

# Simulation and Predictability of Monsoons

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## 1. Introduction

The purpose of this paper is to present three results concerning the simulation and predictability of the Asian summer monsoon. In section 2, we show that the annual cycle of SST is just as important as the annual cycle of solar forcing in the establishment of the Asian summer monsoon circulation and rainfall over India and the adjoining regions. In section 3 we show that the ability of The Center for Ocean-Land-Atmosphere Studies (COLA) general circulation model (GCM) to simulate the interannual variability of monsoon rainfall over India due to global SST anomalies during 1987 and 1988 depends upon the model's ability to simulate the mean monsoon circulation. In section 4 we show that the rainfall difference over India simulated in response to the observed global SST for JJA (1988 - 1987) is not highly sensitive to the atmospheric initial conditions used.

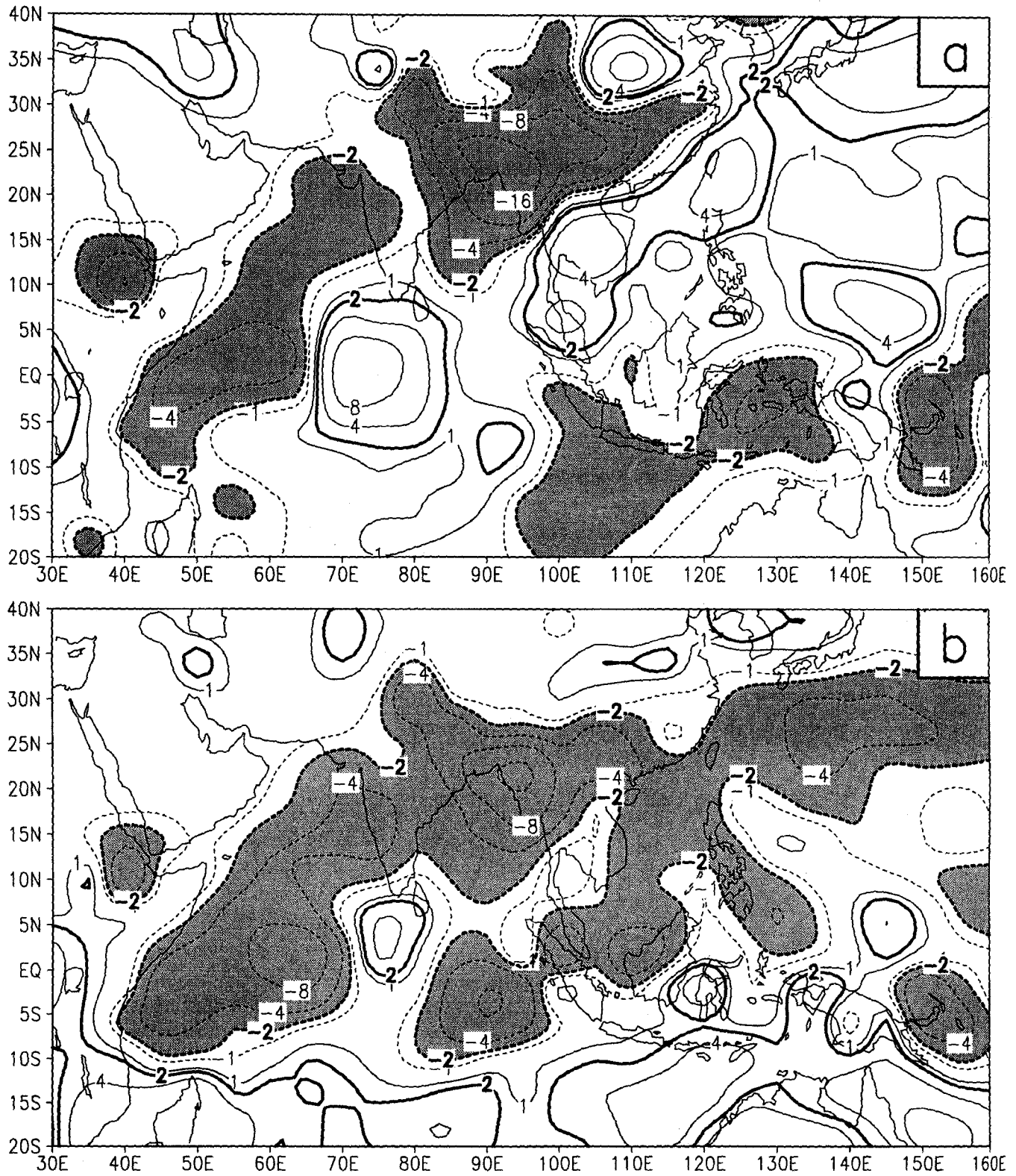
## 2. Role of the annual cycle of solar forcing and SST in the establishment of the Asian monsoon.

The Asian summer monsoon is one of the most dramatic examples of the annual cycle of the coupled ocean-land-atmosphere system. The annual cycle of the solar forcing and the associated heating of the land masses is generally considered to be the most important forcing for the Asian monsoon circulation. However, observations show that with the advancement of the season, the regions of warmest SST in the Indian and Pacific Oceans also advance northward. We wish to investigate the role of the annual cycle of SST in the establishment of the monsoon. In particular we would like to investigate the roles of solar forcing over land and ocean separately. This will necessarily be a hypothetical experiment, because in nature heating of the both the continents and the oceans is caused by the annual cycle of the solar forcing.

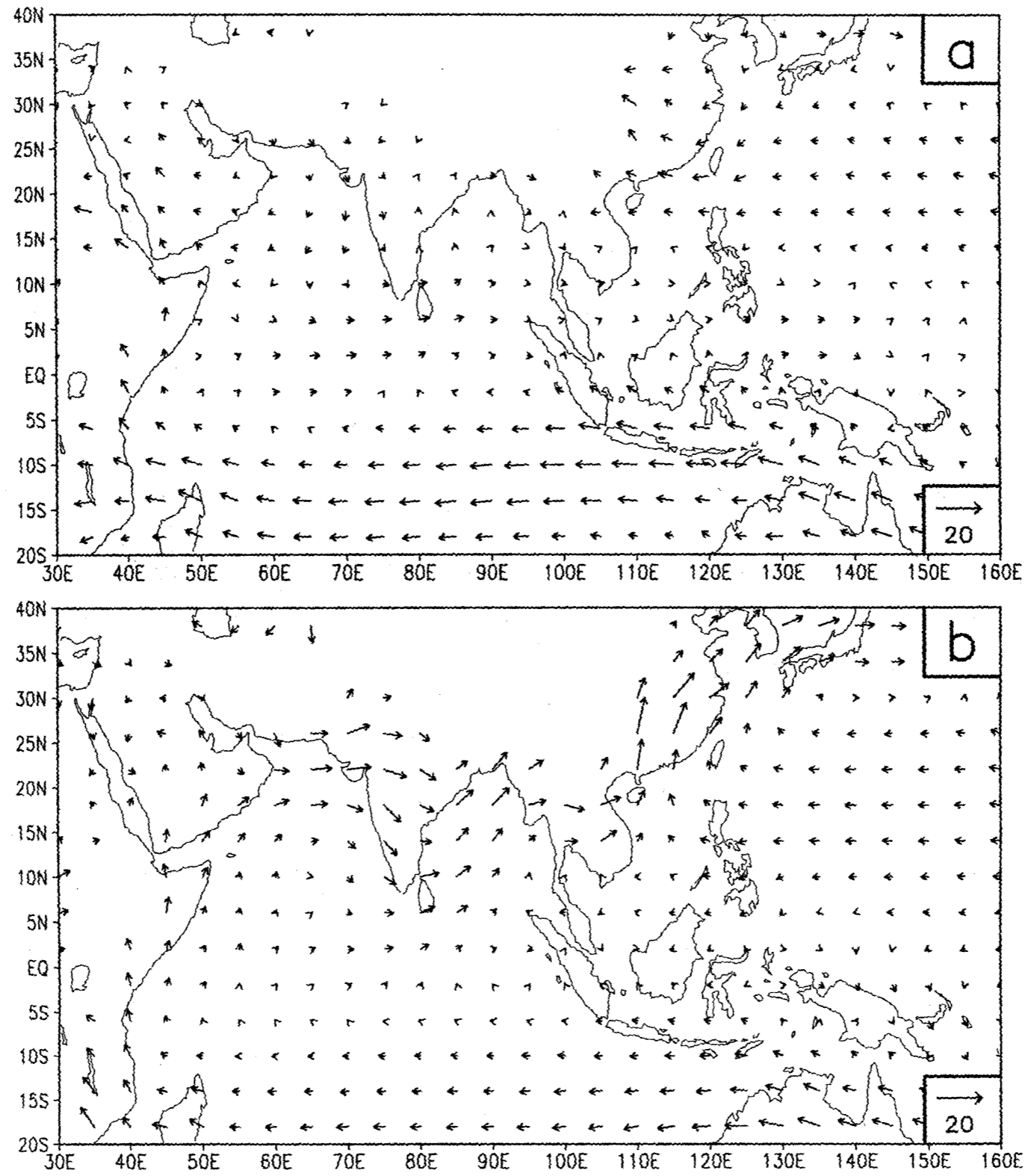
We carry out three integrations with the COLA GCM, all of which are integrated through the boreal summer, ending on 1 September. The control integration is initialized on 1 January, 1987 and uses prescribed seasonally varying climatological SST and seasonally varying solar forcing. The FIXED SUN integration is initialized on 1 March, 1987 and uses prescribed seasonally varying climatological SST, but the solar forcing is fixed at 21 March values throughout the course of the integration. The FIXED SST integration is initialized on 1 March, 1987 and uses normal seasonally varying solar forcing, but the SST is fixed at 1 March climatological values throughout the course of the integration. The global climatological SST (and sea ice) used for all three integrations is that of Reynolds and Roberts (1987).

The simulated anomalies (relative to the control integration) of the FIXED SUN and FIXED SST integrations are analyzed for the boreal summer period. The JJA mean precipitation anomaly for the FIXED SUN integration is shown in Fig. 1a, and for the FIXED SST integration is shown in Fig. 1b. In both integrations there is a dramatic reduction in the monsoon rainfall over the Arabian Sea, India, the Bay of Bengal and SE Asia. This reduction reaches a magnitude of  $16 \text{ mm day}^{-1}$  over Bangladesh in both integrations. There is also a nearly complete collapse of the monsoon flow and the Somali Jet, evident in the JJA mean 850 mb wind field for the FIXED SUN integration (Fig. 2a) and the FIXED SST integration (Fig. 2b).

These results clearly show that the annual cycle of SST is crucially important for the



1. JJA precipitation anomaly for (a) FIXED SUN and (b) FIXED SST. Contours are  $\pm 1, 2, 4, 8, 16 \text{ mm day}^{-1}$ . Dashed contours are negative. Below  $-2 \text{ mm day}^{-1}$  shaded.



2. JJA 850 mb wind anomaly for (a) FIXED SUN and (b) FIXED SST. Vector at bottom denotes magnitude in  $\text{m s}^{-1}$ .

establishment of the monsoon circulation and rainfall. This is particularly relevant for the modeling of the couple climate system. If a coupled ocean-atmosphere model is not capable of simulating the observed annual cycle of SST, the simulated monsoon circulation could be highly deficient.

### **3. Dependence of a GCM's ability to simulate the interannual variability of the monsoon on its ability to simulate the mean monsoon**

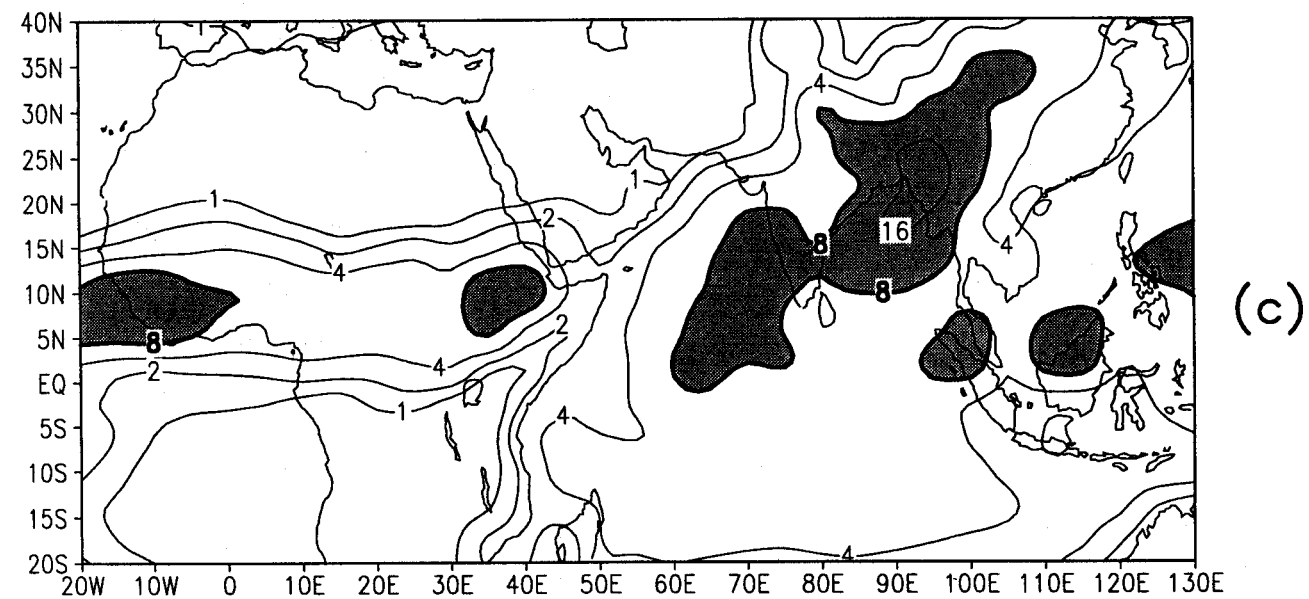
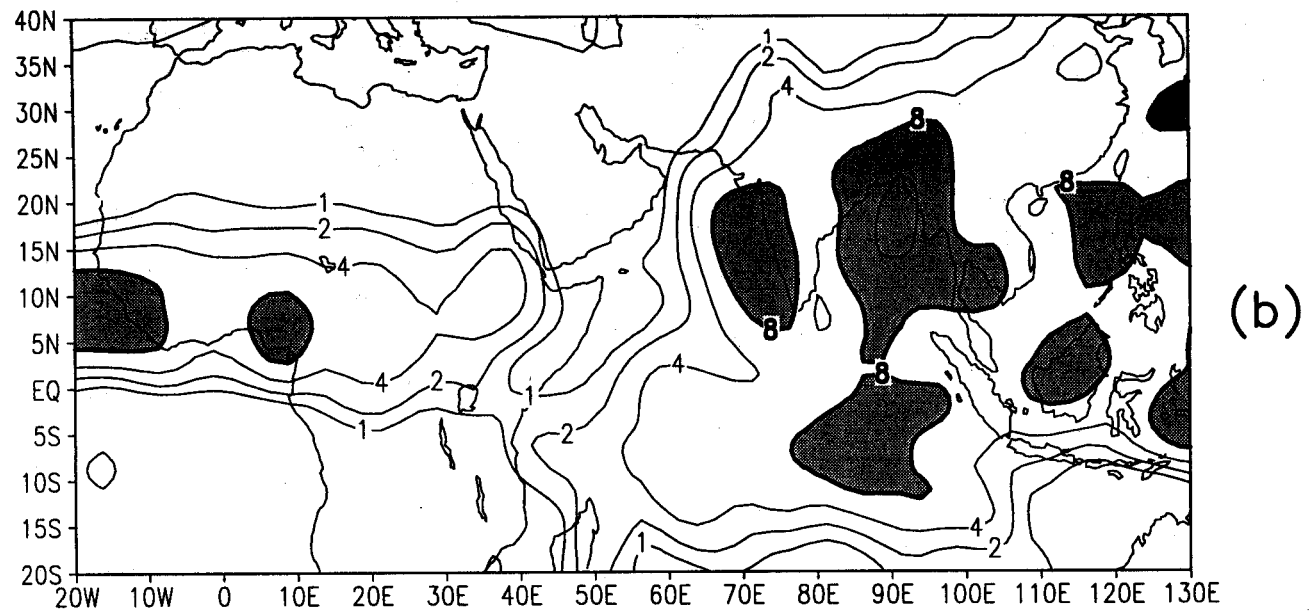
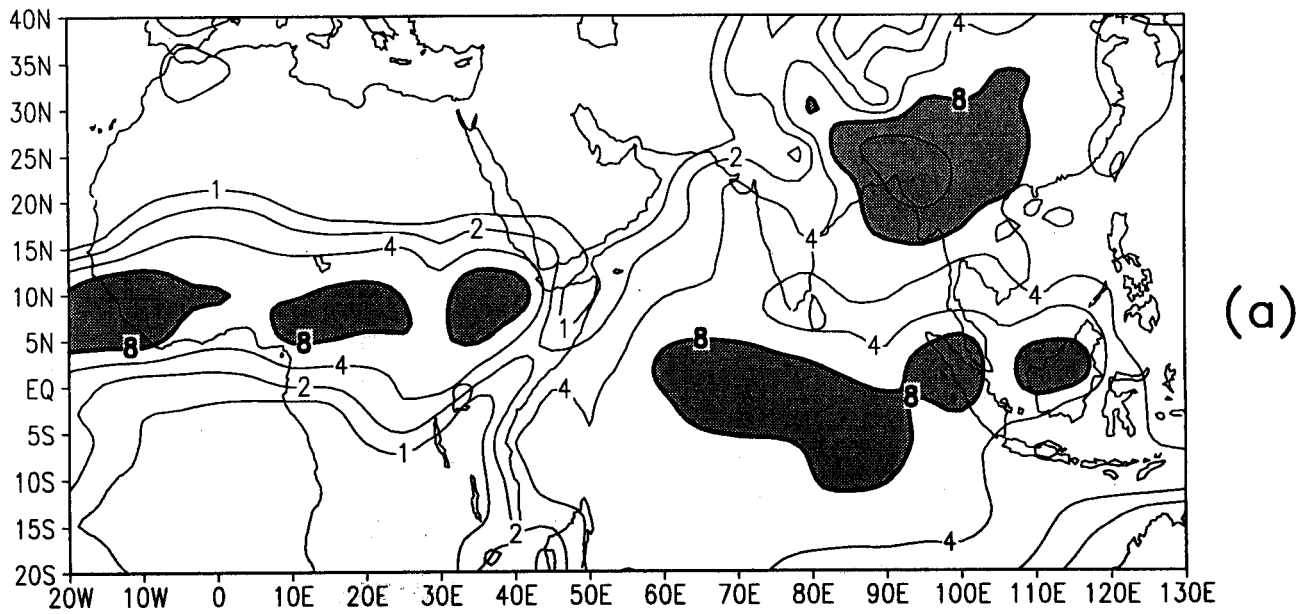
The summer monsoon rainfall over India was significantly below normal during 1987, and above normal during 1988. The tropical Pacific sea surface temperature (SST) was significantly below normal during 1988 and above normal during 1987. Thus, the simulation of 1988-1987 monsoon rainfall anomalies provides an ideal case to test the hypothesis of Charney and Shukla (1981) on the influence of boundary conditions on monsoon predictability.

Using an earlier version of the COLA GCM, to be referred to as the OLD model, Fennessy and Shukla (1990) carried out six 90 days integrations, starting from the observed initial state of the atmosphere on 1,2,3 June, 1987 and 1,2,3 June, 1988, using the observed time-varying SST (Reynolds, 1988). These six integrations were repeated using seasonally varying climatological SST (Reynolds and Roberts, 1987). The simulated June-July-August seasonal mean (JJA) rainfall anomalies formed by taking the difference between the observed SST ensembles and the climatological SST ensembles in each year were compared to the anomalies observed over India in 1987 and 1988. This comparison showed that even with the observed global SST the model was unable to simulate what could be considered to be two of the largest Indian monsoon rainfall anomalies of the century.

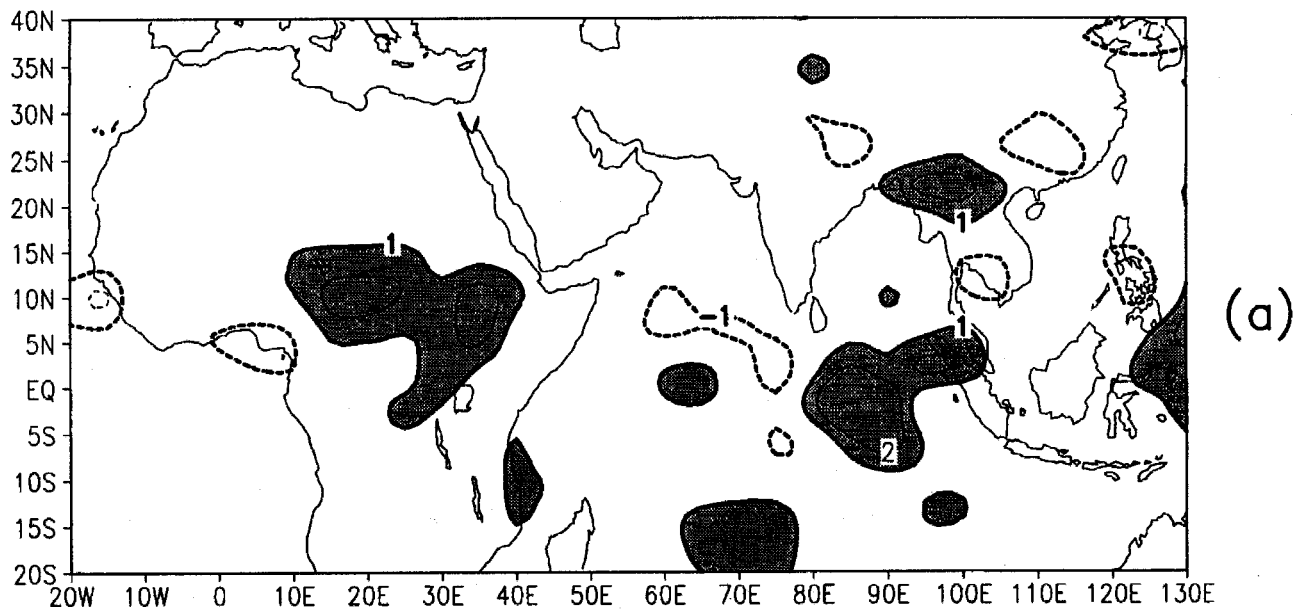
There are two possible interpretations of this result: one, that the mean climate of the model was too unrealistic to be sensitive to the influence of the boundary conditions, or, two, that the monsoon fluctuations are not sensitive to the global SST anomalies, and especially the tropical Pacific SST anomalies which were quite large during 1987 and 1988. Rather than abandoning the hypothesis of the influence of boundary conditions on monsoons, which is further supported by the results of Palmer et al. (1992) and Mo (1992), we decided to improve the simulation of the mean climate of the model. As described in Fennessy et al., 1994, we carried out a large number of sensitivity studies involving changes in vegetation, soil wetness, cloudiness and the representation of orography. We found that the replacement of the enhanced silhouette orography in the OLD model by a mean orography more representative of the actual terrain heights produced a more realistic simulation of the monsoon rainfall. The COLA model using the mean orography will be referred to as the NEW model. A description of the model formulation is given by Fennessy et al., 1994.

We repeated the twelve 90 day integrations for 1987 and 1988 with the NEW model. Figure 3a shows the monsoon region JJA 1988 mean rainfall for the OLD model and Fig. 3b shows the corresponding observed rainfall. The observed precipitation field is a combination of the Global Precipitation Climatology Center [of the Global Precipitation Climatology Project, Janowiak and Arkin (1991)] gridded station data over land, and precipitation derived from microwave sounding unit satellite data over ocean (Spencer, 1993). Figure 3c shows the NEW model result. The mean monsoon rainfall over India is highly deficient in the OLD model, but well simulated in the NEW model..

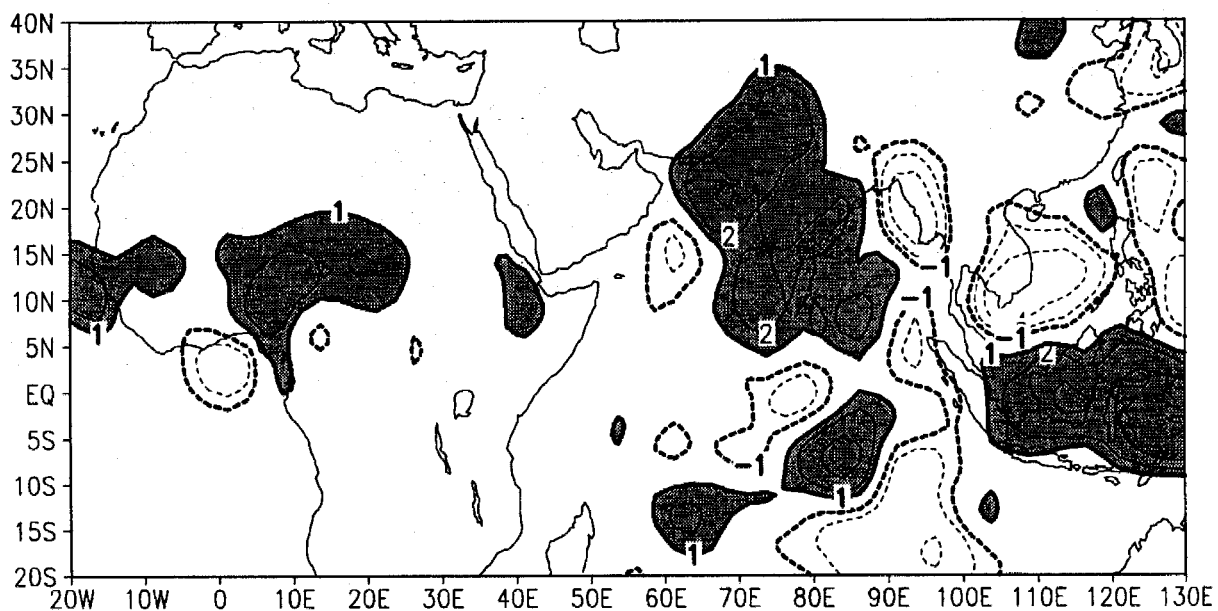
Figures 4a, 4b, and 4c show the JJA 1988 minus JJA 1987 rainfall difference for the OLD model, the observations and the NEW model. The OLD model did not simulate the observed rainfall anomalies over India. The simulated rainfall anomalies over the entire Asiatic monsoon



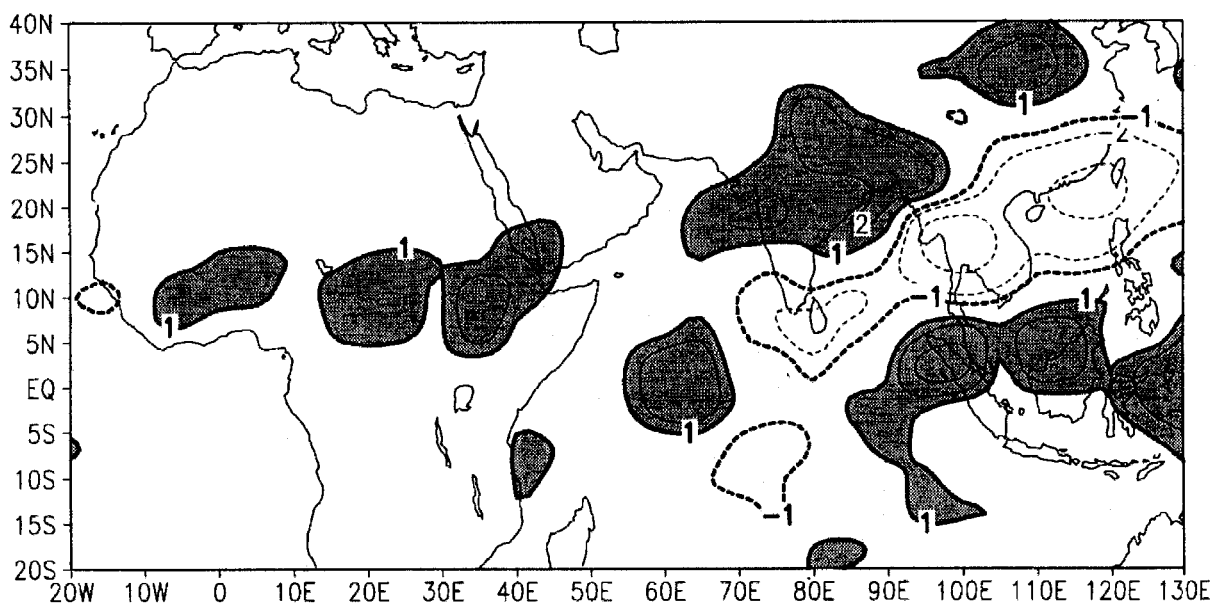
3. JJA 1988 mean precipitation for (a) OLD GCM ensemble, (b) observations (see text) and (c) NEW GCM ensemble. Contours are 1, 2, 4, 8, 16 mm day<sup>-1</sup>. Above 8 mm day<sup>-1</sup> shaded.



(a)



(b)



(c)

4. JJA 1988 - 1987 precipitation difference for (a) OLD GCM ensemble, (b) observations (see text) and (c) NEW GCM ensemble. Contours are  $\pm 1, 2, 4 \text{ mm day}^{-1}$ . Dashed contours are negative. Above  $1 \text{ mm day}^{-1}$  shaded.

region, and especially over India, are far more realistic with the NEW model. It should be reiterated that both the OLD and the NEW models used identical initial and boundary conditions.

We have presented an example here that clearly shows that the model's ability to simulate the differences in the 1988 and the 1987 monsoon rainfall crucially depended on the realism of the simulated mean climate itself. The traditional view that even if the mean climate of a model is inaccurate, the anomalies can be simulated correctly is found to be invalid for the simulation of monsoon rainfall anomalies over India.

#### 4. Dependence on initial conditions

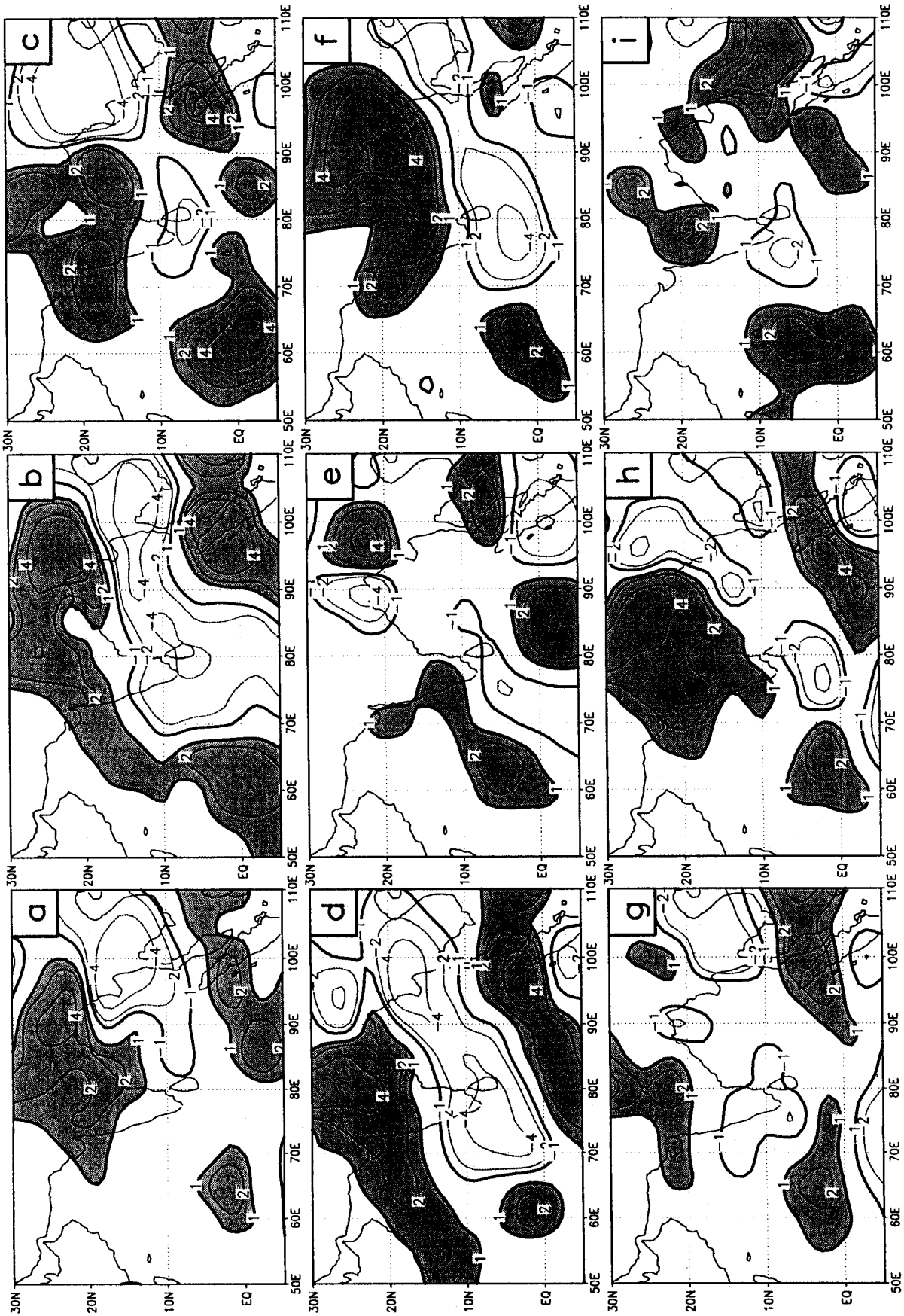
Figures 5a through 5i show 9 different simulated JJA mean precipitation differences for the Indian monsoon region. In each case the precipitation from an integration done using observed time-varying global SST for 1987 is subtracted from the precipitation from an integration done using observed time-varying global SST for 1988 (Reynolds, 1988). Otherwise, the only other differences among the 18 integrations are the observed atmospheric conditions used for initialization, the dates of which are given in Table 1.

TABLE 1. For each precipitation difference presented in Fig. 5 (a through i), the date of the atmospheric conditions used to initiate the integration with 1988 SST, and with 1987 SST.

Fig. 5	88 SST Initiation Date	87 SST Initiation Date
a	1 June 1988	1 June 1987
b	2 June 1988	2 June 1987
c	3 June 1988	3 June 1987
d	1 June 1986	1 June 1986
e	1 June 1989	1 June 1989
f	1 June 1990	1 June 1990
g	1 June 1991	1 June 1991
h	1 June 1992	1 June 1992
i	1 June 1993	1 June 1993

Despite the wide range of initial conditions used in the 18 integrations, the JJA mean rainfall anomalies simulated over India with 1988 SST minus 1987 SST are remarkably comparable in eight of the nine cases. Furthermore, the JJA ensemble mean difference of the last 6 random initial condition cases (Figs. 5d - 5i, ensemble not shown), is nearly indistinguishable from the JJA ensemble mean of the first 3 cases which used realistic initial conditions (Figs. 5a - 5c, ensemble is Fig. 4c).

This suggests that for this set of boundary conditions and for this model, the simulated interannual variability does not have much sensitivity to the initial atmospheric conditions.



5. JJA mean precipitation difference for 1988 SST - 1987 SST for initial atmospheric conditions of (a) 1 June 1988 - 1 June 1987, (b) 2 June 1988 - 2 June 1987, (c) 3 June 1988 - 3 June 1987, (d) 1 June 1988, (e) 1 June 1989, (f) 1 June 1990, (g) 1 June 1991, (h) 1 June 1992 and (i) 1 June 1993. Contours are  $\pm 1, 2, 4$  mm day<sup>-1</sup>. Above 1 mm day<sup>-1</sup> shaded.



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