Sensitivity of convective rainfall to the adjustment parameters in the Betts-Miller scheme

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(Received 18 April 1995, Modified 22 September 1995)

सार—बेट्स मिलर की कपासी मेघ संवहन योजना में प्रयुक्त समायोजन प्राचलों में संवहनी वर्षा की अति संवेदनशीलता के अध्ययन के लिए तीन संख्यात्मक प्रयोग किए गए हैं। संख्यात्मक प्रयोगों से पता चलता है कि संतृप्ति दाब व्यपसरण मान (मानों) के साथ संवहनी वर्षा की पर्याप्त संवेदनशीलता है जबकि संवहनी वर्षा पर स्थायित्व प्रबलता (डब्ल्यू) का प्रभाव न्यूनतम है। परिसीमन एस मान कॉलम में शुष्कता उत्पन्न करता है।

ABSTACT. Three numerical experiments are carried out to study the sensitivity of the convective rain-fall to the adjustment parameters used in the Betts-Miller scheme of cumulus convection. The results of the numerical experiments indicate that the convective rainfall has considerable sensitivity to saturation pressure departure value (*S*), whereas the impact of stability weight (*W*) on the convective rainfall is marginal. The limiting *S* values are found to produce drying of the column.

Key words — Sensitivity experiment, Parameterization, Convective heating, Moistening, Reference profile, Model.

1. Introduction

Cumulus convection is one of the important physical processes in the tropics. The dynamic and thermodynamic states of most of the tropical disturbances are influenced by the cumulus convection. Most of the rainfall during monsoon period over the Indian region is of convective type. As the scales of the convective clouds are much smaller than the grid scale motions, its effects are included through parameterization in numerical models. The parameterization schemes for cumulus convection can be broadly classified into three categories; the moist convective adjustment scheme (Manabe *et al.* 1965), the moisture convergence scheme (Kuo 1965, 1974) and the mass flux type scheme (Arakawa and Schubert 1974).

Betts (1982, 1986) proposed a new convective adjustment scheme purely based on the observations during the GARP Atlantic Tropical Experiments (GATE), Venezuelan International Meteorological and Hydrological Experiment (VIMHEX) and Atlantic Trade Wind Experiment (ATEX). This scheme includes both shallow and deep convection. The deep convective adjustment scheme is similar to the earlier moist convective adjustment schemes except that it uses observed quasi-equilibrium thermodynamic profile as reference state rather than moist adiabat. Betts (1986) has suggested three important adjustment parameters : (*i*) The saturation pressure departure values (*S*), the *S* values determine reference humidity profile, (*ii*) The stability weight (*W*), which decides the slope of reference profile compared to the moist adiabat and (*iii*) the adjustment time scale (τ), which gives the time lag between the large scale forcing and the convective adjustment. Betts and Miller (1986) carried out sensitivity test for adjustment parameters using GATE-wave data set (derived from Thomson *et al.* 1979). The optimum values of the adjustment parameters they found are; the adjustment time τ = 2 hr, stability weight *W* = 0.85 and the saturation pressure departure values equal to −25, −50 and −38 hPa at cloud base, freezing and cloud top levels respectively. Baik *et al.* [1990 (a & b)] incorporated the Betts-Miller scheme in an asymmetric tropical cyclone model and showed that the scheme is able to handle different stages of the evolution of tropical cyclone. Their study also showed that simulation is sensitive to the saturation pressure departure values.

Recently, Alapaty *et al.* [1994 (a)] have carried out sensitivity studies and found that orographic rainfall along the Western Ghats is sensitive to the adjustment time scale and the saturation pressure departure values. In their studies, the slope of the

saturation pressure departure values, in vertical, is kept constant but they have used different saturation pressure departure values at the lowest level. In another study, Alapaty et al. [1994 (b)] have investigated the comparative performance of Kuo and Betts-Miller schemes for a case of monsoon depression. The thermodynamic parameters used by them are very similar to those used by Puri and Miller (1990). The study indicates that the overall performance of the Kuo and Betts-Miller schemes differs significantly and suggest that Betts-Miller scheme needs systematic sensitivity studies regarding the suitability of the adjustment parameters for the monsoon region.

The objective of the present study is to examine the characteristics of the convective rainfall to the adjustment parameters, namely, the saturation pressure departure values and the stability weight. The observations show that the different convective regions have different quasi-equilibrium thermodynamic structures (Betts 1986). The realistic quasi-equilibrium structure can be obtained by incorporating suitable convective parameters for different convective regions. Therefore, it is very necessary to study the impact of these parameters over monsoon region before the scheme will be incorporated in the prognostic models.

In this paper, we have used different adjustment parameters, namely, the different saturation pressure departure values at the lowest level, four sets of slopes of saturation pressure departure values and the six values of stability weights, to study the sensitivity of the convective rainfall during the southwest monsoon season.

2. Data and synoptic situation

During the Monsoon Experiment-79 (MONEX-79), upper air data from radiosonde/rawin observations of five USSR research ships during cruises over the Arabian Sea and the Bay of Bengal in May-July 1979, was collected. These ships moved from Arabian Sea to the Bay of Bengal and were stationary from 11-23 July, 1979 over the Head Bay of Bengal. On 7 July, 1979 there was a depression over Head Bay, it moved in northwest direction and on 10 July, it was observed as a weak low pressure area over the central India. The satellite picture showed clouding over the Head Bay of Bengal, where the ships were at stationary position. During 11-13 July the monsoon was active. In the present study, ship

data of 11, 12 and 13 July 1979 at 0000 and 1200 UTC have been used. The dry bulb and dew point temperature values, averaged for four ships for 19 levels in vertical from 1000 hPa to 100 hPa, have been used.

3. Construction of reference profile

Observational studies over the tropics (Betts 1986) have shown that in presence of deep convection, a quasi-equilibrium structure below the freezing level parallels a moist virtual adiabat (isolines of constant θ_{esv}), above the freezing level, it shows a gradual increase of θ_{es} towards the θ_{es} adiabat established using a saturation point at a low level. In the present study, we assign a reference temperature profile with a minimum θ_{es} at the freezing level by considering the moist virtual adiabatic equilibrium structure as a reference thermodynamic state in the lower troposphere.

3.1. Formulation of reference profile

We have constructed the reference profile following Baik et al. [1990 (a & b)]. The procedure for constructing the reference profile is briefly discussed as follows :

The first guess of potential temperature along the reference profile upto freezing level is,

$$(\partial \theta / \partial P)_{ref} = W (\partial \theta / \partial P)_m \qquad (1)$$

where, W is the stability weight, subscript m means quantity in parenthesis is evaluated along the moist adiabat. Above the freezing level upto cloud top, the reference potential temperature is computed as follows :

$$\theta_{ref}(P) = \theta_m (P) - [a(P - P_t) + b(P_f - P)]/(P_f - P_t) \qquad (2)$$

where,

$$a = \theta_m (P_f) - \theta_{ref}(P_f) \qquad (3)$$

$$b = \theta_m (P_t) - \theta (P_t) \qquad (4)$$

θ_m and θ are the potential temperature values along the moist adiabat and environmental curve respectively and P_f and P_t are pressure values at freezing and cloud top levels respectively. The profile obtained from Eqn. (2) gives an increase of reference potential temperature back to the environmental potential temperature at cloud top.

The moisture reference profile is constructed using the saturation pressure departure values $S(P)$ given by,

$$S(P) = P^* - P \qquad (5)$$

where, P is the pressure value at a particular level and P^* is the pressure at which the parcel would become saturated if lifted adiabatically. The S values are measure of sub-saturation. The parcel is assumed unsaturated.

The S values are expressed in terms of S value at the lowest level (S_a). Upto the freezing level S values are given by,

$$S(P) = S_a[1+n_1(P_a-P)/(P_a-P_f)] \qquad (6)$$

where, n_1 is the slope constant upto freezing level and P_a is the pressure at the lowest level. Above freezing level S values are given by

$$S(P) = S_a[1+n_1-n_2(P_f-P)/(P_f-P_t)] \qquad (7)$$

where, n_2 is slope constant above freezing level. Once S values are determined first guess reference mixing ratio q_{ref} is calculated as:

$$q_{ref} = q(T^*, P^*) \qquad (8)$$

where,

$$T^* = T_{ref}(P^*/P)^{R/C_p} \qquad (9)$$

T_{ref} is the temperature along reference profile and is computed from θ_{ref}. P^* is obtained from Eqn. (5). The q_{ref} is approximated using the mixing ratio formula and the Teten's formula which gives,

$$q_{ref}=(3.7991/P) \exp\{C_1(T^*-273.16)/(T^*-C_2)\} \qquad (10)$$

$$\text{where, } (C_1 = 17.269, \ C_2 = 35.86)$$

Once the first guess reference profile is obtained as above, it is adjusted for the total enthalpy conservation so as to get the final reference thermodynamic structure.

3.2. Formulation of convective heating, moistening and rainfall

Once the reference profiles are determined the convective heating, moistening and rainfall are computed as,

convective heating;

$$\Delta_t = T_{ref} - T \qquad (11)$$

where, T is environmental temperature.

Convective moistening:

$$\Delta q = q_{ref} - q \qquad (12)$$

where, q is mixing ratio of the environment.

Convective rainfall:

$$R_c = -(1/g) \ (C_p/L)\int_{P_b}^{P_t} (T_{ref} - T)\,dp \qquad (13)$$

where, g is acceleration due to gravity, C_p specific heat at constant pressure, L latent heat of evaporation, P_b and P_t are pressure values at cloud bottom and top levels respectively.

4. Results and discussion

4.1. Adjustment parameters

Three sensitivity experiments have been carried out using different S values and stability weights (W). The changes in these parameters are made in the range of known theoretical values to study the characteristics of rainfall. The changes in these parameters are not based on any theoretical criteria, except that changes are made in the close range of the values already suggested by earlier workers [Betts 1986, Baik et al. 1990 (a & b), Alapaty et al. 1994 (a)]. The theoretical value of W suggested by Betts (1982) is equal to 0.9 and by Alapaty et al. [1994 (a)] equal to 0.8. We have chosen the values of W between 0.7 and 0.95.
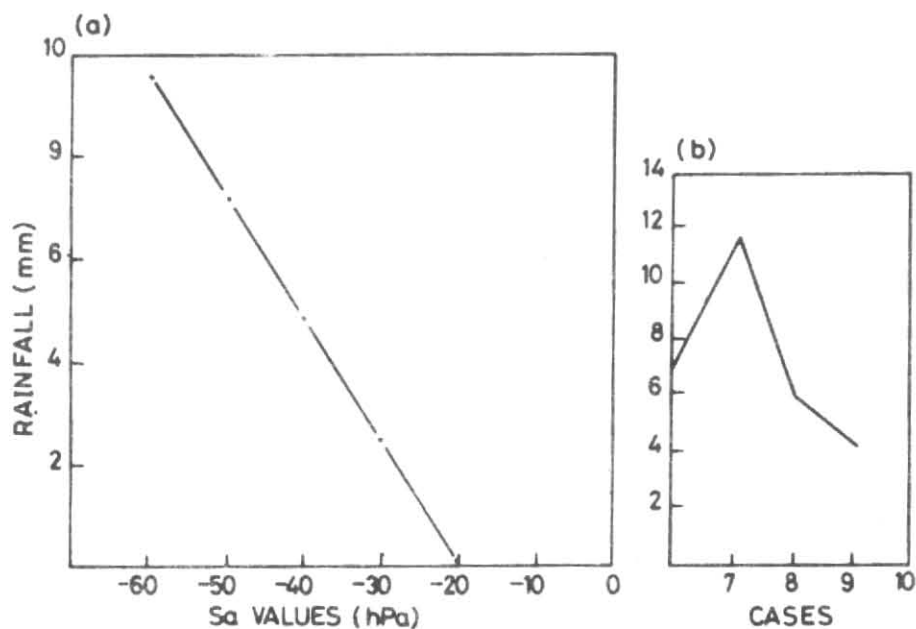
During the monsoon period the lower levels of the atmosphere are in near saturation, so if the parcel is lifted dry adiabatically through 20 to 50 hPa, it becomes saturated. Hence the S_a values are changed from −20 to −60 hPa. The slope constants n_1 and n_2 are fixed numerically.

Table 1 shows the values assigned to S and W. The variation of S values are linear from lowest level to the freezing level and from the freezing level to the cloud top level. The slopes of S values from lowest level to the freezing level and from the freezing level to the cloud top level can be negative or positive. The S values at these levels can be specified by assigning different values to the slope constants n_1 and n_2 as discussed in the previous section. The S value is a measure of the

TABLE 1

Saturation pressure departure (S) and stability weight (W) values for
different numerical experiments

Case	Stability w_t	S values at the lowest level S_a (hPa)	S value at the freezing level (hPa)	S' values at the cloud top level (hPa)
1		-20		
2		-30		
3	0.95	-40	$1.25\,S_a$	$0.75\,S_a$
4		-50		
5		-60		
6			$1.25\,S_a$	$0.75\,S_a$
7			$2\,S_a$	S_a
8	0.95	-50	S_a	S_a
9			$0.75\,S_a$	$0.5\,S_a$
10	0.7			
11	0.75			
12	0.8	-50	$1.25\,S_a$	$0.75\,S_a$
13	0.85			
14	0.9			
15	0.95			

Figs. 1 (a & b). Rainfall (mm) for (a) Cases 1 to 5 and (b) Cases 6 to 9
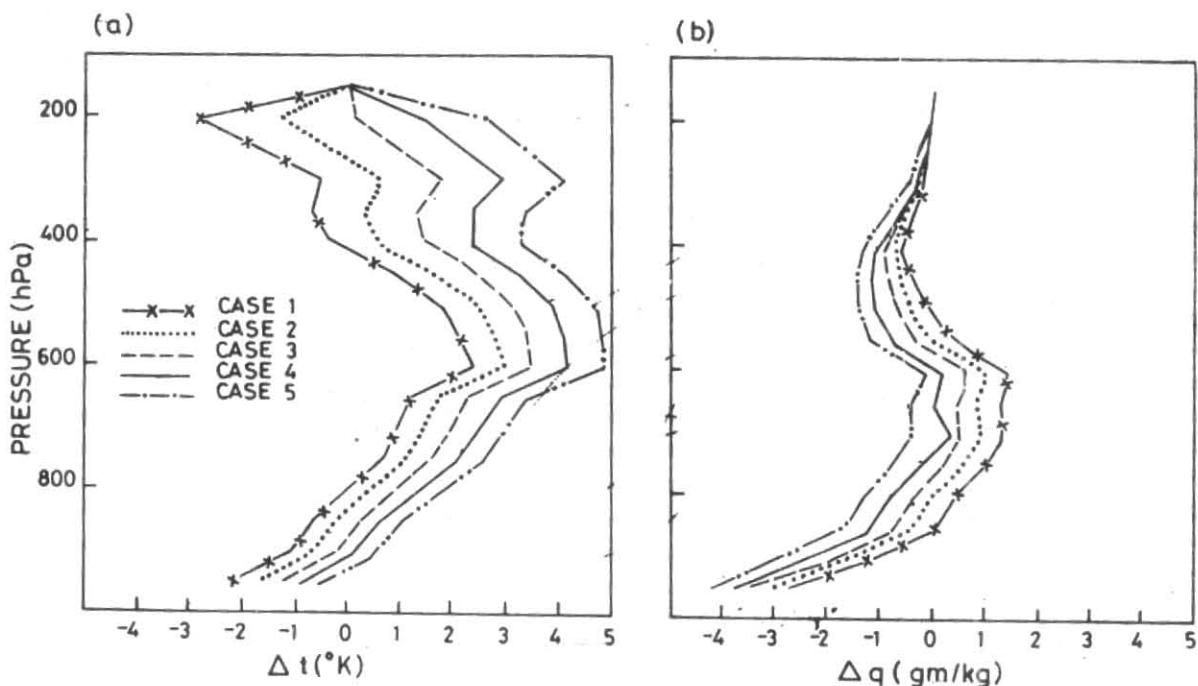
Figs. 2 (a & b). (a) Convective heating (°K) and (b) Convective moistening (gm/kg) for Cases 1 to 5

equilibrium relative humidity or moisture content of the reference profile. A decrease (increase) in S value will lead to more (less) warming and less (more) moistening of the atmosphere and increase (decrease) in the convective rainfall.

The state of the atmosphere due to convection is represented by reference profile. The reference thermodynamic profiles have been constructed by using stability weight value and the saturation pressure departure values as discussed in Section 3. The convective heating and moistening of the atmosphere are computed using Eqns. (11) & (12). The convective rainfall is computed diagnostically using Eqn. (13). The convective heating, moistening and rainfall computed are during the adjustment time period (τ hours). τ could be 2 to 3 hours. The convective rainfall, heating and moistening are presented and discussed for all the experiments. As the results are found similar for 0000 and 1200 UTC for 11, 12 and 13 July 1979, results of 1200 UTC for 12 July 1979 are presented and discussed.

4.2. Experiment 1

In this experiment, the stability weight value and slope of the S values are kept constant, whereas S_a values are decreased from -20 to -60 hPa with the interval of 10 hPa. These are referred to as Case 1 to Case 5 respectively.
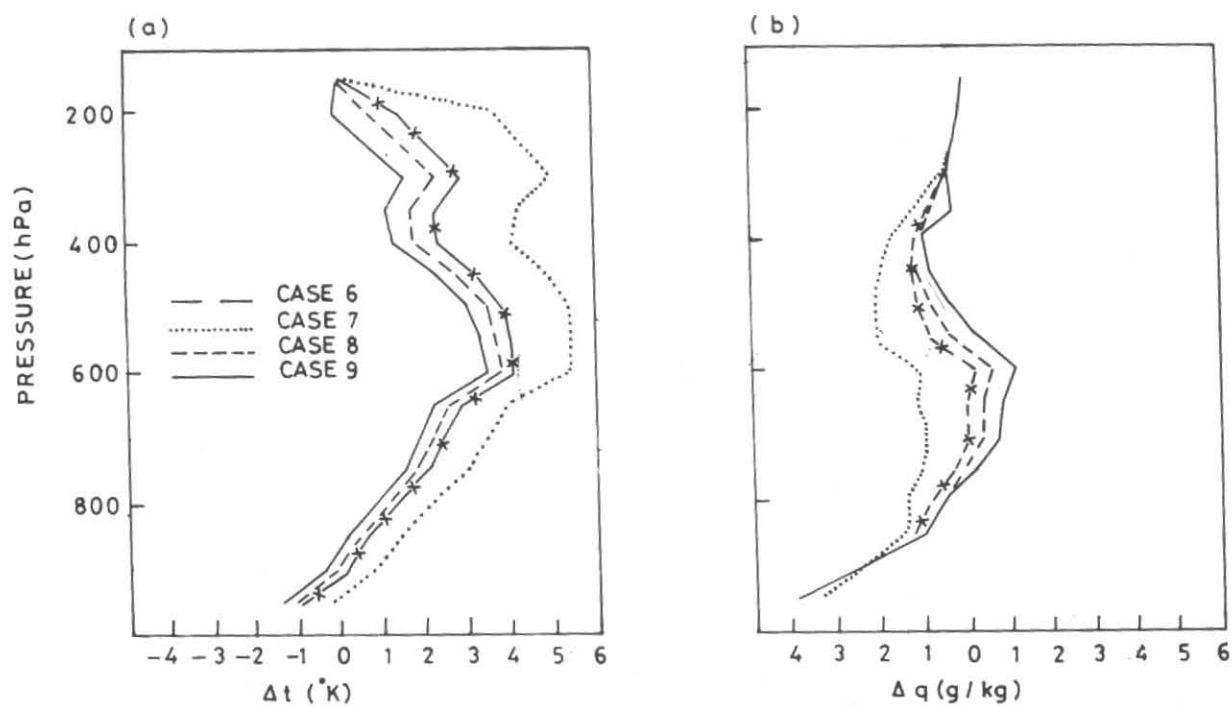
(i) Convective rainfall

Fig. 1 (a) shows the convective rainfall for Case 1 to Case 5. The reference profile in Case 1 is more moist than Cases 2 to 5. The reference profile in Case 5 is the driest and as discussed above, Case 5 has produced maximum and Case 1 has produced minimum rainfall. As the observed rainfall values are not available for the ship data, used in the present study, the computed rainfall cannot be compared with the observation.

(ii) Convective heating and moistening

Figs. 2 (a & b) show convective heating and moistening respectively for Cases 1 to 5. Case 5 shows maximum heating and Case 1 shows minimum heating. Fig. 2 (b) shows moistening due to convection. It is seen from the figure that Cases 1 to 4 show moistening of the middle troposphere, whereas Case 5 shows drying of the whole column of the atmosphere.

4.3. Experiment 2

In the second experiment, stability weight W and the S_a values are kept constant, whereas slopes of S values are changed. They are denoted as Cases 6 to 9.

Figs. 3 (a & b). (a) Convective heating (°K) and (b) Convective moistening (gm/kg) for Cases 6 to 9
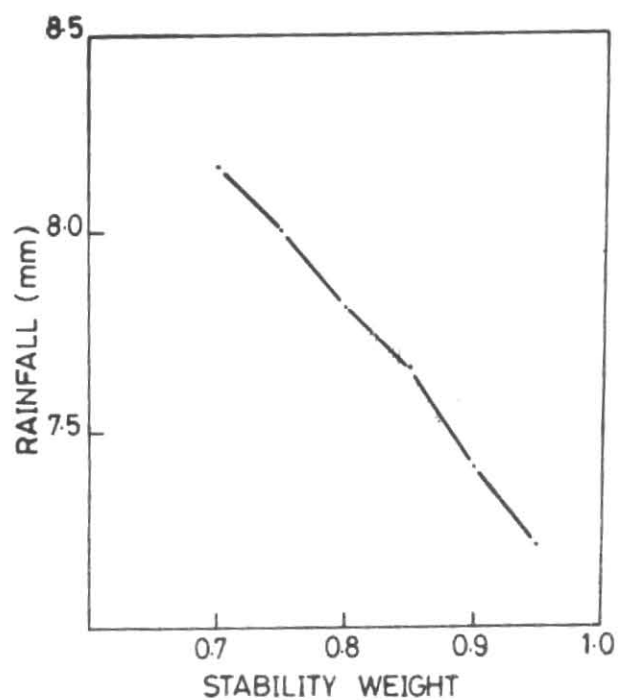

Fig. 4. Plot of convective rainfall (mm) *versus* stability weights

(i) Convective rainfall

Fig. 1 (b) shows convective rainfall for Cases 6 to 9. As expected from S-profile, Case 7 has produced maximum rainfall and case 9 has produced minimum rainfall.

(ii) Convective heating and moistening

Figs. 3 (a & b) show heating and moistening respectively for Cases 6 to 9. It is seen from the Fig. 3 (a) that all the Cases show heating of the atmospheric column from 900 hPa to cloud top level. Fig. 3 (b) shows that Cases 8 and 9 show moistening of the middle tropospheric levels but Cases 6 and 7 shows drying of the atmospheric column.

4.4. *Experiment 3*

It could be seen from Experiment 1 and 2 that $S_a = -50$ hPa and S values of 1.25 S_a at freezing level and 0.75 S_a at the cloud top level have produced drying of the column which is consistant with the earlier budget studies.

To examine further the effect of stability weight on convective rainfall, this S-profile is used for construction of reference state with different stability weight values. We have tested values of stability weight equal to 0.7 to 0.95 with the increment of 0.05. Fig. 4 shows convective rainfall for different values of the stability weight. It is seen from the figure, that when stability weight value is reduced from 0.95 to 0.7 the convective rainfall is increased by 1 mm. We also carried out a number of experiments with different S-profile varying the stability weight. The impact of stability weight on the convective rainfall is found marginal compared to the impact of S values.

5. Summary and conclusions

The USSR research ship data collected during MONEX-79 is used to study the sensitivity of convective rainfall, heating and moistening to the adjustment parameters in the Betts-Miller scheme over the monsoon region. Different saturation pressure departure values and stability weights have been used in the experiments.

The salient features of the study are the following :

(i) Convective rainfall is sensitive to S_a values.

(ii) S-profile obtained from $S_a = -50$ hPa and S values of 1.25 S_a at freezing level and 0.75 S_a at the cloud top level is the limiting S-profile to produce drying of the atmospheric column which is consistent with the budget studies. If reference profile is made more moist than this, there is moistening of middle layers of the column and if it is made less moist, there is drying of the entire column.

(iii) The impact of stability weight on convective rainfall is marginal as compared to the impact of S values.

The sensitivity of adjustment parameters in a prediction model will be examined in a separate study and will be reported later.

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