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Isolated heavy rainfall over Sylhet, Bangladesh and convective instability

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सार – इस शोध पत्र में दक्षिण पश्चिमी मॉनसून ऋतु के दौरान दक्षिणी पवनों से खासी जयंतिया पहाड़ियों के पवनाभिमुख दिशा में स्थित पर्वतीय स्टेशन सिल्हट में हुई भारी वर्षा के दौर से संबंधित तापगतिकी पहलुओं का अध्ययन करने का प्रयास किया गया है। इसके लिए आठ परिस्थितियों का चयन किया गया है और उसका अध्ययन किया गया है जिसमें उन दिनों को शामिल किया गया है जब सिल्हट में इक्के-दुक्के स्थानों पर भारी वर्षा हुई और उसके पूर्ववर्ती तथा परवर्ती दिनों में अपेक्षाकृत कम वर्षा हुई। इन प्रत्येक कालों के लिए जिसमें लगातार बारिश के तीन दिन शामिल हैं, के कन्वेक्टीव एबेलेबल पोटेंशियल एनर्जी (CAPE), कन्वेक्टीव इनहिबिशन एनर्जी (CINE), मॉइस्ट स्टैटिक एनर्जी (MSE), ए नन डायमेन्शनल कायनेटीक पैरामीटर (K), एम एस ई का वर्टिकली वेटेड एवरेज (σ) इत्यादि की गणना उनकी दैनिक भिन्नताओं की जाँच के लिए की गई हैं। यहाँ वर्षा की तीव्रता (FRI) मि. मी. प्रति घंटा में गणना करने के लिए डे एवं दत्ता (2005) द्वारा विकसित संवहनीय वर्षा मॉडल का उपयोग किया गया है जो पूर्णत: संवहन के कारण होता है। इसमें इस प्रकार की आठ परिस्थितियों का अध्ययन किया गया है। इस अध्ययन से यह पता चलता है, कि अधिकांश परिस्थियों में प्रथम दिन की वर्षा से दूसरे दिन की वर्षा में हुई वृद्धि सामान्यतः CAPE तथा पैरामीटर '*K*' में वृद्धि और 'σ' एवं CINE के मान में कमी के अनुरूप हुई है। जबकि तीसरे दिन की वर्षा में कमी सी ए पी ई व पैरामीटर 'के' में कमी तथा सी आई एन ई व σ में हुई वृद्धि के अनुरूप है। अध्ययन से यह भी पता चला है कि उक्त संवहनी वर्षा मॉडल सामान्यत:छ: परिस्थितियों में दैनिक वर्षा के प्रेक्षित उतार चढ़ाव को कम से कम मात्रात्मक रूप से बताने में सक्षम है जबकि शेष दो परिस्थितियों में यह इस प्रकार की अनुरूपता को नहीं दर्शाता है।

ABSTRACT. An attempt has been made to study the thermodynamic aspects associated with spells of heavy rain over a mountainous station Sylhet, located on the windward side of the Khasi-Jayantia hills with respect to southerly wind during the southwest monsoon season. For this purpose, eight cases have been selected and studied, which include, days when isolated heavy rainfall occurred over Sylhet, with preceding and succeeding days reporting comparatively less rainfall. For each of these epochs, consisting of three consecutive days, Convective available potential energy (CAPE), Convective inhibition energy (CINE), Moist static energy (MSE), a non-dimensional kinetic parameter ('*K*'), vertically weighted average value of MSE (σ) etc., have been computed to examine their daily variations. Convective precipitation model, developed by De and Dutta (2005), has been used here to compute rainfall intensity (RFI) in mm/hr, which is solely due to convection. Eight such cases have been studied. It appears from the study that in most of the cases, a rise in rainfall from the first day to second day is generally associated with a corresponding rise in the CAPE and the parameter '*K*', a fall in 'σ' and in CINE. While a fall in rainfall on the third day is associated with a corresponding fall in CAPE and '*K*' and a rise in CINE and 'σ'. The study also shows that the above convective precipitation model, in general, is capable at least qualitatively, in capturing the observed fluctuation of daily rainfall in six cases, whereas the remaining two cases are not in the same conformity.

Key words – Convective instability, Isolated heavy rainfall.

1. Introduction

Sylhet, a mountainous station, located in the north eastern region of Bangladesh. Geologically, the region is complex having diverse sacrificial geomorphology; high topography of Plio-Miocene age such as Khasi and Jaintia hills and small hillocks along the border. At the centre there is a vast low laying flood plain of recent origin with saucer shaped depressions. On many occasions this mountainous station reported heavy rainfall on an isolated day during southwest monsoon season in Bangladesh, which may be attributed to (a) large scale convergence (b) orographic ascent (c) convective instability (d) frontal upgliding etc.

Bonacina (1945) emphasized the importance of convective instability for the generation of intense orographic rain. Mukherjee and Ghosh (1965) suggested a possible role played by the Khasi-Jayantia (KJ) hills in triggering pre-monsoon convective instability over Brahmaputra valley at night. They argued that during night only, when the KJ hills cool down more rapidly than the plane, strong katabatic wind blows down the slope towards the valley, which is being obstructed at least up to 1.5 km at daytime. This in turn brings down southerly/south westerly moist air on the valley, where already easterly/east northeasterly dry air originating from Tibetan plateau prevails. So, a front like structure develops over the valley at night, which causes convective activity to take place at night. Studies by Sarker (1966; 1967) have indicated that in addition to forced orographic ascent, synoptic scale convergence, convective instability may also play very important roles for heavy to very heavy precipitation rate on the windward slope of the Western Ghats. Smith (1979) suggested that heating of the mountain slopes by insolation causes upslope winds leading to thermals above the mountain peak. Grossman & Duran (1984) had attributed the discrepancies between the observed coastal rainfall and the coastal rainfall computed using 2-D dynamical model (Sarker, 1966; 1967) to the frequent shallow and occasional deep convection near the coast. Watnabe and Ogura (1987) pointed out that a mountain range of modest height could trigger the convective instability to enhance rainfall significantly along windward slope.

De & Dutta (2005) have studied the role of convective instability in producing spells of heavy rain at the coastal location on the windward side of the Western Ghats (WG) over the Indian west coast. For that purpose, cases were selected, which include, days when isolated heavy rains occurred at Mumbai (Santacruz), with preceding and succeeding days reporting comparatively less rainfall. Different stability indices were computed on for the days with contrasting rainfall for different cases. Also a simple convective precipitation model was proposed for qualitatively understanding the role of convective instability. Their study showed that a rise in rainfall from the first day to second day is generally associated with a corresponding rise in the positive value of CAPE and the parameter ‘*K*’, a fall in ‘σ’ and a fall in the negative value of CINE. While a fall in rainfall on the third day is associated with a corresponding fall in the positive value of CAPE. The study also showed that the convective precipitation model, in general, is capable, at least qualitatively, of capturing the observed fluctuation in daily rainfall.

Romatschke *et al*. (2010) showed that during monsoon season along nocturnal convective core maxima along the Himalayan foothills are associated with convergence of down slope flow from the Himalayas with moist monsoonal winds at the foothills. Romatschke and Houze Jr. (2011a) analyzed eight years of Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) to examine how convective systems of different types contribute to precipitation of the South Asian monsoon. Their study suggests that along the western Himalayas, precipitation falls mainly from small, but highly convective systems. Farther east along the foothills, systems are more stratiform. These small and medium systems form during the day, as the monsoon flow is forced upslope. Nighttime cooling leads to downslope flow and triggers medium-sized systems at lower elevations. Analyzing above data, Romatschke and Houze Jr. (2011b) showed that in continental regions near the

TABLE 1

Daily rainfall data of Sylhet, Bangladesh for eight different cases

S. No.	Date	24 hour Rainfall (mm)
1.	18 Sep 1996	0.0
	19 Sep 1996	120.0
	20 Sep 1996	6.0
2.	8 Jun 1998	8.0
	9 Jun 1998	201.0
	10 Jun 1998	5.0
3.	4 Aug 2000	43.0
	5 Aug 2000	126.0
	6 Aug 2000	0.0
4.	25 Sep 2000	12.0
	26 Sep 2000	139.0
	27 Sep 2000	9.0
5.	23 Jul 2002	20.0
	24 Jul 2002	108.0
	25 Jul 2002	13.0
6.	2 Aug 2002	12.0
	3 Aug 2002	440.0
	4 Aug 2002	43.0
7.	12 Aug 2000	76.0
	13 Aug 2000	133.0
	14 Aug 2000	37.0
8.	10 Sep 2000	6.0
	11 Sep 2000	161.0
	12 Sep 2000	1.0

Himalayas, medium-sized convective systems are many times triggered at night, as moist upstream flow is lifted over cold downslope flow from the mountains, and reaching maximum development upstream of the central and eastern Himalayas in the early morning hours. Results of Romatschke *et al*. (2010) and Romatschke and Houze Jr. (2011a;b) are in close conformity with the hypothesis made by Mukherjee & Ghosh (1965).

It is observed that quite often station Sylhet on the windward side (with respect to southerly flow in the south-west monsoon season) of the Khasi-Jayantia hills receives heavy rainfall on an isolated day, with comparatively low rainfall or dry weather on preceding and succeeding days. So, in such cases forced orographic lifting alone may not be responsible for such observed heavy rainfall, rather convective instability may play a crucial role in addition with synoptic scale convergence. The station Sylhet, although lie on windward side of KJ hills with respect to the southerly/southwesterly flow during southwest monsoon season, but it is 60 km away from the peak. Although there are studies in different parts of the world, investigating the role of convective instability in producing heavy rainfall, but hardly there are attempts for addressing such problems in Bangladesh.

The objective of the present study is to examine the role of convective instability alone in producing heavy to very heavy rainfall on an isolated day at the said station, preceding and succeeding days with very less rainfall and also to examine the validity of convective rainfall model, proposed by De and Dutta (2005), at least qualitatively, for the present case.

2. Data

Daily rainfall data of Sylhet (24.9° N, 91.9° E) on three consecutive days for the cases under study (Table 1), were collected from Bangladesh Meteorological Department, Dhaka, Bangladesh. Reports on daily synoptic features over Bangladesh on the required dates for selected cases have been collected from Bangladesh Meteorological Department, Dhaka, Bangladesh. The present study requires RS data of Sylhet for the concerned dates. Since RS data for Sylhet is not available, required vertical profiles for temperature, pressure, geopotential height and relative humidity and also the surface pressure, temperature and relative humidity have been generated at the nearest grid point (25° N, 92° E) from ECMWF reanalyzed data.

3. Methodology

Using the generated profiles for temperature, relative humidity, pressure and geo-potential height thermodynamic parameters like CAPE, CINE, K and σ, the vertically weighted averaged Moist Static Energy (MSE) have been computed following De & Dutta (2005),

where, $$K = \frac{|CAPE| - |CINE|}{|CINE|}$$

and

$$\sigma = \frac{\sum_i z_i \, MSE_i}{\sum_i z_i} = \frac{\sum_i z_i \left(C_P \overline{T_i} + g z_i + L q_i\right)}{\sum_i z_i}$$

TABLE 2

Synoptic features for the cases, studied

S. No.	Period	Synoptic feature(s)
1.	17-19 Sep 1996	During this period there was (*i*) an low over southeast Bangladesh which moved in a northerly/north easterly direction into land and weakened on 18th (*ii*) an east-west trough extending from eastern part of India to Assam across north Bangladesh on 19th.
2.	7-9 Jun 1998	During the period there was a low over east Uttar Pradesh, Bihar and adjoining area. From this low an east west trough was extended up to Assam across northern / central Bangladesh.
3.	3-5 Aug 2000	During this period there was no significant synoptic feature was seen however monsoons trough ran from sub-Himalayan West Bengal to Assam across North Bangladesh.
4.	24-26 Sep 2000	During this period there was no significant synoptic feature. Southwest monsoon was week.
5.	22-24 Jul 2002	Throughout the period monsoon trough passed across northern Bangladesh and Southwest Monsoon was active/fairly active over Bangladesh.
6.	30 Jul - 1 Aug 2002	Throughout the period monsoon trough passed across central Bangladesh and Southwest Monsoon was active/fairly active on first two days and was on 3rd day.
7.	11-13 Aug 2000	Throughout the period monsoon trough passed across central/southern Bangladesh and Southwest Monsoon was fairly active over Bangladesh.
8.	9-11 Sep 2000	Throughout the period monsoon trough passed across central/southern Bangladesh and Southwest Monsoon was fairly active over Bangladesh.

TABLE 3

Comparative discussion on different aspects of the results of the cases studied

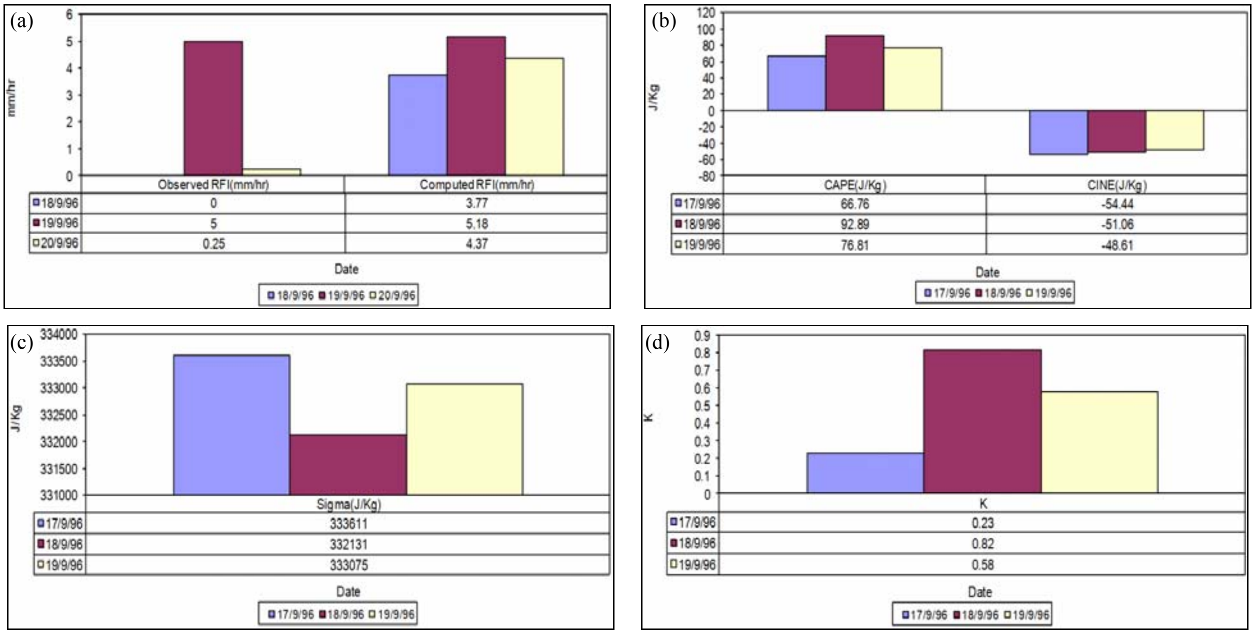
Case	Data used	Parameter	Behaviour	Remark
1.	Vertical profiles of temperature, pressure, geo potential and relative humidity for the dates 17-19 July 1996. Daily rainfall for 18-20 July 1996. Synoptic feature 17-19 July 1996.	Rainfall intensity	From Fig. 1(a), it is clear that the fluctuation in the daily-observed rainfall and that computed are in the same sense.	It appears that, the present convective rainfall model is, at least qualitatively able to capture the fluctuation in the daily-observed rainfall over Sylhet in this particular case.
		CAPE & CINE	Fig. 1(b) shows that an increase in rainfall on the second day of the above spell is associated with a rise in the positive value of CAPE and a fall in the negative value of CINE. It is also seen that the fall in rainfall on the third day of the spell is associated with a fall in CAPE and rise in CINE.	Sudden enhancement of station rainfall on an isolated day may be due to release of enhanced convective instability and fall may be due to a combined effect of enhancement of low level stability and reduction in the release of convective instability.
		σ	Fig. 1(c) shows that a rise in rainfall on the 2nd day is associated with a fall in 'σ'.	Enhanced rainfall may be due to enhanced moist static instability.
		K	Fig. 1(d) shows that the rise in rainfall on the 2nd day is associated with a rise in the value of '*K*' and the fall in rainfall is associated with a fall in the value of '*K*'.	Confirm the combined effect of enhanced convective instability & reduced low level stability in producing enhanced rainfall intensity on an isolated day.
2.	Vertical profiles of temperature, pressure, geo-potential and relative humidity for the dates 7-9 June 1998 Daily rainfall for 8-10 June 1998 Synoptic feature 7-9 June 1998.	Rainfall intensity	Fig. 2(a) shows that the fluctuation in the daily-observed rainfall and that computed are in the same sense.	It appears that, in this case also, the present convective rainfall model is, at least qualitatively able to capture the fluctuation in the daily-observed rainfall over Sylhet.
		CAPE & CINE	Fig. 2(b) shows that an increase in rainfall on the second day of the above spell is associated with a rise in the positive value of CAPE and a fall in the negative value of CINE. It is also seen that the fall in rainfall on the third day of the spell is associated with a fall in CAPE and rise in CINE.	Sudden enhancement of station rainfall on an isolated day may be due to a combined effect of release of enhanced convective instability & reduction in low level stability. Similarly fall may be due to a combined effect of enhancement of low level stability and reduction in the release of convective instability.
		σ	Fig. 2(c) shows that a rise in rainfall on the 2nd day is associated with a fall in σ.	Enhanced rainfall may be due to enhanced moist static instability.
		K	Fig. 2(d) shows that the rise in rainfall on the 2nd day is associated with a rise in the value of '*K*' and the fall in rainfall is associated with a fall in the value of '*K*'.	Confirm the combined effect of enhanced convective instability & reduced low level stability in producing enhanced rainfall Intensity on an isolated day.
3.	Vertical profiles of temperature, pressure, geopotential and relative humidity for the dates 3-5 August 2000 Daily rainfall for 4-6 August 2000 Synoptic feature 3-5 August 2000.	Rainfall intensity	Fig. 3(a) shows that the fluctuation in the daily-observed rainfall and that computed are in the same sense.	It appears that, the present convective rainfall model is, at least qualitatively able to capture the fluctuation in the daily-observed rainfall over Sylhet, in this case also.
		CAPE & CINE	Fig. 3(b) shows that an increase in rainfall on the second day of the above spell is associated with a rise in the positive value of CAPE and a fall in the negative value of CINE. It is also seen that the fall in rainfall on the third day of the spell is associated with a fall in CAPE and rise in CINE.	Sudden enhancement of station rainfall on an isolated day may be due to a combined effect of release of enhanced convective instability & reduction in low level stability. Similarly fall may be due to a combined effect of enhancement of low level stability and reduction in the release of convective instability.
		σ	Fig. 3(d) shows that a rise in rainfall on the 2nd day is associated with a fall in σ.	Enhanced rainfall may be due to enhanced moist static instability in the atmosphere.
		K	Fig. 3(c) shows that the rise in rainfall on the 2nd day is associated with a rise in the value of '*K*' and the fall in rainfall is associated with a fall in the value of '*K*'.	Confirm the combined effect of enhanced convective instability & reduced low level stability in producing enhanced rainfall intensity on an isolated day.

TABLE 3 (*Contd.*)

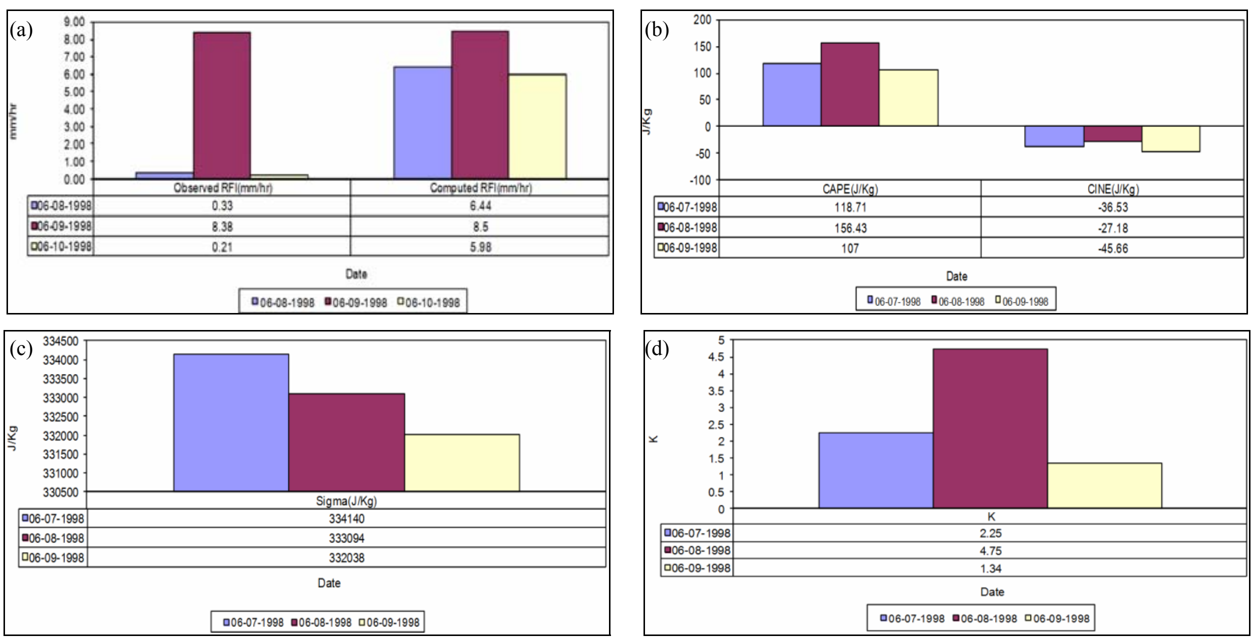
Case	Data used	Parameter	Behaviour	Remark
4.	Vertical profiles of Temperature, pressure, geo-potential and relative humidity for the dates 24-26 September 2000. Daily rainfall over Sylhet during 25-27 September 2000. Synoptic features for the period 24-26 September 2000.	Rainfall intensity	The daily variation of observed and the computed rainfall intensities are shown in Fig. 4(a).	Like other three cases, in this case also, it appears that, the present convective rainfall model is, at least qualitatively able to capture the fluctuation in the daily-observed rainfall over Sylhet.
		CAPE & CINE	The daily variations of CAPE and CINE on these three days are shown in Fig. 4(b). It shows that an increase in rainfall on the second day of the above spell is associated with a rise in the positive value of CAPE and a fall in the negative value of CINE. It is also seen that the fall in rainfall on the third day of the spell is associated with a fall in CAPE and rise in CINE.	Sudden enhancement of station rainfall on an isolated day appears to be due to a combined effect of release of enhanced convective instability & reduction in low level stability. Similarly fall may be due to a combined effect of enhancement of low level stability and reduction in the release of convective instability.
		σ	The daily variation of 'σ' for the period 24-26 September 2000 is shown in Fig. 4(c). It shows that a rise in rainfall on the 2nd day is associated with a fall in σ.	Result suggests that an enhancement in daily rainfall may be due to enhanced moist static instability in the atmosphere.
		K	Fig. 4(d) shows the daily variation of the parameter '*K*' for the period 24-26 September 2000. It shows that the rise in rainfall on the 2nd day is associated with a rise in the value of '*K*' and the fall in rainfall is associated with a fall in the value of '*K*'.	The result Confirms the combined effect of enhanced convective instability & reduced low level stability in producing enhanced rainfall intensity on an isolated day.
5.	Vertical profiles of temperature, pressure, geopotential and relative humidity for the dates 3-5 August 2000 Daily rainfall for 4-6 August 2000 Synoptic feature 3-5 August 2000.	Rainfall intensity	The daily variation of observed and the computed rainfall intensities are shown in Fig. 5(a), which suggests that the fluctuation in the daily-observed rainfall and that computed are in the same sense and can be well compared.	The result suggests that, the present convective rainfall model is, at least qualitatively able to capture the fluctuation in the daily-observed rainfall over Sylhet in this case also.
		CAPE & CINE	The daily variations of CAPE and CINE on these three days are shown in Fig. 5(b), which shows that an increase in rainfall on the second day of the above spell is associated with a rise in the positive value of CAPE and a fall in the negative value of CINE. It is also seen that the fall in rainfall on the third day of the spell is associated with a fall in CAPE and rise in CINE.	In this case also, the result suggests that a sudden enhancement of station rainfall on an isolated day appears to be due to a combined effect of release of enhanced convective instability & reduction in low level stability. Similarly fall may be due to a combined effect of enhancement of low level stability and reduction in the release of convective instability
		σ	The daily variation of 'σ' for the period 22-24 July 2002 is shown in Fig. 5(c). It shows that a rise in rainfall on the 2nd day is associated with a fall in σ.	Enhancement in daily rainfall may be due to enhanced moist static instability in the atmosphere.
		K	Fig. 5(d) shows the daily variation of the parameter '*K*'for the period 22-24 July 2002. It shows that the rise in rainfall on the 2nd day is associated with a rise in the value of '*K*' and the fall in rainfall is associated with a fall in the value of '*K*'.	The result Confirms the combined effect of enhanced convective instability & reduced low level stability in producing enhanced rainfall intensity on an isolated day.
6.	Vertical profiles of Temperature, pressure, geo-potential and relative humidity for the period 30 July-1 August 2002 Daily rainfall over Sylhet during 31 July - 2 August 2002.	Rainfall intensity	Fig. 6(a) shows the daily variation of observed and the computed rainfall intensities, which suggests that, in this case also, the fluctuation in the daily-observed rainfall and that computed are in the same sense	Results of this case also confirms that the present convective rainfall model is, at least qualitatively capable to capture the fluctuation in the daily-observed rainfall over Sylhet.
		CAPE & CINE	Fig. 6(b) exhibits the daily variations of CAPE and CINE on these three days , which suggests that an increase in rainfall on the second day of the above spell appears to be associated with a rise in the positive value of CAPE. It is also seen that the fall in rainfall on the third day of the spell is associated with a fall in CAPE and rise in CINE.	Sudden enhancement of station rainfall on an isolated day appears to be due to a combined effect of release of enhanced convective instability & reduction in low level stability. Similarly fall appears to be a combined effect of enhancement of low level stability and reduction in the release of convective instability.

TABLE 3 (*Contd.*)

Case	Data used	Parameter	Behaviour	Remark
	Synoptic features for the period 30 July-1 August 2002.	σ	The daily variation of 'σ' for the period 30 July-1 August 2002 is shown in Fig. 6(c). It shows that a rise in rainfall on the 2nd day is associated with a fall in σ.	Enhancement in daily rainfall may be due to enhanced moist static instability in the atmosphere.
		K	Fig. 6(d) shows the daily variation of the parameter '*K*' for the period 30 July-1 August 2002. It shows that the rise in rainfall on the 2^{nd} day is associated with a rise in the value of '*K*' and the fall in rainfall is associated with a fall in the value of '*K*'.	The result Confirms the combined effect of enhanced convective instability & reduced low level stability in producing enhanced rainfall intensity on an isolated day.
7.	Vertical profiles of temperature, pressure, geo-potential and relative humidity for the dates 11-13 August 2000. Daily rainfall (mm) over Sylhet during 12-14 August 2000. Synoptic features for the period 11-13 August 2000.	Rainfall intensity	The daily variation of observed and the computed rainfall intensities are shown in Fig. 7(a) which shows that the fluctuation in the daily-observed rainfall and that computed are not at all in the same sense.	In this case the convective rainfall model has failed to capture, even qualitatively, the fluctuation in the observed rainfall intensity over Sylhet.
		CAPE & CINE	The daily variations of CAPE and CINE on these three days are shown in Fig. 7(b). It shows that unlike to first six cases, in this case increase in rainfall on the second day of the above spell is not associated with a rise in the positive value of CAPE or a fall in the negative value of CINE, rather associated with a fall in CAPE and rise in CINE. It is also seen that the fall in rainfall on the third day of the spell is associated with a fall in CAPE and rise in CINE.	In this case convective instability appears to play hardly any role in the observed fluctuation in daily rainfall, rather may be due to some other forcing like orographic ascent, large scale forcing or frontal up gliding.
		σ	The daily variation of 'σ' for the period 11-13 August 2000 is shown in Fig. 7(c). Unlike last six cases, in this case a rise in rainfall on the 2nd day is not associated with a fall in σ, rather with an increase in σ	Result suggests that moist static instability in the atmosphere had very little role in the observed enhancement in daily rainfall.
		K	Fig. 7(d) shows the daily variation of the parameter '*K*' for the period 11-13 August 2000. Unlike first six cases, in this case the rise in rainfall on the 2nd day is not associated with a rise in the value of '*K*', rather with a fall in '*K*'. But the fall in rainfall on third day is associated with a fall in the value of '*K*'.	Result suggests that release of convective instability and reduced low level stability had hardly any influence on the observed fluctuation in daily rainfall over Sylhet.
8.	Vertical profiles of Temperature, pressure, geo potential and relative humidity for the dates 9-11 September 2000. Daily rainfall (mm) over Sylhet during 10-12 September 2000. Synoptic features for the period 9-11 September 2000.	Rainfall intensity	The daily variation of observed and the computed rainfall intensities are shown in Fig. 8(a), which shows that similar to case-7, in this case also the fluctuation in the daily-observed rainfall and that computed are not at all in the same sense.	The proposed convective rainfall model has failed in this case to capture, even qualitatively, the fluctuation in the observed rainfall intensity over Sylhet.
		CAPE & CINE	The daily variations of CAPE and CINE on these three days are shown in Fig. 8(b). Similar to case-7, in this also it can be seen that increase in rainfall on second day is associated with fall in CAPE and rise in CINE.	Similar to case 7, in this case also convective instability appears to have played any significant role in the observed fluctuation in daily rainfall.
		σ	The daily variation of 'σ' for the period 9-11 September 2000 is shown in Fig. 8(c). It shows that a rise in rainfall on the 2^{nd} day is associated with a fall in σ.	Moist static instability, in this case, appears to have played any significant role in the observed enhancement in daily rainfall on 2nd day.
		K	Fig. 8(d) shows the daily variation of the parameter '*K*' for the period 9-11 September 2000. Similar to case-7, in this case also it can be seen that increase in rainfall on second day is associated with fall in the value of '*K*' and the fall in rainfall is associated with a rise in the value of '*K*'.	Combined effect of release of atmospheric convective instability and reduced low level stability appears to have played any significant role in the observed fluctuation in daily rainfall at Sylhet.



Figs. 1(a-d). Daily variation of (a) observed and computed RFI (mm/hr) during 18-20 September, 1996, (b) CAPE and CINE (J/kg) during 17-19 September, 1996, (c) Sigma (J/kg) during 17-19 September, 1996 and (d) '*K*' during 17-19 September, 1996



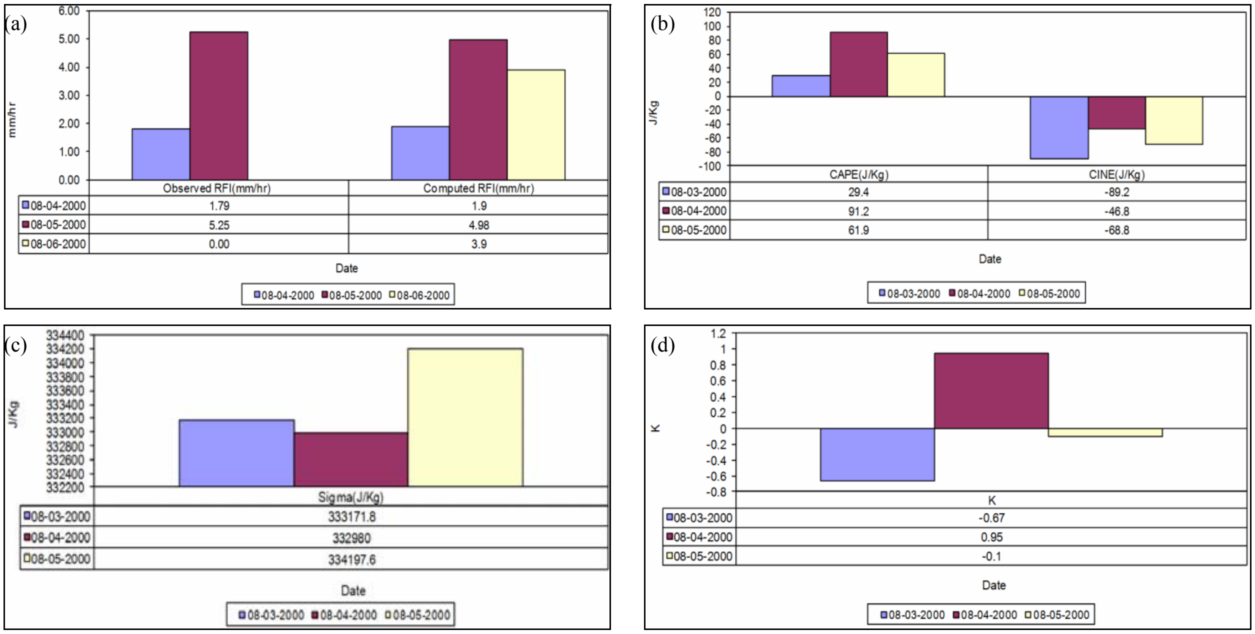
Figs. 2(a-d). Daily variation of (a) observed and computed RFI (mm/hr) during 8-10 June, 1998, (b) CAPE and CINE (J/kg) during 7-9 June, 1998, (c) Sigma (J/kg) during 7-9 June, 1998 and (d) '*K*' during 7-9 June, 1998

Then following De and Dutta (2005) convective updraft at different levels have been computed on individual days for different cases. Afterwards following Sarker (1966; 1967) the convective rainfall intensity (mm/hr) has been computed using this convective updraft, the density (ρ) and saturation-mixing ratio (q) of the air parcel.

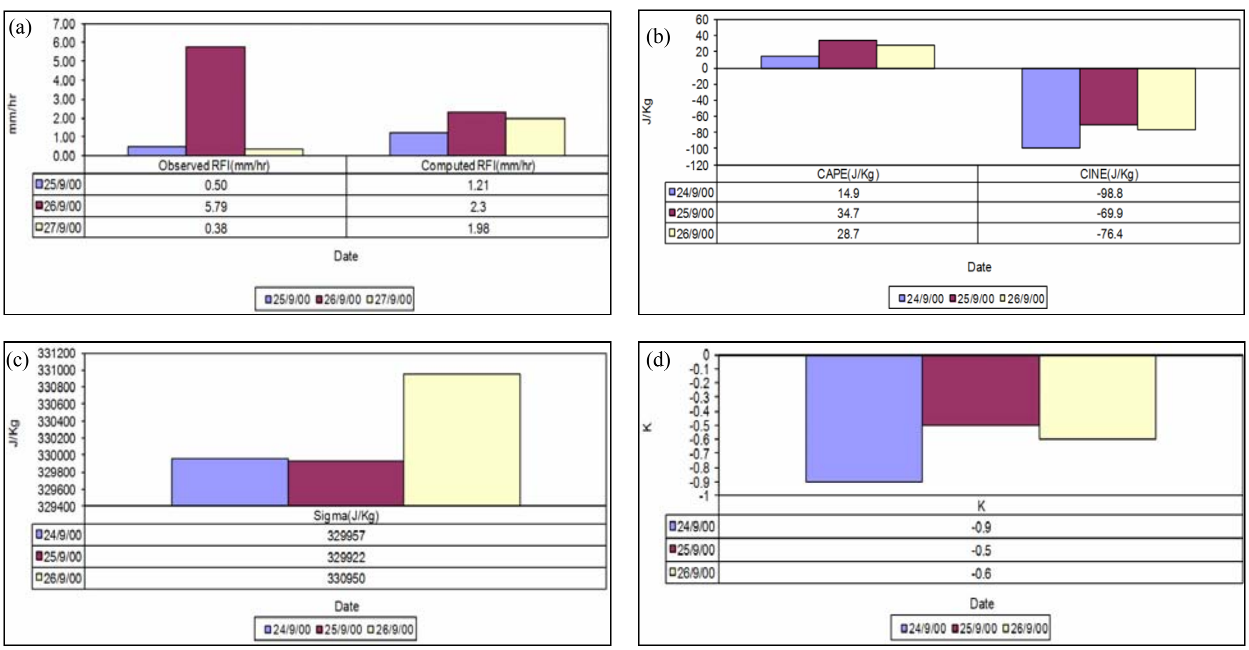
4. Results and discussion

4.1. *Results on thermodynamic and synoptic features*

In the present study, three cases have been selected, in each of which, the station Sylhet in Bangladesh,



Figs. 3(a-d). Daily variation of (a) observed and computed RFI (mm/hr) during 4-6 August, 2000, (b) CAPE and CINE (J/kg) during 3-5 August, 2000, (c) Sigma (J/kg) during 3-5 August, 2000 and (d) '*K*' during 3-5 August, 2000

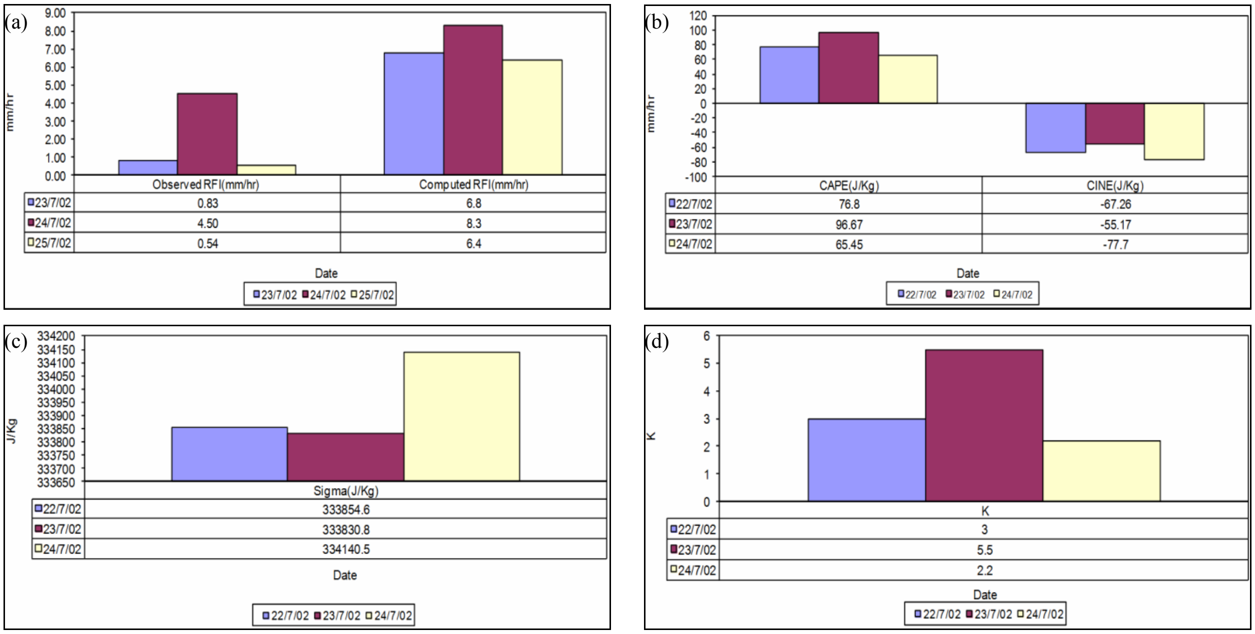


Figs. 4(a-d). Daily variation of (a) observed and computed RFI (mm/hr) during 25-27 September, 2000, (b) CAPE and CINE (J/kg) during 24-26 September, 2000, (c) Sigma (J/kg) during 24-26 September, 2000 and (d) '*K*' during 24-26 September, 2000

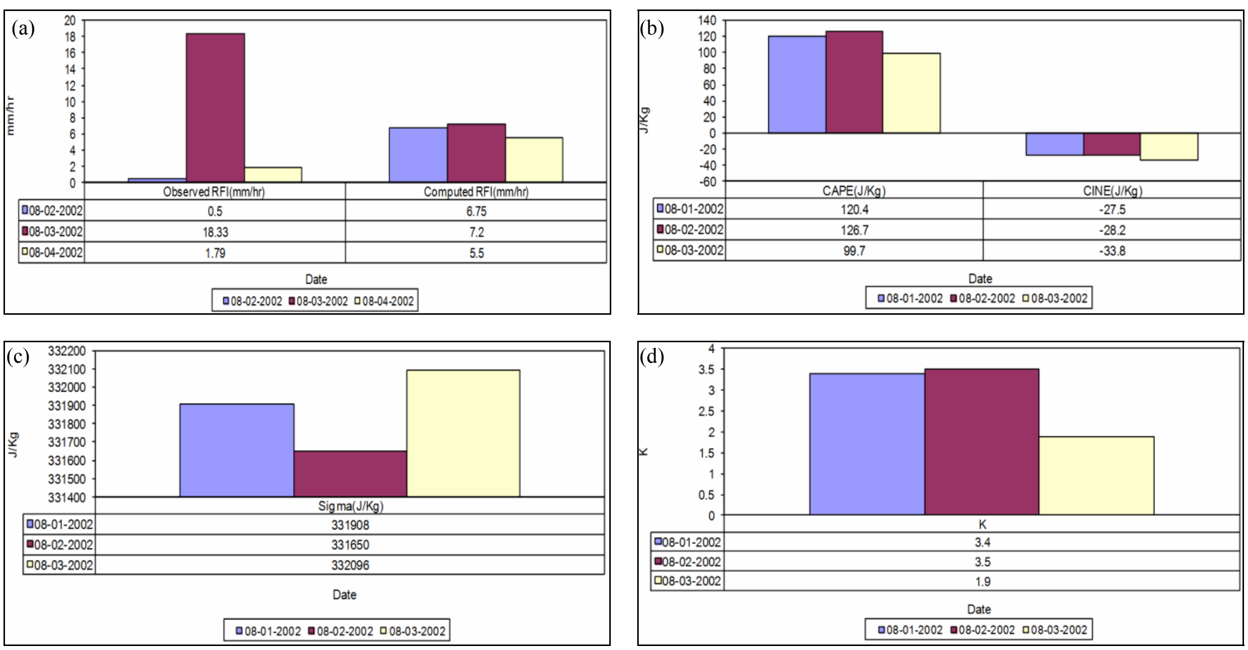
reported isolated heavy rainfall on a day followed and preceded by days with significantly lesser amount of rainfall.

For each case, the synoptic features for identifying large scale forcing on three days of the spell has been studied and given in Table 2. From this table it becomes apparent that, in any of the cases studied, synoptic features did not vary significantly to account for such sudden fluctuation in daily observed rainfall over Sylhet during consecutive three days of rainfall.

A Comparative discussion on different thermo-dynamic aspects of the results of the cases studied is



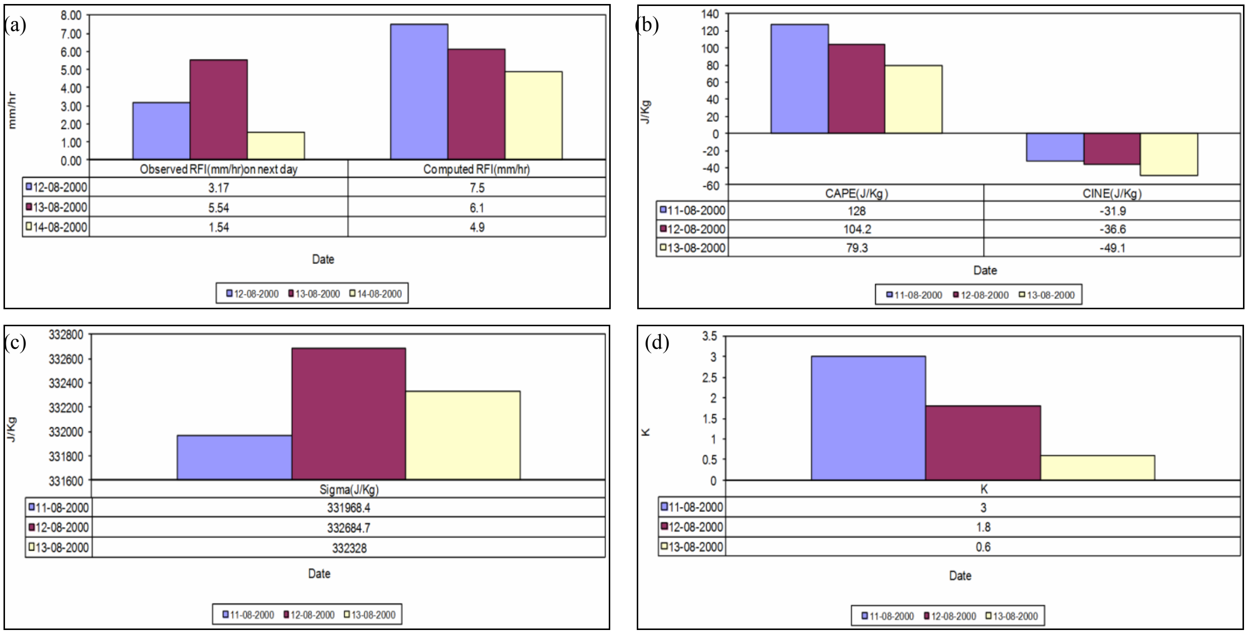
Figs. 5(a-d). Daily variation of (a) observed and computed RFI (mm/hr) during 23-25 July, 2002, (b) CAPE and CINE (J/kg) during 22-24 July, 2002, (c) Sigma (J/kg) during 22-24 July, 2002 and (d) '*K*' during 22-24 July, 2002



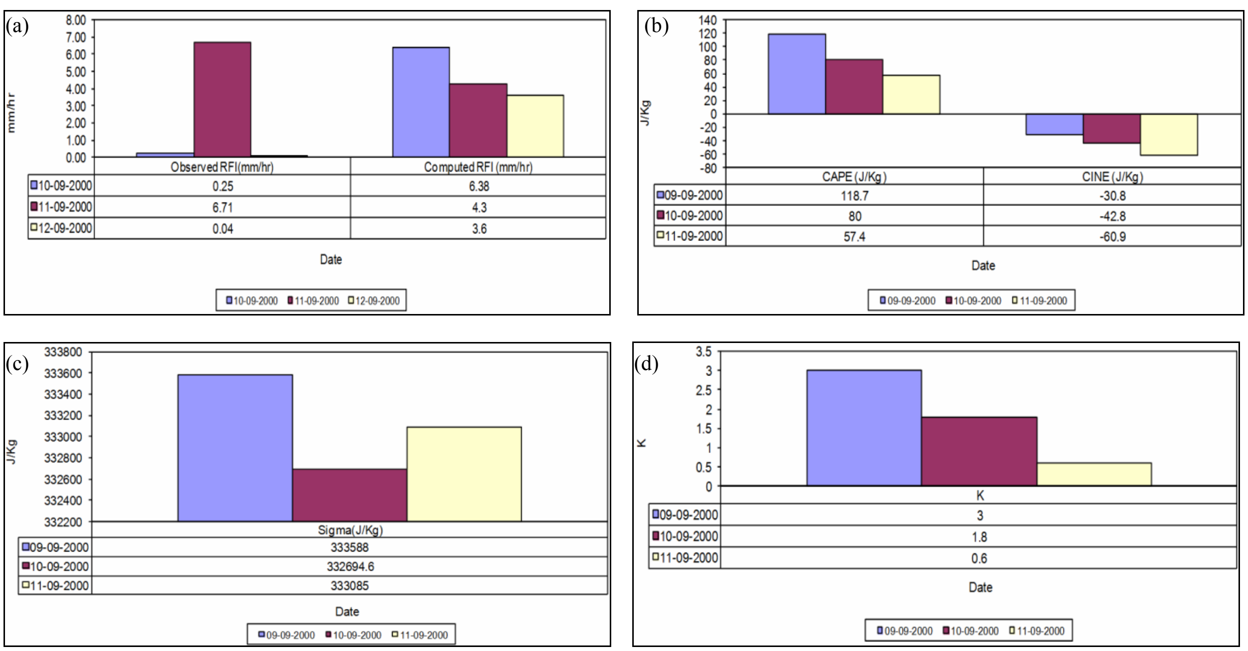
Figs. 6(a-d). Daily variation of (a) observed and computed RFI (mm/hr) during 2-4 August, 2002, (b) CAPE and CINE (J/kg) during 1-3 August, 2002, (c) Sigma (J/kg) during 1-3 August, 2002 and (d) '*K*' during 1-3 August, 2002

given Table 3. To study different thermodynamic aspects of sudden fluctuation in daily observed rainfall, we have used vertical profiles of temperature, pressure, geo-potential and relative humidity, constructed, using daily upper air RS data at the grid point (25° N, 92° E), nearest to the station Sylhet, from ECMWF reanalyzed data for the relevant consecutive three days as shown in Table 3.

From Table 3, it can be seen that out of eight cases, in first six cases, the fluctuation in the daily-observed rainfall and that computed are in the same sense, suggesting that in these six cases, the proposed convective rainfall model is, at least qualitatively able to capture the fluctuation in the daily-observed rainfall over Sylhet.



Figs. 7(a-d). Daily variation of (a) observed and computed RFI (mm/hr) during 12-14 August, 2000, (b) CAPE and CINE (J/kg) during 11-13 August, 2000, (c) Sigma (J/kg) during 11-13 August, 2000 and (d) '*K*' during 11-13 August, 2000



Figs. 8(a-d). Daily variation of (a) observed and computed RFI (mm/hr) during 10-12 September, 2000, (b) CAPE and CINE (J/kg) during 9-11 September, 2000, (c) Sigma (J/kg) during 9-11 September, 2000 and (d) '*K*' during 9-11 September, 2000

However, in the last two cases the computed daily rainfall intensity did not match with observed one, suggesting the proposed convective rainfall model has failed, even in capturing qualitatively the fluctuation of observed daily rainfall on consecutive three days.

The Table 3 indicates that in first six out of selected eight cases, an observed increase in rainfall on the second day of the spell of three consecutive days is associated with a rise in the positive value of CAPE and a fall in the negative value of CINE. It is also seen that the fall in

TABLE 4

Comparison of the vertical velocities obtained from different studies

S. No.	Study	System	Order of computed vertical velocity
1.	Rao and Rajamani (1975) using diagnostic omega equation.	Synoptic scale systems like Monsoon depression.	0.1-4cm/sec with maximum reaching to 5cm/sec between 850 and 700 hPa.
2.	Mukherjee *et al*. (1977) using simple parcel method: Without entrainment effect (I) With entrainment effect (II)	Thunder storms over Mumbai during pre-monsoon season.	(I) 47.5 m/sec (II) 28.6 m/sec
3.	Mukherjee and Choudhury (1979) using parcel method.	Excessive overshooting of cumulonimbus over Calcutta during pre-monsoon season.	88.6 m/sec
4.	Sinha ray *et al*. (1982) using 2-D orographic rainfall model.	Orographic rainfall during southwest monsoon season.	20-30 cm/sec reaching to maximum value 50-60 cm/sec below 850 hPa.
5.	Mukherjee *et al*. (1984) using continuity equation in p-co-ordinate.	Off shore vortex over east Arabian sea during southwest Monsoon season.	Maximum value 2.6 cm/sec at 5 km level.
6.	De and Dutta (2005) using simple parcel method without entrainment effect.	Isolated heavy to very heavy rainfall (Daily).	40-60 m/sec during heavy rain spells.
7.	Present study similar to De and Dutta (2005).	Isolated heavy to very heavy rainfall (Daily).	15-20 m/sec during heavy spells.

rainfall on the third day of the spell is associated with a fall in CAPE and rise in CINE. This results suggest that in these six cases, observed sudden enhancement of station rainfall on an isolated day may be due to release of enhanced convective instability and fall may be due to a combined effect of enhancement of low level stability and reduction in the release of convective instability. However, it can be seen from the same table that in remaining last two cases, such variation in CAPE or CINE was not there, suggesting that in these cases, convective instability might have hardly any significant influence on the observed fluctuation in daily rainfall in the spell of three consecutive days. Similar result follows for the parameter '*K*' also.

From Table 3, one can find that in first six out of eight selected cases, a rise in rainfall on the 2nd day of the spell of three consecutive days, is associated with a fall in 'σ', suggesting a significant role of atmospheric moist static instability in the enhancement of observed rainfall. However, this result doesn't hold good for remaining last two cases.

4.2. *Comparison of the convective updraft*

The computed convective updraft has been compared with the typical vertical velocities computed by earlier investigators during different seasons in India and are shown in Table 4.

In the Table 4, values of vertical velocities have been reported, which were due to large-scale convergence or forced orographic lifting or due to thermal buoyancy effect. It is clearly seen that computed vertical velocity, due to buoyancy only, is always much more than that due to dynamical method or large-scale convergence. It is also observed from the present study that the computed updraft, which is of course due to buoyancy only, is much lesser than that computed in earlier studies. It is known that convective updraft increases from LFC and attains its maximum value at LNB. It has been observed from the cases studied that in all the cases although LFC is at a lower elevation (between 900 hPa and 850 hPa), the LNB is also at a very lower elevation (between 750 hpa and 700 hPa). This may possibly a reason for the lesser values of maximum updraft in the present study.

5. Conclusions

Important conclusions of the study are:

(*i*) In most of the cases, the synoptic features did not vary significantly and therefore cannot be accounted for a sudden sharp change in daily rainfall during given spell of three consecutive days.

(*ii*) In most of the cases, a sharp change in rainfall from a comparatively low rainfall to a comparatively very high rainfall is associated with a rise in the positive value of

CAPE and a fall in the negative value of CINE. Likewise a fall in observed rainfall is associated with a fall in CAPE and rise in CINE.

(*iii*) A sudden rise in rainfall is associated with a fall in the weighted average value of MSE (σ).

(*iv*) In general, a sudden rise in rainfall on 2nd day is associated with a rise in the value of the non-dimensional kinetic parameter (‘K’).

(*v*) The convective rainfall model, in general, captures at least qualitatively, the fluctuations in the daily-observed rainfall intensities in an epoch of three consecutive days.

(*vi*) The study reveals that, in the KJ hills region sudden variation of rainfall away from the peak could be due to a favorable interaction between orographic forcing and convective instability.

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