NOTES AND CORRESPONDENCE

Applying the Betts–Miller–Janjic Scheme of Convection in Prediction of the Indian Monsoon

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ABSTRACT

The performance of the Betts–Miller–Janjic scheme of convection has been investigated for prediction of the Indian monsoons. For this purpose a limited area numerical weather prediction model with two schemes of convection, one with the Betts–Miller scheme and other with the Betts–Miller–Janjic scheme, is run for five cases of monsoon depression that made landfall over the Indian coast. The results from the two schemes are compared.

Detailed analyses of mean sea level pressure, wind, and rainfall have shown that the Betts–Miller–Janjic scheme has considerably improved the rainfall prediction over the Indian landmass and improvement is also seen in the mean sea level pressure fields and cyclonic circulation associated with the depression at the 850-hPa level. The forecast results are further verified by computing the root-mean-square errors, and the difference in the skill scores between the two model runs are tested for their statistical significance. It is found that the Betts–Miller–Janjic scheme has a statistically significant effect on the model skill beyond 24 h, with maximum impact on mean sea level pressure and geopotential height.

1. Introduction

Betts and Miller (1986) proposed a convective adjustment scheme that includes both deep and shallow convection. The deep convection in the Betts–Miller scheme is similar to the other adjustment schemes except that it uses empirically based quasi-equilibrium thermodynamic profiles as a reference state rather than a moist adiabat. The basic shape of these quasi-equilibrium reference profiles is based on the numerous observations. The construction of the reference profiles and the specification of the relaxation timescale are two major components of the Betts–Miller scheme. Observations show that quasi equilibria are different for different convective regions; hence, for proper construction of reference profiles it is necessary to tune the adjustment parameters for different convective regions (Betts and Miller 1986).

The Betts–Miller scheme has been used for simulation/prediction of tropical cyclones (Baik et al. 1990; Puri and Miller 1990) and for the simulation of orographic–convective rainfall over the Western Ghats of India and also for the prediction of monsoon rain over the Indian region (Alapaty et al. 1994a). Alapaty et al. (1994b) in their study with the Betts–Miller scheme on monsoon rainfall prediction found that this scheme is unable to shift the rainfall over land and the rainfall remains mainly over the oceanic region. They suggested that proper selection of adjustment parameters is required for good forecasts of rainfall over the Indian landmass. Slingo et al. (1994) included the interaction of deep convection with the boundary layer, through a simple parameterization scheme for low-level cooling and drying by convective downdraft. Vaidya and Singh (1997) carried out a number of experiments by using various sets of adjustment parameters in the Betts–Miller scheme following Slingo et al. (1994) and found that a particular set of adjustment parameters was able to shift the rainy area over the Indian landmass for a case of monsoon depression.

Janjic (1994) found that Betts–Miller scheme produced spurious rainfall normally over warm water and light rainfall over large oceanic regions. In order to overcome this problem Janjic (1994) assumed that a convective column evolves through different regimes and he postulated that the basic features of the regimes are characterized by a parameter called cloud efficiency (E). From Betts's (1986) observations, he concludes that reference temperature profiles are steady for deep moist convection; however, moisture profiles are more variable and are main identifying features of the different

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convective equilibrium states. With these modifications, the spurious rainfall over the oceanic regions is suppressed, which brought out overall improvement in the rainfall forecast over North America and the surrounding oceans.

The Betts–Miller (Betts and Miller 1986) scheme will hereafter be referred to as BM86 and the Betts–Miller–Janjic (Janjic 1994) scheme will hereafter be referred to as BMJ. In this study we have investigated the impact of the BMJ scheme on forecast fields. This is done by comparing the results of the BMJ scheme with those obtained from BM86. Two sets of model runs are made, one with BM86 and other with the BMJ scheme for deep convection, for five cases of monsoon depression over the Indian region. The detailed analyses of forecast fields are presented and discussed. The differences in the forecasts between the two runs are brought out by applying the Student's *t*-test.

2. The model

The model used in the present study is a limited area model in sigma coordinates [$\sigma = (P - P_t)/(P_s - P_t)$] with variable spacing in the vertical and model top at 25 hPa. A detailed description of the model is given in Singh et al. (1990). Some salient features of the model used in the present study are given here. In vertical there are 12 levels and the horizontal grid distance is 125 km on a Mercator projection. Upper and lower boundary conditions of vanishing σ velocity ($\dot{\sigma}$) are applied at $\sigma = 0$ and 1. A horizontal tendency modification scheme is used for lateral boundary conditions. Potential temperature, variance of potential temperature, and energy-conserving fourth-order difference schemes are used on an Arakawa B grid. The prognostic variables are zonal (u) and meridional (v) wind components, potential temperature (θ), mixing ratio for water vapor (q), and surface pressure (P_s). In addition, $\dot{\sigma}$ is defined at intermediate levels between those where these prognostic variables are defined. For time integration an economic explicit scheme has been adopted. Orography has been extracted from a very high resolution database and is smoothed at model resolution. Objectively analyzed gridpoint data are used as input to the model without initialization.

The physical package used in the study includes the large-scale condensation; dry convective adjustment; horizontal and vertical diffusion processes; calculation of radiation processes; computation of land surface fluxes of momentum, heat, and moisture based on similarity theory; and the use of the surface energy balance to obtain the diurnally varying surface temperature over land following Krishnamurti et al. (1990). In the present study two sets of experiments are carried out. In one experiment the BM86 scheme and in the other the BMJ scheme has been used for the parameterization of deep convection. For the construction of reference temperature ($T_{\rm ref}$) and reference moisture ($q_{\rm ref}$) profiles, Betts and Miller (1986) have defined three adjustment parameters, namely, the stability weight (W_t), which decides the slope of $T_{\rm ref}$ profiles with respect to the moist adiabat; the saturation pressure departure (SPD) values, which are the measure of subsaturation; and the adjustment time period (τ), which gives the time lag between the large-scale forcing and the convective adjustment. The $q_{\rm ref}$ profiles are constructed using the $T_{\rm ref}$ profiles and the SPD values. The SPD values at three characteristic levels are prescribed. These are at cloud bottom (SPD_b), at freezing level (SPD_f), and at cloud top (SPD_t). The SPD values at intermediate levels are linearly interpolated. Details of computation of $T_{\rm ref}$ and $q_{\rm ref}$ are given in Baik et al. (1990). In BM86 the constant values of $\mathrm{SPD}_b = -60$ hPa, $\mathrm{SPD}_f = -70$ hPa, and $\mathrm{SPD}_t = -50$ hPa are used following Vaidya and Singh (1997). In the BMJ scheme the SPD values are computed as a function of E, which varies in space and time. Two extreme SPD profiles are defined; they are $\mathrm{SPD}_{\rm slow}$ (moister) corresponding to cloud efficiency $E_1 = 0.2$ and $\mathrm{SPD}_{\rm fast}$ (drier) corresponding to cloud efficiency of $E_2 = 1.0$. The SPD values in BMJ ($\mathrm{SPD}_{\rm BMJ}$) are computed as

$$\mathrm{SPD}_{\rm BMJ} = \mathrm{SPD}_{\rm slow} + \frac{E - E_1}{E_2 - E_1}(\mathrm{SPD}_{\rm fast} - \mathrm{SPD}_{\rm slow}). \quad (1)$$

The $\mathrm{SPD}_{\rm fast}$ values are the same as in BM86. Here, $\mathrm{SPD}_{\rm slow}$ is proportional to the fast profiles with a factor of proportionality 0.6. We find that the use of $\mathrm{SPD}_{\rm BMJ}$ over land and ocean in the BMJ scheme led to the degradation of the rainfall prediction over land. Similar results were reported by Janjic (1994). Therefore, we have used $\mathrm{SPD}_{\rm BMJ}$ over ocean only and over the land $\mathrm{SPD}_{\rm fast}$ is used. Essentially, the computation of $T_{\rm ref}$ is the same in the BM86 and BMJ schemes; however, for the computation of $q_{\rm ref}$ in BM86, constant values of SPD are used at three characteristic levels; whereas SPD values as a function of cloud efficiency are used for the computation of $q_{\rm ref}$ in the BMJ scheme. A value τ equal to 2 h is used in both the BM86 and BMJ schemes.

3. Data

Five cases of monsoon depression are chosen for this study. All cases selected are bay depressions that made landfall over the east coast of India. The depressions generally move over the Indian subcontinent along a monsoon trough causing moderate to heavy rainfall along the track. They also strengthen the southwesterly wind from the Arabian Sea producing heavy rainfall over the Western Ghats. The five input times are 1200 UTC 6 July 1979 (J79), 1200 UTC 17 August 1994, (A94), 1200 UTC 15 September 1995 (15S95), 1200 UTC 25 September 1995 (25S95), and 1200 UTC 25 July 1996 (J96). The initial data are extracted from the daily analyses provided by the National Centre for Medium Range Weather Forecasting (NCMRWF), except in the case of J79, where they are obtained from the European Centre for Medium-Range Weather Fore-

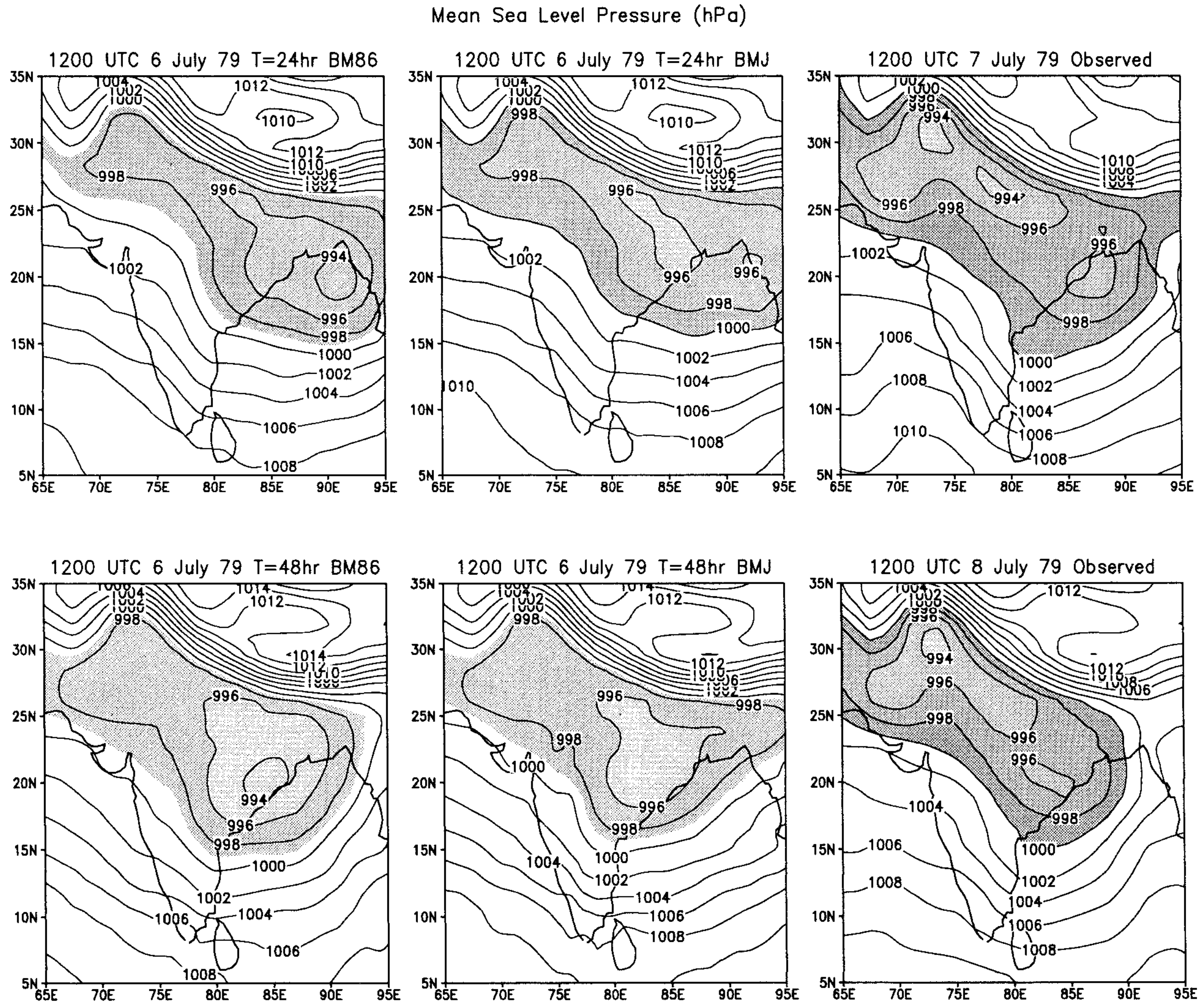

FIG. 1. Forecast and corresponding verification charts of mean sea level pressure (hPa). The region below 1000 hPa is shaded and the contour interval is 2 hPa. Input: 1200 UTC 6 Jul 1979.

casts's First Global Atmospheric Research Program (GARP) Global Experiments IIIb dataset. Very high resolution orography is extracted from U.S. Navy data. Over the oceans, climatological monthly mean sea surface temperature is used. The surface albedo is taken from the 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.

4. Results

In the present study, two sets of forecast results obtained from the BM86 and BMJ schemes for convection for five cases of monsoon depressions are compared. The forecast results of the mean sea level pressure and wind fields of J79 and the rainfall fields of the J79, 25S95, and J96 cases are discussed. Wherever necessary, results of other cases are discussed. The verification statistics of five cases of depression are computed and discussed.

a. Mean sea level pressure fields

The 24- and 48-h predicted and corresponding verification mean sea level pressure (MSLP) fields for J79 are presented in Fig 1. The region below 1000 hPa is shaded. The verification charts at 1200 UTC 7 and 8 July 1979 show all the features of the active monsoon; they are the monsoon trough, which runs from northwest India up to the head of the Bay of Bengal; the low pressure area over northwest India, which is associated with the heat low; and the closed isobars over the depression region. The closed isobar at 996 hPa is observed over the depression region on 7 and 8 July. On 9 July (figure not presented), the depression weakened and no close isobar is seen over the depression region. In the BM86 run the deterioration in mean sea level pressure over the depression area is clearly evident as the minimum pressure values are lower by 2 hPa in 24 and 48 h, and 6 hPa in 72 h of the prediction. On the other hand in the BMJ run the mean sea level pressure values over the depression region are closer to the observations indicating an improved MSLP forecast over the depression area. Similar results are also found in the other four cases.

b. *Wind at 850 hPa*

The 72-h predicted streamline isotachs and the corresponding verifying analyses based on observations of J79 at the 850-hPa level are examined (figure not presented). During the 72 h of model integration, the observed fields show typical strong monsoon conditions. Although the predicted circulation features in the integration domain are similar in both experiments, the BMJ scheme shows better features of cyclonic circulation in the region of depression. Furthermore the westward movement and subsequent landfall of the monsoon depression are better predicted. The observed low-level jet of more than 20 m s^{-1} over the central Arabian Sea is overpredicted whichever scheme is used. The predicted wind speed over this area is more than 30 m s^{-1}. This has also been discussed in the earlier work with the model (Sanjay and Singh 1998). Similar results are found in other cases of depression.

c. *Rainfall fields*

Accuracy of areal distribution and the intensity of the rainfall forecast to a large extent depends on the scheme of convection used in the numerical models. As such in this section, the performance of the BM86 and BMJ schemes of convection is assessed by evaluating the rainfall forecasts for three cases of depression, namely, J79, 25S95, and J96. Since the daily rainfall observations are available at 0300 UTC for verification, the predicted rainfall rates are presented at 0000 UTC, which is closer to 0300 UTC. Figure 2 presents rainfall rates in millimeters per day during 12–36 h of integration along with verification fields at 0300 UTC 8 July 1979, 0300 UTC 27 September 1995, and 0300 UTC 27 July 1996. In the observed fields of 8 July (Fig. 2a) a rainy area tongue from the east coast up to central India is seen when the depression crossed the coast. Another rainfall zone is seen along the west coast on the windward side of the Western Ghats. The depression that formed on 25 September 1995 moved northward and the observed rainfall is seen over West Bengal and the Bihar Plateau (Fig. 2b). In this case no heavy rainfall is observed over the west coast; instead a few stations reported rainfall rates of tens of millimeters per day. On 27 July 1996, the whole of central India received heavy rainfall and the rainfall was also observed over the west coast (Fig. 2c). In all these depression cases a very few stations received rainfall to the north of 25°N.

A careful examination of the predicted rainfall fields reveals that the rainfall areas simulated by the BMJ scheme are more organized in the vicinity of the depression and along the west coast in all three depression cases. The rainy area and the position of maximum rainfall that is associated with the depression are well predicted. The north–south orientation of rainfall along the west coast and the position of the two maxima in the J79 (Fig. 2a) case and the three in the case of the J96 (Fig. 2c) depression are also well predicted. The predicted rainfall rates over the Arabian Sea and the Bay of Bengal are less than 10 mm day^{-1}. The rainfall fields produced by the BM86 scheme, which are associated with depression over land, are similar to those produced by the BMJ scheme. However the rainy area in the case of J79 (Fig. 2a) and of 25S95 (Fig. 2b) has extended into the head of the Bay of Bengal. Although the predicted rainfall at the west coast is oriented north–south, it extends farther west up to the central Arabian Sea in the J79 case, and in the J96 case the maximum of rainfall is located off the west coast. In all three cases, heavy rainfall is seen over the Bay of Bengal.

Figure 3 presents predicted rainfall for the next 24 h of model integration and the corresponding observations at 0300 UTC 9 July 1979, 0300 UTC 28 September 1995, and 0300 UTC 28 July 1996. It is seen from the figure that in the observed rainfall charts the rainfall belt associated with the depression has shifted to the west and farther inland, with heavy rainfall persisting along the west coast on 9 July 1979 (Fig. 3a) and 28 July 1996 (Fig. 3c). On 28 September 1995 (Fig. 3b) the rainfall associated with the depression remained at almost the same location. It can be seen from the figure that during this period the BMJ scheme has also produced better rainfall fields for all three cases of the depression. In the J79 (Fig. 3a) and J96 (Fig. 3c) cases, the east to west shift of the rainy area associated with the depression is clearly seen. In the case of 25S95 the rainy area is well predicted in the vicinity of the depression and along the west coast (Fig. 3b). The BM86 scheme poorly predicted the westward shift of the rainy area in the J79 and J96 cases. Also during this forecast period the maximum rainfall along the west coast is away from the coast and centered in the Arabian Sea.

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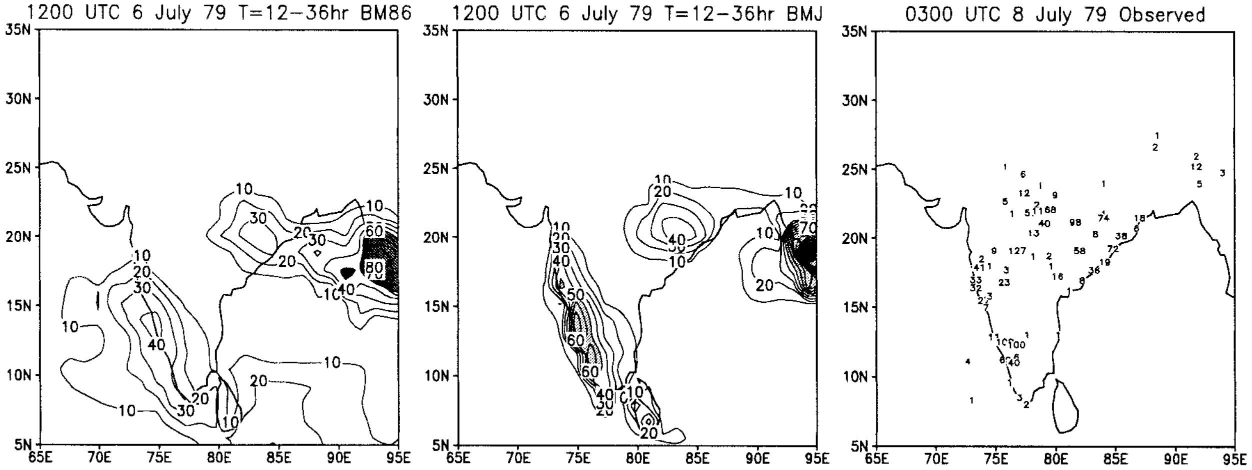
FIG. 2. (a) The 24-h (12–36 h) accumulated rainfall in the BM86 runs, BMJ runs, and corresponding verification rainfall rates (mm day^{-1}). The shading indicates regions with rainfall rates ≥50 mm day^{-1} and the contour interval is 10 mm day^{-1}. Input: 1200 UTC 6 Jul 1979. (b) Same as (a) but for input at 1200 UTC 25 Sep 1995. (c) Same as (a) but for input at 1200 UTC 25 Jul 1996.

(a) Rainfall (mm/day)

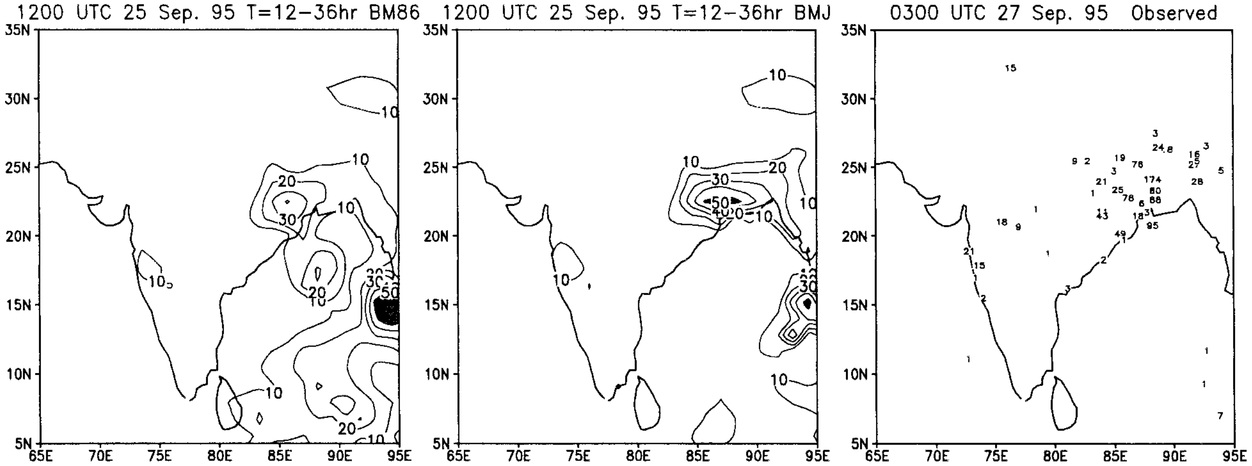


1200 UTC 6 July 79 T=12–36hr BM86

1200 UTC 6 July 79 T=12–36hr BMJ

0300 UTC 8 July 79 Observed

(b) Rainfall (mm/day)

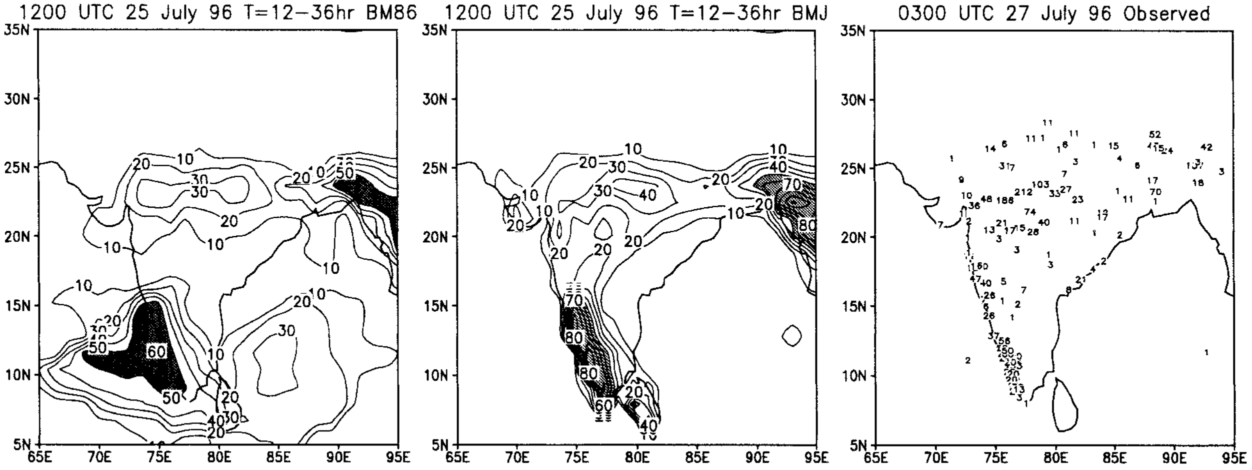


1200 UTC 25 Sep. 95 T=12–36hr BM86

1200 UTC 25 Sep. 95 T=12–36hr BMJ

0300 UTC 27 Sep. 95 Observed

(c) Rainfall (mm/day)

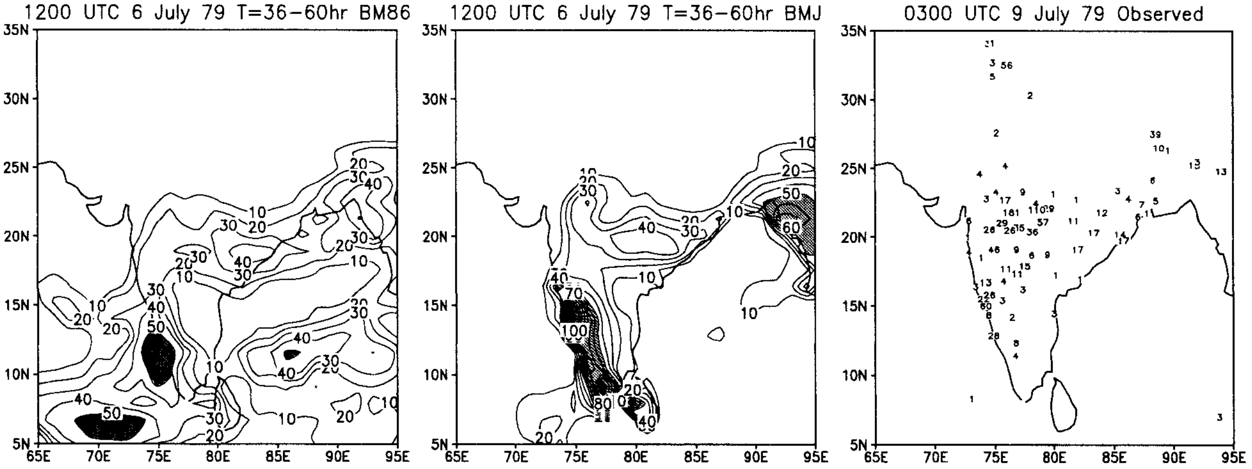


1200 UTC 25 July 96 T=12–36hr BM86

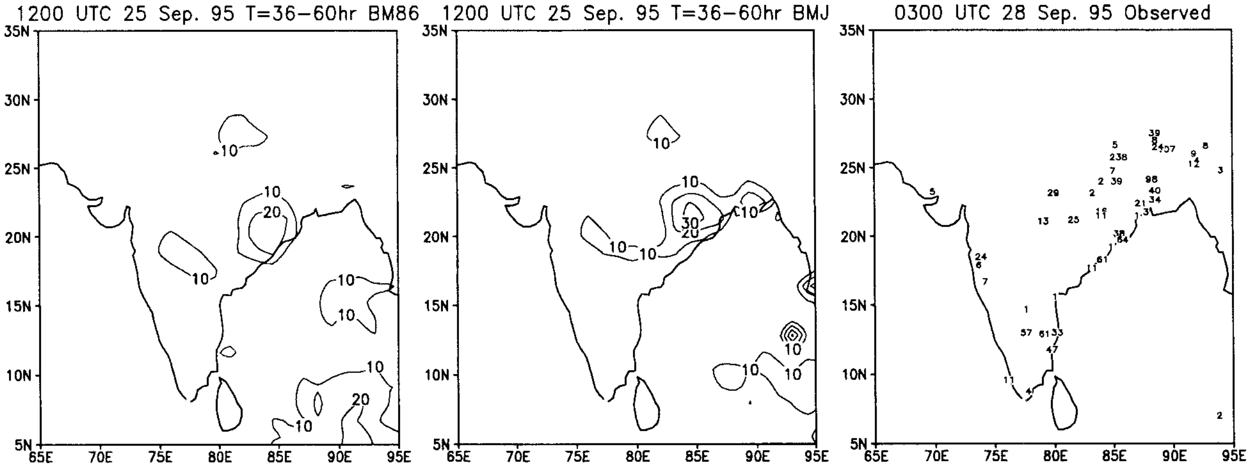
1200 UTC 25 July 96 T=12–36hr BMJ

0300 UTC 27 July 96 Observed

(a) Rainfall (mm/day)



(b) Rainfall (mm/day)



(c) Rainfall (mm/day)

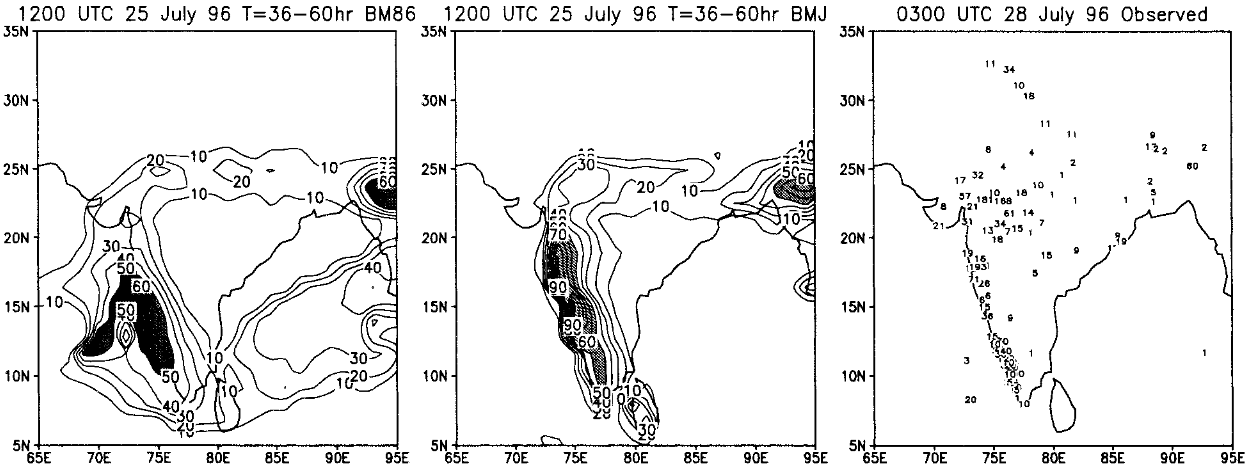


TABLE 1. Average rmse's of various model-predicted parameters for five monsoon depression cases in the BM86 and BMJ model runs. Boldfaced values of BMJ differ from the values of the BM86 run at the 90% significant level.

		Geopotential height (m)				Temp (K)				Wind (m s^{-1})			
	P_s (hPa)	850	700	500	200	850	700	500	200	850	700	500	200
						24 h							
BM86	1.9	17.3	16.9	12.8	24.7	1.5	1.4	1.4	1.6	3.9	3.1	2.9	5.9
BMJ	1.5	12.6	13.3	10.4	14.2	1.3	1.0	1.0	1.3	3.6	2.6	2.4	5.3
						48 h							
BM86	1.9	15.8	15.1	11.0	21.7	1.6	1.3	1.4	1.7	4.2	3.5	2.9	6.3
BMJ	1.6	**12.3**	12.9	10.5	**16.6**	1.6	1.2	**1.1**	1.8	**3.7**	3.1	**2.7**	6.4
						72 h							
BM86	2.2	18.5	17.7	11.6	23.8	1.7	1.4	1.5	1.6	4.7	4.1	3.2	6.8
BMJ	**1.8**	**13.8**	**14.8**	**11.2**	**20.5**	1.9	1.3	**1.3**	1.7	**3.8**	**3.6**	3.0	6.4

Over the Bay of Bengal heavy precipitation is predicted in all three cases. It can be concluded from above results that BMJ has improved rainfall fields over the Indian landmass and suppressed heavy rainfall over oceanic regions. Janjic (1994) also obtained similar results over North America and the surrounding oceans.

The rainfall results discussed above show that the use of the BMJ scheme has improved the rainfall amounts over land areas, in which we are mainly interested during the monsoon period. The predicted rainfall rates over the oceanic region are found more in the BM86 scheme than the BMJ scheme. As the direct rainfall observations are not available over oceanic regions, the rainfall prediction is qualitatively assessed by comparing it with the satellite cloud pictures. The satellite cloud pictures (not presented) on 8 and 9 July 1979 show some cloud patches off the west coast but no clouds over the Bay of Bengal. On 27 and 28 September 1995 there were no clouds over the Arabian Sea and the Bay of Bengal. Also on 27 and 28 July 1996 only a few patches of clouds were seen over the Arabian Sea and the Bay of Bengal. Thus the heavy rainfall is not expected over the Arabian Sea or over the Bay of Bengal.

d. Statistics of forecast results

1) ROOT-MEAN-SQUARE ERRORS

Root-mean-square errors (rmse) are standard measures to assess the forecast results statistically. The rmse of mean sea level pressure, 500-hPa geopotential height, 850- and 200-hPa-level temperature, and wind fields for five cases of monsoon depression for 24, 48, and 72 h of integration are examined. The value of rms errors vary from one case to another. BM86 has errors consistently higher than BMJ for the variables such as mean sea level pressure and wind at the 850-hPa level. It should be further noted that BM86 produces considerably larger-errors in 24-h prediction in the case of 25S95. For other variables error values in BM86 are comparable with those of BMJ.

2) AVERAGE RMSE

Table 1 lists the average rms errors of mean sea level pressure, geopotential height, temperature, and wind for five cases of depression in the BM86 and BMJ schemes for 24, 48, and 72 h of prediction. Most of the variables show lesser errors in BMJ except at higher-level temperature. The errors in BM86 are considerably larger than BMJ for geopotential height and wind. Further the differences in the rmse between the two runs are tested for their statistical significance by applying the Student's *t*-test. The null hypothesis used is that two schemes will have the same scores if tested for an infinite number of cases. The rejection of this hypothesis at a 10% level of significance means there is 90% probability that the difference is real. The boldfaced numbers shown for the BMJ scheme are significantly different from BM86 runs at the 90% confidence level. It is seen from the table that for 24 h of prediction the difference is not significant, as the first 24 h of model integration is the spinup period and beyond this period, the difference is significant for geopotential height almost at all levels, the temperature in middle troposphere, and the wind up to the middle troposphere. The difference is also significant for mean sea level pressure beyond 48 h of prediction.

5. Conclusions

In this paper the impact of the BMJ scheme of convection has been investigated. For this purpose, two sets

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FIG. 3. (a) The 24-h (36–60 h) accumulated rainfall in the BM86 runs, BMJ runs, and corresponding verification rainfall rates (mm day^{-1}). The shading indicates regions with rainfall rates ≥ 50 mm day^{-1} and the contour interval is 10 mm day^{-1}. Input: 1200 UTC 6 Jul 1979. (b) Same as (a) but for input at 1200 UTC 25 Sep 1995. (c) Same as (a) but for input at 1200 UTC 25 Jul 1996.

of experiments are done with a limited area model for five cases of monsoon depression that made landfall over the east coast of India. In one set of experiments, the BM86 scheme of convection has been used, and in the other set, the BMJ scheme has been used. The model is run with two schemes of convection keeping the other physics unchanged. The forecast results show that the BMJ scheme has improved the mean sea level pressure fields over the depression region and improvement is also seen in circulation features around the depression at the 850-hPa level. Furthermore, this scheme has considerably improved the rainfall prediction, and the shift of the rainy area from east to west and the north–south orientation of the rainy area over the Western Ghats are remarkably improved. It is also found that spurious spread of rainfall in the Arabian Sea and in the Bay of Bengal is suppressed in the BMJ scheme. Thus the BMJ scheme of convection has induced overall improvement in the rainfall prediction over the land and is able to suppress the spurious rainfall over oceanic regions. The average rmse's for most of the variables in BMJ are lesser than BM86. The difference in rmse between two runs tested for their statistical significance by applying a Student's *t*-test has shown that rmse difference is significant beyond 24 h for geopotential height at all levels, temperature in the middle troposphere, and wind up to the middle troposphere. The rmse difference is also significant for 72-h mean sea level pressure field.

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