Impact of Convective Downdrafts in a GCM on the Simulated Mean Indian Summer Monsoon and its Variability

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Abstract

The sensitivity of mean monsoon and its variability simulated by Hadley Centre Climate Model to changes in convection scheme, has been examined by integrating the model with and without parameterisation of convective downdrafts. Summer monsoon seasons during 7 years 1982, 1983, 1984, 1987, 1988, 1991 and 1994 have been simulated. These years have been selected for the study as the monsoon rainfall over India showed large interannual variability in these years. Results are compared with NCEP reanalysis circulation and Xie-Arkin precipitation data.

Analysis of the model output shows that some of the systematic errors in the model in the monsoon simulation are reduced with incorporation of downdrafts. The systematic error by which the monsoon low level westerlies extend deep into the west Pacific ocean is substantially reduced by the inclusion of downdrafts. The lower tropospheric monsoon flow over the north Indian ocean is strengthened with downdrafts. TEJ simulated with downdrafts is closer to NCEP reanalysis. Inclusion of downdraft improves the precipitation simulation over land areas of India, and also simulates the correct position of the monsoon trough. When downdrafts are not included there is excessive precipitation over the west equatorial Indian ocean and less precipitation over India. Surface latent heat flux increases with the downdrafts. The systematic error of the model which simulates stronger low level circulation in El Niño years than in La Niña years is reduced, though not completely eliminated. The interannual variability of simulated monsoon precipitation is more realistic with downdrafts. Spells of active and 'break,' or weak monsoon situations, are more prominently simulated when downdrafts are included. Larger number of strong synoptic disturbances are simulated over India with the inclusion of downdrafts.

1. Introduction

Monsoons play a central role in the economic, social and political stability of more than half of the world's population. Primarily monsoons affect agriculture. Indian summer monsoon contributes about 80 % to the annual rainwater potential. High concentration of rainfall during the monsoon season (June–September) makes the economy of India vitally dependent on the performance of monsoons.

Monsoon rainfall varies on a wide range of time and space scales. Droughts and floods have been the most important natural causes of famine. Famines caused by abnormal monsoons, either too wet or too dry, have occurred frequently on the Indian subcontinent. Indian scientists have studied monsoon be-

haviour for more than a century. These studies have shown that the monsoon is related through teleconnection to phenomena occurring over other parts of the world (See Krishna Kumar *et al.*, 1995 for a review).

The role of ocean-atmosphere interactions as a major factor in determining tropical seasonal variability has long been recognised. Shukla (1987) suggested that there are essentially two mechanisms responsible for the interannual variability (IAV) of tropical atmosphere: the internal dynamics, and slowly varying boundary conditions. The slowly varying boundary conditions influencing IAV of monsoon are sea surface temperature (SST), soil moisture, sea-ice and snow at the earth's surface. One of the important boundary forcings is SST over tropical Pacific. There are many observational and modelling studies on the effect of variation of tropical Pacific SST (El Niño) on IAV of monsoon. However, some recent studies (Goswami, 1998) indicate

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that the internal dynamics may also be important for the IAV of monsoon.

El Niño is recognised as one of the major causes of IAV of monsoon. There are extensive observational (Bhalme *et al.*, 1983; Mooley and Parthasarathy, 1983; Rasmusson and Carpenter, 1983) and modelling studies (WCP, 1986; WCRP, 1992; Palmer and Sperber, 1996; Ju and Slingo, 1995; Soman and Slingo, 1997) on the possible effect of El Niño on monsoon. The correlation between Niño-3 SST anomalies and All India Rainfall (AIR) for the period 1871–1994 is -0.57 , which confirms significant impact of El Niño on Indian summer monsoon. In short, warm SST anomalies in the equatorial central and east pacific (El Niño) is often related to drought over India and anomalously cold SSTs (La Niña) with flood or above average rainfall years.

Models differ in their simulation of IAV of monsoon precipitation in AMIP integrations (Sperber and Palmer, 1996). This shows sensitivity of monsoon simulation to resolution and physical parameterisations. Convection parameterisation is one of the important physical processes parameterised and sensitivity to parameterisation of convection has been studied by Slingo *et al.* (1994). The physical parameterisation of different subgrid scale processes used in the models may contribute to the internal dynamics and the way the models respond to boundary forcings. In the present study, we examine the effect of parameterisation of convection on the simulated mean monsoon and its variability.

In the tropics cumulus convection plays an important role, the released latent heat driving the large scale motions of the tropics and midlatitudes. As a result cumulus parameterisation is one of the major physical processes that are parameterised in the numerical models. Updrafts and downdrafts are important components of the convective systems, playing an important role in the energetics of the cloud system and in the interaction of deep convection with sub-cloud layer and surface processes.

The Hadley Centre (HC) AGCM (based on the UKMO Unified Model) simulates the mean monsoon circulation and rainfall reasonably well (Inness *et al.*, 1994). The parameterisation of cumulus convection included in this model is a mass flux penetrative convection scheme (Gregory and Rowntree, 1990), with the addition of an explicit downdraft representation (Gregory and Allen, 1991). Preliminary studies (Inness *et al.*, 1994) conducted at HC have indicated that inclusion of downdrafts in the convection scheme improves the long term monsoon mean state simulated by the model. Impact of downdrafts on the simulated Indian summer monsoon for 1991 by UKMO GCM showed improvement in the rainfall and 850 hPa circulation with downdrafts (Nagaratna, 1996).

Recently, climate models are being increasingly

used to study the IAV of monsoon, with a view to evolve methods for seasonal predictions. It is of interest to study the impact of changes in parameterisation scheme on the simulation of mean summer monsoon rainfall and its IAV. The objective of the present paper is to study the role of convective downdrafts in the simulation of monsoon rainfall. The study also attempts to understand the impact of convective downdrafts on monsoon simulation during years of strong tropical SST anomalies. The years selected on the basis of Indian rainfall for the study are 1982, 1987, 1991 (below normal years), 1983, 1988, 1994 (above normal years) and 1984 (normal year).

2. Model description

The HC climate model (HadAM2b, version 4.0) has horizontal resolution of 2.5° in latitude by 3.75° in longitude. A regular latitude-longitude grid is used in the horizontal with variables arranged according to the Arakawa 'B' grid. A hybrid vertical coordinate system (Simmons and Burridge, 1981) is used with 19 levels. The bottom 4 of the 19 layers are terrain following sigma layers and the top 3 layers pure pressure layers, with a smooth transition in between. The atmospheric model equations are a quasi-hydrostatic version of the full primitive equations in spherical polar coordinates with a complete representation of the coriolis force in which the usual shallow atmosphere approximation is relaxed (White and Bromely, 1995). A 30 minute timestep is used to compute increments from both dynamical and physical routines although full radiation calculations are performed only every 3-hours for economy. The various parameterisations in the model are briefly discussed below:

- 1) *Radiation*: The scheme consists of 2 parts, the solar radiation and long-wave radiation. The scheme uses 4 spectral bands for solar radiation as defined by Slingo (1989) and six bands for long-wave radiation (Slingo and Wilderspin, 1986).
- 2) *Boundary layer*: The boundary layer can occupy up to the bottom 5 atmosphere model layers. A first-order turbulent mixing scheme is used to mix the conserved thermodynamic variables and momentum in the vertical (Smith, 1990b).
- 3) *Large-scale cloud and precipitation*: Large-scale clouds (Smith, 1990a; Smith and Gregory, 1990) are represented by their liquid water (or ice) content. Large-scale precipitation is calculated in terms of water or ice-content of the clouds; frozen cloud fall out scheme allows cloud ice to contribute to the water and ice budget of lower levels as it falls.

- 4) *Gravity wave drag*: Gravity wave drag is applied to momentum components in the free atmosphere using a parameterisation based on a prescribed sub-grid scale orographic variance field, and the vertical stability profile as a function of height through the atmospheric column (Palmer *et al.*, 1986)
- 5) *Convection*: Convective rainfall and snowfall are calculated using a mass flux penetrative convection scheme (Gregory and Rowntree, 1990) with the addition of an explicit downdraft representation (Gregory and Allen, 1991). The scheme is designed to simulate the effects of shallow, mid-level and deep convection upon the large-scale flow. The magnitude of convective activity is calculated by considering the stability of lowest convective layers only.

The scheme represents an ensemble of clouds using a bulk one-dimensional cloud, based upon parcel theory, modified by entrainment and detrainment. Thus the parcel characteristics calculated by the cloud model represent average over the entire ensemble.

Downdrafts are an important component of many deep convective systems. Downdrafts maintain the heat and moisture budgets of the sub-cloud layer. Deep convective clouds contain both upward and downward motion. The downward motion is driven by the evaporation of falling precipitation and also by the drag of the precipitation on the air through which it falls. The study of Gregory and Miller (1989) showed that contribution to net convective heating by downdrafts is large. Studies conducted at HC (Inness *et al.*, 1994 and Gregory, 1994) have shown that inclusion of downdrafts improved the mean simulations of climate in many regions of the world. In the present study, the effect of inclusion of downdrafts on the monsoon simulation is examined.

3. Experimental design

Recognising the possible influence of El Niño on the Indian summer monsoon simulation, El Niño years 1982, 1983, 1987, 1991 and 1994, La Niña year 1988 and normal year 1984 have been selected for the present study. The 1982/83 El Niño event started in the northern hemispheric spring of 1982, peaked in Dec. 1982 and persisted till May 1983. In the beginning of the 1983 monsoon season, warm SST anomalies in the Pacific decreased, and the Southern Oscillation Index became positive. The monsoon rainfall over India was 13.8 % below normal in 1982, while it was 12.1 % above normal in 1983 (Parthasarathy, 1994). The monsoon rainfall was 1.9 % below normal in 1984. The El Niño event of 1987 started in the latter part of 1986 and persisted till the beginning of 1988, and was less strong compared to the

1982/83 event. During spring and early summer of 1988, there was rapid change from warm to cold SST anomalies in the Pacific, which was the development of a major La Niña. The monsoon rainfall over India was 18.2 % below normal in 1987, and it was 12.8 % above normal in 1988 (Parthasarathy, 1994). However, 1991 and 1994 were both El Niño years, but the Indian summer monsoon rainfall was 8 % below normal in 1991, while it was 10.1 % higher than normal in 1994 (Parthasarathy, 1995). In short, these years showed strong IAV of monsoon rainfall over India.

In this study, we have integrated the model for the monsoon season (June–September) of the years 1982, 1983, 1984, 1987, 1988, 1991 and 1994. The initial condition of 1 June of corresponding years has been used for integrations. The model integration from 1 June till end of September has been carried out for all years. The observed boundary forcing of SST and sea-ice used is GISST1.1 (Global sea-Ice and Sea Surface Temperature) data prepared by Hadley Centre for Climate Prediction and Research, U.K., which provides complete global coverage. These simulations are carried out with a convection scheme which includes downdraft processes. Another set of parallel integrations without downdrafts was also carried out.

The model output from these integrations are compared among themselves and with NCEP Reanalysis data (Kalnay *et al.*, 1996), and Xie-Arkin precipitation data (Xie and Arkin, 1997) for the respective years.

4. Results

The inclusion of downdrafts in the convection scheme has shown a major impact on the mean and IAV of the monsoon circulation and precipitation. The sensitivity of the monsoon simulation to the inclusion of downdrafts is assessed in terms of circulation at 850 hPa, 200 hPa, precipitation and mean sea level pressure (P_{msl}) over the monsoon region. The impact of convective downdrafts on the mean summer monsoon over India is discussed in section 4.1, its IAV in section 4.2 and on the transient disturbances during the monsoon season in Section 4.3.

4.1 Impact on the mean Indian summer monsoon

Winds at 850 hPa during the monsoon season (hereafter referred to as JJAS), averaged for 7 years considered in the study namely, 1982, 1983, 1984, 1987, 1988, 1991 and 1994 (hereafter referred to as climatology), in the experiments without and with downdrafts is shown in Figs. 1a and 1b respectively. NCEP Reanalysis wind at 850 hPa, average for the same 7-year period is shown in Fig. 1c, for comparison. It can be seen from Figs. 1a and 1b, that the monsoon low level flow through the Indian Ocean and across the Indian subcontinent is simulated rea-

Fig. 1. JJAS wind climatology at 850 hPa (a) without downdrafts (b) with downdrafts (c) NCEP reanalysis.

sonably well. Easterly winds to the south of the equator turn northwards, and form a cross equatorial jet along the Africa coast. This flow then turns to a westerly flow with a jet maximum located over the Arabian sea. Close observation shows that there are some differences in simulation with and without downdrafts. The low level westerly jet over the Arabian sea is stronger by about 5 m/sec in simulation with the downdrafts. The westerly jet extends over the Philippines and the west Pacific in experiments without downdraft. The NCEP Reanalysis data do not show such an extension to the west Pacific (Fig. 1c). This error is reduced by inclusion of downdrafts. Over northern India the easterlies, north of the monsoon trough is better simulated by the inclusion of downdrafts. These differences can be clearly seen from Fig. 4a, which shows difference (downdrafts minus no downdrafts) of wind at 850 hPa.

JJAS climatology winds at 200 hPa, without and with downdrafts, are shown in Figs. 2a and 2b. For comparison NCEP Reanalysis JJAS wind at 200 hPa averaged for the same 7-year period as the model climatology described here, is shown in Fig. 2c. The Tropical Easterly Jet (TEJ) is simulated reasonably well by the model. However, the TEJ showed southward spread in the simulation with downdrafts compared to TEJ simulated without downdrafts. TEJ in the west Pacific is improved with downdrafts. TEJ simulated with downdrafts is closer to NCEP reanalysis. The winds in the equatorial Indian ocean, between 60–95E are underestimated (by about 5 m/sec) without downdrafts. This is clearly seen from Fig. 4b, showing difference (downdrafts–no downdrafts) of 200 hPa wind. The strength of wind in this region with downdrafts is in agreement with NCEP observations (Figs. 2b and 2c).

JJAS precipitation climatology for experiments without downdrafts (Fig. 3a) and with downdrafts (Fig. 3b) is compared with Xie-Arkin precipitation data for JJAS, averaged for the same 7-year period (described as climatology here) shown in Fig. 3c. These figures show that the magnitude and position of precipitation maximum off the Indian west coast is not correctly simulated when downdrafts are not included. The magnitude is less, and the maxima is wrongly located in the Arabian sea to the west of its observed position. The precipitation over the Bay of Bengal has increased substantially with the inclusion of downdrafts. The location of the precipitation maximum is shifted slightly south and is closer to the location seen from Xie-Arkin data. The excessive precipitation over the west equatorial Indian ocean is substantially reduced when the downdrafts are included. The difference (downdraft minus no downdraft) of JJAS precipitation climatology is shown in Fig. 4c. It is clearly seen from this difference figure that the inclusion of downdrafts in-

creases precipitation over India, and reduces it over oceanic areas south of India. The precipitation is also decreased over the south China sea. A large difference in precipitation of the order of 6 mm/day is seen over peninsular India.

Downdrafts affect the large-scale environment through compensating “up-sidence,” and detrainment of downdraft air within the boundary layer. Downdrafts act as a heat sink, bringing cold dry air from mid-troposphere to the boundary layer and increase surface evaporation over large regions of the tropical oceans where convection occurs (Gregory, 1994). JJAS climatology of surface latent heat flux (SLHF) for experiments without, and with downdrafts, is shown in Figs. 5a and 5b respectively. Difference (downdrafts–no downdrafts) of SLHF climatology is shown in Fig. 5c. SLHF increases with downdrafts over India. A large increase in SLHF over tropical oceans (specifically the Arabian sea and Bay of Bengal) (Fig. 5c) indicates enhanced evaporation with the inclusion of downdrafts.

Formation of low pressure over the Indian continental land mass (Heat low) is important for the development of the monsoon circulation. JJAS climatology of P_{mst} simulated without and with downdrafts by the model are shown in Figs. 6a and 6b. Figure 6c shows difference (downdrafts–no downdrafts) of P_{mst} climatology. The position of the monsoon trough which extends from northwest India to the Head of Bay of Bengal is crucial to the correct simulation of rainfall over India during the monsoon season. The position of the monsoon trough shows some difference in the two simulations without and with downdrafts. Without downdrafts the monsoon trough, instead of extending to the head of the Bay of Bengal, extends southward along the east coast of India. In the simulations with downdrafts, the monsoon trough position is more realistic (Y.P. Rao, 1976).

4.2 Impact on Interannual variability of the Indian summer monsoon

All India summer monsoon rainfall for the period 1980–1994 (Parthasarathy, 1995), observed normalised, is shown in Fig. 7. This data has been prepared based on a well distributed network of 306 raingauge stations, one from each of the districts in plain regions (29 subdivisions) of India. It is clearly seen from the Fig. 7, that there are several years where the rainfall is above, or below normal by more than one standard deviation (S.D.), leading to widespread floods and droughts. The years 1982/1983, and 1987/1988, show strong IAV of rainfall associated with El Niño/La Niña. The southern oscillation index in May 1991, and 1994, was close to –1.3. In spite of this, these years had very different monsoon rainfall over India.

The impact of the inclusion of downdrafts in the

Fig. 2. JJAS wind climatology at 200 hPa (a) without downdrafts (b) with downdrafts (c) NCEP reanalysis.

Fig. 3. JJAS precipitation climatology (a) without downdrafts (b) with downdrafts (c) Xie-Arkin data.

Difference (downdrafts – no downdrafts)

Fig. 4. Difference (downdrafts–no downdrafts) of JJAS climatology of (a) wind at 850 hPa (b) wind at 200 hPa (c) precipitation.

Fig. 5. JJAS surface latent heat flux climatology (a) without downdrafts (b) with downdrafts (c) Difference (downdrafts–no downdrafts).

JJAS Mean Sea Level Pressure

Fig. 6. JJAS P_{msl} climatology (a) without downdrafts (b) with downdrafts (c) Difference (downdrafts-no downdrafts).

Fig. 7. Normalised all India summer monsoon rainfall (AISMR) time series from 1980–1994.

convection scheme on the IAV of the simulated summer monsoon is brought out by examining the contrast in lower level winds, and precipitation between the pairs of strong and weak monsoon years. The wind differences at 850 hPa are shown in Fig. 8, Fig. 9 and Fig. 10 for the pairs 1982–83, 1987–88, and 1991–1994 respectively. These figures also show observations based on the corresponding data from NCEP reanalysis. During strong El Niño years, the model has a systematic error by which it simulates a stronger low level circulation in the second half of the season (Harrison *et al.*, 1997 and Martin, 1999). This is consistent with stronger low level westerly winds in 1982, compared to 1983 (Figs. 8a and 8b) and stronger winds in 1987 compared to 1988 (Figs. 9a and 9b). Figures 8b and 9b show that inclusion of downdrafts reduces this systematic error although it does not completely eliminate it. Figure 8c shows that there was no difference in the strength of low level westerlies in 1982 and 1983. NCEP reanalysis (Fig. 9c) shows stronger low level circulation in 1988 compared to 1987. It is seen that stronger monsoon circulation of 1994 compared to 1991 is simulated with the inclusion of downdrafts (Fig. 10b). NCEP reanalysis data also shows stronger westerlies over peninsular India in 1994 compared to 1991 (Fig. 10c). However, the difference (1994–1991) is overestimated in the model simulation compared to NCEP.

The differences of JJAS precipitation without and

with downdrafts for the 3 pairs of years (1983–82, 1988–87, 1994–91) are shown in Fig. 11, Fig. 12 and Fig. 13. The observed differences based on Xie-Arkin data are also included in these figures. In Xie-Arkin data (Fig. 11c) precipitation is more in 1983 compared to 1982 over most of the monsoon region except part of the northwest Pacific. Both the experiments, without and with downdrafts, failed to simulate larger precipitation in 1983 compared to 1982. Most of the GCMs failed to simulate stronger monsoon in 1983 compared to 1982 (WCP, 1986). There are some improvements in the simulation with downdrafts over India, as there is reduction in the negative difference in precipitation between 1983 and 1982. There is more precipitation along part of the west coast in 1983 compared to 1982. Improvement is also noticed over the equatorial Indian ocean (Figs. 11a and 11b). Difference in (1988–1987) and (1994–1991) indicate that the precipitation over India in strong monsoon years is more compared to weak monsoon years only when downdrafts are included in convection scheme (Fig. 12b and 13b). It is erroneously more in weak monsoon years compared to strong monsoon years without downdrafts (Fig. 12a and 13a). The stronger monsoon of 1988 compared to 1987 is clearly seen in Xie-Arkin data, and is very much similar to the simulated difference (1988–1987) with downdrafts. However, Xie-Arkin data shows more precipitation in 1994 compared to 1991 only over north India, whereas the model with

(1983–1982) JJAS wind at 850hPa

Fig. 8. Difference (1983–1982) of JJAS wind at 850 hPa (a) without downdrafts (b) with downdrafts (c) NCEP reanalysis.

(1988–1987) JJAS wind at 850hPa

Fig. 9. Difference (1988–1987) of JJAS wind at 850 hPa (a) without downdrafts (b) with downdrafts (c) NCEP reanalysis.

(1994–1991) JJAS wind at 850hPa

Fig. 10. Difference (1994–1991) of JJAS wind at 850 hPa (a) without downdrafts (b) with downdrafts (c) NCEP reanalysis.

Fig. 11. Difference (1983–1982) of JJAS precipitation (a) without downdrafts (b) with downdrafts (c) Xie-Arkin data.

Fig. 12. Difference (1988–1987) of JJAS precipitation (a) without downdrafts (b) with downdrafts (c) Xie-Arkin data.

Fig. 13. Difference (1994–1991) of JJAS precipitation (a) without downdrafts (b) with downdrafts (c) Xie-Arkin data.

downdrafts simulated a stronger monsoon in 1994 compared to 1991 over peninsular India.

The summer monsoon precipitation over India varies on an intraseasonal scale which also contributes to interannual variability. To gain insight into the intraseasonal variability simulated by the model and impact of downdrafts on the intraseasonal variability, time series of precipitation averaged over 65–95E, 5–30N for 1982, 1983, 1987, 1988, 1991 and 1994 with and without downdrafts is shown in Figs. 14a, 14b, 14c, 14d, 14e and 14f. The figures indicate that spells of active and ‘break’ or weak monsoon situations are more prominently simulated when downdrafts are included. The precipitation over the region in all years is increased with the inclusion of downdrafts in June, July and August. In September there is not much difference between the time series with and without downdrafts. In strong monsoon years (1983, 1988 and 1994), there is a large difference between the time series of precipitation with and without downdrafts. This shows that impact of downdrafts in strong monsoon years is more compared to weak monsoon years.

Cumulative precipitation during summer monsoon season averaged over region 65E–95E, 5N–30N over land grid points of the model is given in Table 1. For comparison, observed all India summer monsoon rainfall (Parthasarathy, 1995) has been given for the corresponding years. The precipitation increases with the inclusion of downdrafts in all years except 1987. In El Niño years (1982, 1987, 1991 and 1994), the model overestimates precipitation (except for the case of 1994), whereas in La Niña year 1988 and normal year 1984, the model underestimates it. Differences in precipitation (1983–1982), and (1994–1991), is not correctly simulated even with the inclusion of downdrafts. However, downdrafts reduce the difference in precipitation for these two pairs of years, showing improvement in simulation. Larger precipitation in 1988 compared to 1987 is simulated only with the inclusion of downdrafts.

4.3 Impact on transient disturbances during the monsoon season

A good part of the rainfall during the monsoon season is generated by westward passage of transient disturbances forming over the Bay of Bengal. These transient disturbances are lows or depressions. Sometimes disturbances also form over the Arabian sea. Monsoon depressions are low pressure systems with 2 or 3 closed isobars (at 2 mb intervals) and wind speed ranging between 8.5–13.5 m/sec. Weaker systems with only one closed isobar and wind speeds less than 8.5 m/sec are called lows (Y.P. Rao, 1976). During the monsoon season series of lows or depressions form over the north Bay of Bengal, move in westnorthwesterly or westerly direction across the country and give widespread rains

in the southwest quadrant with many heavy falls. Occasionally they take a more northerly course, and break up over the Himalayan mountains. Low pressure areas can also form over land in the monsoon trough region.

The HC model is able to simulate these disturbances (Ashok *et al.*, 1998a; 1998b) during the monsoon season. To study the impact of downdrafts in the convection scheme on these disturbances simulated by the model, number of lows and depressions during 1982, 1983, 1984, 1987, 1988, 1991 and 1994 in the experiments with and without downdrafts are presented in Table 2. These monsoon disturbances are counted over the area 30–120E, 0–40N and with the time interval of 1-day. Examination of the table shows that the total number of systems simulated by the model is more when downdrafts are included in the convection scheme. The increase in the number of strong systems simulated is large. During the 7 monsoon seasons under study, simulations without downdraft generated 6 systems with 2 or more closed isobars, while simulations with downdrafts had 18 such systems.

5. Conclusions

The sensitivity of mean and IAV of monsoon simulated by HC Climate Model to changes in the parameterisation of cumulus convection is examined. The GCM was integrated for 7 monsoon seasons with, and without, the inclusion of convective downdrafts.

The mean monsoon low level flow through the Indian Ocean and across the Indian subcontinent is simulated reasonably well in both experiments with and without downdrafts. However, the earlier version of the model without downdrafts had a systematic error by which the monsoon westerlies extended deep into the west Pacific ocean. With the inclusion of downdrafts this error was substantially reduced. The lower tropospheric monsoon flow over the north Indian ocean strengthened with the inclusion of downdrafts. The position of monsoon trough is correctly simulated with the downdrafts. The TEJ simulated with downdrafts is closer to NCEP reanalysis.

The location and magnitude of the precipitation maximum off the west coast of India, and over the Bay of Bengal is correctly simulated with inclusion of downdrafts. Downdrafts improve the precipitation over India and also reduces excessive precipitation over the equatorial Indian Ocean, between 60°E and 90°E and over the northwest Pacific ocean.

The sign of circulation differences between pairs of weak and strong monsoon years is correctly simulated for 1991 and 1994 when downdrafts are included in convection parameterisation. The model failed to simulate stronger monsoon circulation of 1983 compared to 1982 and 1988 compared to 1987 in both experiments with and without downdrafts.

Time series of precip. rate averaged over(65–95E, 5–30N)

Fig. 14. Time series of total precipitation rate averaged over 65–95E, 5–30N without and with downdrafts (a) 1982 (b) 1983 (c) 1987 (d) 1988 (e) 1991 and (f) 1994.

This appears to be due to a systematic error in the model's sensitivity to strong El Niño/La Niña. Precipitation differences between pairs of strong and weak monsoon years is closer to observed differences with the inclusion of downdrafts.

Time series of precipitation averaged over 65–95E, 5–30N suggest that there is an increase in precipitation over India with the inclusion of downdrafts in June, July and August. Spells of active and break or weak monsoon situations are more prominently sim-

Table 1. JJAS precipitation (mm) averaged over (65E–95E, 5N–30N).

Year	Model		Observed (Parthasarathy, 1995)
	Without downdrafts	with downdrafts	
1982	765.5	898.0	735.4
1983	568.1	792.4	955.7
1984	584.0	747.0	836.7
1987	761.8	745.1	697.3
1988	633.8	845.3	961.5
1991	814.5	939.9	784.5
1994	538.4	872.5	938.1

Table 2. Number of lows/depressions.

Year	No. of systems with 1 closed isobar		No. of systems with 2 or more closed isobars	
	without downdrafts	with downdrafts	without downdrafts	with downdrafts
1982	5	6	0	4
1983	4	5	1	2
1984	4	9	0	0
1987	2	2	0	1
1988	3	7	0	2
1991	8	7	3	5
1994	5	1	2	4
total	31	37	6	18

ulated when downdrafts are included. It is also seen that the impact of downdrafts is more during strong monsoon years (1983, 1988, 1994) than in weak monsoon years (1982, 1987, 1991). A larger number of strong synoptic disturbances are simulated over India when convection includes downdrafts.

The inclusion of downdrafts did not completely overcome the systematic error of the model, by which it simulates stonger monsoon during El Niño years. However, this error is considerably reduced . On the whole, implementation of downdrafts in the convection scheme has significantly improved both the mean monsoon and its variability.

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GCM でシミュレートされたインド モンスーンとその変動に対する 積雲対流ダウンドラフトの効果

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ハドレーセンターの気候モデルによってシミュレートされたインドモンスーンとその変動の積雲対流スキームの違いに対する感度を、対流スキームがダウンドラフトを含む場合と含まない場合を比較することによって調べた。1982、1983、1984、1987、1988、1991 及び 1994 年の 7 年のモンスーン期間のシミュレーションを行った。これらの年は、インドのモンスーンの降水量の平年偏差が大きい年を選んだ。シミュレーションの結果を、NCEP の再解析データの循環場及び Xie-Arkin の降水量のデータと比較した。

モデルの結果を解析した結果、ダウンドラフトを入れることにより、モデルのモンスーンのシミュレーションの系統誤差のいくつかが小さくなることが示された。モンスーンの下層西風が大西洋の奥深くまで侵入するという系統誤差は、ダウンドラフトを入れることにより顕著に小さくなる。北インド洋の対流圏下層のモンスーン流もダウンドラフトを入れると強くなる。TEJ (熱帯東風ジェット) はダウンドラフトを含むモデルの方が NCEP の再解析に近い。ダウンドラフトを入れることにより、インド陸上の降水及びモンスーントラフの位置が改善される。ダウンドラフトを含まない場合は、西赤道インド洋での降水が少ない。ダウンドラフトを入れると、地表面での潜熱フラックスが増加する。ラニーニャ年よりエルニーニョ年に下層の循環を強くシミュレートするという系統誤差は、ダウンドラフトを入れることにより、完全になくはしないが、小さくなる。モンスーン降水量の年々変動はダウンドラフトを入れた方が実際に近い。モンスーンの活発期と休止期 (弱い期間) は、ダウンドラフトを含む方がはっきりとシミュレートされる。より多くの強いシノプティックスケールのじょう乱がダウンドラフトを含む場合にシミュレートされる。