Cumulus convection and lateral boundary conditions in a limited area model

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Abstract. Three versions of Kuo's cumulus parameterization have been tested in a limited area model to investigate their comparative performances. Results show that the version of Anthes produces better forecasts than those produced by other versions. To identify a suitable scheme of lateral boundary conditions for the limited area model, impact of two time-invariant and two time-dependent boundary conditions have been examined. The forecasts suggest that the time-dependent tendency modification scheme, based on large-scale tendencies obtained from observed data, is a better boundary scheme for the model. Furthermore, the forecast produced with the revised version of the model incorporating improved versions of Kuo's scheme and lateral boundary conditions shows an overall improvement.

Keywords. Limited area model; cumulus convection; lateral boundary conditions; sponge damping; Kuo's cumulus parameterization.

1. Introduction

Cumulus convection is considered to be one of the important facets of numerical modelling for short and medium range weather prediction, particularly over the monsoon region. Another important component of modelling which is peculiar to limited area models, is the specification of lateral boundary conditions.

In the present paper, an attempt was made to study different versions of Kuo's scheme and lateral boundary conditions in a limited area model (Singh *et al* 1990) to identify suitable schemes of convection and boundary conditions. Comparatively better schemes that emerged from the above investigation are incorporated in the model to produce 48 h forecasts.

The paper presents different versions of Kuo's scheme and lateral boundary conditions. The forecast produced with the improved version of the model is discussed.

2. Description of the model

The model is a regional six-level primitive equation model in σ -coordinates. The model is staggered in both vertical and horizontal directions. Arakawa's *B*-type of staggering was used in the horizontal direction. The six sigma levels were close to 950, 850, 700, 500, 300 and 150 hPa. The top of the model was fixed at 100 hPa. The horizontal domain extends from 10°S to 40°N and 50°E to 120°E. The horizontal domain had 45×33 grid points on a Mercator projection with 150 km as grid length.

The lateral boundary conditions are given in §5. In the vertical, the boundary

condition $\dot{\sigma} = 0$ at $\sigma = 0$ and $\sigma = 1$ was used. Mass, energy, potential temperature and the variance of potential temperature conserving schemes (Arakawa and Mintz 1974; Arakawa and Lamb 1977) for space derivatives were used. The horizontal advection terms in the momentum equations were computed with fourth-order accuracy finite difference scheme (Arakawa's 13-point Jacobian scheme). The other terms were computed with a second-order accuracy finite difference scheme. For time integration, a leap frog scheme with Asselin (1972) time filter was used with a time-step of 3 minutes. The physical processes incorporated in the model are: large-scale condensation, dry convective adjustment, horizontal and vertical diffusion, sensible heat supply and evaporation over the sea. Three versions of convection were incorporated in the model. A detail description of the model may be found in Singh *et al* (1990).

3. Data

The FGGE IIb grid point data of 12 GMT 7 July 1979 were used as input to the model for all numerical experimentations. The dominant synoptic feature was an intense monsoon depression centred over the head Bay of Bengal on 7 July. This system moved initially westward and subsequently northwestward and dissipated on 9 July.

4. Study on cumulus convection

The cumulus parameterization scheme of Kuo (1965, 1974) has been widely used in large-scale numerical weather prediction models due to its simple formulation and computational economy. Several investigators showed that the classical scheme of Kuo (1965) underestimated rainfall rates. Furthermore, it was noted that there was a disproportionate partitioning of the available moisture supply into moistening and heating. Kuo (1974) recognized the shortcomings of his earlier scheme and introduced a more realistic division of the moisture by bringing in a moistening parameter b . Considerable attention has been focussed on improving the performance of Kuo's (1974) scheme by trying to find the most appropriate value of the moistening parameter b . In the following section an outline of the Kuo's scheme is given.

4.1 An outline of the Kuo's scheme

In the Kuo's scheme of cumulus parameterization the heating and vertical flux of moisture is invoked only if the sounding is conditionally unstable and the net convergence of moisture is positive. Following Kanamitsu *et al* (1983), the large scale supply of moisture (net convergence of moisture) I_L is given by

$$I_L = \int_{\sigma_b}^{\sigma_r} (\partial q / \partial t) d\sigma. \quad (1)$$

Krishnamurti *et al* (1983a) introduced an additional source of moisture supply ηI_L which is a non-measurable mesoscale (or sub-grid scale) supply. The term ηI_L was introduced to provide sufficient moisture supply in the vertical column to account

for the observed rainfall rates and moistening. The total moisture supply was expressed by

$$I = I_L(1 + \eta). \quad (2)$$

η is known as the mesoscale convergence parameter. Following Kuo (1965), the maximum amount of moisture supply required to produce a grid square cloud was expressed by

$$Q = - \int_{\sigma_b}^{\sigma_r} (q_s - q) d\sigma - \frac{C_p}{L} \int_{\sigma_b}^{\sigma_r} (T_s - T) d\sigma. \quad (3)$$

The first term on the right side is denoted as Q_q and the second term as Q_θ . The terms Q_q and Q_θ respectively denote the supply needed for moistening and heating of a unit column. Introduction of a parameter b following Kuo (1974), the rainfall rate R and moistening rate M may be expressed by

$$R = I_L(1 + \eta)(1 - b), \quad (4)$$

$$M = I_L(1 + \eta)b. \quad (5)$$

Following Kuo (1974), the two additional parameters a_θ and a_q may be expressed by

$$a_\theta = \frac{I(1 - b)}{Q_\theta} = \frac{I_L(1 + \eta)(1 - b)}{Q_\theta}, \quad (6)$$

$$a_q = \frac{Ib}{Q_q} = \frac{I_L(1 + \eta)b}{Q_q}. \quad (7)$$

In this formulation there are two unknown parameters b and η that are to be determined.

The heating and moistening by clouds are proportional to the temperature and humidity difference between the model cloud and the environment. Consequently the heating and moistening at each level are expressed as

$$\partial T / \partial t = a_\theta (T_s - T), \quad (8)$$

$$\partial q / \partial t = a_q (q_s - q). \quad (9)$$

From (6) and (7), a_θ and a_q are determined if b and η are known and thus the parameterization is closed.

In the following section we shall show how b and η are determined by different versions of Kuo's scheme.

4.2 Three versions of Kuo's scheme

(i) Kuo (1974) version (KU74): This is essentially the earlier Kuo (1974) scheme of parameterization. The parameters b and η are set zero. The coefficients a_θ and a_q are determined as follows:

$$a_\theta = I_L / Q_\theta, \quad (10)$$

$$a_q = 0. \quad (11)$$

The above formulation for computation of a_θ and a_q was used by Krishnamurti *et al* (1980). This version will hereafter be referred to as KU74.

(ii) *Anthes (1977) version (AN77)*: The parameter η is set zero. The parameter b is computed following Anthes (1977).

$$b = \begin{cases} \left(\frac{1 - \langle RH \rangle}{1 - RH_c} \right)^n & \text{when } \langle RH \rangle > RH_c \\ 1 & \text{when } \langle RH \rangle \leq RH_c \end{cases} \quad (12)$$

where $\langle RH \rangle$ is the mean relative humidity in the cloud layer and RH_c is the critical relative humidity below which there is only moistening. The values, $RH_c = 0.5$ and $n = 3$ are used in the present study.

The heating and moistening rates were calculated following the usual Kuo (1974) scheme. The coefficients a_θ and a_q are determined by

$$a_\theta = (1 - b)I_L/Q_\theta, \quad (13)$$

$$a_q = bI_L/Q_q. \quad (14)$$

This version will hereafter be referred to as AN77.

(iii) *Krishnamurti et al (1983) version (KR83)*: Krishnamurti *et al* (1983a) proposed a closure for b and η by a screening multiple-regression analysis of GATE observations. The normalized heating and moistening R/I_L and M/I_L were regressed against a number of large-scale variables. Based on GATE observations, significant correlations for moistening and heating were noted by them from the following relations,

$$M/I_L = a_1\zeta + b_1\bar{\omega} + c_1, \quad (15)$$

$$R/I_L = a_2\zeta + b_2\bar{\omega} + c_2. \quad (16)$$

where ζ is the relative vorticity at 700 hPa and $\bar{\omega}$ is the vertically-averaged vertical p -velocity. a_1, a_2, b_1, b_2, c_1 and c_2 are coefficients of regression. Magnitudes of these coefficients are given by Arunkumar (1989). Expressions for b and η can be obtained from (4), (5), (15) and (16).

$$b = \frac{a_1\zeta + b_1\bar{\omega} + c_1}{(a_1 + a_2)\zeta + (b_1 + b_2)\bar{\omega} + (c_1 + c_2)}, \quad (17)$$

$$\eta = (a_1 + a_2)\zeta + (b_1 + b_2)\bar{\omega} + (c_1 + c_2) - 1. \quad (18)$$

Thus the values of b and η could be determined with model values of ζ and $\bar{\omega}$. The coefficients a_θ and a_q were then obtained by

$$a_\theta = I_L(1 + \eta)(1 - b)/Q_\theta, \quad (19)$$

$$a_q = I_L(1 + \eta)b/Q_q. \quad (20)$$

The scheme will be referred to as KR83.

4.3 Numerical experiments

Two numerical experiments using the three versions outlined in the previous section were made. In the first experiment (EX1), following Kanamitsu *et al* (1983) the

conditions to be satisfied for invoking convection are: (i) conditionally unstable atmosphere, (ii) positive moisture convergence in the cloud layer and (iii) environmental mean relative humidity in the cloud layer exceeds a critical value of 80%. In the second experiment (EX2) convection is invoked if conditions (i) and (ii) of EX1 are satisfied. No constraint is imposed on mean relative humidity.

In both the experiments the time-invariant lateral boundary conditions were used.

4.4 Discussion

In both experiments the model was integrated up to 48 h using input data of 12 GMT 7 July 1979.

In the first experiment (EX1) the forecast results of KU74, AN77 and KR83 were found very similar. In the second experiment (EX2) both KU74 and KR83 schemes produced spurious results. Hence, the forecast results of KU74 of EX1 (EX1/KU74) and AN77 of EX2 (EX2/AN77) are discussed below for comparison.

(i) *850 hPa wind*: Figure 1 shows 48 h predicted 850 hPa winds of EX1/KU74 and EX2/AN77 schemes. The observed winds of 12 GMT 9 July 1979 are also shown in the same figure for comparison. It can be seen that in both the experiments the circulation features are reasonably well-predicted, particularly the cyclonic circulations associated with the depression, circulations around the equator and the cross-equatorial flow. However, the easterlies to the north and westerlies to the south of the depression are found to be weaker. It can also be seen that the westerlies off the west coast are overpredicted by 10–15 kt.

(ii) *Rainfall*: The predicted rainfall rates (12–36 h) of EX1/KU74 and EX2/AN77 are shown in figure 2. The observed rainfall during the 24 h period ending at 00 GMT 9 July 1979 (Source: Krishnamurti *et al* 1983b) are also shown in the same figure. In general, the areal distribution of rainfall is predicted better in EX2/AN77. The predicted rainfall rates associated with the depression are underpredicted in both the experiments. Grell *et al* (1991), in their semiprognostic tests in middle latitude with three versions of Kuo's scheme noticed underprediction of heating and moistening rates. They noted the need to include mesoscale moisture convergence to correctly predict the heating and moistening rates in large-scale models.

In EX1/KU74 the rainy area associated with the depression has two maxima, one of 20.6 mm at 20°N, 85°E and the other of 10.2 mm at 20°N, 76°E. The observed rainfall maximum associated with the depression is 50 mm at 22°N, 80°E. However, in EX2/AN77 the rainy area associated with the depression shows three rainfall maxima one of 12.4 mm at 18°N, 83°E, other of 10.2 mm at 22°N, 78°E and another of 24.4 mm at 20°N, 75°E.

(iii) *Track of the depression*: The predicted track of the depression of EX1/KU74 and EX2/AN77 is shown in figure 3. For comparison, the observed track of the depression is also shown in the figure. It can be seen that in both EX1/KU74 and EX2/AN77 the predicted tracks are to the north of the observed track and the movement is slower in the case of EX2/AN77 in the first 24 h. In the next 24 h the depression moved westward in EX2/AN77 while in EX1/KU74 the movement is towards southwest. The 48 h forecast position of the depression is slightly to the south of the actual in EX2/AN77 while it is located far to the south-east in EX1/KU74. Thus, the westward movement of the depression in a 24–48 h period is better predicted in EX2/AN77.

Figure 1a.

Figure 1b.

Figure 1c

Figure 1. 850 hPa wind (a) 48 h forecast from EX1/KU74, (b) 48 h forecast from EX2/AN77 and (c) Observed at 12 GMT 9 July 1979.

Figure 3. Predicted and observed tracks of the monsoon depression at 850 hPa level.

Table 1. Predicted and observed phase speeds and positional errors of the monsoon depression at 850 hPa.

<i>t</i> (h)	Phase speed (km/24 h)			Positional error (km)	
	EX1/KU74	EX2/AN77	Observed	EX1/KU74	EX2/AN77
0–24	570	490	560	110	110
24–48	200	405	420	310	190

(iv) *Phase speed and positional error*: The predicted and observed phase speed of the monsoon depression and the positional errors are shown in table 1. It can be seen that the predicted phase speed of the depression in the first 24 h of EX1/KU74 is comparable to the observed phase speed while the predicted phase speed of EX2/AN77 is less than the observed. In the next 24 h the predicted phase speed of EX1/KU74 is less than half of that observed while the phase speed of EX2/AN77 is comparable to the observed.

The positional error is the same for both EX1/KU74 and EX2/AN77 in the 24 h forecast. In the 48 h forecast the positional error is much higher in the case of EX1/KU74 scheme.

(v) *RMS error*: The root mean square (RMS) errors for *u* and *v* components of wind and geopotential height (*Z*) at 850, 500 and 200 hPa for both EX1/KU74 and EX2/AN77 are shown in table 2. It can be seen that the RMS errors of *u*, *v* and *Z* are slightly less for EX2/AN77 at all the three levels in both 24 and 48 h forecasts. Slingo *et al* (1988), in their study of impact of various modified physical processes in

Table 2. 24 and 48 h RMS errors of u , v (ms^{-1}) and Z (m) at 850, 500 and 200 hPa levels for experiments EX1/KU74 and EX2/AN77.

Level (hPa)	Variable	24 h		48 h	
		EX1/KU74	EX2/AN77	EX1/KU74	EX2/AN77
850	u	3.6	3.6	5.8	5.6
	v	3.2	3.2	3.1	3.0
	Z	40.8	40.6	67.2	67.9
500	u	3.1	3.0	4.6	4.7
	v	2.9	2.8	3.8	3.7
	Z	47.1	45.0	86.7	83.7
200	u	5.0	4.8	7.2	7.2
	v	4.8	4.8	4.4	4.5
	Z	73.3	71.6	122.9	120.4

the ECMWF model, showed that improvements in RMS wind errors at 850 hPa could be found only after day 2 forecast.

From the above discussions on wind field, rainfall, track of the depression, phase speed, positional error and RMS error it can be inferred that EX2/AN77 is a better scheme for cumulus parameterization.

5. Study of lateral boundary conditions

The treatment of lateral boundaries is an important problem for regional NWP models. Over the years, a number of techniques for treating lateral boundaries have been tested. Sundstrom and Elvius (1979) and Davies (1983) have presented excellent reviews of commonly used lateral boundary conditions for regional models. In this study two time-invariant and two time-dependent lateral boundary conditions have been applied to examine their impact on model forecasts. In all experiments the EX1/KU74 version of convection has been incorporated.

5.1 Four schemes for lateral boundary conditions

(i) *Fixed boundary conditions without sponge damping (B_1)*: In this, all the prognostic variables at the boundary were kept fixed throughout the period of integration i.e. the initial values were not modified at the boundary. This scheme will hereafter be referred to as the B_1 scheme.

(ii) *Fixed boundary conditions with sponge damping (B_2)*: The sponge damping scheme of Perkey and Kreitzberg (1976) was adopted. Following their scheme the prediction of any dependent variable X can be written as

$$X_n(I) = X_p(I) + W(I) \left. \frac{\partial X_m}{\partial t} \right|_I \Delta t, \quad (21)$$

where subscripts n and p denote the new value after the boundary condition is applied and a previous value at a former time and m is the model-computed tendency.

The values of the weighting coefficients W were assigned as 0, 0.4, 0.7, 0.9 and 1.0 for the boundaries, the first, second, third and all other interior grid points respectively. We tested with a few other combinations of weighting coefficients and found that the above mentioned combination produced best result.

This scheme was a special case of the 'tendency modification scheme' of Perkey and Kreitzberg (1976) for cases where external large-scale tendencies at the boundaries were not available. This scheme will be referred to as the B_2 scheme.

(iii) *Time-dependent boundary conditions without sponge damping (B_3)*: In this scheme the tendencies of the prognostic variables at the boundary were calculated from the 12-hourly observed analyses and the boundary values were updated using the following relation,

$$X_n = X_p + (\partial X_{\text{obs}}/\partial t)\Delta t, \quad (22)$$

where X_n and X_p are the new and previous values of any variable X , and $\partial X_{\text{obs}}/\partial t$ is the tendency calculated from the 12-hourly observed data. This scheme hereafter will be referred to as the B_3 scheme:

(iv) *Time-dependent boundary conditions with sponge-damping (B_4)*: The tendency modification scheme of Perkey and Kreitzberg (1976) was applied. In this scheme the prediction of any variable X is given by

$$X_n(I) = X_p(I) + W(I) \left. \frac{\partial X_m}{\partial t} \right|_I \Delta t + [1 - W(I)] \left. \frac{\partial X_{\text{ls}}}{\partial t} \right|_I \Delta t, \quad (23)$$

where the subscripts n and p denote the new value and the previous values at a former time, m denotes the model computed tendency and ls denotes the large-scale tendency. The weighting coefficients $W(I)$ are the same given in B_2 scheme.

The large scale tendencies were computed from 12-hourly observed data. The scheme will be referred to as the B_4 scheme.

5.2 Discussions of results

The four lateral boundary conditions were applied in the regional model to examine their impact on model forecasts. In all experiments, the model was integrated up to 48 h using input data of 12 GMT 7 July 1979. The results are discussed below.

(i) *RMS error*: The RMS errors of u and v components of wind and geopotential height (Z) at 850, 500 and 200 hPa level are shown in table 3. It is evident that the RMS errors of the three variables at all three levels were less in the time-dependent scheme B_3 and B_4 compared to the time-invariant schemes. Among the time-dependent schemes, the RMS errors of u and v for B_4 scheme at all the levels were less than those of the B_3 scheme for a 24 h forecast, while for Z it was higher at 850 and 500 hPa and lower at 200 hPa for the B_4 scheme. In a 48 h forecast the RMS error of u and v at 850 and 200 hPa of B_4 were slightly higher than B_3 , while it was the opposite at 500 hPa. The 48 h RMS error of Z in B_4 was lower at all levels compared to B_3 . Among the time-invariant schemes B_2 seemed to be slightly better than B_1 in a 24 h forecast at all levels. In a 48 h forecast, the RMS errors of u and v for B_1 at 850 and 500 hPa are less than B_2 , and the error of Z for B_2 was less at all levels compared to B_1 . We infer that B_4 has comparatively less RMS errors.

Table 3. 24 and 48 h RMS errors of u , v (ms^{-1}) and Z (m) at 850, 500 and 200 hPa levels for experiments B_1 , B_2 , B_3 and B_4 .

Level (hPa)	Variable	24 h				48 h			
		B_1	B_2	B_3	B_4	B_1	B_2	B_3	B_4
850	u	3.6	3.5	3.4	3.1	5.8	5.9	4.3	4.4
	v	3.2	3.3	2.9	3.0	3.1	3.6	3.1	3.3
	Z	40.8	40.3	26.3	26.5	67.2	55.6	34.6	27.7
500	u	3.1	2.9	2.6	2.4	4.6	4.7	3.5	3.4
	v	2.9	2.8	2.1	1.9	3.8	3.7	3.0	2.8
	Z	47.1	47.5	28.5	30.1	86.7	70.5	43.1	36.5
200	u	5.0	4.7	4.7	4.4	7.2	7.2	5.2	5.3
	v	4.8	4.5	4.5	4.1	4.4	4.4	3.8	3.9
	Z	73.3	68.7	50.5	48.8	122.9	101.3	72.7	64.1

(ii) *Track of the depression:* The predicted tracks of the monsoon depression at 850 hPa of B_1 , B_2 , B_3 and B_4 are shown in figure 4. The observed track is also shown for comparison. We find that the time-invariant schemes B_1 and B_2 show faster movement in the first 24 h than the time-dependent schemes B_3 and B_4 . The track of B_4 shows a westward movement along the observed track and tracks of B_1 , B_2 and B_3 show west-northwestward movement in the first 24 h. In the next 24 h B_3 and B_4 show faster movement than the time-invariant schemes. During this period, only the track of B_4 has a northerly component of motion similar to the observed while the tracks of other schemes have a southerly component of movement. Thus, the track of B_4 was found to be comparatively closer to that observed, although the initial movement was quite slow. Krishnamurti *et al* (1989) found a predicted track very close to that observed with the use of their so-called 'perfect boundary conditions' based on observed data analyses in FSU high resolution regional model.

(iii) *Phase speed:* The predicted phase speeds of the depression at 850 hPa for all the four boundary schemes are shown in table 4. The observed phase speeds are also shown in the same table for comparison. In the first 24 h the predicted phase speed of B_1 was close to the observed phase speed while the phase speeds of other schemes were less. The much slower movement of the depression in B_3 and B_4 in the first 24 h was reflected in their phase speeds being less than half the observed value. In the subsequent 24 h, the phase speeds of B_3 and B_4 were comparable to those observed and those of B_1 and B_2 were lower.

(iv) *Rainfall:* The accumulated 48 h rainfall produced by B_1 , B_2 , B_3 and B_4 is shown in figure 5. The accumulated rainfall at the northern and eastern boundaries are much reduced in B_2 and B_4 when compared with B_1 and B_3 . This is due to the reduction of spurious divergence at the boundaries in B_2 and B_4 . The reduction of divergence at the boundaries in B_2 and B_4 could be attributed to the application of sponge damping. However, the rainfall distribution well inside the boundary region is similar in all the four boundary schemes. Thus, the reduction of spurious divergence at the boundary does not appear to have a significant impact on the interior forecast. Kurihara *et al* (1989) have also obtained a similar reduction in rainfall at the boundaries in their study with a version of the radiation boundary condition. Thus, B_2 and B_4 seem to handle the spurious divergence at the boundaries more effectively.

Figure 4. Predicted track of the monsoon depression at 850 hPa level for (a) B_1 and B_2 schemes and (b) B_3 and B_4 schemes.

Table 4. Predicted and observed phase speeds of the monsoon depression at 850 hPa.

$T(h)$	Phase speed (km/24 h)				Observed
	B_1	B_2	B_3	B_4	
0–24	570	410	250	240	560
24–48	200	325	400	420	420

The results presented in §5 reveal that the time-dependent tendency modification scheme (B_4) is a superior lateral boundary condition for the model.

6. Prediction with revised version of the model

The study on cumulus convection discussed in §4 reveals that the Anthes (1977) scheme in Experiment 2 (EX2/AN77) scheme produced better forecasts. Similarly, from the study on lateral boundary conditions discussed in §5 it was found that the time-dependent tendency modification scheme (B_4), based on large-scale tendencies obtained from observed data produced better forecasts. A prediction experiment was carried out with the revised version of the model incorporating the EX2/AN77 scheme of convection and B_4 scheme for lateral boundary conditions.

6.1 Forecast results

The revised version of the model was integrated up to 48 h using input data of 7 July 1979. As the result has been discussed in detail in §§4 and 5, the salient features of the forecasts are presented below.

(i) *Track of the depression*: The predicted and observed tracks of the monsoon depression are shown in figure 6. It can be seen that the predicted track of the depression is quite close to that observed although the speed of movement was slower. Compared to the tracks in the previous experiments, this was the best predicted track.

Figure 6. Predicted track of the monsoon depression at 850 hPa level with revised version of the model.

Table 5. 24 and 48 h RMS errors of u , v (ms^{-1}) and Z (m) at 850, 500 and 200 hPa levels with revised version of the model.

Level (hPa)	Variable	24 h	48 h
850	u	3.1	4.1
	v	2.9	3.1
	Z	25.9	27.6
500	u	2.2	3.6
	v	2.0	2.8
	Z	29.1	34.8
200	u	4.5	5.1
	v	3.9	4.0
	Z	47.9	64.5

Figure 7. Predicted rainfall (mm) for the period $T = 12-36$ h with revised of the model.

(ii) *RMS errors:* The RMS errors of u and v components of wind and geopotential height at 850, 500 and 200 hPa levels are shown in table 5. In general, the RMS errors of all the three variables are lower at all levels compared to other experiments reported in this paper.

(iii) *Rainfall:* The predicted rainfall rates (12–36 h) are shown in figure 7. It can be seen that the areal distribution of rainfall is predicted well. In this case there are two rainfall maxima, one near 84°E , 19°N of 10 mm and another of 21.2 mm near 73.5°E , and 20°N . The spurious rainfall amounts near the eastern boundary are reduced.

7. Conclusions

Based on a case study of numerical prediction of one depression we reach the following conclusions. The study on cumulus convection revealed that inclusion of the Kuo (1974) scheme with Anthes (1977) criteria for computing the moistening parameter b produced better forecasts. The study also suggests that there should be a check on the environmental mean relative humidity of the cloud layer for invoking convection in the model so as to avoid spurious forecasts. The study on lateral boundary conditions suggests that the time-dependent tendency modification scheme of Perkey and Kreitzberg (1976) based on the large-scale tendencies from 12-hourly real data analyses was a better scheme. This result emphasizes the importance of using global models to provide lateral boundary conditions for operational regional models. Furthermore, the revised version of the model incorporating an improved version of convection and tendency modification scheme for lateral boundary conditions produced overall improved forecasts.

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