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The estimation of heavy rainfall using INSAT-1B satellite data

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सार—इस शोध-पत्र में उपग्रह इनसेट-1 बी के 3 घंटेवार आंकड़ों का प्रयोग करते हुए, मानसून ऋतु के दौरान भारत पर भारी संवहनी वर्षा के आकलन की योजना प्रस्तुत की गई है। इस योजना में संवहनी बादल संरचना, आकाश में और समय के साथ बादल की वृद्धि और विद्यमान पर्यावरणीय अवस्थाओं को ध्यान में रखत हुए जीवनवृत्त उपागम का उपयोग किया गया है। भारी वर्षा उत्पन्न करने में सूक्ष्म मापी संवहनी समिश्र अतिलंघित चोटियाँ और बादल विलयन की भूमिका का विवेचन किया गया है। अगस्त 1986 और अगस्त 1987 में हुई दो बहुत भारी वर्षा की घटनाओं पर यह योजना लागू की गई है और वर्षा आकलन के कुछ महत्वपूर्ण पहलुओं का विवेचन किया गया है। स्वतंत्र आंकड़ा समुच्चय के लिए वर्षा आकलन का वास्तव में प्रतिशत विचलन +111% और −43% के मध्य रहता है और आकलन का 85%, ±50% की त्रुटि के अन्दर रहता है। यह योजना लगभग वास्तविक-समय आधार पर वर्षा आकलन बताती है और भविष्य में प्राप्त अनुभवों से इसकी विशुद्धता में सुधार होने की संभावना है।

ABSTRACT. A scheme for the estimation of heavy convective rainfall over India during the monsoon season using 3-hourly INSAT-1B satellite data has been presented in this paper. The scheme uses 'life history' approach, taking into account the convective cloud structure, cloud growth in space & time and the prevailing environmental conditions. The role of mesoscale convective complex, overshooting tops and cloud mergers in producing heavy rains is discussed. The scheme is applied to two very heavy rainfall events of August 1986 and August 1987 and some important aspects of the rainfall estimation have been discussed. For an independent data set, the percentage deviations of the rainfall estimates from actual lie between +111 % and −43 %, and 85 % of the estimates lie within an error of ±50 %. The scheme provides rainfall estimates on a near real-time basis and its accuracy is expected to improve with the experience gained in future.

1. Introduction

The heavy rainfall in tropics is usually associated with deep convective cloud systems. This convective nature of rainfall is also responsible for its large variability in space and time, which is often not reflected in rainfall recorded with the existing sparse distribution of raingauges. The monitoring of deep convective activity with a geostationary satellite affords a means of estimating heavy rainfall in near real-time at a much better resolution in space and time. Although these estimates cannot achieve the accuracy of actual observations, the satellite derived estimates can supplement raingauge observations and radar estimates. In remote, uninhabited areas the satellite-derived rainfall estimates may be the only data available and such estimates over catchments of mountainous rivers are very important for predicting flash floods.

The geostationary satellites provide a high frequency of earth coverage, up to once every half-hour, and permit the observation of the life history of clouds. Scofield and Oliver (1977, 1980) have developed the cloud history technique for estimating convective rainfall using half-hourly data received from SMS/GOES satellites. In Scofield-Oliver technique the rainfall estimates computed at half-hourly intervals are based on observations of cloud top temperatures and cloud growth or divergence aloft, overshooting tops, cloud mergers and environmental precipitable water. As against half-hourly operation of SMS/GOES statellites, the Indian National Satellite, INSAT-1B, has been operationally providing the cloud imagery at 3-hourly intervals only. The authors have used this INSAT-1B imagery for the estimation of heavy rainfall. This paper presents an adoption of Scofield-Oliver scheme for estimating heavy rainfall over India during the southwest monsoon season, using INSAT-1B Very High Resolution Radiometer (VHRR) data received at 3-hourly intervals. This cloud imagery has a ground resolution of 2.75 km in the visible channel (VIS : 0.55-0.75μm) and 11.0 km in the infrared channel (IR : 10.5-12.5μm).

2. Characteristics of convection in monsoon field

2.1. *Convection classes* — The tropical convection is divided into 3 main classes, *viz.*, small scale convection, cumulonimbus convection and large scale convection (Ludlam 1983). In the small-scale convection, also called cumulus convection from the small heap-clouds that commonly form in it, the individual clouds are several kilometres apart, have dimensions of 1-2 km and are usually insufficient for shower formation. These fair-weather clouds are formed under relatively stable atmospheric conditions due to the heating of air in contact with warm land or water surfaces. During the monsoon season such clouds occur north of monsoon trough in the Indo-Gangetic plains and also over the west Arabian Sea.

The cumulonimbus convection occurs under the conditions of atmospheric instability when the subsequent convective cells reach progressively greater heights till they become thunderstorms. The depth of convection often increases suddenly from a few kilometres to the entire depth of the troposphere. Comulonimbus convection is usually associated with an organised tropical disturbance including a tropical cyclone and ITCZ.

In the large-scale convection, the warm moist air heated over the equatorial oceans at the surface streams towards the poles and arrives at higher latitudes in the region of synoptic scale convergence, producing on its way extensive deep but almost horizontally layered clouds with embedded cumulonimbus clouds.

2.2. *Convection in monsoon field*

The extensive clouds mass in the form of monsoon clusters observed over south and southeast Asia in association with summer monsoon comprises the large scale organised convection. The monsoon circulation operates on a variety of scales and a distinction, *a priori* between them is difficult (Warner 1984). Accordingly, the convection manifests itself in a variety of shapes and organisations. The experience of the authors with INSAT-1 and NOAA imagery for monsoon periods has shown that heavy rainfall producing convective systems consist of :

(*i*) Synoptic-scale disturbances, like monsoon depressions, vortices in the monsoon trough or along the west coast, weak low level circulation (Mishra and Singh 1977, Veeraraghavan *et al.* 1983, Mishra and Jain 1979) ;

(*ii*) Mesoscale convective complexes ;

(*iii*) Single-clustered convective systems ;

(*iv*) Multi-clustered convective systems, quasi-circular or linear in shape (Mishra and Singh 1980 ; Onkari Prasad *et al.* 1983) :

(*v*) Regenerative systems (Veeraraghavan *et al.* 1983).

These convective systems are similar to those observed over U.S.A. by several workers (Scofield 1985, Ward 1981, Maddox 1980, Spayed and Scofield 1983). However, the cloud mass associated with deep convection in monsoon field is often so extensive and pervasive that a distinction between individual cloud systems is very difficult. Consequently, the convective mergers cannot always be detected precisely. This deep convective cloud field has longer life spans compared to thunderstorms of pre-monsoon or winter seasons extending from several hours to even more than one day. The deep layer cloud field is long-lasting, seen over relatively larger area and somewhat stationary. The anvils are extensive and have much larger temporal and space dimensions. The extent and merging of anvils masks the development of freshly growing convection underneath. A part of the thick anvil may also be at times confused with the deep convection, but presence of sharp gradients in cloud top temperature field can reveal the active convective clouds.

With exception to the tropical cyclonic storm and ITCZ clouds, much higher convective cloud tops are usually observed over India in the monsoon season as compared to the rest of the year. INSAT-1 data show that during post-monsoon, winter and pre-monsoon seasons the cloud tops are only sometimes colder—60°C and rarely colder than —70°C. By contrast deep convective cloud tops during monsoon frequently grow colder than -70°C and tops with —89°C have been recorded.

The characteristics of the monsoon convective cloud regime are somewhat different from the convective cold-top storms discussed by Scofield and Oliver (1977, 1980) and Scofield (1987). The environmental tropopause taken by Scofield & Oliver is at —62°C whereas the monsoon tropopause occurs around —75°C. The strong divergence aloft does occur during monsoon over India, but it is not caused by the splitting of a westerly jet stream as considered by Scofield and Oliver. However, a number of heavy rain producing systems during monsoon have long life and are slow moving, similar to saturated environment thunderstorms of Scofield and Oliver (1980). These cloud systems are seen in several consecutive 3-hourly satellite pictures and have life periods of 6-18 hours. The 3-hourly INSAT-1B data, thus, holds promise for estimating heavy convective rainfall during the monsoon regime, although the more frequent half-hourly data would be more advantageous as it would take into account the short-period convective processes.

3. Scheme for heavy convective rainfall estimation over India during southwest monsoon season

3.1. *Basic considerations* — The W. M. O. Report (1982) has considered the adjustment of Scofield/Oliver technique for estimating heavy convective rainfall from 3-hourly satellite inputs. Two factors of the technique, *viz.*, overshooting tops and cloud mergers cannot always be detected with 3-hourly data. The report, therefore, considers that cloud top temperature and cloud growth are the only factors which can be derived from 3-hourly frequency and assigns rainfall estimates for various conditions of these factors only. Therefore, the basic approach is that rapidly expanding thunderstorms with coldest top produce the heaviest rainfall.

The experience of authors with INSAT-1 data has shown that rainfall is invariably associated with deep convective cloud clusters of monsoon season whose tops reach —40°C. Further cloud growth is accompanied with increased rainfall rate. A threshold of —40°C for cloud top temperature (CTT) has been assumed for rainfall estimation, instead of —32°C assumed by Scofield and Oliver (1977). Further, Scofield/Oliver technique assumes the summer tropopause at —62°C, a representative value for U.S.A., for estimating rainfall from cold-top thunderstorms. Instead the authors have assumed the tropopause temperature of —75°C, as the representative value over India during monsoon. In this way, we can also give due weightage to overshooting tops by assigning suitably higher rainfall values to tops colder than —75°C. The Scofield/Oliver moisture correction factor for taking into account relatively drier environment is not needed in our case because of the preponderence of moisture in monsoonal atmosphere.

Since these monsoon systems are usually long-lasting, large-area storms, the saturated environment may be taken as a constant factor for enhancing the rainfall estimates. From these considerations, the authors have empirically devised a scheme for estimating 3-hourly rainfall from satellite-derived CTT distribution and its change over the 3-hour period. For simplicity, CTT's are divided into 3 classes, *viz.*,—40°C to — 59° C, —60°C to —74° C and—75°C and colder.

3.2. *The scheme*

The scheme provides 3-hourly rainfall estimates for deep convective systems occurring during the monsoon season using 3-hourly INSAT-1 daytime VIS and round the clock IR imagery received from INSAT-1B satellite. The IR picture is contoured to show CTT isotherms at 10°C interval from 0° to—70° C and at 5° C interval thereafter. The scheme consists of 2 parts :

(*i*) *Location of the active portion of the convective system* — The active portion of the storm is the area of strong updrafts and coincides with the heavy rain. It is identified in IR picture by the coldest cloud tops, the strongest CTT gradients within the anvil, or the cold cloud edges showing the least movement. In VIS imagery it is seen as very bright and more textured area. Griffith *et al*. (1976) have shown that the brighter the cloud in VIS imagery the heavier the rainfall. The overshooting tops cast shadows on the underlying anvil and are readily detected in VIS pictures in the morning and afternoon when sun angle is low. The active portion lies along upshear edge of the anvil in strong vertical wind shear environment and near the centre of anvil in weak shear environment (Scofield 1984). Only cold active portion of the anvil is used in cloud growth computation.

(*ii*) *Computation of 3-hourly rainfall estimate for the active portion*

For the active portion, the cloud top temperature and cloud growth during past 3 hours are determined in terms of changes in CTT and in cloud area. They will fall in either of the two categories :

(*a*) Cold cloud isotherm (—40°, —60° or —75° C) expands in size or remains the same and

(*b*) Cold cloud isotherm decreases in area or cloud top warms up.

The rainfall estimate for them can be read from Table 1.

In addition, the authors have attempted to estimate rainfall within the anvil area but outside the most active portions, considering the overall CTT field. The upshear side of the anvil, where CTT reaches —70°C and has closely packed isotherm (≈ 5°C in 1° latitude or closer) is associated with a rainfall of 10 mm in 3 hours. For anvil areas between —40°C and —70°C, a rainfall amount of 5 mm has been assigned. However, places far removed from convective tops and on the downwind side do not receive any rainfall.

The proposed scheme (Table 1) has been derived from the past rainfall data and the corresponding INSAT-1B imagery, including that for the heavy rainfall event of August 1986 described in Sec. 4. The application of the scheme to an independent data set for the heavy rainfall event of 11 August 1987 for verification appears in Sec. 5.

TABLE 1

Estimation of 3-hourly rainfall (mm) from changes in cold cloud tops

Cloud top temp. (°C)	Increase in length along axis		
	>2° Lat. (mm)	>1° Lat. & ⩽2° Lat. (mm)	⩽1° Lat. or no change (mm)
(a) Expansion of coldest CTT isotherm in past 3 hours			
—40 to —59°C	40	20	10
—60 to —74°C	60	40	30
—75°C or colder	125	70	50

(b) Contraction of coldest CTT isotherm or warming by ⩾15°C

Cloud top temperature	*Rainfall (mm)*
—40° to —59°C	5
—60° to—74°C	15
—75°C or colder	25

(c) Elsewhere within anvil having CTT gradients more than 5°C in 1° Lat.

Anvil temperature	*Rainfall (mm)*
—40° to —69°C	5
—70° C or colder	10

4. Heavy rainfall event of August 1986

4.1. *Synoptic situation*

A monsoon depression formed in the central Bay of Bengal on the morning of 11 August 1986 when it lay centred near 18.0° N, 86.5° E. It intensified into a deep depression on 11th evening, moved westward and crossed north Andhra coast close to Kalingapatnam on 12th night. It continued to move as deep depression over east Madhya Pradesh on 13th and then weakened into a depression near Raipur on 14th morning. It further moved northwestward and weakened into a well marked low over central Madhya Pradesh on 15th morning. Very heavy rainfall occurred over Andhra Pradesh, Vidarbha and Madhya Pradesh in the second week of August 1986 in association with this depression and caused large scale floods.

4.2. *Data used*

The INSAT-1B cloud imagery in the thermal infrared channel, with CTT isotherms at —40°, —50°, — 60°, —70°, —75°, —80° and —85°C superposed on them, were generated at 3-hourly intervals between 11 and 16 August 1986. The CTT contours were generated with the software available in Data Analysis and Interactive Display Sub-system of INSAT-1 Meteorological Data Utilisation Centre at New Delhi. The INSAT-1B VIS and IR data were also analysed in a man-computer interactive environment in order to derive the intensity of the synoptic scale disturbance and the movement and intensity changes of the convective system. The system intensity was also observed by applying enhancement technique on the infrared imagery, The VIS and enhanced IR pictures showing active portions of the deep convective system on 11 August 1986 are seen in Fig. 1. With these data, point rainfall has been derived at specific locations, using the scheme outlined in Sec. 3. The 3-hourly estimates have been aggregated to 24-hr periods ending at 0300 GMT and compared with the corresponding surface raingauge observations of 24-hr rainfall recorded at 0300 GMT as available from the surface observatories/raingauge stations.

4.3. *Results and discussion*

4.3.1. *Rainfall estimation for* 11 *August* 1986

An intense mesocale convective system had developed off north Andhra coast southeast of Visakhapatnam, on the night of 10 August 1986 and subsequently moved inland. This large convective system covering an area of more than 25 (degree Lat.)^2 had a slow movement, a life span of about 27 hours and its highest tops stayed colder than —80°C from 21 GMT of 10th to 12 GMT of 11th. It clearly showed characteristics of Mesoscale Convective Complex (MCC) of Maddox (1980) between 1800 GMT of 10th and 15 GMT of 11th; the cold cloud area enclosed by —60° C CTT contour was consistently greater than 1,30,000 km^2 and its eccentricity was 0.7 or greater. On 11th this MCC, with overshooting tops colder than the environmental tropopause and reaching —89° C, persisted over north Andhra coast (Fig. 2). Between 0300 and 1500 GMT, Visakhapatnam was located below the most active portion of the storm, the overshooting tops. During this period, Waltair recorded 140.5 mm of rainfall, while Table 2 (a) estimates a rainfall of 140 mm. At 0900 GMT, Visakhapatnam was at the northern edge of overshooting tops and in the sharpest CTT-gradient ; this corresponds to the time of maximum rainfall rates inferred from surface raingauge reports. The satellite data estimated the 24-hr rainfall at 0300 GMT of 12th as 170 mm while the actual rainfall was 178 mm at Waltair and 151 mm at Visakhapatnam. Outside the core, tight CTT gradients on upwind (at the anvil level) side in the northeast sector indicated active portions of the storm, while warmer tops and weak CTT gradients towards west showed the spread of anvil cirrus by the strong upper tropospheric easterly flow. These factors as well as ongoing changes in the evolution of convection were reflected in rainfall estimates for 8 stations (Table 2a) derived from CTT contour maps (Fig. 2). The estimates show a range of deviations from actual, from —61% for Kalingapatnam to +25% for Nidadevolu (Table 2a).

4.3.2. *Merger of convective tops*

The merger of deep convective storms with overshooting tops was observed on 13th over Vidarbha (Fig. 3). The developing convective storms with the cloud tops colder than —80° C were located at 19.9° N, 79.1° E and 20.4° N, 80.3° E at 1800 GMT of 13th. By 2100 GMT, they moved closer and merged together near 20.0° N, 79.4° E at Chandrapur. As a result of the merger the coldest isotherm of —80° C expanded. The rainfall estimate for Chandrapur is 75 mm between 1800 and 2100 GMT and 280 mm for 24 hours ending on 14 August 1986 (Table 2c). The influence of merger and cloud top expansion is supported by the actual 24-hr rainfall of 329 mm recorded at Chandrapur.

The convective merger was also observed between 2100 GMT of 10th and 00 GMT of 11th (Fig. 4) over north Andhra coast, wherein the IR imagery showed an updraft intensification within the core region through a fall in the coldest CTT by 6° C, which reached —89° C. After the merger, the central region of the storm remained practically stationary and the coldest CTT isotherm of —85°C expanded by 1.1°. The 3-hour rainfall estimate at the core for this situation from Table 1 is 70 mm. This is supported by the actual 3-hour rainfall of 42.2 mm recorded at the nearest station, Visakhapatnam. Considering that Visakhapatnam was located just at the periphery of —85° C isotherm, it is concluded that the actual rainfall within the core of the storm would have been much greater. A few more convective mergers were identified during this event over the Bay of Bengal but they have not been discussed for want of actual rainfall data for verification.

4.3.3. *Comparison of actual and estimated rainfall*

The satellite estimated and actual rainfall amounts for this rainfall event (Table 2 a-d) show that percentage deviations of the estimates from actual lie within — 61% and +114%. Out of 28 rainfall estimates presented here, about 93% lie within an error of ±50%. The r.m.s. error of rainfall estimates in the present sample is 39.2 mm and mean error is 31.2 mm.

The extreme errors in the sample reveal some interesting yet unexplainable aspects. At 0300 GMT of 12th, Kalingapatnam recorded a 24-hr rainfall of 115 mm whereas Table 2(a) gives an estimate of 45 mm. Between 0300 and 1200 GMT of 11th, the station was at the periphery of active convection, far removed from the core and under the convective clouds which were warming up. During this period Kalingapatnam received a rainfall of 89.9 mm as against our estimate of 35 mm. This appears to be due to satellite data input at a coarse frequency of 3-hour intervals, because of which short-period rapid developments could have been missed. Further, after 1200 GMT the convective core moved further away and the station came under stratified anvil warmer than —40° C so that the scheme did not estimate any rainfall, but actually light rain continued.

The other extreme error relates to the estimated 24-hr rainfall of 150 mm at Wardha at 0300 GMT on 14th, while the actual rainfall recorded was 70 mm. The station was located away from the core but within the active portion of the convective storm and CTTs over the station ranged between —60°C and—73° C between 12 GMT of 13th and 00 GMT of 14th when most of the rainfall would have occurred in the convective merger sequence. The spatial variation of convective rainfall in this case is highlighted by 329 mm recorded at Chandrapur and 70 mm at Wardha on 14th.

Further, under similar situations of being away from the core, rainfall estimates for Kalingapatnam and Wardha showed opposing deviations from actual as discussed above. This large mesoscale variability of convective rainfall is also seen in 190 mm recorded at Vijayawada and 95 mm at Ganuavaram for the 24-hr ending at 0300 GMT of 12 August 1986, while the estimate comes to 115 mm (Table 2a).

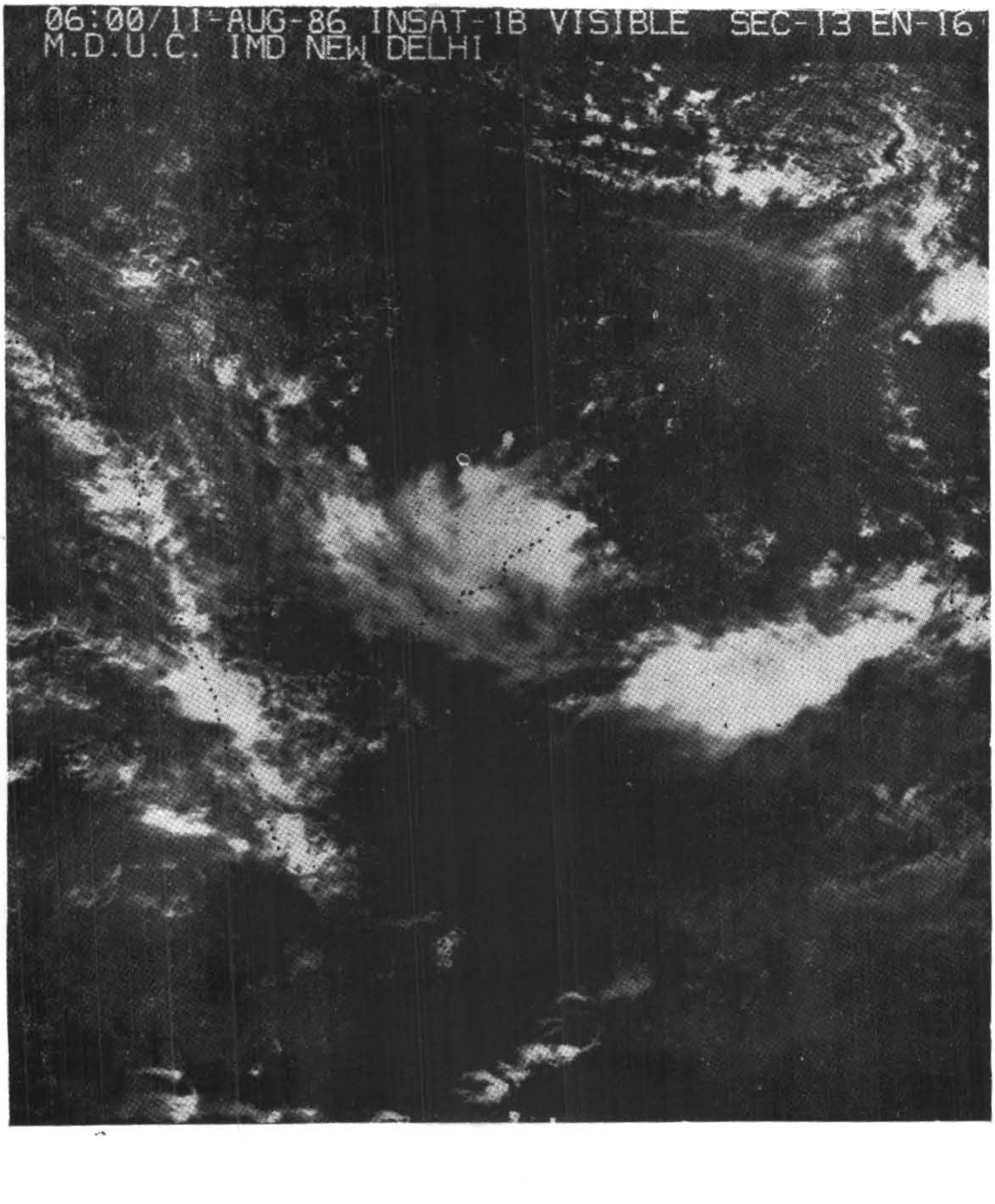

Fig. 1 (a). INSAT-1B VIS image of 0600 GMT on 11 August 1986 showing mesoscale convective complex over north Andhra coast

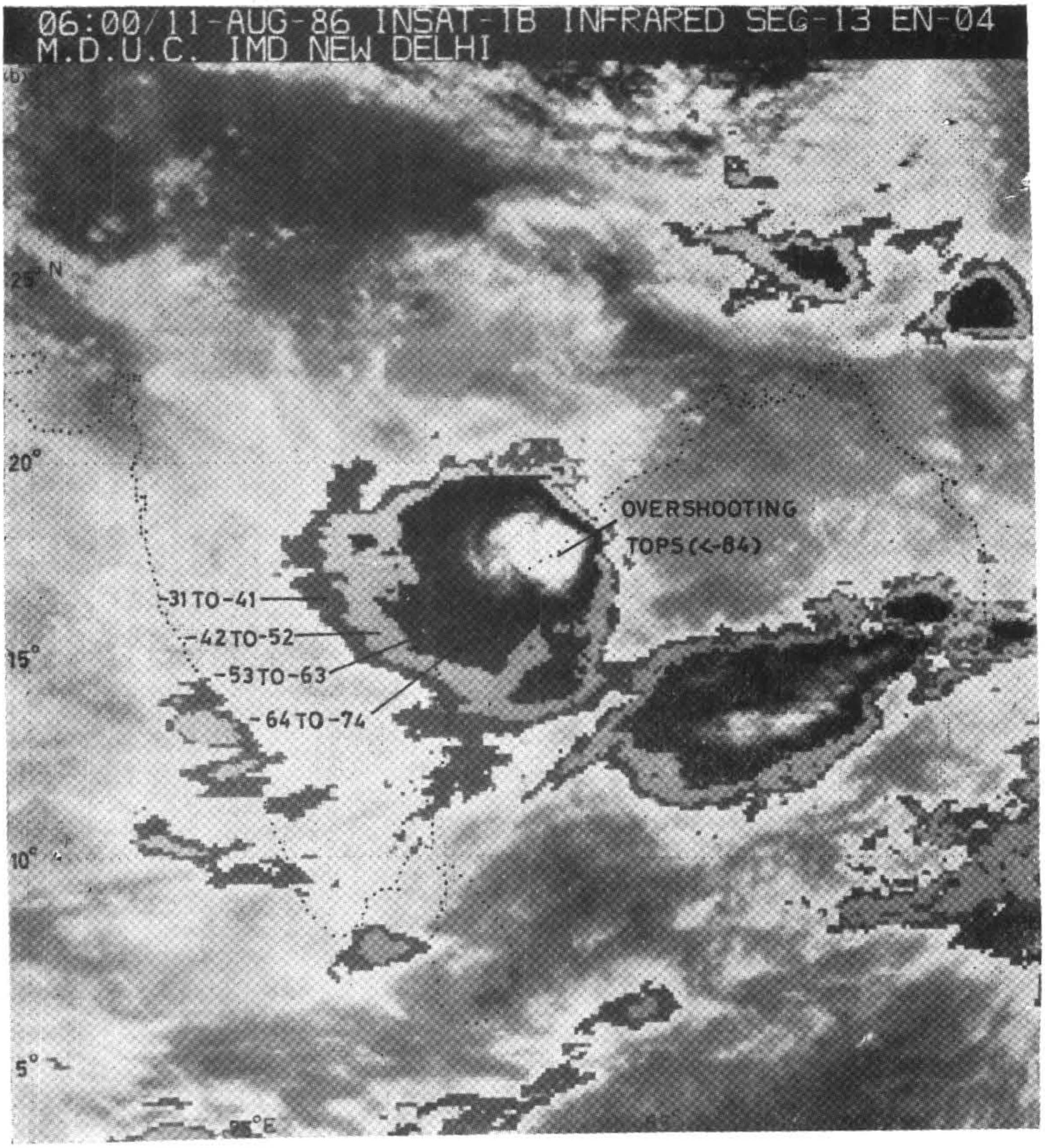

Fig. 1 (b). INSAT-IB enhanced IR image of 0600 GMT on 11 August 1986 showing mesoscale convective complex over north Andhra coast

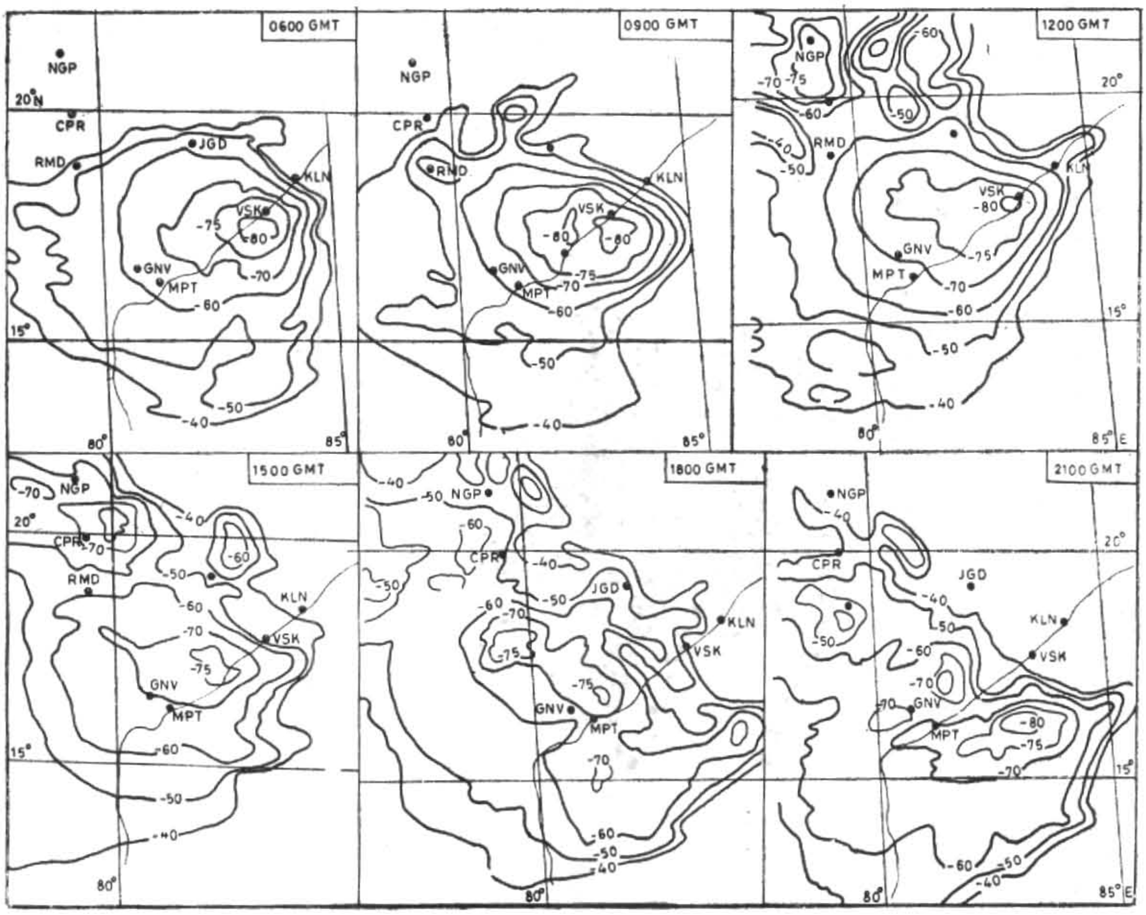

Fig. 2. Cloud top isotherms for 11 August 1986 derived from INSAT-1B IR data and showing overshooting tops

TABLE 2

Satellite estimate of 24-hour rainfall (mm) ending at 0300 GMT

Station	Time (GMT) 03-06	06-09	09-12	12-15	15-18	18-21	21-00	00-03	Total	Actual realised	Percentage deviation
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
(a) 12 August 1986											
Kalingapatnam	10	05	20	10	00	00	00	00	45	115	—61%
Waltair	25	50	50	15	10	05	05	10	170	178	—4%
Kakinada	15	30	15	15	10	10	10	10	115	102	+13%
Masulipatnam	05	50	15	15	15	05	05	00	110	116	—5%
Ongole	00	00	05	05	05	05	05	00	25	26	—4%
Jagdalpur	10	15	15	10	05	00	00	00	55	60	—8%
Vijayawada	10	15	10	10	30	15	15	10	115	190	—39%
Nidadevolu	10	50	25	15	25	25	15	10	175	140	+25%

TABLE 2 (*contd*)

Station	Time (GMT) 03-06	06-09	09-12	12-15	15-18	18-21	21-00	00-03	Total	Actual realised	Percentage deviation
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
(b) 13 August 1986											
Visakhapatnam	10	15	10	05	00	05	10	05	60	42	+43%
Kakinada	30	10	10	10	05	10	05	05	85	91	—7%
Masulipatnam	30	10	05	05	05	05	05	05	70	110	—36%
Jagdalpur	00	00	05	05	00	00	00	15	25	37	—32%
Vijayawada	30	00	10	30	05	05	05	00	85	90	—6%
Nidadevolu	10	15	30	15	10	05	10	15	110	110	—35%
Chandrapur	05	30	30	50	75	25	05	00	220	270	—19%
Ramagundam	05	10	30	10	30	10	10	00	105	162	—35%
Hanamkonda	05	05	30	10	10	05	00	10	75	91	—18%
(c) 14 August 1986											
Ramagundam	10	10	15	20	30	30	10	05	130	143	—9%
Chandrapur	00	15	30	50	50	75	50	10	280	329	—15%
Nagpur	00	10	15	30	30	30	05	00	120	125	—4%
Wardha	00	10	30	30	30	30	15	05	150	70	+114%
Nazibabad	10	10	10	30	30	40	15	05	150	100	+50%
Jagdalpur	15	10	30	30	30	15	05	00	135	121	+12%
(d) 15 August 1986											
Hosangabad	00	30	30	30	15	00	00	00	105	150	—30%
Ujjain	00	00	10	50	25	30	30	15	160	110	+45%
Indore	00	00	10	30	15	30	50	30	165	120	+37%
Bhopal	00	00	30	30	10	00	00	00	70	90	—22%
Panchaman	00	30	50	30	05	00	00	00	115	90	+28%
(e) 12 August 1987											
Sultanpur	15	10	00	50	25	25	25	15	165	135	+22%
Gorakhpur	15	15	05	20	30	15	05	05	110	193	—143%
Ballia	15	05	00	50	50	15	05	15	155	84	+85%
Bahraich	05	15	40	40	30	30	05	00	165	111	+49%
Allahabad	15	05	00	40	50	50	25	15	200	95	+111%
Varanasi	15	05	00	10	70	25	25	25	175	165	+6%
Chhapra	10	05	00	40	70	50	15	10	200	179	+12%
Patna	05	00	00	15	30	50	10	05	115	124.6	—8%
Japla	30	05	10	10	60	50	15	05	195	135	+44%
Koilwar	15	05	00	05	70	25	15	25	160	124	+29%
Sabour	10	05	00	00	00	30	05	00	50	82	—39%
Aurangabad	30	05	05	00	40	50	15	05	150	101	+49%
Darauli	15	05	05	10	40	15	15	05	120	151	—21%
Mahua	05	05	00	10	20	30	05	05	80	130	—38%
Hatwa	15	10	00	10	40	15	05	05	100	119	—16%
Islampur	25	05	10	10	40	50	05	05	150	155	—3%
Rafiqganj	30	05	05	00	60	50	10	15	175	110	+59%
Gaya	30	05	10	05	60	50	10	05	175	130	+35%
Hiranpur	05	10	05	05	00	15	30	05	75	104	—28%
Maheshi	05	05	05	20	40	50	05	15	135	104	+30%

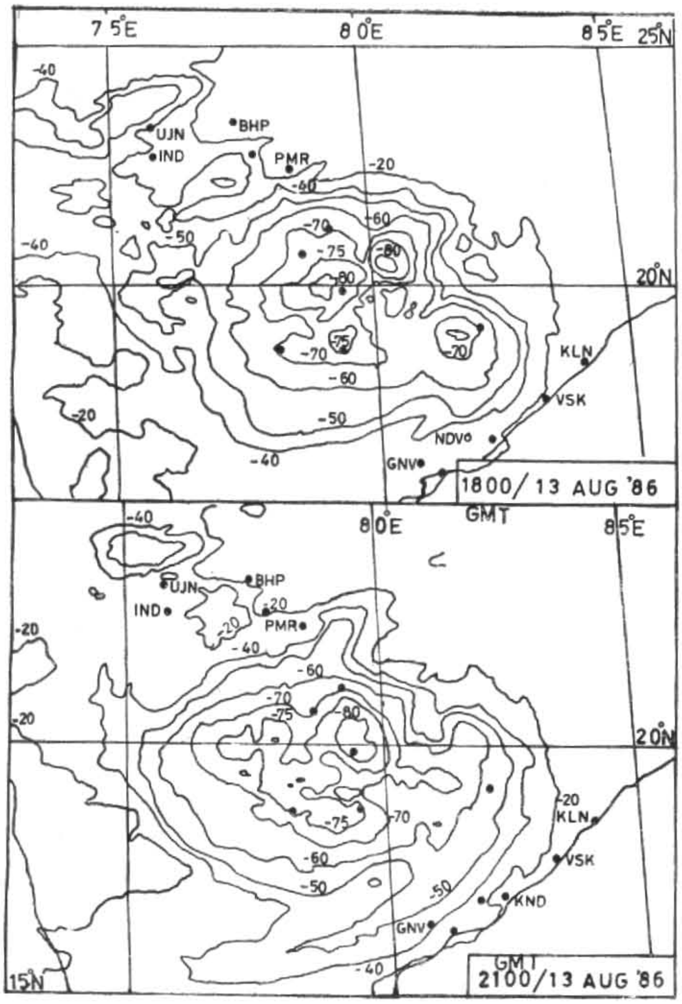

Fig. 3. INSAT-1B cloud top isothems for 13 August 1986 showing convective merger over Vidarbha

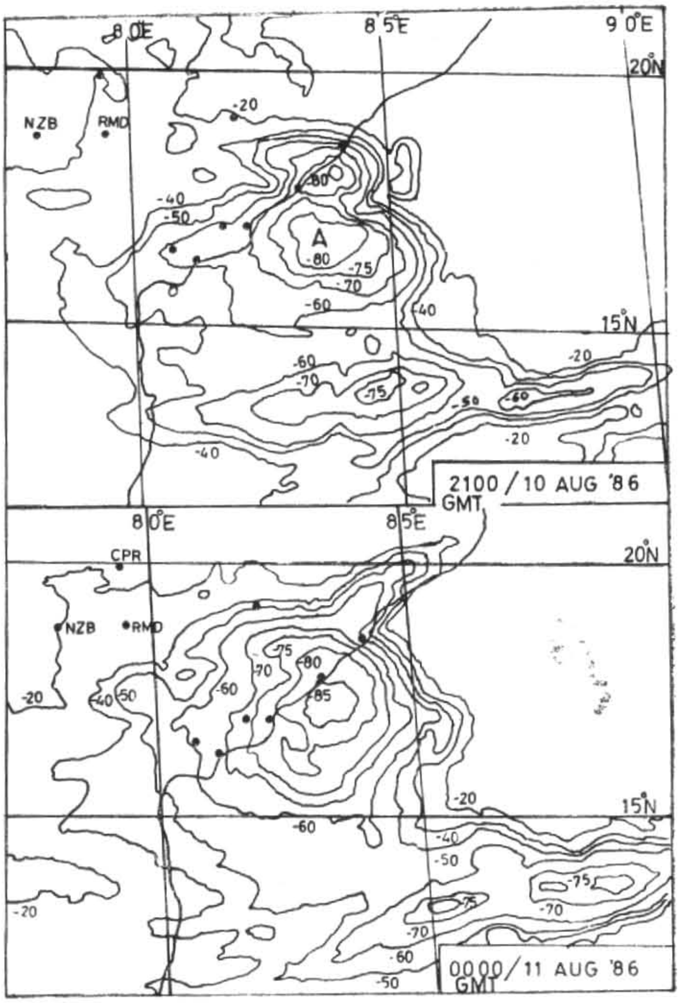

Fig. 4. Cloud top isotherms from INSAT-1B IR data for 10-11 August 1986 showing connective mergers and overshooting tops within mesoscale connective complex

5. Heavy rainfall event of 11 August 1987

5.1. *Data analysis*

On 11-12 August 1987, heavy to very heavy rainfall occurred over east U.P. and Bihar under the influence of an active monsoon trough. The satellite data corresponding to this rainfall event has been used as an independent data set to test the proposed scheme. INSAT-1B IR data for this spell was processed for deriving CTT maps at 3-hourly intervals. Fig. 5 shows four selected CTT maps of this period depicting the salient features described below. Fig. 6 shows locations of all the stations for which the rainfall has been estimated.

On 11 August 1987, an intense mesoscale convective system existed at 03 GMT over east U.P. and neighbourhood. The storm had its core around Jaunpur with the highest cloud tops reaching —75° C. This storm weakened slowly till 09 GMT when another intense convective area started developing around Nainital. During the next 6 hours the two convective storms merged together and the composite cloud system developed further, while moving southeastwards.

At 15 GMT (Fig. 5a), the storm had its core located to the north of Allahabad with the coldest convective tops reaching —80° C. Also, the area covered by —60° C CTT contour exceeded 6 deg^2, thus acquiring the size and shape of an MCC (Maddox 1980). At the same time, another intense convective development started around Ballia. The two storms merged together by 18 GMT resulting in further growth of the MCC. The consequent updraft intensification was seen in the overshooting tops reaching —85° C (Fig. 5b). The MCC developed further and reached its peak at 21 GMT when —85° C CTT contour covered the maximum area (Fig. 5c). At this time —60° C CTT contour covered an area exceeding 25 deg^2. Subsequently, the MCC started weakening although the cloud system continued to show all the characteristics of MCC even after 03 GMT of 12 August'87. The core region of the MCC showed a southeastward/eastward shift before 18 GMT and a southwestward shift thereafter.

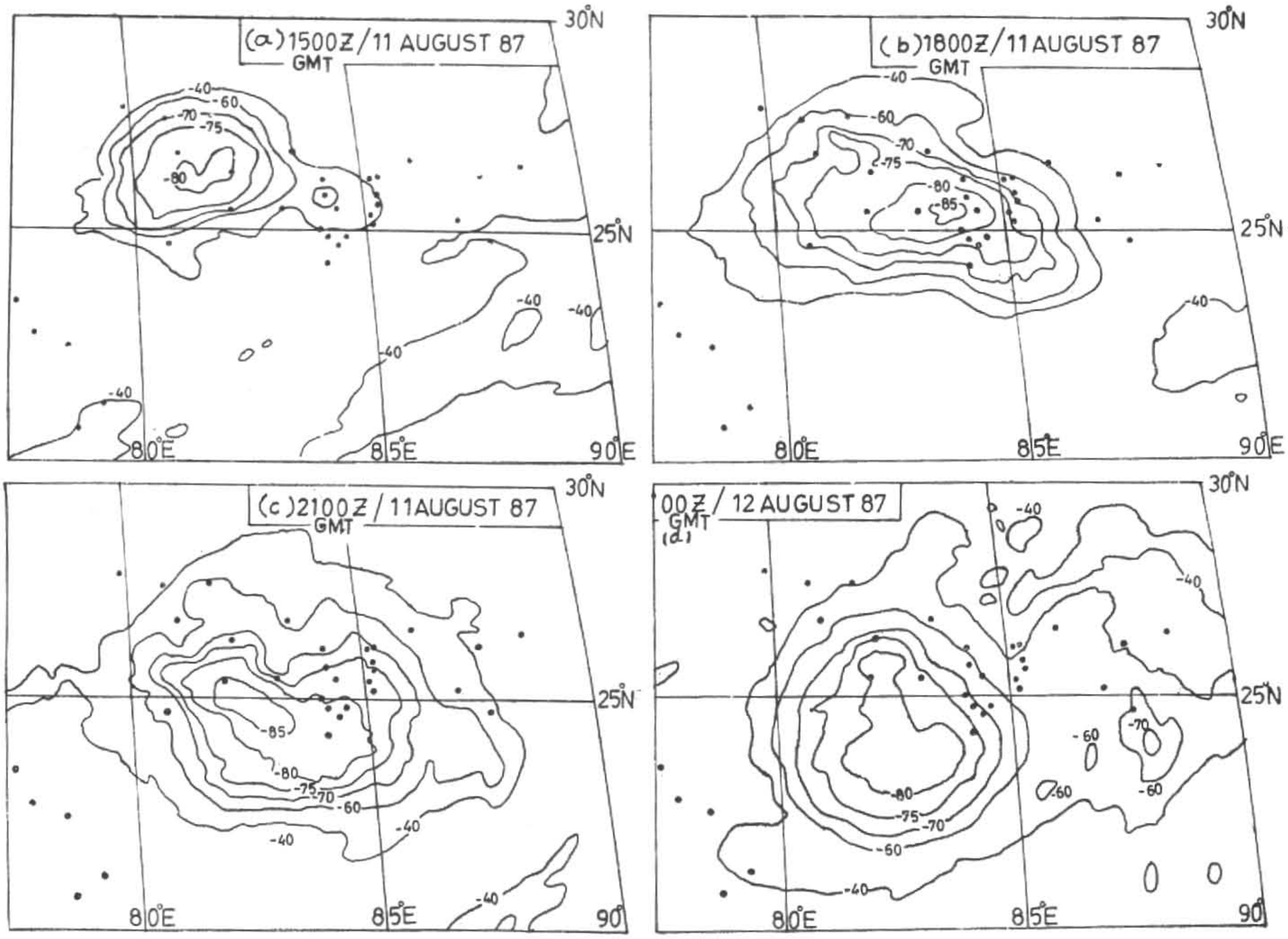

Fig. 5. Cloud top isotherms for 11-12 August 1987 derived from INSAT-1B infrared data showing cold cloud top expansion and merger

5.2. *Discussion of results*

As in the previous case, the growth of the mesoscale convective system, the formation and behaviour of MCC and changes in the core region were the salient features observed in the satellite data and taken into account by the scheme. The rainfall was estimated for 20 stations from CTT maps for 24-hr ending at 03 GMT on 12 August 1987 (Table 2e). The cumulative 24-hr estimates (Col. 10) are compared with the actual rainfall realized (Col. 11) of the table. Out of 20 stations, estimates for 85% lie within an error of ±50%. The percentage deviations of the estimates from actual lie between +111% and —43%. The r.m.s. error of rainfall estimates for this sample is 53.3 mm and mean error is 46.1 mm.

The rainfall estimate for Allahabad is 200 mm while actual realized was 95 mm only — an overestimate of 111%. The data availability at 3-hourly intervals, the period which is very large compared with the time scale of convective activity, appears to have contributed substantially to the error. As an example, at 15 GMT the core of MCC with overshooting tops colder than —80° C was located about 1° latitude north of Allahabad (Fig. 5a). Another core of rapidly growing convection was located about 3° east of the station. The CTT over Allahabad was —70° C. However, by 18 GMT the convective core to the north of the station had dissipated and the core area to its east grew up and expanded towards Allahabad, so that the CTT over Allahabad

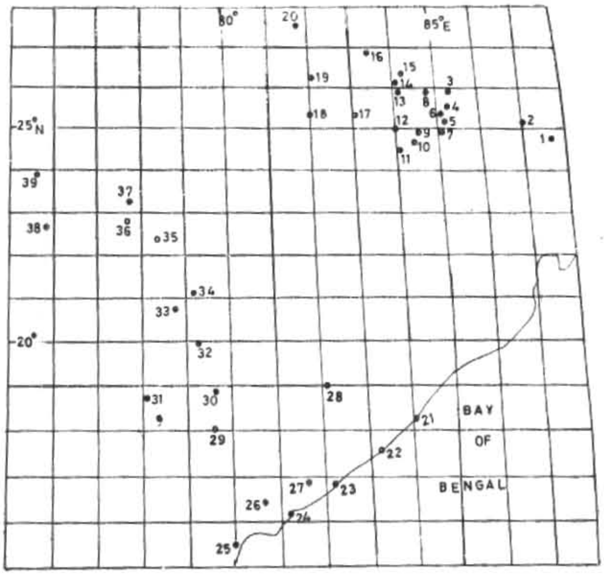

Fig. 6. Location map of raingauge stations. Names of stations indicated by numbers are : (1) Hiranpur, (2) Sabour, (3) Mahuwa, (4) Patna, (5) Islampur, (6) Mahesi, (7) Gaya, (8) Chhapra, (9) Rafiqganj, (10) Aurangabad, (11) Japla, (12) Koilwar, (13) Ballia, (14) Darauli, (15) Hatwa, (16) Gorakhpur, (17) Varanasi, (18) Allahabad, (19) Sultanpur, (20) Behraich, (21) Kalingapatnam, (22) Visakhapatnam, (23) Kakinada, (24) Machilipatnam, (25) Ongole, (26) Vijayawada, (27) Nidadevolu, (28) Jagdalpur, (29) Hanamkonda, (30) Ramagundam, (31) Nizamabad, (32) Chandrapur, (33) Wardha, (34) Nagpur, (35) Panchman, (36) Hoshangabad, (37) Bhopal, (38) Indore and (39) Ujjain

became —79° C. It appears that between 15 and 18 GMT there must have been a period of time when the cloud tops over Allahabad warmed up sufficiently before growing up again. If satellite data were available at 30 minute interval, this could have been shown clearly and could have reflected into a lower rainfall estimate. Further, abrupt changes in the CTT pattern particularly in the core region during 3-hr intervals presented here confirm this view.

This scheme may not apply to cases where the rainfall is predominantly orographic. In such cases heavy rainfall can occur even with relatively warmer cloud tops, so that the scheme would underestimate the rainfall amount. This happened with two stations, Jayanagar and Bahadurganj, situated close to foothills in the northern Bihar. On 11 August 1987 both these stations were located far away from the mesoscale convective system described above and had CTT's lying between —20° and —40°C. As per the scheme, the 24-hr rainfall estimate at 03 GMT of 12th for Jayanagar and Bahadurganj was 40 mm and 35 mm respectively, while the actual rainfall recorded was 155 mm and 140 mm respectively. Scofield (1987) also has pointed to the orographic effect producing extreme rainfall not accounted for by this technique.

6. Conclusion and outlook

The authors have presented a simple scheme for the estimation of heavy convective rainfall over India during the monsoon season, using the available 3-hourly INSAT-1 data. The results of estimation for an independent data set (Sec. 5 and Table 2e) are encouraging This preliminary scheme of rainfall estimation can be applied operationally and further improvements in the technique may be expected to emerge with its progressive use. The authors hope that this satellite product will find an immediate application in flood forecasting during the monsoon season

The examination of rainfall estimates (Secs. 4 and 5) points to a limitation of this scheme that it does not take into account short period convective process occurring on time scales shorter than 3 hours. As a result, many convective developments, mergers and overshooting tops might go unnoticed. The half-hourly satellite data may obviate this difficulty and will, in any case, provide a better accuracy for rainfall estimates. It is hoped that with future expansion of INSAT meteorological data processing facility, half-hourly data will be available round the clock on an operational basis. The rainfall estimation scheme can then be redesigned for this finer temporal input. These and other refinements in the technique in the light of its use will lead to higher accuracies and demands for this product will build-up among meteorologists and hydrologists.

The tracking of cloud features related to mesoscale convective systems in satellite imagery and of features important to their propagation dynamics, have direct applications to the short range forecasting of heavy precipitation. The senior author has used this approach for the qualitative prediction of heavy rainfall over periods of 6-12 hours on an operational basis, since the monsoon season of 1985. The success score of the prediction has been encouraging. The authors expect to cover this subject in a separate paper in future.

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