Impact of modified physics in limited area model forecasts

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A number of physical factors have been introduced to improve limited area model forecasts. The factors include land surface fluxes, shallow convection and radiation. The model including these additional physical factors (modified physics) is run for five cases of monsoon depression which made landfall over the Indian coast, and the results are compared with those of the control run. The forecasts are verified by computing the root mean square and mean errors. The differences in these skill scores between the two model runs are tested for their statistical significance. It is found that the modified physics has a statistically significant effect on the model skill with the maximum impact on the mean sea level pressure and the temperature.

Detailed analyses of mean sea level pressure, wind, rainfall and temperature further confirm that the modified physics has maximum impact on mean sea level pressure and temperature and marginal impact on wind and rainfall. Furthermore, analyses of some model parameters related to physics at a grid point for one case of depression were done. The results show that the inclusion of the land surface physics, shallow convection and radiative processes have produced a better precipitation forecast over the grid point.

1. Introduction

The NWP modelling studies (e.g. Krishnamurti and Ramanathan 1982; Mohanty *et al* 1984) suggest that the important processes in the intensification of the tropical systems are the release of convective instability and these systems are very sensitive to the intensity and location of the diabatic heating in the troposphere. Slingo *et al* (1988) showed that although the representation of convective processes in models are clearly important, the development and release of convective instability is also dependent on other aspects of the physical parametrizations, particularly the radiative cooling and the vertical fluxes of heat and moisture from the surface, through the boundary layer. Several studies with high resolution limited area models (e.g. Krishnamurti *et al* 1990; Dastoor and Krishnamurti 1991) showed sensitivity to the physical parameterizations used.

The objective of this study is to investigate the significance of changes in physical processes on the forecast fields. The changes involve the introduction of a parameterization of shallow convection, detailed calculation of radiative processes including cloud feedback processes, computation of land surface fluxes of momentum, heat and moisture based on the similarity theory and the use of a surface energy balance to obtain the diurnally varying surface temperature over land. Also a modified Kuo scheme is used for deep cumulus parameterization. Section 2 briefly describes the model including the physics and changes to the physics. We have run the model with control and modified physics for five cases of monsoon depression over the Indian region. The data used and the two experiments conducted are described in section 3. Section 4 presents the forecast verification by computing the skill scores for all the five cases. The differences in the forecasts between the two model runs are brought out by applying the student's t-test. Detailed analyses of forecast fields are presented and discussed in section 5. The summary and concluding remarks are given in section 6.

2. Model

A limited area primitive equation model in σ-coordinate system is used in the present study. A detailed

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description of the model and its performance is presented in Singh *et al* (1990). Some salient features of the model are given here. The basic equations include the equations of motion, mass and moisture conservation, the first law of thermodynamics and the pressure tendency equation. In vertical, between sigma equal to 0 and 1 there are ten model sigma levels (0.97, 0.92, 0.85, 0.665, 0.443, 0.298, 0.20, 0.133, 0.088, and 0.035). The wind components, mixing ratio, potential temperature and geopotential height are defined at these levels. The vertical σ-velocity ($\dot{\sigma}$) is defined at intermediate levels. The variables are staggered in horizontal and vertical; Arakawa B-type staggering is used. Mass, energy, potential temperature and variance of potential temperature conserving finite difference scheme is used to compute space derivatives. For time integration, an economic explicit scheme is used. For the present study the horizontal domain extends from 10°S to 40°N and 40°E to 115°E. A horizontal grid of 125 km on the Mercator projection is used. In vertical the boundary conditions are $\dot{\sigma} = 0$ at $\sigma = 1$ and at $\sigma = 0$. A horizontal tendency modification scheme is used for lateral boundary condition. Orography is extracted from a very high resolution data base and is smoothed at the resolution of the model. The objectively analysed grid point data are used as input to the model without initialization.

2.1 *Control physics*

The model's physical parameterization used in the control version includes the Kuo-Anthes type of cumulus convection, large-scale condensation, dry convective adjustment, surface fluxes of momentum, heat and moisture over the sea, momentum transfer from the land surface, vertical diffusion of fluxes in the planetary boundary layer and horizontal diffusion. A detailed description of the control physics is given in Singh *et al* (1990).

2.2 *Modified physics*

In the present study a more detailed physical parameterization package based on Krishnamurti *et al* (1990) is included in the limited area model. These include the introduction of a parameterization of shallow convection, detailed calculation of radiative processes including cloud feedback processes, computation of land surface fluxes of momentum, heat and moisture based on the similarity theory and the use of a surface energy balance to obtain the diurnally varying surface temperature over land. Also a modified Kuo scheme is used for deep cumulus convection.

2.2a *Modifications to Kuo convection scheme*

The parametrization of deep cumulus convection is based on the method proposed by Kuo (1974). It is assumed that the cumulus convection always occurs in regions of deep layers of conditionally unstable stratification over areas of mean low level convergence and that the vertical profiles of temperature and humidity inside the cloud follow those of a moist adiabat. In the control model physics the moistening parameter "b" which determines the partitioning between convective heating and moistening is computed as proposed by Anthes (1977). To provide sufficient moisture for the moistening of the vertical column and to account for the observed rainfall on a large scale Krishnamurti *et al* (1983a) introduced a mesoscale moisture convergence parameter "η" in addition to the moistening parameter "b". By assuming that the warming and moistening rates are related to two large scale parameters; vertically averaged vertical velocity "ω" and 700 hPa relative vorticity "ζ", they assumed a multilinear regression relationship between "η", "b", "ζ" and "ω". This formulation for "b" and "η" which is found to enhance the latent heat release in a more realistic way is used in the modified Kuo scheme which is described in detail by Krishnamurti *et al* (1990). Also the cloud base is redefined as the condensation level for near surface air rather than that for air with the mean characteristics of the well mixed layer. This change is found to enhance the occurrence of cumulus convection which was previously underestimated by the control physics.

2.2b *Parameterization of shallow convection*

The presence of shallow non-precipitating cumulus clouds is assumed to enhance the vertical diffusion of sensible heat and moisture within the cloud. It has the effect of transporting moisture from the boundary layer into a cloud layer above. In response to the enhanced moisture supply, the deep convective regions become more active, releasing more precipitation. The effects of shallow cumulus convection are parameterized in the model using a simple eddy diffusion method which represents the turbulent transports of sensible heat and moisture within the cloud layer, through the cloud base and through the level of nonbuoyancy.

2.2c *Radiation scheme*

The radiation scheme introduced in the model is described in detail by Krishnamurti *et al* (1990). It includes a parameterization for the major shortwave absorption processes in the stratosphere, troposphere and at the earth's surface. This is a function of the water vapour distribution, the cloud coverage, the zenith angle of the sun, the albedo of the earth's surface and the ozone distribution. The specification of clouds is based on threshold values of relative humidity. Three types of clouds (low, medium, or high) are assumed to be present when the mean relative humidity in a layer exceeds the threshold values. This sky condition is used in the computation of the solar radiation absorbed or scattered by clouds. A fast method of computing the transmission functions for carbon-di-oxide and water vapour by band-wing scaling approximation is used in the computation of longwave radiative fluxes. Radiation effects are updated every six hours.

2.2d *Modifications to surface fluxes*

The surface fluxes of momentum, heat and moisture are evaluated in the model using bulk aerodynamic formulae. In the control model physics the bulk coefficients over the sea were estimated following Kondo (1975) as a function of stability. Over land, the heat and moisture fluxes were not computed, the momentum flux was obtained using a constant drag coefficient ($C_d = 0.0043$). In the modified physics package expressions derived for stability dependent bulk coefficients as implied by similarity theory are used. The same expressions are used over land and sea. The computation of surface fluxes over the land requires the knowledge of temperature and specific humidity at the surface. A surface energy balance is used to obtain the surface temperature over land. Surface specific humidity is obtained by parameterizing the soil moisture availability using a ground wetness parameter expressed as a function of observed rainfall rate, surface temperature, albedo and terrain height using a regression equation following Dastoor and Krishnamurti (1991).

The large scale condensation, dry convective adjustment, horizontal diffusion and the vertical diffusion processes are similar in both model versions.

3. Data and experiments

Five cases of monsoon depression are chosen for this study. All cases selected are Bay depressions which made landfall over the Indian coast. These depressions frequently move over the Indian subcontinent and cause moderate to heavy rainfall along the tracks besides activating the monsoon. The five input dates are 1200 UTC of 6th July 1979, 16th August 1994, 15th and 25th September 1995 and 25th July 1996. The data are extracted from the daily analyses provided by NCMRWF, except in the case of 6th July 1979 which are obtained from ECMWF FGGE IIIb data sets. Orography is extracted from the US Navy data tape and smoothed to the model's domain. Over the oceans, the prescribed monthly mean sea surface temperature is used as the surface temperature. The surface albedo is taken from climatological fields. Monthly mean ground surface temperature is used as a first guess at the initial time for computing the ground surface temperature over land areas.

The model runs with the control physics and the modified physics are carried out for all five cases of depression. These runs hereafter will be referred to as CTL run and MDF run respectively.

4. Verification of forecast results

Root-mean-square (r.m.s) errors are standard measures of verifying the forecasts and they give a good overview, with a few large errors weighted more than many small errors. The r.m.s errors of mean sea level pressure, 850 and 200 hPa temperatures, 500 hPa geopotential height and 850 and 200 hPa wind for all five cases at days 1, 2 and 3 are computed and shown in figure 1. The light and dark bars are for CTL and MDF runs respectively. The r.m.s errors are found to vary considerably from one case to another. This figure also shows that CTL has errors consistently higher than MDF for most of the variables except for mean sea level pressure on day 1, 850 hPa wind and 500 hPa geopotential height in some cases.

The differences in the r.m.s errors and mean errors between the two model versions are tested for their statistical significance by applying a student's t-test. The results are presented after computing the average skill scores for the five cases of depression. The null hypothesis is that any two model versions, run over an infinite number of cases would have the same scores. A rejection of this hypothesis at a level of 5% means that there is a 95% probability that the difference is real.

4.1 *Average RMSE*

Table 1 lists the average r.m.s errors of mean sea level pressure, wind, temperature, geopotential height and specific humidity for the five cases of depression in CTL and MDF runs for days 1, 2 and 3. Most of the variables show lesser values for MDF compared to CTL by this measure of error, except for 500 hPa temperature, wind in the lower and middle troposphere, and geopotential height and specific humidity in the lower troposphere. The maximum changes are found for mean sea level pressure and temperature. All the average r.m.s errors shown in table 1 for MDF were compared with those of CTL using the student's t-test in order to assess the statistical significance of the differences. The bold-faced average r.m.s values for MDF runs shown in table 1 are those which are significantly different from CTL runs at the 95% confidence level. Temperature in the entire troposphere and 200 hPa wind show significant differences during day 1–3. For mean sea level pressure the differences are significant beyond day 1. The geopotential height and specific humidity show very few significant differences. These results further confirm that the modified physics improves the forecast skill particularly of mean sea level pressure and temperature.

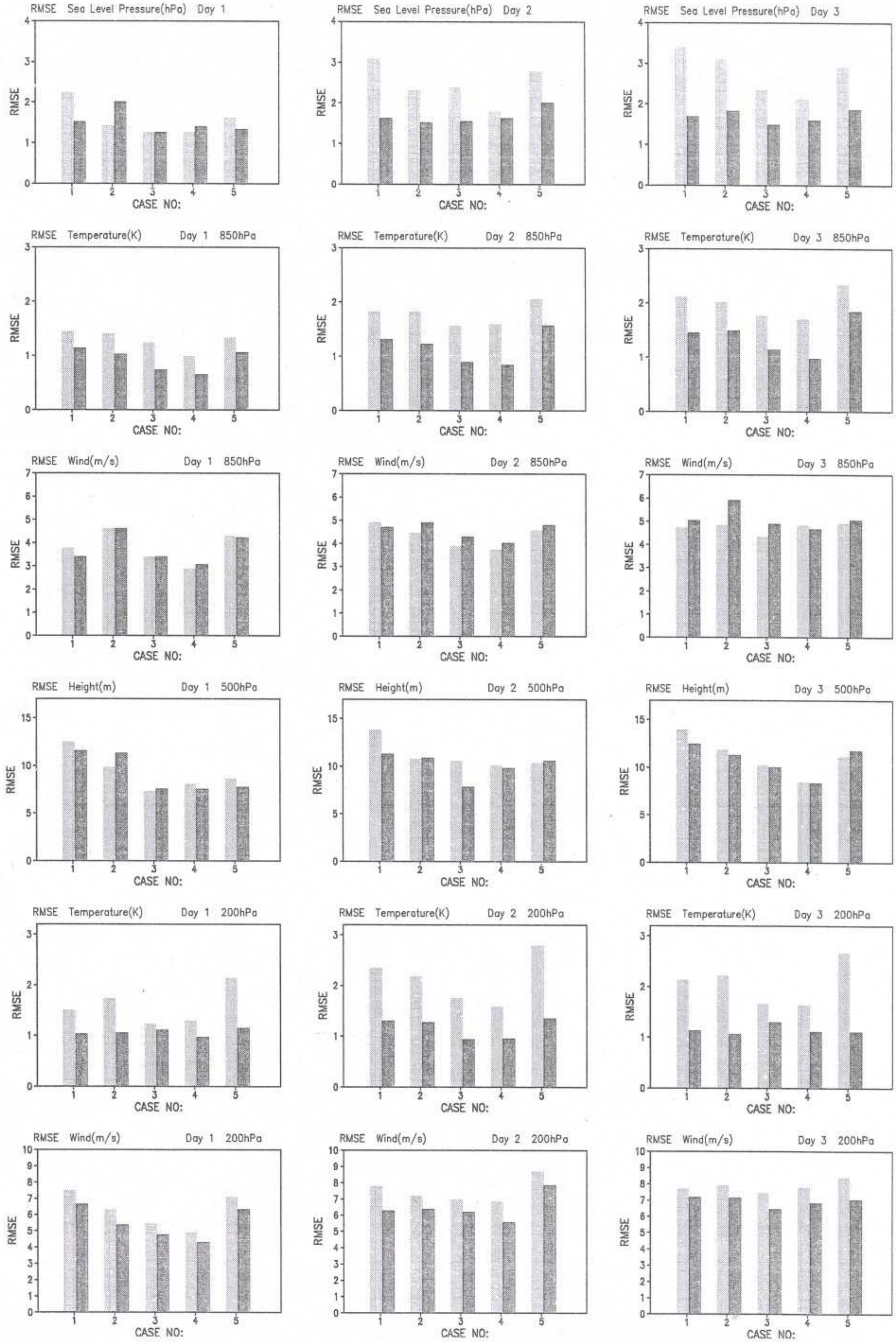

Figure 1. Root mean square errors of various model parameters for five cases of monsoon depression (input dates: 1200 UTC of (1) 6th July 1979, (2) 16th August 1994, (3) 15th September 1995, (4) 25th September 1995 and (5) 25th July 1996). Light and dark bars are for CTL and MDF model runs respectively.

Table 1. *Average root mean square (r.m.s) errors of various model parameters for the five monsoon depression cases in CTL and MDF model runs.*

RMSE: Average of five monsoon depression cases.

	slp hPa	Wind (ms^{-1})				Temperature (K)				Geopotential height (m)				Specific humidity (gm/kg)		
		850	700	500	200	850	700	500	200	850	700	500	200	850	700	500
Day 1																
CTL	1.6	3.8	3.3	3.8	6.3	1.3	1.0	0.9	1.6	9.1	10.3	9.3	22.4	1.4	1.1	0.8
MDF	1.5	3.8	3.3	3.7	**5.5**	**0.9**	**0.9**	**0.9**	**1.1**	10.1	11.5	9.2	15.9	1.6	1.1	0.7
Day 2																
CTL	2.5	4.3	4.0	4.4	7.5	1.8	1.4	1.1	2.1	14.4	12.8	11.1	24.6	1.9	1.3	1.0
MDF	**1.7**	4.6	4.1	4.3	**6.5**	**1.2**	**1.1**	**1.2**	**1.2**	10.8	12.8	10.1	**16.7**	1.9	1.4	**0.8**
Day 3																
CTL	2.8	4.7	4.5	4.7	7.8	2.0	1.6	1.1	2.1	15.5	12.5	11.1	26.8	2.1	1.6	1.1
MDF	**1.7**	5.1	4.8	4.8	**6.9**	**1.4**	**1.3**	**1.4**	**1.1**	**10.0**	12.7	10.8	21.1	2.0	1.7	**0.9**

Note: Bold-face values differ from the values of CTL run at 95% significance level.

Table 2. *Same as in table 1, except for average mean errors.*

ME: Average of five monsoon depression cases.

	slp hPa	Wind (ms^{-1})				Temperature (K)				Geopotential height (m)				Specific humidity (gm/kg)		
		850	700	500	200	850	700	500	200	850	700	500	200	850	700	500
Day 1																
CTL	2.6	3.0	2.6	3.1	5.0	−0.7	−0.4	−0.3	−0.9	1.6	−1.3	0.3	−11.4	−0.7	−0.2	−0.3
MDF	2.3	2.9	2.6	3.1	**4.4**	**0.0**	−0.2	−0.2	**−0.1**	**−2.8**	−3.2	−0.4	**−0.8**	**−0.2**	**0.2**	**−0.2**
Day 2																
CTL	6.3	3.4	3.2	3.5	5.9	−1.1	−0.7	−0.3	−1.5	7.7	3.5	3.5	−13.8	−1.0	−0.4	−0.4
MDF	**2.8**	3.5	3.2	3.5	**5.0**	**0.0**	**−0.4**	**−0.6**	**−0.2**	**1.1**	**0.5**	**0.9**	**0.2**	**0.0**	**0.5**	**−0.1**
Day 3																
CTL	7.9	3.8	3.5	3.8	6.1	−1.2	−0.8	−0.4	−1.4	9.2	4.3	3.3	−14.8	−1.1	−0.6	−0.5
MDF	**2.9**	3.9	3.7	3.9	**5.4**	**0.1**	**−0.5**	**−0.8**	**−0.1**	**1.9**	**1.1**	**−0.2**	**0.0**	**0.1**	**0.7**	**0.0**

Note: Bold-face values differ from the values of CTL run at 95% significance level.

4.2 *Average mean errors*

The grid point differences of forecast and analysed fields averaged over the entire domain are termed the mean errors. They are important measures of skill of the forecasts, since they show biases in the model. Table 2 shows the average mean errors of mean sea level pressure, wind, temperature, geopotential height and specific humidity for the five cases of depression in CTL and MDF runs for days 1, 2 and 3. The overestimation of mean sea level pressure and the cold bias for temperature at all levels except 500 hPa as seen in CTL is found to have reduced considerably in the MDF run. For wind, the average mean errors show marginal change between CTL and the MDF runs. The difference in the mean errors for all variables that are statistically significant at the 95% confidence level is shown bold faced in table 2. The mean sea level pressure, temperature and geopotential height at all levels show significant change beyond day 1. The difference in average mean errors in specific humidity is also found to be significant. These results suggest that the MDF run is able to produce a better forecast by consistently maintaining a low bias for most of the variables.

5. Analyses of forecast fields

Further evaluation of forecasts is done by analysing the mean sea level pressure, wind, rainfall and temperature for all five cases produced by CTL and MDF runs (figure not presented). A careful comparison of the two runs further confirms that the modified physics has maximum impact on mean sea level pressure and temperature, and marginal impact on wind and rainfall, though the magnitude differs from one case to another. In this section we present in detail the results of one case of depression i.e. 6th July 1979 and wherever necessary other cases are discussed.

5.1 *Mean sea level pressure*

The mean sea level pressure forecasts and the corresponding verification fields are given in figure 2. The area below 1000 hPa is shaded in all the plots. The verification analyses show the synoptic features of an active monsoon with the monsoon trough extending from the monsoon depression in Head Bay of Bengal, to the heat low region over northwest India. The minimum pressure associated with the depression is found to be 996 hPa, while over the heat low it is 994 hPa. The model forecasts have a general tendency to overestimate the mean sea level pressure and MDF run could produce a low pressure area of 998 hPa covering the entire monsoon trough. In the CTL run the deterioration in the forecasted mean sea level pressure is clearly evident as the minimum pressure over the entire monsoon trough region is about 1000 hPa even on day 1 and is higher by day 3. The improvement found in the mean sea level pressure forecasts are evident in the other four cases also. This further validates our results that inclusion of modified physics improves the skill score for mean sea level pressure.

5.2 *850 hPa wind*

Figure 3 presents the 850 hPa wind forecasts and the corresponding verifying analyses based on observations for this case. During the 3-day forecast period the verification analyses show a typical active monsoon condition. The CTL and the MDF runs show that in general the cross equatorial flow over the Arabian Sea is predicted properly. The low level jet of more than $20\,\mathrm{ms}^{-1}$ seen over central Arabian Sea in the verification fields is overestimated by both model runs. This was also noted in an earlier work with the model (Singh *et al* 1990). An analysis of the vorticity field indicated development of inertial unstable regions south of the jet maxima possibly resulting into the amplification of the low level jet. While CTL shows a maximum wind speed of around $25\,\mathrm{ms}^{-1}$ on day 3, MDF shows still higher speed of about $30\,\mathrm{ms}^{-1}$ which might be due to the use of a variable mixing length (l) formulation in the vertical diffusion parameterization in the modified physics package whereas the control run uses a constant mixing length ($l = 30\,\mathrm{m}$). The southern equatorial trough is not well simulated by the model. The westward movement and subsequent landfall of the monsoon depression is predicted well. In the region of depression the streamline analyses for MDF show better features of the cyclonic circulation than those found in the CTL run. However, the wind vector difference of the forecast field from the verifying analyses (figure not presented) shows a marginal impact. Similar results are found in the other four cases also.

5.3 *Rainfall*

The one-day accumulated rainfall ending 0000 UTC 8th and 9th July 1979 based on the analysed rainfall rates which is redrawn from Krishnamurti *et al* (1983b) rainfall atlas is shown in figure 4 and that produced by CTL and MDF is presented in figure 5. Regions where rainfall is more than $2\,\mathrm{mm\ day}^{-1}$ are shaded. The predicted rainfall totals are presented leaving the first 12 hours of forecast as the verifying rainfall analyses (figure 4) valid for 0000 UTC only are available. In MDF the predicted rainfall is more organised and is seen to be confined mainly over land. During the 24 hours ending 0000 UTC 8th July 1979 both the experiments gave comparable rainfall

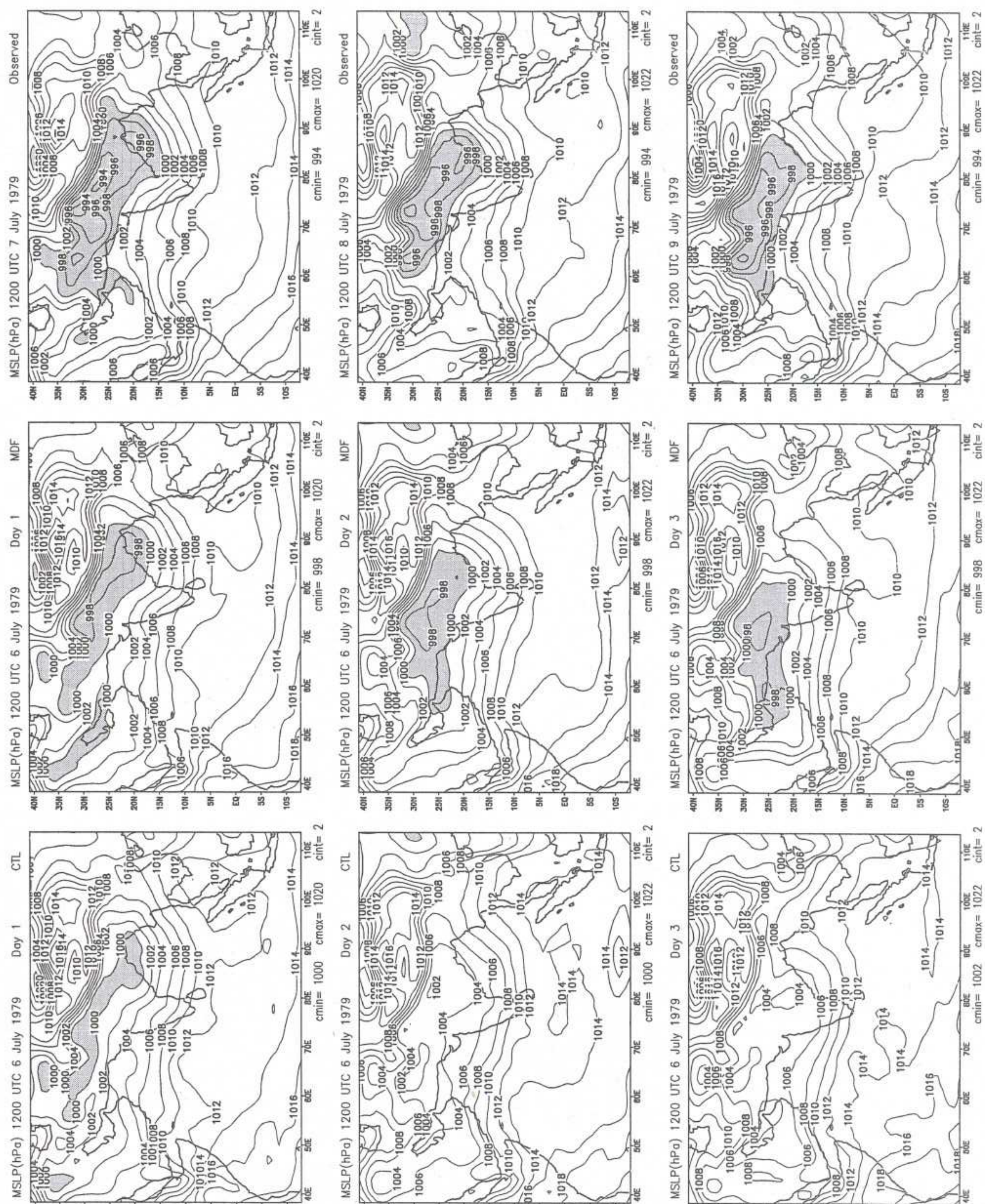

Figure 2. Forecast and corresponding verification charts of mean sea level pressure (hPa). The regions below 1000 hPa are shaded. Input: 1200 UTC 6th July 1979.

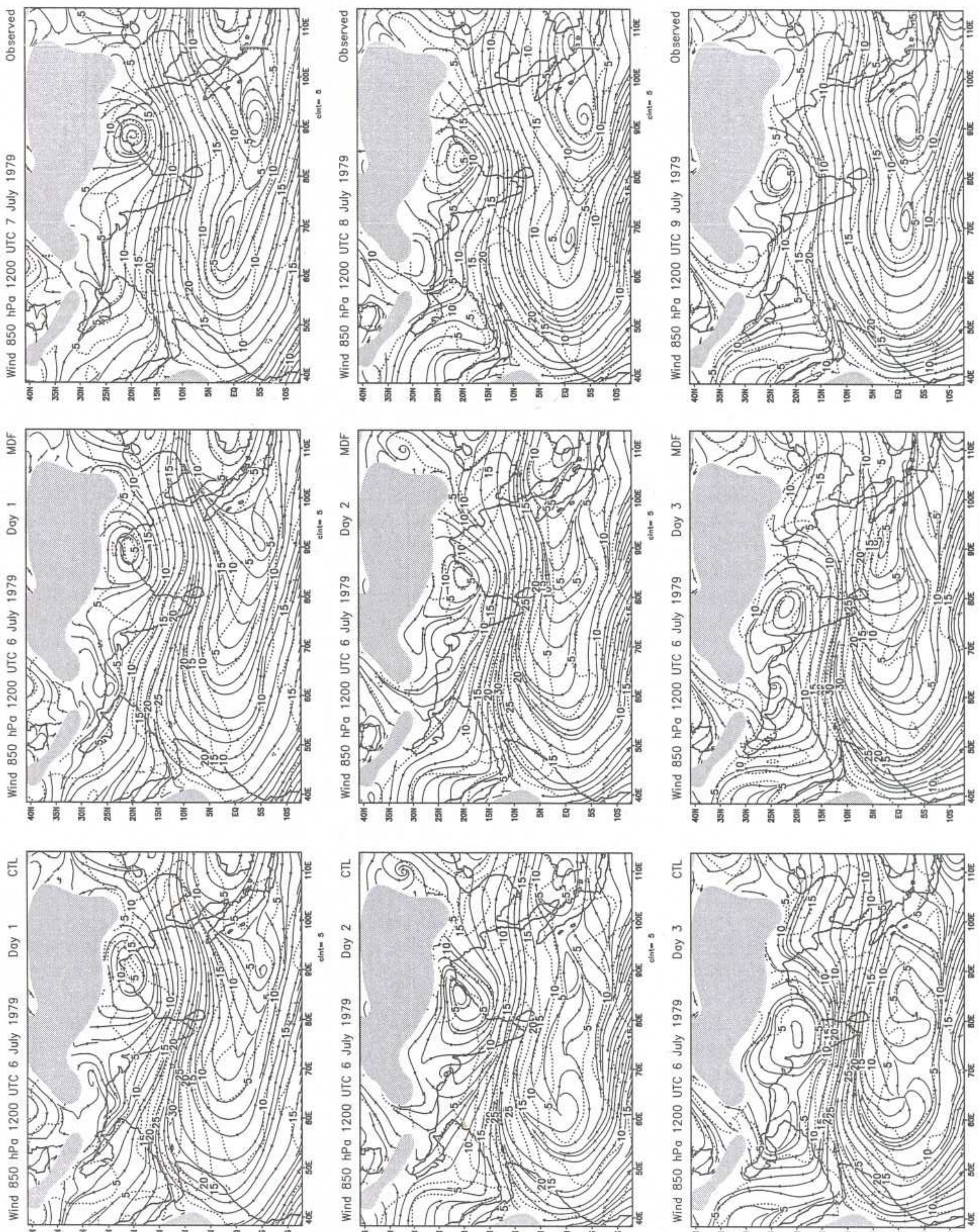

Figure 3. Same as in figure 2, except for 850 hPa wind (ms^{-1}).

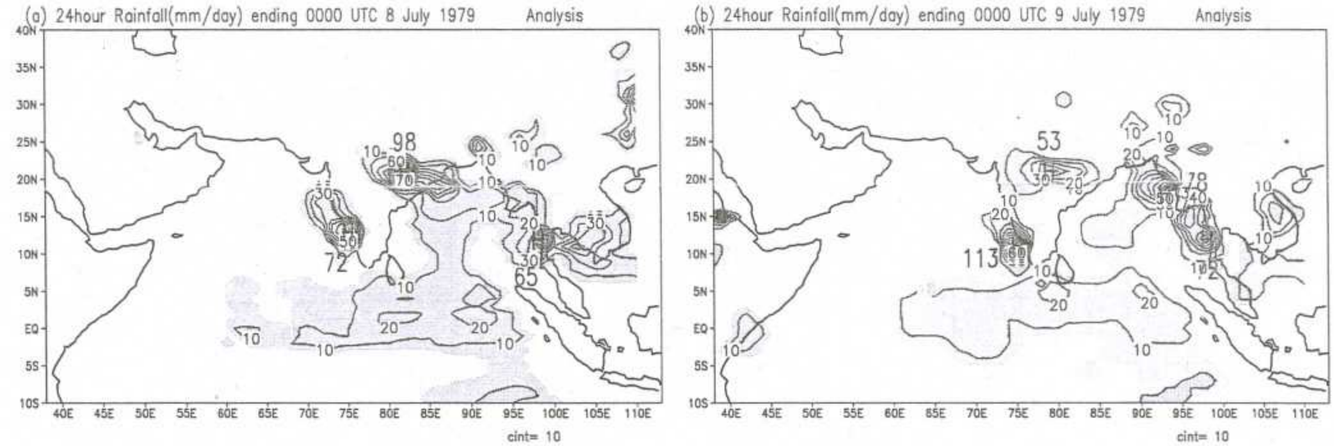

Figure 4. One day accumulated analysed rainfall (mm day^{-1}) ending 0000 UTC: (**a**) 8th July and (**b**) 9th July 1979. Figures redrawn from Krishnamurti *et al* (1983b) rainfall atlas. Regions with rainfall above 2 mm day^{-1} are shaded.

associated with the monsoon depression in the order of 25 mm day^{-1} which was much less than the actual observed magnitude (98 mm day^{-1}). Also the region of maximum rain is seen to be shifted to the south east of the analysed rainfall. In the next 24 hours CTL did not predict any significant amount of rainfall associated with the depression while MDF shows a rainfall maxima of 57 mm day^{-1} which is found to be comparable to the analysed rainfall (53 mm day^{-1}) though the location is slightly shifted to the south. The rainfall along the west coast of India shows a maxima of 72 and 113 mm day^{-1} during these two days. The CTL run is not able to forecast this rainfall properly and shows a maxima of 73 mm day^{-1} in the 24 hours ending 0000 UTC of 9th July 1979, but the location is shifted northward than the analysed position. The MDF run shows better rainfall forecast though the magnitudes are lesser than the verifying analysis. The predicted rainfall maxima is 42 mm day^{-1} and 82 mm day^{-1} during the two-day period. The spurious rainfall over the eastern boundaries seen in CTL is found to have reduced in MDF run for all the cases. Thus the precipitation forecasts for this case is seen to have improved considerably when modified physics is used. Except for the case of 16th August 1994, in all other cases of depression the MDF run could not produce improved rainfall over the west coast of India. In general the amount of enhancement in rainfall associated with the depression in MDF run is found to vary from one case to another.

5.4 *Temperature*

Meridional-height cross sections of zonal mean temperature errors in CTL and MDF runs for days 1, 2 and 3 are presented in figure 6. The zonal means are taken over the Indian region (70°–100°E) and presented over the latitudes 10°–30°N. The model predicted temperature is underestimated in both the experiments up to the middle troposphere and overestimated above up to the tropopause. In CTL the cold bias in the lower troposphere is found to be more than those in the MDF, with the maximum impact of about 2 K seen on day 3. The relative warming of 2 K in MDF could be attributed to the presence of radiation and land surface processes. In the middle troposphere the cold bias has slightly increased in MDF. This could be due to the overestimation of radiative cooling in this region. Overall it can be inferred that the inclusion of modified physics has improved the temperature structure in the lower troposphere. The other cases also show a positive impact with the modified physics though the magnitude of improvement is found to differ from one case to another.

5.5 *Grid point analysis*

To illustrate the difference in the forecast between the two model versions, we compare at a selected grid point (18.9°N/76.0°E) the temporal evolutions of the equivalent potential temperature (θ_e), the vertical profile of which is related to convective instability. This grid point location is under the influence of the monsoon depression by day 3, and the maximum rainfall rates are produced in MDF. In figure 7 the vertical-time cross sections of θ_e, difference of θ_e between MDF and CTL runs, and the relative humidity are presented. The time section of rainfall rates is also presented in this figure. Dashed and solid lines are for CTL and MDF runs respectively. This figure shows that the forecasts from the two model versions differ considerably in the lower troposphere during the daytime where as during the night changes are marginal. In CTL the vertical profile of θ_e shows a marginal change during the entire forecast period, suggesting that the boundary layer has not become sufficiently unstable to release convective available potential energy (CAPE) and as such very little precipitation at this grid point could be produced by this model run. This might be due to the trapping of moisture in a very

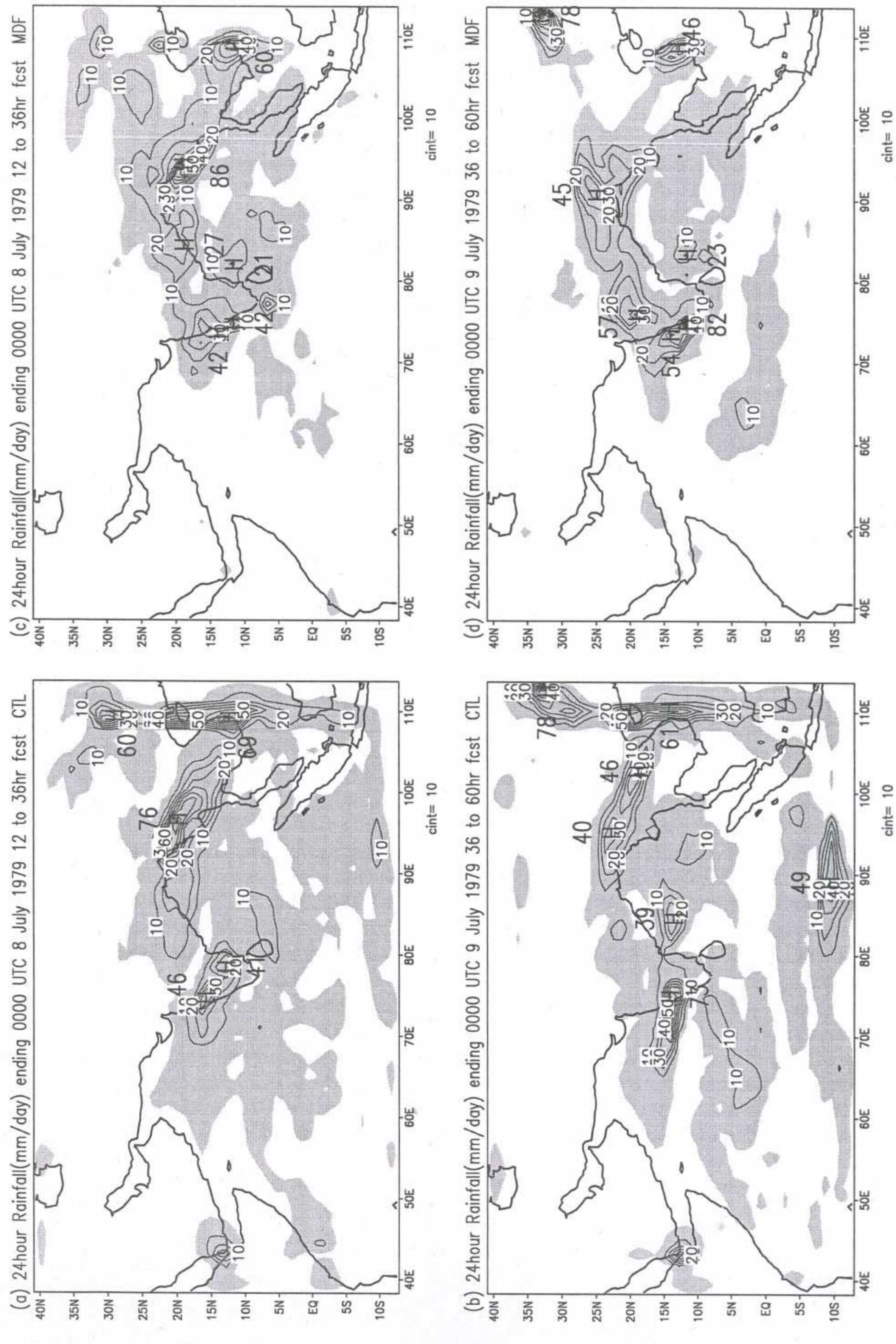

Figure 5. 24-hour accumulated rainfall (mm day $^{-1}$) in CTL run [(a) and (b)] and in MDF run [(c) and (d)].

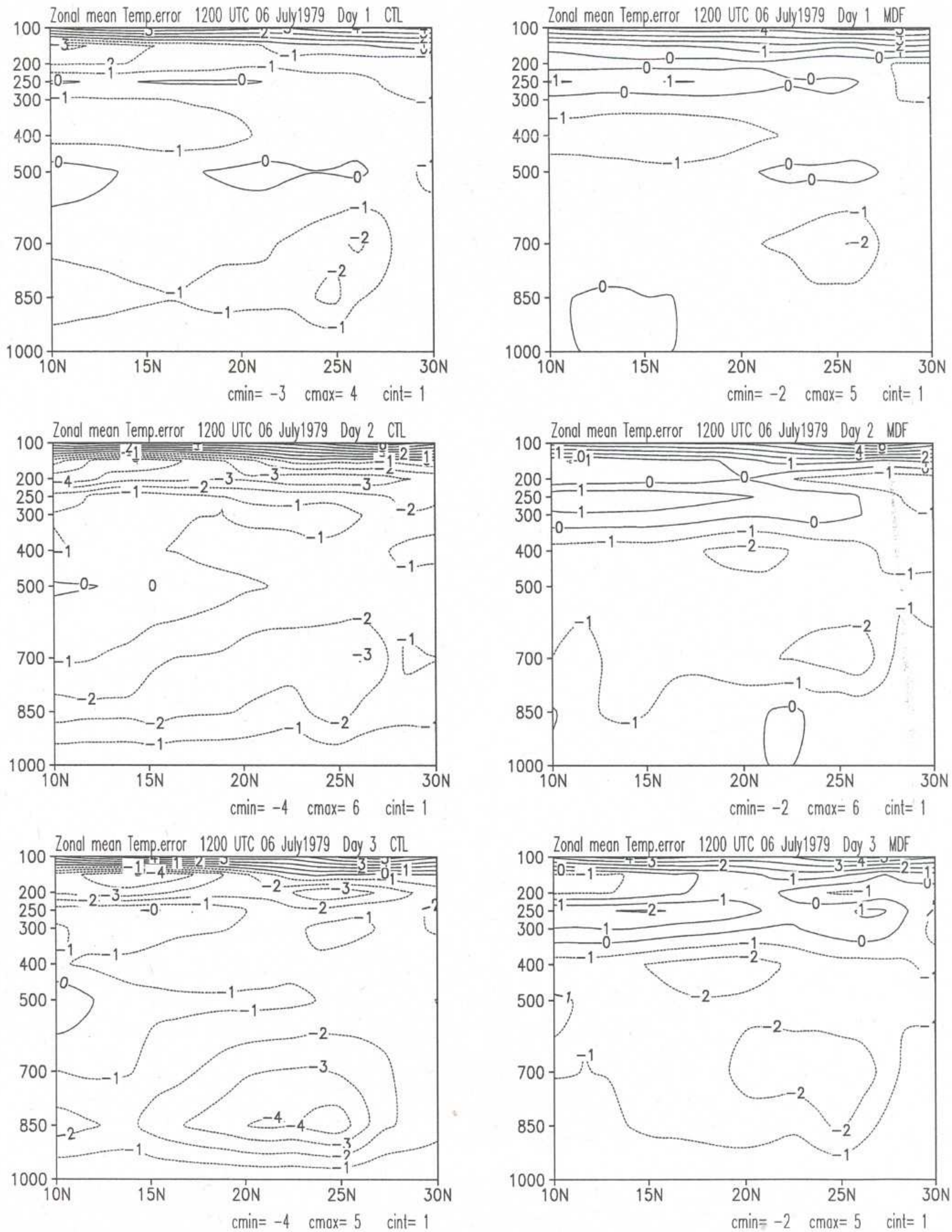

Figure 6. Meridional-height cross section of zonal mean temperature errors (K) in CTL and MDF runs. Zonal means are taken over the longitudes 70°E to 100°E.

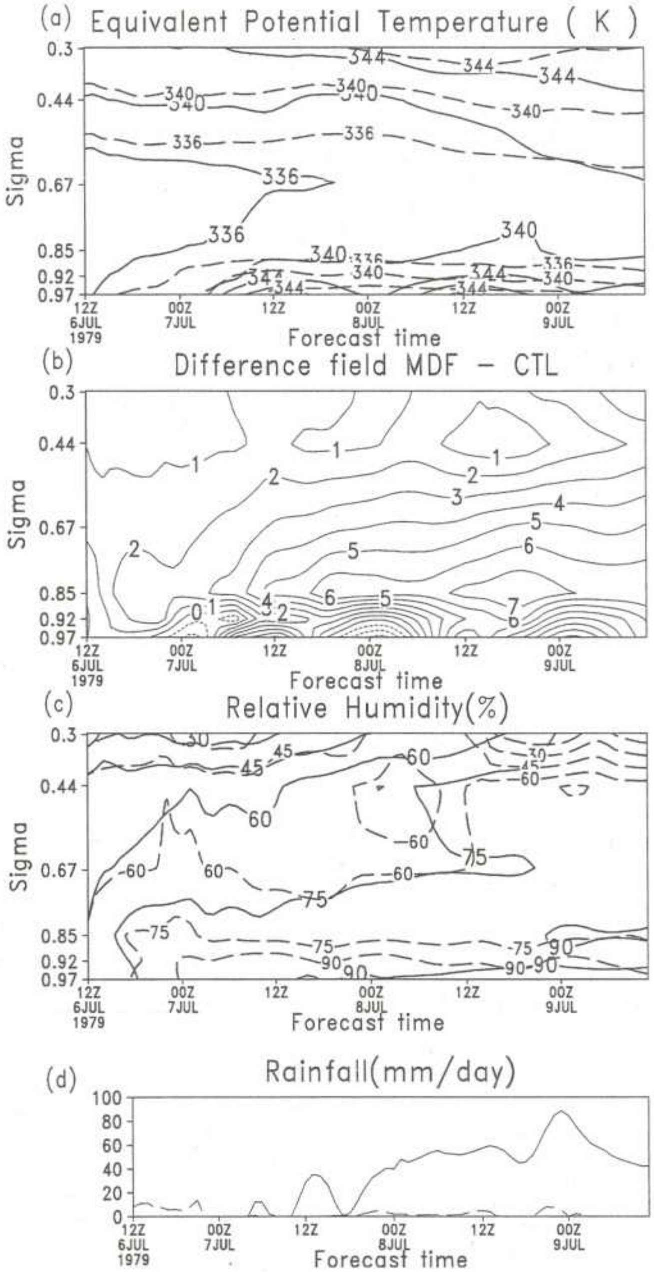

Figure 7. At grid point 18.9°N/76.0°E the vertical-time sections of: (**a**) Equivalent potential temperature, θ_e (K); (**b**) difference of θ_e (K) between MDF and CTL runs; and (**c**) relative humidity (%); (**d**) Time section of rainfall (mm day^{-1}) in CTL (dashed lines) and MDF (solid lines) model runs.

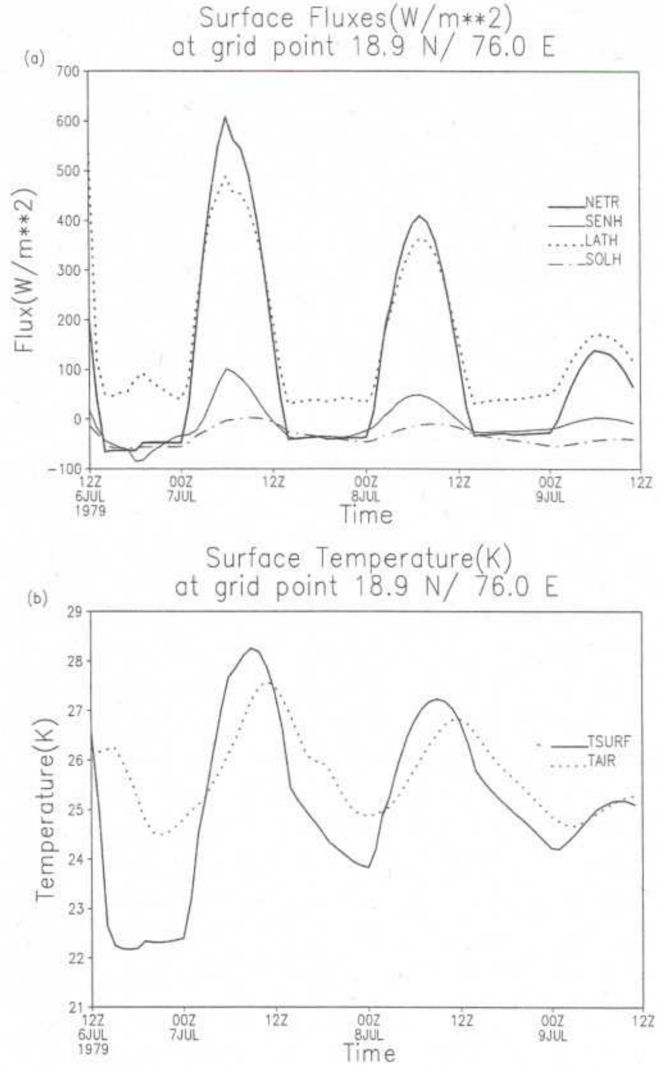

Figure 8. Time sections of surface parameters in MDF run at grid point 18.9°N/76.0°E: (**a**) Different components of surface energy balance; the net radiation at the earth's surface (thick line), the fluxes of sensible heat (thin line), latent heat (dotted line) and soil heat (dashed line), Unit: W m^{-2}; and (**b**) Diurnal variation of surface temperature (thick line) and the top of surface layer temperature (dotted line), Unit: K.

shallow layer near the surface due to poor vertical transfer as seen from the vertical-time cross sections of relative humidity (figure 7c). In MDF the presence of land surface fluxes and shallow convection gives a more efficient vertical transfer of moisture that gives a vertical profile of θ_e suitable for release of CAPE/convective rainfall at this grid point (figure 7d). The improved rainfall is possibly the result of complex interactions of land surface processes, boundary layer and convection.

In figure 8(a) the time sections of the different components of surface energy balance such as the net radiation at the earth's surface (thick line), the fluxes of sensible heat (thin line), latent heat (dotted line) and soil heat (dashed line) for the same grid point in MDF are presented. The net radiation is seen to reach a maximum of 600 Wm^{-2} around the local noon on day 1. The incoming radiation at the earth's surface decreases for this grid point as clouding starts after day 1. A proper partitioning of this radiative flux into sensible and latent heat fluxes is crucial for the correct simulation of the near surface temperature in the model. It is seen that a major part of the radiative flux is converted to latent heat, with only a small fraction contributing to increase the sensible heat at the earth's surface. Figure 8(b) shows the simulated diurnal variations of surface temperature (thick line) and the top of the surface layer temperature (dotted line) for the same grid point. The diurnal range in the surface temperature is seen to reduce from day 1–3 as this grid point came under heavy clouding under the influence of the monsoon depression. The first 12 hours of integration shows a sharp drop in surface temperature. This could be due to the use of climatological monthly mean surface temperature as the initial guess which remains unadjusted due to the absence of initialization in the model. The top of surface layer temperature shows a uniform diurnal variation with a lagged maxima and minima with respect to the surface temperature. In general the near surface parameters appear to be satisfactorily simulated by the modified physics.

6. Summary and concluding remarks

In this paper an attempt has been made to assess the impact of a modified physics package (Krishnamurti *et al* 1990) in limited area model forecasts. Besides, other necessary physics, the modified physics includes the effects of shallow convection, detailed calculation of radiative processes with cloud feedback processes, computation of land surface fluxes of momentum, heat and moisture based on similarity theory and the use of a surface energy balance to obtain the diurnally varying surface temperature over land. Also, a Kuo scheme modified by Krishnamurti *et al* (1983a) is used. The model is run with the control physics and the modified physics for five cases of Bay depression which made landfall over the Indian coast. The r.m.s errors of mean sea level pressure, wind, temperature, geopotential height and specific humidity computed for all five cases show considerable variation from one case to another. Also it is found that the r.m.s errors are consistently higher in the control run than those in the modified run for most of the variables. The differences in the r.m.s errors and mean errors between the two model runs are tested for their statistical significance by applying a student's t-test. The statistical test further confirms that the modified physics significantly improves the forecast skill particularly of mean sea level pressure and temperature. The average mean errors in modified physics show better forecast by consistently maintaining a low bias for most of the variables. Arakawa (1997) discussed that in a hydrostatic atmosphere the ratio of geopotential energy to the internal energy of an air column is almost a constant ($= 0.4$). Thus out of a total amount of heat received by a grid column as a result of a "physics" call, approximately 60% goes directly to increase the internal energy, while the remaining 40% only gets converted into the gravitational potential energy of the column. This seems to explain the reason for geopotential field not showing significant improved forecast skill with the modified physics eventhough significant improvements are found in temperature field.

Further, a detailed analysis of the forecast clearly brings out the positive impact of modified physics on mean sea level pressure and temperature and marginal impact on wind and rainfall, though the magnitude differs from one case to another. The overestimation of the low level jet over the Arabian Sea in both the experiments seems to have masked out the improved features of the cyclonic circulation associated with the monsoon depression obtained with the modified physics, thereby not improving the forecast skill for low level wind field eventhough significant improvement is seen for this field in the upper troposphere. The low pressure area over the monsoon trough extending from the region of monsoon depression in Head Bay of Bengal to the heat low region over northwest India is found to be better predicted with the modified physics. Over the region of monsoon depression the vertical structure of the temperature in the lower troposphere is improved considerably with the modified physics. Furthermore, the temporal evolution of model parameters related to physics is examined at a grid point in the region of monsoon depression. It is found that the vertical structure of equivalent potential temperature is simulated well by the modified run which produced substantial improvement in rainfall forecast over the grid point by enhancing the convective overturning at the right location. The time sections of the different components of surface energy balance and surface temperature show that in general the surface parameters are satisfactorily simulated by the modified run. Since the modified physics has only a little variation in convection scheme from that of control physics, the improvement in rainfall forecast at this grid point could be attributed to the inclusion of land surface physics, shallow convection and radiative transfer processes. Based on the evaluation of the statistical performance of the two model runs and also on the basis of the detailed analysis of the forecast fields, it should be noted that the modified physics improved considerably the mean sea level pressure and temperature forecast fields and marginally the wind and rainfall fields.

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