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551.579 : 551.577 : 551.515.2 : 551.521.32

OLR values over Indian region and heavy rainfall events over Mumbai during a North West Pacific system located west of 140° East

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सार – भारतीय क्षेत्र में ओ.एल.आर. मानों के संबंध में भारतीय ग्रीष्मकालीन मॉनसून वर्षा पर तीव्र निम्न दाब प्रणाली (उष्णकटिबंधीय दाब और उससे अधिक) का सकारात्मक प्रभाव तब दिखाई देता है जब यह उत्तर-पश्चिम प्रशांत महासागर के 140 डिग्री पूर्व और 30 डिग्री उत्तर पर स्थित होती है तथा पश्चिमी अथवा उत्तर-पश्चिमी दिशा में आगे बढ़ती है। यदि पश्चिमी अथवा उत्तर पश्चिमी दिशा की ओर तीव्र निम्न दाब प्रणाली के 130 डिग्री पूर्व के पश्चिम में और 17 डिग्री उत्तर के उत्तर में स्थित है तो मुंबई ओर उसके आस–पास के क्षेत्र में भारी वर्षा (≥65 मि.मी.) से लेकर अत्याधिक भारी वर्षा (≥250 मि.मी.) तक हो सकती है बशर्ते उपग्रह से प्राप्त मेघ चित्र में आई. टी. सी. जेड मुंबई अक्षांश के आस पास / मुंबई अक्षांश से गुजरता हुआ दिखे और इसे उत्तर-पश्चिम प्रशांत महासागर अथवा 850 एच.पी.ए. ओर 700 एच.पी.ए. पर पूर्व–पश्चिम द्रोणी में प्रेक्षित किया जाए तथा इसे 60 डिग्री पूर्व के 19 डिग्री उत्तर से 25 डिग्री उत्तर / पूर्व के बीच देखा गया हो और उत्तर-पश्चिम प्रशांत महासागर तक प्रेक्षित किया गया हो। उत्तर पश्चिमी प्रशांत महासागर की प्रणाली की स्थिति और मुंबई में भारी वर्षा की घटनाओं के बीच कोई सीधा संबंध नहीं है।

ABSTRACT. Positive impact of an intense low pressure system (tropical depression and above) on Indian summer monsoon rainfall is visible in terms of OLR values over Indian region when it is located west of 140° E and south of 30° N over North West Pacific and moves in westerly or northwesterly direction. If an intense low pressure system moving in a westerly or northwesterly direction is located west of 130° E and north of 17° N over North West Pacific, heavy rainfall (≥ 65 mm) to extremely heavy rainfall (≥ 250 mm) may occur over Mumbai and neighborhood provided either ITCZ in satellite clouds picture is seen passing through nearby - Mumbai latitude/Mumbai latitude and along west coast of India and is observed up to northwest Pacific system or east-west trough at 850 hPa and above / 700 hPa and above is seen between 19° N to 25° N/E of 060° E and is observed up to north west Pacific system. There is no one-to-one relationship between position of northwest Pacific system and heavy rainfall events over Mumbai.

Key words – Intense low pressure system, OLR, ITCZ, East-west trough.

1. Introduction

Past studies highlight the role of North West Pacific (NWP) weather systems in modulating the performance of Indian summer monsoon. Kumar *et al*., 2011 have observed that when the NWP system reaches west of 140° E and follows westerly or northwesterly track, the monsoon system over the country in general gets strengthen due to extension of east-west trough horizontally and vertically. They have further mentioned that when an NWP system reaches west of 120° E, monsoon depression (MD) forms over the Bay if there is a low pressure area (LPA) over the Bay. Monsoon lows and upper air cyclonic circulations had also formed under such conditions. In 94% cases each, MD and LPA had formed over the Bay when the NWP systems were located south of 25° N. Attempts have been made to examine the impact of an NWP system located west of 140° E and moving in northwest/westerly direction on Indian summer monsoon rainfall (ISMR) in terms of OLR values over Indian region.

Frequent heavy (HY) to very heavy (VHY) rainfall occurs in Mumbai during southwest monsoon season.

Kumar *et al.* (2010) have observed that 47% of the total Low Level Vertical Wind Shear (LLWS: 10.1 per month) over CSI Airport Mumbai is observed during southwest monsoon season. They have further observed that whenever surface wind is reported ≥ 15 knots (including gusts), with precipitation, LLWS can be forecast. Thus, correct forecast of HY thunder with HY rain/HY rainfall (+ TSRA/ + SHRA) through Terminal Aerodrome Forecast (TAF) and HY to extremely HY rainfall in general forecasting will help the aviation industry in proper planning of their day to day flights. Attempts have been made to further augment the existing meteorological conditions, which are known for extreme weather events over Mumbai and its suburbs.

Srinivasan *et al*. (1972) had observed that active monsoon conditions over north Konkan were usually associated with a trough of west coast of India, formation/ movement of a depression / low from north Bay of Bengal across central parts of the country, presence of mid-tropospheric cyclonic circulation (MTC) off north Maharashtra-south Gujarat coasts between 700 and 500 hPa pressure heights and strong pressure gradient along the west coast. Ramanna (1969) observed that during 60 years period around 20% of the cyclonic systems had formed in the Bay between 15° N and 25° N after the cyclonic systems of the South China Sea crossed the coast in the same latitude during July and August. Clearly there is a link between cyclonic systems of South China Sea, monsoon depression (MD) / low over North Bay and active monsoon conditions over north Konkan. Ramage (1971) had also observed that on 25th July 1967 (the day of extensive rain over different regions connected with the systems), three separate systems contributed to the activity, sub-tropical cyclones at 25° N / 075° E (strong) and 21° N / 106° E (weak) and MD at 20.5° N / 087.5° E. He had mentioned further that a possible 4th low was centred near 10° N / 115° E; to the south of each of these systems a lower tropospheric westerly maximum was causing significant downstream convergence. Grossman and Durran (1984) had found that blocking effect of the Western Ghats to be adequate for initiating convection on the windward side and could lead to a deep convection if 850-500 hPa layers were sufficiently moist and if the basic monsoon current was sufficiently strong. This factor remains always dominant when any cyclonic system develops over the North Bay. Shyamala and Mukherjee (1985) had observed that formation of a low level circulation (LLC) at 850 hPa over Arabian Sea and adjoining north Maharashtra-south Gujarat coasts was necessary for HY rainfall over north Konkan at the time of formation of monsoon depression. Prasad and Agrawal (1996) had noted that east-west trough line along 19° N - 21° N along with the above mentioned conditions resulted in HY rainfall over Mumbai. Shyamala and Shinde (1999) had observed that cyclonic circulation over Saurashtra, south Gujarat region and adjoining north east Arabian Sea at 0.9 km and at 850 hPa level give rise to widespread rainfall activity in north Konkan, south Gujarat region and Saurashtra. Dutta and De (1999) had observed that in most of the cases strength of easterly at 200 hPa (over Mumbai) is much more on the day of light rainfall and also in most of the cases the depth of the layers of westerly wind is less on the day of light rainfall. Kumar (2001) had observed that heavy rainfall over Mumbai occurs only when cross equatorial flow is strong. Under these conditions Minicoy Islands/southern peninsular India report at least 30-50 knots winds at different heights from 0.6 km to 700 hPa pressure height with core of low level jet (LLJ) at 850 hPa. Shyamala and Iyer (2005) had observed that the exceptionally heavy rain event of 12-13 July 2000 over Mumbai was associated with the development of a meso-scale intense convective vortex off Mumbai is the synoptic scenario of well marked low pressure area (LPA) over the Bay of Bengal. Joseph (2006) stressed the role of LLJ at 850 hPa and development of mesoscale convective system as possible causes for heavy rains of July 2005 in Mumbai. Kumar *et al*. (2007) had observed that when the low level westerly at 850 hPa is reported ≥ 30 knots by Minicoy/Amini Divi islands or any other station along the west coast off peninsular India from Thiruvananthapuram to Mumbai and Wind-Temperature-Humidity (WTH) index reaches critical value, very HY to extremely HY rainfall occurs over Mumbai and suburbs. Based on this model even the unprecedented rainfall of 26 July (944 mm) and very HY rainfall of 9 September 2005 (223 mm) have been forecast for all domestic flights in the significant weather charts indicating occasional CB around Mumbai (VABB) 24-30 hrs early. Shyamla and Bhadram, 2006 had observed that (a) Synoptic conditions of low pressure area over Bay of Bengal and its movement inland were present during 25-26 July, (b) Monsoon trough in the lower and middle tropospheric levels was very active between 2.1 and 4.5 km above Sea level during 25-26 July, (c) Accentuation of Arabian Sea monsoon current, formation of convective cloud band from the Arabian Sea towards the low pressure area in the Bay and its movement northward were present. Strengthening of low-level winds over Mumbai to 30-35 knots was noticed on 26/0530 IST compared to 25-30 knots on 25 July and (d) Development of mid-tropospheric dryness in the atmosphere with strong vertical wind shear over Mumbai from 26/0530 hr IST led to high conditional instability and formation of supper thunderstorm cells. Mesoscale intense convective system formed over Mumbai and resulted in very heavy convective rainfall from 26/1430 hr IST. They have further mentioned that the exceptional rainfall event of 26 July 2005 over Mumbai occurred due to the interaction between mesoscale and synoptic scale systems.

TABLE 1

OLR values during the storm period of an NWP system 06 w

Date	Latitude (North)	Longitude (East)	A. M. of OLR	Position of 06 w at 1200 UTC (North/East)
19 July 2006	12.5	079.5 – 093.5	235.0	12.0/139.6 TS
	13.5		224.0	
	14.5		230.0	
20 July 2006	14.5	078.5 – 093.5	212.0	14.2 / 136.3 TS
	15.5		195.0	
	16.5		178.0	
21 July 2006	16.5	077.5 – 093.5	137.0	16.2 / 131.7 TY
	17.5		137.0	
	18.5		138.0	
22 July 2006	18.5	076.5 – 093.5	165.0	17.4 / 128.8 TY
	19.5		169.0	
	20.5		173.0	
23 July 2006	20.5	075.5 – 093.5	190.0	20.4 / 125.8 TY
	21.5		211.0	
	22.5		222.0	
24 July 2006	22.5	074.5 – 093.5	226.0	22.4 / 122.1 TS
	23.5		223.0	
	24.5		217.0	
25 July 2006	24.5	073.5 – 093.5	221.0	24.6 / 117.7 TS
	25.5		211.0	
	26.5		201.0	
26 July 2006	26.5	072.5 – 093.5	163.0	24.9 / 115.6 TD
	27.5		170.0	
	28.5		176.0	
21 July 2006	26.5	077.5 – 093.5	216.0	16.2 / 131.7 TY
	27.5		204.0	
	28.5		200.0	

2. Data and methodology

Tracks of intense low pressure systems over North West Pacific (NWP) have been collected from Joint Typhoon Warning Center (JTWC) Guam website. NOAA satellite cloud pictures have been used. OLR values for July 2006 have been received from Additional Director General of Meteorology (Research), Pune. Map of OLR values for the period 19th July, 2006 to 26th July, 2006 has been generated from the website http://www.esrl.noaa.gov/psd/data/composite/day/. Upper air winds and 0300 UTC rainfall data (2007-2011) for Meteorological Office, Santacruz, and Regional Meteorological Centre, Colaba, Mumbai have been collected from Meteorological Office Mumbai and Regional Meteorological Center, Colaba respectively. World Area Forecast Centre (WAFC) London charts have been used for 850, 700 and 500 hPa pressure heights.

Kumar *et al.* (2011) have mentioned that southwest monsoon extends eastwards as a distinct current (winds) up to 30° N and 140° E, which is clearly seen up to

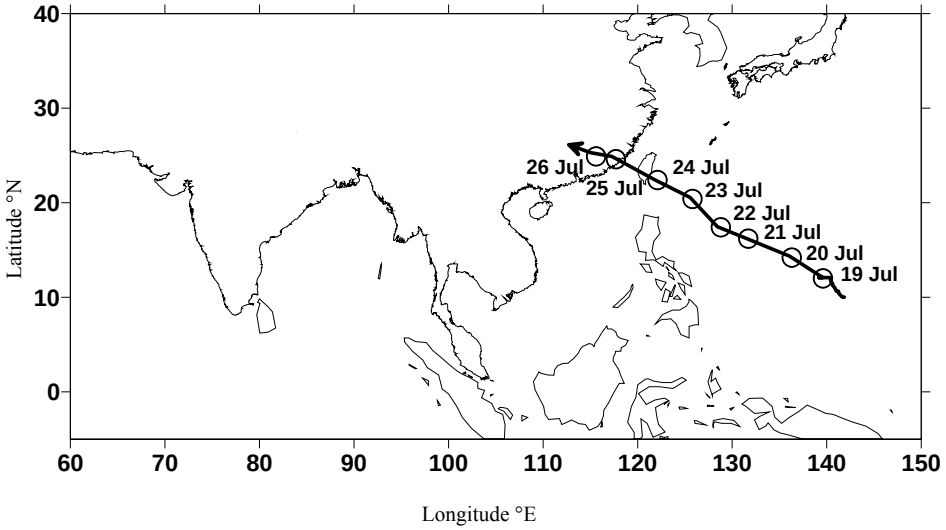


Fig. 1. Track of low pressure system 06 w during 19th July, 2006 to 26th July, 2006

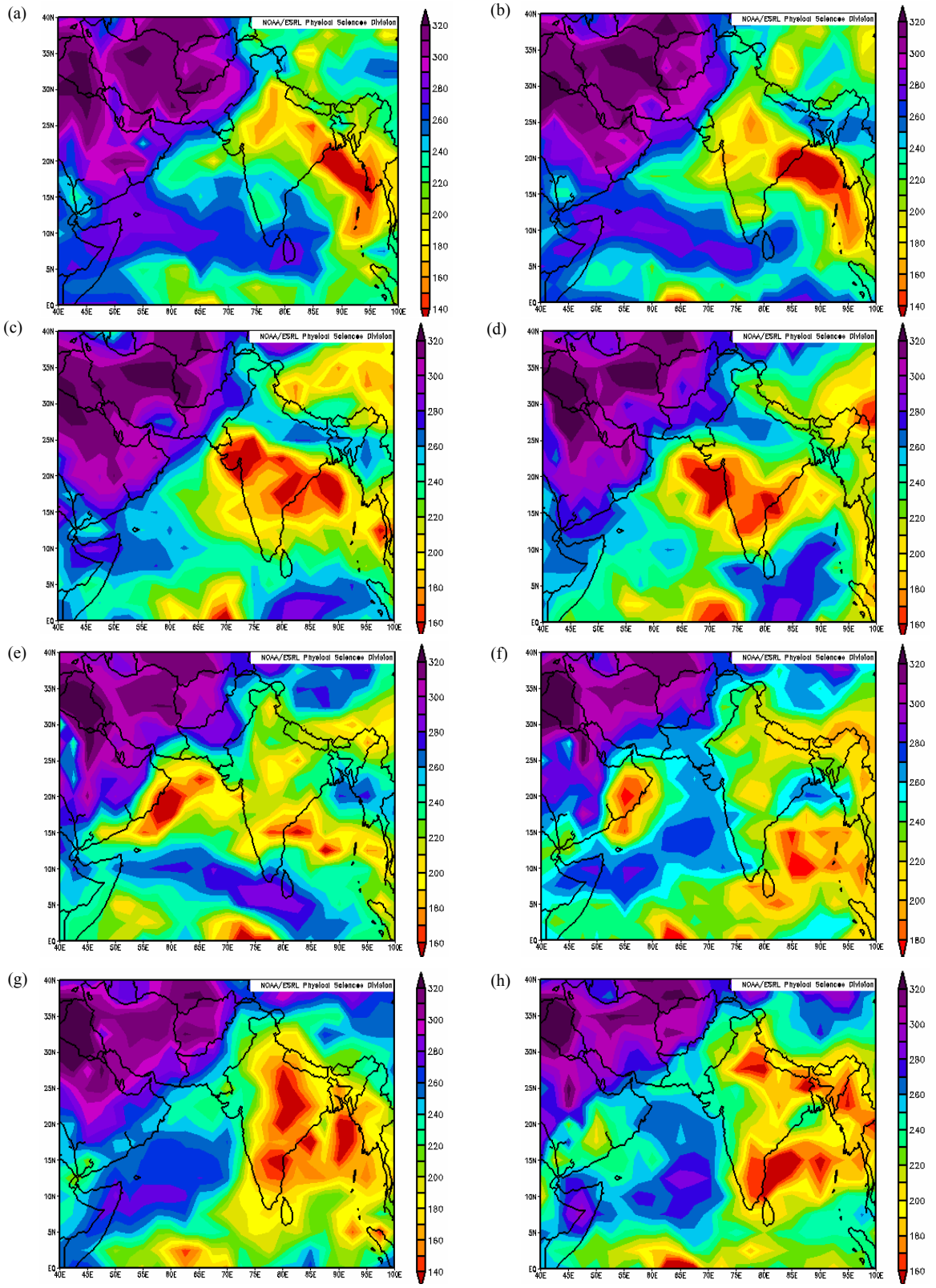
850 hPa constant pressure chart. As a result they have considered NWP systems up to 140° E for the study. To examine the direct impact of an NWP system on ISMR in terms of OLR values (Table 1), an ideal example of an NWP system has been considered. A tropical storm (TS), 06 w, was centered near 12.0° N / 139.6° E at 1200 UTC on 19th July 2006, became typhoon (TY: surface winds in circulation ≥ 64 knots) on 21st and dissipated as a tropical depression (TD) on 26th at 1200 UTC near 24.9° N/ 115.6° E. It followed northwesterly track (Fig. 1). Mohanty and Dash (1994) had observed that the flow entering the northern hemisphere during the summer monsoon months is concentrated at three regions at about 045º E - 055° E, 080º E - 090° E and 100º E - 120° E corresponding to the three branches of monsoon, *viz*., Arabian Sea, Bay of Bengal and south China Sea. They further observed that the peaks of the flow are at 050° E, 080° E and 105° E. As such starting OLR values has been considered from 079.5° E to 093.5° E (up to Bay islands longitude). Every day one degree shifting in longitude value and two degree in latitude value has been carried out for calculating OLR values which covered Indian region from 12.5° N to 28.5° N / 72.5° E to 093.5° E. For each day, arithmetic mean of OLR values for one degree latitude, within the specified longitude range, has been calculated for three different latitudes in continuity.

JTWC, Guam issues bulletins every six hourly for 0000, 0600, 1200 and 1800 UTC for an intense low pressure system over NWP. The bulletin contains about position, other related vital information and forecast of the track of the NWP system in advance for at least 48-120 hrs at 12 hrs interval. Whenever an NWP system reaches west of 130° E and north of 17° N, ITCZ in satellite cloud picture is seen passing through Mumbai/nearby-Mumbai latitude (18.58° N) and continues up to the NWP system. In upper air charts east-west trough is also seen either from 850 hPa or 700 hPa passing through Mumbai/nearby Mumbai latitude and is seen between 19° N to 25° N and is observed up to the NWP system. The east-west trough can be observed up to 500 hPa. This observation is in agreement with the findings of Prasad and Agrawal (1996) that the east-west trough line along 19° N - 21° N, along with the above mentioned synoptic conditions resulted in HY rainfall over Mumbai. In another situation extreme weather over Mumbai occurs when ITCZ in satellite clouds picture is seen from Mumbai latitude and along the west coast of India and extends up to the NWP system. Under both these conditions HY to extremely HY rainfall may be forecast for Mumbai and suburbs depending upon other synoptic situations.

3. Results and discussion

3.1. *Thermodynamic analysis*

Rao (1976) had observed that dew point depression (DPD) is generally 4 °C or less during active monsoon with the average DPD at Mumbai during weak monsoon as high as 10 °C at 650 hPa. Kumar *et al*. (2007) had found that HY rainfall had occurred over Mumbai on maximum occasions, when DPD was observed ≤ 5 °C from 1000 ft (010 flight level: FL) to 400 hPa pressure heights and above. Rao (1976) had also observed that normal dry bulb temperature at Mumbai at 500 hPa (18500 ft / FL 185) is about -3 °C for July. Kumar *et al*.



Figs. 2(a-h). Composite OLR values on (a) 19th July, 2006, (b) 20th July, 2006, (c) 21st July, 2006, (d) 22nd July, 2006, (e) 23rd July, 2006, (f) 24th July, 2006, (g) 25th July, 2006 and (h) 26th July, 2006. (*Source* : http://www.esrl.noaa.gov/psd/data/composites/day/)

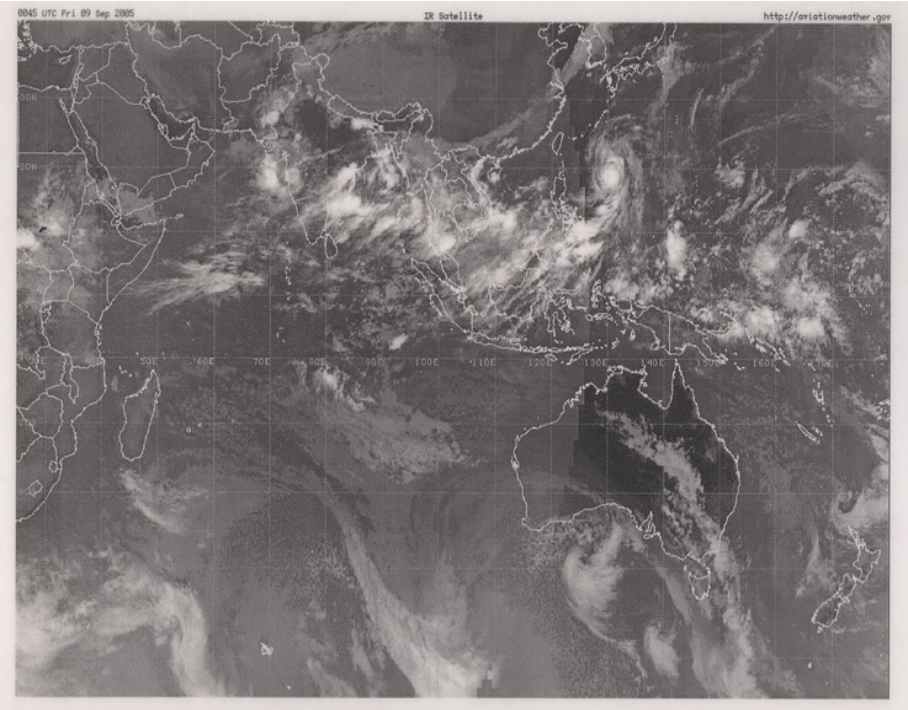


Fig. 3. NOAA satellite cloud picture (IR) 0045 UTC, 9 September, 2005

(2007) had observed that HY rainfall had occurred over Mumbai on maximum occasions when freezing level range was found between 5100-5900 GPM. They had also mentioned that Mumbai morning ascent of 25th July, 2005 showed veering of the wind from 0.6 km (2000 ft) to 200 hPa (290/35 to 090/45 knots) which had resulted into warm air advection from 0.6 km to 200 hPa. Severe thunderstorm started around 0900 UTC (to 1200 UTC) and moderate thunder storm continued till 2000 UTC on 26th July 2005. It has been noticed on many cases that for thunderstorm activity, veering of wind at least up to FL 140 remains very prominent.

3.2. *OLR values, NWP system and ISMR*

Comparison has been done by considering rainfall activity over the country for the week ending on 19th July and 26th July 2006 during the period of two NWP systems (05w and 06w) with different synoptic situations. It is mentioned in the weekly weather report issued by IMD that subdued rainfall activity prevailed over the country in general for the week ending 19th July. During the week the following important synoptic situations were observed: Under the influence of an upper air cyclonic circulation over the northwest Bay on 14th an LPA formed over North Bay and adjoining Bangladesh and Gangetic West Bengal on 15th. It lay over Gangetic West Bengal and neighbourhood on 16th, Jharkhand and adjoining northern part of Orissa on 17th and became less marked over Chhattisgarh and adjoining Jharkhand on 18th. However, the associated upper air cyclonic circulation extending up to 3.6 km above sea level remained over Madhya Pradesh till 19th. Another upper air cyclonic circulation was observed between 3.6 and 7.6 km above sea level over Gangetic West Bengal and adjoining northwest Bay on 19th. The seasonal east-west trough at sea level generally passed through Rajasthan, Uttar Pradesh, Bihar, Gangetic West Bengal and thence to the North Bay / East Central Bay. The Tropical Storm (TS) 05 w was located near 23.3° N / 124.0° E at 0000 UTC on 13th which dissipated as TS near 27.0° N / 118.1° E at 1200 UTC on 14th. The impact of TS 05 w on ISMR was seen for only two days during the week. Another TS 06w, which was located near 12.0° N / 139.6° E at 1200 UTC on 19th became TD at 0000 UTC on 26th near 24.9° N / 115.6° E. OLR values mentioned under Table 1 have been calculated from 19th to 26th during the storm period of the TS 06 w. The upper air cyclonic circulation of 19th moved over to Gangetic West Bengal and neighborhood, extending up to mid tropospheric levels on 20th morning and an LPA formed

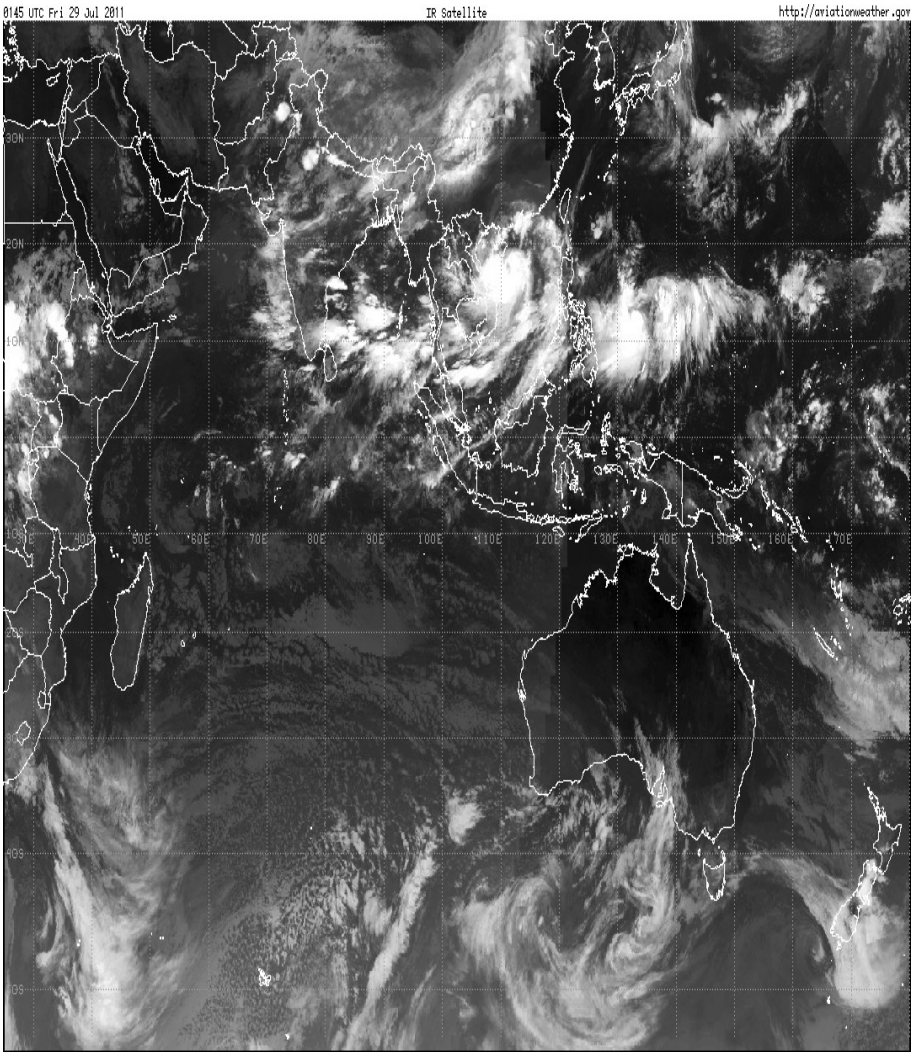


Fig. 4. NOAA satellite cloud picture (IR) 0145 UTC 29 July, 2011

over there in the evening. It moved through Jharkhand, Chhattisgarh, Madhya Pradesh and became less marked over northwest Madhya Pradesh and adjoining east Rajasthan on 24th. The upper air cyclonic circulation over Northeast Arabian Sea off Saurashtra coast persisted there on 20th lay over Saurashtra, Kutch and neighborhood on 21st and merged with the cyclonic circulation associated with LPA on 22nd. The minimum OLR values on 21st may be associated with the LPA, other synoptic situations and TY 06w. But minimum OLR values on 26th from 072.5° E to 093.3° E for the latitudes 26.5° N, 27.5 N° and 28.5° N are mainly associated with TD 06 w [Fig. 2(h)]. It is also confirmed by the fact that on 21st (when minimum OLR values were observed) higher OLR values have been found for the above selected region on 26th. It is mentioned in the weekly weather report, issued by IMD Pune, for the week ending on 26th that a gradual change in the upper troposphere flow pattern and the formation of an LPA caused a revival of the rainfall activity in general and southwest monsoon covered the entire country on 24th. The NWP system 06w covered the entire week. So it can be said that impact of NWP system is clearly visible on ISMR in terms of OLR values.

3.3. *NWP system and HY rainfall events over Mumbai*

Kumar *et al.* (2007) had mentioned some conditions for occurrence of HY to extremely HY rainfall over Mumbai and suburbs. Favourable HY rainfall conditions

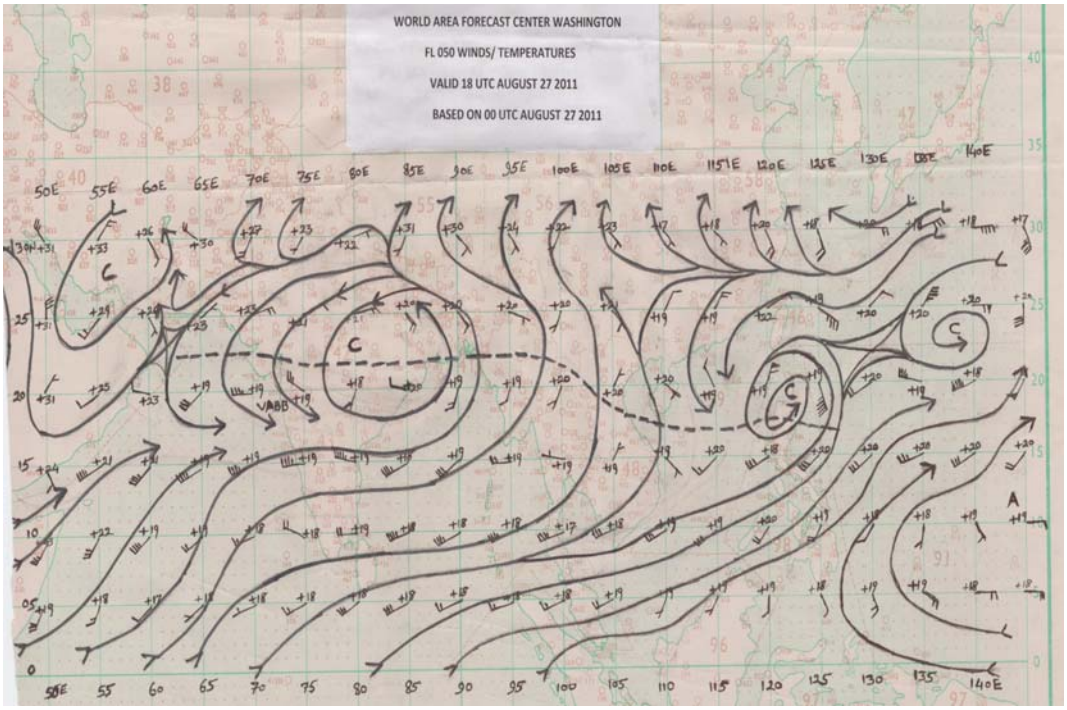


Fig. 5. 850 hPa constant pressure chart valid 1800 UTC 27 August, 2011

were observed on 8th September 2005 before issuing national significant weather chart (NSWC) at 0900 UTC. Bulletin issued by JTWC, Guam at 0300 UTC on 8th for an NWP system has been referred. The tropical storm 15 w was located at 0000 UTC on 8th near 15.3° N / 134.4° E. Its position at 0000 UTC on 9th had been forecast near 18.5° E / 129.9° E and Mumbai is located almost in the same latitude (18.58º N / 072.49º E). Thus occasional CB has been marked around Mumbai (VABB) in national significant weather charts issued at 0900 and 2100 UTC on 8th. From NOAA satellite cloud picture (IR) taken at 0045 UTC on 9th (Fig. 3), ITCZ is clearly seen from 19° N / 070° E passing through Mumbai to the tropical storm 07 w area south of 20° N and west of 132° E. Occasional CB has been marked again around Mumbai in national significant weather chart (NSWC) issued at 0300 UTC on 9th. HY rainfall started around 0800 UTC on 9th over Santacruz, 223 mm and 217 mm rainfall amounts were recorded on 10th at 0300 UTC over Santacruz and Colaba respectively. In a similar situation when a tropical storm 03 w was centered at 1200 UTC on 27th June 2006 near 17.9° N / 113.8° E occasional CB has been marked in NSWC issued at 1500 UTC on 27th. Santacruz recorded 113 mm rainfall at 0300 UTC on 28th. Kumar *et al*. (2007) mentioned that Santacruz received HY to very HY rainfall continuously for 5 days from 1st to 5th July 2006 that never has been found in 21 years study period. Besides other favourable synoptic situations (including a deep depression which crossed Orissa coast between Paradip and Chandbali on 2nd evening and followed west northwest track and an upper air circulation between 1.5 and 5.8 km over Gujarat state and neighbourhood), a tropical storm 04 w was centered at 0000 UTC on 1st near 8.5° N / 137.6 E, at 0000 UTC and on 5th near 17.9° N / 130.9° E as a super typhoon and at 0600 UTC on 6th near 20.0° N / 128.4° E as a typhoon. Santacruz and Colaba recorded 120.3 and 107.1 mm rainfall at 0300 UTC on 6th and at 0300 UTC, on 7th just 7.1 and 0.2 mm respectively as the storm moved north of Mumbai latitude at 0600 UTC on 6th. From NOAA satellite cloud picture taken at 1515 UTC on 3rd ITCZ is seen from Gujarat state up to the tropical storm 04 w located north of 15° N and west of 135° E. On 25th June 2009 a TS 04 w was located near 17.4° N and 118.1° E at 1200 UTC and occasional CB has been marked in NSWC issued at 1800 UTC on 25th for FIR Mumbai. HY rainfall started over Santacruz after 0000 UTC on 26th and 121 mm rainfall (Colaba : 99.6 mm) was recorded up to 0300 UTC of 27th. NOAA satellite cloud picture (IR) taken at 2345 UTC on 2nd September 2009 shows ITCZ passing through east of 073° E / 23° N to the NWP system 13w. Thus on 3rd September 2009 occasional CB has been marked around Mumbai in NSWC issued at 0600 UTC as TD 13 w was forecast to reach 17.9° N / 129.3° E at 0000

UTC on 4th and Santacruz recorded 160.6 mm (Colaba : 73.3 mm) at 0300 UTC on 4th.

To examine whether there is one-to-one relation between HY rainfall events over Mumbai (Santacruz and Colaba) and positions of NWP systems have been examined for five years (2007 to 2011). During 2011 monsoon season HY to very HY rainfall was observed for a few days continuously over Mumbai during last week of July (5 days) and August (4 days) when one NWP system each (10 w and 14 w) was located north of 17° N and west of 125° E in both the months. The details of location of the systems and rainfall (in mm at 0300 UTC) are as under:

Date Time (UTC)	*Location*	*Date*	*Rainfall over Colaba/Santacruz*
27 Jul 1200	17.4° N / 120.4° E (TS)	28 Jul	68.0/5.9
28 Jul 0600	18.0° N / 114.8° E	29 Jul	66.0/97.8
29 Jul 0000	18.4° N / 112.3° E	30 Jul	63.0/73.2
30 Jul 0000	19.3° N / 108.0° E	31 Jul	210.9/192.2
31 Jul 0000	18.7° N / 104.6° E (TD)	01 Aug	102.6/65.8
01 Aug	No system	02 Aug	16.6/17.7
26 Aug 0600	17.2° N / 123.6° E (STY)	27 Aug	37.0/83.0
27 Aug 0000	18.2 N° / 122.4° E	28 Aug	89.0/220.4
28 Aug 0000	20.5° N / 121.4° E (TY)	29 Aug	178.6/232.0
29 Aug 0000	22.9° N / 120.5° E (TS)	30 Aug	109.4/48.0
30 Aug 0000	24.4° N / 119.2° E	31 Aug	0.6/9.5

In a different situation extreme weather events over Mumbai have been observed when ITCZ in satellite clouds picture is seen from Mumbai latitude and along the west coast of India and continues up to the NWP system. HY to VHY rainfall occurred over Mumbai from 27th July 2011 to 31st July 2011 under aforesaid condition. ITCZ in satellite clouds picture of 29th July 2011 at 0145 UTC (Fig. 4) is seen from 20° N / 70° E along the west coast of India and continues up to 120° E through NWP system located near 18.4° N / 112.3° E on 29th July at 0000 UTC. On 27th August 2011 ITCZ in satellite clouds pictures is seen passing through Mumbai latitude and up to NWP system, East-west trough at 850 constant pressure chart of 27th August (World Area Forecast Centre: WAFC, Washington chart based on 0000 UTC 27 August, valid 1800 UTC 27 August 2011) was seen from 060° E - 100° E / 20° N - 25° N and 100° E - 127° E / 15° N - 20° N (Fig. 5). East west trough at 850 hPa constant pressure chart of 29th August (WAFC chart, based on 0000 UTC 29th August valid 1800 29th August 2011) was seen 070° E - 085° E / 20° N - 25° N, 085° E - 100° E / 15° N - 20° N and 100º E - 130° E / 20° N - 25° N. Alto Stratus (AS) clouds are seen very prominently when there is an east-west trough at 850 hPa and above / 700 hPa and above.

Thus, if moderate (25 knots wind at 850 hPa reported by at least on station along the west coast) to HY rainfall conditions (Kumar *et al*., 2007) over Mumbai are observed, position of an NWP system, if any, will help in forecasting very HY to extremely HY rainfall over Mumbai. Continuous moisture feeding from southern hemisphere is needed for occurrence of an extreme weather event. NOAA satellite cloud picture also helps in identifying the position of ITCZ besides 850 hPa constant pressure chart.

3.4. *Adverse weather and damages*

It is mentioned in Weather in India (2006) that on 27th July, 2005 Mumbai (Santacruz) recorded highest ever rainfall of 94.4 cm which caused its isolation from the remaining parts of the country. It also damaged properties worth crores of rupees and rendered many people homeless in the regions. Heavy rain and flood related events took a toll of 831 in Maharashtra. Also flight operations at Chhatrapati Shivaji International Airport Mumbai remain suspended for two days.

4. Conclusions

(*i*) Impact of NWP system on ISMR is clearly visible in terms of OLR values over Indian region.

(*ii*) If moderate (25 knots winds is reported by at least one station along the west coast) to HY rainfall conditions are observed over Mumbai and if an NWP system is expected to reach west of 130° E and north of 17° N, HY to extremely HY rainfall may be forecast for Mumbai and its suburbs.

(*iii*) ITCZ in satellite cloud picture is seen passing from Mumbai/ nearby Mumbai latitude up to the NWP system. East-west trough around Mumbai latitude is seen either from 850 hPa or from 700 hPa to 500 hPa, which extends up to the NWP system.

(*iv*) In a different situation extreme weather events over Mumbai have been observed when ITCZ in satellite clouds picture is seen from Mumbai latitude and along the west coast of India and extends up to the NWP system.

(*v*) Veering of the winds from 010/020 FL to at least 140 F/L (600 hPa) has been found conducive for thunderstorm activity.

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