MAUSAM, **59**, 1 (January 2008), 1-14

551.515.4 : 551.509.313

Simulation of mesoscale structure of thunderstorm using ARPS Model

KULDEEP SRIVASTAVA, S. K. ROY BHOWMIK, H. R. HATWAR,

ANANDA K. DAS and AWADHESH KUMAR

India Meteorological Department, New Delhi – 110 003, India

(*Received 6 May 2006, Modified 19 March 2007*)

e mail : kuldeep.nhac@gmail.com

सार – इस षोध पत्र में ए. आर. पी. एस. (उन्नत क्षेत्रीय पूर्वानुमान प्रणाली) निदर्ष का उपयोग करते हुए दिल्ली में गर्ज के साथ तूफान की दो घटनाओं का मेसोस्केल पर संरचनाओं का अनुकरण किया गया है। दिल्ली में रेडियोसौन्दे आंकड़ो का उपयोग करते हुए तथा संवहनी गतिविधि का पता लगाने के लिए संभाव्य तापमान विचलन का प्रयोग करते हुए संख्यात्मक परीक्षण किए गए। अनुकरण प्रयोग से गर्ज के साथ तूफान के गुटों से संबद्ध प्रबल उर्ध्ववाहों और अपवाहों का पता चला है जिससे बहुत ही प्रबल स्थानीकृत संवहन की विद्यमानता का पता चलता है। इस अनुकरणीय अध्ययन में गर्ज के साथ तूफान के विकास और मूल्यांकन तथा संबद्ध वर्षा के क्षेत्र के प्रसारण का स्पष्ट रूप से उल्लेख किया गया है।

ABSTRACT. In this paper mesoscale structures of two thunderstorm events over Delhi have been simulated using ARPS (Advanced Regional Prediction System) model. Numerical experiments were carried out using radiosonde data of Delhi and applying a potential temperature perturbation for triggering convective activity. The simulation exercise demonstrates strong updrafts and downdrafts associated with the thunderstorm cells, indicating the presence of very strong localized convection. The development and evolution of thunderstorm and propagation of associated precipitation zone are clearly brought out in this simulation study.

Key words – Thunderstorm, Up drafts and down drafts, ARPS model.

1. Introduction

Thunderstorm is one of the most spectacular and hazardous weather phenomena in the atmosphere. Indian region experiences thunderstorms at higher frequency throughout the year except during the winter months. The annual frequency of thunderstorm days is highest over northeastern parts of country followed by southern peninsula and northern parts of country. Lowest frequency of occurrence is over western parts of country. In the monsoon months the thunderstorm activity is generally along and over the area north of mean position of the monsoon trough zone. Thunderstorm is a mesoscale phenomenon having a time scale of a few hours and spatial scale of few kilometers and as such conventional network of synoptic observations is not adequate to provide an accurate picture of occurrence of this phenomenon. Thunderstorms cause loss of property and lives because of lightning, thunder, heavy rain, flash flood, strong and gusty winds associated with them. There are also some benefits from thunderstorms. These convective cells transports sensible heat and latent heat from surface to upper troposphere, release convective instability, help nitrogen fixation in the atmosphere etc. Hence timely and location specific prediction of occurrence of thunderstorms is very important. The conventional forecasting tool available with forecaster to predict thunderstorm is the use of various instability indices such as Showalter's stability index (Showalter, 1953); Galway's lifted index (Galway, 1956); George's K index (George, 1960) etc. These indices had been used by many researchers for forecasting thunderstorm over Indian stations but the degree of success varied in each case (Jeevananda Reddy & Prakash Rao, 1977; Suresh 1996; Mukhopadhyay *et al*., 2003, Sivaramakrishnan & Ramakrishnan, 1995, etc.)

To explain thunderstorm we mainly use two instabilities CAPE & CINE. CAPE (Convective Available Potential Energy) is the amount of energy available for upward acceleration of a particular parcel. CAPE is defined only for parcels that are positively buoyant some where in the vertical profile. CAPE is the amount of Convective Available Potential Energy of a parcel lifted from Level of Free Convection (LFC) to Level of Neutral Buoyancy (LNB). Physically CAPE is the maximum amount of potential energy, possessed solely due to convection, convertible to vertical kinetic energy. In *T*-Φ gram, it represents positive area.

It is found that CAPE is good indicator of stability of the atmosphere. The following table gives those thresh hold values (Sen, 2005).

CAPE below 0 (J/kg)	*Stable*
CAPE = 0 to 1000 (J/kg)	Marginally Unstable
CAPE = 1000 to 2500 (J/kg)	Moderately Unstable
CAPE = 2500 to 3500 (J/kg)	Very Unstable
CAPE above 3500 to 4000 (J/kg)	Extremely Unstable

CINE (Convection Inhibition Energy) is analogous to CAPE. Physically CINE may be interpreted as the amount of energy that must be supplied to an air parcel up to LFC following pseudo adiabat through the surface wet bulb temperature (to overcome resistance inhibiting convection) owing to low level stability of the atmosphere. It refers to a negative area on the thermodynamic diagram.

In the recent time, a significant progress has been noticed in the field of Numerical Weather Prediction (NWP). Various regional models have come up with the capability of predicting synoptic scale systems, but these models generally fail to capture mesoscale weather events due to poor resolution, error in the treatment of different physical process and lack of high density observations which go as input to the models. In order to deal with the mesoscale weather events, recently various non-hydrostatic mesoscale models (such as MM5, RAMS, ARPS, etc.) are developed by various institutes. The main specialty of RAMS and ARPS model is that these models can be run for a particular station by using radiosonde data for that station and artificial triggering mechanism. To deal exclusively with the mesoscale systems like thunderstorms, a nonhydrostatic model known as Advanced Regional Prediction System (ARPS) was developed by Center for Analysis and Prediction of Storms (CAPS) at Oklahoma University, U.S.A. The ARPS Model includes inbuilt package for data ingest, quality control and objective analysis. Also radar data, satellite data and surface data can be ingested in the model. Since this model can be run for a particular station by using radiosonde data for that station and artificial triggering mechanism, so this model is very useful to predict local thunderstorm events. In this paper the

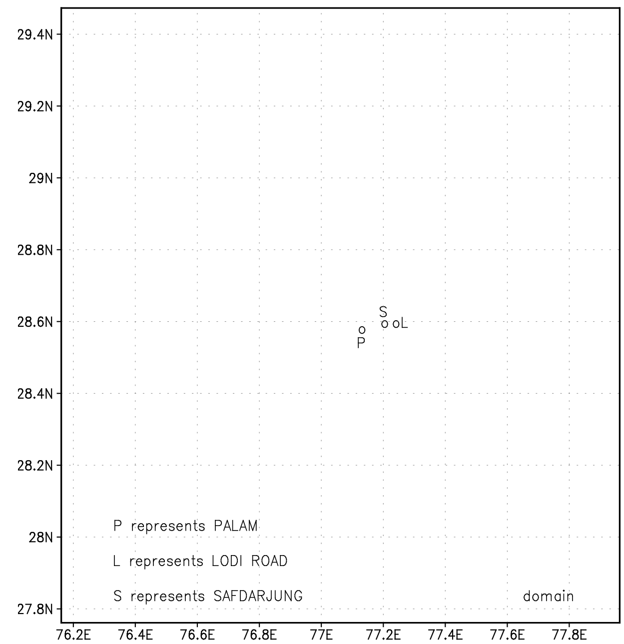


Fig. 1. Model domain

capability of the ARPS model has been demonstrated for simulation of two thunderstorm events, which occurred over Delhi on 4 August and 9 September 2005. Detailed descriptions of the model is available in the papers by Xue *et al*., (2000, 2001).

2. Data sources, domain and design of experiment

Data used for this study are:

(a) Radiosonde (RS/RW) data of Delhi (Lat. 28.58° N, Long. 77.20° E).

(b) Terrain field of 5 minutes (~ 10 km) resolution.

(*Source* : CAPS, Oklahoma
Website ftp:// ftp.caps.ou.edu /ARPS)

(c) Domain selected for the model run is presented in the Fig. 1. The Fig shows that all the three observatories namely Safdarjung, Lodi Road and Palam are inside domain. Safdarjung and Lodi Road are located within the distance of 1.5 km. While distance between Palam and Safdarjung is 8.0 km and between Palam and Lodi Road is 9.5 km.

The storm was initiated by a 4° C bubble shaped perturbation with radii 10 km in *x* and *y* direction and 1.5 km in vertical direction. This was used to trigger the

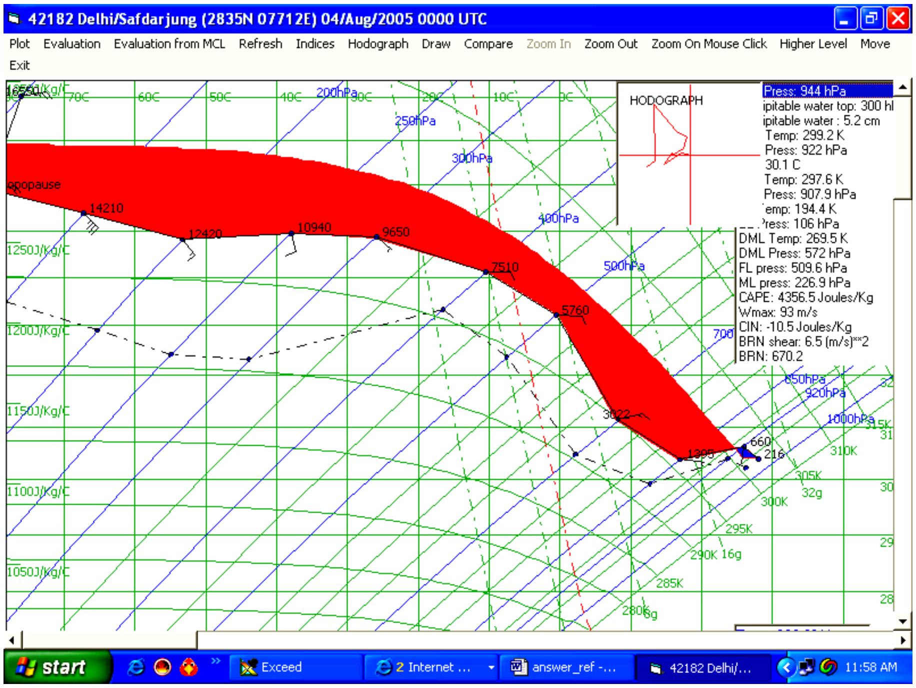


Fig. 2. Tephigram of Delhi 0000 UTC of 4 August 2005

convection. The configuration used in these experiments are as given below:

Central latitude (Delhi)	28.58° N
Central longitude (Delhi)	77.20° E
Dimension size (No of Grids) in *X*, *Y* & *Z* direction	37, 37, 25
Grid spacing (meters) in *X*, *Y* & *Z* direction	10000, 10000, 500
Run mode	3-D run
Model initialization option	Initialize using analytic function
Time step for model integration	12 second
Boundary conditions	Zero gradient (east, west and top), Periodic (north and south)
Turbulent mixing option	1.5 TKE turbulent mixing
Moist processes option	Moist processes are activated
Microphysics option	Kain Fritsch warm rain microphysics
Surface physics option	Surface fluxes are calculated from the constant surface drag coefficients, predicted surface temperature and surface volumetric water content
Convective cumulus parameterization	Kain -Fritsch Cumulus parameterization (Kain and Fritsch, 1990)

3. Results and discussion

Two case studies selected for this study are the thunderstorms events of 4 August and 9 September 2005, which occurred over Delhi. Model has been run using 0000 UTC RS/RW observations of the particular date for the 24 hour forecast. 24 hour forecast fields of updraft and downdraft vertical velocity during the genesis, maturity and dissipation of the thunderstorms are analyzed. The corresponding forecast fields of rainfall are also validated against Self-Recording Rain Gauge (SRRG) observations.

3.1. *Case-I (4 August 2005)*

(a) *Synoptic condition*

On 4 August 2005, an upper air cyclonic circulation was lying over southwest Rajasthan and neighborhood extending between 1.5 and 4.5 km above mean sea level.

(b) *Tephigram of 4 August 2005*

T-Φ gram of 0000 UTC of 4 August 2005 is shown in Fig. 2. *T*-Φ gram of 4 August 2005 is depicts large positive area (shaded gray in the picture) and very small negative area (shaded black in the picture). It means CAPE value is very large while CINE value is very small.

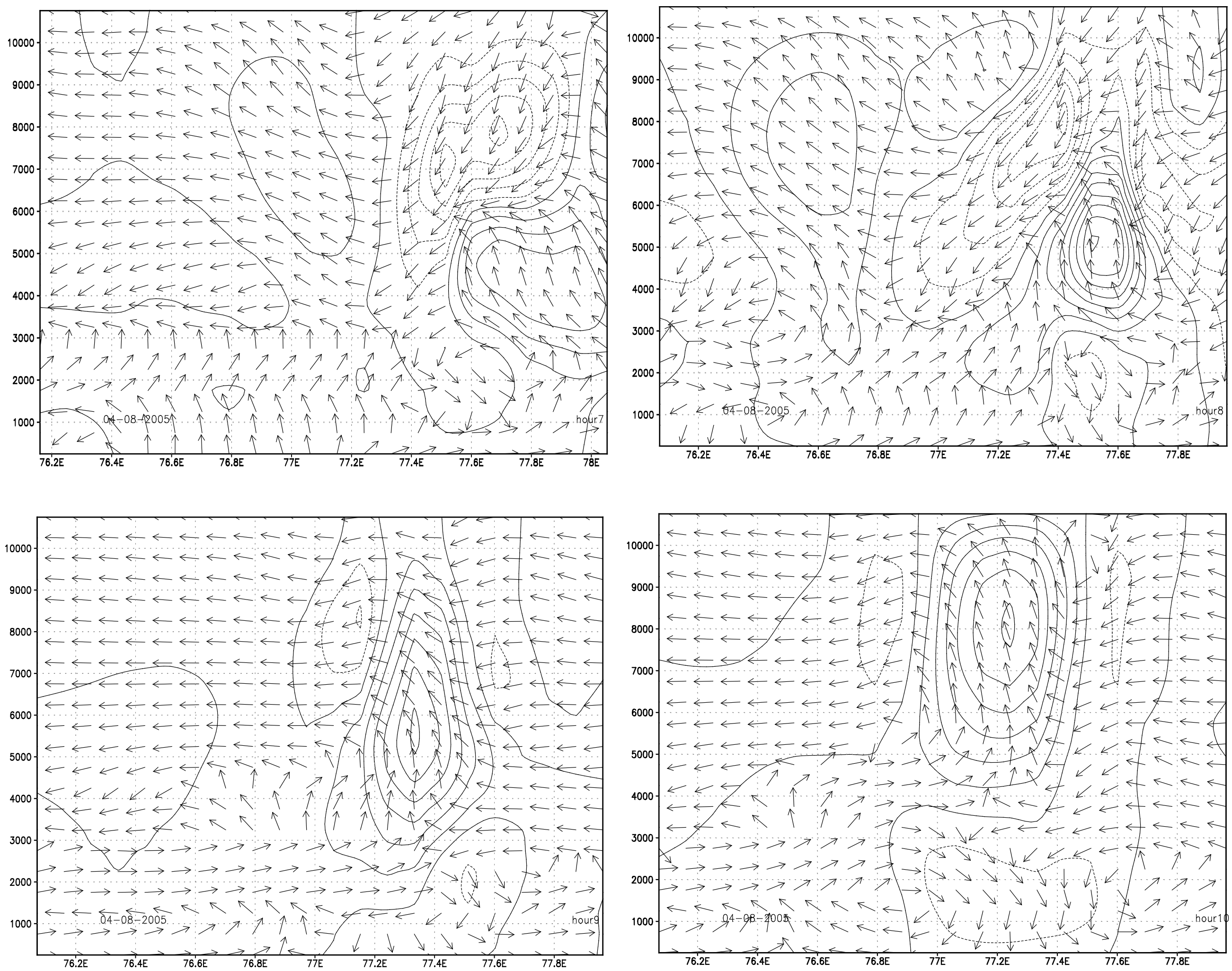


Fig. 3. Height longitude section of vertical motion (ms^{-1}) at forecast hour 7 to 10 of 4 August 2005

corresponding value of CAPE and CINE are respectively 4356.5 Joules/kg is – 10.5 Joules/kg. (Shown on the top right panel of the *T*-Φ gram). The high value of CAPE indicates that atmosphere is extremely unstable in this case. Also value of CINE is negative, *i.e.*, very small in this case. It is well known fact that for occurrence of thunderstorm one of the favorable conditions is that the CAPE should have very high value and CINE should have very small value. So *T*-Φ gram of this case suggests that there is a favourable chance of occurrence of thunderstorm.

(c) *Satellite pictures (04 August 2005)*

Satellite pictures for 04 August 2005 are shown in the Fig. 6 and corresponding cloud top temperatures are given in the Table 3. Taking Delhi as a centre (C), the area shown in the satellite pictures is divided into eight directions namely north (N), northeast (NE), east (E), southeast (SE), south (S), southwest (SW), west (W), northwest (NW). This table shows time in IST, Direction of cloud & cloud top temperature in degree centigrade. The satellite pictures alongwith corresponding cloud top temperature clearly depicts the increase and decrease in the vertical extension of the convective cloud.

(d) *Updrafts and downdrafts*

The *X-Z* cross-section of vertical velocity from time t = 7 hour to t = 10 hour, *i.e.*, (from 1230 local time to 1530 local time) along 28.8° N latitude is shown in Fig. 3.

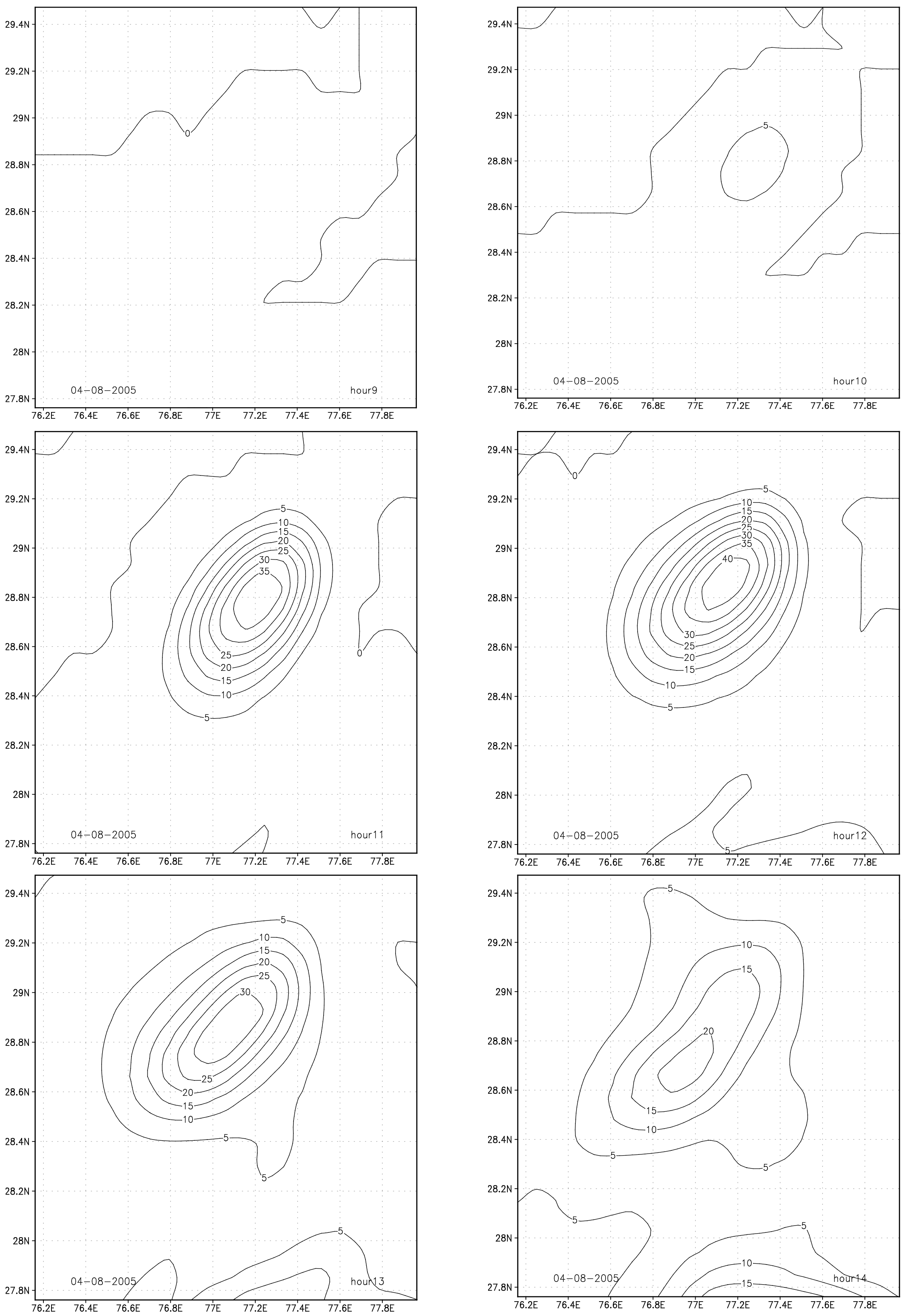


Fig. 4. Latitude longitude section of hourly rainfall (mm) at forecast hour 9 to 14 of 4 August 2005

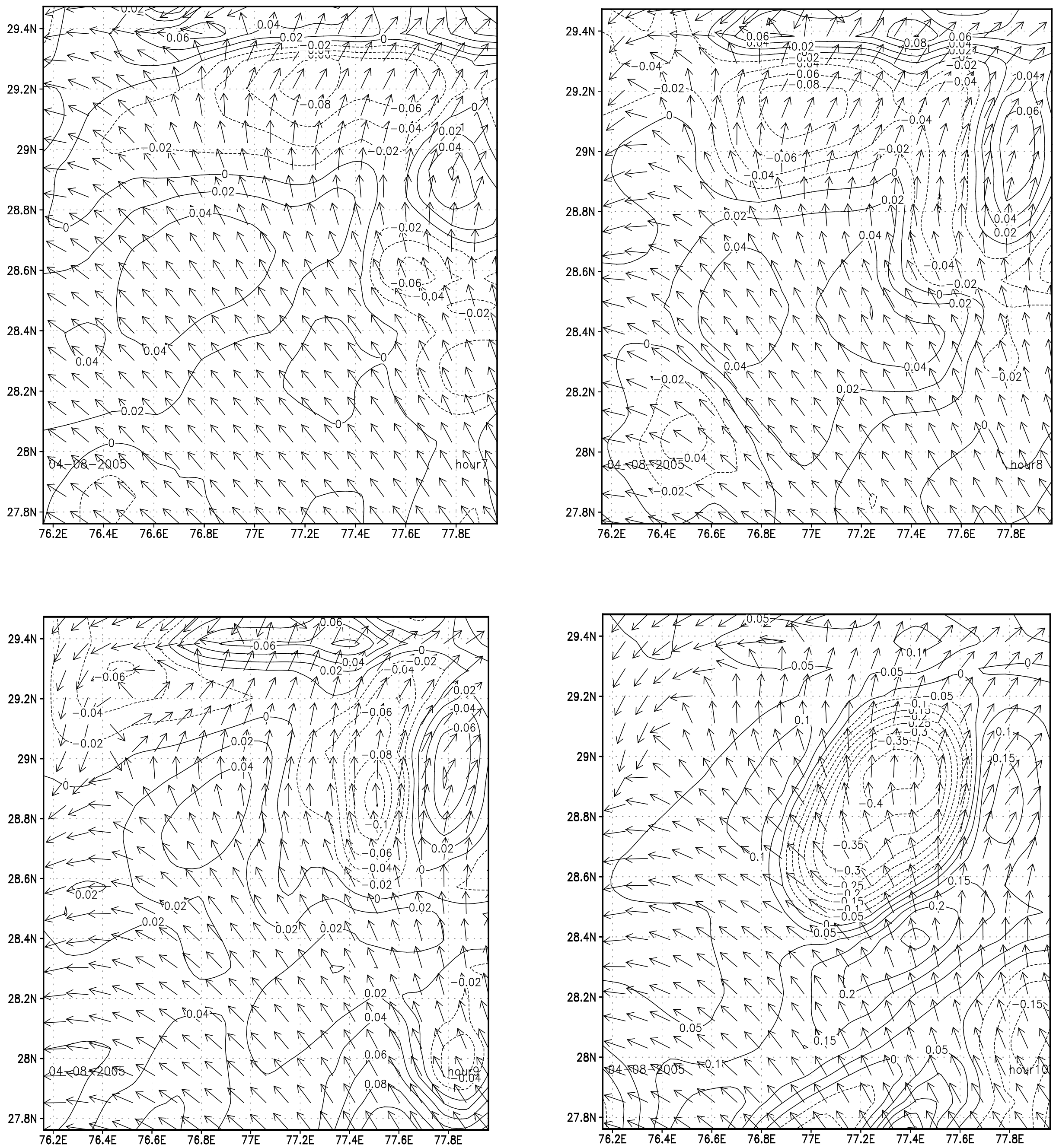
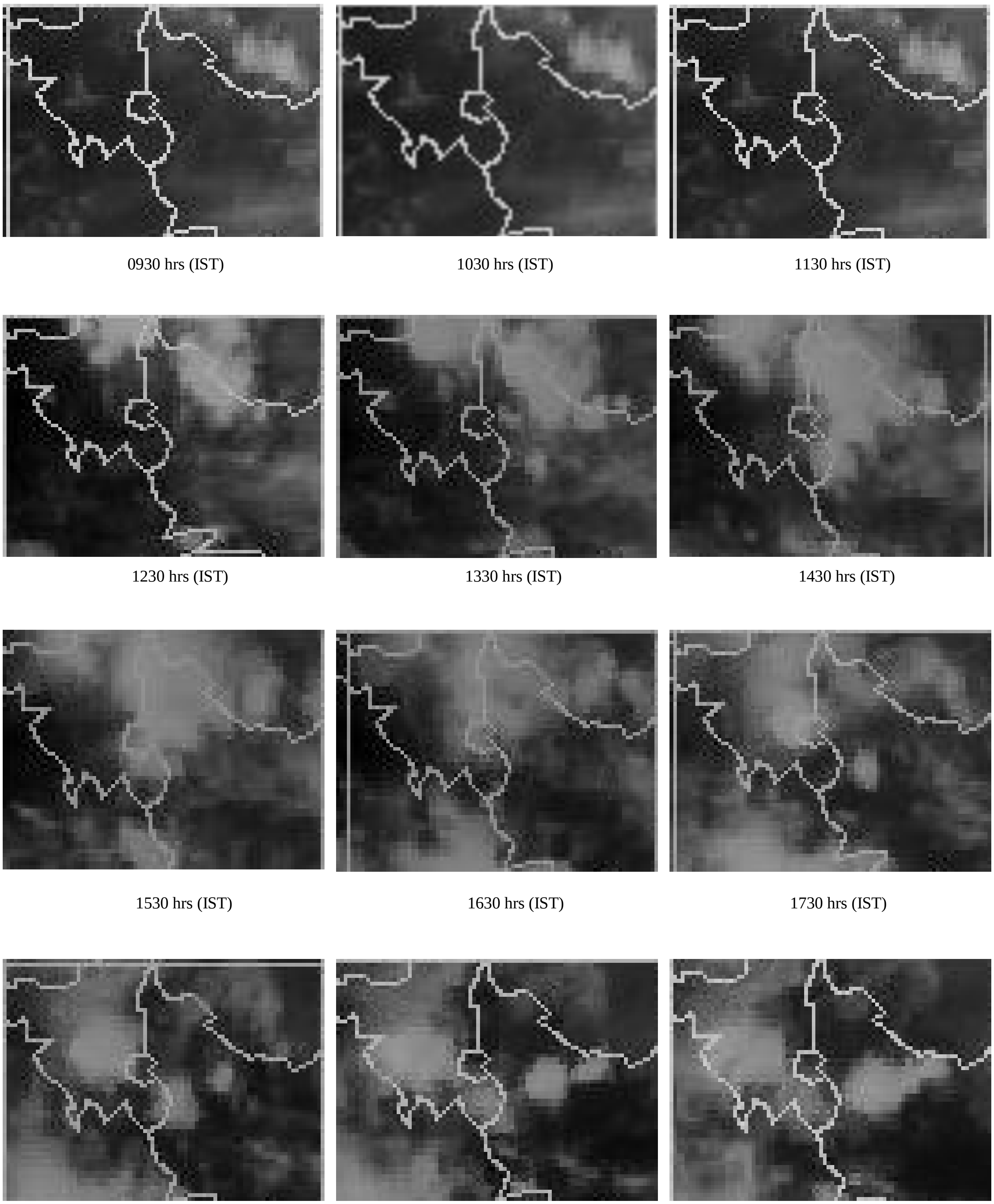


Fig. 5. Latitude longitude section of horizontal & vertical motion (ms^{-1}) at forecast hour 7 to 10 at 850 hPa level of 4 August 2005

Where upward vertical velocity are represented by solid contours while downward vertical velocity are represented by dotted contours. Upward vertical velocity from surface up to 6000 meter is noticed at the 7th forecast hour. This is found to be well matching with the developing stage of thunderstorm when increase in the vertical extension of cloud is noticed in the corresponding satellite (INSAT) imagery Fig. 6. At the 8th forecast hour (1330 hrs IST), we observe upward vertical motion from 3000 m to 7500 m and downdraft from 3000 m to surface. This is matching



0930 hrs (IST) | 1030 hrs (IST) | 1130 hrs (IST)

1230 hrs (IST) | 1330 hrs (IST) | 1430 hrs (IST)

1530 hrs (IST) | 1630 hrs (IST) | 1730 hrs (IST)

1830 hrs (IST) | 1930 hrs (IST) | 2030 hrs (IST)

Fig. 6. Satellite pictures of 4 August 2005

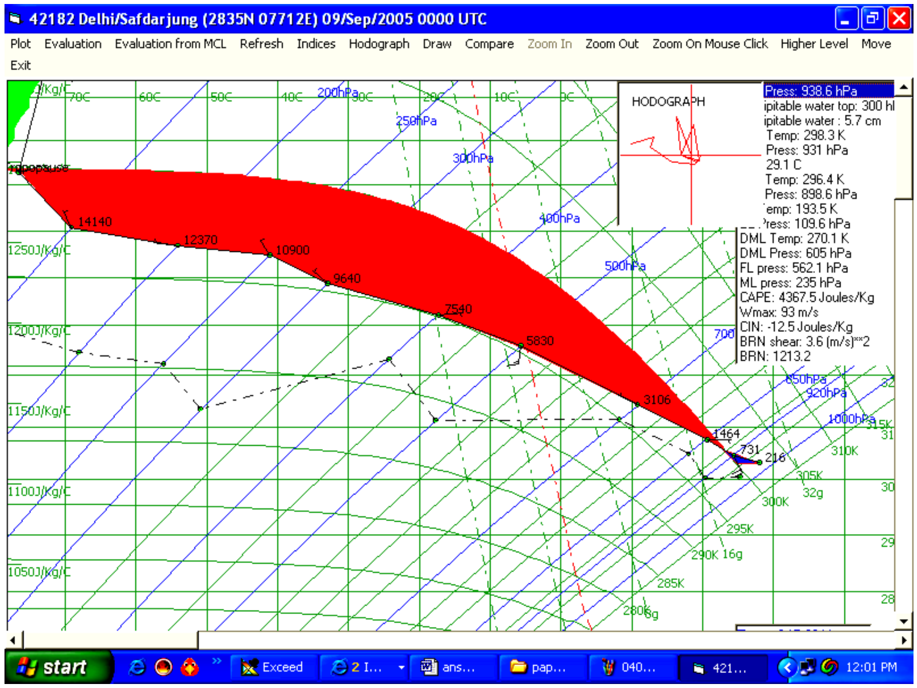


Fig. 7. Tephigram of Delhi 0000 UTC of 9 September 2005

TABLE 1

One hourly SRRG rainfall observations of 4 August 2005

S. No.	Date	Rainfall recorded between time interval (Time in hrs IST)	Rainfall (mm) Safdarjung	Rainfall (mm) Palam	Rainfall (mm) Lodi Road	Model (Maximum intensity) (mm)
1	04 Aug 2005	1130 – 1230	0.0	0.0	0.0	0.0
2	04 Aug 2005	1230 – 1330	0.0	0.0	0.0	0.0
3	04 Aug 2005	1330 – 1430	0.0	0.0	0.0	0.0
4	04 Aug 2005	1430 – 1530	0.0	0.0	0.0	5.0
5	04 Aug 2005	1530 – 1630	35.0	0.0	2.0	35.0
6	04 Aug 2005	1630 – 1730	0.0	0.7	18.0	40.0
7	04 Aug 2005	1730 – 1830	0.0	0.3	0.0	30.0
8	04 Aug 2005	1830 – 1930	0.0	0.0	0.0	20.0
		Total	35.0	1.0	20.0	130.0

with the vertical extension of convective cloud associated with the mature stage of the thunderstorm when both updraft and down draft co-exist. At the 9th forecast hour (1430 hrs IST) strong vertical updraft (from 3000 m to 9000 m) and downdraft (from 3000 m to surface) persisted. At the 10th forecast hour (1530 hrs IST) strong vertical updraft (from 4000 m to 10000 m) and downdraft (from 3000 m to surface) prevailed. The shift in the base of upward velocity from 3000 m to 4000 m at the 10th forecast hour indicates the dissipating stage of the thunderstorm. At the 10th forecast hour weakening of updraft and persistence of downdraft reveals the dissipating stage of the thunderstorm.

The hourly-INSAT imageries Fig. 6 clearly suggest that the genesis and dissipation of the storm took place during 1430-1730 hrs IST. The model could simulate the formation of storm, which started at 8th forecast hour. In the following hours the storm-attained maturity with gradual westward movement.

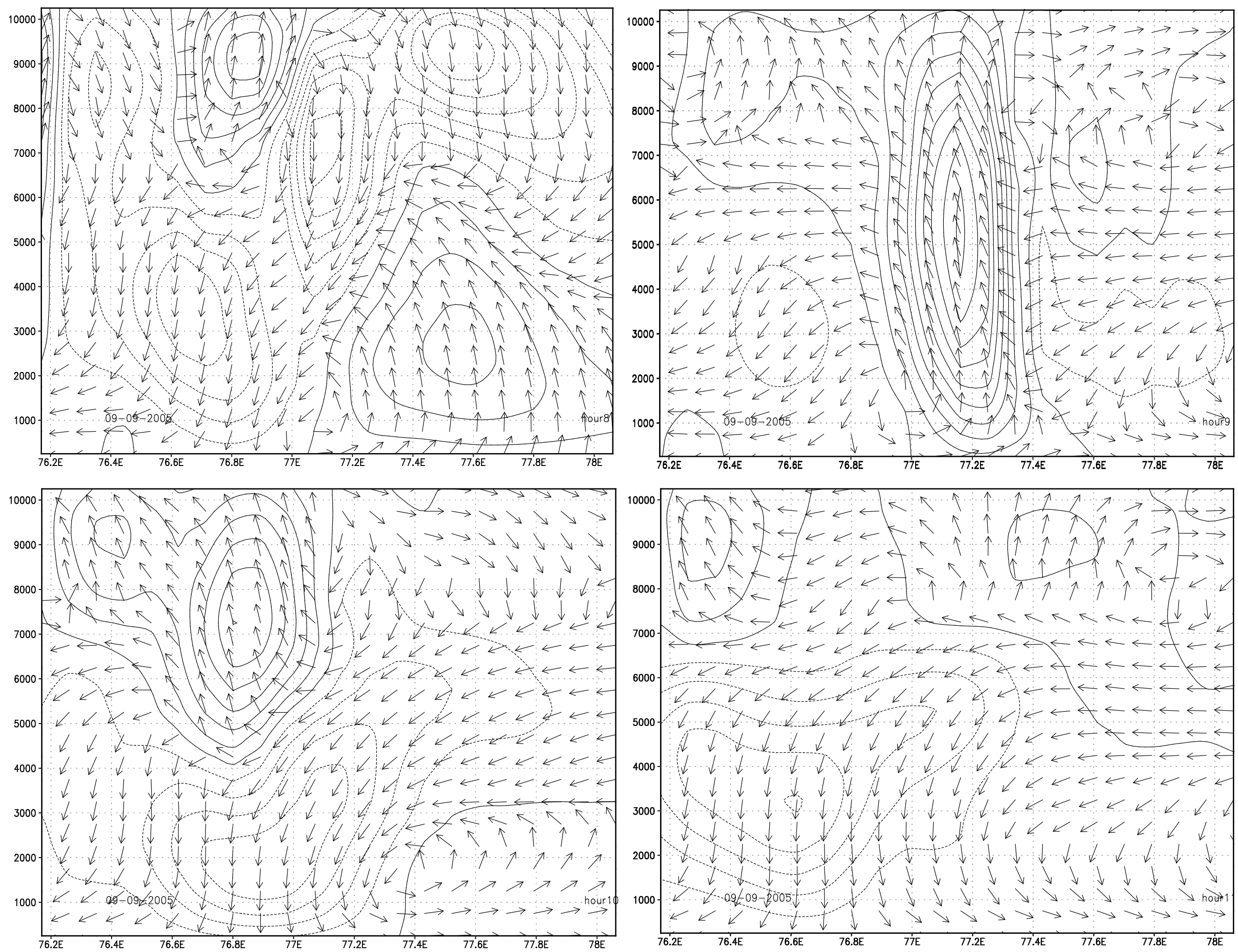


Fig. 8. Height longitude section of vertical motion (ms^{-1}) at forecast hour 8 to 11 of 9 September 2005

Fig. 5 presents the 850 hPa wind pattern for 4 August 2005. Contour lines display the vertical velocity. Positive contour indicates vertical upward motion and negative contour indicates vertical downward motion. The Figure illustrates how location and intensity of updrafts and downdrafts changes with time.

(e) *Rainfall*

The hourly rainfall simulated by the model is shown in Fig. 4. Model did not show any rainfall up to 9th forecast hour. Model started producing rainfall from 10^{th} forecast hour. The rainfall patch is centered near Lat. 28.8° N / Long. 77.3° E. The intensity as well the spatial coverage of rainfall started increasing with the time up to 12th forecast hour, there after it started decreasing. The center of rainfall maxima in the forecast is also found moving westwards. The direction of movement is found to the corresponding movement of cloud as noticed in the corresponding satellite pictures. The cumulative rainfall at 14^{th} forecast hour became 130 mm.

The corresponding one hourly actual rainfall observations of Delhi (Safdarjung, Palam and Lodi Road) recorded by Self Recording Rain Gauge (SRRG) and hourly model forecast rainfall are shown in Table 1. The Table shows that rainfall occurred between 1530 hrs IST and 1630 hrs IST at Safdarjung, between 1530 hrs IST and 1730 hrs IST at Lodi Road and between 1630 IST and 1830 hrs IST at Palam. Safdarjung received 35 mm and Lodi Road 20 mm rainfall while Palam observatory reported only 1 mm. Thus simulated cumulative rainfall of 130 mm is found to be over estimated.

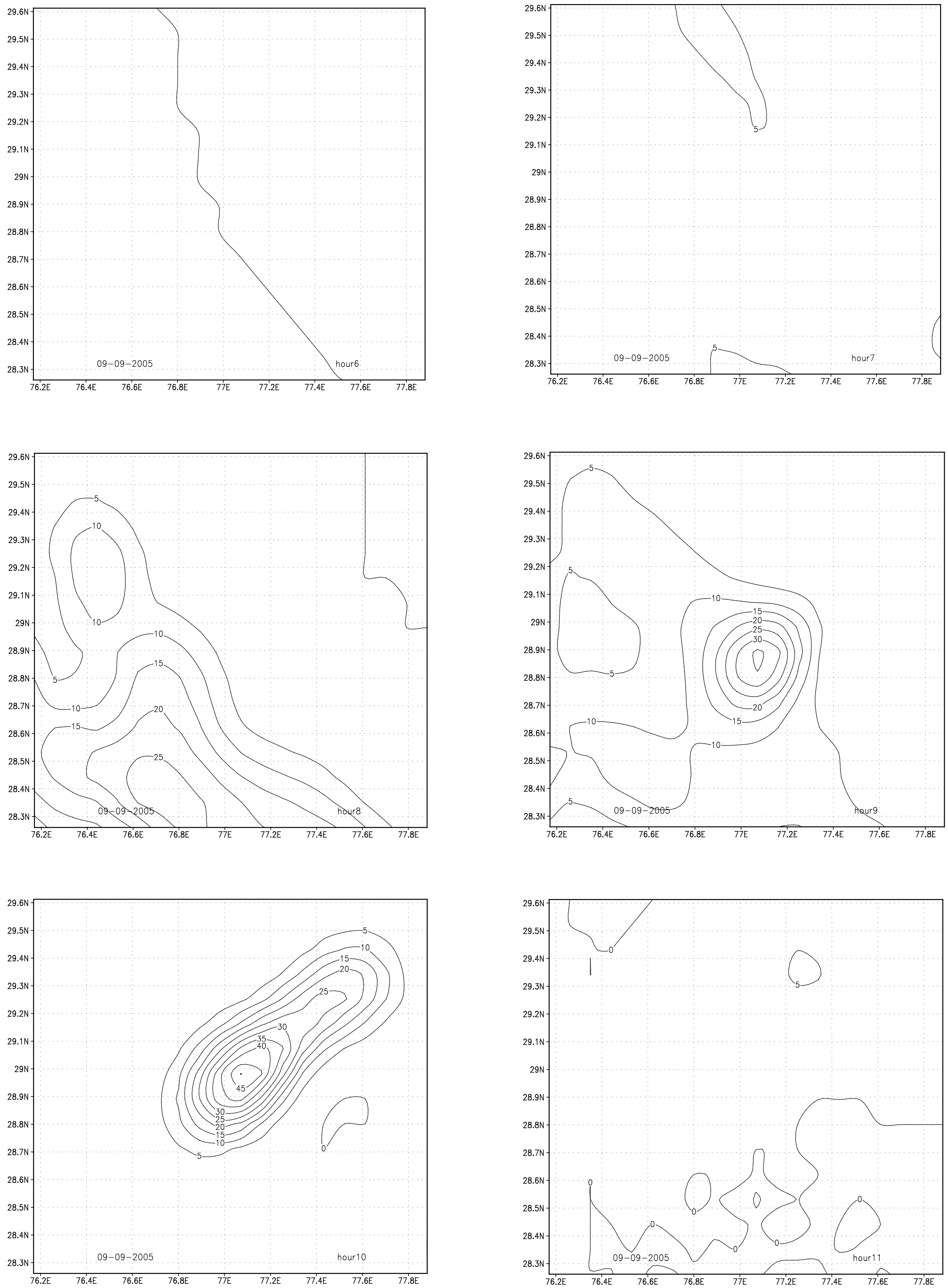


Fig. 9. Latitude longitude section of hourly rainfall (mm) at forecast hour 6 to 11 of 9 September 2005

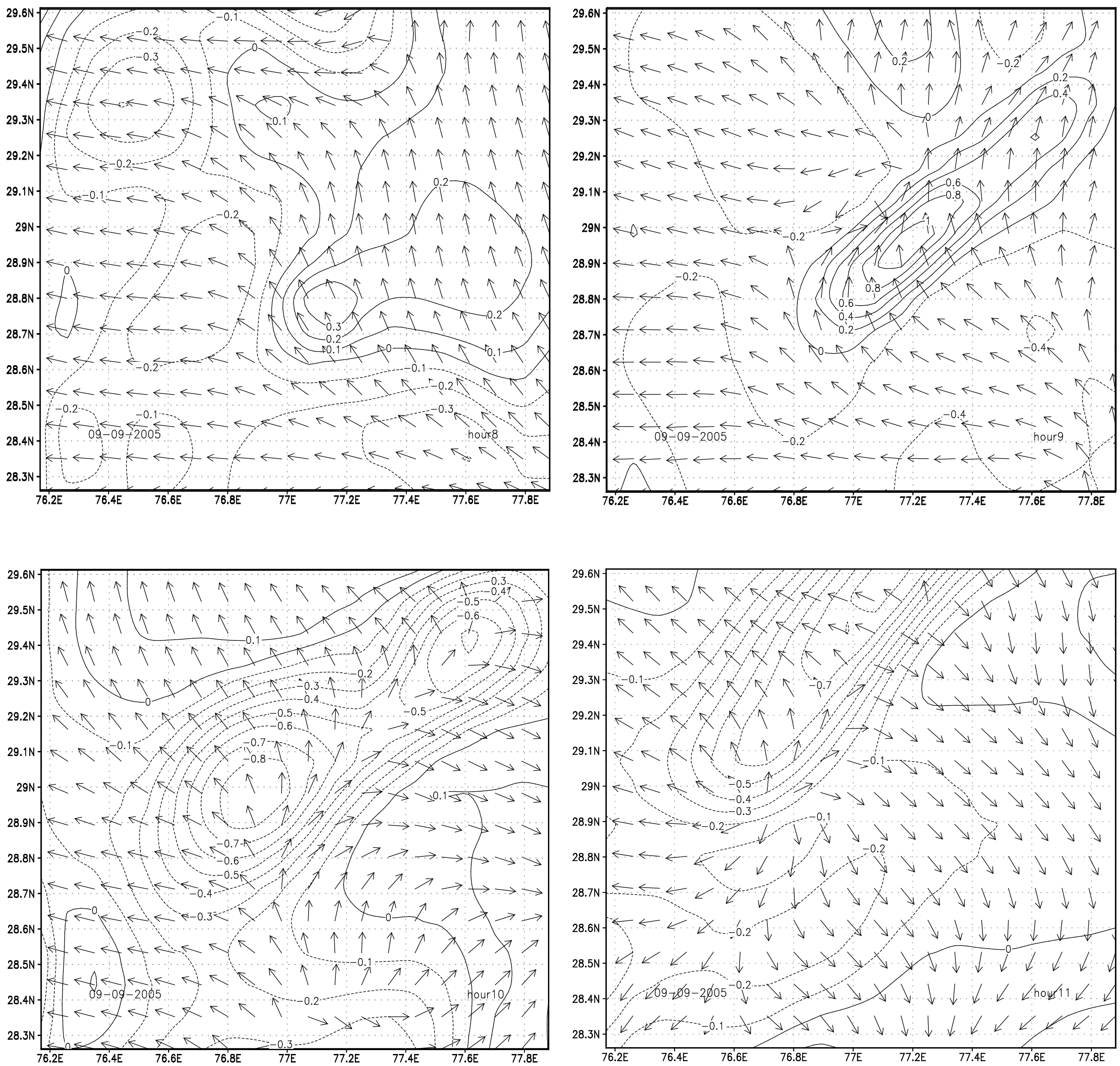


Fig.10. Latitude longitude section of horizontal & vertical motion (ms^{-1}) at forecast hour 8 to 11 at 850 hPa level of 9 September 2005

3.2. *Case-II (9 September 2005)*

(a) *Synoptic condition*

A cyclonic circulation lay over Pakistan and adjoining northwest Rajasthan extending up to 1.5 km above mean sea level on 9 September 2005.

(b) *Tephigram of (9 September 2005)*

T-Φ gram of 0000 UTC of *9 September 2005* is shown in Fig. 7. The *T*-Φ shows large positive area (shaded gray in the picture) and very small negative area (shaded black in the picture). It means CAPE value is very large (4367.5 Joules/kg) while CINE value is very small

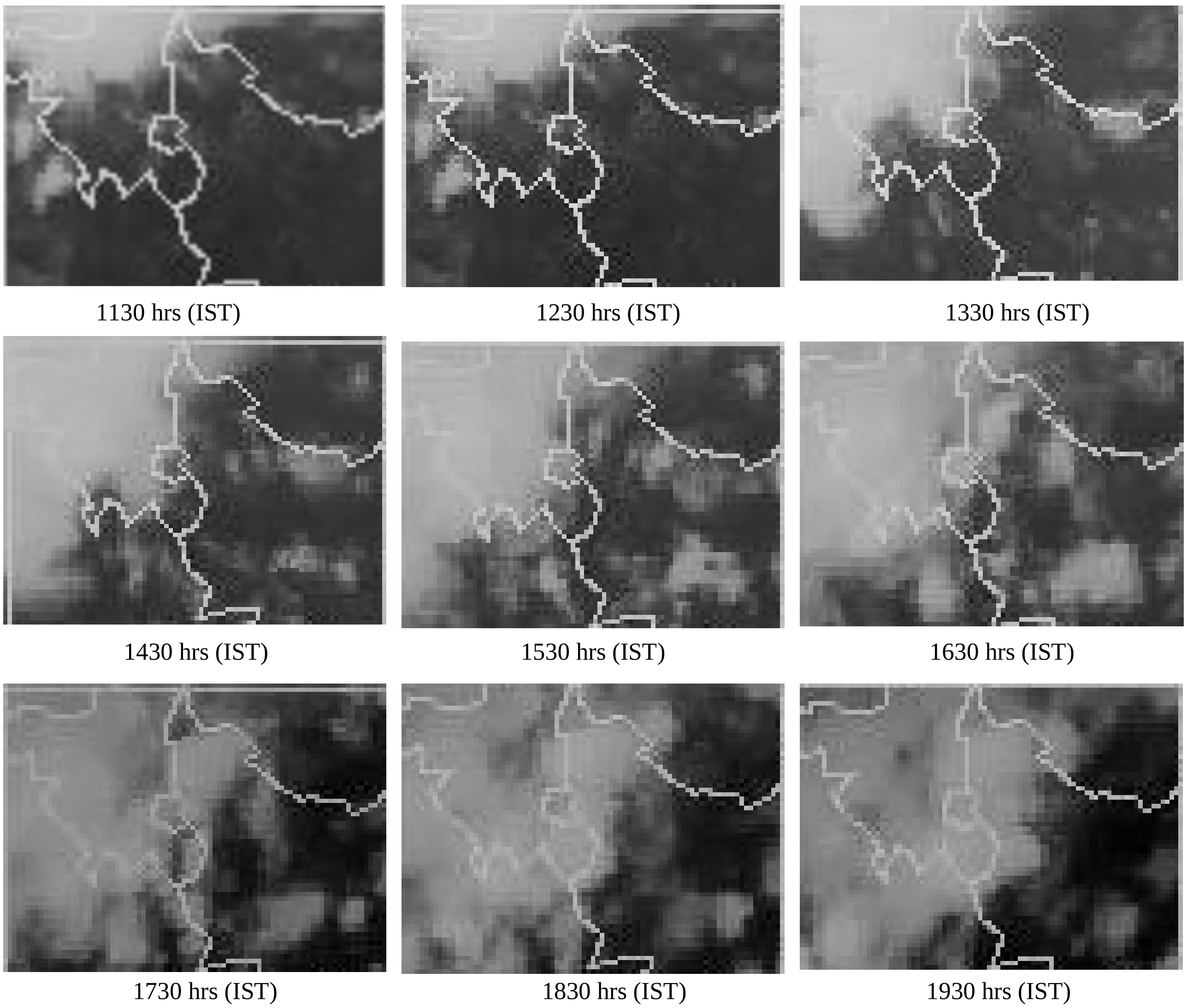


Fig. 11. Satellite pictures of 9 September 2005

(–12.5 Joules/kg). This indicates that atmosphere is extremely unstable and there is a favourable chance of occurrence of thunderstorm.

(c) *Satellite pictures (9 September 2005)*

Satellite pictures for 9 September 2005 are shown in the Fig. 11 and corresponding cloud top temperatures are given in the Table 4. Increase or decrease in the vertical extension of the convective cloud can be clearly noticed in the satellite pictures and corresponding cloud top temperature.

(d) *Updrafts and downdrafts*

The *X-Z* cross section of vertical velocity is from time t = 8 hour to t = 11 hour, *i.e.*, (1330 local time to 1630 local time) along 28.75° N latitude is shown in Fig. 8. Upward vertical velocity (from surface to 5000 meter) is noticed at 8th forecast hour. This is found to be well matching with the developing stage of thunderstorm when increase in the vertical extension of cloud is noticed in the corresponding satellite (INSAT) imagery (Fig. 11). At the 9th hour (1430 hrs IST) forecast we observe strong vertical motion (updraft) from (surface to 10000 meter) and downdraft (from 4000 meter to surface). This is matching well with the vertical extension of convective cloud associated with the mature stage of thunderstorm when updraft and downdraft coexist. At the 10th forecast hour (1530 hrs IST) strong updraft at higher level (from 5000 m to 10000 m) and downdraft at lower level (from 6000 m to surface) persisted. In this stage downdraft is more prominent than updraft. The shift in the base of upward motion from surface to 5000 m at the 10th forecast

TABLE 2

One hourly SRRG rainfall observations of 9 September 2005

S. No.	Date	Rainfall recorded between time interval (Time in hrs IST)	Rainfall (mm) Safdarjung	Rainfall (mm) Palam	Rainfall (mm) Lodi Road	Model (Maximum intensity) (mm)
1	9 Sep 2005	1130 – 1230	0.0	0.0	0.0	0.0
2	9 Sep 2005	1230 – 1330	0.0	0.0	0.0	25.0
3	9 Sep 2005	1330 – 1430	0.0	0.0	0.0	40.0
4	9 Sep 2005	1430 – 1530	0.0	0.0	0.0	45.0
5	9 Sep 2005	1530 – 1630	10.0	0.0	23.0	5.0
6	9 Sep 2005	1630 – 1730	14.0	5.3	13.0	0.0
7	9 Sep 2005	1730 – 1830	0.6	0.1	0.0	0.0
8	9 Sep 2005	1830 – 1930	0.0	0.0	0.0	0.0
		Total	24.6	5.4	36.0	115.0

TABLE 3

Cloud top temperature on 4 August 2005

Time in hrs (IST)	Direction of cloud patch	Cloud top temperature in degree centigrade	Direction of cloud patch	Cloud top temperature in degree centigrade
0930	NE	–20		
1030	NE	–21		
1130	NE	–24		
1230	NE	–26	N	–31
1330	NE	–31	N	–41
1430	NE	–37		
1530	NE	–40	C	–41
1630	C	–38		
1730	C	–31		
1830	Cloud patch moved westward			

TABLE 4

Cloud top temperature on 9 September 2005

Time in hrs (IST)	Direction of cloud patch	Cloud top temperature in degree centigrade	Direction of cloud patch	Cloud top temperature in degree centigrade
1130	NW	-43		
1230	NW	-45		
1330	NW	-46		
1430	NW	-51	West-NW	–47 & –48
1530	NW	-51	West-NW	–47 & –48
1630	C	-47	West-NW	–40 & –45
1730	C	-43		
1830	C	-40		
1930	C	-40		

hour indicates the dissipating stage of the thunderstorm. At 11th forecast hour both updraft and downdraft are weakening. This is clearly an evidence of the dissipating stage of the thunderstorm.

The hourly-INSAT imageries (Fig. 11) clearly suggest that the genesis and dissipation of the storm took place during 1330-1730 IST. The model could simulate the formation of storm, which started at 8th forecast hour.

In the following hours the storm attained maturity with gradual east-northeasterly movement.

Fig. 10 presents the 850 hPa wind pattern for 9 September 2005. The figure illustrates how location and intensity of updrafts and downdrafts changes with time.

(e) *Rainfall*

The cumulative rainfall simulated by model is shown in Fig. 9. Model did not show any rainfall upto 8th forecast hour near Lat. 28.58° N / Long. 77.2° E. Model started producing northwest / southeast oriented patch of rainfall from 9th forecast hour near Lat. 28.58° N / Long. 77.2° E. The intensity as well as spatial coverage of rainfall started increasing with the forecast hour. The center of maxima in forecast rainfall is also found moving slightly east northeastwards. The direction of movement is similar to the direction of movement of cloud as noticed in the corresponding satellite pictures near Delhi. The cumulative rainfall at 11th forecast hour was 115 mm.

The corresponding hourly cumulative rainfall observations of Delhi (Safdarjung, Palam and Lodi Road) recorded by Self Rain Gauge and hourly model forecast rainfall are shown in Table 2. The Table shows that rainfall occurred between 1530 hrs IST and 1830 hrs IST at Safdarjung, between 1530 hrs IST and 1730 hrs IST at Lodi Road and between 1630 hrs IST and 1830 hrs IST at Palam. Safdarjung received 24.6 mm and Lodi Road 36.0 mm rainfall while Palam observatory has reported only 5.4 mm. Thus simulated cumulative rainfall of 115 mm is found to be over estimated.

4. Conclusions

Following conclusions can be drawn from the two case studies illustrated in this paper:

(*i*) The ARPS model is capable of simulating updrafts and downdrafts and their horizontal propagation associated with a thunderstorm during the developing, mature and decaying stage of the convective system.

(*ii*) The model is able to simulate temporal (hourly) and spatial distribution of rainfall associated with a thunderstorm. But the simulated rainfall is found to be over estimated.

Thus, the study suggests that the model with the incorporation of local RS/RW observations as input has the potential to predict localized thunderstorm events. Application of this procedure is expected to be useful in aviation forecasting and in generating location specific forecasts.

Acknowledgements

The authors are thankful to Director General of Meteorology, India Meteorological Department (IMD), New Delhi for rendering all facilities. The authors also gratefully acknowledge Mr. A. K. Mitra, Meteorologist Gr-II, Satmet Division, I.M.D. New Delhi, for providing necessary support.

References

Galway, J. G., 1956, "The lifted index as a predictor of latent instability", *Bull. Amer. Met. Soc*., **37**, 528-529.

George, J. J., 1960, "Weather Forecasting for Aeronautics", Academic Press, p637.

Jeevananda Reddy, S. and Rao, Prakash, 1977, "A simple method of forecasting thunderstorms", *Indian J. Met. & Geophys*., **28**, 2, 255-257.

Kain, J. S. and Fritsch, J. M., 1990, "A one-dimensional entraining/detraining plume model and its application in convective parameterisation", *J. Atmos. Sci*., **47**, 2784-2802.

Mukhopadhyay, P., Sanjay, J. and Singh, S. S, 2003, "Objective forecast of thundery/nonthundery days using conventional indices over three northeast Indian stations", *Mausam*, **54**, 4, 867-880.

Sen, P. N., 2005, "Thermodynamics of the Atmosphere – Lecture notes of the second SERC school on aviation meteorology", AFAC, Coimbatore, India.

Showalter, A. K., 1953, "A stability index for thunderstorm forecasting", *Bull. Amer. Met. Soc*., **34**, 6, 250-252.

Sivaramakrishnan, T. R. and Ramakrishnan, B., 1995, "An analytical study of thunderstorms over Madras", *Mausam*, **46**, 3, 291-296.

Suresh, R., 1996, "An objective operational forecast of rainfall based on single Radio-Sonde ascent data, Book of abstracts", Tropmet 96, National symposium on Meteorology and Natural Disasters, 14-17 Feb 1996, Andhra University, Visakhapatnam, MO-27.

Xue, M., Droegemeier, K. K. and Wong, V., 2000, "The Advance Regional Prediction System (ARPS) – A multi- scale non-hydrostatic atmospheric simulation and prediction Model. Part I : Model dynamics and verification", *Meteorl. Atmos. Phy*., **75**, 161-193.

Xue, M., Droegemeier, K. K., Wong, V., Shapiro, A., Brewester, K., Carr F., Weber, D. Liu, Y. and Wang, D., 2001, "The Advance Regional Prediction System (ARPS) – A multi-scale non-hydrostatic atmospheric simulation and prediction tool. Part II: Model physics and application", *Meteorology and Atmospheric Physics*, **76**, 143-165.