Thermodynamic Adjustment Parameters in the Betts–Miller Scheme of Convection

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ABSTRACT

The sensitivity of the prediction of a monsoon depression to the adjustment parameters in a Betts–Miller scheme of deep convection is examined and an optimum parameter set is identified for the monsoon depression. For this purpose, a number of experiments have been carried out with a limited area model by assigning different values to the adjustment parameters, namely, the saturation pressure departure, the stability weight, and the adjustment time period. When one parameter is varied, the other two are kept constant. Results indicate that the depression track is sensitive to all three adjustment parameters. The upper-tropospheric temperature is sensitive to the stability weight and the rainfall rates are sensitive to the saturation pressure departure values. The rainfall shows minor sensitivity to the stability weight and the adjustment time period. A set of adjustment parameters that produced the best forecasts is taken as the optimum parameter set for the monsoon depression.

1. Introduction

During the summer monsoon season the Indian subcontinent receives heavy rainfall. The heavy rainfall is mainly due to low pressure areas and depressions over the head of the Bay of Bengal and offshore vortices in the Arabian Sea. Sometimes these systems may intensify into cyclones and give rise to very heavy rainfall. In order to simulate the heavy rainfall rates, the physical processes, especially convective processes, should be properly incorporated into the prediction models. Kuo versions of convection parameterization have been widely used in monsoon simulation and prediction (Krishnamurti et al. 1980; Singh et al. 1988, 1990).

Betts (1986) proposed a new convective adjustment scheme based on observations. In this scheme the thermodynamic profile is adjusted toward an observed quasi-equilibrium state as a reference profile, rather than toward the moist adiabat. Janjic (1994) infers from Betts's (1986) data that the reference temperature profile seems to be a rather steady feature and the reference humidity profiles are more variable. These humidity profiles appear to be the main identifying features of the different convective equilibrium states. Betts (1986) suggested three adjustment parameters for the construction of thermodynamic reference profile. These are (i) the saturation pressure departure (S) values, which determine reference humidity profile; (ii) the stability weight (W_t), which decides the slope of reference temperature profile compared to the moist adiabat; and (iii) the adjustment timescale (τ). This gives the time lag between the large-scale forcing and the convective adjustment. Betts and Miller (1986) formulated and tested the convective adjustment scheme of Betts (1986) for different datasets, such as the Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE), Barbados Oceanographic and Meteorological Experiment, etc. Betts and Miller (1986 hereafter referred to as BM). Baik et al. (1990) also used this scheme for simulation of tropical cyclone. Puri and Miller (1990) compared the performance of Kuo and Betts–Miller schemes using Australian Monsoon Experiment datasets of four tropical cyclones. They found that vertical consistency of meteorological parameters is better predicted with the Betts–Miller scheme. Alapaty et al. (1994b) found that monsoon rainfall is predicted better by the Kuo scheme than those predicted by the Betts–Miller scheme. Although Alapaty et al (1994b) have used almost similar adjustment parameters as Puri and Miller (1990), their results on Kuo and Betts–Miller schemes differed significantly. Based on their studies, Alapaty et al. (1994b) suggested that the systematic sensitivity studies were needed to identify the suitable thermodynamic adjustment parameter set over the monsoon region.

In the present study we have attempted to identify a suitable set of adjustment parameters for a monsoon depression. For this purpose a number of experiments were carried out by changing the value of one adjustment parameter while keeping the other two parameters fixed.

2. The model

A limited area primitive equation model in a σ-coordinate system has been used in the present study. A

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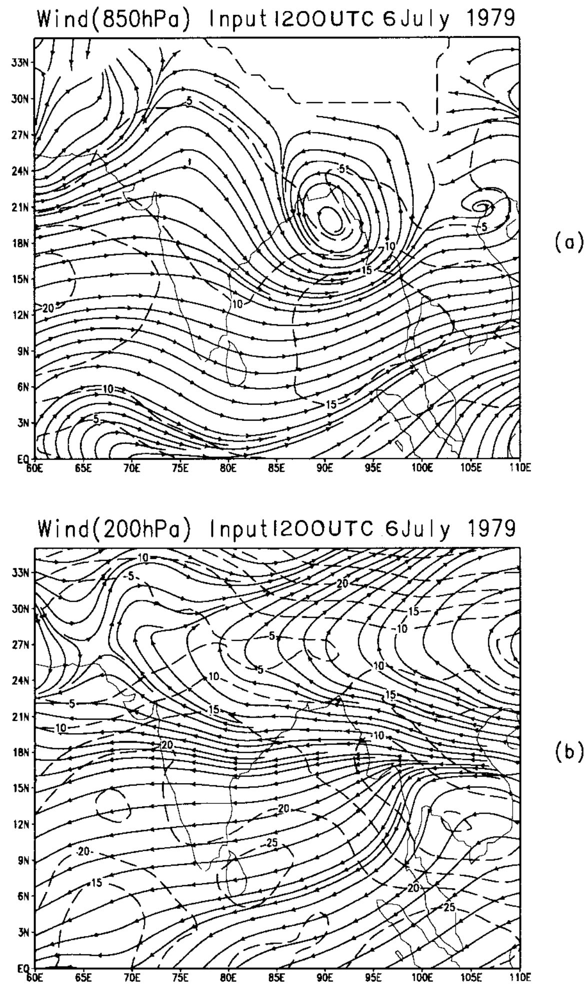

FIG. 1. Wind fields at 1200 UTC 6 July 1979 at (a) 850-hPa and (b) 200-hPa levels.

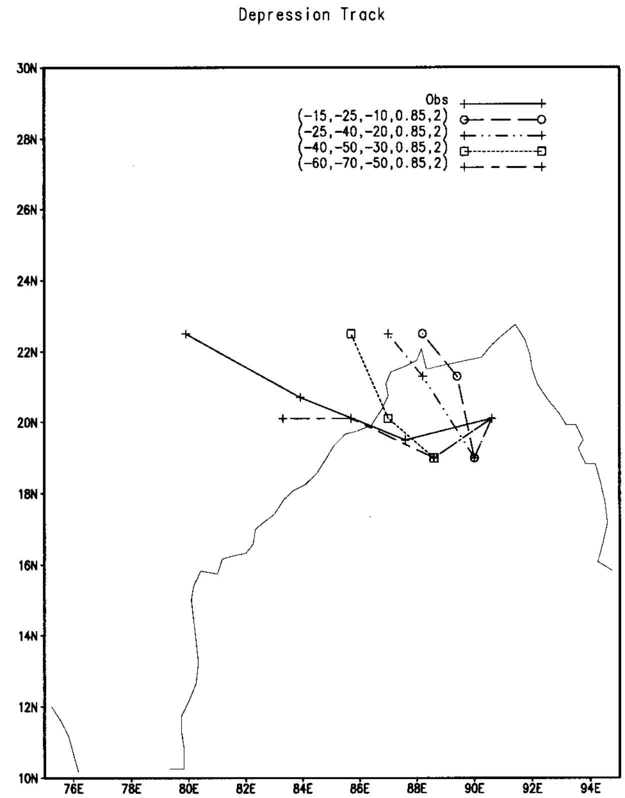

FIG. 2. Observed and predicted depression tracks for four *S* sets.

detailed description of the model is given in Singh et al. (1990). The model has 10 σ levels in the vertical. The vertical sigma levels are 0.97, 0.92, 0.85, 0.67, 0.44, 0.3, 0.2, 0.13, 0.09, and 0.035. The wind components, mixing ratio for water vapor, potential temperature, and geopotential height are defined at these σ levels. The vertical σ velocities ($\dot{\sigma}$) are defined at intermediate levels. In the horizontal, Arakawa's B type of staggering with horizontal grid distance of 125 km on a Mercator projection is used. A mass, energy, potential temperature, and variance of potential temperature conserving finite-difference scheme for space derivatives and an economic explicit scheme for marching in time are used. In the vertical, $\dot{\sigma} = 0$ at $\sigma = 0$ and $\sigma = 1$. In the horizontal perfect lateral boundary conditions are used.

Following Krishnamurti et al. (1990), the physical processes included in the model are the surface fluxes of momentum, heat, and moisture; PBL processes; large-scale condensation; radiation; and dry convective adjustment scheme. The surface fluxes are computed by similarity theory. The ground temperature needed for the computation of sensible heat and latent heat fluxes over land is obtained by solving the surface energy balance equation. The monthly mean ground temperature is used as a first guess at the initial time for solving the energy balance equation.

For parameterization of cumulus convection the Betts–Miller scheme has been used. In this scheme, the local thermodynamic structures are constrained by the convection and adjust toward an observed quasi-equilibrium thermodynamic state as a reference profile. The Betts–Miller scheme has shallow convection as well as deep convection. In the present experiment we have included deep convection only. The reference profile is constructed following Betts and Miller (1993) and Slingo et al. (1994). For details the reader is referred to Betts and Miller (1993).

3. Data

The input data of 1200 UTC 6 July 1979 for the present study is extracted from First GARP Global Experiment III B global analysis produced at the European Centre for Medium-Range Weather Forecast (ECMWF) and interpolated on a model grid. The domain extends from 40° to 110°E and 10°S to 40°N. The topography is interpolated on a model grid from a U.S. Navy dataset at 10′ resolution. Monthly mean climatological values

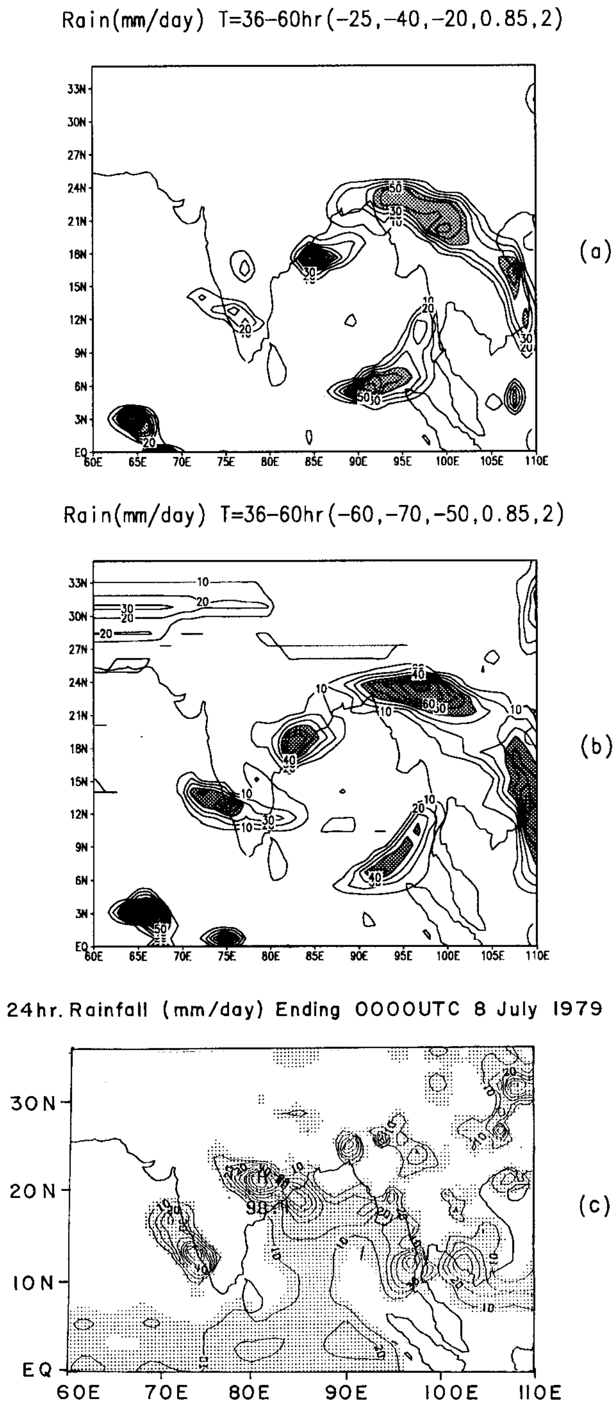

FIG. 3. Observed and predicted rainfall for (a) *S* set 2 (b) *S* set 4, and (c) observed.

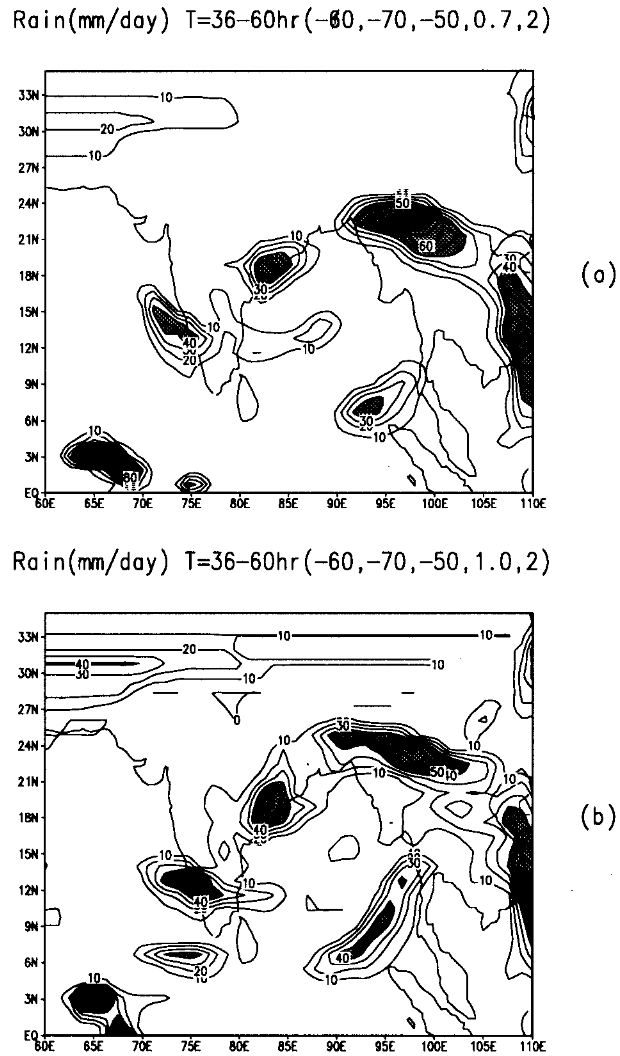

FIG. 4. Predicted rainfall for stability weights equal to (a) 0.7 and (b) 1.0.

of sea surface temperature for July are used. The surface albedo is taken from climatological fields.

Initial 850- and 200-hPa level streamlines and isotachs are shown in Fig. 1. The monsoon depression is located at the head of the Bay of Bengal. The maximum wind speed of 20 m s^{-1} in association with a low-level jet over the Arabian Sea is seen. At the 200-hPa level an east–west running ridge is seen at 20°N. An easterly jet with wind strength of more than 25 m s^{-1} is seen at 10°N. Initially, depression moved in the southwest direction and then the northwest direction and on 8 July it crossed the coast. Heavy rainfalls were reported along the depression track and also over the west coast.

4. Results

We have carried out a number of experiments with a limited area model using different sets of adjustment parameters in the Betts–Miller scheme. In these experiments, we have varied one adjustment parameter and kept the other two parameters fixed. The constant values are chosen from the earlier studies (BM; Slingo et al. 1994).

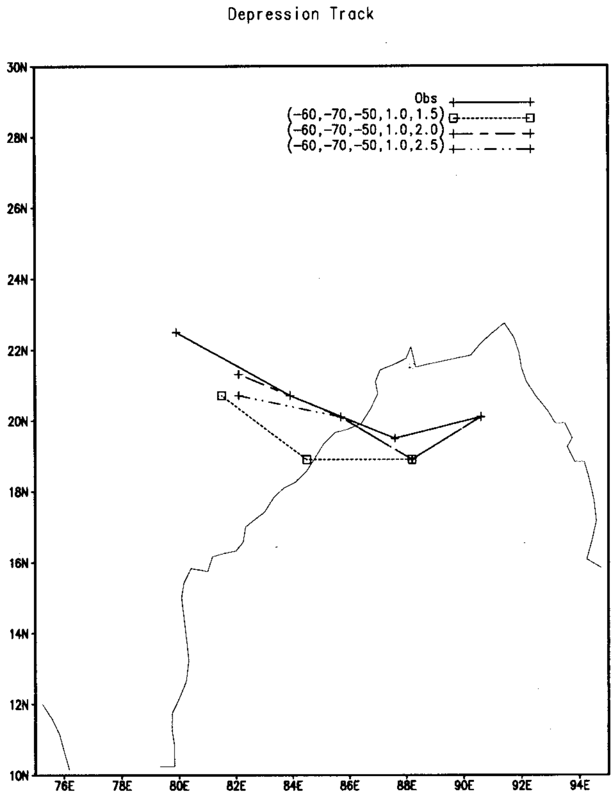

FIG. 5. Observed and predicted tracks for three adjustment time periods.

*a. Application of different sets of saturation pressure departure (*S*) values*

In this experiment, the W_t equal to 0.85 and τ equal to 2 h are kept constant, and S (S_b, S_f, S_t) values are varied. The S_b, S_f, and S_t are three specified S values at three levels corresponding to the cloud base, the freezing level, and the cloud-top level, respectively. In selecting the different sets of S values, we have taken into consideration the S values used by BM, Alapaty et al. (1994a), and Slingo et al. (1994). The four sets of S values, in hectopascals, used in the present study are S set 1 (−15, −25, −10), S set 2 (−25, −40, −20), S set 3 (−40, −50, −30), and S set 4 (−60, −70, −50). The S set 1 represents a reference profile that is moister than the optimum reference profile used by BM. The S set 2 values are comparable to the optimum set values of BM and are equal to those used by Slingo et al. (1994). The S set 3 and S set 4 values represent reference profiles drier than the BM optimum set. It should be noted that in the above S sets the S values are successively decreased from S set 1 to S set 4.

1) DEPRESSION TRACK

Figure 2 shows the observed and predicted tracks obtained by using four sets of S values. It can be seen that S set 1 and set 2 have produced tracks that are far different from the observed track. The track produced by S set 3 is comparable with the observed track up to 48 h, beyond that, the track is far different from the observed track. The fourth set of S values has produced the best track up to 72 h.

2) RAINFALL

The rainfall rates and their areal distributions in S set 1, set 2 and set 3 are found to be more or less similar. As such, the rainfall in respect of S set 2 only is presented in Fig. 3a. The rainfall from S set 4 is presented in Fig. 3b. The corresponding observed rainfall is given in Fig. 3c (Krishnamurti et al. 1983). As can be seen from Fig. 3, the position and rates of maximum rainfall associated with the depression and over the west coast are well simulated with the S set 4. A decrease of 10 hPa in S set 4 values did not improve the rainfall forecast. Hence it can be concluded that a further decrease of S values is not desirable. It should therefore be noted that the depression track and rainfall are best predicted using S set 4. A few pockets of spurious rainfall are seen in the domain. These spurious rainfalls could perhaps be due to use of a uniform moisture reference profile over the entire domain. Janjic (1994) found an improved rainfall forecast with variable moisture profiles.

b. Application of different stability weight (W_t*) values*

In this experiment the set of S values that has been found to produce the best results (S set 4) and the adjustment time period of 2 h are kept constant and W_t values are varied. Alapaty et al. (1994a) have suggested W_t equal to 0.8, and the value of 0.85 was found suitable for the GATE wave dataset by BM and also by Slingo et al. (1994) for global climate studies. We have selected three values of W_t =: 0.7, 0.85, and 1.0.

1) DEPRESSION TRACK

The predicted tracks for different stability weight values (figure not presented) show that the track predicted by a W_t value equal to 0.7 is far different from observations. The stability weight values of 0.85 and 1.0 have produced similar tracks up to 48 h, but beyond that the track with W_t equal to 1.0 is closer to the observation.

2) TEMPERATURE

The W_t values determine the reference temperature profile. Hence, it is appropriate to study the distribution of temperature for different values of W_t. For this purpose the temperature difference $\Delta T = T(\text{pred}) - T(\text{obs})$ is computed at 700 hPa and at 400 hPa. A careful anal-

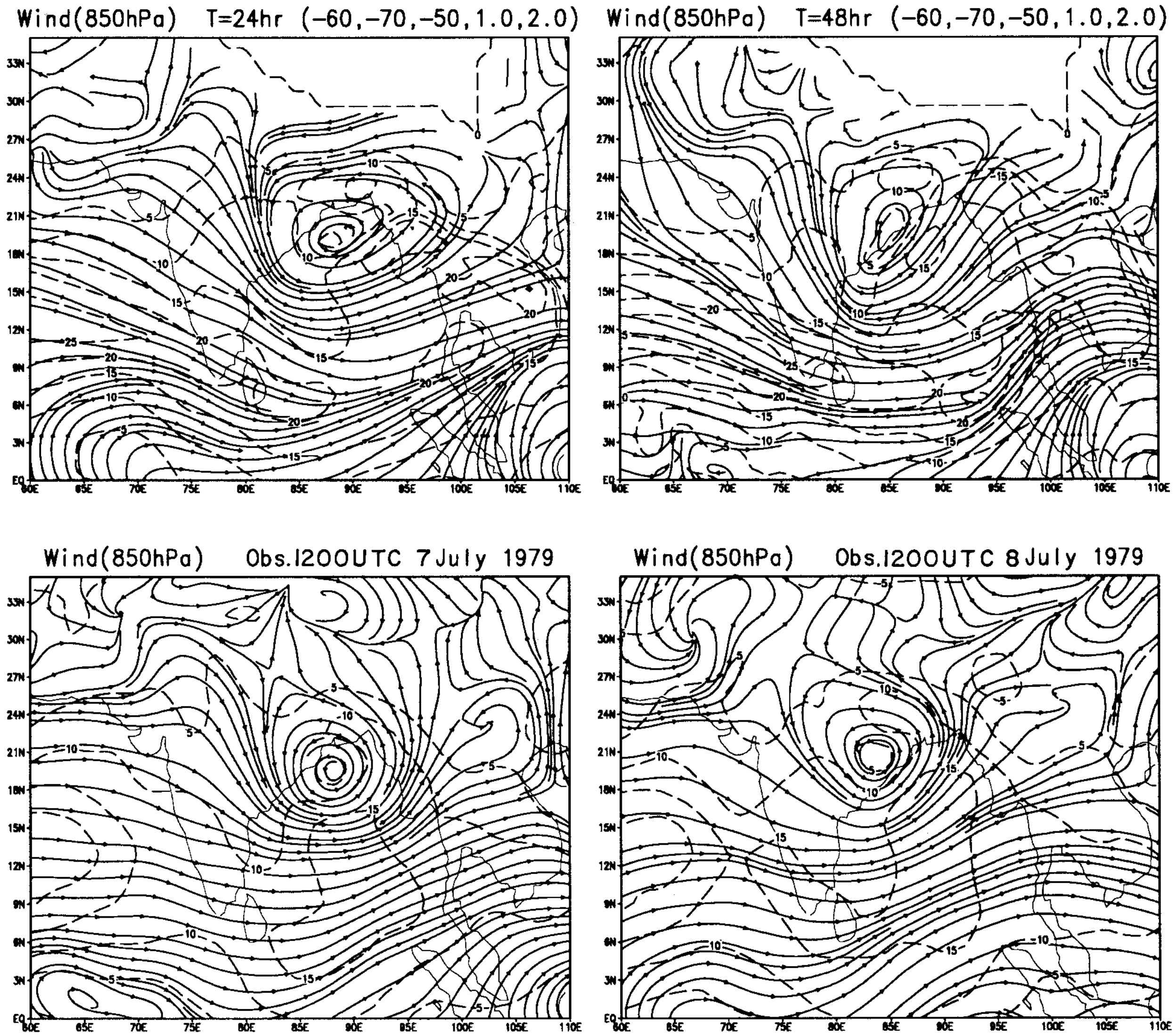

FIG. 6. Observed and predicted 850-hPa wind fields for the optimum parameter set.

ysis of ΔT fields at 700 hPa shows that the temperature remains unaffected with the change in W_t from 0.7 to 1.0. However, the 400-hPa temperatures for $W_t = 0.7$ and $W_t = 0.85$ are lower by 2°–4°C The predicted temperatures for W_t equal to 1.0 are found closer to the observations.

3) RAINFALL

The observed and predicted rainfalls for W_t equal to 0.85 have already been presented in Fig. 3. The rainfalls with W_t equal to 0.7 and 1.0 are presented in Fig. 4. The rainfall rates with different values of W_t are found similar; however, the areal distribution of rainfall with W_t equal to 1.0 is found somewhat closer to the observed rainfall distribution. It may therefore be inferred that a stability weight value of 1.0 has produced the best forecast results.

c. Application of different adjustment time period

The set of S values (S set 4) and the stability weight of 1.0, which have been found to produce the best forecast, are kept constant and the adjustment time period (τ) is varied in this experiment. The different values of τ selected are 1.5, 2.0, and 2.5 h.

Figure 5 shows the observed and predicted tracks for different τ values. Up to 24 h of the integration period, the predicted tracks are similar for all three τ values. Beyond 24 h of integration the τ equal to 2 h has produced the track that is closer to the observed track. The track predicted by τ equal to 2 h is the best.

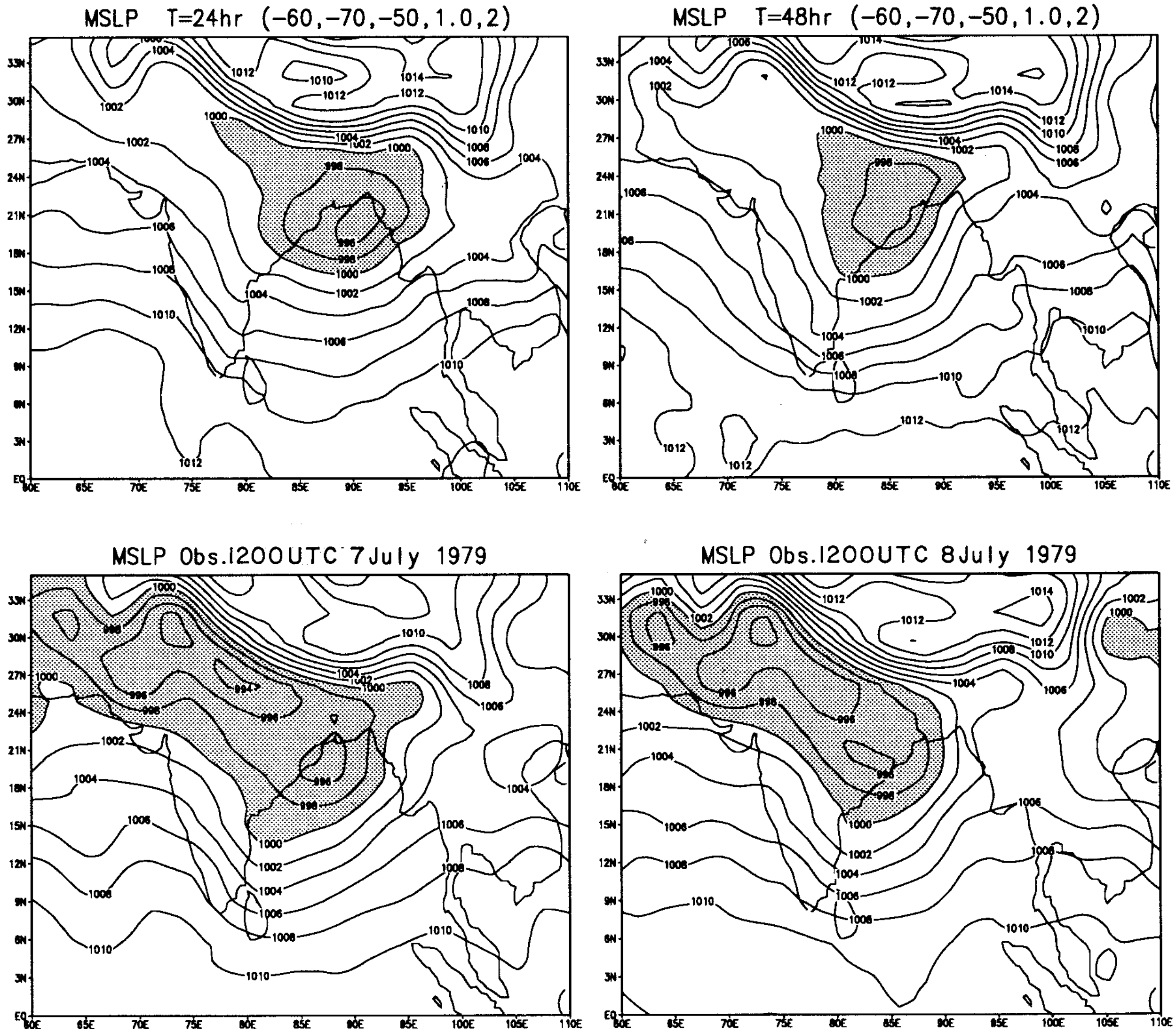

FIG. 7. Observed and predicted mean sea level pressure fields for the optimum parameter set.

Rainfall fields for all three values of τ are compared (figures not presented). It is found that as the τ value decreased from 2.5 to 1.5 h, the magnitude of the maximum rainfall value associated with depression increased slightly; however, the areal distribution of rainfall for all τ is found to be similar.

The results of the study show that the S values of -60, -70, and -50 hPa; stability weight equal to 1.0; and the adjustment period of 2 h are optimum adjustment parameters for this monsoon depression.

d. Other predicted fields with optimum adjustment parameters

This section presents and discusses the predicted parameters of wind and mean sea level pressure for optimum adjustment parameters. The 24- and 48-h predicted and observed wind fields at the 850-hPa level are presented in Fig. 6. It is seen that the circulation features are simulated well by the model. At the 850-hPa level the predicted winds in the vicinity of the depression center and the position of the low-level jet are predicted well. The predicted wind speeds of the low-level jet are more than the observed by 5–10 m s^{-1}. The position of the easterly jet and the anticyclone at the 200-hPa level (figure not presented) is well simulated by the model. Figure 7 shows predicted and observed mean sea level pressure charts. The area covered by the 1000-hPa isobar is shaded. It is found that areal coverage of the 1000-hPa isobar, which is associated with the depression, is well predicted; whereas the low pressure area, which is associated with the heat low over northwest India, is absent in the predicted chart. The heat low being the weak system perhaps gets filled up during integration of the model.

5. Summary

A limited area model has been used to study the sensitivity of prediction of a monsoon depression to the adjustment parameters in the Betts–Miller scheme of convection. A number of experiments have been carried out by systematically changing the adjustment parameters, namely, the *S* values, W_t, and τ. When one parameter is changed, the other two are kept constant. We have chosen four sets of *S* values, three values of W_t and τ each. Evaluation of the results obtained from the various experiments shows that a particular set of adjustment parameters produced the best forecasts. This particular set could be taken as optimum adjustment parameters for this monsoon depression.

It is pointed out by Baik et al. (1990) that rainfall prediction is more sensitive to *S* values compared to W_t and τ values. Alapaty et al. (1994a) have shown improvement in predicted rainfall over the monsoon region when *S* values were decreased from -30 to -50 hPa, and a minor improvement in rainfall was found with a considerable decrease in τ values. We also find in the present study the rainfall sensitivity to the *S* values. The successive reduction of *S* values from *S* set 1 to set 4 has improved the predicted rainfall in the vicinity of the depression and also along the west coast of India. Furthermore the rainfall is found to be less sensitive to W_t and τ.

For the monsoon region, Alapaty et al. (1994a,b) have further shown that rainfalls in the Betts–Miller scheme are mostly confined to the small coastal regions and are poorly predicted over the land areas. In our study with *S* set 1, set 2, and set 3, we have found heavy rainfalls over small coastal regions of the head of the Bay of Bengal and none over the adjacent land areas. However, the *S* set 4 has produced rainfall over land areas, which is in contrast with our results from *S* set 1, set 2, and set 3, as well as from the findings of Alapaty et al (1994a,b). It should be noted that by tuning the adjustment parameters in the Betts–Miller scheme, the rainfall shifts over the Indian landmass and is found closer to the observations. The salient features of this study are as follows.

1) The depression track is sensitive to all three adjustment parameters.
2) The rainfall prediction is more sensitive to *S* values compared to W_t and τ.
3) The upper-tropospheric temperatures are sensitive to W_t values.
4) There exists a lower limit to *S* values below which rainfall prediction does not show improvement.
5) The *S* values of -60, -70, and -50 hPa; W_t equal to 1.0; and τ equal to 2 h have produced the best results and could be taken as the optimum adjustment parameter set for this monsoon depression.

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