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ENSO-Monsoon relationships in a greenhouse warming scenario

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Abstract. Recent studies based on observed climatic data indicate weakening of the relationship between El Niño-Southern Oscillation (ENSO) and Indian summer monsoon rainfall, possibly due to global warming. Transient climate change simulations of a coupled ocean-atmosphere GCM (ECHAM4/OPYC3) project a change towards enhanced ENSO activities in the tropical Pacific, as well as increase in mean monsoon rainfall and variability over India. However, the interannual correlations between the two are strong throughout the 240 year simulation. Analysis of monsoon viz-a-viz ENSO in the model simulations suggest a diminished impact of warm ENSO (El Niño) events on monsoon, while the impact of cold ENSO (La Niña) events remains unchanged in the scenario. Anomalous warming over the Eurasian landmass as well as enhanced moisture conditions over the Indian monsoon region in the global warming scenario have possibly contributed to the weakening of the impact of warm ENSO events on monsoon.

Introduction

El Niño-Southern Oscillation (ENSO) is known to be a strong large-scale forcing for the interannual variability of monsoon rainfall (drought conditions over India accompany warm ENSO events and vice versa). However, in the recent past there were two major ENSO events (the longest 1991-1995 and the strongest 1997) but none was accompanied by large-scale drought conditions over India. Thus the climate during the 1990's attracted great attention towards possible changes in ENSO-monsoon association.

The ENSO-monsoon teleconnections discussed in several studies (Pant and Parthasarathy, 1981; Rasmusson and Carpenter, 1983), involve significant simultaneous relationship between monsoon rainfall and various ENSO indices. Precursors of ENSO evolution have been widely used as predictors for seasonal forecasting of monsoon rainfall over India (Krishna Kumar *et al.*, 1995). However, there are evidences of considerable secular variations in ENSO-monsoon association possibly due to (i) epochal variations in monsoon rainfall (Kripalani and Kulkarni, 1997) and (ii) changes in the ENSO characteristics (Parthasarathy *et al.*, 1991; Krishna Kumar *et al.*, 1999a). Krishna Kumar *et al.* (1999b) provide observational evidence indicating the possible role of global warming in the weakening of ENSO-monsoon relationship in recent decades.

Meehl and Washington (1996) have shown in a simulation study that increasing concentration of atmospheric CO_2 leads to increase in sea surface temperature (SST) via cloud cover and cloud albedo feedback. This warming is greatest east of 180° longitude in the tropical Pacific accompanied by shifts in large-scale rainfall and circulation. These anomalies are reported to resemble some aspects of El Niño, particularly the events of the 1990's. Transient climate change simulations of coupled Ocean-Atmosphere General Circulation Model (ECHAM4/OPYC3) project a change towards an El Niño-like mean SST state with increased variability leading to increased number of extremes, with a strong skewness towards cold events (Timmermann *et al.*, 1999).

There have been several model-based studies showing intensification of monsoon rainfall in response to increasing concentration of atmospheric CO_2. Zhao and Kellog (1988) compared the response of monsoon to a doubling of CO_2 in five coupled models, and concluded that wetter summer conditions were likely to occur over India and south-east Asia. Using a coupled model Meehl and Washington (1993) reported an increase in the mean as well as the variability of Indian summer monsoon rainfall under doubled CO_2 conditions, and attributed it to stronger warming of land compared to the ocean. In a transient climate change simulation, Bhaskaran *et al.* (1995) found intensification of monsoon along with a northward shift in the monsoon circulation, which was also partly attributed to greater warming of land compared to ocean. Using ECHAM4/OPYC3 climate change simulations, Hu *et al.* (2000) have reported an intensification of mean monsoon rainfall and variability. In some studies using transient (Kitoh *et al.*, 1997) and time-slice (Douville *et al.*, 2000) climate change experiments, an intensification of monsoon rainfall was noted to be associated with greenhouse warming, despite weakening of winds. Douville *et al.* (2000) argue that this apparent paradox may be mainly due to increased atmospheric moisture in the warming scenario.

The present study examines the impact of increasing greenhouse gas concentration on ENSO-monsoon association, using the transient climate change simulations of coupled atmosphere-ocean GCM ECHAM4/OPYC3 of Max-Planck-Institute fur Meteorologie (MPI), Hamburg, Germany (referred to as MPI model hereafter). Several observational studies have indicated that the correlation between the all-India monsoon rainfall and Niño3 (5°S - 5°N, 150°W - 90°W) SST is concurrent and even follows the monsoon season (Krishna Kumar *et al*, 1995), attaining a peak during the autumn (SON) season. Keeping this in view, the present study uses the relation between Niño3 surface air temperatures (SON) and monsoon rainfall to represent ENSO-monsoon association.

The Transient Climate Change Experiments of MPI Model.

The climate change experiments of the MPI model (Roeckner *et al.*, 1999) include a multi-century control integration (CTL) with a constant atmospheric forcing (CO_2, CH_4 and N_2O fixed at the observed 1990 values), climatological aero-

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sols and ozone with no anthropogenic sulfur cycle. A 100-year spin-up, with constant flux adjustment, followed by another 300 years of simulation gives climatology that serves as a reference for the time-dependent forcing experiments. The greenhouse gas integration (GHG) uses the forcing that represents the observed changes due to all the greenhouse gases from 1860 to 1990 and IS92a emission scenario thereafter.

Data

The present study uses data on monthly rainfall, surface air temperature, tropospheric winds (u,v) and specific humidity (at 850 and 200 hPa) from the MPI model simulations. Rainfall and temperature data have been obtained from the IPCC-Data Distribution Centre (IPCC-DDC). The upper air data on humidity and winds have been obtained from (MPI), Hamburg, Germany. All-India monsoon rainfall series has been obtained by averaging the rainfall over land grid points over India, for the monsoon season, June-September (JJAS). Similarly, the autumn (SON) seasonal mean surface air temperature series, averaged over the Niño3 region, has been used to represent ENSO.

Characteristics of monsoon rainfall and ENSO in the MPI model simulations

Validation of the MPI model simulations of the climate over Indian region and the associated sensitivity aspects are discussed by Rupa Kumar and Ashrit (2000). It is found that the model underestimates summer monsoon rainfall and shows a higher interannual variability when compared to the observations. However, the simulated mean annual cycle of precipitation and the dominant modes of variability are comparable with the observations.

The model simulations over tropical Pacific suggest a change towards warmer mean state in Niño3 temperatures and enhanced variability (Figure. 1a,b). Simulated monsoon rainfall over India also shows a change towards higher mean state with increased variability (Figure. 1c,d and Table 1.). The long-period correlation between monsoon rainfall and the Niño3 temperatures shows a drastic change from -0.60 during 1860-1979 to -0.07 during 1980-2099, indicating a break-

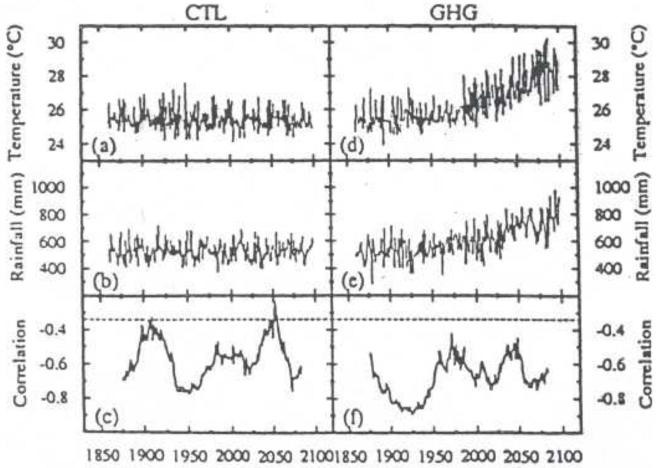

Figure 1. Variation of (a) Niño3 SST (SON), (b) all-India summer monsoon (JJAS) rainfall and (c) their 31-point sliding correlation in MPI model simulation during 1860-2099, for the CTL case. The panels (d), (e) and (f) indicate the same as (a), (b) and (c) respectively, but for the GHG case. (dashed line in (c) and (f) indicates 5% significance level).

Table 1. Simulated all-India monsoon rainfall statistics

	P1:1860-1919	P2:1920-1979	P3:1980-2039	P4:2040-2099
	Mean Monsoon rainfall (mm/season)			
CTL	530	534	524	536
GHG	531	541	614	740
	Standard Deviation (mm/season)			
CTL	80	73	79	61
GHG	83	82	98	96

down in the ENSO-Monsoon relation. This is apparently due to the trends in the two series opposing the interannual relationship. Indeed, the correlations over 31-point sliding windows, after removing the linear trends in both the series, are strong throughout the 240-year simulation indicating the continued presence of a strong inverse relationship into the future (Figure. 1e,f). The apparent conflict between interannual and long-term aspects of the ENSO-Monsoon relationship could be due to the dynamical and non-dynamical components of monsoon system responding differently to the associated forcings (Stephenson *et al.*, 2000).

El Niño and La Niña composites of monsoon anomalies

The spatial patterns of monsoon rainfall anomalies composited for the El Niño (La Niña) years in the historical record show widespread deficient (excess) rainfall all over India (Pant and Rupa Kumar, 1997). In the present study, similar composite analysis is done on the Indian summer monsoon, by identifying warm/cold ENSO events based on the simulated Niño3 temperatures. Since the Niño3 temperature series has a strong long-term trend in the GHG scenario, analysis is carried out by dividing the total period into four equal parts (P1: 1860-1919, P2: 1920-1979, P3: 1980-2039, P4: 2040-2099). Initially, El Niño and La Niña years have been identified based on the exceedance of the Niño3 surface air temperature anomalies above/below one standard deviation during the corresponding period. However, due to the presence of strong skewness in the series, this approach yielded a highly varying number of El Niño and La Niña events in different sub-periods. The composites of monsoon rainfall anomalies based on the standard deviation criterion are therefore not comparable across the four periods, because of marked differences in the sample size. Further, due to the increasing trend in the series, all warm anomalies tend to occur in the latter half of the concerned period while all cold anomalies tend to occur in the first half. To ensure an even distribution of the El Niño/La Niña events identified for compositing, the 240-year series was divided into 16 sub-periods of 15 years each and the warmest year was identified as an El Niño and coldest as La Niña in each of these 16 sub-periods. Monsoon rainfall anomaly for the warmest year was computed relative to 15 years average in each of the sub-periods to obtain a set of 16 El Niño-related monsoon rainfall anomalies. Similarly 16 monsoon rainfall anomalies from years representing La Niña conditions were also obtained. Both these anomalies, in terms of all-India summer monsoon rainfall, are shown in Figure 2a,b for both CTL and GHG cases. In the case of CTL, the El Niño related monsoon rainfall anomalies show no trend, indicating a stable response of the model to a fixed greenhouse gas forcing corresponding to 1990. On the other hand, the El Niño related rainfall anomalies in GHG indicate a clear trend suggesting diminishing impact of the warm conditions on the monsoon rainfall as the greenhouse

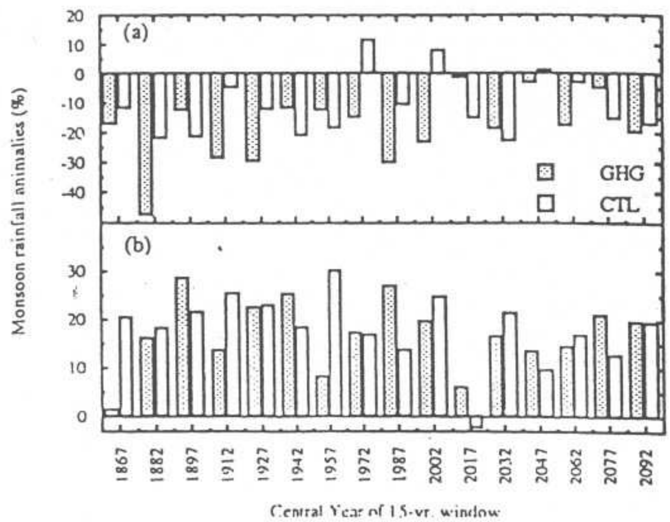

Figure 2. All-India summer monsoon rainfall anomalies in (a) El Niño (b) La Niña conditions in the CTL and GHG simulations.

gas forcings are compounded. It is interesting to note that the rainfall anomalies in CTL are generally weaker than those in GHG, particularly before the 1980's. In the GHG simulation during the period prior to 1980's changes in forcing represent observed changes in greenhouse gas concentrations, which are at relatively lower levels than that in CTL fixed at 1990 levels. During this period the monsoon rainfall anomalies associated with El Niño are strong and they diminish with changes in the forcing at the observed rate. On the other hand La Niña-related monsoon rainfall anomalies (Figure. 2b) in CTL and GHG are comparable all through the simulation. These anomalies show no remarkable change into the future, except for secular fluctuations. Such a stable response of the monsoon to the cold ENSO events could have contributed to the persistence of strong correlations between monsoon rainfall and the Niño3 temperatures (Figure 1e,f), despite a diminishing impact of warm ENSO events.

To summarize the spatial patterns of the El Niño and La Niña-related rainfall anomalies, four consecutive 15-year sub-periods are combined and the corresponding composites averaged, to obtain composites representing four longer (60-year) sub-periods (P1-P4). Although four cases in 60 years is a conservative estimate of the number of extreme conditions, they are evenly spread in the corresponding sub-periods and hence provide well-represented composites of extreme El Niño/La Niña conditions. The spatial patterns of monsoon rainfall anomalies (Figure 3) for warm ENSO conditions show a diminishing impact of El Niño in the form of decrease in the area under deficient rainfall and also in the magnitude of all-India mean anomalies. However, cold ENSO conditions show no change in the impact on monsoon rainfall anomalies, even in the last 60 years, when the model simulates strong La Niña-type of events. Reduced impact of El Niño on monsoon rainfall during multi-decadal epochs of above-normal monsoon rainfall has also been noted from the observed record of the past century (Kripalani and Kulkarni, 1997).

Enhanced warming over Eurasian region and a southeastward shift in the Walker Circulation anomalies are argued as plausible mechanisms countering the historical monsoon-ENSO inverse relation (Krishna Kumar *et al.*, 1999b). In the model simulation, the changes (P4-P1) in warm ENSO anomaly composites of pre-monsoon Eurasian temperatures (Figure 4a), lower tropospheric monsoon winds (Figure 4b) and specific humidity over the monsoon region (Figure 4c) suggest that enhanced Eurasian warming, stronger monsoon winds and additional moisture buildup have all contributed to the weakening of the impact of warm ENSO events on Indian monsoon. Changes in 200 hPa velocity potential anomalies (Figure 4d,e) indicate a weakening and southeastward shift of subsidence associated with Walker Circulation. However, these changes are not as conspicuous as those in the observations noted earlier by Krishna Kumar *et al.* (1999b).

Conclusions

(1) The GHG climate change simulation of the MPI model shows an increase in the mean monsoon rainfall despite a change towards a warmer mean state of ENSO.
(2) The ENSO-monsoon association, in CTL and GHG simulations is strong, all through the period of the simulations.
(3) The GHG simulation suggests decrease in the impact of El Niño events on monsoon as the greenhouse gas concentrations are increased.

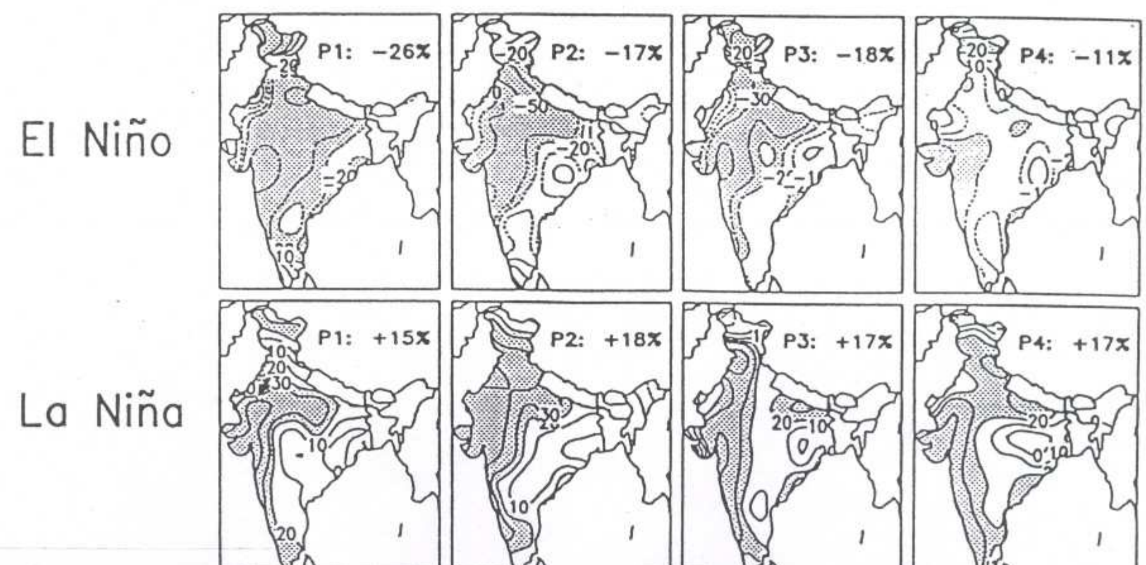

Figure 3. Monsoon rainfall anomalies representing El Niño/La Niña in four sub-periods in the GHG simulations. Spatially averaged anomalies are given on top of each panel.

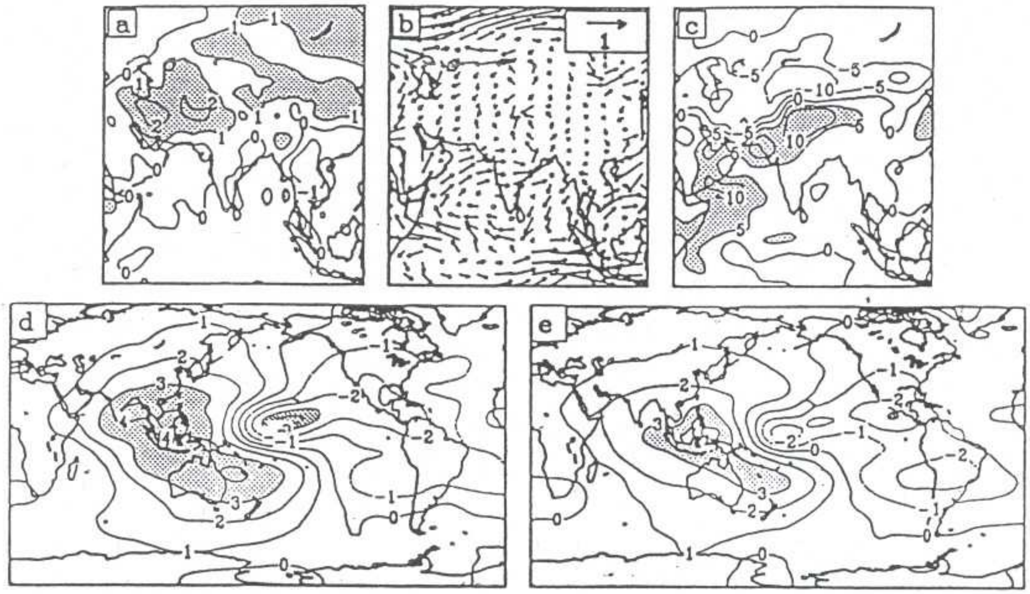

Figure 4. Change (P4-P1) in the warm ENSO anomaly composites of (a) Eurasian temperature (°C) during MAM; (b) 850 hPa winds (ms^{-1}) during JJAS; and (c) 850 hPa specific humidity (% of P1 climatology). The bottom panels show composites of 200 hPa velocity potential (χx 10^6) anomalies during JJAS for P1 (d) and for P4 (e).

(4) The impact of La Niña on monsoon remains largely unchanged, which seems to have maintained strong correlations between monsoon rainfall and Niño3 temperatures.

(5) Enhanced Eurasian warming, stronger monsoon circulation, additional moisture buildup as well as shifts in subsidence patterns associated with Walker circulation seem to have contributed to a weakening of the ENSO-monsoon relationship.

The results presented in this paper are based on the climate change simulations of a single realization of a model, which may not be adequate to generalize the above conclusions. Similar analyses of ENSO-monsoon association in the greenhouse warming scenario using ensembles of models with multiple realizations are required to establish signal-to-noise ratios.

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