes can be seen on 25th July [Fig. 1(a)] which we believe had triggered the formation of meso-scale low in the area of convective instability where strong convergence zone of humidity existed. Fig. 1(b) presents the surface features of both the weather systems after interaction just hours after very heavy rain in Karachi. Independent status of the seasonal low over southwestern parts which shifted slightly westward from its normal position and the newly developed meso-scale



Figs. 1(a&b). Surface maps at 1200 UTC (a) A monsoon depression over the Bay of Bengal and a low over south Pakistan on 25 July 2003 and (b) Dissipating depression merging with meso-scale low over southeastern parts of Pakistan on 28 July 2003



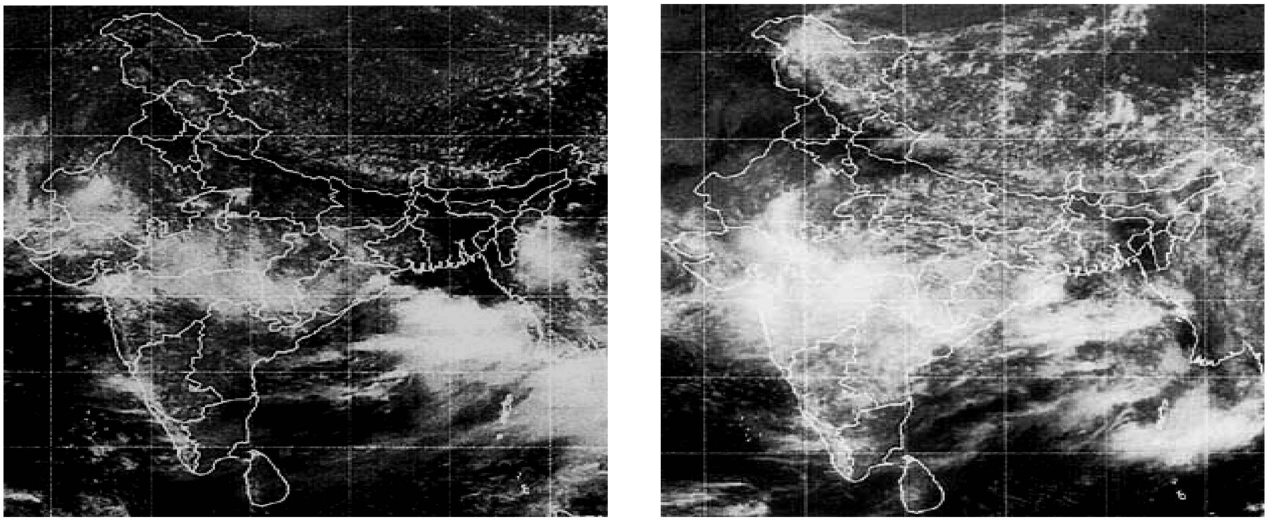
(a) 24 July at 850 hPa

(b) 24 July at 700 hPa

(c) 28 July at 850 hPa

(d) 28 July at 700 hPa

Figs. 2(a-d). Streamline fields on 24 and 28 July 2003 at 850 hPa and 700 hPa (1200 UTC local time 1700 hrs)



(a) INSAT (1200 UTC) of 24th July

(b) INSAT (1215 UTC) of 28th July

Figs. 3(a&b). Satellite picture (a) shows monsoon depression formation at the Bay of Bengal and meso-scale low over Rajasthan (India) and adjoining parts of Pakistan and (b) Interaction of both the systems is taking place over southeastern parts of Pakistan

low on southeastern regions of Pakistan could be seen in Fig 1(a). The tropical depression suffered gradual dissipation as it moved westward over central India whereas meso-scale low remained almost stationary.

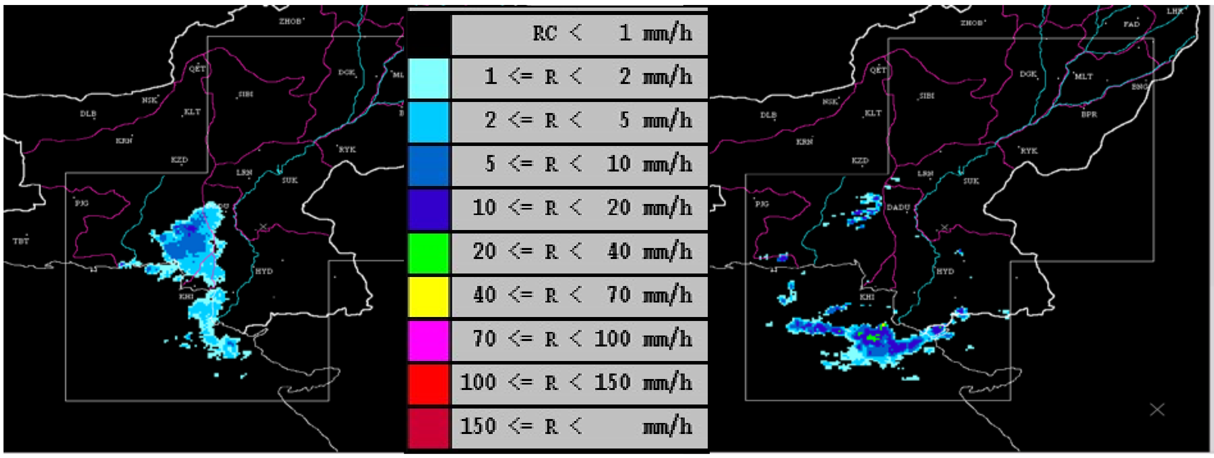
The meso-scale low was fed by moist easterlies across the gangetic plains of India from the Arabian Sea and southwest currents continued getting strength and it produced moderate rain in areas under its influence from 25 to 28 July 2003. It maintained its independent status until merger took place on 27 July with westward moving Bay's monsoon depression. Both the systems merged together and regained strength after a little pause. After their merger the intensity of precipitation was significantly increased on 27th July and a large area came under its influence. The interacted system yielded moderate to heavy precipitation over the areas of southern Sindh including Karachi moving further west and southwestward. At Karachi airport, the rain started at 1015 UTC and totaled 21 mm till 1200 UTC of 28th July. During next three hours a sharp increase in intensity occurred as 79 mm precipitation was accumulated during this 3 hours interval. Later on it changed into drizzle and then stopped at 2305 UTC of 28th July yielding only 5.5 mm from 1500 UTC to 2305 UTC. The interacted system further moved southwestward in the Arabian Sea and rainfall activity was diminished over the coastal land areas.

3. Meso-scale system and moisture convergence

The development of meso-scale low over Rajasthan was an interesting issue of concern for meteorologists of the region. The area where the inception of meso-scale low took place is sandy desert extremely hot and dry in summer. The coincidence of favourable shift in winds combined with input of cold air and moisture feeding from different sources made its birth possible. Formation of meso-scale low over Rajasthan adjoining southeastern areas of Sindh and tropical depression on the Bay of Bengal can be seen more clearly at 700 hPa than 850 hPa on 24th July [Figs. 2(a&b)] based on NCEP reanalysis data.

Regarding the area-specific diagnosis of moisture contents variation from lower to upper troposphere, vertical cross sections of relative humidity on 27th and 28th July were drawn along 68° E. On 27th July at 0000 UTC, maximum relative humidity was found near 21° N, which expanded up to 25° N at 1200 UTC showing maximum values between 700-400 hPa. Well-marked minimum in relative humidity near the surface could be seen north of 27° N latitude over the region of heat low up to shallow layers of troposphere.

Almost 100% humidity prevailed over the area between 21° N - 26° N from surface to mid-troposphere



(a) 28 July 0000 UTC

(b) 28 July 1200 UTC

Figs. 4(a&b). Karachi radar (C-Band 5 cm) echoes (24°, 54´ N, 67°, 08´ E) showing cloud clusters around Karachi on 28th July, 2003

on 28th July. These humid zones earlier prevailed over Rajasthan and then moved westward along with the westward moving rain bearing systems. A minimum in relative humidity with values of relative humidity at the center as being 30% existed at the mid-troposphere between latitudes 12° N and 15° N, well south of the region of the system being investigated.

The satellite pictures of INSAT shown in Figs. 3(a&b) indicate the extensive monsoon cloud band during the active monsoon conditions on 24 and 28 July. On 24th July, the cloud patches including mainly cumulus and altocumulus started appearing over southeastern parts of Sindh marking the location and development of meso-scale low pressure system. Gradually, the cloud clusters increased in size and prevailed over vast area into patches. They covered almost whole of Sindh province and neighbouring parts of India until 25th July. On 28 July 2003 very heavy rains between 15-30 cm in 24-hours occurred over Gujarat, Saurashtra and Kutch region of India.

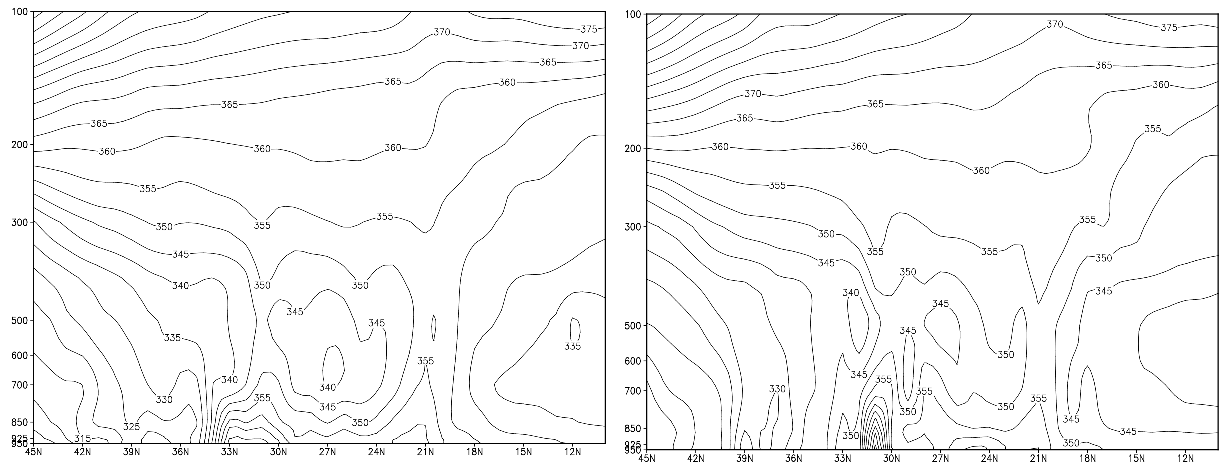
The mechanism of moisture supply from the Bay of Bengal and the Arabian Sea as well as relative location of both the low pressure systems from formation stage to dissipation can be seen clearly in Figs. 3(a&b). Initially, both the systems were fetched with moisture supply from the Bay of Bengal but they maintained their independent status. It persisted till 27th July following a gradual decrease on daily basis as the depression moved away from Bay in westward direction. Moisture supply from the Bay weakened considerably and the Arabian Sea has become the new source of moisture supply on 27 July as it often happens in the case of a monsoon depression over western India which enhances moisture advection from the Arabian Sea.

The Radar images covering the surrounding area in 300 km radius around Karachi are shown in Figs. 4(a&b) which projects the different stages in the life history of the meso-scale system between the intervals when it produced heavy downpour in Karachi. Reflectivity of cloudclusters showed increase in the period of heavy rain. All the recorded images are not shown. However, changes took place in shape and size of cells with varied span of life. Further movement of the system in southwestward direction after heavy downpour on land can also be seen in radar image of 28th July at 1200 UTC. Main precipitation amounts occurred on 28th July in Karachi between 0000 and 1200 UTC. The strong weather system sweeping northern and eastern sectors comprised of high intensity radar echoes approaching Karachi is apparent in Fig. 4(a).

4. Convective instability and cold air advection

During July southwestern parts of India and adjoining southeastern parts of Pakistan get intensely

(a) 27 July 0000 UTC (b) 27 July 1200 UTC



Figs. 5(a&b). Vertical profile of pseudo-equivalent potential temperature (K) along longitude 68° E located east of Karachi (a) 27 July 0000 UTC and (b) 27 July 1200 UTC

heated. Convectively unstable vertical currents with lack of moisture in the middle troposphere usually develop to produce local dust/sand storms or simply dust devils. Convergence of humidity is an important indicator that marks the regions of convective instability fetched with moisture from a source outside the region. Pseudo-equivalent temperature is also a key parameter that plays an important role to produce convective instability $\left(\frac{\partial \theta_l}{\partial Z}\right)$ conditions. Both these parameters are simultaneously reviewed in common perspective. The vertical profile of Pseudo-equivalent temperature, along 68° E longitude that runs east of Karachi, is shown in Fig. 5(a&b). It is evident that the minima exist in the layer 700 hPa to 500 hPa between 24° N and 28° N on 27th July 2003 whereas maxima prevailed near the surface. A sharp upward decrease of Pseudo-equivalent potential temperature $\left(\frac{\partial \theta_l}{\partial Z}\right)$ confirms the existence of strong convective instability area east of Karachi.

The lowest values of Pseudo-equivalent temperature may also be seen from the surface to 400 hPa along 10-18° N. Between these two minima, the weak maxima also existed near the surface. Strong convection combined with moisture flux convergence fed into cyclonic circulation. Vertical motions associated with cyclonic circulation led the lifted air mass to condensation and thence to produce precipitation. This process continued till favourable conditions on the surface and upper air existed due to the larger circulation in the lower middle troposphere.

For investigation of such conducive indicators, divergence field of moisture flux at 500 hPa was drawn. Well-marked convergence zone of humidity on 24th July appeared at 500 hPa over Rajasthan and adjoining areas of lower Sindh. It increased in intensity with the passage of time due to continued moisture supply through low level easterlies. The strongest moisture convergence zone could be seen on 26th July to 28th July and onward with its center slightly shifted southward. Divergence zone prevailed over northern half of Pakistan and even over the Heat Low (west central parts of Pakistan) during the period from 25th July to 28th July. Moisture convergence over meso-scale low was rather stronger than that of tropical depression.

As circulation is directly related to vorticity, therefore, a well-marked increase in vorticity can be observed in such convectively unstable areas. Keeping in view all possible reasons behind the inception and further development of meso-scale low, analysis of vorticity field deemed necessary. A strong positive vorticity area existed over the Arabian Sea just off the coast of Sindh, southeast of Karachi on 27 July. After 24 hours, a strong positive vorticity area appeared in the north of already existing positive center covering most parts of upper Sindh whose trough was extended up to the coastal line including

Karachi. Both positive areas were closely located north-south sandwiching a weak negative area between them. In short, maximum of relative vorticity was located over and east of Karachi while minimum existed west of it when the heavy rainfall occurred in Karachi and its eastern suburbs on 28th July 2004.

To investigate the behaviour of constant pressure heights and thermal regime of the prevailing atmosphere, the height and temperature fields at 500 hPa were analyzed with a view to diagnose cold temperature advection from north Pakistan. This analysis showed that on 25th July, an isotherm -4° C at 500 hPa level was passing across north of Pakistan whereas -2° C showed a significant troughing southward on the eastern edge, indicating cold air advection to southern latitudes. Tibet Plateau remained a warm center during the period with a gradual increase in temperature. Later on temperature gradient over the north of Pakistan increased and below freezing isotherms further penetrated southward pouring the cold air to southern latitudes. At the same time, temperatures over the Tibet Plateau continued increasing reaching in double figure on 28th July. Thus, cold air advection was taking place in the mid-troposphere over Sindh, Pakistan and western India which were the location of meso-scale low and tropical depression respectively. This cold air advection resulted in enhancing the vertical motion field around the two disturbed areas.

5. Conclusions

Following conclusions have been drawn on the interaction of meso-scale low and a monsoon depression:

(*i*) A meso-scale low developed into an intense low over the area of strong convergence of moisture in the south of monsoon trough under continuous moisture supply from the Arabian Sea or the Bay of Bengal or both. The heat low mainly existing over Balochistan shifted westward and gradually became insignificant.

(*ii*) The meso-scale low maintained its independent status consistent with the formation of a monsoon depression over the Bay of Bengal as lower level moisture supply and cold air advection aloft from northern latitudes continued. The convective instability continued increasing with the continuous feeding.

(*iii*) Under these conditions, the intensity of a meso-scale low over western parts of Rajasthan (India) or southeastern Sindh increased whereas monsoon depression continued losing its strength during the journey on land towards the meso-scale low. Both the systems yielded moderate to heavy precipitation in the area under influence according to their positions independently.

(*iv*) The weakening depression continued moving westward but the meso-scale low remained more or less stationery at its original position. Finally both the systems approached each other. During the process of interaction, the rainfall activity was significantly reduced in its radial extent and decreased to its minimum near the center.

(*v*) After the interaction took place between the two systems, the intensity of precipitation over Gujarat, Saurashtra and Kutch region of India and over southern Pakistan had sharply increased associated with intense lightening and thunderstorm activity. The combined system moved in southwest direction sweeping over Karachi and entered the Arabian Sea horizon. The interaction resulted into a heavy downpour on its track of advancement. Cold air advection from north Pakistan in the middle troposphere led to enhanced vertical motion in the vicinity of the disturbed area.

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