MAUSAM, **57**, 3 (July 2006), 411-418

551.509.313

Value addition in district level dynamical forecast during intense rainfall spells over the west coast of India

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(*Received 17 April 2006*)

सार – मानसून ऋतु के दौरान भारत के पश्चिमी तट पर भारी वर्षा की घटनाओं का अरब सागर के ऊपर पवनों की अधिकतम गति के क्रोड (कोर) के साथ घनिष्ठ संबंध है। इस शोध–पत्र में ई. सी. एम. डब्ल्यू. एफ. (यूरोपीय मध्यम अवधि पूर्वानुमान केन्द्र) द्वारा 850 हैक्टापास्कल पर पूर्वानुमानित 72 घंटे के प्रवाह प्रतिरूप का उपयोग किया गया है जिससे पश्चिमी तट पर भारी वर्षा का पूर्वानुमान करने के लिए जिला स्तरीय गतिकीय पूर्वानुमान प्रणाली की क्षमता बढ़ाने हेतु मात्रात्मक पद्धति का विकास किया जा सके। यह देखा गया है कि पश्चिमी तट पर वर्षा की मात्रा का पश्चिमी तट पर अरब सागर में पवन की अधिकतम गति के 72 घंटे के ई. सी. एम. डब्ल्यू. एफ. द्वारा किए गए पूर्वानुमान के साथ महत्वपुर्ण सहसंबंध है। पश्चिमी तट पर भारी वर्षा के क्षेत्र के अक्षांशीय विस्तार का पश्चिमी तट पर पवन की अधिकतम गति के क्रोड (कोर) के साथ महत्वपूर्ण सहसंबंध है। इस शोध–पत्र में यह बताया गया है कि ग्रीष्मकालीन मानसून ऋतु के दौरान भारत के पश्चिमी तट पर भारी वर्षा के 72 घंटे का पूर्वानुमान करने के लिए पवनों की अधिकतम गति के 72 घंटे के पूर्वानुमानित क्रोड (कोर) और विस्तार की तीव्रता और स्थिति की क्षमता बढ़ाने के लिए संभावित पूर्वसूचकों के रूप में उपयोग किया जा सकता है।

ABSTRACT. Occurrences of intense rainfall events over west coast of India during monsoon are intimately linked to the core of maximum winds over the Arabian Sea. ECMWF (Europian Centre for Medium Range Weather Forecasting) predicted 72 hr flow pattern at 850 hPa has been used to develop a quantitative method for value addition in the district level dynamical forecast system for intense rainfall over the west coast. It has been found that the amount of rainfall over the west coast is significantly correlated to 72 hr ECMWF forecast of maximum wind speed over the Arabian Sea along the west coast. The latitudinal width of the heavy rainfall belt over the west coast has got significant correlation with the location of maximum wind core along the west coast. It has been shown that the strength and location of the 72 hr predicted core and fetch of maximum winds could be used as potential predictors in the value addition for 72 hr heavy rainfall forecast along the west coast of India during summer monsoon.

Key words – District level dynamical forecast, Value addition, Predictor, Summer monsoon, Low Level Jet (LLJ), Model Output Statistics (MOS).

1. Introduction

The west coast of India receives copious rainfall during summer monsoon. On some occasions the rainfall may be exceptionally heavy exceeding 25 cm per day. The dynamics of convection leading to such intense rainfall events along the west coast of India is an important area of investigation associated with the monsoon variability. Keeping in view the importance of intense rainfall events along the west coast, recently an observational campaign, the Arabian Sea Monsoon Experiment (ARMEX), was conducted under Indian Climate Research Programme (ICRP) during 2002-03. One of the main objectives of ARMEX was to collect reliable observational data over the Arabian Sea and west coast for detailed investigation of intense rainfall events during monsoon (Sikka, 2005; Bhat *et al.*, 2005; Routray *et al.*, 2005).

The prediction of intense rainfall events along the west coast for smaller spatial resolution such as district level is a very challenging task. The task becomes more difficult if the predictions are attempted for 3 days in advance as the conditions change very rapidly over the Arabian Sea during the monsoon. The system for district level rainfall forecast, being developed in the India Meteorological Department (Lal *et al.*, 2006) requires quantitative methods in the value addition for 3-day district level heavy rainfall forecast along the west coast. Several predictors were tried for this purpose during 2005 monsoon. The ECMWF's 3-day forecasts of 850 hPa flow patterns over the Arabian Sea were used to delineate the core of maximum winds along the west coast. As 850 hPa level was the height most favoured by the lower tropospheric wind maximum (Joseph and Raman, 1966) the core parameters of this level were used in

TABLE 1

Heavy to very heavy R/F spells over the west coast of India during Southwest Monsoon, 2005

S. No.	Heavy R/F spell duration	Date	Heavy R/F belt over the west coast	Principal R/F Amounts (in cms recorded at 0300 UTC)
1.	17-30 June	17 June	11º-14º N	Kozhikode-11, Alleppey-7
		18	14º-16º N	Panjim-11, Karwar-8
		19	12º-19º N	Alibag-11, Mangalore-9, Goa-8, Honavar-7
		20	9º-16º N	Mangalore-22, Ratnagiri-9
		21	9º-16º N	Cochin-15, Mangalore-13, Panjim-12, Karwar.12, Agumbe-12, Kozhikode-11, Penambur-11, Mercara-10
		22	11º-17º N	Karwar-23, Honavar-22, Goa-21, Ratnagiri-14, Mangalore-13, Kozhikode-7
		23	13º-20º N	Mumbai (Colaba)-21, Alibag-21, Harnai-19, Ratnagiri-12, Honavar-10, Agumbe-7
		24	17º-20º N	Mumbai (Santacruz)-12, Bhira-11, Dahanu-7
		25	13º-20º N	Surat-18, Agumbe-15, Porbandar-7
		26	20º-23º N	Bulser-38, Baroda-15, Surat-14
		27	21º-24º N	Ahmedabad-12, Surat-11, Baroda-10, Bhira-21
		28	14º-23º N	Broach-27, Valsad-25, Mahuva-23, Surat-11, Dahanu-8, Mumbai (Santacruz)-7
		29	20º-23º N	Amreli-29, Bhavnagar-17, Baroda-16, Surat-8
		30	19º-23º N	Surat-22, Rajkot-15, Dahanu-15
2.	21-27 July	21 July	18º-20º N	Mumbai (Santacruz)-10, Dahanu-9
		22	16º-19º N	Alibag-19, Ratnagiri-14
		23	13º-19º N	Panjim-10, Ratnagiri-8
		24	13º-19º N	Honavar-19, Panjim-18, Karwar-15
		25	15º-18º N	Goa-22, Harnai-15, Ratnagiri-9
		26	14º-17º N	Agumbe-12, Bhira-16, Ratnagiri-9
		27	18º-20º N	Mumbai (Santacruz)-94, Bhira-16, Mumbai (Colaba)-7
3.	1-6 August	1 August	16º-19º N	Mumbai (Santacruz)-21, Mumbai (Colaba)-16, Alibag-13
		2	17º-19º N	Mumbai (Santacruz)-18, Ratnagiri-15, Alibag-15, Harnai-10, Mumbai (Colaba)-9
		3	15º-17º N	Ratnagiri-9
		4	12º-17º N	Mangalore-10, Ratnagiri-8
		5	19º-21º N	Dahanu-10, Surat-7
		6	17º-18º N	Harnai-9
4.	11-12 September	11 September	17º-19º N	Bhira-9
		12	17º-19º N	Mumbai (Santacruz)-9, Bhira-9
5.	22-24 September	22 September	16º-20º N	Panjim-17, Dahanu-15, Mumbai (Santacruz)-8, Dahanu-15
		23	16º-20º N	Goa-12, Mumbai (Santacruz)-9
		24	16º-20º N	Goa-12, Bhira-10

computations. It was found that the location and the strength of the core of maximum winds provided predictive indications of the quantity and latitudinal location of intense rainfall along the west coast. The 72 hr prognostic outputs of ECMWF were used to develop the statistical relationships between the predicted core of maximum winds and the intensity of rainfall along the west coast.

The relationship between the strength of winds over the Arabian Sea and the monsoon rainfall along the west coast of India dates back to 1966, when Findlater (1966) discovered that the strength of low level jet over the Arabian Sea was closely linked to the west coast rainfall. Further studies by Joseph and Raman (1966) and Findlater (1969, 1977) have established that the cross-equatorial flow and the strength of winds over the Arabian Sea are important components of Indian monsoon. What is required is the judicious use of model output statistics to determine the exact location and the amount of heavy rainfall along the west coast during the monsoon 3 days in advance. This is precisely the aim of the present work.

2. Data and methodology

ECMWF-predicted 72 hr winds at 850 hPa have been used to determine the locations and strengths of the core of maximum winds over the Arabian Sea. The predicted core parameters valid for previous day (1200 UTC) have been used to compute the correlations with 24 hr rainfall recorded at 0300 UTC. Several correlations (CCs), namely, the CC between maximum wind speed over the western Arabian Sea and the west coast rainfall amount, the CC between maximum wind speed over the west coast itself and the rainfall, the CC between the latitudinal location of maximum wind core and the corresponding location of heavy rainfall belt etc have been tried. Only significant correlations have been presented and used in the regressions. All heavy rainfall spells along the west during 2005 monsoon have been considered for developing the statistical relations. The longest spell in 2005 monsoon occurred during the advance phase of monsoon along the west coast from 17-30 June.

3. Results and discussion

3.1. *Intense rainfall spells over the west coast during southwest monsoon, 2005*

The onset of southwest monsoon, 2005 over Kerala was on 8th June. The longest heavy rainfall spell over the west coast occurred during the advance phase of monsoon during June. There were 5 intense rainfall spells over the west coast during 2005 monsoon. Table 1 summarizes the latitudinal extents and heavy rainfall amounts during the observed five spells. During June spell a systematic northward shift of heavy rainfall belt could be seen. The rainfall activity was quite intense during 20-27 June which mainly extended from Karnataka to Gujarat coast with systematic northward progression with monsoon advance.

In July one week's intense rainfall spell was observed from 21-27 July. Exceptionally heavy rainfall of 94 cms occurred at Mumbai (Santacruz) during this particular spell. The intense rainfall activity along the west coast continued in the first week of August. Cumulative rainfall of 143 cms was reported at Mumbai (Santacruz) during these two spells showing the severity of flood situation in Mumbai.

During September two brief spells of intense rainfall activity *i.e.*, from 11-12 and 22-24 September were observed along the west coast. A total of 32 intense rainfall days have been considered for determining the statistical relations between low level jet parameters and the rainfall over west coast.

3.2. *ECMWF-predicted maximum wind core parameters during intense rainfall spells over the west coast*

ECMWF-predicted maximum wind core parameters at 850 hPa during the intense rainfall spells over the west coast have been presented in Table 2. The prognostic charts alongwith the satellite imageries and realized rainfall for the periods 24-28 June and 23-27 July have been presented in Figs. 1 and 2 respectively. During July, 15ºN seems to be the most favoured location for core of maximum winds along the west coast. There was a systematic northward shift of maximum wind core from 10° N to 20º N along the west coast during the advance phase of monsoon (17-28 June). It may be mentioned that the heavy to very heavy rainfall over Gujarat on 25th June occurred in association with the Cyclonic Circulation over Saurastra & Kutch and adjoining areas whereas 15 cms rainfall over Karnataka coast occurred in association with the core of maximum winds. Thus the 3 day predictions of ECMWF of maximum wind core at 850 hPa could be used as potential indicator for monsoon advance along the west coast. As seen in Table 1 the maximum wind core was stablized at 15º N after the monsoon covered the entire west coast. This is reflected in core locations during July spell. The exceptionally heavy rainfall over Maharashtra coast during July spell resulted from the constant hitting of maximum wind core at 15º N for about one week. Another factor which might have contributed to exceptionally heavy rainfall was the jet speed over the Arabian Sea (60 kts). It is seen from Table 2 that during the entire monsoon season, 2005 the winds at 850 hPa reached 60 kts for 3 days only *i.e.*, from 1200 UTC of 24th to 1200 UTC of 26th. Not only were these, the highest maximum winds of 40 kts over the west coast predicted for this period. The unique feature preceding the occurrence of 94 cm rainfall in Mumbai was the appearance of jet speeds over a long fetch of about 500 sq. kms over the Arabian Sea. These qualitative relationships will become clearer when the statistical correlations are discussed in next section. Table 2 brings out another factor which contributes to the intense rainfall activity over the west coast *i.e.*, the northeastward shift of the centre of maximum wind fetch.

The predicted fetch centre at 1200 UTC of 26th July was 12.5º N, 62º E which was the northeastern most location of the low level jet core over the Arabian Sea during the entire season. Thus ECMWF-predicted winds over the Arabian Sea seem to provide enough indications

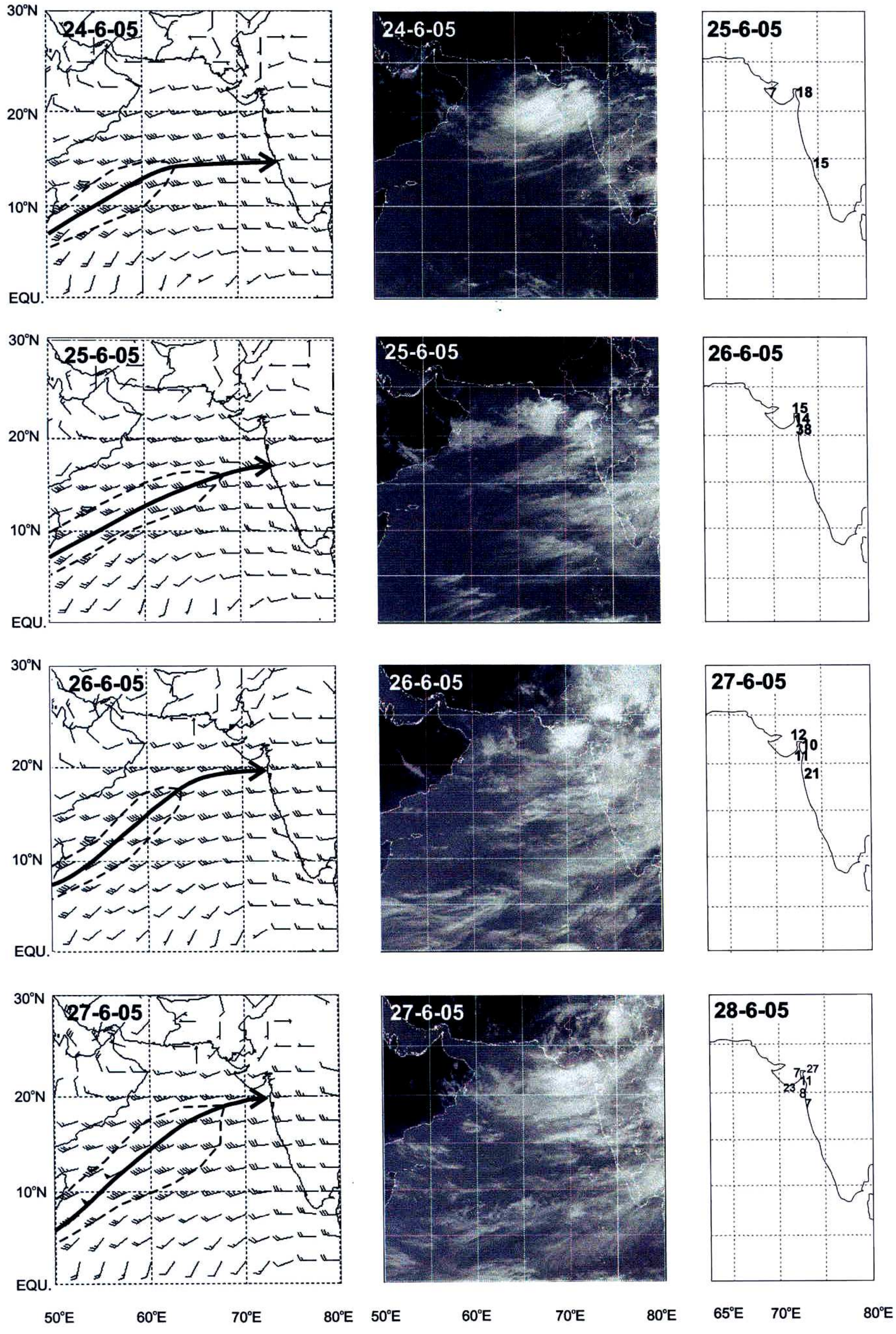

Fig. 1. ECMWF predicted 72 hr winds at 850 hPa for 1200 UTC, INSAT IR pictures of 0900 UTC and 24 hr realized rainfall during 24-28 June

TABLE 2

ECMWF predicted max. winds at 850 hPa along the West Coast/Arabian Sea (valid for 1200 UTC)

Date	Max. wind speed along the West Coast (kts)	Max. wind speed over the Arabian Sea (kts)	Location of max. wind core along the West Coast	Longitudinal extent of max. wind region over the Arabian Sea	Centre of the max. wind region over the Arabian sea
16 June 2005	20	40	10º N	20º	9.5º N, 60º E
17	30	45	12.5º N	20º	7.5º N,60º E
18	30	45	15º N	18º	9.5º N, 59º E
19	30	50	15º N	20º	11.2º N, 60º E
20	30	50	15º N	18º	11.2º N, 59º E
21	25	50	14º N	19º	11º N, 59º E
22	25	45	15º N	15º	12º N, 57.5º E
23	25	45	15º N	17.5º	12.5º N, 58.5º E
24	25	45	15º N	15º	11º N, 57.5º E
25	30	45	17.5º N	17.5º	11º N, 58.5º E
26	30	45	20º N	15º	13º N, 59º E
27	30	50 (2 grids)	20º N	18º	13º N, 59º E
28	30	50	17.5º N	18º	13º N, 59º E
29	30	50	17.5º N	18º	13º N, 59º E
20 July 2005	20	45	15º N	15º	11º N, 52.5º E
21	30	55	15º N	15º	11.5º N, 52.5º E
22	30	50	15º N	13º	9.5º N, 56.5º E
23	40	55	15º N	10º	11º N, 55º E
24	40	60	15º N	11º	11º N, 56º E
25	40	60	15º N	12.5º	12.5º N, 56.5º E
26	40	60 (2 grids)	14º N	13º	12.5º N, 62º E
31	40	50	18º N	18º	11º N, 59º E
1 August 2005	40	55	18º N	20º	12.5º N, 60º E
2	30	45	18º N	10º	10º N, 55º E
3	30	45	18º N (about 5º width)	10º	10º N, 55º E
4	30	50	18º N (about 5º width)	10º	12.5º N, 60º E
5	30	50	18º N (about 5º width)	9º	12.5º N, 58.5º E
10 September 2005	30	40	15º N (about 5º width)	10º	10º N, 55º E
11	30	40	14º N (about 3º width)	10º	10º N, 57º E
21	30	25	16.5º N (about 3º width)	20º	12.5º N, 60º E
22	30	30	15ºN	13º	12.5º N, 58.5º E
23	20	25	15ºN	8º	12.5º N, 54º E

of amount and location of heavy rainfall over the west coast of India. Four maximum wind core parameters, *i.e.*, maximum wind speed over the west coast, maximum wind speed over the Arabian Sea, latitudinal location of maximum wind core over the west coast and centre of fetch of maximum winds over the Arabian Sea could provide enough indications of amount and location of heavy rainfall along the west coast.

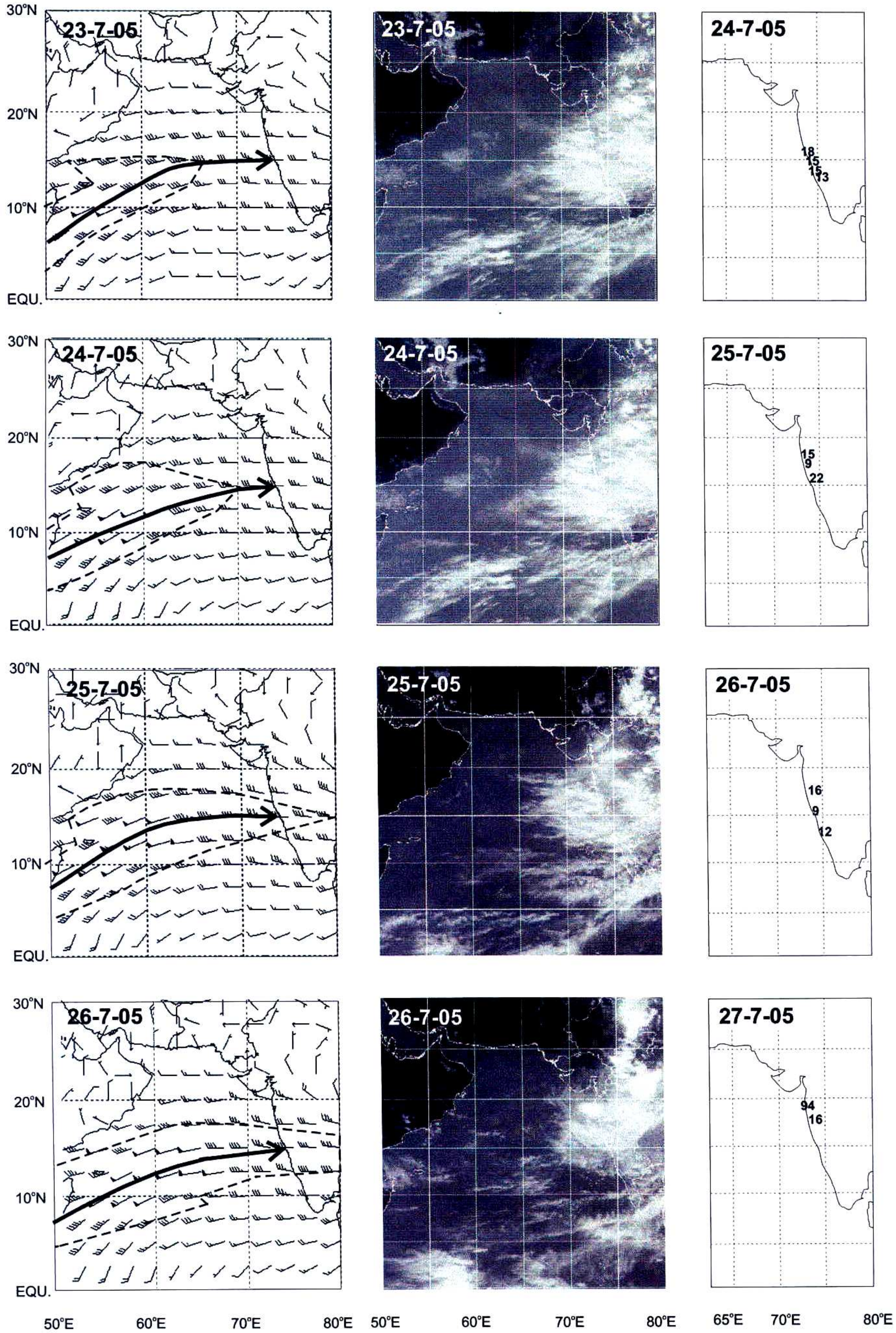

Fig. 2. ECMWF predicted 72 hr winds at 850 hPa for 1200 UTC, INSAT IR pictures of 0900 UTC and 24 hr realized rainfall during 23-27 July

TABLE 3

Linear regressions for 72 hr heavy rainfall forecast over the west coast

Predictor	Correlation coefficient	Regression equation (R = rainfall in cms, W=wind speed in kts, L_1 = heavy rainfall latitude in ° N, L_2 = location of max. wind core in °N)
ECMWF predicted max. wind speed over the West Coast (1200 UTC of previous day)	0.4*	$R = 1.01W - 15.58$
ECMWF predicted max. wind speed over the Arabian Sea (1200 UTC of previous day)	0.4*	$R = 0.61W - 13.76$
ECMWF predicted Latitudinal location of the max. wind core over the coast (1200 UTC of previous day)	0.6*	$L_1 = 0.69L_2 + 6.31$

*significant at 99% level

3.3. *Statistical relations between ECMWF-predicted maximum wind speed and amount of rainfall over the west coast*

The correlations between the maximum wind speeds over the Arabian Sea/west coast and the west coast rainfall amount have been presented in Table 3. Though both the correlations are 0.4, the west coast rainfall is more sensitive to the core strength at the coast itself. It is evident from the regressions that the coefficient of wind maximum at the coast is 1.01 whereas the coefficient of Arabian Sea maximum is only 0.61. Thus the actual rainfall is more responsive to the maximum winds over the coast itself. The correlations are significant at 99% level and have enough predictive value due to large degrees of freedom. Very high magnitudes of correlations should not be expected due to the fact that the predictions of maximum winds were based on 3 days old analyses. Obviously, highest correlations will be found with the predictions based on latest analysis but these will have very little forecasting value as the lead time will be reduced to less than 24 hrs. For a lead time of 3 days a statistically significant CC of 0.4 is reasonably good for heavy rainfall predictions. As all intense rainfall spells pertaining to different monsoon months were considered in computations, the CCs could be treated as representative for the entire monsoon season. The regressions show that a predicted maximum wind of 40 kts over the west coast of India would produce about 25 cms of average heavy rainfall (exceptionally heavy) over the west coast. Heavy rainfall (exceeding 6.5 cms) warnings for west coast should be given when the predicted maximum winds over the west coast exceed 22 kts. Very heavy (exceeding 12.5 cms) rainfall corresponds to the predicted maximum winds of 29 kts. The predicted maximum wind speed exceeding 40 kts is a necessary and sufficient condition for exceptionally heavy rainfall (exceeding 25 cms) over the west coast of India during monsoon. Such predictions could be easily made 3 days in advance. The maximum winds over the western Arabian Sea could also be used as predictors for west coast rainfall. It is advisable to predict exceptionally heavy rainfall over the west coast when jet speeds exceeding 60 kts appear over the Arabian Sea in the prognostic charts. Maximum wind speed of 35 kts over the Arabian Sea would correspond to heavy rainfall over the west coast.

For predictions aimed at smaller spatial resolutions such as district level it is necessary to pinpoint the exact locations (districts) of intense rainfall. This aspect is discussed in the next section.

3.4. *Statistical relations between maximum wind core location/fetch with intense rainfall over the west coast*

Several correlations between the predicted locations/ fetch of wind maxima over the Arabian Sea and the intense rainfall belt over the west coast were computed. Two correlations *i.e.*, the CC between the longitude of the fetch centre over the Arabian Sea and the intense rainfall belt over the west coast and the CC between the latitude of wind maximum over the west coast and intense rainfall belt over the west coast were found to be statistically significant. As seen in Table 3 the correlation between the predicted location of maximum wind core (for 1200 UTC of previous day) and the latitudinal location of intense rainfall (24 hr rainfall recorded at 0300 UTC of next day) is 0.6. The regression between these two parameters shows that if maximum wind core over the west coast is located at 15° N then the intense rainfall would be centred around 16.5° N. Thus it would be advisable to issue heavy rainfall warnings for the districts located in the latitudinal belt of 14° - 17° N. Maximum wind core and rainfall relationship shows that the extension of heavy rainfall belt is more towards north of the core which can be easily understood from the dynamical consideration as the strong positive vorticity zone is located north of the core. The identification of the districts for intense rainfall 3 days in advance using the above-mentioned relationship derived from ECMWF model outputs are very useful in heavy rainfall predictions for smaller spatial resolutions over the west coast of India during the monsoon.

Another predictor which is useful in value addition for 3-day forecasts is the longitude of the maximum winds fetch centre over the Arabian Sea. It was found that for the same wind speed a more easterly location of the maximum wind fetch is conductive for heavier rainfall over the west coast. The heavy rainfall amount over the west coast was found to be very sensitive to the maximum wind fetch location over the Arabian Sea.

4. Conclusions

The results of the model output statistics have shown that

(*i*) The ECMWF-predicted flow pattern at 850 hPa can be used quantitatively in the value-addition for 72 hrs heavy rainfall forecasts over the west coast of India during southwest monsoon. The potential predictors for such forecasts are the strength and location of maximum winds over the west coast and the Arabian Sea which could be determined from ECMWF outputs 3 days in advance.

(*ii*) The statistical correlations computed on the basis of intense rainfall spells during 2005 monsoon have shown that the predicted maximum wind speeds in the core region of the low level jet over the Arabian Sea/west coast could be potential predictors for the average amount of heavy rainfall along the west coast.

(*iii*) The predicted latitude of the core of maximum winds along the west coast could be used in the identification of districts that are likely to be affected by the intense rainfall activity. The districts located within 2º North and 1º South of the core axis should be pinpointed for heaviest rainfall.

(*iv*) The movement of the fetch of maximum winds over the Arabian Sea could be used in the prediction of strengthening/weakening of the intense rainfall activity along the west coast. Heavy rainfall magnitude is very sensitive to the longitudinal location of the fetch over the Arabian Sea.

Acknowledgements

Thanks are due to Shri S. R. Kalsi, Addl. Director General of Meteorology (Services), Shri S. K. Subramanian, Dy. Director General of Meteorology (Cyclone Warning) and Dr. H. R. Hatwar, Dy. Director General of Meteorology (Dynamic Meteorology) for useful discussions during the course of the study. Smt. Indu Bala, Assistant Meteorologist, Smt. Premlata Kataria, Smt. Vandana Agrawal, Shri R. P. Sharma and Shri K. K. Pokhriyal, Scientific Assistants are thanked for their assistance in the preparation of the manuscript. Shri Chander Prakash prepared the diagrams.

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