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Idealized simulation of a thunderstorm over Kolkata using RAMS

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ABSTRACT

An idealized simulation of a thunderstorm is attempted using Regional Atmospheric Modeling System (RAMS). The storm was reported on 1200 UTC of 14 July 1998 over Kolkata station. The upper air sounding data collected over Kolkata station at 0600 UTC under GEWEX Asian Monsoon Experiment is perturbed with a warm bubble to trigger the convection. Subsequently the model is run for 12 hour in forecast mode with two horizontal resolutions namely 5 km and 1 km. Analyzing different forecast fields such as temperature, total cloud condensate, vertical velocity, rainfall, it is found that 5 km grid has produced a strong convection after one hour model run. However it could not generate the convection around 1200 UTC which is the time of actual report of the thunderstorm. On the contrary, the 1 km simulation showed formation of storm after one hour integration and also at 1100 UTC i. e. after five hour of integration. The time of simulated convection by 1 km grid at 1100 UTC is very close to that of actual report. As such this study indicates that cloud resolving grid length of 1 km has better simulated the thunderstorm compared to the 5 km grid resolution.

INTRODUCTION

Since the first article written on the tornadic super cell of Kolkata on 8 April 1838 (Floyd 1838) lot of research was carried out towards a better understanding and forecasting of thunderstorms (locally known as Nor'westers) over Kolkata region during pre-monsoon months (March, April, May) using diagnostic and/or statistical techniques. However hardly any attempts have been made to utilize dynamical three-dimensional models to simulate/predict these violent weather systems. As thunderstorms by their spatial (2~20 km) and temporal dimension (few hours) typically fits to meso-γ scales (Orlanski 1975) large-scale analyses with coarse resolution often do not resolve them properly. As the signature of these systems remain absent in the initial conditions, numerical models generally fail to simulate the evolution of the three dimensional structure of the systems. Mainly due to this practical limitation scientists across the globe attempted a technique of perturbing the initial atmosphere with a warm bubble to initiate the convection and further allow the model to simulate the system. Number of studies using this technique have been done elsewhere. Brooks & Wilhelmson (1992) carried out numerical simulations of low precipitating thunderstorm over Oklahoma. They used Klemp-Wilhelmson (1978) cloud model to simulate the event on 26 April 1984. They initialised all the experiments with a warm bubble having a horizontal radius 10 km and vertical semi axis of 1.4 km above the ground. They ran the simulations in each environment with two different maximum temperature perturbations namely 4^{o} K and 5^{o} K. They concluded that the cloud model could simulate many features of low precipitating storms although it was not having a detailed microphysics. Secondly the model evolution was found to be sensitive to the magnitude of initial thermal perturbation. Pielke et al. (1992) simulated the Del City 20 May 1977 tornadic thunderstorm using three nested grids with resolutions 1 km, 333 m and 111m. They triggered the storm with a warm cube of dimensions 10 km x 10 km x 3 km, which was 1.5^{o} C warmer and 2 gm kg^{-1} moister than the environment. They could explain with this idealized experiment the mechanism of the formation of tornado. Model simulation could successfully bring out the pressure deficit, vorticity, vertical velocity associated with the storm. Proctor & Bowles (1992) simulated a microburst near Denver on the afternoon of 11 July 1988. They used a nonhydrostatic cloud model Terminal Area Simulation System (TASS). TASS was documented by Proctor (1987a). TASS was initialized with a spheroidal thermal bubble at model time zero with peak amplitude of 1.5°C, a diameter of 5 km and a depth of 2.5 km. Thus it is seen that the technique of simulating thunderstorm using a thermal bubble to perturb the initial atmosphere gives a unique opportunity to study different characteristic features of the storm and help further to better understand the inherent dynamical and physical processes of the storm. Keeping this in view an attempt is made in this paper to simulate the thunderstorm of 14 July 1998 over Kolkata station.

DATA USED

GEWEX (Global Energy Water Cycle Experiment) Asian Monsoon Experiment was conducted during May-July 1998 over Asian region. As a part of this programme upper air sounding over nine Indian stations along the monsoon trough region at six hourly intervals were taken. The upper air data collected at 00, 06, 12 and 18 UTC have given us an advantage to attempt mesoscale simulation. On 14 July 1998 Kolkata station reported severe thunderstorm at 1200 UTC. The observation suggested that the storm was continuing at 1200 UTC and there was some rain and thunderstorm between 0600 and 1200 UTC. The 24 hour accumulated rainfall reported on 03 UTC of 15 July suggested that the storm has caused 47 mm of rain. The upper air data collected at 06 UTC of 14 July 1998 is used as the initial profile in this study. To provide ground truth at high-resolution USGS (United States Geological Survey) topography and land use and vegetation data at 30 arcsec (~1 km) resolution are used.

METHODOLOGY

Version 4.30 of Regional Atmospheric Modelling System (RAMS) developed at Colorado State University and ATMET (Atmospheric, Meteorological, and Environmental Technologies) is utilized in this study. RAMS is a state-of-the art nonhydrostatic, compressible mesoscale model. It has variety of features that enable it to run at very high resolution even of the order of few meters. RAMS model and its different features are documented in detail by two very comprehensive studies by Pielke et al. (1992) and Cotton et al. (2003). Brief outline of the model is given below.

1.	Basic Equations	Non-hydrostatic time-split compressible	
2.	Vertical Coordinate	Terrain following height coordinate	Gal-chen * Somerville (1975), Clark (1977)
3.	Grid staggering	Rotated Polar Stereographic transformation, Arakawa-C grid stagger	
4.	Time differencing	Hybrid combination of leap-frog and forward-in-time	
5.	Advection	Leapfrog type schemes and forward-upstream schemes (Tremback et al.,1987)	
6.	Turbulence closure	Smagorinsky (1963) deformation-K closure with stability modifications made by Lilly (1962) and Hill (1974)	
7.	Cloud microphysics	Single moment bulk scheme	Walko et al., 1995
8.	Radiation	Two stream scheme interacts with liquid and ice hydrometeors	Harrington (1997)
9.	Land surface model	Soil/vegetation/snow parameterization - LEAF-2	Walko et al. (2000)
10.	Lateral Boundary	Radiative Boundary condition	Klemp & Wilhelmson (1978)
11.	Initialization	Horizontally Homogeneous from a single sounding	

In this study RAMS is initialized with the 0600 UTC upper air sounding data of 14 July 1998 over Kolkata station. RAMS is run with two resolutions 5 km and 1 km. Number of grid points along x-y direction are 61 x 61. 30 unevenly spaced terrain following levels are used in the vertical. The vertical levels are stretched in the ratio 1.1:100; 2000 which implies the first level will have a thickness of 100 m, the next level will be of thickness 110 m and so on till the level reaches the thickness of 2000 m. Simplified scheme of Mahrer & Pielke (1977) are used to consider short wave and long wave radiation in the model simulation. Bulk microphysics of Walko et al. (1995) is used to explicitly predict the hydrometeor mixing ratios or the constituents of cloud. No cumulus parameterization is used in the present simulation as the resolution of the model is almost reaching cloud-resolving scale. Eddy diffusion coefficients are computed as per Smagorinsky (1963) formulation. Klemp-Wilhelmson (1978a) radiative lateral boundary condition is used along with Raleigh absorbing layer in the upper five levels.

A warm bubble of the size 10x10x13 grid points along x, y and z direction with ice-liquid potential temperature perturbed by 5° K and initial relative humidity field perturbed by 25% is used to trigger the initial atmosphere. The warm bubble is activated once at the first time step after the start of the model run. From the second time step onwards the model is allowed to evolve the convection. The model is integrated for 12 hours ending at 1800 UTC of 14 July 1998 to study the reported thunderstorm of 14 July 1998.

DISCUSSION

The TEPHI gram plot of the upper air sounding at 0600 UTC 14 July 1998 over Kolkata is shown in Fig.1. It is clear from the thermodynamic plot that the atmosphere was conditionally unstable at 0600 UTC. The plot of dry bulb (T) and dew point (Td) temperature as obtained from upper air observation at 0600 and 1200 UTC are plotted in Fig.2. The close proximity of the T and Td (Fig.2) at 1200 UTC clearly suggests that the atmosphere was reaching towards saturation at the evening hour. The thermodynamic indices namely convective available potential energy (CAPE), stability index (SLI), humidity index (HI) and total-total index (TT) are computed based on the upper air data at 0600 and 1200 UTC and shown in the Fig.2. The mathematical formulae and physical meaning of the indices are shown in Table 1. From Fig. 2 it is found that SLI is -5.97 at 0600 UTC, which suggests large parcel instability in the middle tropospheric level. The value of SLI at 1200 UTC is -1.57, which implies that atmosphere is approaching

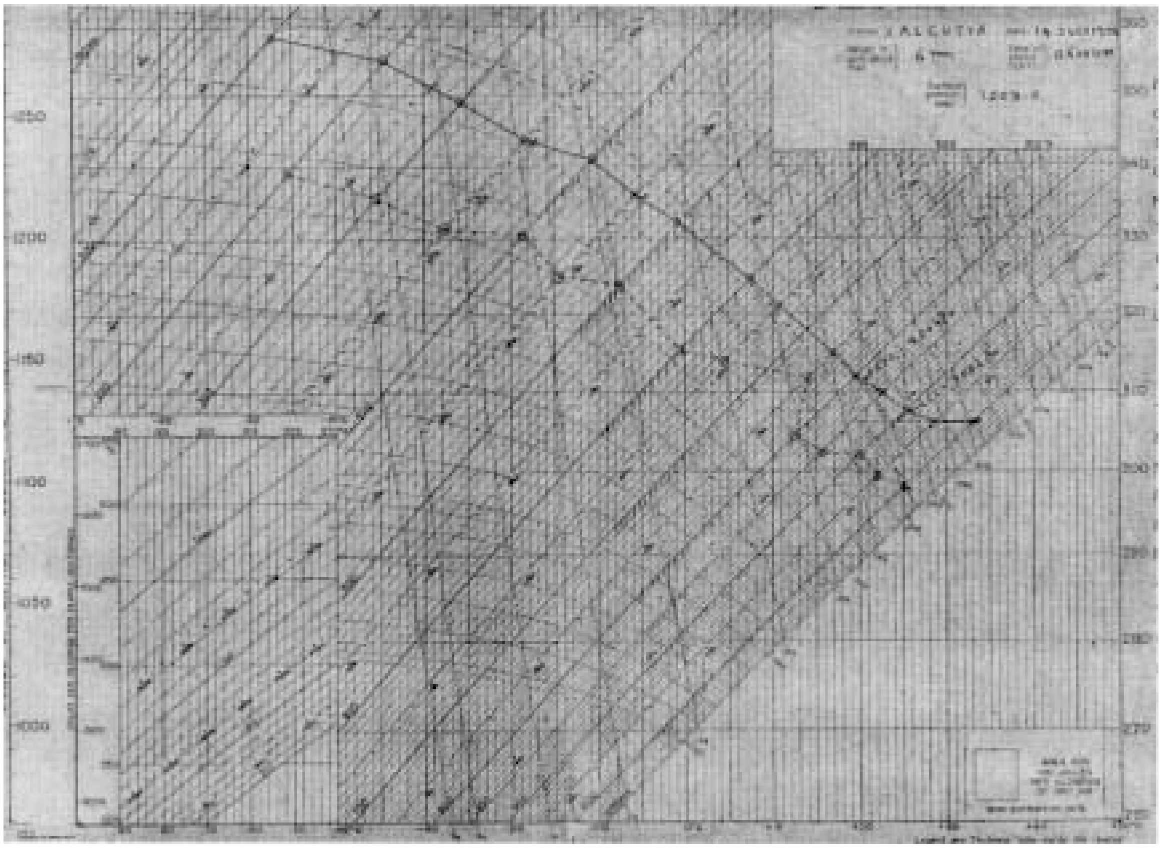

Figure 1. TEPHI gram plot showing T and Td at different standard pressure levels at 0600 UTC over Kolkata

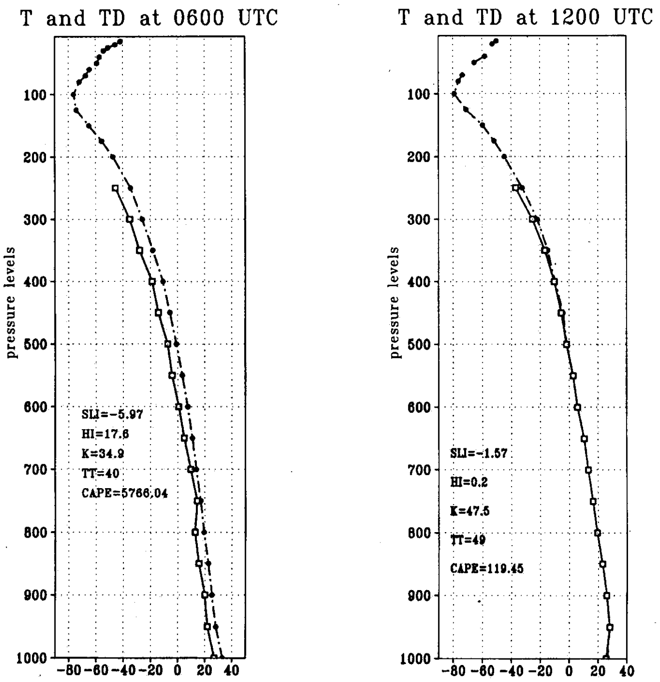

Figure 2. Plot of observed T and Td at different pressure levels (dashed line stands for T and solid line for Td) at 0600 and 1200 UTC and values of thermodynamic indices.

Table 1. Description of Indices

Indices	Code	Reference(s)	Expression	Explanation	Comments
Convective Available Potential Energy	CAPE	Moncrieff and Miller (1976)	$g \int_{Z_{LFC}}^{Z_{LNB}} \frac{T_{ve} - T_{vp}}{T_{ve}} dz$	T_{ve} is the virtual temperature of the environment and T_{vp} is the virtual temperature of the parcel. Z_{LNB}- and Z_{LFC} are the height at level of neutral buoyancy and level of free convection	
Surface lifted Index	SLI	Means (1952)	$T_{500} - T'_{sfc\delta500}$	T is the environmental temperature (°C) at 500 hPa. T′ is the temperature of the parcel at 500 hPa after it is lifted dry adiabatically of from surface (sfc) to its condensation level and moist adiabatically thereafter	Thermal stability of the atmosphere at 500 hPa in terms environmental temperature and parcel temperature.
Humidity Index	HI	Litynska et al (1976)	$(T - T_d)_{850} + (T - T_d)_{700} + (T - T_d)_{500}$	T and T_d are the dry bulb and dew point temp. Subscripts indicate the pressure levels in hPa	measure of saturation at 850 700 and 500 hPa
Total Total	TT	Miller (1967)	$2(T_{850} - T_{500}) - (T_{850} - T_{d850})$	Notations similar to HI	Lapse rate between 850 and 500 hPa and measure of saturation at 850 hPa

towards saturation at 500-hPa levels. Values of HI at 0600 and 1200 UTC are 17.6 and 0.2 respectively. HI represents the level of saturation of the atmosphere at 850, 700 and 500 hPa. The reduction of HI value from 17.6 to 0.2 implies that atmosphere is close to saturation at three specified levels at 1200 UTC. Similar indication is seen from CAPE values. CAPE at 0600 UTC is 5766.04 J kg^{-1} and that at 1200 UTC is 119.45 J kg^{-1}. The decrease in CAPE clearly suggests the atmosphere has released some of its available energy during 0600 UTC to 1200 UTC. Thus computations of these indices further establish the fact that is reflected by T and Td plot that ambient atmosphere was unstable at 0600 UTC and by evening it starts reaching saturation. With this background atmosphere the model is started at 0600 UTC of 14 July 1998. The warm bubble is applied at first time step and subsequently model is integrated for 12 hours with 5 and 1 km grid resolution. The results of 5 km and 1 km grid resolutions are discussed separately below.

a) Results of 5-km grid simulation

The one hourly forecast of dry bulb and dew point temperature at Kolkata location 22.65° N, 88.45° E is plotted in Fig.3. It can be seen from Fig.3a that predicted T and Td curves are close to each other at 1 hour forecast. At 500 hPa T and Td has coincided with each other implying complete saturation. On 2 hour forecast plot (Fig.3b) T and Td is seen to come even closer in the lower as well as upper levels. However from 3 hour forecast onward T and Td curves are seen to be away from each other signifying unsaturated atmosphere and an atmosphere with less instability. On Figs 3i, 3j and 3k a lower level inversion is found to develop in the plot of T. Thus the plots of T and Td (Fig.3) clearly suggest that the simulated environment reaches saturation on 1 and 2 hour forecast and in subsequent hours it shows a relatively unsaturated atmosphere. To examine the temporal evolution of the storm, vertical velocity at Kolkata latitude is analyzed (Fig not shown). In consistence with the T, Td plot, a strong vertical velocity (Fig not shown) of 10 ~ 12 m s^{-1} is found to develop after 1 hour forecast. Strong positive vertical velocity of the order of 4~6 m s^{-1} is seen in the 2 and 3 hour forecast (Fig not shown). The strong positive vertical velocity in x-z plane is seen to occur at around 88.3° E longitude, which is close to the longitude of Kolkata station. The cross section of vertical velocity is considered at 22.65° N latitude, so effectively the location of simulated strong positive vertical velocity becomes 22.65° N, 88.3° E which is very much close to the location of Kolkata station. However the predicted vertical velocity between 4 hour to 12 hour does not show strong convection over Kolkata. This as such suggests that during first three hour of integration the model simulates the storm. To further analyse the model results, one hourly plots of vertical cross section of 12-hour prediction of total cloud condensate at 22.65° N latitude are shown in Fig.4. The total cloud condensate comprises of all the prognosed cloud constituents namely cloud liquid water, pristine ice, graupel, aggregate, snow and hail. Thus the plot of total cloud condensate represents the evolution of model-simulated cloud. After one-hour integration model has produced a vertical column of cloud (Fig.4a) with total cloud condensate mixing ratio 6 gm kg^{-1}. The location of this columnar cloud is found to be around 88.3°E and very much in consistence with the vertical velocity field. The value of predicted total cloud condensate is found to reduce to 1.8 gm kg^{-1} on 2 and 3 hour forecast (Figs 4b and 4c). Total cloud condensate plots do not show formation of cloud in and around Kolkata location during 4 to 12 hour forecast. Thus analyses of the simulated temperature, vertical velocity and total cloud condensate clearly suggest that the model has simulated the storm after 1 hour integration and it has gradually dissipated in the following 2 and 3 hour forecast. In the remaining hours model could not simulate any significant convection. The forecast precipitation rate and 12 hour accumulated precipitation are shown in Figs 5 and 6a respectively. From the precipitation rate (cm hr^{-1}) it is evident that model has produced very high precipitation (20 cm hr^{-1}) during first hour forecast and it has reduced in the subsequent forecast hours. The twelve-hour accumulated forecast precipitation (Fig.6a) is found to be around 24 cm. The India Meteorological Department report of Kolkata station suggests the rainfall due to the system was 4.7 cm. The storm was reported at 1200 UTC and during past six hours. Thus in comparison to observation the 5 km grid simulation has over predicted the rainfall and the time of occurrence of the storm appeared to be much early than the report.

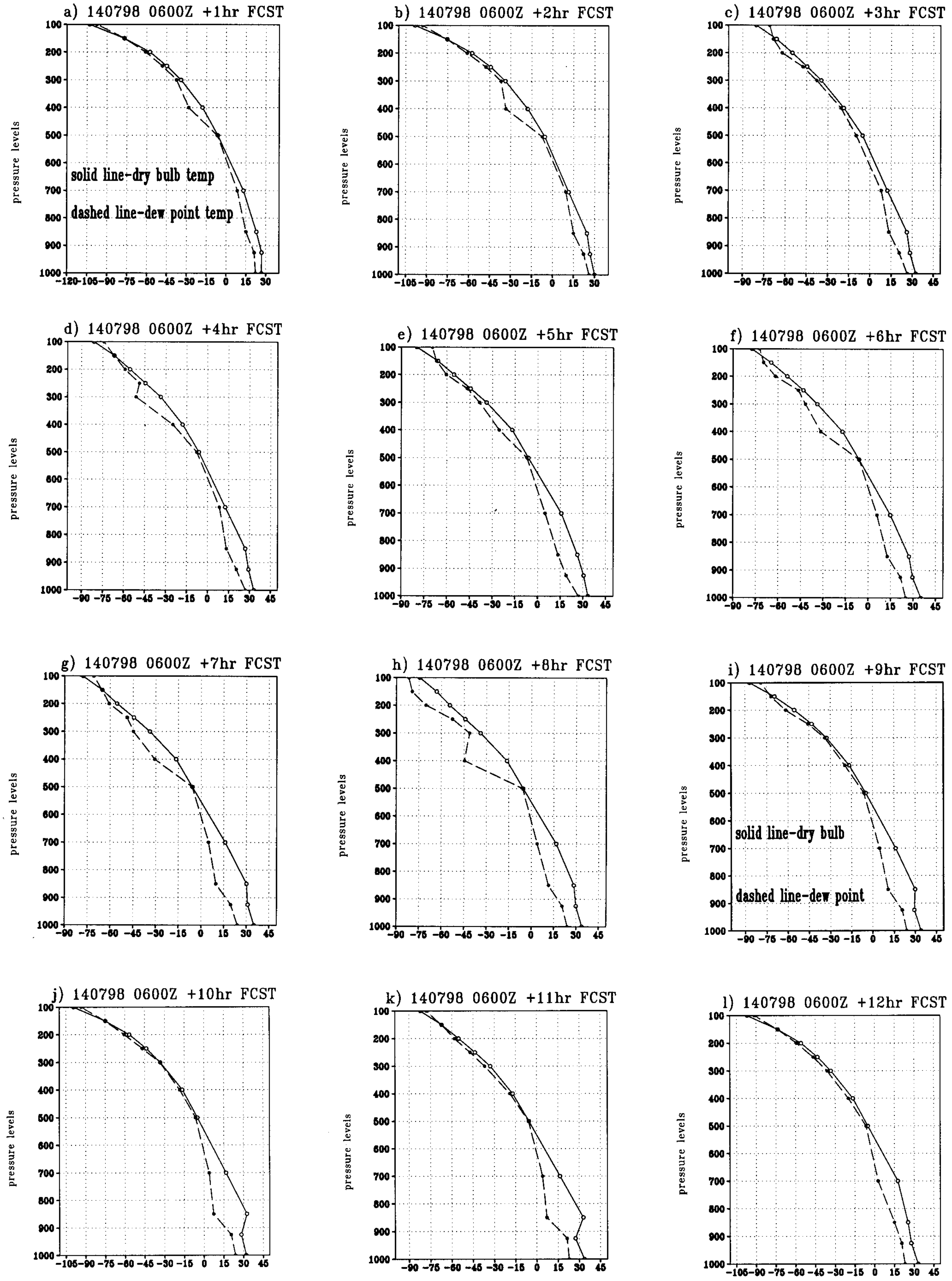

Figure 3. Plot of T and Td with pressure levels at Kolkata lat-lon as simulated by RAMS in each hour (a) to (l) for a total period of twelve hour with 5 km grid resolution.

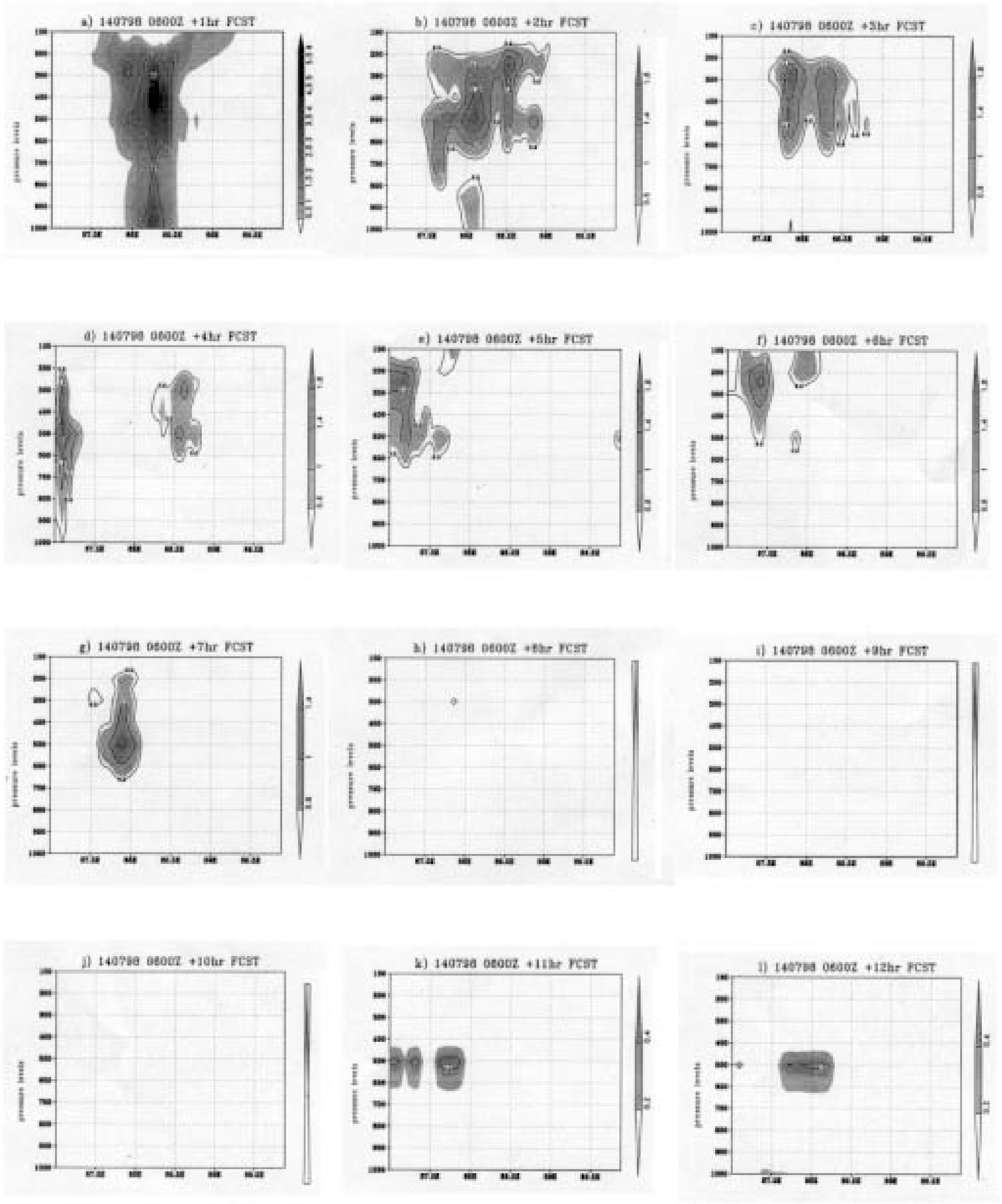

Figure 4. Cross section of hourly forecast of total cloud condensate (gm kg^{-1}) at Kolkata (a) to (l) for a total period of twelve hour with 5 km grid resolution.

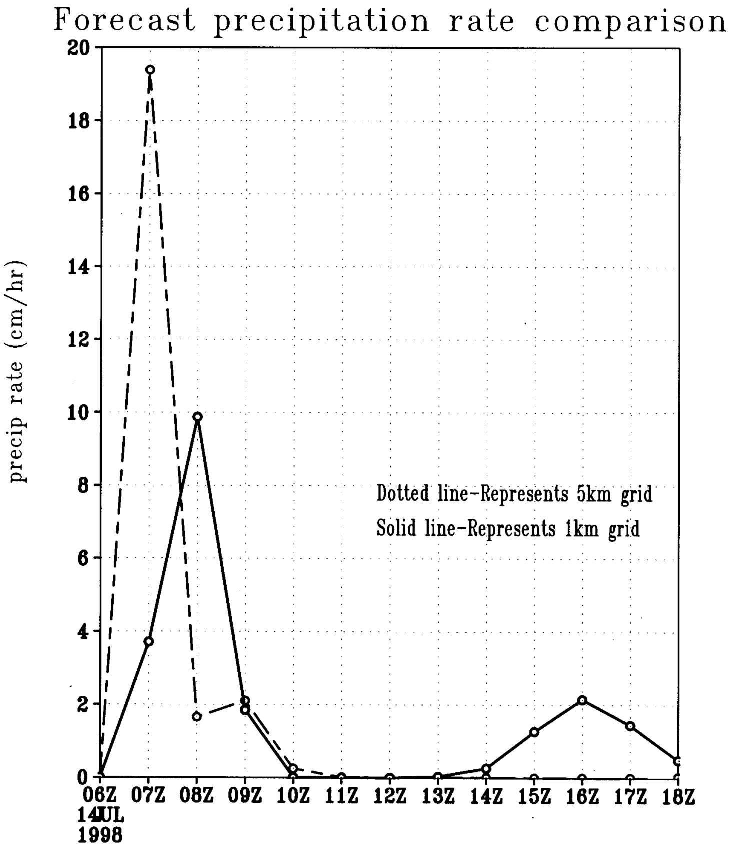

Figure 5. Comparison of forecast precipitation rate over Kolkata by 5 km and 1 km grid domain.

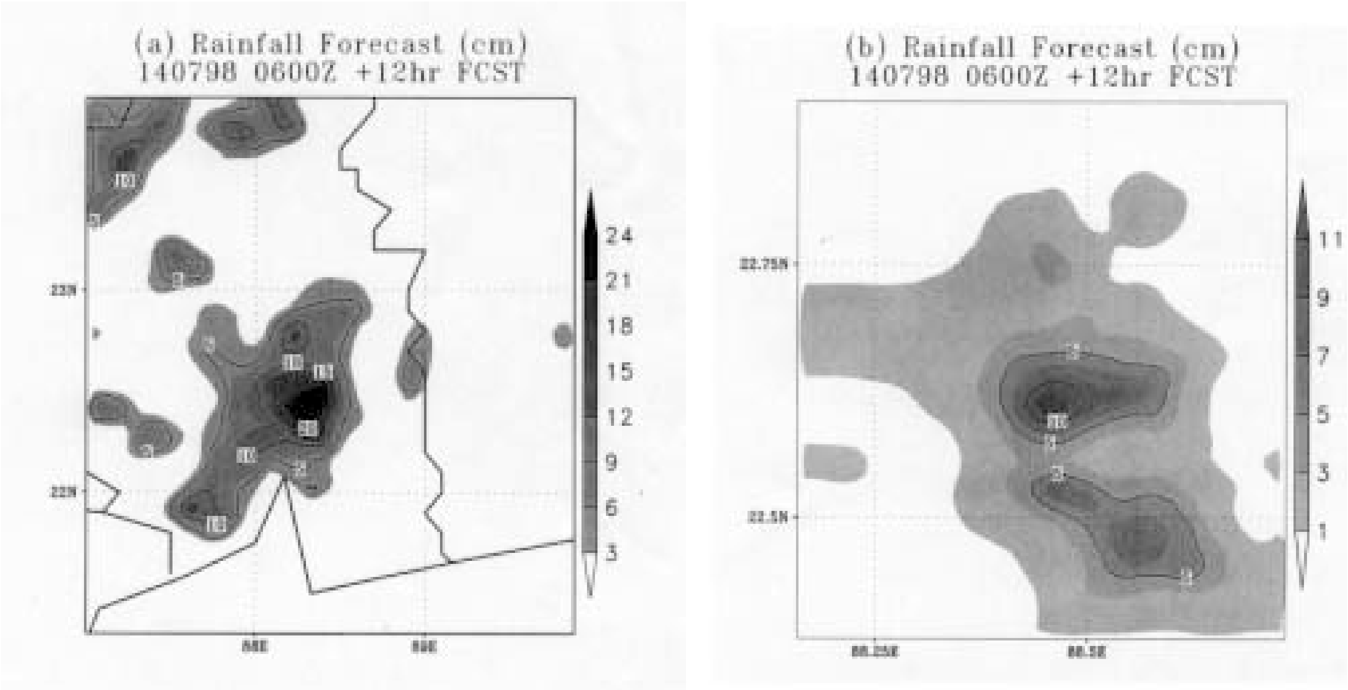

Figure 6. Comparison of forecast twelve hour accumulated precipitation by a) 5 km and b) 1 km grid recolution.

b) Results of 1 km grid simulation

The vertical profile of air temperature and dew point temperature as obtained from RAMS simulation with 1 km grid resolution are shown in Fig.7. It may be noted that at one hour forecast both the profile are superimposed on each other at all the levels (Fig. 7a). This clearly indicates that the atmosphere is totally saturated. If the temperature profiles of Fig. 7 are compared with that of Fig. 3, it can be seen that the level of saturation is more in 1 km simulation than that of 5 km grid domain. Figs 7b, 7c and 7d further suggest that simulated atmosphere was very close to saturation at 2, 3 and 4-hour forecast. At 5 and 6 hour forecast (Figs 7e and 7f) the two curves (T and Td) become apart and again at 7 hour forecast T and Td become adjacent to each other at 1000 hPa level and in the middle and upper troposphere. This implies that simulated atmosphere is close to saturation on first three hour forecast and again on 7, 8 and 9 hour forecast and this as such is conducive for the instability to grow. The x-z cross section of predicted vertical velocity (m s^{-1}) at 22.65°N is shown in Fig.8. Fig.8a shows the 1-hour forecast of vertical velocity. At 88.5°E a strong positive vertical velocity of the order of 16 m s^{-1} is seen (Fig.8a). The region of strong vertical velocity is found to get shifted eastwards on 2 hour forecast (Fig.8b) and the maximum values of positive vertical velocity is found to be 6 m s^{-1}. In subsequent forecast hour the model shows dissipation of the strong vertical motion. However at 8 hour forecast (Fig.8h) vertical velocity again starts building. On 9 hour forecast a strong positive velocity of the order of 9 m s^{-1} is predicted at 88.5° E, which gets dissipated in the following three hour. Thus in contrast to 5 km grid simulation 1 km grid run has simulated a strong convection at one hour and nine hour forecast. This clearly suggests that 1 km grid is able to generate the convection in late afternoon hours, which the coarse grid is unable to produce. The one hourly prediction of total cloud condensate superimposed by streamlines of horizontal and vertical velocity are shown in Fig.9. This figure will clearly bring out the upward motion and associated cloud formation as predicted by RAMS. Fig.9a shows a strong upward motion associated with cloud condensate taking a columnar shape typically seen for thunderstorms. The highest value of cloud condensate is found to be 3.2 gm kg^{-1} located between 600-200 hPa and the base appears to be around 900 hPa where the value of cloud condensate is around 0.2 gm kg^{-1}. This matches well with the TEPHI gram plot (Fig.1) of 0600 UTC where the Level of Free Convection (LFC) is found to be at 820 hPa. The strong vertical motion and associated cloud persists in the 2 hour forecast (Fig.9b) and subsequently the storm is found to be dissipated. At 8 hour forecast the vertical motion is again seen associated with cloud. At 9-hour forecast strong upwards motion and columnar cloud appears and this is seen to be dissipated in the 10 and 11 hour forecast. In analyzing wind vectors (Fig not shown) it is found that the finer grid (1 km) is able to show a closed circulation north of Calcutta after 9 hour forecast and this infact has further enhanced the lower level convergence in the region. This low level convergence has resulted strong vertical lift that is seen in the 9 hour forecast shown in Fig.9. To compare the predicted precipitation rate by 5 km and 1 km grid, let us refer Fig.5. This figure clearly indicates that forecast precipitation rate by 1 km grid resolution has two maxima; one of them is attained after 2 hour integration and the other after 9 hour integration. The first maxima suggests precipitation rate of 10 cm hr^{-1} and the second is of 2 cm hr^{-1}. It appears from these figures that 1 km grid has simulated the storm at around 7~8 UTC and at 15~16 UTC. As per the observation there was report of rain and thunder at 1200 UTC and during past six hours. Thus the observation suggests some convective activity before 1200 UTC. In comparison to observation, 1 km grid domain is found to well simulate the convective activity at two times although the second convection has been simulated with a lag of two hour, which means model, generates the convection at 14 UTC (at 8 hour forecast) instead of 12 UTC. To compare the 12-hour accumulated forecast precipitation let us refer Fig 6. Fig 6b shows the 12 hour accumulated precipitation in cm by 1 km grid domain. The highest amount of rain predicted over Kolkata by 1 km grid domain is 11~13 cm. Thus although both the domains (5 km and 1 km) have over predicted the precipitation, 1 km grid domain has over predicted with lesser amount. However the location of rainfall is found to be in and around Kolkata station by both the domains.

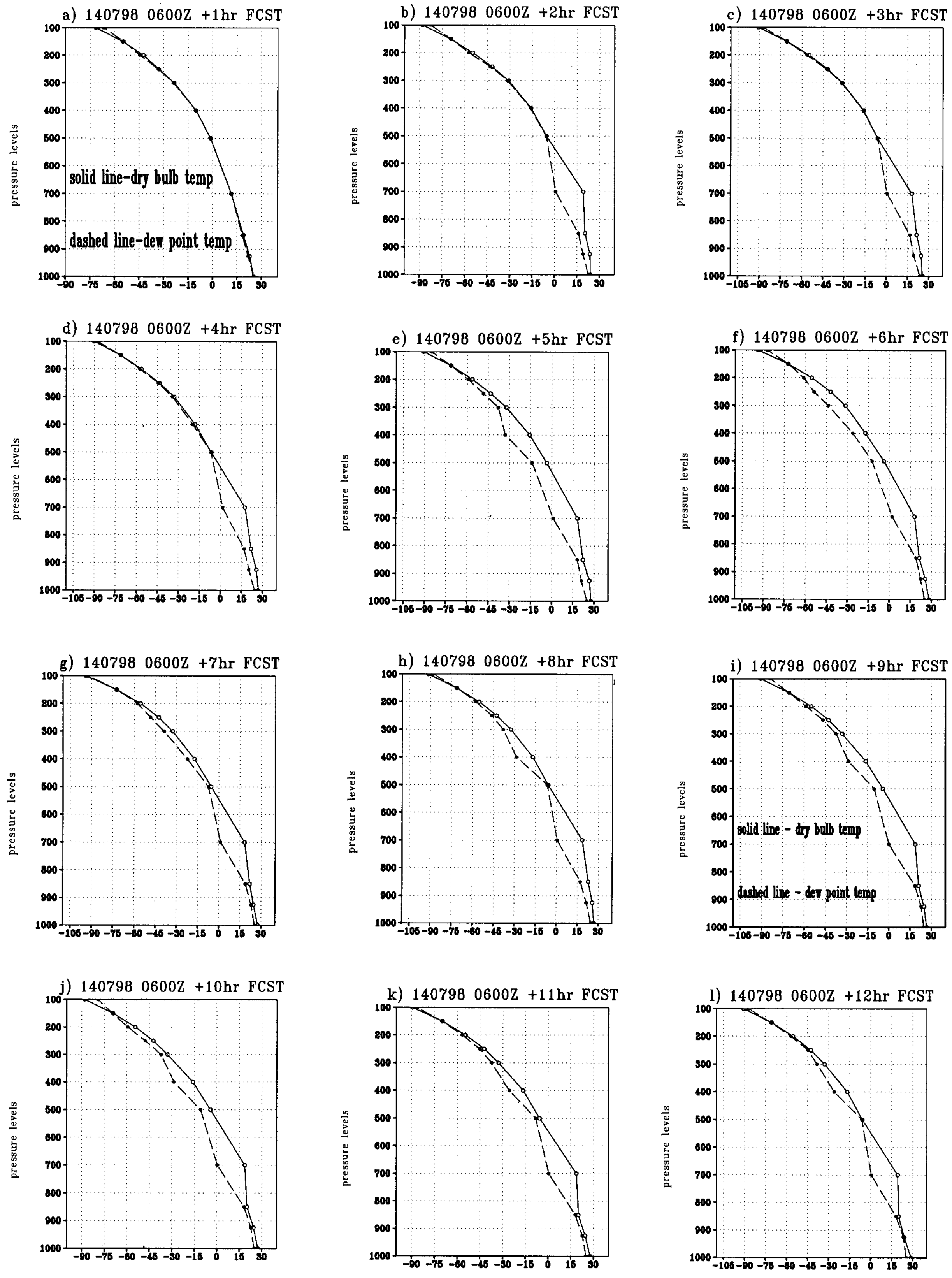

Figure 7. Plot of T and Td with pressure levels at Kokata lat-lon as simulated by RAMS in each hour (a) to (l) for a total period of twelve hour with 1 km grid resolution.

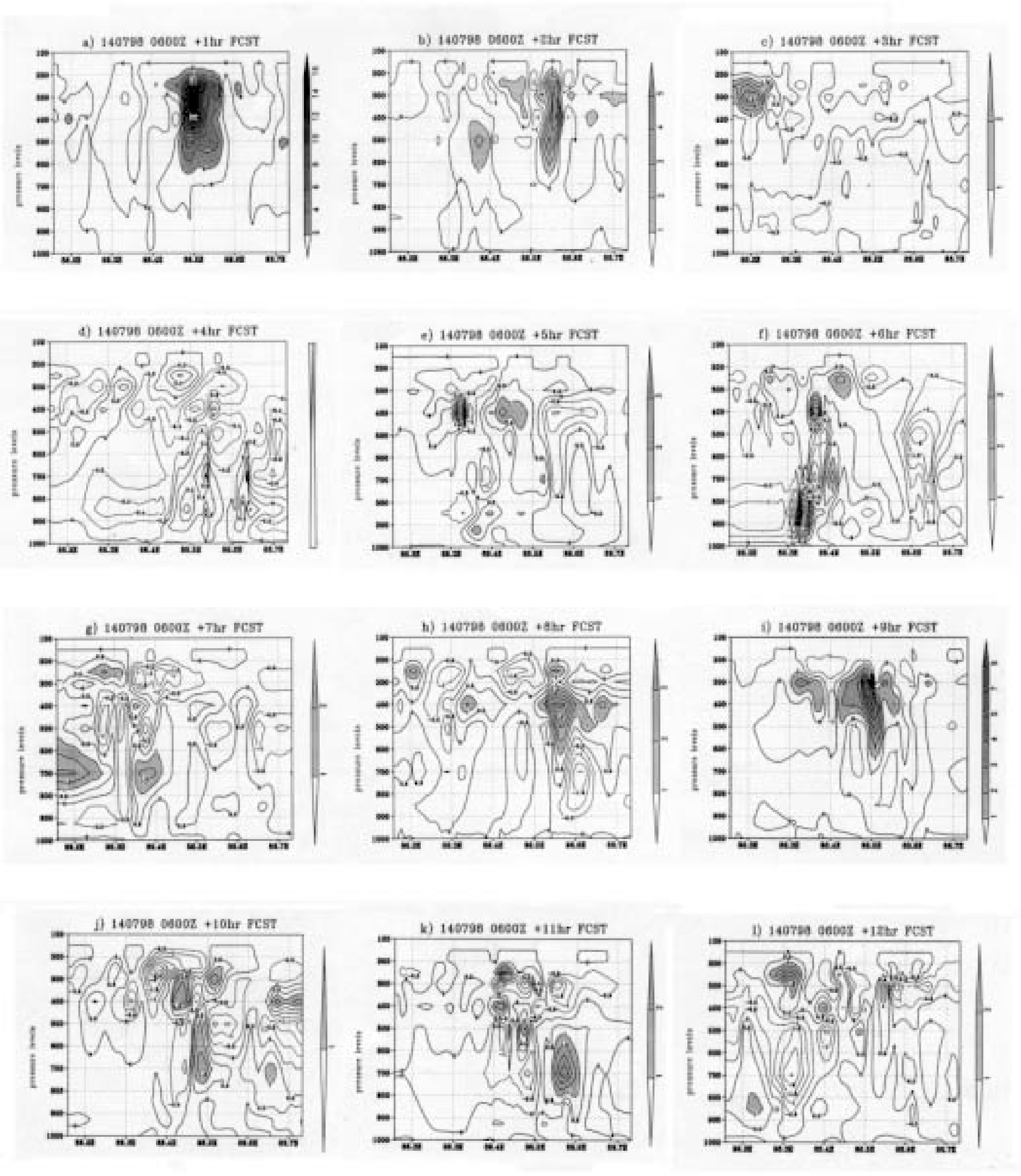

Figure 8. Cross section of hourly forecast of vertical velocity (ms^{-1}) at Kolkata (a) to (l) for a total period of twelve hour forecast with 1 km grid resolution.

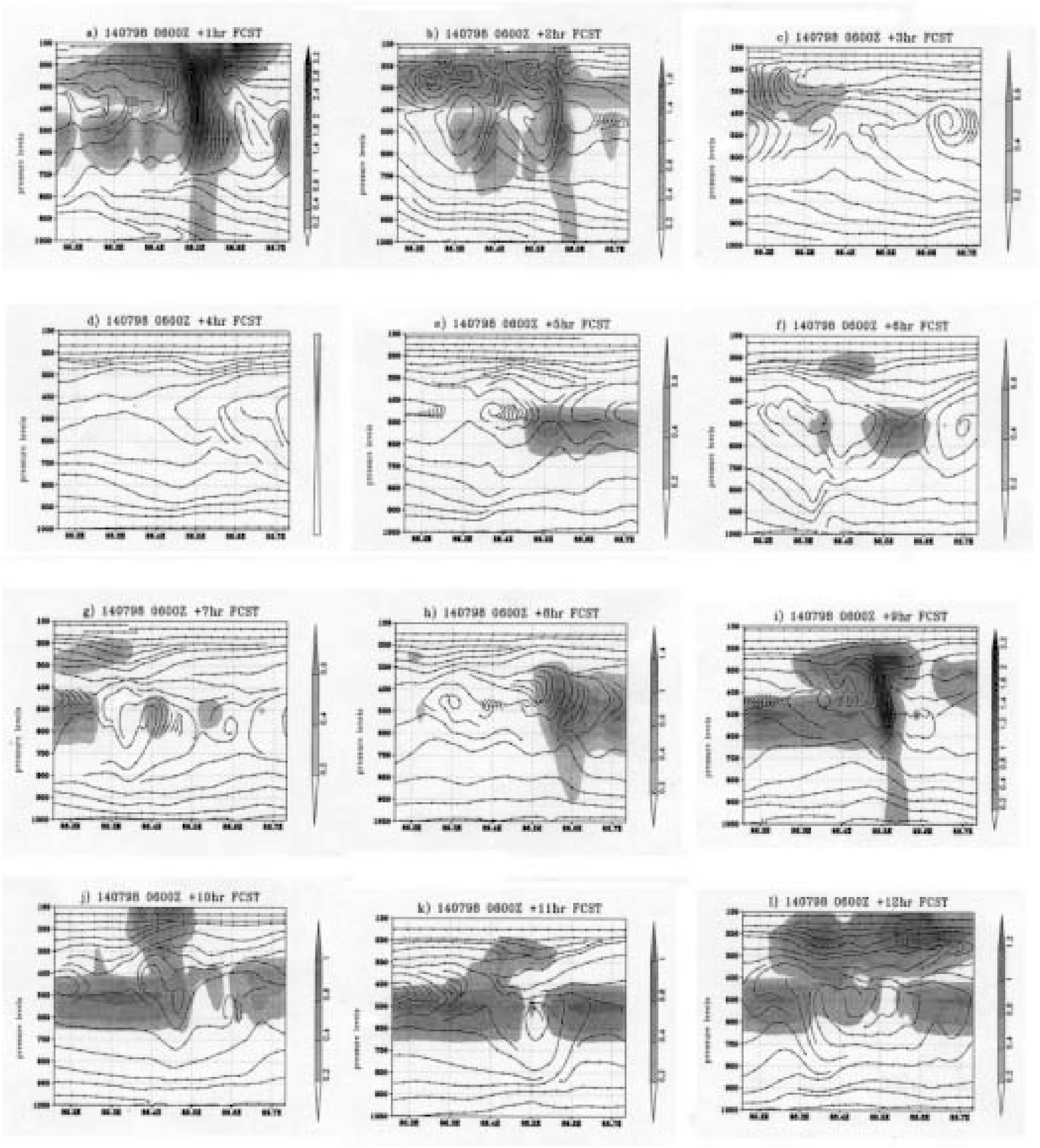

Figure 9. Cross section of streamline of u and w along with total cloud condensate (gm kg-1) in each forecast hour with 1 km grid resolution.

CONCLUSIONS

Thunderstorm of 14 July 1998 is simulated with 5 km and 1 km grid resolution using RAMS. The model is initialized with 0600 UTC rawinsonde data over Kolkata station collected as part of GAME 1998. The moisture and potential temperature of the initial atmosphere is perturbed with a thermal bubble. 12-hour forecasts are performed using both these grids. Analysis of forecasts by both the grids suggest that after one hour integration a strong convection associated with development of towering cloud and upward motion is simulated by both the grids. In consistence the coarse grid (5 km) has produced very high precipitation rate of the order of 20 cm hr^{-1} after one hour forecast. As per the IMD observation the storm was reported to occur over the station at 1200 UTC and there was report of thunder and rain during past six hours. The coarse grid could not reproduce the convection in the afternoon as per the IMD observation. The predicted precipitation also is found to be much more (24 cm) than what is realized (4.7 cm). In contrast the 1 km grid has simulated two strong convections. The first convection is simulated at 1~2 hour forecast and the second one at 8 hour forecast. After 1~2 hour forecast model simulates the environment of 0800 UTC (1300 IST) and this is the time when generally the convective activity starts developing at the Gangetic planes. The systems reach maturity by afternoon (1200 UTC) and as per the IMD report of 14 July 1998, the thunderstorm was reported at 1200 UTC. The 1 km grid simulation reproduces the second peak of convective activity after 9 hour forecast i. e. at 1500 UTC, which is three-hour lag with the actual observation. This lag of model simulation and actual realisation may be attributed to the limitation of idealized simulation where the system does not interact during its time of evolution with the ambient atmosphere where as in reality it actually does so. The vertical velocity and total cloud condensate are found to be of higher intensity in 1 km grid simulation than that of 5 km grid. The evolution of cloud condensate by 1 km grid domain in different forecast time (Fig. 9) has clearly indicated the convective development over the station at two times. This is again reflected by the forecast precipitation rate by 1 km grid. Thus this study does establish the fact that different dynamical features of the thunderstorm over Kolkata are better reproduced by the 1 km grid compared to the coarse grid of 5 km resolution. This may be attributed to the very high (1 km) resolution of the finer grid of the model that enables it to resolve circulations at cumulus level.

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