

Distribution of precipitable water contents over Indian monsoon region

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सार – इस षोध – पत्र में दक्षिण-पश्चिम मानसून 2005 के दौरान भारतीय क्षेत्र में वर्षणीय जलांशों के स्थानिक वितरण की जाँच की गई है। वर्षणीय जलांशों को भारत मौसम विज्ञान विभाग के प्रचालनात्मक संख्यात्मक मौसम पूर्वानुमान तंत्र की वस्तुपरक विप्लेषण फील्ड से लिया गया है। इस अध्ययन से पता चला है कि वर्षणीय जलांशों का वितरण मानसून के वर्षण तंत्र के विस्तृत लक्षणों का पता लगाने में सक्षम है। इस सूचना की वास्तविक समय पर उपलब्धता भारी वर्षा की घटनाओं का मॉनीटरन करने और उनका पूर्वानुमान लगाने में उपयोगी सिद्ध हो सकती है।

ABSTRACT. This paper investigates the spatial distribution of precipitable water contents over Indian region for the southwest monsoon 2005. The precipitable water contents are derived from the objective analysis field of operational Numerical Weather Prediction system of India Meteorological Department. The study shows that the distribution of PWC is capable to capture large scale features of monsoon precipitation system. Real-time availability of this product is expected to be useful in monitoring and prediction of heavy rainfall events.

Key words – Precipitable water contents, Monsoon rainfall, Objective analysis field.

1. Introduction

Precipitable Water Content (PWC) is a quantity, which measures the water vapour content of the atmosphere in a column extending from the surface of the earth to the top of the atmosphere. The depth of this condensed water (in millimeter) is the measure of how much water vapour is available for conversion to precipitation. There has been growing operational requirement to generate this product for real time monitoring and prediction of heavy rainfall events.

Currently PWC is derived from a variety of sources including radio-sondes (RS), aircraft, surface observations and in recent years by various satellite instruments (like GPS – Global Positioning System). These individual sources of data have certain limitations. RS provides relatively accurate point measurement for deriving PWC but observations are not available over desert and mountainous areas and over oceanic areas. Another problem with the RS observations is the sampling error if the network is not adequately dense. In recent years, satellite radiance data has been widely used to retrieve PWC over many parts of the globe. But the accuracy of the product is limited due to the deficiency in the algorithm. For the present study PWC is derived from the objective analysis field of the operational Numerical

Weather Prediction (NWP) system of India Meteorological Department (IMD). The objective of this study is to examine the potential of these PWC data to monitor precipitation systems during Indian summer monsoon. In this paper, distribution of PWC over Indian region has been investigated for the summer monsoon 2005. The investigation is carried out based on case studies of synoptic interest as well as based on monthly mean features.

2. Methodology and source of data

The PWC in an atmospheric column is given by :

$$PWC = \frac{1}{g} \int_{p_{sur}}^{p_{top}} q dp$$

where the limit of the integration is from the surface to the top of the atmosphere up to which the value of specific humidity q is non-zero and g is the acceleration due to gravity.

The primary data used for deriving PWC are from the daily objective analysis fields (at the resolution of

$1^\circ \times 1^\circ$ Lat. / Long.) of the operational NWP system of India Meteorological Department. The operational system consists of real time processing of data received on Global Telecommunication System (GTS), decoding and quality control procedure and a multivariate optimum interpolation scheme. The first guess field for running the analysis is obtained online from the global forecast (T-80/18L) run at National Centre for Medium Range Weather Forecasting (NCMRWF), Noida. The input data used for the analysis consist of: Surface – SYNOP/SHIP; Upper air – TEMP/PILOT, SATOB; Aircraft reports – AIREP, AMDAR, CODAR. These are extracted and decoded from the raw GTS data sets. All the data are quality controlled and packed into a special format for objective analysis. The methodology applied for objective analysis scheme is the statistical 3-dimensional multivariate Optimum Interpolation (OI) scheme (Dey and Morone, 1985). The scheme is based on applying correction to a first guess, the corrections being the weighted average of residuals (observation-first guess) at the observation locations. The variables analyzed in this scheme are geopotential (z), u and v components of wind and specific humidity. Temperature (T) field is derived from geopotential field hydro statistically. Analysis is carried out on 12 sigma (pressure divided by surface pressure) surfaces 1.0, 0.9, 0.8, 0.7, 0.6, 0.5, 0.4, 0.3, 0.2, 0.1, 0.07, 0.05 in the vertical and on $1^\circ \times 1^\circ$ horizontal Lat./Long. grid for a regional domain covering Lat. 30° S to 60° N and Long. 0° to 150° E. The quality of this dataset is reasonably good as reflected in other diagnostic studies (Roy Bhowmik, 2002; 2003)

The PWC at the resolution of $1^\circ \times 1^\circ$ Lat. / Long. is computed for the domain covering from equator to Lat. 40° N and Long. 60° E to 100° E. Corresponding daily rainfall analysis at the same resolution is obtained from the use of daily land rain gauge observations following the method described by Thiebaut and Pedder, 1987. The data period for this study is from 01 June to 30 September of southwest monsoon 2005.

3. Broad features of southwest monsoon 2005

The seasonal rainfall pattern of south west monsoon over India shows that large values of rainfall occur along the west coast and over the northeast India (Rao, 1976) where blocking effects of topography induce upward vertical velocity and enhance precipitation on the windward side and suppress precipitation on the lee side. The rain shadow due to Western Ghats spreads over a large area over the peninsular India. The subdivisions in northwest and southeast India get the least amount of rainfall. The local scale features and passage of synoptic scale monsoon systems further modify this gross picture.

According to the convention of IMD, Indian summer monsoon is termed as a normal monsoon when the total rainfall of the season (June to September) for the whole country is within 10% of the long term average. In the monsoon season of 2005, total rainfall for the whole of the country was 99% of the long term average. Onset of monsoon over Kerala was on 5 June, about 4 days latter than the normal date of 1 June. The monsoon covered the entire country on 30 June, about two weeks ahead of its normal date of 15 July. During this monsoon season a total of 12 low pressure systems formed over Indian region. Out of these, 8 formed over the Bay of Bengal, 2 over the Arabian Sea and 2 over the land. Five low pressure systems were depressions and one was of cyclonic storm intensity. The monthly distribution of monsoon low pressure systems during this season shows that 2 depressions and 1 well marked low pressure area formed in June, 1 depression and 2 well-marked low pressure areas in July, only one well marked low pressure area in August and 1 cyclonic storm, 2 depressions and 1 well marked low pressure area formed in September.

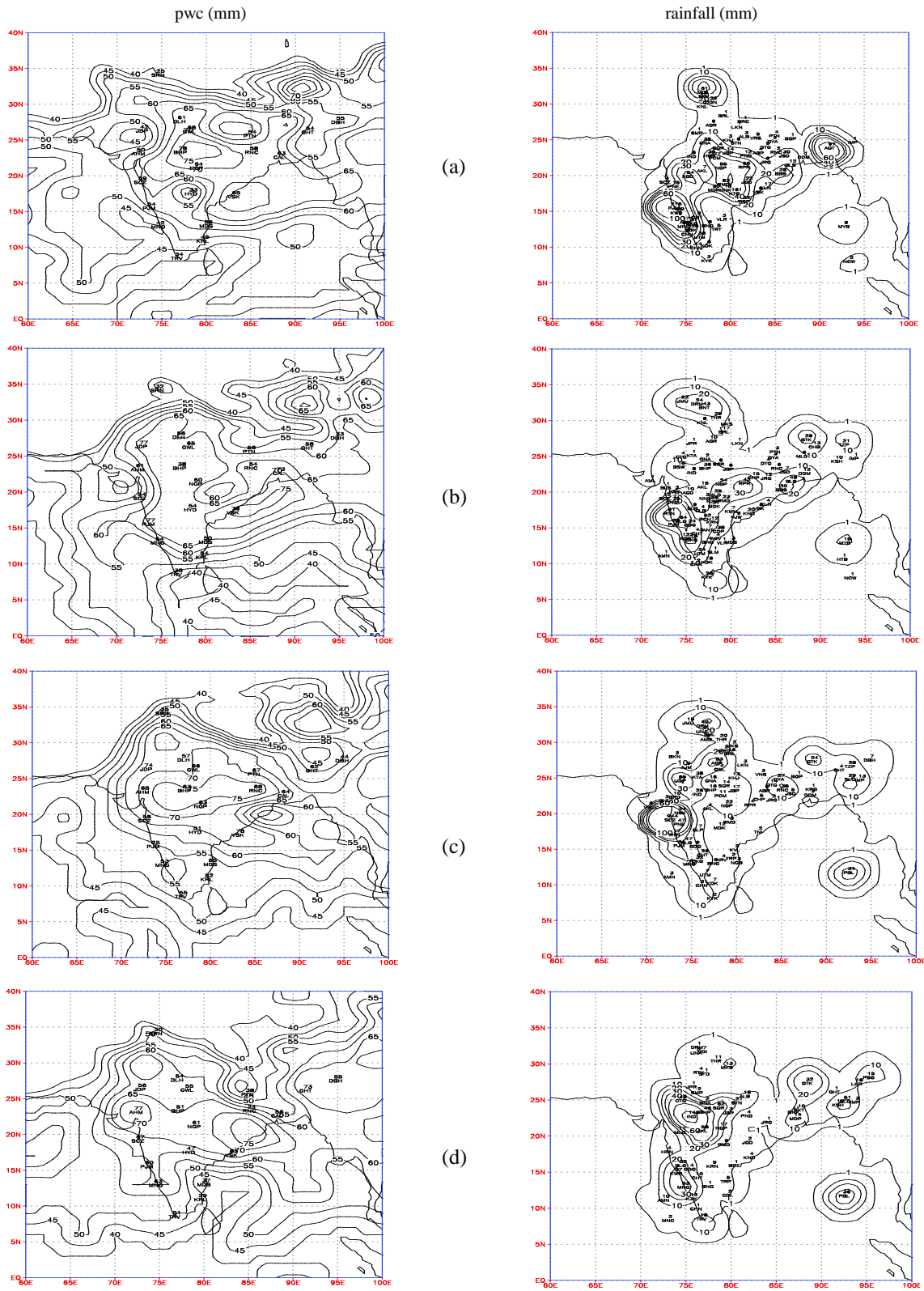
4. Case studies

Monsoon depression is the main rain producing system of summer monsoon over Indian region which forms over the northwest Bay of Bengal and moves northwest wards across the country giving rise to heavy to very heavy falls during its passage. In this section a case study of an episode of monsoon depression is illustrated to correlate the spatial pattern of PWC during the passage of the system. The spatial distributions of PWC in relation to occurrences of heavy rainfall are examined. The case studies selected are: (i) the exceptionally heavy rainfall occasion of 27 July over Konkan-Goa and (ii) monsoon depression of 18-22 September.

As mentioned in section-1 that the computed PWC from RS observations, being station value is not compatible with the grid point objective analysed value. Because of this limitation, the validation exercise is carried-out by superimposing the computed PWC values with the corresponding objective analysis of PWC. In the rainfall analysis also station rainfall observations are superimposed for some selective station.

Case 1 : *Exceptionally heavy rainfall occasion of 27 July over Konkan Goa*

On 27 July an unprecedented rainfall of 94.4 cm in 24 hours was reported at Santa Cruz (Mumbai). Presence of well marked low pressure area over Madhya Pradesh, well marked offshore trough at the surface along the west coast and east-west oriented shear line in the lower tropospheric levels must have contributed to a favorable



Figs. 1(a-d). PWC analysis (mm) with super-imposed computed PWC (mm) from RS observations and corresponding rainfall analysis (mm) with superimposed rainfall observations (mm) of some selective stations for (a) 25 July (b) 26 July, (c) 27 July and (d) 28 July 2005

setting for the occurrence of this meso scale exceptionally heavy rainfall event. The distribution of PWC and corresponding rainfall for 25 July to 28 July are shown in Figs. 1 (a-d). As stated before, the plots of computed PWC (in mm) from RS observations are superimposed with the objective analysis of PWC. Similarly rainfall plots (in mm) of some selective stations are super-imposed with the corresponding objective analysis of rainfall. On 25 and 26 July, in the objective analysis, PWC of order more than 65 mm prevailed over a large area in the central parts of the country extending up to west coast of India. The distribution of computed PWC also indicates that the magnitude of PWC over the Central India (Bhopal 78 mm, Gwalior 68 mm, Nagpur 66 mm, Delhi 61 mm on 25 July; Jodhpur 77 mm, Gwalior 65 mm on 26 July) exceeded 65 mm. The value of computed PWC over the extreme south (Trivandrapuram 34 mm on 25 July and 38 mm on 26 July) as well as over the extreme north (Srinagar 25 mm on 25 July and 32 mm on 26 July) was considerably less. The objective analysis of PWC is found to in well agreement with the plots of computed PWC. The gradient of PWC is found to be stronger along the west coast. On 27 July, an east west oriented close isoline of 75 mm PWC lay over central India extending up to north Gujarat region. The pattern is consistent with the computed PWC as plotted over the area (like Jodhpur 74 mm, Nagpur 63 mm, Bhopal 63 mm, Ranchi 68 mm). On 28 July, Ahmedabad is found to report PWC of amount 77 mm where a close isoline of 70 mm is located in the corresponding analysis. Thus an inter-comparison reveals that the spatial distributions of PWC during 25-28 July are consistent with the plots of computed PWC from RS stations.

The objective analysis of rainfall of 25 July shows four heavy rainfall belts over south Konkan Goa (the innermost isoline of 100 mm), Central India (40 mm), extreme north India (40 mm) and over northeast India (60 mm). The heavy rainfall belts over central and extreme north India are in well agreement with the higher values of PWC prevailed over these areas. For the heavy rainfall belts over south Konkan Goa and northeast India, the magnitude of PWC has been relatively less (55 mm). The enhanced rainfall activities may be due to orographic effect. The distribution of rainfall of 26 July (heavy rainfall belts over Konkan Goa, parts of central India and extreme north India) is found to be well consistent with the corresponding PWC distribution.

The exceptionally heavy rainfall event of Mumbai on 27 July 2005 is not adequately captured in the corresponding rainfall analysis, carried out at the resolution of $1^\circ \times 1^\circ$. It is because of large spatial variability of rainfall. Though Santacruz reported 94 cm, the neighbouring station Colaba (at 20 km distance)

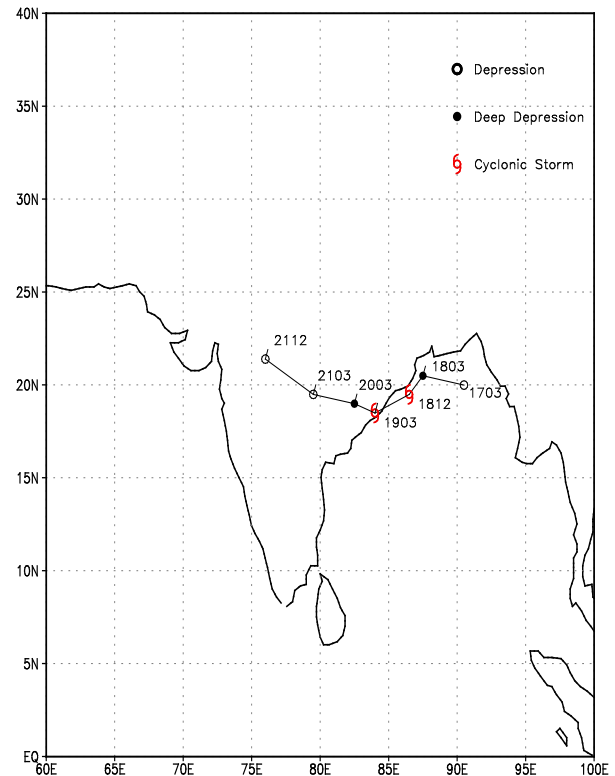
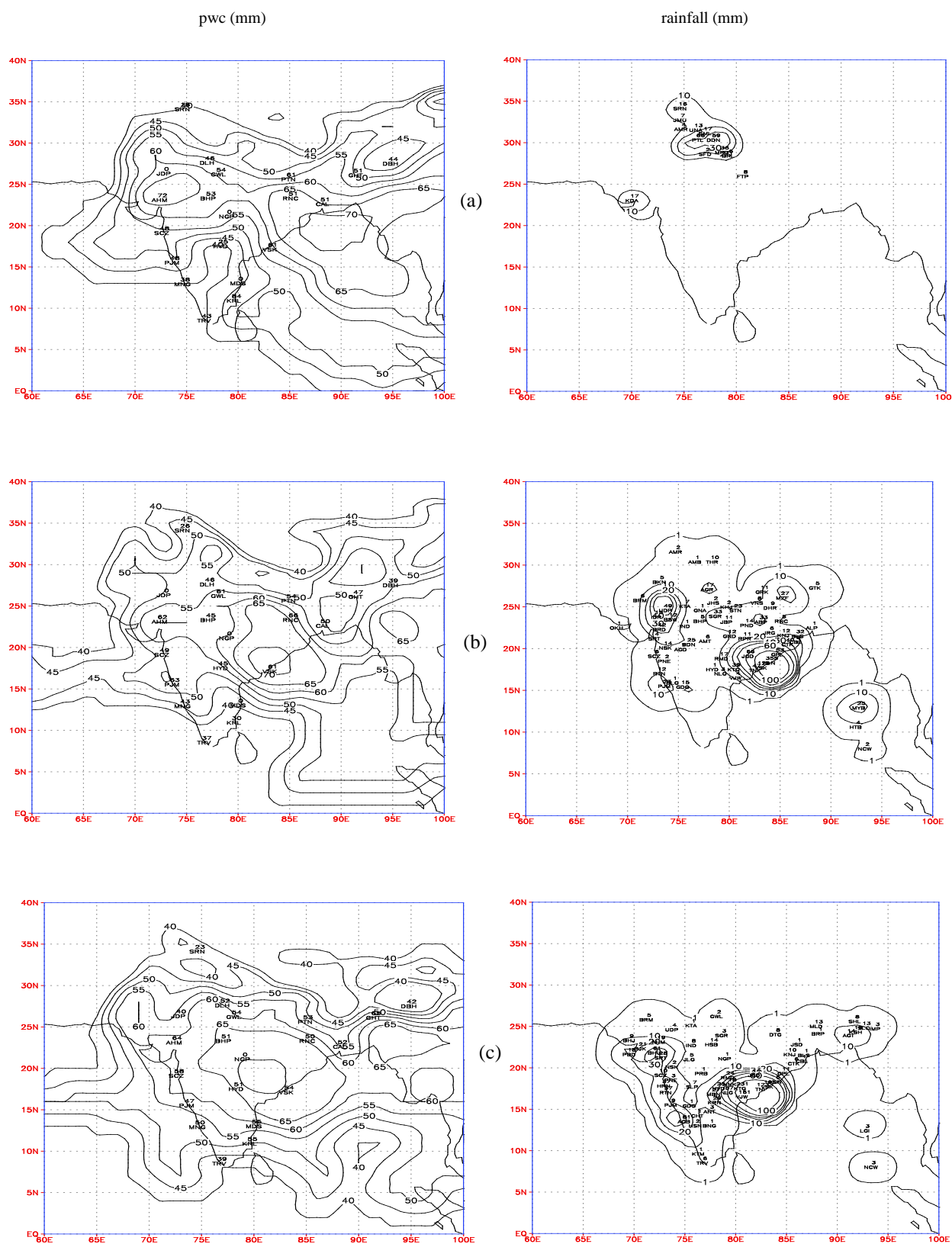


Fig. 2. Track of monsoon depression during 17-21 September 2005

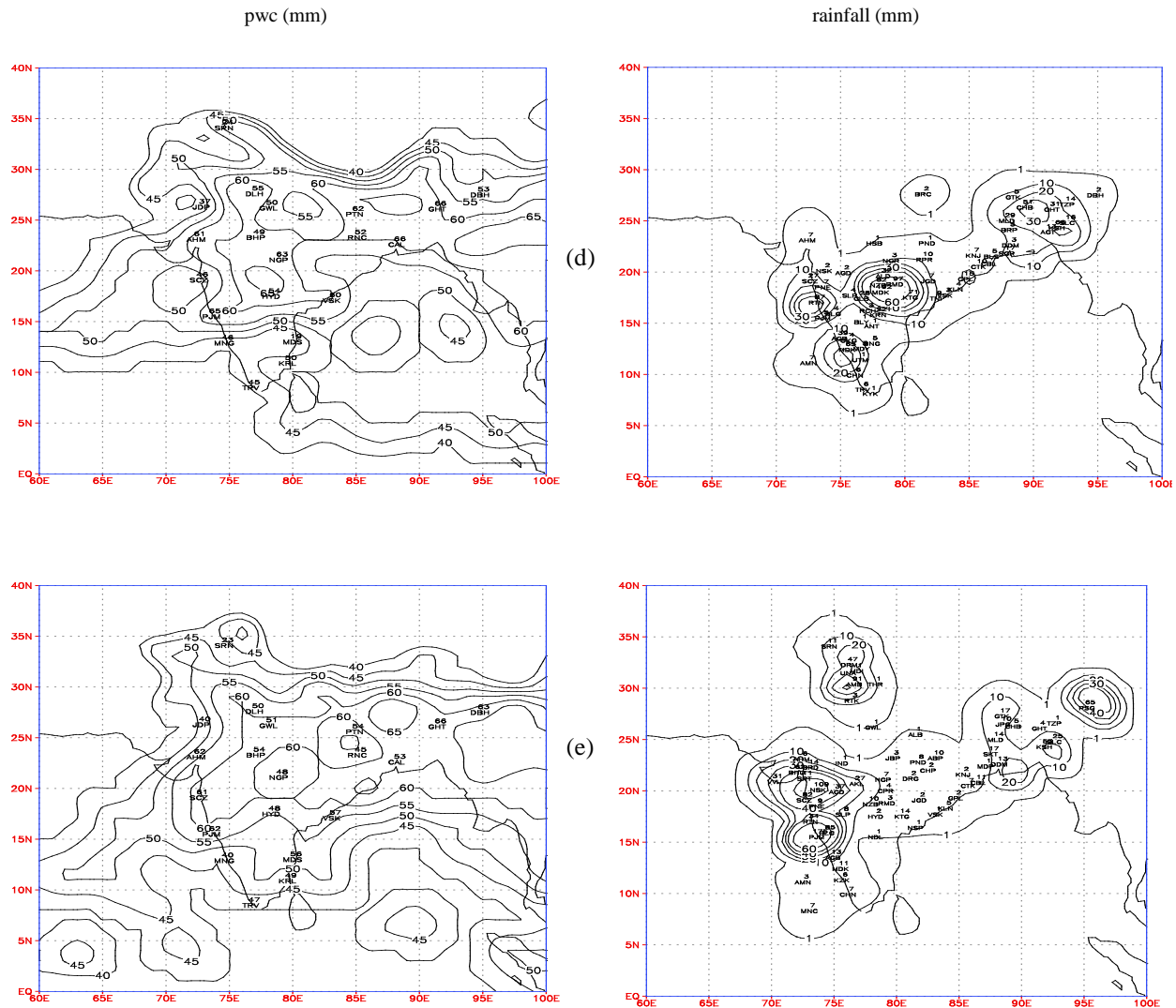
reported only 7 cm rainfall. The exceptionally heavy rainfall belt of 27 July over north Konkan may be due to the combined effect of offshore trough, orographic influence and explosive growth of PWC (PWC of order 75 mm located to the north east on 27 July) during 26-27 July in presence of well marked low pressure system over west Madhya Pradesh and adjoining Vidarbha. The heavy rainfall belt of 28 July over north Gujarat region is consistent with the PWC maxima which are found to be located over the area centered at Ahmedabad.

Case 2 : Monsoon depression of 18-22 September

A low pressure area formed over the Andaman Sea and adjoining east-central Bay of Bengal on 16 September, became depression on 17 September morning and deep depression on 18 September morning. It concentrated into a cyclonic storm on the same day evening and crossed north Andhra Pradesh coast near Kalingapattanam on 19 morning. Moving in a west northwesterly direction weakened into a deep depression at 0230 hours (IST) of 20 September. It became depression at 1730 hours (IST) of 20 September and



Figs. 3(a-c). Same as Fig. 1 corresponding to (a) 18 September, (b) 19 September, (c) 20 September 2005

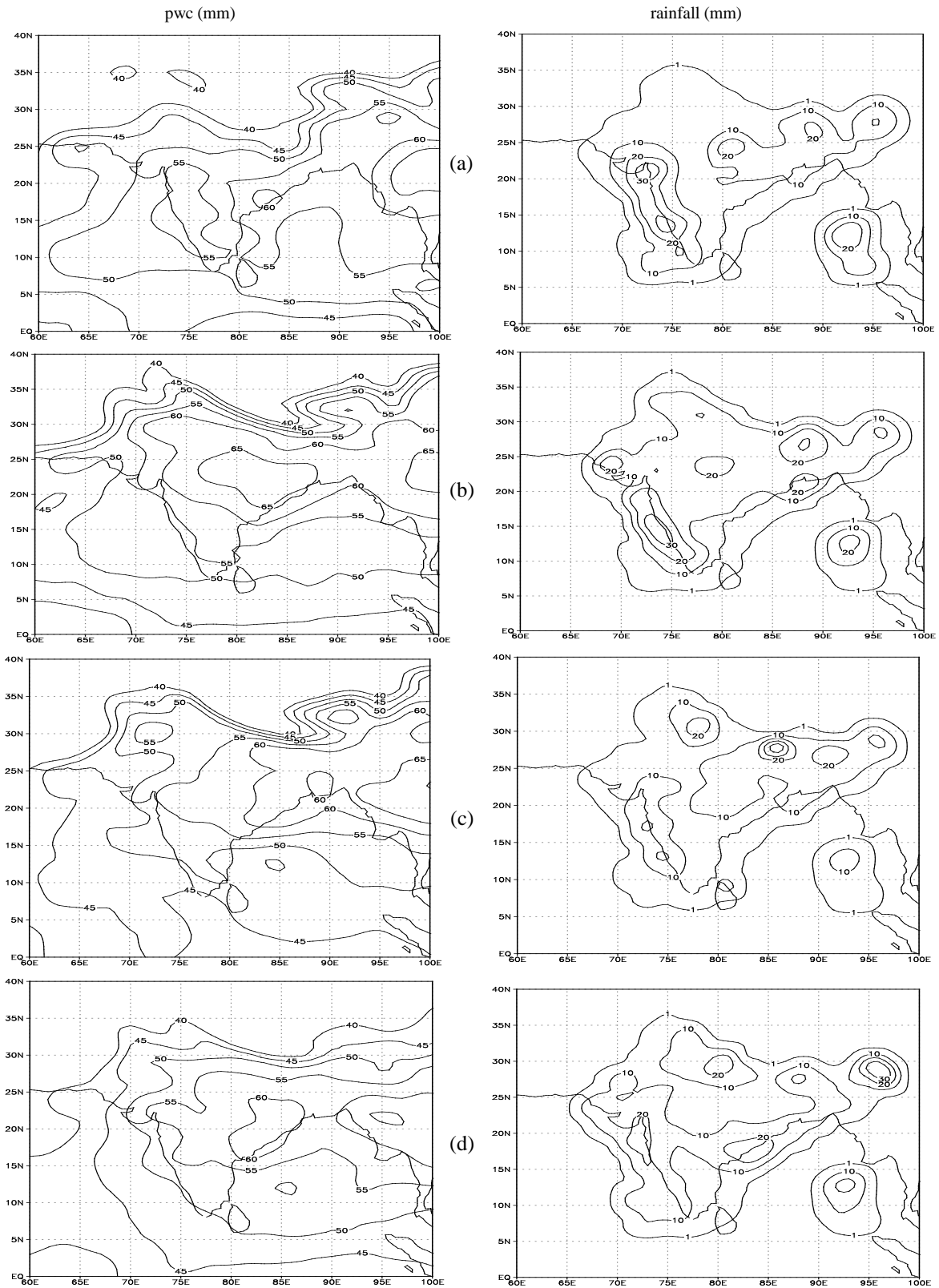


Figs. 3(d&e). Same as Fig. 1 corresponding to (d) 21 September and (e) 22 September 2005

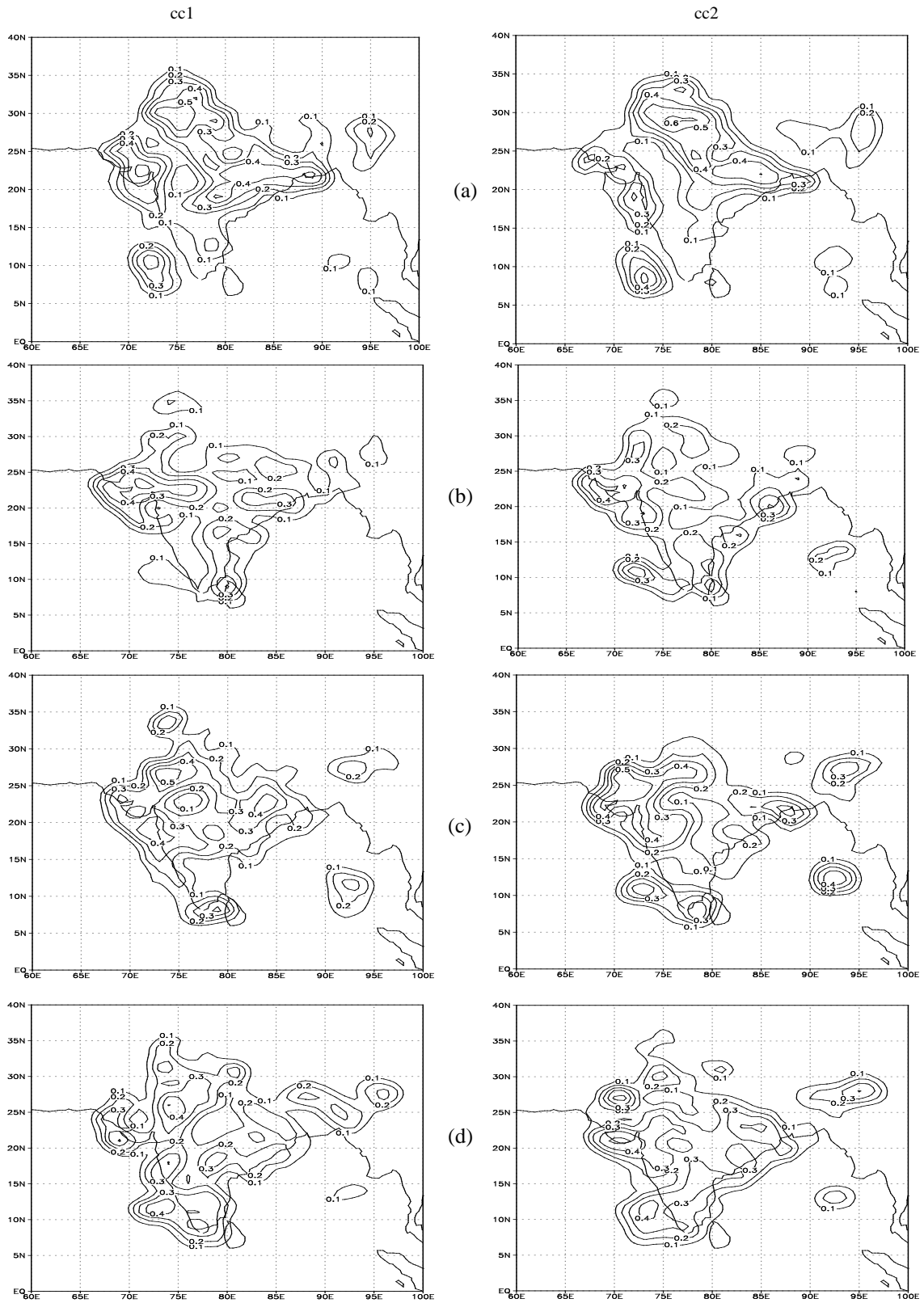
weakened into a well marked low pressure over north Maharashtra on 22 September morning. Subsequently, it lay as a low pressure area over southwest Madhya Pradesh and adjoining Gujarat region on 23 September, over northeast Rajasthan and adjoining northwest Madhya Pradesh on 24 September, over Uttaranchal on 25 September and then became less marked. The track position of this system is given in Fig. 2.

Figs. 3(a-e) present distribution of PWC and corresponding rainfall for the period from 18 to 22 September. On 18 September when the system lay as deep depression (in the morning) near Orissa coast and a mid-tropospheric cyclonic circulation lay over Gujarat region, two maxima of PWC (more than 70 mm) are

noticed, one over the north Bay and adjoining Orissa coast and another over South Gujarat region. The magnitude of computed PWC at Ahmedabad was 72 mm. On 19 September, as the system was moving westerly direction, the PWC maxima over the Bay moved across the land and lay over South Orissa and adjoining Andhra Pradesh. On 19 September a rainfall belt of 100 mm lay centred over South Orissa and neighbourhood and another rainfall belt of 40 mm over South Gujarat region. On 20 September similar pattern persisted both for the PWC and rainfall distributions. As the system was moving west northwesterly direction on 21 September, the PWC maxima (65 mm) shifted over Vidarbha with centre near Lat. 18° N / Long. 80° E. On 22 September, a close isoline of 65 PWC was located over central parts of the



Figs. 4 (a-d). (a) Spatial distribution of monthly mean PWC (mm) and corresponding 24 hours mean rainfall (mm) for the month of June 2005, (b) Same as (a) except for the month of July 2005, (c) Same as (a) except for the month of August 2005 and (d) Same as (a) except for the month of September 2005



Figs. 5 (a-d). Spatial distribution of correlation coefficient between daily PWC and corresponding 24 hours rainfall reported on the next day (CC1) and same day (CC2) for the month of (a) June, (b) July, (c) August and (d) September 2005

country extending up to Western Ghats and adjoining Sea areas.

The case study illustrated reveals that the spatial distribution of PWC is able to capture large scale monsoon precipitation system during the passage of this monsoon depression.

5. Inter-comparison of monthly mean fields

The spatial pattern of mean PWC (mm) and corresponding mean rainfall distribution (mm) for the month of June, July, August and September 2005 are presented in Figs. 4 (a-d) respectively. The lowest value of PWC of order less than 40 mm occurred over North India in the month of June and the highest value of order more than 65 mm occurred over North East India in July and August.

The distribution of PWC in June Fig. 4(a) is characterized by a zone of higher magnitude of PWC (of order more than 55 mm) along the East Coast and adjoining areas extending up to northeastern parts of India and northern parts of the Bay of Bengal and Andaman Sea. Another belt of higher order of PWC (55 mm) lay (north-south oriented) along the west coast of India. The spatial distribution of PWC is consistent with the heavy rainfall belt of order 20 to 30 mm along the west coast and over the eastern parts of the country. In June two depressions formed, one over the northeast Arabian Sea and adjoining Saurashtra & Kutch and another over land in Gangetic West Bengal and both were short lived.

In July, monsoon has been active over Indian region. Low pressure systems formed over the Bay of Bengal one after another and followed almost normal track along with the monsoon trough across central India and adjoining Gujarat region. These systems resulted in persistent rainfall activities leading to flooding over Gujarat, Madhya Pradesh, Maharashtra, Orissa and interior Karnataka. Fig. 4(b) presents corresponding PWC and the rainfall distribution. A close isoline of 65 mm PWC is found to be centered over the east central India and an isoline of 60 mm PWC covered the most parts of the country. The gradient of PWC is stronger to the north. This pattern is well matching with the corresponding rainfall distribution. A rainfall belt of order 10-20 mm lay over the central parts of the country. The magnitude of PWC along west coast over the domain of orographic heavy rainfall belt (20-30 mm) has been of order 55 mm. A few pockets of higher PWC (50-60 mm) are also noticed along the foothills of Himalayas and over northeastern states of the country.

The rainfall activity was subdued in August. The monsoon trough was close to the foothills of the Himalayas. The offshore trough along west coast of India was almost absent. The corresponding [Fig. 4(c)] PWC distribution shows a few pockets of higher magnitude (60 mm) of PWC along the foothills of India. The PWC over the eastern parts of the country was more than 65 mm. The magnitude decreases gradually southwestwards. The gradient to the north continues to be stronger. The corresponding rainfall distribution shows pockets of higher rainfall of order 20-30 mm along the foothills of Himalayas. The rainfall along the Western Ghats is of the order of 10 mm.

In September, one cyclonic storm formed over the northwest Bay and moved west-north-west wards across central India. Another depression that formed over the northeast Arabian Sea moved inland. The distribution of PWC Fig. 4(d) shows a close isoline of 60 mm PWC over parts of Orissa and adjoining Andhra Pradesh. The pattern is found to be well consistent with the rainfall belt of 20 mm confined over a small pocket in Andhra Pradesh and adjoining Orissa.

6. Spatial distribution of correlation co-efficient

The spatial distribution of correlation coefficient (CC) between PWC and 24 hours realised rainfall for the month of June, July, August and September are presented in Figs. 5(a-d) respectively. In this Figure the left panel represents CC between PWC and corresponding rainfall reported on the next day and the right panel is the CC with the rainfall reported on the same day. For the convenient of description we call them as CC1 and CC2 respectively.

In the month of June, CC1 of order more than 0.3 (which is significant at 5 % level) was located over Saurashtra & Kutch and adjoining Gujarat and north Konkan, over the domain of Mid Tropospheric Circulation (MTC). Another belt of higher CC1 (0.3 and above) was located along the domain of monsoon trough. A small pocket of CC1 more than 0.3 is also noticed centred over Lakshadweep area. Similar pattern is noticed for the case of CC2 (CC with the same day rainfall). CC2 is found to be slightly higher compared to CC1.

For the month of July, higher CC1 (0.3 and above) is found centred over Saurashtra & Kutch and adjoining areas of Gujarat, Rajasthan, Madhya Pradesh and north Konkan. Another small belt of higher CC1 is located over the eastern parts of monsoon trough. The pattern remains broadly same in case of CC2, except CC1 is found to be higher over the area of Lakshadweep.

In the month of August, CC1 of order more than 0.3 was located along west coast, Gujarat region, east central India and over the tip of peninsular India. Like CC1, CC2 of order more than 0.3 are found over west coast extending over the domain of MTC in Gujarat and adjoining north Maharashtra.

For the month of September, higher CC1 (0.3 and above) is found over most parts of the country and higher values are centred over the domain of mid tropospheric circulation (MTC) in Gujarat region and adjoining states and over the domain of monsoon low in east central India. The pattern remains broadly similar with CC2.

7. Conclusions

Following conclusions may be drawn from this study:

(i) PWC derived from the daily objective analysis of IMD's operational NWP system is consistent with the computed PWC from RS observations.

(ii) Case studies illustrated suggest that the spatial distribution of PWC is able to capture heavy rainfall belts. The broad scale monsoon precipitation systems during the passage of monsoon depression are realistically reflected in the PWC analysis.

(iii) The result of the monthly distribution of PWC is found to be well consistent with the study of Ananthakrishnan *et al.* (1965), who computed PWC from RS data of Indian stations.

(iv) The orographic heavy rainfall belts along the Western Ghats and foothills of the Himalayas, and heavy rainfall belts over the areas of monsoon circulations are well captured in the monthly mean field of PWC.

(v) The spatial distribution of co-relation co-efficient, computed based on daily data between PWC and rainfall shows that the CC is more than 0.3 over the domain of MTC, Monsoon low pressure system and Western Ghats, which is statistically significant at 5% level. The spatial pattern of CC between PWC and corresponding rainfall of next day and the CC with the rainfall of same day broadly remains the same. These features are, in general, common for each of the monsoon months (June, July, August and September).

Real-time availability of this product is expected to benefit various user communities involved with the task of monitoring and prediction of monsoon activity and flood events.

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