Effect of Cumulus Parameterization on the Indian Summer Monsoon Simulated by the COLA General Circulation Model

By D.R. Pattanaik

India Meteorological Department, Pune, India

and

V. Satyan

Climate and Global Modelling Division, Indian Institute of Tropical Meteorology, Pune, India

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Abstract

The sensitivity of the Indian summer monsoon to cumulus convection parameterization is investigated using the Center for Ocean-Land-Atmosphere studies (COLA) General Circulation Model (GCM). Two simulations for a period of nine years are performed with observed sea surface temperature, one parameterizing convection using the Kuo scheme and the other using a type of Arakawa Schubert scheme (the Relaxed Arakawa-Schubert [RAS] scheme). Dynamic fields such as winds, velocity potential, etc., are compared with the corresponding fields of National Center for Environmental Prediction (NCEP) reanalysis data sets. The model simulated precipitation is compared with the corresponding observed precipitation data.

The seasonal climatology of nine years of model integration shows that the differences between the two cumulus convection schemes have significant impact on the Indian summer monsoon circulation and its associated precipitation. The large-scale features are better simulated with the RAS scheme than with the Kuo scheme. The RAS scheme simulates stronger low level westerly over the Arabian sea, which leads to more moisture transport from the Arabian sea to the central India, than the Kuo scheme. The convective heating over the Bay of Bengal and the Arabian sea regions is larger with the RAS scheme than with the Kuo scheme, except near the surface and in the upper troposphere. With the RAS scheme, the convective heating maximum in the upper troposphere is more intense in the Bay of Bengal region than in the Arabian sea. Compared to the RAS scheme, the Tibetan anticyclone becomes weaker and shifts eastward, accompanying weaker tropical easterly jet, with the Kuo scheme. Similarly the divergent outflow in the upper troposphere associated with Asian monsoon is reduced significantly with the Kuo scheme than with the RAS scheme. Although both schemes are unable to simulate the Indian monsoon rainfall close to observation, the RAS scheme simulates and resolves better the positions of rainfall maxima over the Bay of Bengal and west coast regions. These differences are attributed to the closures and feedbacks of the two cumulus parameterization schemes. The GCM simulated time series of rainfall with both schemes shows that the intra-seasonal variation (monsoon cycle) is phase-locked to the seasonal migration.

1. Introduction

Monsoon circulation and its associated precipitation that dominates over India, Southeast Asia, and the western Pacific in summer is one of the most important climatological systems that have been studied extensively. From a global perspec-

tive, Krishnamurti et al. (1985) found that the monsoon circulation is associated with the much larger planetary scale divergence wave traversing eastward around the globe. The wave reaches its largest amplitude over the monsoon region, and strongly modulates the monsoon activity. Using numerical simulations Krishnamurti and Ramanathan (1982) studied the sensitivity of monsoon onset to the large-scale differential heating by modifying the initial moisture and mass convergence fields, and found that the evolution of the monsoon circulation is

Corresponding author: V. Satyan, Climate and Global Modelling Division, Indian Institute of Tropical Meteorology, Pune-411008, India. E-mail: satyan@tropmet.ernet.in
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quite sensitive to the intensity and location of the diabatic heating in the troposphere. Miller et al. (1992) found that errors in the simulated tropical circulation can often be related to errors in the mean distribution of heating. Furthermore, Chen and Yen (1993) suggested that the interannual variability of the tropical easterly jet is related to that of planetary-scale divergent circulation in the tropics, and can be attributed to the interannual variation of tropical diabatic heating. The latent heat released by cumulus convection contributes to a major part of tropical diabatic heating and therefore plays a major role in the maintenance of the general circulation in the tropics.

Cumulus convection influences the large-scale atmospheric flow mainly; (i) through the release of latent heat by condensation, (ii) by transporting sensible heat, moisture and momentum, and (iii) indirectly through its interaction with radiation. The release of latent heat by cumulus convection is one of the primary processes by which the solar energy input to the equatorial regions is transferred to the upper troposphere, and then polewards by the Hadley circulation. Hence it is very important how convection is treated in the model. Although the monsoon is affected by many factors, this study will focus on the effect of cumulus convection, as it is one of the most important physical processes for the monsoon simulation.

Slingo et al. (1988) studied the sensitivity of the monsoon simulation to convective parameterization using the European Center for Medium-Range Weather Forecasts (ECMWF) operational forecast model. They found that modification in convective parameterization has significant impact on the simulation of the monsoon circulation and precipitation. Zhang (1994) investigated the effect of cumulus convection on the Asian summer monsoon circulation using the General Circulation Model (GCM) from Canadian Climate Center (CCC). He performed two simulations, one parameterizing convection using a mass flux scheme and the other without convective parameterization. The results show that convection has significant effects on the monsoon circulation and its associated precipitation. A similar study by Slingo et al. (1994) compared two convective parameterization schemes, namely Kuo (1974) and Betts-Miller (1993) using the UK Universities Global Atmospheric Modelling Programme GCM. They found that both convection schemes give reasonable simulations of the time-mean climate, but the representation of the main modes of tropical variability is markedly different. They found that the Kuo scheme has much weaker variance, confined to synoptic frequencies near 4 days, and a poor simulation of intraseasonal variability. Whereas the convective adjustment scheme has much more transient activity at all time scales. Similarly, Baik and

Takahashi (1995) found that simulated climatology was very sensitive to the convective adjustment time scale in a convection scheme. In their study the sensitivity of the simulated large-scale structures to the Betts-Miller and the Arakawa-Schubert cumulus parameterizations was examined. They emphasised that the precipitation distribution over the tropical western Pacific which is the most active convective region in the atmosphere, is very sensitive to the choice of cumulus parameterization and the convective adjustment parameters.

Dewitt (1996) tested three different convection schemes: Kuo, Betts-Miller, and Relaxed Arakawa-Schubert ((RAS) Moorthi and Suarez 1992) using Center for Ocean-Land-Atmosphere studies (COLA) GCM. Dynamic fields were compared with the ECMWF analysis. His study was for a period of seven years from 1983 to 1989. From his results, it is found that the GCM with the RAS convective scheme simulated the climate for this period better than the Kuo or Betts-Miller scheme. The precipitation and circulation associated with the Indian summer monsoon are also shown to improve when the RAS scheme is used. Later Kirtman and Dewitt (1997) computed the model wind stress from the study of Dewitt (1996) using all the three convection schemes. In their study, the three wind stress fields are then used to force an ocean model. Their results show that the ocean simulation with the wind stress resulting from the RAS scheme gives a thermal structure that is in good agreement with the analysed wind stress simulation, and the ocean analysis.

Our aim in this study is to document improvements that can be expected in atmospheric circulation and associated precipitation of the Indian monsoon region if the convection scheme is changed. Interaction of parameterized convection and monsoonal circulation over the Indian region is focused. We have tested two convection schemes: the Kuo scheme, and the RAS scheme using the same COLA GCM used by Dewitt (1996). Our study is for a period of nine years with special emphasis over the Indian monsoon region. For the validation of the model results we used the reanalysis product along with the observations. A comparative study of the mean behaviour of the Asian summer monsoon and its interannual and intraseasonal variability has been carried out by Annamalai et al. (1999) using the reanalyses from ECMWF and NCEP. In the present study the model results from both integrations are compared with the NCEP reanalysis. The model simulated rainfall is compared with observed precipitation (Xie-Arkin (1996)) for the same period. A brief description of the GCM used, and details of the experiments are given in Section 2. A description of two convection schemes is presented in Section 3. The GCM simulations of the Indian

summer monsoon, along with the results from observations and reanalysis are discussed in Section 4. Finally, a conclusion is presented in Section 5.

2. Model description and experimental design

2.1 The COLA GCM

The COLA GCM used in this study is based on a modified version of the NMC (National Meteorological Center, now NCEP) global spectral model used for medium range weather forecasting (see Sela 1980 for original formulation; see Kinter et al., 1988 for modified version). The GCM horizontal resolution is triangular truncation at a total wave number of 30, corresponding to $3.75^\circ \times 3.75^\circ$ grid. The vertical structure of the model is represented by 18 unevenly spaced levels using sigma as the vertical co-ordinate. For the varying height of the surface, the U.S. Navy ten minute resolution model terrain height data set was used for each COLA GCM Gaussian grid box.

The land surface parameterization was changed to Simple Biosphere (SiB), a biophysical formulation after Sellers et al. (1986) by Sato et al. (1989) and later simplified by Xue et al. (1991). The sub-grid scale vertical transfer of momentum, heat and moisture in the atmosphere is treated using the level 2.0 closure scheme of Mellor and Yamada (1982). The GCM employs an efficient radiation scheme which resolves the diurnal cycle and includes terrestrial radiative heating (Harshvardhan et al. 1987) and solar radiative heating (Lacis and Hansen 1974; modified by Davies 1982). Short and longwave radiative fluxes are computed every three and six hours respectively in the present version of the GCM. The original version of the model employs a modified version of the Kuo convection scheme (Anthes 1977; after Kuo 1965) to represent deep precipitating convection. In one of the integrations, the Kuo convection scheme is replaced by the RAS scheme of Moorthi and Suarez (1992). In conjunction with the deep convection, a shallow non-precipitating convection is modelled following Tiedtke (1983) in both integrations. Since occurrence of shallow convection depends upon the presence of moisture accession into the column, we need the careful treatment when we apply the Kuo scheme for deep convection. If deep convection occurs at the grid point, shallow convection is not allowed in the column. Whereas with the RAS scheme shallow convection is allowed at all grid points, including those for which deep convection already occurred. In addition to deep convection and shallow convection the COLA GCM also includes the process of large scale condensation (relative humidity criteria as in Sela 1980). The large scale condensation is computed after the convection adjusts the atmosphere.

The model employs diagnosed clouds for cloud-radiation computation, as implemented by Hou

(1990) which is based on the work of Slingo (1987). In the radiation transfer model, convective type and stratiform type of clouds are considered separately. Convective type is diagnosed according to the three hour mean convective precipitation rate, whereas stratiform clouds are computed from relative humidity (RH). These RH-dependent clouds are divided into 3-layers, high, middle, and low clouds. The RH clouds will form when RH exceeds a certain critical RH. For more details see Dewitt (1996).

2.2 Experimental design

The COLA GCM has been used for a wide variety of applications. The present experiments were designed to evaluate the sensitivity of monsoon circulation and its associated precipitation to the cumulus parameterization schemes in COLA GCM. Two simulations are performed, one parameterizing cumulus convection using the Kuo scheme and the other using the RAS scheme. The integrations are started from NMC analysis of 1st January, 1986 and ended on September 30, 1994. The snow cover and soil moisture are prescribed initially, but predicted thereafter. Temporally varying observed monthly mean Sea Surface Temperature (SST) (objectively analysed) was used (Reynolds 1988). We used the model integrated output to evaluate the ability of the convection schemes to reproduce mean and interannual variability of the atmospheric circulation and precipitation in response to varying SST. Here, we have compared the seasonal climatology (June to September, JJAS) of these 9 years of model integrated data with the corresponding data from observation and the NCEP reanalysis.

3. Convection schemes used

3.1 Kuo scheme

The Kuo scheme allows cumulus convection for conditionally unstable columns. The precipitation is proportional to the total moisture accession. It is equal to the sum of convergence of moisture into the column and evaporation into the column. In those columns for which deep convection is diagnosed, the accessed moisture is partitioned into two parts. One part is responsible for heating (rain) the atmosphere, and the other part is for moistening (increasing RH) the atmosphere based on the column integrated relative humidity. The partition is done by introducing a parameter b (moistening parameter) which is a function of column integrated relative humidity as discussed in Anthes (1977). Thus fraction " b " of total moisture convergence is used to increase the humidity of the column, while the remaining fraction " $(1-b)$ " of total moisture convergence is condensed in cumulus convection and is precipitated out. The cloud temperature and specific humidity are determined by lifting of air parcel from the lowest model layer dry adiabatically up to the lifting condensa-

tion level (cloud base) and moist adiabatically up to the level where the cloud temperature and the environment temperature are the same (cloud top).

3.2 RAS scheme

The RAS scheme differs from the common implementation of the Arakawa-Schubert (1974) scheme (Lord et al. 1982) in two ways. First, the normalised mass flux which is an exponential function of height in the original formulation is replaced by one which is a linear function of height. Secondly, the parameterization relaxes the large scale atmosphere toward quasi-equilibrium instead of requiring quasi-equilibrium at each time step the cumulus convection is called. Each time the cumulus convection is called, all levels above the sub-cloud layer are checked for the possibility of convection. RAS implementation of deep convection in COLA GCM uses an assumed fixed Planetary Boundary Layer (PBL) depth and allows re-evaporation of falling convective rain closely following that of Sud and Molod (1988). The re-evaporation parameter in the RAS scheme reduces the excessive warming and drying in the lower troposphere. Clouds with the same specified cloud base, but different detrainment levels (cloud tops), are known as different cloud types. Convection occurs in the RAS scheme if the integrated buoyancy of a parcel lifted from the top of the PBL exceeds a critical value, which depends only on the depth of the cloud. The cloud work function is an integrated measure of the difference between the moist static energy in the cloud and that in the environment.

3.3 Major differences in the two schemes

The basic difference between the two schemes is that in the Kuo scheme deep convection occurs in the presence of a conditionally unstable column, and a positive moisture source. The Kuo scheme provides direct measures of the cumulus scale heat and moisture fluxes in terms of the measurable large scale variable, without having to compute cloud dynamical processes (such as entrainment, detrainment and cloud microphysical processes). The vertical distribution of the heating and moistening of the environment is based on the vertical distribution of temperature and specific humidity differences between the cloud and the environment. In the RAS scheme cumulus convection occurs for those cloud types for which the cloud work function exceeds an empirically determined value. The RAS scheme parameterizes the deep convection with an ensemble of clouds and it interacts strongly with the boundary layer, thereby differing from the Kuo scheme which parameterizes the deep convection with a single cloud, and uses moisture convergence and surface evaporation as the key variables. The RAS scheme specifically includes the effect of cumulus induced subsidence which modifies the environment

through warming and drying. The latent heat released within the clouds maintains the vertical mass flux of the clouds, and thereby, the cumulus-induced subsidence in the environment. The drying and warming of the environment, maintained by the cumulus-induced subsidence, are the indirect effects of condensation and release of latent heat.

4. Results and Discussion

4.1 Mean climate

The global annual mean energy budget and hydrological cycle averaged for a period of nine years from 1986 to 1994 are given in Table 1. As shown in part (a) of Table 1 the results show that Out going Longwave Radiation (OLR) is underestimated by the GCM with both convection schemes in comparison to its value in the NCEP reanalysis. This is due to poor cloud-radiation interaction in the GCM. Total precipitation with both convection schemes is greater than that from the corresponding observed precipitation. It is seen that total precipitation in the GCM with the RAS scheme is more than that with the Kuo scheme. Comparing the GCM simulation with both convection schemes (part (b) of Table 1), the evaporation from the surface is decreased in the GCM with the Kuo scheme, as a result the moisture supply to the atmospheric column is reduced in the GCM with the Kuo scheme than in the RAS scheme. Comparing the GCM response to two different convection schemes over the land and ocean region, the bottom portion of Table 1 shows the global mean values of different parameters over the land and ocean regions separately. Although there is almost no difference of large scale precipitation with the RAS scheme and the Kuo scheme over the whole region (part 'b' of Table 1), the large scale precipitation increases with the Kuo scheme than with the RAS scheme over the land region only. Whereas over the oceanic region the convective precipitation increases with the RAS scheme than with the Kuo scheme. Also the evaporation from the surface is more with the RAS scheme over the oceanic region and more with the Kuo scheme over the land region. If we consider the Indian region, the moisture supply by evaporation from the surface is reduced in the Kuo scheme. The area averaged mean value of evaporation rate over the Indian region (70°E–90°E, 5°N–30°N) for the same nine years period with RAS and Kuo schemes are 4.03 mm/day and 3.66 mm/day respectively. Similarly the area averaged mean value of evaporation rate over the Arabian sea region (60°E–70°E, 5°N–15°N) for the same nine years period with RAS and Kuo schemes are 6.72 and 6.11 mm/day respectively.

4.2 Circulation

The Figure 1 shows the simulated mean wind at lower and upper troposphere along with that from

Table 1. The global annual mean value of different meteorological parameters averaged from 1986 to 1994 from analysis as well as model output. The analysis field of OLR is obtained from NCEP whereas the precipitation is from a precipitation observation (Xie-Arkin).

(a)	RAS	Kuo	Analysis
outgoing long-wave radiation (watts/m ²)	231.45	230.70	237.27
total precipitation (mm/day)	3.51	3.38	2.65
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(b)			
evaporation from the surface (mm/day)	3.50	3.42	
convective precipitation (mm/day)	2.60	2.46	
largescale precipitation (mm/day)	0.91	0.92	
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land region (ocean region) only :-			
evaporation from the surface (mm/day)	1.83(4.18)	1.85(4.04)	
convective precipitation (mm/day)	1.71(2.91)	1.52(2.80)	
largescale precipitation (mm/day)	0.56(1.03)	0.74(0.95)	
total precipitation (mm/day)	2.27(3.94)	2.27(3.76)	

NCEP reanalysis. In the lower troposphere the GCM simulated seasonal climatology from June to September (JJAS) of nine years of model integration (1986–1994) of wind fields shows good simulation of low level westerly with the RAS scheme than with the Kuo scheme when compared with the corresponding JJAS climatology from the NCEP reanalysis (Figs. 1a, b, c). The weakening of low level westerly over the Arabian sea in the simulation with the Kuo scheme can be seen from the difference of 850 hPa wind between the RAS scheme and the Kuo scheme as shown in Fig. 2. The weakening of low level westerly over the Arabian sea in the Kuo scheme results in less moisture transport from the Arabian sea to central India. Figure 2 also shows stronger cyclonic vorticity over the western Pacific region in the RAS scheme than with the Kuo scheme. In the upper troposphere the Indian summer monsoon is characterised by a poleward migration of the subtropical westerly jet, and the subsequent establishment of the easterly jet over the Indian ocean. The establishment of the easterly jet is clearly seen in JJAS climatology from the NCEP re-

analysis for the same nine years (Fig. 1d). The GCM simulates with fairly good accuracy the strong tropical easterly over the monsoon region with both convection schemes (Fig. 1e and 1f). Both schemes simulate reasonably well the tropical easterly jet which extends from Indo-China to the west coast of Africa. Compared with the NCEP reanalysis (Fig. 1d), the RAS scheme gives a more realistic simulation of the intensity of the tropical easterly jet (Fig. 1e) than the Kuo scheme (Fig. 1f). The strength of the easterly jet is weaker in the Kuo scheme by about 3 ms^{-1} over the region of the north equatorial Indian ocean and adjoin southern India. The position and intensity of the tropical easterly jet over the Indian region is influenced by the position and intensity of the Tibetan anticyclone. Figure 3 shows the mean JJAS climatology of 200 hPa streamline simulated with the RAS and the Kuo schemes along with that from the NCEP reanalysis. The Tibetan anticyclone in the RAS simulation (Fig. 3b) is well positioned if we compare it's observed position in the NCEP reanalysis (Fig. 3a), whereas in the simulation with the Kuo scheme the anticyclone is shifted eastward

Fig. 1. Mean wind (m sec^{-1}) for June to September (JJAS) from 1986 to 1994 at upper and lower troposphere. (a) NCEP reanalysis at 850 hPa. (b) RAS scheme at 850 hPa. (c) Kuo scheme at 850 hPa. (d) NCEP reanalysis at 200 hPa. (e) RAS scheme at 200 hPa. (f) Kuo scheme at 200 hPa.

Fig. 2. Mean wind difference for June to September (JJAS) at 850 hPa from 1986 to 1994 between RAS and Kuo scheme.

(Fig. 3c).

The establishment of the Tibetan high is closely related to the building up of the elevated monsoon heat source over the plateau. The maintenance of the tropical easterly jet is usually explained as being connected with the zonally symmetric north-south differential heating between the Tibetan plateau and the upper troposphere above the Indian ocean. The maintenance of the Tibetan high, and the warm temperatures are attributed by Flohn (1964, 1968) to sensible heat transfer from the elevated land mass, and to diabatic heating by cumulus convection. Flohn's study shows that convective clouds are the dominant cloud types over western and central Tibet during the summer. According to Flohn, the warmest air associated with the Tibetan high is located roughly at 82°E, 30°N. His study shows large seasonal mean thickness between the 300 and 500 hPa surfaces over the Tibetan plateau corresponding to a large mean layer temperature and it is associated with strong thermal winds.

The seasonal mean thickness between 300 and 500 hPa surfaces averaged over the region 80°E–90°E, 25°N–35°N from our nine year integrations with the RAS and the Kuo schemes are 3840.4 gpm and 3818.9 gpm respectively. This indicates a larger mean layer temperature and a consequently intense Tibetan anticyclone simulation in the GCM with the RAS scheme than that with the Kuo scheme. Due to the larger value of mean layer temperature between 300 and 500 hPa surfaces the thermal wind to the south of the anticyclone is

stronger in the RAS scheme than the Kuo scheme. The weakening of the Tibetan anticyclone in the Kuo scheme can be seen from the 200 hPa geopotential height with both convection schemes along with that from the NCEP reanalysis (Fig. 4). The 200 hPa geopotential height over the Tibetan region in the case of the RAS simulation (Fig. 4b) is closer to that of the NCEP reanalysis (Fig. 4a), although still it is underestimated. While in case of the Kuo scheme (Fig. 4c) it is significantly reduced. So it is seen that the RAS scheme simulates a stronger Tibetan anticyclone than the Kuo scheme.

Consequent largescale impact due to weakening of the tropical easterly jet with the Kuo scheme can be visualized by analyzing the velocity potential (Fig. 5). The velocity potential field associated with the divergent circulation is a very useful measure to identify the planetary scale motion. Climatologically there is a strong divergent outflow over the Indian and Asian summer monsoon regions, and a strong convergence over the south-east Pacific ocean to the east of the divergent centre and over Iran and Arabia to the west of it. These correspond to the east-west monsoonal circulations identified by Krishnamurti (1971). It was shown by Krishnamurti et al. (1990) that strong monsoons, like that of 1988, are characterised by highly intense and large scale east-west circulation.

The GCM simulated JJAS mean velocity potential at 200 hPa simulated with the RAS scheme (Fig. 5b) agrees reasonably with the JJAS observed climatology of velocity potential from the NCEP re-

Fig. 3. Mean streamlines for June to September (JJAS) from 1986 to 1994 at 200 hPa level. (a) NCEP reanalysis. (b) RAS scheme. (c) Kuo scheme.

analysis (Fig. 5a), while in case of the Kuo scheme (Fig. 5c) the divergent circulation is weaker. The analyzed JJAS climatology (Fig. 5a) of velocity potential displays one minimum over the western Pacific region, which is an active convective region over the globe. The divergent center from western Pacific is extended up to the Bay of Bengal. In the normal monsoon year the center of divergence associated with the Asian monsoon is centered near the Bay of Bengal. The two centers of divergent circulation simulated by the GCM are very strong with the RAS scheme than with the Kuo scheme

(Fig. 5b and 5c). With the Kuo scheme the two centers are broader and weaker in strength, meaning the upper level divergent circulation is underestimated in the Kuo scheme. The divergent center over the western Pacific is shifted eastward in the simulation with the Kuo scheme. The negative values of difference of GCM simulated velocity potential at 200 hPa between the RAS scheme and the Kuo scheme (Fig. 5d) over the Asian monsoon region and the western Pacific suggest that there is enhanced upper level divergent outflow over this region. The positive differences over the eastern Pa-

Fig. 4. Mean geopotential height (gpm) for June to September (JJAS) from 1986 to 1994 at 200 hPa. (a) NCEP reanalysis. (b) RAS scheme. (c) Kuo scheme. 12000 is subtracted in figs. a, b and c. The shaded region is gpm value greater than 12460 in figs. a, b and c.

cific suggest that there is enhanced sinking motion over this region in the GCM with the RAS scheme.

Chen and Yen (1993) found that the weakening of the planetary-scale divergent circulation and consequent weakening of the tropical easterly jet can be attributed to the weakening of tropical diabatic heating. The GCM simulated area averaged convective latent heating rates over the three different regions are shown in Fig. 6. The two oceanic regions considered here are the Arabian sea (60°E–70°E, 5°N–15°N) (Fig. 6c), and the Bay of Bengal

(85°E–95°E, 5°N–15°N) (Fig. 6b). To see the effect of oceanic region and land region separately we also plotted the convective latent heating profile of land only region over the Indian monsoon region from 60°E–110°E, 5°N–25°N (Fig. 6a). In the oceanic regions, except the lowest levels close to surface and the upper troposphere, the convective latent heating is higher with the RAS scheme than that with the Kuo scheme (Fig. 6b and Fig. 6c). With the RAS scheme the convective latent heating over the Bay of Bengal region is more intense compared to that over

Fig. 5. Mean velocity potential ($1 \times 10^6 \text{ m}^2 \text{ sec}^{-1}$) for June to September (JJAS) from 1986 to 1994 at 200 hPa. (a) NCEP reanalysis. (b) RAS scheme. (c) Kuo scheme. (d) The difference of RAS and Kuo scheme (b-c). The shaded region is negative.

the Arabian sea region. This is particularly so for the heating maxima in the upper troposphere. The difference of convective latent heating produced by the two schemes is seen to be more over the Bay of Bengal region. Whereas over the land only region (Fig. 6a) convective latent heating profiles with both schemes remain almost close to each other in comparison to the oceanic region as shown in Figs. 6b and 6c. This shows that the latent heat released by cumulus convection over the Bay of Bengal region contributes a major part to tropical diabatic heating and hence to the monsoon heat source for the southwest Indian monsoon. Our analysis of convective latent heating shows that cumulus convection is deeper and more intense with the RAS scheme than the Kuo scheme. It is also seen that (Fig. not shown) the shallow convective heating contributes significantly to the total diabatic heating in the RAS scheme than with the Kuo scheme at the surface and lowest model layers.

The ocean heat source over the Bay of Bengal region contributes to the Tibetan anticyclone during the southwest monsoon season. As shown earlier (Fig. 4b and 4c) the stronger Tibetan anticyclone in the RAS simulation is due to more heating over the Bay of Bengal region. The difference of

convective latent heating with both schemes is not prominent over the land region (Fig. 6a), but is more prominent over the oceanic region particularly over the Bay of Bengal region. As a result, the latent heat release in the RAS scheme contributes more to the total diabatic heating which is responsible for the stronger divergent centers at 200 hPa and consequent stronger easterly jet than with the Kuo scheme.

4.3 Rainfall

The arrival and active phases of monsoon rainfall over India can be understood by looking at the time series of daily mean rainfall. The GCM simulated time series of daily mean rainfall averaged over the region 5°N – 30°N , 60°E – 100°E from 1986 to 1994 with two convection schemes, show the south-west monsoon rainfall over India from June to August with active and break phases of rainfall (Fig. 7). This shows that the monsoon cycle in the model is phase-locked to the seasonal migration. The time series of daily rainfall shows stronger monsoon over the Indian region with the RAS scheme than the Kuo scheme throughout the period. The time series of daily rainfall in both schemes also show a tendency of early onset of southwest monsoon over

Fig. 6. Mean vertical profile of convective latent heating ($^{\circ}\text{K day}^{-1}$) for June to September from 1986 to 1994 using both convection schemes averaged over the three different regions. (a) 60°E – 110°E , 5°N – 25°N (land only). (b) 85°E – 95°E , 5°N – 15°N (Bay of Bengal) (c) 60°E – 70°E , 5°N – 15°N (Arabian sea).

India with the RAS scheme. In the RAS scheme there is a sharp increase of rainfall around the 2nd week of May, whereas the normal onset of southwest monsoon over the southern tip of India is around 1st June. The tendency of earlier onset and stronger monsoon in the RAS scheme might be due to the fact that with the RAS scheme it tends to be more active over the oceanic region. If we see the strength of Indian summer monsoon in terms of strength of

low level wind speed over the Arabian sea, the GCM simulated daily mean time series of kinetic energy averaged over the region (5°N – 20°N , 60°E – 100°E) also shows stronger monsoon in the RAS scheme than the Kuo scheme throughout the period (Fig. not shown).

The region considered above for the rainfall time series covers some part of the oceanic region. To understand how the convective activity over the Ara-

Fig. 7. Time series of daily mean rainfall (mm) from 1986 to 1994 averaged over the region 60°E – 100°E , 5°N – 30°N from the GCM with RAS and Kuo schemes. The solid line is for RAS scheme and dotted line for Kuo scheme.

bian sea is related to the onset of the southwest monsoon over India, Mohanty et al. (1982) studied the heat, moisture and moist static energy budgets over the Arabian sea for the year 1979. They found that onset of monsoon over India is characterised by an increase of deep convection over the Arabian sea, extending up to the Bay of Bengal and across peninsular India. In their observational study Pearce and Mohanty (1984) found that the onset involves the organised release of convective instability in which the moisture distribution throughout both the lower and middle upper troposphere plays a crucial role.

To understand why the RAS scheme is more active over the Kuo scheme, mainly over the tropical ocean where plenty of moisture is available, one has to consider the difference in physical mechanisms of convection. In the case of the RAS scheme there is strong interaction with the boundary layer. The transport of moisture and sensible heat from the surface to the cloud base is reflected in cloud base moist static energy, which has a large influence upon cumulus activity. In the case of the Kuo scheme, the mechanism responds to the entire column moisture convergence plus evaporation. Over the oceanic region, particularly when winds are very strong, there is plenty of evaporation and sensible heat near the surface. Because of this, the RAS scheme triggers convection using its high cloud base energy drawing even more moisture from aloft, whereas the Kuo scheme uses only the moisture that has converged and evaporation. If there is no large-scale convergence, the Kuo scheme uses only evaporation. The

RAS scheme, with high cloud base moist static energy near the surface, will trigger convection and force the convergence to respond as a consequence of condensation heating. Although the Kuo scheme is strongly linked with the dynamical motion, intense convergence is required to activate the feedback between dynamics and diabatic heating. Again in a moisture convergence closure scheme, like the Kuo scheme, the magnitude of convergence depends on the model resolution. It should be noted here that because experiments in this study have been conducted with a coarse resolution model (T30), it is possible that the RAS scheme imparts a stronger role to convection while the Kuo scheme makes it a passive responder to the large scale convergence.

Next, we show the nine years seasonal climatology of spatial rainfall distribution from June to September from the GCM simulation with the RAS and the Kuo schemes along with observed rainfall (Fig. 8). The observed rainfall (Fig. 8a) shows heavy precipitation over the west coast of India and the head of the Bay of Bengal with relatively less rainfall over land region of India. Another rainfall maximum is seen over the western Pacific, which is the most active convective region in the globe. With the RAS scheme (Fig. 8b) the GCM simulates precipitation reasonably well, both the west coast and the head of the Bay maxima, although they are displaced southward. With the Kuo scheme maximum rainfall is observed south of Trivandrum ($08^{\circ}29'\text{N}$, $76^{\circ}55'\text{E}$) close to the equator, which is far south of the observed maximum. The west coast maximum is not at all

Fig. 8. Mean rainfall (mm/day) for June to September (JJAS) from 1986 to 1994 . (a) Xie-Arkin. (b) RAS scheme. (c) Kuo scheme. The shaded region is rainfall greater than 7 mm/day.

Fig. 9. GCM simulated difference of seasonal (JJAS) mean rainfall (mm/day) from 1986 to 1994 between RAS and Kuo schemes (RAS-Kuo). The shaded region is positive.

clear in the simulation with the Kuo scheme. The rainfall maximum over the western Pacific is better simulated in the RAS scheme and is closer to the observation, whereas it is underestimated in the Kuo scheme. The deficiency in simulations with both convection schemes is that the rainfall from June to September is mainly concentrated over oceanic regions with very little rainfall over peninsular India (Fig. 8b and 8c).

It is seen from the earlier studies that in the case of Indian monsoon rainfall most of the GCMs simulate maximum rainfall over oceanic regions, while the rainfall over the Indian land region is underestimated (WMO 1990). Although both schemes are unable to simulate Indian monsoon rainfall close to observation, the RAS scheme does better as the positions of rainfall maxima over the Bay of Bengal, and the west coast regions, are relatively better simulated and resolved in the RAS scheme than in the Kuo scheme. Considering the magnitude of seasonal rainfall over the land region of India, it is clear from Figure 9 that over the Indian land region it is more in the RAS simulation than with the Kuo simulation. The area averaged (70°E – 90°E , 5°N – 30°N) mean precipitation rate during June to September over the Indian land region for the same nine years period with the RAS scheme and the Kuo scheme are 5.33 mm/day and 4.29 mm/day respectively.

5. Conclusions

The effect of the parameterization of cumulus convection on the Indian summer monsoon has been investigated using COLA GCM. The convection schemes compared in the experiments are the Kuo scheme, and the Relaxed Arakawa-Schubert scheme. The model simulated meteorological fields are compared with the corresponding fields from the NCEP reanalysis except the precipitation. The model simulated precipitation is compared with observed precipitation. We have emphasised the Indian monsoon region in this study.

The results show that change in convective parameterization has significant impact on the simulation of the monsoon circulation and precipitation. The monsoon circulation is better simulated in the GCM with the RAS scheme compared to the Kuo scheme. The upper level divergent centers and the intensity of Tibetan anticyclone is weak in the simulation with Kuo scheme. Again the position of the Tibetan anticyclone is well simulated with the RAS scheme while it is shifted eastward in simulation using the Kuo scheme as compared to that of the NCEP reanalysis. The strength of the easterly jet is underestimated in the simulation with the Kuo scheme. The large scale features are better simulated with the RAS scheme compared to the Kuo scheme.

The GCM simulated daily time series of monsoon

rainfall over the Indian monsoon region with both convection schemes shows that the monsoon cycle in the model is phase-locked to the seasonal migration. One common problem with both convection schemes pertains to the simulation of the Indian summer monsoon rainfall. Maximum rainfall is simulated over oceanic regions in both the schemes, while rainfall over the land region of India is underestimated. Although both convection schemes are unable to simulate Indian monsoon rainfall close to observation, RAS does better in the sense that the position of rainfall maxima over the Bay of Bengal and west coast regions are relatively better simulated and resolved in the RAS scheme than with the Kuo scheme.

As mentioned earlier, the treatment of shallow convection was different in both the experiments. Thus, this study actually assesses the differences between the combined shallow and deep convection schemes. Dewitt (1996) mentioned that he believed that the impact of shallow convection is not significant. We have the same view on it. The impact of shallow convection will be evaluated in our future study.

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COLA 大気大循環モデルで再現されたインド夏季モンスーンに対する 積雲パラメタリゼーションの効果

D.R. Pattanaik

(India Meteorological Department)

V. Satyan

(Indian Institute of Tropical Meteorology)

インド夏季モンスーンの積雲対流パラメタリゼーションに対する感度を、COLA 大気大循環モデルを用いて調べた。観測された海面水温を与えて、Kuo と Relaxed Arakawa-Schubert (RAS) の2つの積雲対流方式を用いてそれぞれ9年間のシミュレーションを行った。力学場として風や速度ポテンシャルなどの場を NCEP の再解析値と比較した。また、降水は対応する観測と比較した。

9年間の季節シミュレーションの結果は、2つの積雲対流方式の違いが、インド夏季モンスーン循環とその降水に大きなインパクトを持っていることを示した。大規模場の特徴は Kuo 方式に比べて RAS 方式の方がより良く再現される。RAS 方式は Kuo 方式に比べて、アラビア海上の下層の西風を強め、そこからインド中央部への水蒸気輸送を増す。ベンガル湾とアラビア海領域上の対流加熱は地上付近と上部対流圏を除いて RAS 方式の方が大きい。その RAS 方式の場合、上部対流圏の対流加熱の極大値はベンガル湾の方が、アラビア海よりも大きい。RAS 方式に比べて、Kuo 方式では、チベット高気圧は弱く、東にシフトし、上層の熱帯東風ジェットも弱い。同様に、モンスーン循環の一部としての上部対流圏の発散外出流も Kuo 方式の方が明らかに弱い。両方式ともインドのモンスーンの降水について観測に非常に近い再現はできないが、ベンガル湾上や西海岸上の降水の極大は RAS 方式の方がより良く再現する。これらの違いが2つの積雲パラメタリゼーションのクロージャーとフィードバックの違いに関連付けられる。また、シミュレートされた降水の時系列は、モンスーンの季節内変動の位相が季節進行に対して固定されている様子を示している。