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Simulation of weather systems over Indian region using mesoscale models

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With 8 Figures

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Summary

Simulation studies have been carried out for two weather systems namely; a pre-monsoon thunderstorm over east coast of India and a weak cyclonic circulation associated with feeble low pressure area over south peninsular India. Two sets of forecast results are obtained: one using Advanced Regional Prediction System Model and other using Weather Research and Forecasting Model. The model performances are compared by examining the predicted parameters like mean sea level pressure, wind, moisture fields and rainfall. The rainfall prediction is assessed qualitatively by comparing the spatial distribution with satellite cloud images and quantitatively by comparing rainfall rates with Tropical Rainfall Measuring Mission products and/or the observed station values reported in Indian Daily Weather Reports. It is found that in case of idealized simulation of thunderstorm, Advanced Regional Prediction System Model has well predicted the spatial distribution of rainfall which is consistent with the clouding in satellite cloud images. It also has simulated the diverging winds at lower levels associated with downdraft during mature/dissipation stage of thunderstorm. Weather Research and Forecasting Model failed to predict these features. In case of a weak cyclonic circulation simulation experiment, Advanced Regional Prediction System model is able to simulate the rainy area better compared to those produced by Weather Research and Forecasting Model. Both models failed to produce observed heavy precipitation rates.

1. Introduction

An accurate location specific and timely prediction is required to avoid loss of lives and property due to strong winds and heavy precipitation associated with sever weather systems. Understanding dynamics/physics of isolated heavy precipitation and other typical dynamical features associated with systems such as thunderstorms, squall lines, tornados, strong convection embedded in synoptic scale systems etc; is essential for better prediction. The State-of-the-art nonhydrostatic and compressible models such as Mesoscale Model (MM5) developed by Penn-State University/NCAR USA, Regional Atmospheric Modeling System (RAMS) of Colorado State University, USA and the Advanced Regional Prediction System (ARPS) model developed at the Center for Analysis and Prediction of Storms at University of Oklahoma, Norman, USA have shown capabilities of simulating mesoscale systems and/or mesoscale features associated with synoptic scale systems over USA, elsewhere and also over Indian region. The Weather Research and Forecasting (WRF) Model is a next-generation mesoscale numerical weather prediction system designed to serve both operational forecasting and atmospheric research. The development of WRF model has been a collaborative effort by the National Center for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration, the National Centers for Environmental Prediction (NCEP) and the Forecast Systems

Laboratory (FSL), University of Oklahoma and many others. WRF model is currently in operational use at NCEP.

Following are few recent studies over Indian region using these models. Mesoscale features associated with tropical cyclone such as; warm core, strong winds at and around center, are simulated using MM5 (Trivedi et al, 2002). MM5 has been used for simulation of Orissa Super Cyclone of 1999 and to study the impact of parameterization of physical processes on prediction of tropical cyclones over the Bay of Bengal (Mohanty et al, 2004; Mandal et al, 2004). MM5 is used by India Meteorological Department for prediction of rainfall. RAMS has been used for idealized simulation of July 1998 thunderstorm over Kolkata, India (Mukhopadhyay, 2004). In this study the sensitivity to grid resolution has been examined. It is found that the time of simulation of convection is better predicted by 1 km grid resolution compared to 5 km. The thunderstorms over northeast India are simulated using ARPS model by Mahapatra et al (2004). Simulations showed high values of updrafts and downdrafts inside the thunderstorm, indicating strong convection within a much localized area. ARPS has been tested for prediction of depression during southwest monsoon season and cyclone formed over Indian region by Vaidya et al (2004). The study showed that rainfall at southwest sector of depression and warm core associated with the cyclone are well simulated. WRF model was used for simulation of depression formed over Bay of Bengal and severe cyclonic storm formed over Arabian Sea during 2–5 October 2004 and 30 September–3 October 2004, respectively (Rama Rao et al, 2005). It is found that model is able to predict movement and intensity and well captured heavy rainfall areas. Recent diagnostic studies related to thunderstorm are, identification of suitable stability index for the thunderstorms over northeast India which is useful as a predictor for thundery/non-thundery days (Mukhopadhyay et al, 2003) and examination of movement, vertical extent and other features of two sever nor'westers during April 2003 over Kolkata (Mukhopadhyay et al, 2005) using Doppler radar and satellite observations. It is found from Doppler radar studies that at the time when the thunderstorm was over station, the convection has reached upto 16 km and the vertical velocities of the order of 6–10 m/s were observed.

The purpose of present study is to examine the performance of WRF model over Indian region by comparing the results with those obtained by ARPS model. The aim of the study is not to decide which model is better/suitable over Indian region; however the limited experiments conducted definitely give some clues about the model performances. Further it is to be noted that comparatively advanced version of ARPS is used in this study, however WRF model is still in its' development stage. This study is presented in the following manner. In Sect. 2, weather systems are described; Sect. 3 gives brief description of model, data and experiments conducted, Sect. 4 discusses results and Sect. 5 conclusions.

2. Weather systems

The occurrence of pre and post monsoon thunderstorms over Indian continent is a special feature. Thunderstorms are associated with heavy rainfall during short duration of 2–3 hours. It is useful for vegetations when it is in hot summer season. The synoptic scale weather systems like off shore trough, low-pressure area, depressions are common during southwest/northeast monsoon season. Tropical cyclones generally form during pre/post monsoon season. Following are details of weather systems studied in the present paper.

2.1 Thunderstorm

India Meteorological Department (IMD, web site: http://www.imd.ernet.in) reported a thunderstorm at Machilipatnam over east coast of India on 0000 UTC of 2 June 2005 and the rainfall reported is 3 mm on 0300 UTC of 2 June 2005. At this time, the northern limit of southwest monsoon was far away south in the Bay of Bengal and it had not reached southern tip of Indian landmass. As such this is a case of premonsoon thunderstorm.

2.2 A case of cyclonic circulation

A closed isobar of 1008 hPa was seen on surface chart over Maldives and neighborhood on 0300 UTC of 12 April 2001 published in Indian Daily Weather Reports (IDWR). The cyclonic circulation (here after referred to as cycer) was associated with this feeble low pressure area extending upto lower tropospheric levels. On 0300 UTC of 13 April 2001 it was over Kerala coast and adjoining parts and extended upto mid tropospheric levels. April is a transition month from winter to summer over India. This cyclonic circulation has formed when Indian region was under the influence of weak north–south pressure gradient and there was no strong large scale atmospheric activity.

3. The model, data and experiments

The ARPS model is a nonhydrostatic, compressible model developed at Center for Analysis and Prediction of Storms at University of Oklahoma, Norman, USA. The model uses terrain following vertical z-coordinate system. In horizontal Arakawa C-grid staggering is used. For space difference fourth-order accurate scheme for advection terms and for time difference leapfrog and split-explicit schemes are used. The physics include 1.5-order Turbulent Kinetic Energy (TKE) based explicit scale turbulence and Planetary Boundary Layer (PBL) parameterization. At the lateral boundaries 5-cell wide relaxation zone is used and at upper level Raleigh damping is applied. The detailed model discussion is found in Xue et al (2000; 2001). For cumulus convection two schemes used are: Kain–Fritsch scheme (1993) (hereafter referred as KF scheme) and Betts–Miller–Janjic (Betts and Miller, 1986; 1993; Janjic, 1994) scheme (hereafter referred as BMJ scheme). In the present study arps5.0.0 version is used.

WRF model has a Static Initialization (SI) component to produce terrain, landuse, soil data etc. on the simulation domain. WRF model supports nesting. The WRF model is fully compressible, non hydrostatic with mass-based terrain following vertical co-ordinate. In horizontal Arakawa C-type of grid staggering is used. For time integration Runga-Kutta 3rd-order accurate scheme is used. The physics includes WSM 3-class simple ice scheme for microphysics, Monin-Obukov for surface layer physics, thermal diffusion for landsurface and YSU scheme for PBL parameterization. For cumulus convection two schemes used are same as above namely; KF and BMJ schemes. In the present study WRF V2.0.3.1 version is used.

For a case of the thunderstorm, both models are initialized with a radiosonde sounding data of Machilipatnam at 0000 UTC of 2 June 2005

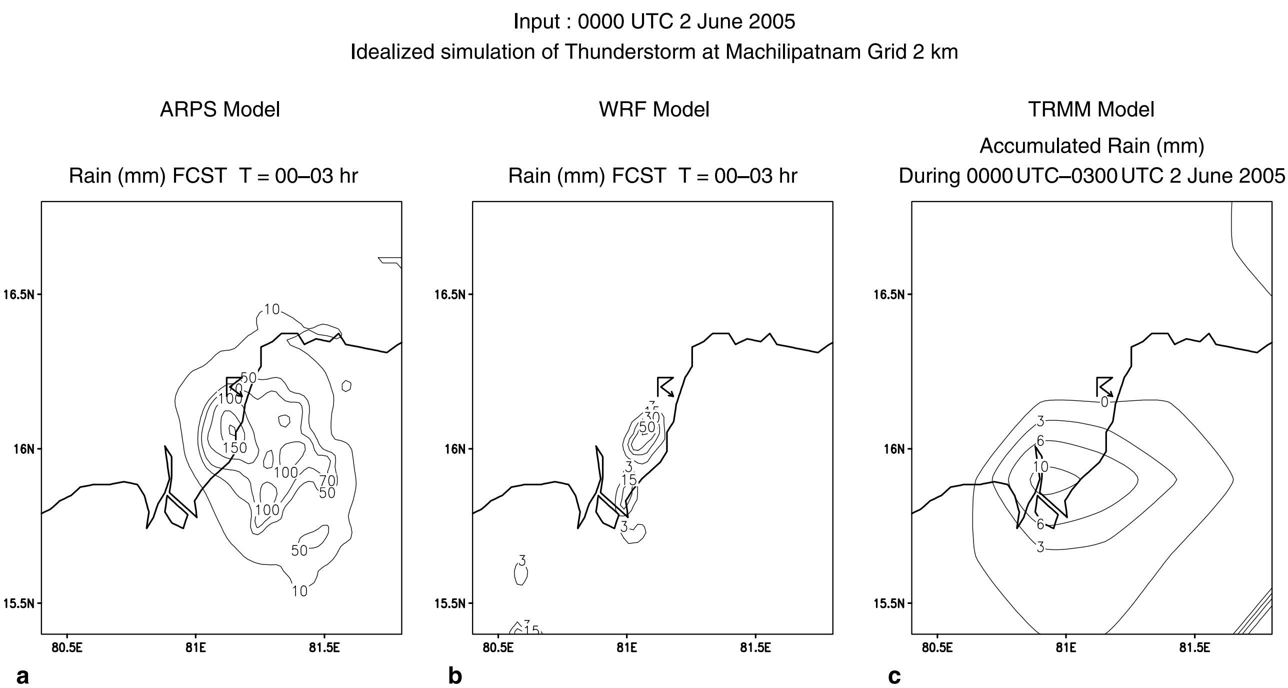

Fig. 1. Three hours accumulated rainfall (mm), (**a**) predicted by ARPS model, (contour levels 0, 10, 50, 70, 100, 150), (**b**) predicted by WRF model (contour levels 0, 3, 15, 30, 50), and (**c**) TRMM rainfall values (contour levels 0, 3, 6, 10)

from web site of University of Wyoming (*http://weather.uwyo.edu/upperair/sounding.html*). The integration domain extends from 80.34° E to 81.76° E and 15.40° N to 17.0° N with 2 km horizontal grid resolution. The thermal bubble of 2° K amplitude with horizontal radius of 10 km and vertical radius of 1.5 km is introduced as a perturbation. The number of grid points in horizontal are 91×91 and in vertical 35 levels are used. In this case model is integrated for 3 hours. For a case of cycer, model is initialized with data at 0000 UTC of 12 April 2001. The data extends from 55.3° E to 96.68° E and 8.56° S to 30.73° N for ARPS model with horizontal resolution of 50 km and 25 vertical levels. For WRF model, domain is 56.4° E to 95° E and 8° S to 29.3° N with horizontal resolution of 48 km and 18 vertical levels. With 25 km ARPS model runs are taken and domain of integration is 65.9° E to 86.6° E and 2° N to 22° N. With 16 km grid resolution WRF model runs are taken for a domain 68° E to 83.8° E and 3° N to 18.6° N. The model domains are selected in such a way that the disturbances remain in the center as far as possible. This version of WRF model works with odd ratio of coarse to fine grid resolution, in the present study it is selected to be 3:1. The coarse grid resolution selected is 48 km and with 3:1 ratio gives fine grid resolution of 16 km. The coarse grid of 48 km is closer to the 50 km grid resolution selected in ARPS model experiments. The input to the model is prepared by interpolating global reanalyzed data of NCEP/NCAR at $2.5^\circ \times 2.5^\circ$ lat × lon resolution with 17 levels in vertical on model grid.

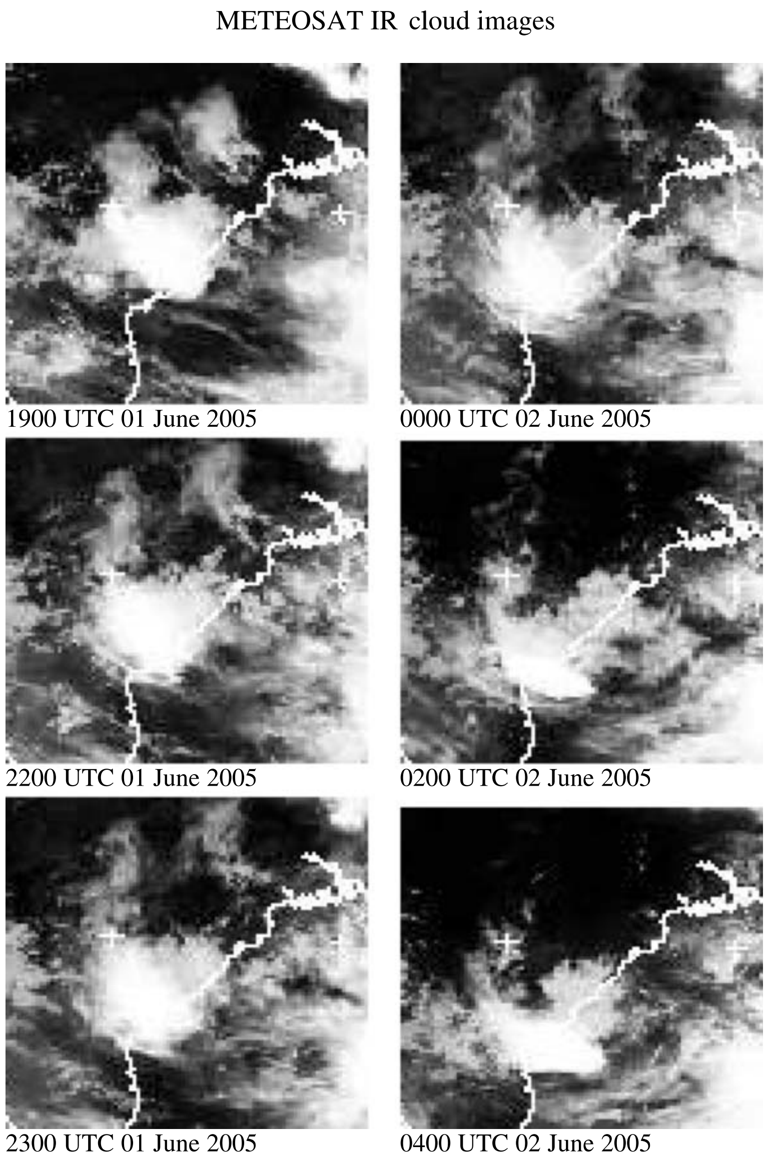

Fig. 2. IR cloud images from METEOSAT satellite

For coarse grid (50 and 48 km) grid points are 91×91 in horizontal and for fine grid they are 91×91 for ARPS and 109×109 for WRF model. The boundary fields for coarse grid run are prepared at every 6 hour interval from reanalyzed NCEP/NCAR data and for fine grid resolution

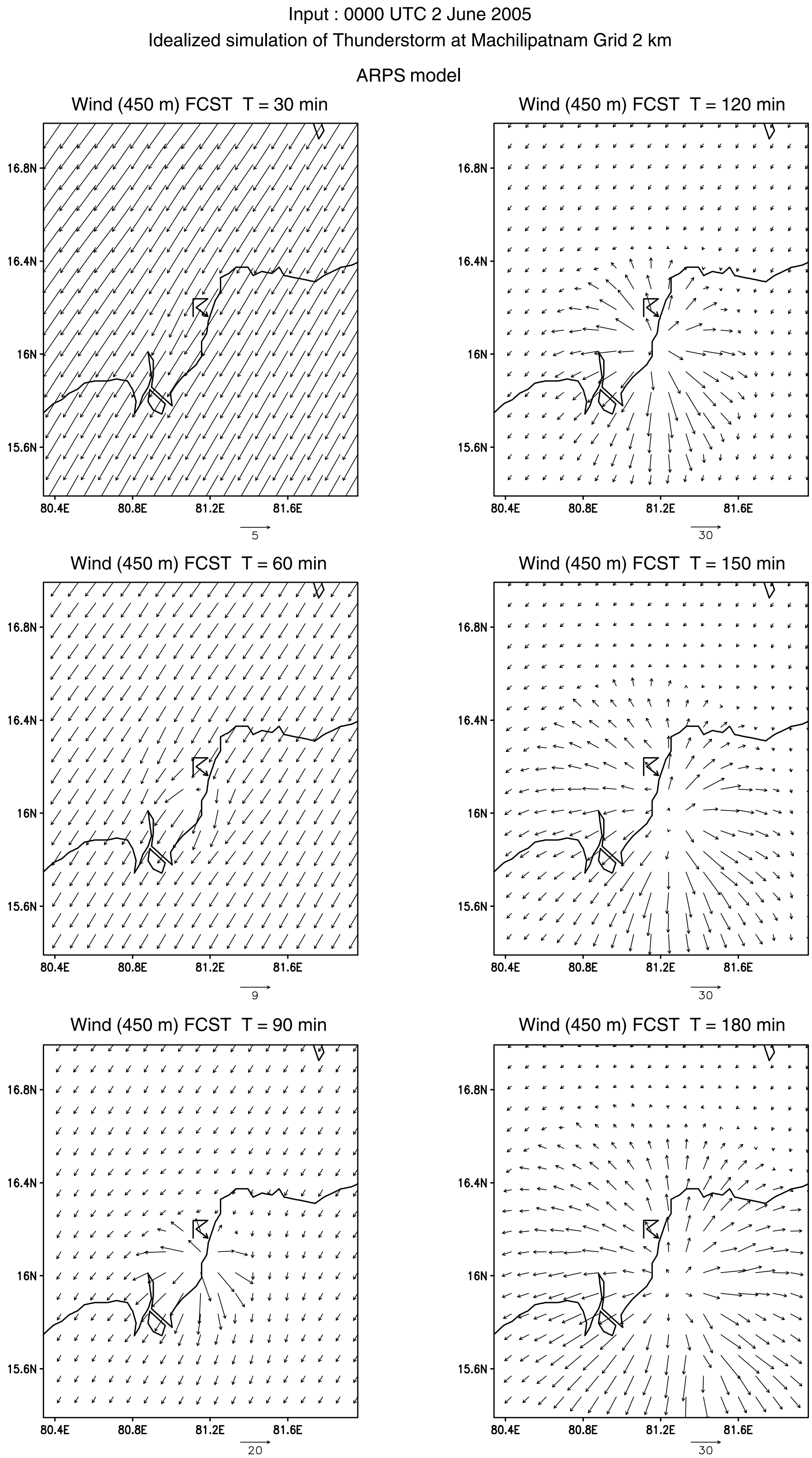

Fig. 3. Half hourly predicted wind field at 450 meter level by ARPS model (m/s)

they are obtained from coarse forecast fields (one-way nesting). The cumulus scheme kept same in coarse and the subsequent fine grid run. In all experiments models are integrated for 24 hours.

4. Results

For a thunderstorm simulation the rainfall fields are examined and the location of rainy area and/or rainfall rates are compared with satellite

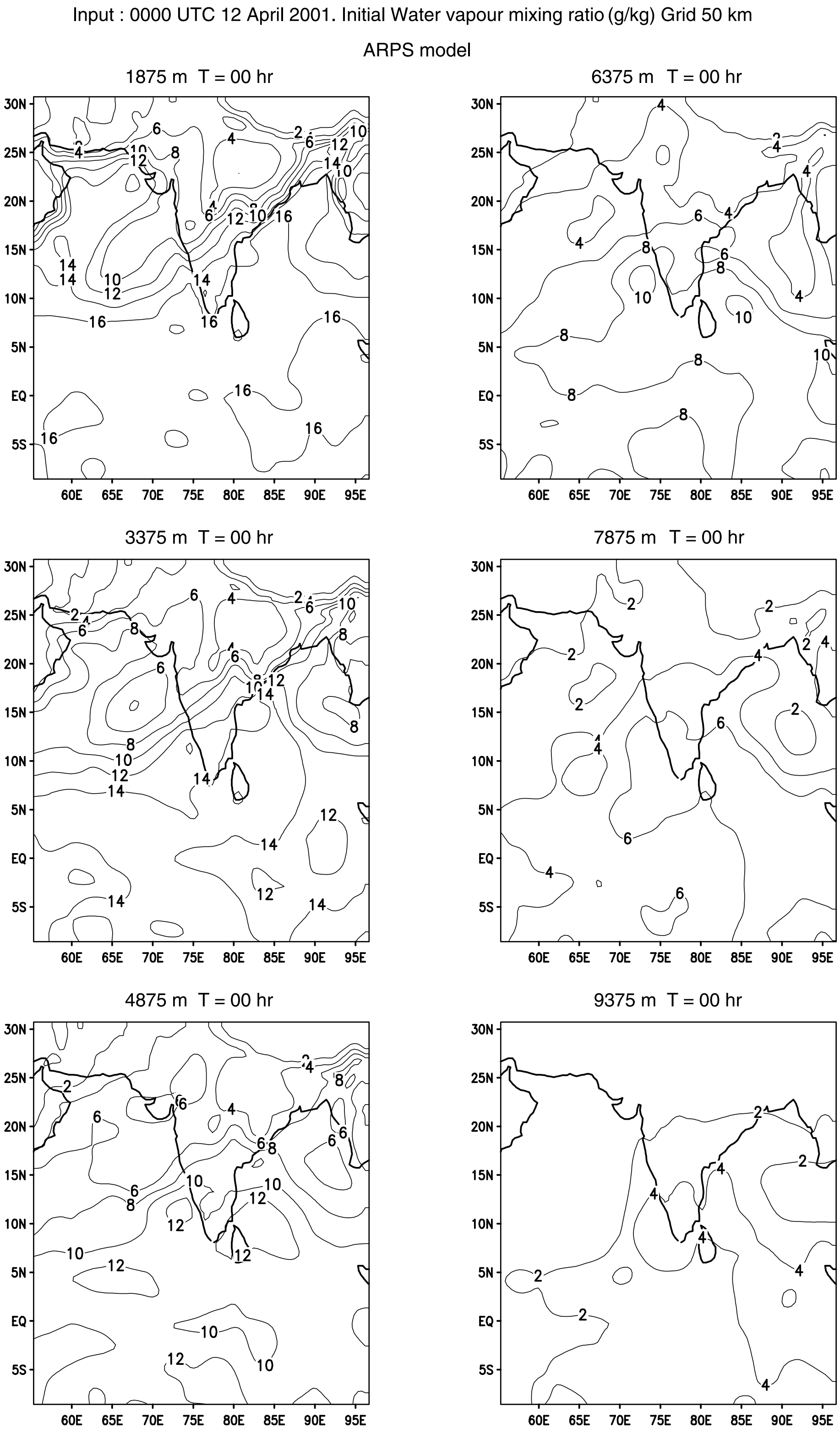

Fig. 4. Initial water vapor mixing ratio values (g/kg) at different levels for ARPS model. Contour interval is 2 g/kg

cloud images and 3-hourly 0.25° × 0.25° Rainfall Data Product from Tropical Rainfall Measuring Mission (TRMM) and with the station reports by India Meteorological Department. The other features like wind, vertical velocity and pressure fields are also examined. For a case of cycer, the predicted fields of wind, moisture and rainfall are compared. Although the purpose of the

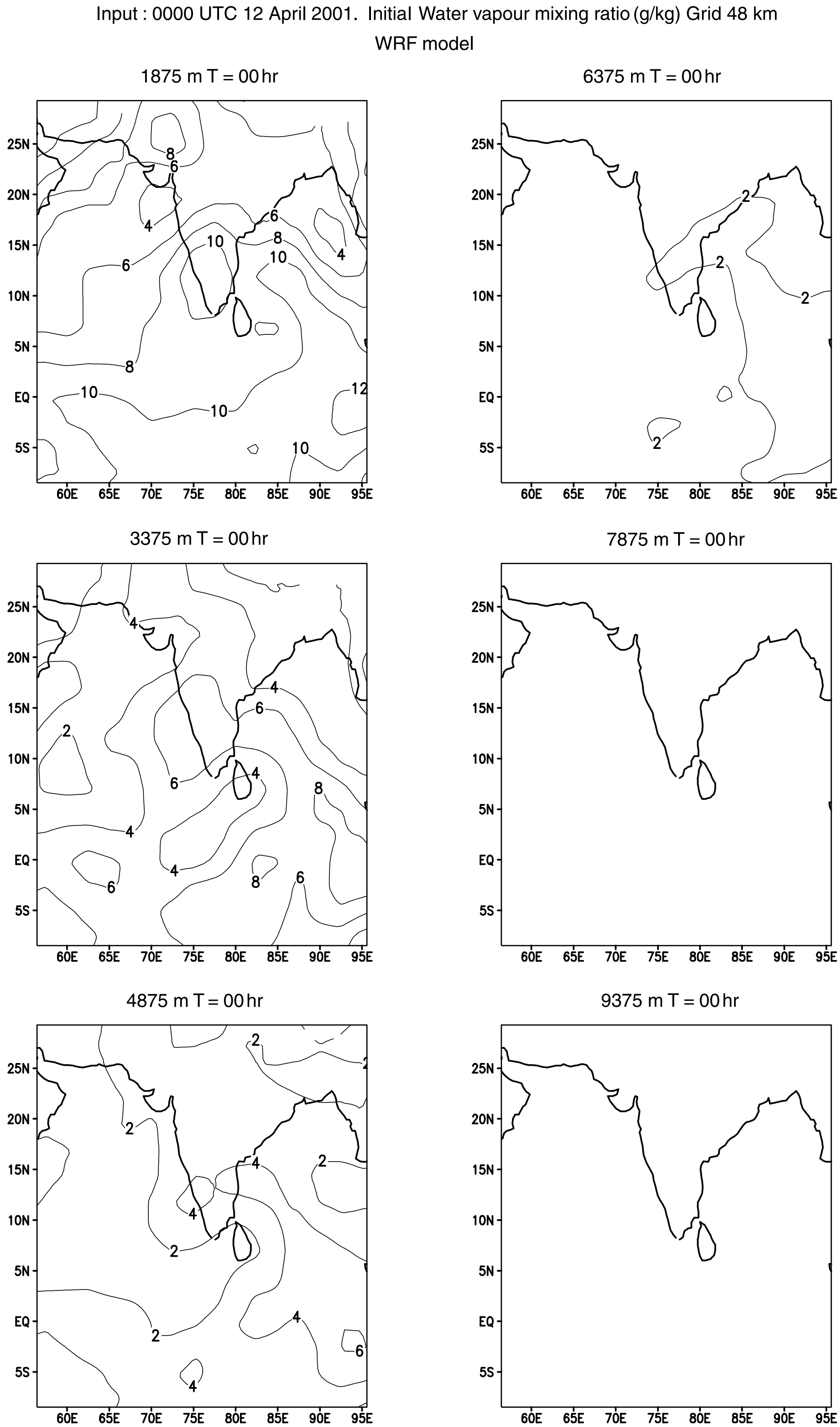

Fig. 5. Same as Fig. 4, but for WRF model

study is not to compare cumulus parameterization schemes, as the rainfall prediction depends basically on the cumulus parameterization scheme used, KF and BMJ schemes results are presented side by side for comparison.

4.1 Thunderstorm simulation

Most of the thunderstorms produce heavy rainfall during it's lifecycle of 1–3 hours. The rainfall reported at the Machillipatanam station is 3 mm at 0300 of 2 June 2005. For the verification of rainfall, TRMM rainfall values are used which are available over land and over the nearby oceanic region. Figure 1 shows plots of three hours accumulated rainfall fields produced by ARPS (Fig. 1a), WRF model (Fig. 1b) and TRMM (Fig. 1c). The METEOSAT IR cloud images are also examined during the period of thunderstorm and are shown in Fig. 2. It is seen that the clouds are not over station location on 1900 UTC and 2200 UTC of 1 June and from 2300 UTC of 1 June to 0000 UTC of 2 June clouds are seen at and around station. Further from cloud images of 0200 UTC and 0400 UTC of 2 June it can be seen that dense clouds are seen and are orientated in northwest to southeast direction. It is seen from Fig. 1 that the rainy area produced by ARPS model matches well with the TRMM rainfall product and the clouding seen in satellite images. WRF model produced smaller rainy area. Both the models produced rainfall rates one order more than the rainfall rates in TRMM data and reported by IMD. The predicted position of maximum rainfall is slightly away from the position seen in TRMM data set.

The other features like vertical velocity, mean sea level pressure (MSLP) fields and low level winds are examined. It is found that vertical velocity values of more than 8 m/s are produced at proper location and time by ARPS and WRF model produced vertical velocity of order of 8 m/s during the initial 1–2 hours of model integration. Closed isobars with high MSLP values at thunderstorm location are well produced by ARPS model compared to WRF model (figures not shown). Figure 3 shows the wind field at 450 meter level by ARPS model. It is seen that ARPS model very well simulated divergent winds which are associated with the downdraft in thunderclouds. Such downdrafts in thundercloud produce meso high at the surface which is characteristic feature of thunderstorm during mature and dissipation stages. Further the location of divergent winds coincides with clouding in satellite images. WRF fail to produce such divergent winds at proper locations.

4.2 A case of cyclonic circulation

Under the influence of the cycer, peninsular India received wide spread rainfall of considerable amount during 24 hours ending 0300 UTC of 13 April 2001. A station Kozikode on west coast received 172 mm of rainfall during 24 hours. The model results are judged in respect of predicted wind, moisture fields and rainfall.

4.2.1 Wind and moisture fields

Initial wind and moisture fields are decisive for prediction of rainfall. It is found that, the cyclonic circulation at off the tip of Indian peninsula is seen upto 7875 meter level in the initial wind fields of ARPS model; however it is seen upto 3375 meter in WRF model. At higher level a north–south trough along 70° E with strong

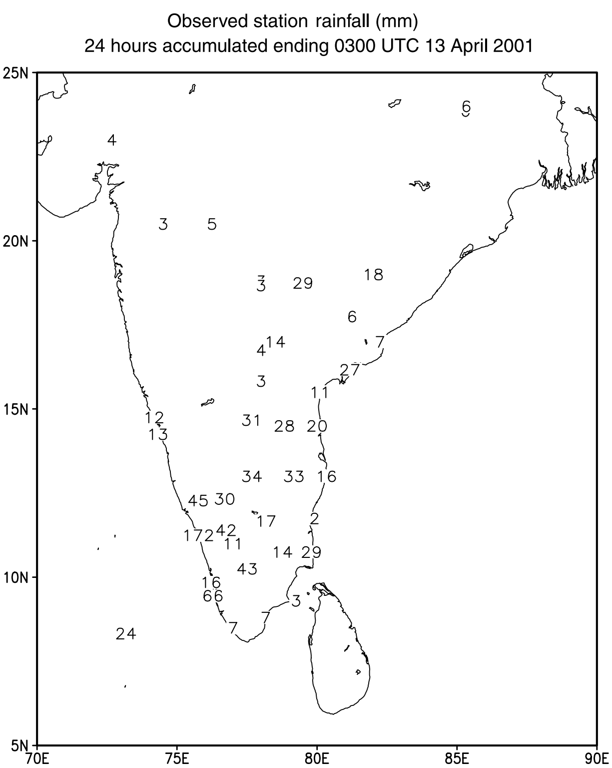

Fig. 6. 24 hours accumulated observed station rainfall values (mm) ending at 0300 UTC 13 April 2001

winds associated with it is seen in WRF model's input wind fields (figures not shown). The predicted wind fields show cyclonic circulation upto 6375 meter level in ARPS forecast, however WRF produced cyclonic circulation upto 4875 meter level and trough along 70° E with strong winds associated with it (figures not shown). Figures 4 and 5 show input values of water vapour mixing ratio for ARPS and WRF model, respectively. It is seen from Fig. 4 that mixing ratio values over peninsular India are around 8–16 g/kg upto 6375 meter level and 4–6 g/kg at higher levels in ARPS model. In case of WRF model, they are 2–10 g/kg upto 6375 meter level and less than 2 g/kg at higher levels as seen from Fig. 5. The predicted water vapour mixing ratio values are less in WRF model compared to ARPS model (figures not shown).

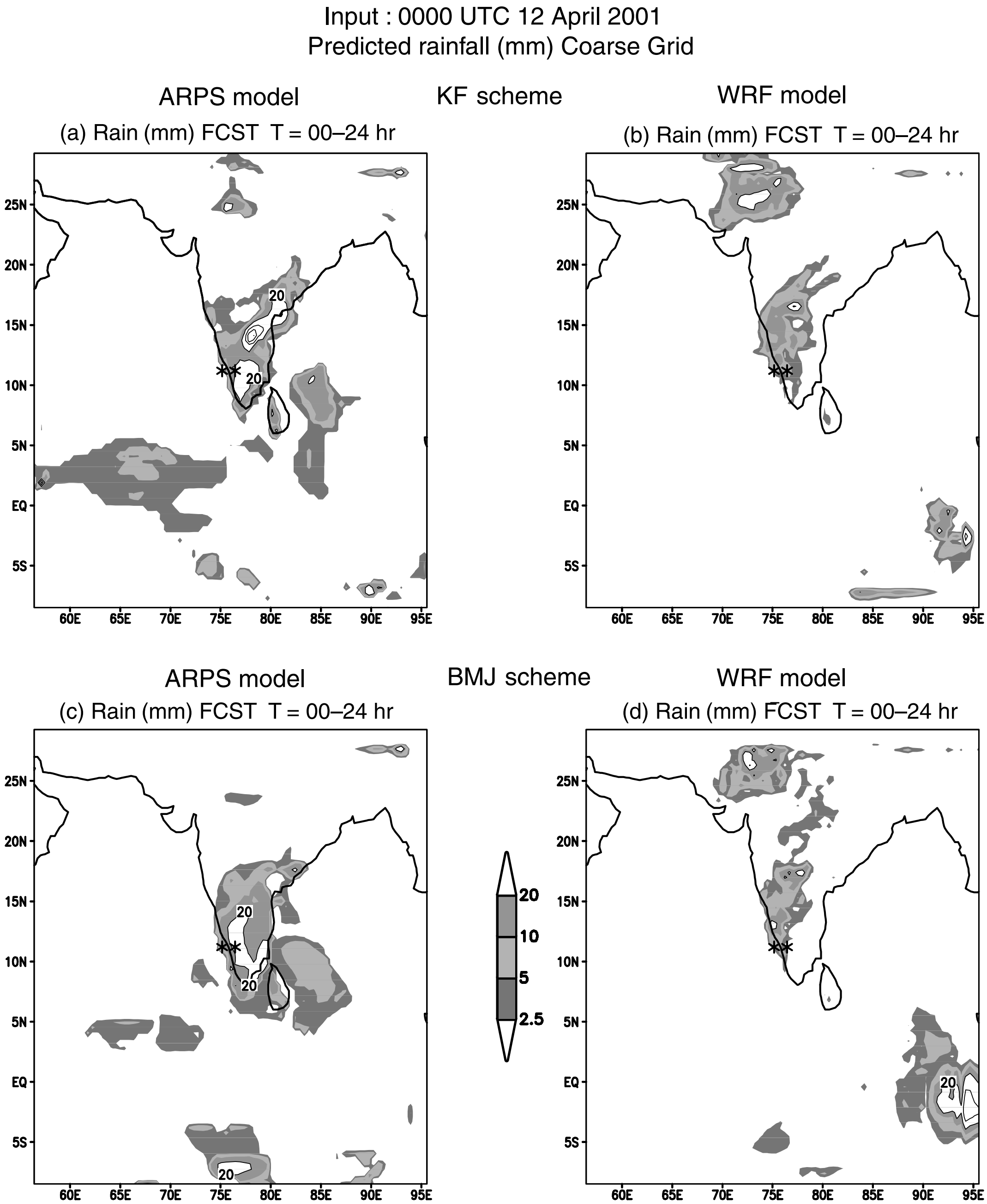

Fig. 7. One day predicted rainfall (mm) with coarse grid resolution (**a**) KF scheme with ARPS model, (**b**) KF scheme with WRF model, (**c**) BMJ scheme with ARPS model, and (**d**) BMJ scheme with WRF model. Contour interval is 20 mm/day

4.2.2 Rainfall

Figure 6 shows observed 24 hours accumulated station rainfall values ending at 0300 UTC 13 April 2001 as reported in IDWR. Figures 7 and 8 present one day predicted rainfall rates by coarse and fine grid resolutions, respectively. It is to be noted that the observed rainfall is south of 13° N and well distributed over the peninsular India. Most of the stations reported rainfall rates greater than 20 mm (Fig. 6). In Figs. 7 and 8, two stars is a location of Kozikode station. Both the convection parameterization schemes in ARPS model produced rainfall south of 15° N covering peninsular India and ranging from 5–40 mm with coarse grid resolution. In fine grid resolution experiment, heavy precipitation is produced along east coast by KF scheme. BMJ scheme produced qualitatively similar rainfall fields in coarse and fine grid experiments. WRF model produced rainfall at and around 15° N and no rainfall

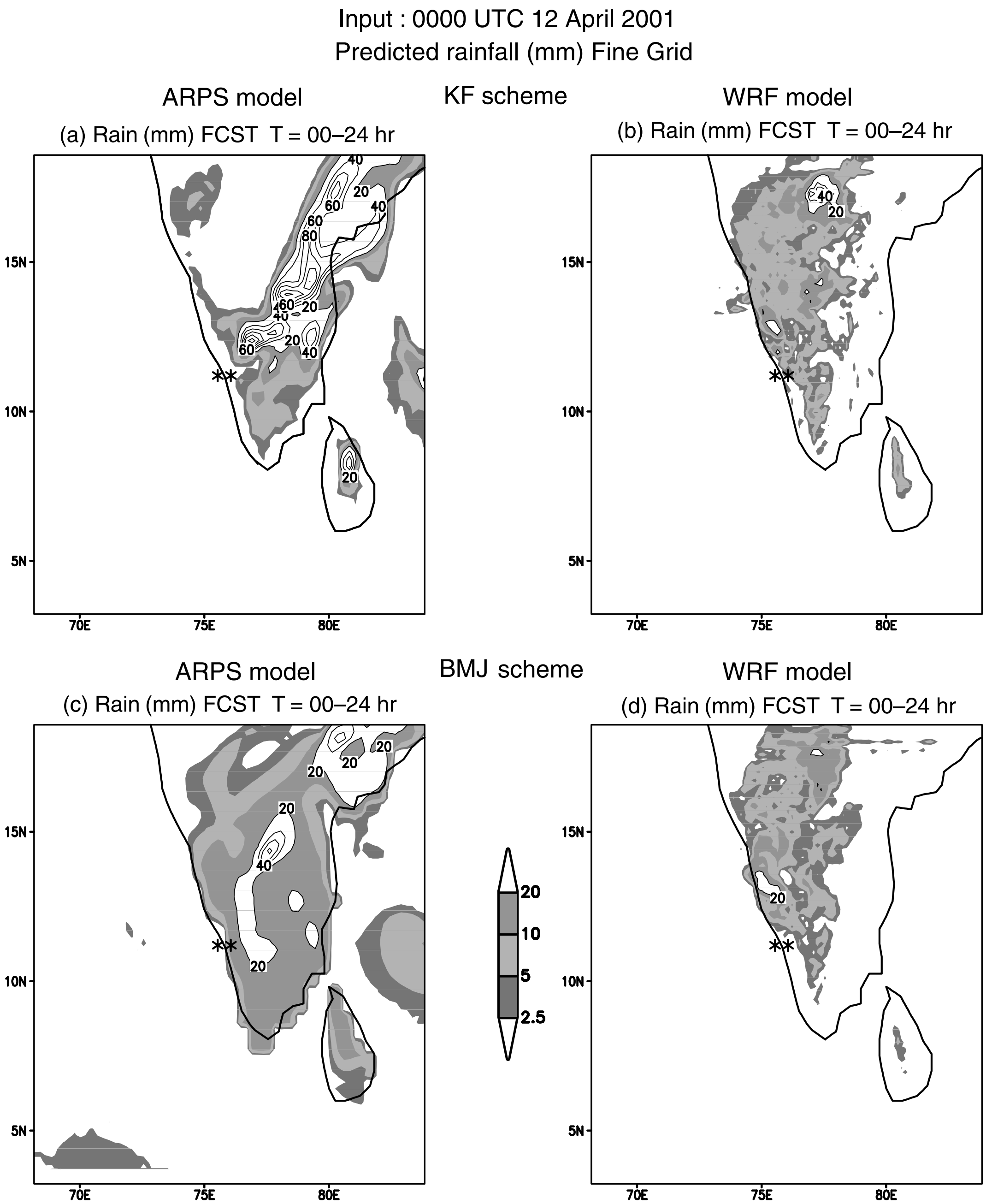

Fig. 8. Same as Fig. 7, but with fine grid resolution

simulated over tip of peninsular India and east coast. It also produced spurious rainfall over west central parts of India (at and around 25° N, 75° E). Both the models could not produce the heavy precipitation at Kozikode station.

5. Conclusions

An idealized simulation of thunderstorm and rainfall associated with a weak cyclonic circulation are attempted using ARPS and WRF model. It is found that ARPS is able to produce rainy area at proper location in case of thunderstorm which is matching with the clouding in METEOSAT IR cloud images. The rainfall rates are over predicted by both the models. The characteristic features like strong vertical velocity, diverging winds associated with downdraft are well simulated by ARPS model. WRF model has produced strong vertical velocity associated with thunderclouds but failed to produce other features.

An attempt has been made to simulate the rainfall associated with a feeble low pressure area. A cyclonic circulation associated with feeble low pressure area at off tip of Indian peninsula has produced wide spread rainfall of 20–60 mm/day. Only one station Kozikode at west coast reported 172 mm of rainfall. ARPS model has produced 5–40 mm/day rainfall covering peninsular India south of 15° N. WRF model produced rainfall rates of 5–20 mm/day but covers the western side of peninsular India; over east coast no rainfall is produced. Both the models are also integrated with comparatively fine grid resolution of 25 km and 16 km. The fine grid runs unable to capture the heavy precipitation of 172 mm at Kozikode station. Input fields of wind and moisture are examined which are important for rain production. It is found that the cyclonic circulation (and hence instability) and sufficient amount of moisture is present upto higher levels in case of ARPS model, but is confined to lower troposphere in case of WRF model over the peninsular Indian region. In general the difference in rainfall could be attributed to the difference in depth of cyclonic circulation and amount and depth of moisture fields. The north–south trough along 70° E might be responsible for spurious rainfall over west central India in experiment with WRF model.

Comparatively latest version of ARPS model is used in the present study. The WRF model is still in developing stage. WRF model has produced marginally satisfactory results. This is preliminary attempt with WRF model. Further testing of more cases with higher and improved version of WRF model is required. Conclusions are based on limited experiments hence it is not appropriate at this stage to comment/conclude on the performance of WRF model over Indian region. However study will provide some guidelines to the ARPS/WRF model users over Indian region.

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