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Sensitivity of Mesoscale Model Forecast During a Satellite Launch to Different Cumulus Parameterization Schemes in MM5

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Abstract—The identification of the model discrepancy and skill is crucial when a forecast is issued. The characterization of the model errors for different cumulus parameterization schemes (CPSs) provides more confidence on the model outputs and qualifies which CPSs are to be used for better forecasts. Cases of good/bad skill scores can be isolated and clustered into weather systems to identify the atmospheric structures that cause difficulties to the forecasts. The objective of this work is to study the sensitivity of weather forecast, produced using the PSU-NCAR Mesoscale Model version 5 (MM5) during the launch of an Indian satellite on 5th May, 2005, to the way in which convective processes are parameterized in the model. The real-time MM5 simulations were made for providing the weather conditions near the launch station Sriharikota (SHAR). A total of 10 simulations (each of 48 h) for the period 25th April to 04th May, 2005 over the Indian region and surrounding oceans were made using different CPSs. The 24 h and 48 h model predicted wind, temperature and moisture fields for different CPSs, namely the Kuo, Grell, Kain-Fritsch and Betts-Miller, are statistically evaluated by calculating parameters such as mean bias, root-mean-squares error (RMSE), and correlation coefficients by comparison with radiosonde observation. The performance of the different CPSs, in simulating the area of rainfall is evaluated by calculating bias scores (BSs) and equitable threat scores (ETSs). In order to compute BSs and ETSs the model predicted rainfall is compared with Tropical Rainfall Measuring Mission (TRMM) observed rainfall. It was observed that model simulated wind and temperature fields by all the CPSs are in reasonable agreement with that of radiosonde observation. The RMSE of wind speed, temperature and relative humidity do not show significant differences among the four CPSs. Temperature and relative humidity were overestimated by all the CPSs, while wind speed is underestimated, except in the upper levels. The model predicted moisture fields by all CPSs show substantial disagreement when compared with observation. Grell scheme outperforms the other CPSs in simulating wind speed, temperature and relative humidity, particularly in the upper levels, which implies that representing entrainment/detrainment in the cloud column may not necessarily be a beneficial assumption in tropical atmospheres. It is observed that MM5 overestimates the area of light precipitation, while the area of heavy precipitation is underestimated. The least predictive skill shown by Kuo for light and moderate precipitation asserts that this scheme is more suitable for larger grid scale (> 30 km). In the predictive skill for the area of light precipitation the Betts-Miller scheme has a clear edge over the other CPSs. The evaluation of the MM5 model for different CPSs conducted during this study is only for a particular synoptic situation. More detailed studies however, are required to assess the forecast skill of the CPSs for different synoptic situations.

Key words: Mesoscale model, CPSs, entrainment/detrainment, skill scores, TRMM, synoptic validation.

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1. Introduction

Weather plays a crucial role in the planning and execution of spacecraft launch operations. Each launch vehicle has a specific tolerance for wind shear, cloud cover, temperature, whereas lightening constraints are common for all types of vehicles. A recent satellite launch (PSLV-C6) was made by Indian Space Research Organization (ISRO) in May 2005. The launch site (SHAR) is on the east coast of India (Sriharikota, 13.72°N, 80.2°E) and falls in the vicinity of the tropical cyclone (SINGH *et al.*, 2005) landfall zone. Consequently weather forecast is very important during satellite launch. The presence of convective storm activity in the vicinity of the spacecraft launch site can be significant due to the lightening strikes and electrostatic discharges, which can damage or destroy the launch vehicle and/or its payload. Cumulus convection is one of the processes that plays an important role in weather by influencing the dynamic and thermodynamic state of the atmosphere. Since the convective elements are normally of the order of 1 km in size, fine resolution is required in the numerical model for an explicit treatment of the convective process. On the other hand parameterization schemes allow us to use coarser grid in numerical simulation where the horizontal scale of the phenomena is of the order of several thousands of kilometers. Therefore the selection of a proper cumulus physics option is extremely important in real-time applications of numerical weather prediction models.

The objective of this study is to observe the sensitivity of real-time forecasts produced during the previously mentioned satellite launch using the fifth-generation Pennsylvania State University-National Center for Atmospheric Research (NCAR) Mesoscale Model version 5 (MM5; GRELL *et al.*, 1994), to different cumulus parameterization schemes in the model. One benefit to the mesoscale modeling community from such real-time evaluation studies is that in such cases the model in general is subjected to a particular synoptic condition and not tuned to a specific case to obtain better results. Also due to the large number of forecasts generated during such experiments, statistical evaluation works as an appropriate tool in identifying model forecast errors and its sensitivity to various physics options in the model. Ultimately this information may become helpful not only for selecting proper physics options but also for sorting out the sources of model forecast errors, which in turn is useful for the efforts to improve the assumptions made in the formulation of different physics options.

Many cumulus parameterization schemes (CPSs) have been developed and implemented in numerical weather prediction models that implicitly account for the associated subgrid exchanges of mass, heat, and moisture. The basic feature that differentiates CPSs is the closure assumptions upon which they are based. The schemes vary in complexity from simple moist convective adjustment to sophisticated mass flux-type schemes (DAS *et al.*, 2002). It is recognized that convection in nature often develops mesoscale organization and these resolvable mesoscale structures develop from initially unresolvable cumulonimbus clouds that in itself provides a major challenge to mesoscale modelers. The representation of convection in the models is strongly scale-dependent (MOLINARY and DUDEK, 1992). The adequate representation of convective processes is particularly important in numerical models, but there is no universally accepted framework for representing such processes with grid scales that prohibit fully explicit representation (GOCHIS *et al.*, 2002). CPSs are developed for specific synoptic conditions, and are evaluated in a limited number of cases (KUO *et al.*, 1996; WANG and SEAMAN, 1997; PENG and TSUBOKI, 1997; YANG *et al.*, 2000; GOCHIS *et al.*, 2002; YANG and TUNG, 2003; DAS *et al.*, 2002). YANG and TUNG (2003) performed an evaluative study to discern the performance of four CPSs, the Anthes-Kuo (ANTHES, 1977), Betts-Miller (BETTS and MILLER, 1986), Grell (GRELL, 1993), and Kain-Fritsch scheme (KAIN and FRITSCH, 1993) in the rainfall forecasts over Taiwan using MM5. They showed that none of these CPSs consistently outperforms the others in all measurements of forecast skill. The skill of the MM5 model in simulating the Indian summer monsoon is studied by DAS GUPTA *et al.* (2005) and the results show that the model performs reasonably well except for heavy rainfall events. In general, for simulations with fine horizontal resolutions (~15 km) MM5 tends to overpredict the area of light rainfall, and underpredict the area of heavy rainfall (YANG and TUNG, 2003; GALLUS, 1999).

During the initial days of forecast, the Bay of Bengal was quite calm without any synoptic systems. Most parts of the Bay of Bengal and the region around SHAR are associated with very low (2–4 m/s) wind speed. A well-marked trough over south central India was also observed during the period. A region of high wind speed (9-10 m/s) was seen on the western coast of India. Significant rainfall was observed over south east Indian coasts during 29 April to 1 May. Heavy rainfall with thunderstorm activity was observed over the launch site SHAR on 1 May. There were light rainfall events over the Indian region throughout the study period. Even in the case of light rainfall events CPSs can become active and can have significant impact on the circulation. The light rainfall at one place in the domain can change the wind field at another place.

Parameterized moist downdrafts are crucial for reproducing many of the observed mesoscale characteristics, as well as correct large-scale temperature fields. Therefore verification of these mesoscale features is an important element of evaluating CPS performance. Conclusions of these evaluative studies of CPSs are often speculative because of the complexity of the parent model and case dependency of the results. We will not attempt here to make an absolute statement about which parameterization is best as a whole, but will try to evaluate their performance in this particular synoptic condition and the statistical effect they have on the model forecast error. The model predicted meteorological fields such as wind speed, temperature and relative humidity by different CPSs are statistically evaluated by comparison with the radiosonde observations from 25 April to 05 May, 2005. The first 24 h model predicted rainfall by different CPSs, during the simulation period, is evaluated by comparing with the TRMM observed rainfall and calculating statistical skill scores.

2. Model Description

In the present study we use a well-studied mesoscale model, namely MM5. MM5 is the latest version of the mesoscale model originally developed by ANTHES and WARNER (1978) known as Fifth Generation NCAR/Penn State Mesoscale Model. This non-hydrostatic version employs reference pressure as the basis for terrain following vertical coordinate and with a fully compressible system of equations. In combination with multiple-nest capability, a four-dimensional data assimilation technique and a variety of physics options make the model capable of simulations on finer scales, limited only by data resolution, quality and computer resources. The model was run with 25 km horizontal resolutions with a single domain. Twenty-seven unevenly spaced full-sigma levels were used in the vertical, with the maximum resolution in the boundary layer. Ten-minute averaged terrain/landuse data were interpolated to the 25-km model grids. Figure 1 shows the model domain used for the simulation.

For the present study, the following physics options are employed:

(i) *Planetary Boundary Layer (PBL)*—the PBL technique is the Medium Range Forecast (MRF) of the National Centre for Environmental Prediction (NCEP) by HONG and PAN (1996). In MM5 version 3.7 MRF PBL was made compatible with polar physics, particularly sea-ice fraction. Another modification in MRF PBL is to remove the effect of convective velocity on the surface momentum stress during the day time, and which should help to alleviate a day-time low wind speed bias (DUDHIA, 2005).

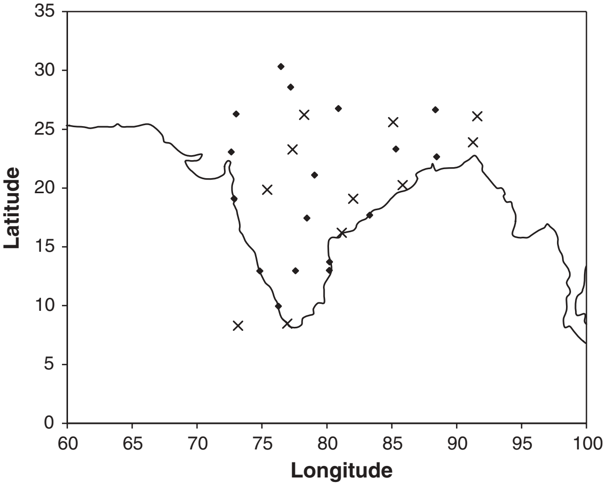

Figure 1
Model domain and radiosonde locations (×, ♦) where local data is used to enhance model initial condition. Locations shown by symbol "♦" are selected for point validation.

(ii) *Cloud microphysics*—A simple treatment of cloud microphysics (DUDHIA, 1989) in which both ice and liquid phases are permitted for cloud and precipitation.

(iii) *Cumulus parameterization*—Four CPSs have been selected on the basis of their widespread use in numerical models and the representation of different closure assumptions and scale considerations. Since numerous references are available on the conceptual formulation of these CPSs, here we are not describing them in detail. The CPSs selected for the present study are as follows

a. Anthes- Kuo scheme (Kuo)

The original KUO (1974) scheme determines the amount of rainfall, convective heating, and moisture convergence. The Kuo scheme used here is a modified version described in ANTHES *et al.*, (1987) and GRELL *et al.*, (1994), in which the moistening is vertically distributed based on relative humidity.

b. Grell Scheme (Grell)

The Grell scheme (described in GRELL *et al.* 1994) is essentially a simplified Arakawa-Schubert scheme. Its closure is based on the quasi-equilibrium assumption following the ARAKAWA-SCHUBERT (1974) scheme.

c. Kain-Fritsch scheme (KF)

The KAIN and FRITSCH (1993) scheme is an improved version of the FRITSCH and CHAPPELL (1980) parameterization. In the cloud model (KAIN and FRITSCH 1990) that is used to determine vertical profiles of heating and drying, entrainment and detrainment rates depend on the buoyancy of mixtures of clear and cloudy air.

d. Betts-Miller scheme (BM)

The deep convection parameterization developed by BETTS (1986) adjusts the grid-column sounding toward a reference sounding that is designed to resemble the quasi-equilibrium thermodynamics sounding observed in association with deep convection. In MM5, this deep convection algorithm is used in combination with the shallow convection scheme of JANJIC (1994). More details about this scheme are available in BETTS and MILLER (1993).

(iv) *Cloud-radiation scheme*—The radiation parameterization used is NCAR Community Climate Model (CCM2). It has multiple spectral bands in shortwave and longwave, but the radiative properties of clouds are based on the grid point relative humidity values from the model (HACK *et al.*, 1993). It also provides radiative fluxes at the surface.

(v) *Surface scheme*—The land surface model (Noah-LSM) is capable of predicting soil moisture and temperature in four layers, as well as canopy moisture and water equivalent snow depth. It also outputs surface and underground run-off accumulation. The LSM makes use of vegetation and soil type in handling evapotranspiration, and effects such as soil conductivity and gravitational flux of moisture. The Noah-LSM can also optionally use satellite derived climatological albedo, instead of relating albedo to landuse type.

3. Data Used

3.1. Initial Conditions for MM5

Initial data were generated for a 25-km resolution by interpolating the NCEP/AVN global analysis at 75-km resolutions to the model grid. The same model forecasts for every 6 hours were linearly interpolated in time to provide the lateral boundary conditions. Daily 00 GMT analysis as well as forecast validation up to 48-h forecast were downloaded from the NCEP site (ftp://ftpprd.ncep.noaa.gov/pub/data/nccf/com/gfs) during 25 April to 04 May, 2005.

3.2. Radiosonde/in situ

Since global field becomes interpolated from coarse resolution to mesoscale, the interpolated fields may not represent the actual mesoscale feature. Therefore, enhancement of global fields by local observations has to be done to derive realistic mesoscale simulations. The asynoptic data (wind, moisture and temperature profile) from radiosonde and microwave remote sensing is most useful for this purpose. In this study the local radiosonde data available at different stations in the domain is used to improve the initial fields. Figure 1 shows the stations from where the local data are incorporated in the model initial conditions. The local data were injected using Cressman objective analysis schemes of MM5. Daily 00 GMT upper air data were downloaded during 25 April to 04 May, 2005 from Wyoming University Website (http://weather.uwyo.edu/upperair/sounding.html). The 00 GMT SHAR local GPS data of wind profile over SHAR, provided in real time by SHAR met facility from 28 April onwards, was also included in the model initial conditions using an objective analysis technique. These data were of very high vertical resolution and taken only during satellite launch.

3.3. TRMM - Microwave - Infrared Merged Precipitation Data - 3B42

The Tropical Rainfall Measuring Missions (TRMM) was launched in November 1997 in a 350-km altitude 35° inclination orbit for the quantitative measurements of precipitation over the entire tropics on a continuous basis. The low inclination (35°) of the orbit permits documentation of the important diurnal rainfall cycle (KISHTAWAL and KRISHNAMURTI, 1998). In this study TRMM Microwave Imager (TMI) derived rainfall product 3B42RT is used for the period 25 April to 3 May, 2005. The algorithm 3B-42 produces TRMM-adjusted microwave merged - infrared (IR) precipitation (ADLER *et al.*, 2000). The precipitation product 3B42 uses the high quality precipitation estimates from TRMM as the calibrating mechanism for estimates from other geostationary satellite data. This scheme allows estimation of surface rain at finer time and space scales than is available from TRMM microwave imager. The gridded rainfall estimates are on a 3-hour temporal resolution and

0.25°×0.25° spatial resolution in a global belt extending from 50° South to 50° North latitude. The daily accumulated rainfall is obtained by combining eight, 3-hourly observations from TRMM.

4. Forecast and Evaluation Method

4.1. Forecast Method

The standard method of MM5 initialization is used, which is discussed in MM5 user's manual. GRIB formatted data on pressure levels are read and interpolated to MM5 grid. The next step is to assimilate the local radiosonde observations using Cressman objective analysis scheme of MM5. Then vertical interpolation is carried out to generate model initial, lateral and lower boundary conditions. Daily, from 25 April to 04 May 2005, the model was initialized with 00GMT for 48-h period integration using four different CPSs.

4.2. Evaluation Method

4.2.1. Data comparison method

We have selected 17 radiosonde locations (stations indicated by the symbol "♦" in Fig. 1) for point validation on the basis of the availability of data at additional vertical levels. Model forecasted temperature, wind and relative humidity were verified with these radiosonde observations. After the forecast calculation is completed, bilinear interpolation is conducted to obtain model forecast data at the radiosonde locations.

4.2.2. Statistical parameters

For calculating statistical parameters we selected the same radiosonde locations mentioned above. Mean bias (MB), root-mean-squares error (RMSE), and correlation coefficient were used to assess temperature, wind speed, and relative humidity forecast. The MB associated with model tendency to overforecast or underforecast the observed quantity (WILKS, 1995) is given by

$$MB = \frac{1}{N}\sum_{i=1}^{N}(o_i - f_i),$$

where N is number of forecast/observation pairs in the sample, f_i is the forecast, and o_i is the observation.

The precipitation forecasts by the four different CPSs are compared to the observations and are evaluated quantitatively calculating statistical skill scores (such as the threat and bias scores; ANTHES, 1983; ANTHES *et al.*, 1989) for different rainfall thresholds (0.1, 1, and 10 mm). BSs and ETSs are calculated from Table 1, which is

Table 1

Rain contingency table used for verification. Each element of the matrix (A, B, C, and D) holds the number of occurrence in which the observations and/or the model forecasts reach a precipitation threshold amount for a given forecast period

	Observed	
Forecasted	Rain	No rain
Rain	A	B
No rain	C	D

equivalent to a 2 × 2 matrix, where A, B, C, and D holds the number of occurrences, in which the observation and model did, or did not reach certain threshold amounts of precipitation for a given period of the forecast (24-h accumulated in this study). A detailed description of rain contingency tables and formulas used for calculating skill scores is available in YANG and TUNG (2003) and COLLE *et al.* (1999).

5. Results

5.1. Point Validation of Wind, Temperature, and Moisture Field

In this section the results of point validation of wind speed, temperature and relative humidity over some selected stations are presented. The 24-h and 48-h predicted wind, temperature and relative humidity profiles using different CPSs are compared with radiosonde over 17 selected stations (stations with "♦" in Fig. 1). For brevity, we are presenting only the result obtained for the 24-h forecast by different CPSs over SHAR valid at 00 GMT of 29 April (Figs. 2–4). From Figure 2a it is seen that model predicted westerly jet location by all the CPSs is slightly shifted downward (~10 km) compared to the radiosonde observed jet location (~11 km). The vertical trend in wind speed is well predicted by all the CPSs. The differences between model predicted and observed wind varies from −6 to 10 m/s. Among the CPSs Betts-Miller scheme differs more from observation in reproducing wind speed. Figure 3a indicates that model predicted temperature profile is well matching with the radiosonde profile. The differences between model predicted and radiosonde observed temperature ranges from −3 to 2°C (Fig. 3b). Compared to other CPSs the predicted temperature by Betts-Miller scheme differs more from the observation, particularly at lower levels (~1 km) and upper levels (~13 km). The predicted relative humidity (Fig. 4a) is always higher than the observed humidity in the upper levels and differences as high as 70% are observed.

We have taken 17 stations for the computation of statistical parameters (stations with "♦" in Fig. 1). The 24-h and 48-h predicted fields by different CPSs were compared with radiosonde observation and the statistical parameters such as correlation coefficient, RMSE and bias were calculated. The statistical parameters

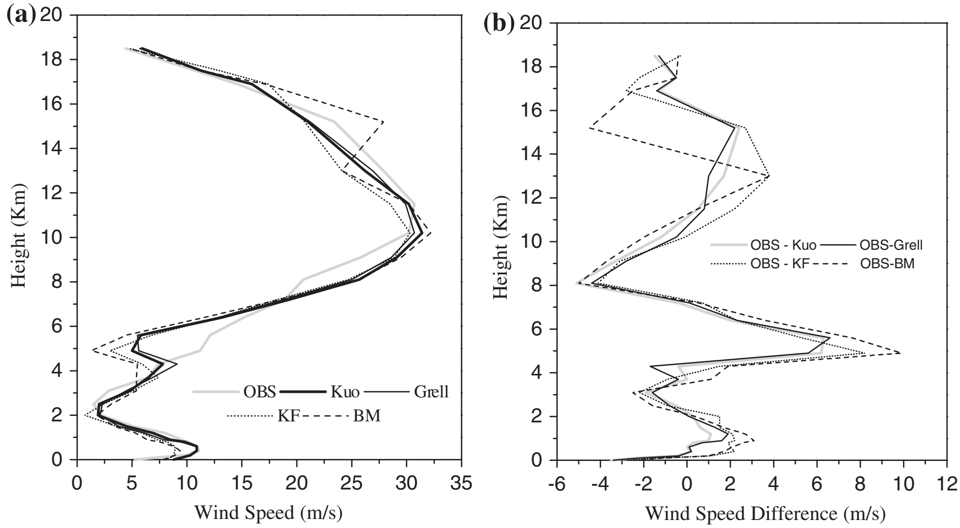

Figure 2
(a) Comparison of 24-h model predicted wind speed (m/s) with observation over SHAR valid at 00 GMT of 29 April, (b) difference between the observed and model predicted wind speed (m/s).

were computed for individual station as well as for individual height. These results are for all simulations carried out during 25 April to 04 May, 2005. All the simulations were of 48-h duration, except the simulation from 04 May, 2005, which was of 30-h duration. Thus for each height, there are at least 10 samples available in computing statistical parameters for a single variable at a particular station.

The vertical variation of RMSE and biases in the 24-h and 48-h predicted wind speed, temperature and relative humidity by different CPSs is depicted in Figs. 5–10. Wind speed (Figs. 5, 6) is underestimated by all CPSs except in the upper levels. There is a sharp overestimation in the 24-h (Fig. 7) and 48-h (Fig. 8) predicted temperature by all the CPSs at heights 14–16 km. The forecast by all the CPSs overestimates humidity (Figs. 9, 10) except at lower levels. The 24-h and 48-h forecast by the Grell scheme shows less rms error and bias particularly in the upper levels. Compared to other CPSs, error in the predicted humidity is less for the Kain-Fritsch scheme in the lower troposphere. Among the CPSs the predicted wind, temperature and humidity fields by the Betts-Miller scheme differ more from observation.

From the overall statistics obtained for all vertical levels from 24-h and 48-h forecast by different CPSs based on the 17 selected stations, it is clear that the RMSE of wind speed, temperature and relative humidity show no significant differences among the four CPSs. Compared to other CPSs, the Grell scheme shows slightly less RMSE for wind speed, temperature and relative humidity in both 24-h and 48-h

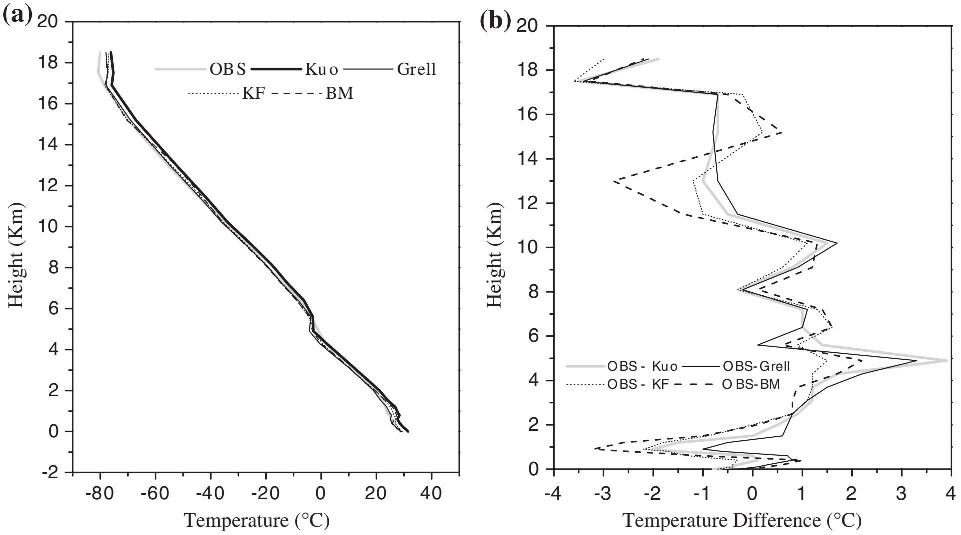

Figure 3
As in Figure 2, but for temperature (°C).

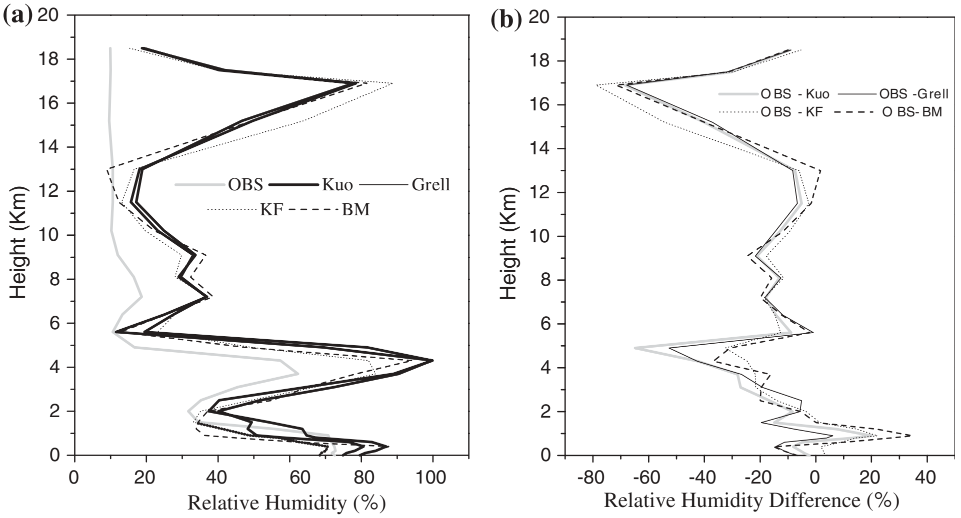

Figure 4
As in Figure 2, but for relative humidity (%).

prediction. From the overall statistics it is observed that all the CPSs overestimate temperature and relative humidity in the 24-h and 48-h prediction, while wind speed is underestimated.

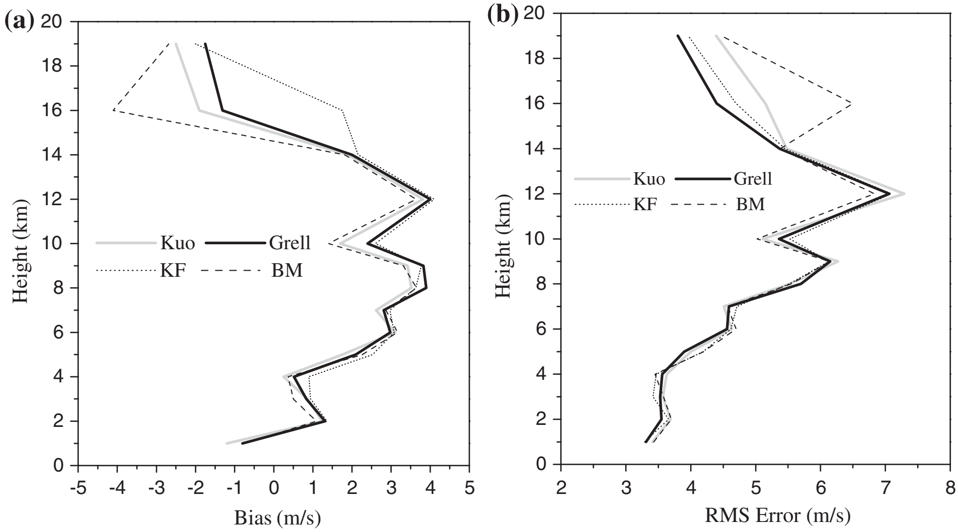

Figure 5
Vertical profile of, (a) bias, (b) RMS error, in the model predicted wind speed (m/s) obtained by all 24-h forecasts over selected stations during the period of study.

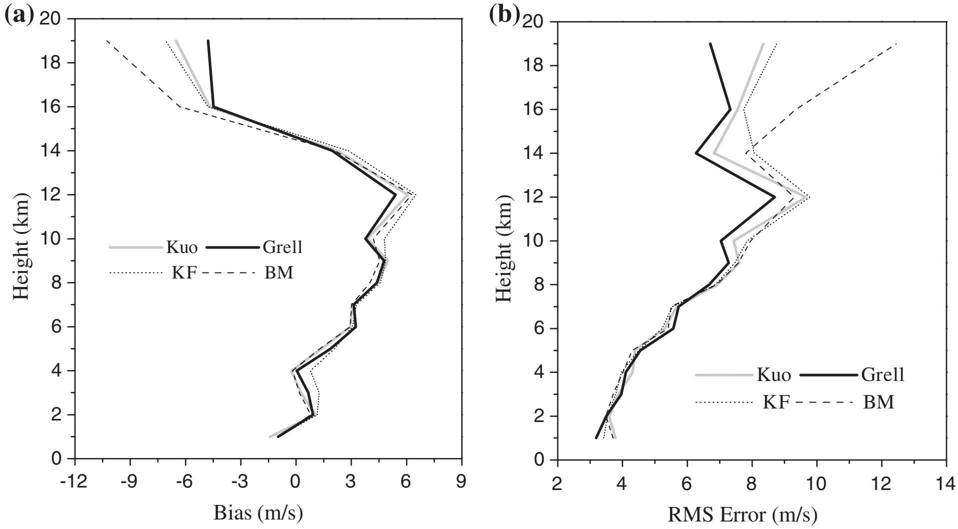

Figure 6
As in Figure 5, but for 48-h forecast.

5.2. Statistical Validation of Rainfall

Twenty four hours predicted rainfall from each simulation is compared with the TRMM observed rainfall during the study period. For evaluating the predictive skill

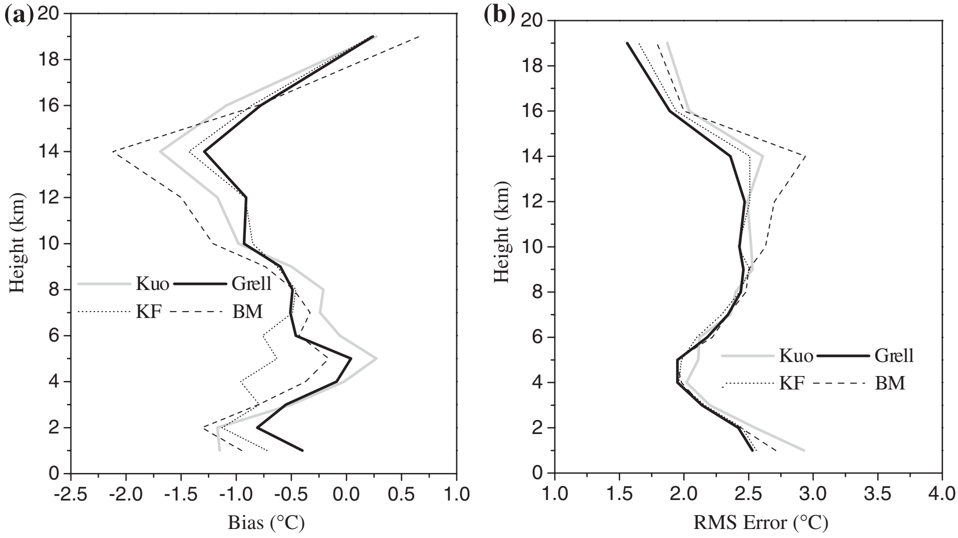

Figure 7
Vertical profile of, (a) bias, (b) RMS error, in the model predicted temperature (°C) obtained by all 24-h forecasts over 17 selected stations during the period of study.

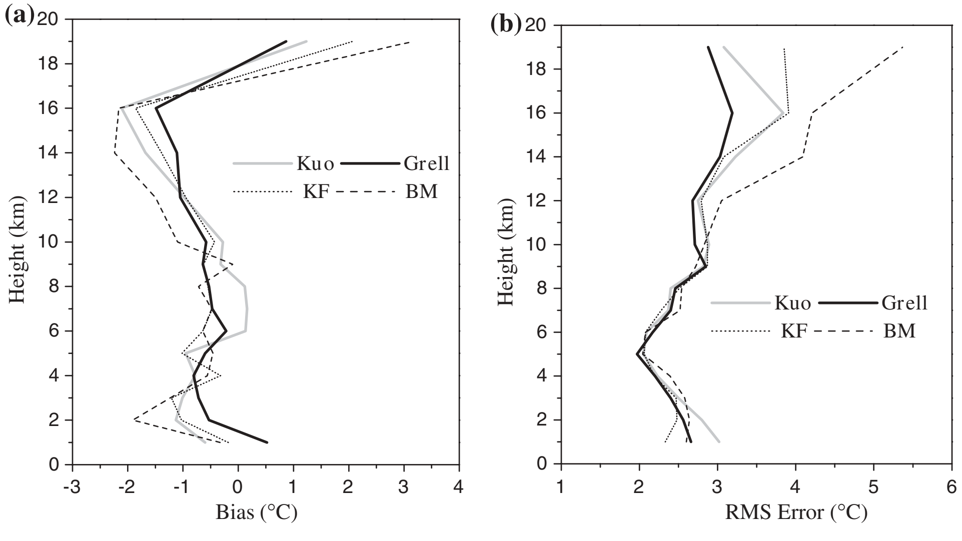

Figure 8
As in Figure 7, but for 48-h forecasts.

of different CPSs in simulating an area of rainfall, Bias scores (BSs) and Equitable threat scores (ETSs) are computed for different rainfall thresholds (0.1,1 and 10 mm). The number of grid points observed in each of the rainfall thresholds is

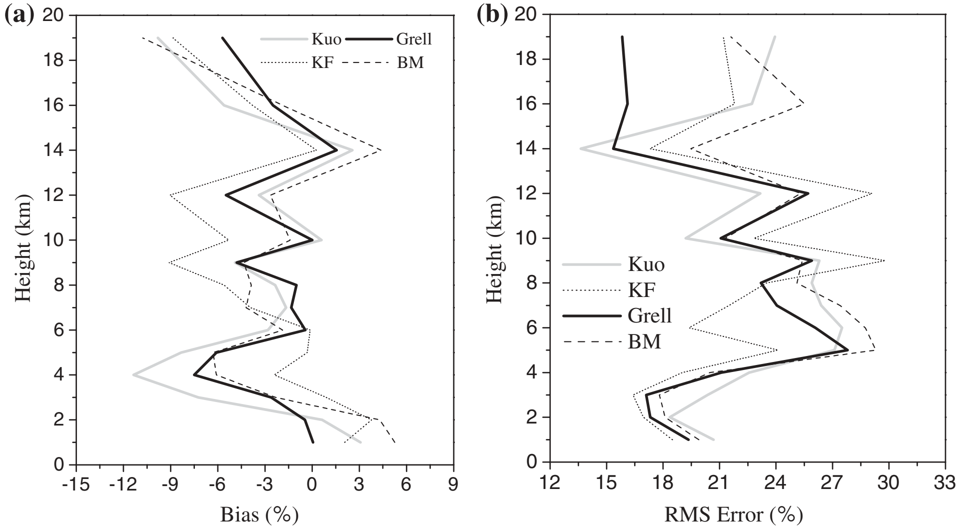

Figure 9
Vertical profile of, (a) bias, (b) RMS error, in the model predicted relative humidity (%) obtained by all 24-h forecasts over 17 selected stations during the period of study.

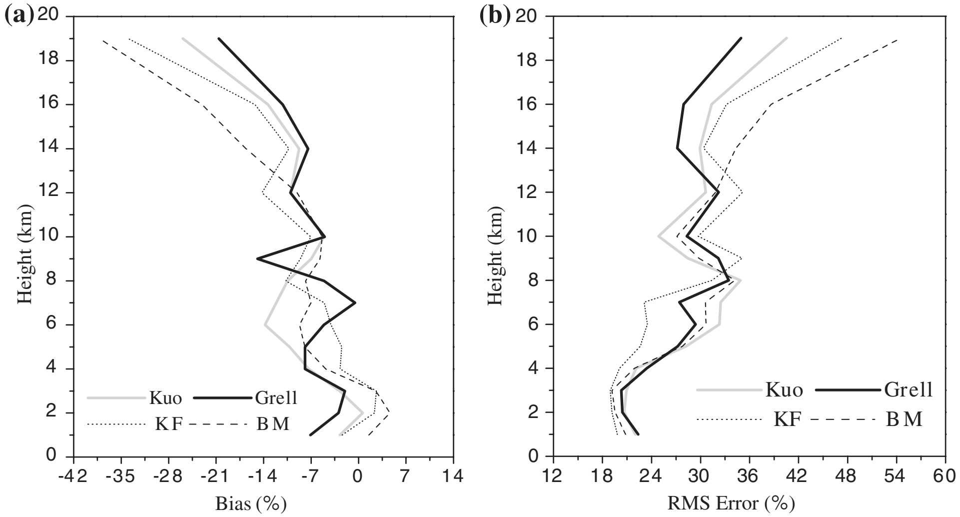

Figure 10
As in Figure 9, but for 48-h forecasts.

shown in Table 2. Figure 11 shows the BSs obtained for 24-h prediction by different CPSs at different thresholds. It is clear that the forecast given by all the CPSs estimate/underestimate the rainfall area for light/heavy precipitation. The forecast

Table 2

The number of grid points in each of the rainfall thresholds considered for computing the skill scores

Cases	1	2	3	4	5	6	7	8	9
> = 0.1<1	1295	1250	1170	1288	1636	1095	1310	1312	1299
> = 1<10	1551	1431	1749	1909	2234	1580	2119	1872	1908
>10	0922	0498	1021	0716	0546	0697	1396	1224	1325

using Betts Miller scheme always lies closer to the observation. The ETSs obtained at different rainfall thresholds are shown in Figure 12. The low averaged ETSs by all the CPSs for the area distribution of precipitation demonstrate that considerably more improvement is needed both in the model resolutions and the assumptions made in the formulation of different CPSs for better forecast skill. In the predictive skill for the area of light precipitation (0.1 mm/day) the Betts-Miller scheme has a clear edge over the other CPSs (Fig. 12a). This may be due to the incorporation of shallow convection with the normal deep convection in this scheme where parameterized shallow convective elements rise without precipitation formation through the top of the boundary layer into the free atmosphere. In case of moderate rainfall (1 mm/day), Grell scheme demonstrates better forecast skill in the majority of the cases (Fig. 12b) and for heavy rainfall (10 mm/day) CPSs give mixed results (Fig. 12c). The least predictive skill shown by Kuo for light and moderate precipitation asserts that this scheme is more suitable for larger grid scale (> 30 km). The performance of the CPSs in predicting rainfall area varies with the rainfall thresholds for which they have used. The predictive skill of CPSs in simulating area of rainfall is more (less) for low (high) thresholds, which is consistent with the earlier studies (WANG and SEAMAN, 1997; YANG and TUNG, 2003).

5.3. Synoptic Validation of Rainfall

The simulated rainfall features reproduced by different CPSs during the forecast period are validated against TRMM observed rainfall throughout the study period. There were light rainfall events over the Indian region throughout the study period. Significant rainfall events were observed over the southeast Indian coast on 29 April and two subsequent days. Heavy rainfall with thunderstorm activity was observed near the launch site SHAR on 1 May. The first 24-h forecasted rainfall by different CPSs is compared with the corresponding TRMM observation for all the days during the time period. For brevity we are presenting only the rainfall features obtained for 1 May. The observed and model simulated accumulated rainfall using different CPSs for 1 May is presented in Figures 13 and 14. It is clear, as seen in the previous section, that except in the case of Betts-Miller scheme, MM5 simulations using the CPSs overestimate low rainfall while heavy rainfall is underestimated. Among the CPSs Kuo produces the worst simulation, which is similar to the results

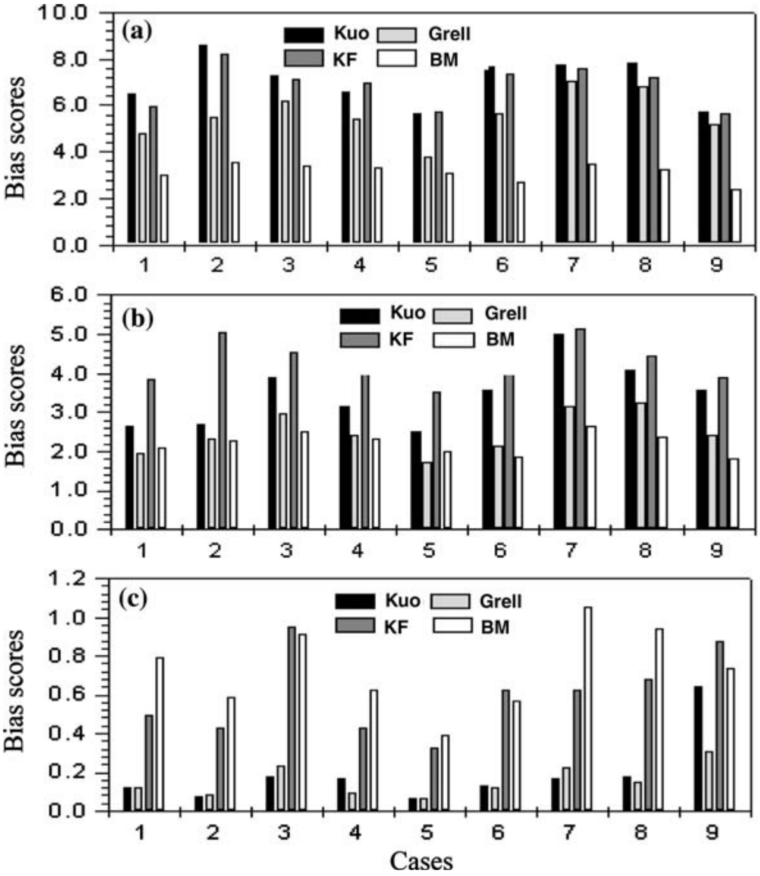

Figure 11
Bias scores (BSs) at different thresholds (a) 0.1, (b) 1 and (c) 10 obtained for the first 24-h prediction of accumulated rainfall from 9, 48-h forecasts (from 25 April to 3 May).

obtained in 5.2. This indicates that this scheme is minimally useful in model simulation with high resolution. The criteria used in this scheme that large-scale moisture convergence associated with a high degree of conditional instability is required for the activation of CPS, may be one of the reasons for the worst simulation. The underestimation of rainfall shown by Betts-Miller over the Indian land mass may be due to the basic assumption used in this scheme such that adjusting the grid-column sounding towards a reference sounding in order to resemble the quasi-equilibrium thermodynamic state associated with deep convection over the region. Even though none of the CPSs simulated rainfall features correctly, the simulation by the Kain–Fritsch scheme lies closer to the observed one.

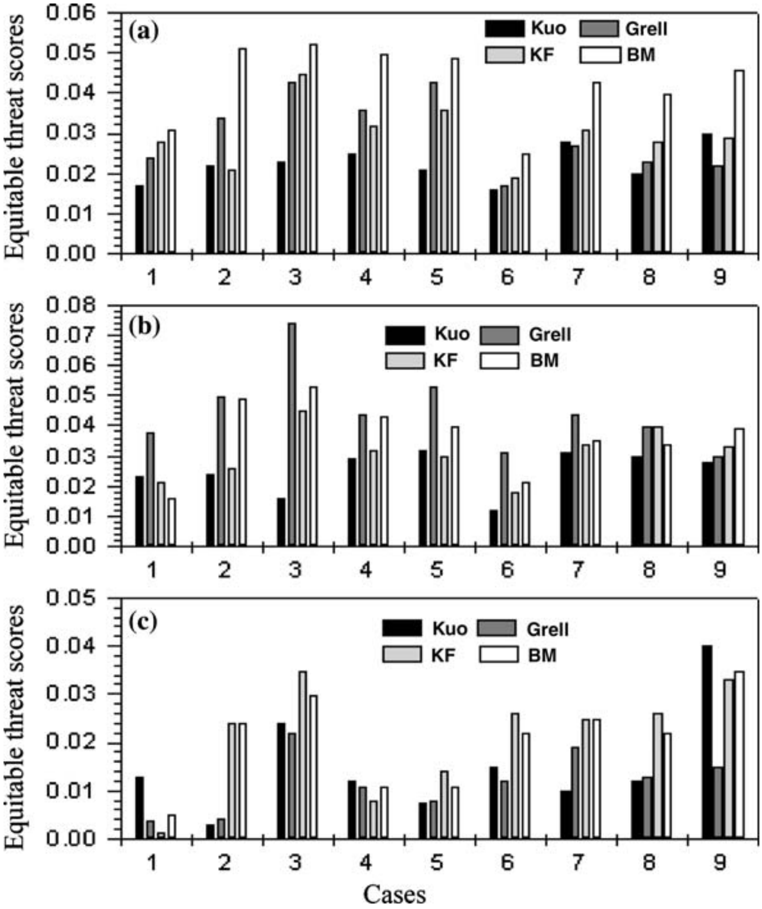

Figure 12
As in Figure 11, but for equitable threat scores (ETSs).

6. Discussion and Conclusions

The mesoscale model MM5 has been integrated during pre-launch and up to PSLV-C6 launch from SHAR. The model initial condition is enhanced by available radiosonde profiles from nearby land stations. The model predicted wind, temperature and moisture for different cumulus schemes were compared with local radiosonde observations over selected stations for 24-h and 48-h predictions. The statistical parameters (RMS error, bias and correlation coefficient) were calculated for different CPSs to evaluate the model forecast. The analysis indicates that all the CPSs overestimate temperature and relative humidity but underestimate the wind speed. It was found that model simulated wind speed and temperature by all the CPSs are in reasonable agreement with that of radiosonde observation. The downward shifting of the position of westerly jet in the simulated wind field can be due to the model's failure in capturing the proper terrain features. The model simulation displays differences in the predicted circulation features among the CPSs throughout the model domain for 00GMT 29 April, 2005. During that period rainfall activity prevailed only over the southeast Indian coast (Figure not shown). This demonstrates that representation of convection in mesoscale models has a marked influence not only on the simulated precipitation over that region, but also on the simulated circulation pattern and moisture fields over nearby regions. That is, a light rainfall at one place in the domain can change the wind and moisture fields at another place. Also the light rainfall observed in all the cases over some locations in the domain can result from CPS activation. These results are consistent with the previous studies (STENSRUD, 1996; GOCHIS *et al.*, 2002).

Among the CPSs, the Grell scheme gives slightly better forecasts of wind, temperature and moisture fields particularly in the upper levels which can be due to the assumption that no direct mixing is allowed between updraft and downdraft and with the surrounding atmosphere, and thereby not disturbing conserved mass flux in a vertical column of cloud. Which suggests that representing cloud entrainment/detrainment may not necessarily be a beneficial assumption in tropical regions. The low error shown by the Kain–Fritsch scheme in the predicted relative humidity, particularly at lower levels can be attributed to the explicit treatment of convective downdrafts by this scheme. The high error shown by Betts-Miller scheme in reproducing temperature and moisture field may be ascribed to the absence of explicit parameterization of subgrid-scale cloud and mesoscale processes in this scheme. The forecasts given by all the CPSs overpredicted (underpredicted) the area of low (high) precipitation. A similar result is also obtained for GULLUS (1999) and

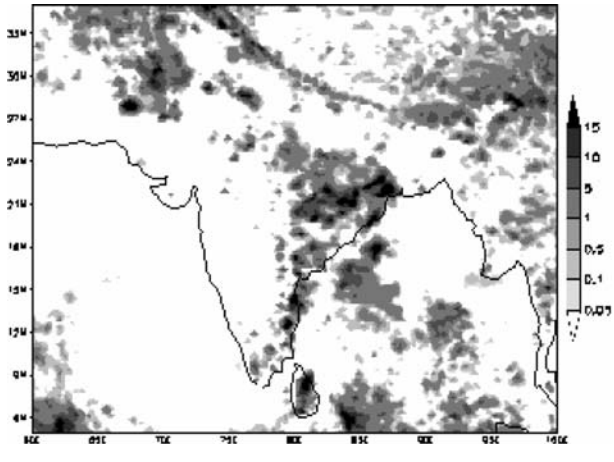

Figure 13
24h accumulated rainfall (mm) from TRMM valid for 1st May 2005.

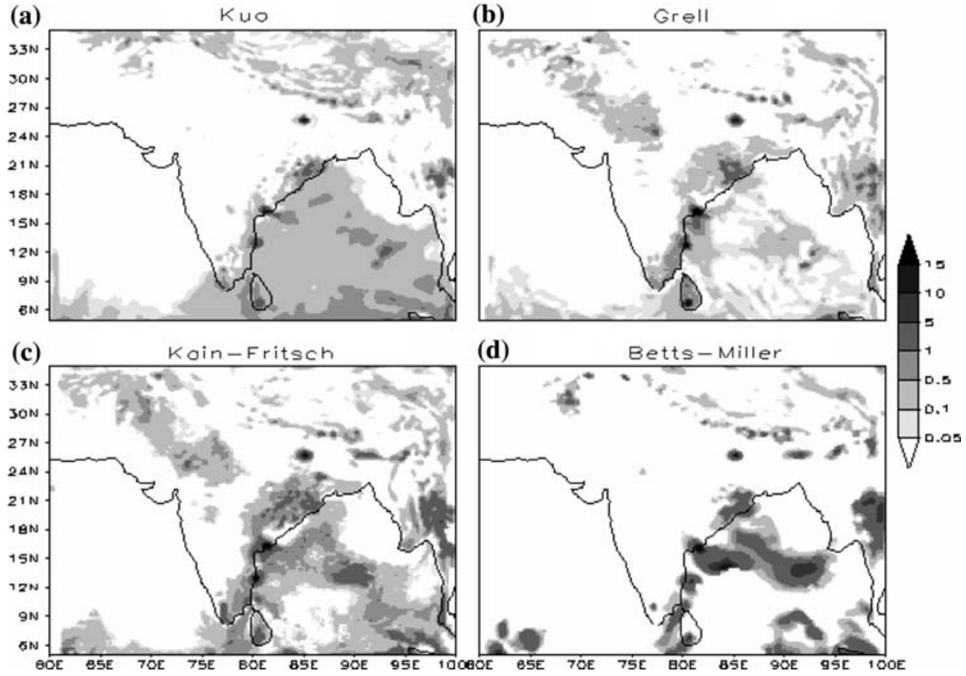

Figure 14
24-h forecasts of accumulated rainfall (mm) for different CPSs valid at 00 GMT of 1 May, 2005.

YANG and TUNG (2003). In predictive skill for the area of light precipitation, Betts-Miller scheme has a clear edge over other CPSs, which can be due to the incorporation of shallow convection with the normal deep convection in this scheme. In such cases parameterized shallow convective elements rise without precipitation formation through the top of the boundary layer into the free atmosphere. The performance of CPSs in predicting the area distribution of precipitation varies with the rainfall thresholds for which they have tested. All the CPSs show less forecast skill in simulating areas of heavy precipitation. The slight advantage of KF scheme in simulating rainfall distribution as compared to other schemes may be due to the comparatively better distribution of moisture in the lower levels by this scheme, which is supported by the enhanced circulation features shown by this scheme (Figure not shown). The low values of skill scores shown by all the CPSs indicates that predicting summer precipitation is still difficult for mesoscale models, which is consistent with the results obtained by WANG and SEAMAN (1997) over the United states.

The present study elucidates the weather forecast skill of MM5 over the Indian region for the pre-monsoon period, which is still not extensively evaluated. The study shows that MM5 simulates the tropical atmosphere satisfactorily even though predicted humidity differs highly with the observation. The study substantiates the sensitivity of simulated meteorological features by the model to the way in which the convective processes in the atmosphere are parameterized in the model. Although there are some common features, the comparative performance of the different schemes differs throughout the simulation period. Even though these differences can be attributed to the different type of assumptions used in these schemes, their sensitivity to different cases (different synoptic situation and conditions) makes their application in mesoscale models highly complicated. The characterization of the model errors for different CPSs provides more confidence on the model outputs and qualifies which CPSs are to be used for better forecasts. Cases of good/bad skill scores can be isolated and clustered into weather systems to identify the atmospheric structures that cause difficulties to the forecasts. The evaluation of MM5 model for different CPSs conducted during this study is only for a particular synoptic situation, more detailed study however is required to assess the forecast skill of the CPSs for different synoptic conditions.

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