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Coupled Multi Model Response of “Active” and “Break” Phases of Indian Summer Monsoon to Enhanced CO_2 Effect

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ABSTRACT

The simulations by number of coupled GCMs under Intergovernmental Panel on Climate Change Assessment Report-4 are used to study implication of possible global climate change on Indian Summer Monsoon. The focus is on variability of Indian Summer Monsoon within the season. The end of 20th century (1981-2000) of Climate of 20th Century (20C3M) simulation is used as control. The simulated daily mean cycle and standard deviation of precipitation over northwest and central Indian region during summer monsoon season of ten models are validated with corresponding observation from Indian Institute of Tropical Meteorology. MIROC3.2 (medres) and MRI-CGCM2.3.2 models capture mean cycle fairly well and CGCM3.1 (T47), ECHO-G, INM-CM3.0 and ECHAM5/MPI-OM models simulate daily variation realistically. Geographical distribution of mean summer monsoon season precipitation indicates that precipitation over northwest and central Indian region in four models (GISS-ER, INM-CM3.0, IPSL-CM4 and ECHO-G) is either very less or absent due to lack of northward progression of monsoon. The gross features of mean monsoon precipitation distribution over India are captured by six models excluding these four models. Thus the active/break spells are identified for six models. Main characteristics of active/break composite precipitation anomaly over India are well depicted by majority of models when compared with observed OLR active/break composite, although models have trouble in simulation of details over larger Asia W. Pacific region.

The sensitivity to climate change has been assessed from the coupled GCMs simulations from two experiments namely, 1% per year CO_2 increase to doubling (1pctto2x) and 1% per year CO_2 increase to quadrupling (1pctto4x). Daily mean cycle and standard deviation of precipitation in enhanced CO_2 experiments does not consistently and significantly change in all models except an increase in mean precipitation and moderate increase in standard deviation in MRI-CGCM 2.3.2. The impact of increased CO_2 on frequency and duration of active/break spells of Indian Summer Monsoon is not consistent among the models as well as two experiments. Exception is only CGCM 3.1 (T47) model, in which decrease in frequency and duration of active, short and total break spells is noticed with increased CO_2. The active/break composite precipitation anomalies strengthen and enlarge to greater area moderately (significantly) in doubled (quadrupled) CO_2 experiment.

Introduction

Increase in emissions of greenhouse gases (GHG) and aerosol concentrations have led to enhanced radiative heating of the earth (IPCC, 1990). Warming of the earth is evident from increase in temperature and other changes such as decrease in snow cover and ice extent and thickness, rise in sea level and ocean heat content, changes in extremes of weather and climate in the climate system (IPCC, 2001). An increase in climate variability and some extreme events such as floods and droughts is projected (IPCC, 2001).

The perspective of possible influence of global climate change on monsoon and its variability remains a major issue of concern for the large population of developing country like India where the agriculture and thus economy is closely linked with the behavior of the monsoons. The only tool providing quantitative estimate of the climate of the future is the numerical model that simulate all the important processes governing the future evolution of the climate.

Early studies of numerical climate projections were carried out using General Circulation Models (GCMs) of the atmosphere coupled with simple mixed layer or slab ocean (IPCC,1990,1992, Zhao and Kellog,1988), followed by studies using GCMs of the atmosphere coupled to oceanic general circulation model commonly referred as Atmosphere-Ocean General Circulation Models (AOGCMs). The current versions of AOGCMs provide reliable simulations of the large scale features of the present day climate (IPCC, 2001). However, there are few causes for concerns in numerical climate projections such as inter model differences and the uncertainties on the regional scale. Several region-specific studies that assessed changes in Asian Summer Monsoon (ASM) to increasing GHG analyzed mean monsoon and its interannual variability (Meehl and Washington, 1993, Lal et.al.1994, Lal et.al.1995, Bhaskaran et.al.1995, Rupakumar and Ashirt, 2001, Ashrit et.al.2001, Ashirt et.al.2003). Though few (Bhaskaran et.al.1995) looked at intraseasonal variability also. Subsequently an attempt of intercomparison of nine AOGCMs simulations of regional biases for seven different regions including South Asia has been made by Kittel et.al. (1998). It was observed that the sensitivity of precipitation in response to enhanced GHGs among the models is in better agreement that is independent of magnitude and large range of biases in control climate compared to observations. Thus implying possibility that other than biases, deficiencies in simulations might play role in sensitivities among models. This suggests the need to concentrate on coupled model validation and climate change projections of regional details not only on seasonal mean but also on variability within the season.

To carry out comprehensive and systematic evaluation of simulation of expected climate change patterns under range of emission scenarios constructed by Intergovernmental Panel on Climate Change (IPCC), variety of experiments are performed by different modeling groups in the world. At the request of the JSC / CLIVAR Working Group on Coupled Modeling (WGCM), the Program for Climate Model Diagnosis and Intercomparison (PCMDI) is archiving AOGCMs output to support the Working Group 1 component of the IPCC's 4th Assessment Report (IPCC-AR4). The data archived by the PCMDI from each participating coupled ocean-atmosphere model are made available (http://www-pcmdi.llnl.gov/ipcc/ about_ipcc.php) to the international research community on request. The same data is utilized in the present study.

We have chosen to focus here on the assessment of anticipated climate change impact on summer monsoon on sub seasonal scale in number of AOGCMs specific to Indian subcontinent. We are prompted by the fact that in the past, inter comparison of response of intraseasonal variability of Indian Summer Monsoon (ISM) to climate change by AOGCMs has not been carried. The study of behavior of intraseasonal variability of ISM in projected climate change is very useful considering its impact on agriculture.

In view of this, we begin with comparison of the daily climatological mean and variability of summer precipitation over northwest and central India (73^0-82^0E; 18^0-28^0N) in AOGCMs with observations. Evaluation of the frequency and duration of active and break (long, short and all) spells and composite rainfall pattern during active/break phases of ISM in the present-day climate and projected enhanced CO_2 simulations of AOGCMs has been made.

Two experiments namely 1pctto2x (1%/year CO_2 increase to doubling) and 1pctto4x (1%/year CO_2 increase to quadrupling) have been used to study the influence of climate change relative to control simulation. In the present article, 'Climate of the 20^{th} Century (20C3M)' experiment is used as control. Out of about 23 models participating in IPCC-AR4 project, daily data common to all three experiments viz. Control, 1pctto2x and 1pctto4x is available for about 11 models. We restricted the analysis to 10 models due to some technical problem with the data of one of the models.

The paper is organized as follows: The next section 2 contains a brief background of intraseasonal variability of ISM. The numerical models and experimental design are briefly described in section 3. Section 4A is reserved for details of data sets utilized both from model and observations. Methodology for identifying active and break spells during ISM is discussed in section 4B. Results are provided in section 5 and summarized in section 6.

2. Intraseasonal variability of ISM

Large variations of ISM on wide range of space and time scales are well known and extensively documented. Within the life cycle of summer monsoon, there are fluctuations between 'active' and 'break' phases. During 'active' period, there is heavy rainfall over most parts of the country. The opposite phase with reduced rain over most parts of the country but increased along the foot hills of Himalayas and southeast peninsula is termed as the 'break' spell.

The important time scales of variation of circulation and rainfall over the Indian region on subseasonal scale are 3-7days, 10-20 days and 30-60 days. The detail discussion on mechanism of these different modes of intraseasonal variability is beyond the scope of this study**.**

3. Description of Models and Experimental Design

IPCC is established with an objective of assessment of scientific information on climate change. Working Group 1 of the IPCC focuses on the physical climate system, atmosphere, land surface, ocean and sea ice and the choice of variables archived at the PCMDI reflects this focus. This is an unprecedented effort made by the international modeling community to create valuable coupled model simulations.

The brief description of models used in the present study is outlined in the table-1. CGCM3.1 (T47) model is referred as CGCM3.1 in further discussion. Details of various parameterizations, time and space integration schemes, number of vertical levels etc. are described in model documentation that is available on http://www-pcmdi.llnl.gov/ipcc/modeldocumentation/ipccmodeldocumentation.php.The description of models and experiments, participated in IPCC-AR4 are given on http://www-pcmdi.llnl.gov/ipcc/infoforanalysts.php. Both 1pctto2x and 1pctto4x are idealized experiments. Though the choice of 'mean climate' is left to users by IPCC, use of model mean climate based on the 1981-2000 period of the 'all forcing 20th Century' runs was encouraged. Thus in the present study, we have chosen "20th Century Climate in Coupled Models" (20C3M) as control or mean with which climate change experiments have been compared. 20C3M is a pilot project of Coupled Model Inetrcomparison project (CMIP). In 1pctto2x experiment, CO_2 is increased by 1% per year for 70 years (time of doubling) and with doubled CO_2 additional 150 years run is carried. CO_2 is increased at the rate of 1% per year for 140 years (time of quadrupling) and then an additional 150 years is made with quadrupled CO_2 in 1pctto4x.

4. Data and Methodology

A. Datasets used

Daily precipitation data from three experiments (20C3M, 1pctto2x and 1pctto4x) carried by ten coupled atmosphere-ocean GCMs that participated in IPCC-AR4 is used. It is downloaded from PCMDI ftp site ftp.climate.llnl.gov. The details of model simulated data available for twenty-years in various models are provided in table-2. The period 1981-2000 from 20C3M of all the models is considered as base period.

Daily precipitation from model simulations are compared with rainfall observations over Indian land prepared by Indian Institute of Tropical Meteorology (IITM), Pune, India (personal communication, J.V. Revadekar) using data of 200 well distributed stations published by India Meteorological Department (IMD) in Indian Daily Weather Report (IDWR). From this daily rainfall, grid point data on 0.5^0x$0.5^{0,}$ was prepared for the period 1901-2004 using inverse distance method. This data for the period 1981-2000 is used for validation of control simulations of models.

Precipitation climatology from Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) is used for comparison with model climatology. In CMAP dataset, precipitation values are obtained from 5 kinds of satellite estimates (GPI, OPI, SSM/I scattering, SSM/I emission and MSU) and blended NCEP/NCAR Reanalysis precipitation values. This data set consists of monthly averaged precipitation rate climatology (mm/day) from which summer monsoon season climatology is estimated. The data is 2.5^0 x 2.5^0 gridded (144x72) and covers 88.75^0N to 88.75^0S and 1.25^0E to 358.75^0 E (eastward). The data is downloaded from "ftp://ftp.ncep.noaa.gov/pub/precip/cmap/". The detail description of CMAP precipitation data is available in Xie and Arkin, (1997).

The observations of number of break spells and days for 1981-2000 have been obtained from India Meteorological Department (Personal communication).

B. Methodology for identification of active/break days

Several parameters over different regions such as OLR over 73^0-82^0E; 18^0-28^0N (Krishnan et al., 2000), circulation at 850hPa at 90^0E; 15^0N (Goswami and Ajaymohan, 2001), rainfall over monsoon zone (Gadgil and Joseph, 2003), Indian daily rainfall (Ramesh Kumar and Prabhu Desai, 2004) have been used for identification of breaks by researchers in the recent past. Studies on active phase of monsoon are limited compared to breaks. Indian daily rainfall in the July and August (Ramesh Kumar and Prabhu Desai, 2004), Low level zonal wind (Joseph and Sijikumar, 2004) has been used for identification of active days.

We cataloged active/break days based on precipitation anomaly over central and northwest India. The reason for selection of this region is that the spatial pattern of mean % departure of rainfall during ISM breaks obtained by Ramamurthy (1969), shows presence of large negative rainfall anomalies over central and northwest India, while anomalies of opposite sign over northeastern parts and southeastern peninsula. The proposed criteria in the present study, for identification of active and break days differ only in sign of rainfall anomaly. We hypothesize that active and break phases are two opposite phases of intraseasonal variability.

The procedure adopted for identification of active/break days in the present analysis is sequentially described below.

1. Climatology and standard deviation (S.D.) of daily precipitation averaged over

(73^0-82^0E; 18^0-28^0N) for the ISM season is calculated for three experiments of models, based on 20-year data listed in table-2. The region (73^0-82^0E; 18^0-28^0N) is hereafter referred as Indian core region. The standardized daily precipitation anomalies during ISM season over Indian core region of each year are obtained by subtracting daily climatology and dividing by S.D. of precipitation for that day. Considering the sudden onset and large temporal variations of rainfall over India thereafter during summer monsoon season, the use of daily climatology and S.D. to get standardized anomalies is required.

2. The periods are isolated as active (break) when standardized rainfall anomaly over Indian core region, exceeds (less than) 0.7 (-0.7) for three consecutive days. It is documented that duration of breaks varies from few days to few weeks. Breaks are classified as long when number of break days exceeds 6 days (that is when number of break days are greater than or equal to 7 days) and short when it's duration is less than 7 days.

3. Gadgil and Joseph (2003) (hereafter referred as GJ2k3) define active/break days based on the rainfall over the monsoon zone. Their criteria for identification of break is such that breaks are common to traditional breaks documented by Ramamurthy (1969) for 1901-1967 and beyond 1967 by De et. al. (1998). The criteria used for identification of break in the present study and GJ2k3 are analogues in some respects such as both are based on daily rainfall and Indian core region over which rainfall is averaged is a part of monsoon zone. However, selection of rainfall threshold in two studies is dissimilar. In GJ2k3, rainfall threshold that differs over eastern and western zone is considered whereas single threshold of standardized rainfall anomaly over Indian core region is used in the present study. Break day is defined in GJ2k3 as one in which the average rainfall over eastern and western zone is below 7.5mm/day and 2.5mm/day respectively. The threshold values for eastern and western zone are selected based on the following observations. The standard deviation (S.D.) of the daily average rainfall over the eastern zone is 7.55mm/day and western zone is 6.27mm/day. Though the mean daily rainfall over eastern zone is much higher (11.17mm/day) than over western zone (6.62mm/day), the percentage departure of rainfall during breaks is much larger over the western zone than eastern zone. Thus the threshold chosen over eastern zone is 1 S.D. and that over western zone is 0.4 S.D. Indian core region over which rainfall anomalies are averaged for identification of active/break spells in the present study is a subset of monsoon zone. Thus the threshold of 0.7 for standardized rainfall anomaly over Indian core region used in the present study is the mean of threshold rainfall values of 1 S.D. for eastern zone and 0.4 S.D. for western zone from GJ2k3.

4. The onset / withdrawal of ISM simulated by various models may not coincide with corresponding observations due to systematic errors. Thus the identification of active/break spells is limited to the period from 12 June-15 September, in order to avoid the inclusion of false active/break situations

beginning before the date of advance of monsoon over the entire country and after the date when withdrawal of monsoon started.

5. Results

A. Daily mean and standard deviation of precipitation

The mean daily cycle of precipitation from 16May-15October based on twenty-years, averaged over Indian core region for control (20C3M), 1pctto2x and 1pctto4x experiments of ten models and IITM observations are shown in figure 1(a-j). The daily precipitation climatology of models is validated with corresponding observed rainfall climatology represented by IITM daily rainfall data (J.V. Revadekar, personal communication) described in section 4A. Comparison with observed data allows for validation of present day climate in models with regard to mean and standard deviation of precipitation. The observed rainfall climatology is calculated for the same 20-years period as the control experiments of various AOGCMs and area-weighted mean over Indian core region.

Results noted from figure 1(a-j) are described below.

- Mean daily cycle of observed rainfall climatology shows almost normal distribution reaching peak at the end of July. Sudden rise is associated with onset of monsoon in early June and slow decrease after July as a result of monsoon withdrawal. Comparison of control simulations with observation shows that, among all the models, MIROC3.2 (medres) best reproduces daily cycle. MRI-CGCM2.3.2 also compares well with observation but there are few deficiencies such as late onset, peak reaches much late at the end of August. Few models such as CGCM3.1, ECHAM5/MPI-OM, and both versions of GFDL models have double peak during the season. Double peak has also been noticed in mean daily precipitation cycle of regional climate model PRECIS (Providing Regional Climates for Impacts Studies) developed by Hadley center for climate prediction and research, U.K. (Chattopadhay et.al.2006). However the second peak is not distinct in PRECIS, unlike models in the present study. INM-CM3.0 and ECHO-G models have peak much latter than observed. Large underestimation in GISS-ER relative to observations and absence of precipitation in IPSL-CM4 model is associated with lack of northward progress of monsoon during the season, as will be discussed in section 5B.

- The response of daily precipitation climatology over Indian core region to increased CO_2 is evaluated by comparing 1pctto2x and 1pctto4x with control simulation. Marked increase in mean precipitation throughout the season consistently in both climate change scenarios (larger in 1pctto4x than 1pctto2x) is observed only in MRI-CGCM2.3.2 model. Bhaskaran (1995) found higher daily rainfall over India throughout the summer monsoon season in the doubled CO_2 simulation of United Kingdom Meteorological Office (UKMO) coupled climate model. The increase in daily (Chattopadhay et.al.2006) and annual cycle (Rupakumar et.al.2005) of precipitation over India at the end of 21st century under scenarios of increasing greenhouse gas concentrations and sulphate aerosols has also been noticed in regional model 'PRECIS' simulation. Recently, using ECHAM4 atmospheric GCM, the intensification of mean Indian summer monsoon rainfall in future in time slice experiment with doubling CO_2 concentration has also been reported (May,2004). Inter model differences are observed in response to climate change such as ECHAM5/MPI-OM, ECHO-G models show increase in precipitation only during later part of the season from mid-August while GISS-ER model shows decrease till mid-August. The response to enhanced CO_2 is small in GFDL-CM2.0 model.

Daily S.D. of precipitation over Indian core region based on 20-years from 16May-15October for control and climate change experiments along with IITM observations is illustrated for ten models in figure 2(a-j). Following are the results from figure 2(a-j) :

- The temporal variability of S.D. during summer monsoon season is similar to mean, stating that larger variability is associated with higher mean.

- Control simulation of few models (ECHO-G, CGCM3.1, INM-CM3.0, ECHAM5/ MPI-OM) fairly agrees with observations. Little underestimation in MRI-CGCM2.3.2 and GISS-ER models relative to observed. Peak is much prior in middle of June in MIROC3.2 (medres), ECHAM5/MPI-OM and both versions of GFDL model. S.D. is negligible in IPSL-CM4 model due to absence of precipitation.

- In the projected climate change, increase in S.D. in future by majority of models (both versions of GFDL, MRI-CGCM2.3.2, MIROC3.2 (medres), CGCM3.1, ECHAM5/MPI-OM) is seen. Result implies larger daily variation in precipitation over Indian core region in projected changes in future as suggested by majority of the models. Future projected changes under increasing greenhouse gas concentrations and sulphate aerosols in simulation of regional climate model (PRECIS) also indicated increase in daily S.D. of precipitation over India (Chattopadhay et.al.2006).

B. Geographical distribution of summer monsoon precipitation climatology

In order to examine the features of monsoon climatology, the spatial distribution of summer monsoon (June-September) precipitation climatology in control (20C3M) experiment of 10 models over 65^0-95^0E; Eq-35^0N is shown in figure 3. Precipitation climatology during summer monsoon from CMAP observation is shown in figure 4, for comparison with models. The purpose is to select those models for identification of active / break spells, in which basic features of monsoon such as extension of Tropical Convective Zone (TCZ) northward up to Indian core region is simulated. The large-scale rainfall during summer monsoon over Indian region is associated with the occurrence of TCZ over the heated subcontinent. The main features as seen from figure 4 are two maxima; one over west coast of India and the other over head Bay of Bengal and the rain shadow over southeast peninsula. The precipitation varies between 2-7mm/day over rest of the Indian region. Figure 3(a-j) shows that some of the models simulate gross features reasonably well, while few models have difficulty in simulation of basic characteristic of northward movement of TCZ, resulting in absence of precipitation north of 15-18^{0}N. This problem is more severe in IPSL-CM4 model in which TCZ is confined to southern tip of the peninsula throughout the summer monsoon season. The west coast maxima are simulated by GFDL-CM2.0, GFDL-CM2.1 and ECHAM5/MPI-OM models though magnitude and position differs from observation. Based on temporal variation of daily precipitation climatology over Indian core region and spatial distribution of precipitation climatology averaged over summer monsoon, it is clear that precipitation over Indian core region is very less in GISS-ER, INM-CM3.0 and ECHO-G models and absent in IPSL-CM4. Thus break/active spells are not identified for these four models. Identification of active/break spells and composite analysis is carried for rest of the six models viz. GFDL-CM2.0, GFDL-CM2.1, MIROC3.2 (medres), MRI-CGCM2.3.2, CGCM3.1, ECHAM5 / MPI-OM.

C. Active / Break spells

The number and duration of active/break spells of ISM simulated by six AOGCMs in 20-years from control and increased CO_2 simulations have been calculated. Identification of active/break spells is confined only to six models as there is no precipitation over Indian core region in rest four models as discussed in previous section 5b. The criteria proposed for identification is described in the section 4b. The break spells and their duration in control experiment of models are compared with corresponding observations from India Meteorological Department (Personal communication). However, observations for active spells are not available. The frequency and duration of active/break spells in the projected climate change have been compared with control experiment.

Number of active spells in 20-years for six models in three experiments (20C3M, 1pctto2x and 1pctto4x) is shown in figure 5a and their duration is shown in figure 5b. Similarly number of spells of short, long and total breaks in models and observations are shown in left panels in figure 5 (c, e and g) respectively. The duration of short, long and total breaks in models and corresponding observations are shown in right panels in figure 5(d, f and h) respectively. It is noticed that response to climate change is not consistent among the models as well as doubled and quadrupled CO_2 experiments for few models. Bhaskaran et.al. (1995) did not notice any significant change in intraseasonal variability of monsoon rainfall over India with doubled CO_2 simulation of coupled climate model of UKMO. The number of active spells found to reduce in projected climate change in GFDL-CM2.0, CGCM3.1 and ECHAM5/ MPI-OM models. Both doubled and quadrupled CO_2 experiments indicate decrease in active days in all models except MIROC3.2 (medres) which shows increased active days. UKMO coupled climate model in doubled CO_2 simulation showed increase in heavy rainfall days over India in summer monsoon season (Bhaskaran et.al.1995). Comparison of frequency and duration of short break spells in control simulation of models with observation shows that all models except both versions of GFDL model overestimate short break spells. Future climate change simulations indicate decrease in total number of short break spells and duration in CGCM3.1, ECHAM5/MPI-OM and increase in MRI-CGCM2.3.2 model. In GFDL-CM2.0 and MIROC3.2 (medres) models both short break spells and days decreased (increased) in 1pctto2x (1pctto4x). Frequency and duration of long and total break spells are overestimated in all models compared to observation. The number and duration of long break spells reduced in GFDL-CM2.1 and MRI-CGCM2.3.2 models in increased CO_2 experiments compared to control. In CGCM3.1, the long break spells decreased while there is inconsistency among doubled and quadrupled CO_2 experiments for duration of long breaks. The frequency and duration of long breaks in MIROC3.2 (medres) does not show uniform results in the two climate change experiments. The climate change experiments shows decrease in total break spells and their duration in GFDL-CM2.1 and CGCM3.1 models. The total break spells in ECHAM5/MPI-OM model reduced but duration increased (decreased) in doubled CO_2 (quadrupled CO_2). There is no uniformity in the results of two climate change experiments for rest of the models.

D. Composite analysis

The precipitation anomaly during break/active spells of ISM is constructed using composite technique for control and climate change experiments. The purpose is to study the response of composite precipitation anomaly during break/active spells to climate change in various models. Break (active) composite precipitation anomalies in control experiment of models are compared with break(active) composite OLR anomaly from GJ2k3 that are based on period 1974-1989, as satellite OLR data is available over this period. Rainfall used in GJ2k3 is available only over land while OLR data is present over both land and ocean, so the active/break composite precipitation anomalies from control experiment of coupled models in the present study are compared with OLR anomalies of GJ2k3 rather than rainfall anomaly. Break and active composite OLR anomalies from GJ2k3 are reproduced in figure 6a and 6b respectively. The reason for selecting OLR observation from GJ2k3 is that their criteria for identification of breaks is mostly similar to the one used in the present study as discussed in section 4b. OLR is a measure of cloud-top temperature and is often used as surrogate for precipitation due to unavailability of rainfall data. Deep convection in the tropics is associated with cold cloud top temperatures. Thus regions of low OLR values ($<240 W/m^2$) correspond to regions of intense cloudiness and high rainfall. In contrast, high OLR values ($>240 W/m^2$) are indicative of suppressed cloudiness and drier atmosphere.

All break composite precipitation anomaly over 30^0-150^0E; 30^0S-40^0N in GFDL-CM2.0 model is illustrated in figures 7a, b, c respectively for three experiments viz, control, 1pctto2x and 1pctto4x. Similar plots for GFDL-CM2.1, MRI-CGCM2.3.2, MIROC3.2 (medres), CGCM3.1, ECHAM5/MPI-OM models are shown in figures 8-12 respectively. There are three panels a, b and c in figures 7-12 corresponding to control, 1pctto2x and 1pctto4x respectively. We begin with comparison of break composite precipitation anomalies in control experiment of models with rain break composite OLR anomalies from GJ2k3 shown in figure 6a.

In control experiment of majority of models, there is increased precipitation over northeast India associated with movement of monsoon trough during break. The broad features of break composite precipitation anomalies such as large negative anomalies over Indian core region and negative anomalies over rest of the Indian region seems to be reasonably well simulated by most of the models as seen in OLR anomalies (of opposite sign to that of precipitation anomalies) of GJ2k3 (figure 6a). However, closer observation indicate difficulties in some of the models such as in MIROC3.2 (medres) the negative precipitation anomalies extend far westward covering Arabian sea reaching close to Africa coast. Majority of models simulate increased rainfall in Indian Ocean over Equatorial region of Indian longitudes suggesting active phase of oceanic TCZ as also seen in OLR anomalies shown in figure 6a. Thus break composite precipitation anomaly forms north-south dipole over Indian longitudes. GFDL-CM2.0 and CGCM3.1 models failed to simulate this north-south dipole. The break composite OLR anomalies of GJ2k3 in figure 6a shows increased convection over tropical west Pacific over same latitudinal belt as suppressed convection over Indian region suggesting presence of east-west dipole pattern. This feature in precipitation anomaly is seen in MIROC3.2 (medres), ECHAM5/MPI-OM models and to some extent in MRI.CGCM2.3.2 and CGCM3.1 model. The observed break composite OLR anomalies (figure 6a) south of 15^0N in West Pacific are positive (suppressed convection) giving rise to north-south dipole opposite to that over Indian longitudes. Break composite precipitation anomalies of ECHAM5/MPI-OM model resemble north-south dipole OLR anomalies over tropical west pacific though anomalies over southern part of dipole are smaller precipitation anomalies in MRI-CGCM2.3.2 model also simulate north-south dipole pattern that are smaller and westward of its corresponding observed OLR anomalies shown in figure 6a.

Active composite precipitation anomaly over 30^0-150^0E; 30^0S-40^0N in GFDL-CM2.0 model is illustrated in figures 13a, b, c respectively for three experiments viz, control, 1pctto2x and 1pctto4x. Likewise three panels a, b and c in figures 14-18 respectively illustrates active composite precipitation anomaly for GFDL-CM2.1, MRI-CGCM2.3.2, MIROC3.2(medres), CGCM3.1, ECHAM5/MPI-OM models. Comparison of active composite precipitation anomaly in control experiment of models with active composite OLR anomalies of GJ2k3 shown in figure 6b suggest that models simulate large positive anomalies over central India that is also seen as enhanced convection (negative OLR anomalies) in GJ2k3. The bimodal structure in convection during Asian summer monsoon seen from two preferred locations of convection over Indian longitudes (figure 6b), one over the continent and the other over equatorial Indian Ocean is simulated by all models except CGCM3.1.

The responses of break/active composite precipitation anomaly to projected climate change in various models are described below.

- Break composite precipitation anomaly in projected climate change experiments shows intensification of negative precipitation anomalies over India and increase in their spatial extent in all models except GFDL-CM2.0. In quadruple CO_2 experiment the intensification and spatial spread is larger than double CO_2 experiment, specifically in MIROC3.2 (medres) model. Strengthening of positive anomalies over equatorial Indian Ocean (IO) in projected climate change is noticed in MRI-CGCM2.3.2, MIROC3.2 (medres) and ECHAM5/MPI-OM. In contrast, positive rainfall anomalies over equatorial IO seen to decrease in magnitude as well as spatial extent with climate change in GFDL-CM2.1 model.

- The response of active composite precipitation anomaly to climate change differ in magnitude and position of precipitation anomaly for various models. The results are not consistent in two experiments of climate change alike break composite. Majority of models suggests spread and intensification of positive (negative) precipitation anomalies over Indian region (Indian ocean) in doubled CO_2 experiment. The spread and intensification is even larger in quadrupled CO_2 experiment.

6. Conclusions

The multi model climate change simulations of active/break spells during Indian summer monsoon are assessed. The daily mean cycle and S.D. of precipitation over Indian core region during summer monsoon season is validated with observations. This allows to assess systematic errors. Comparison of spatial distribution of summer monsoon precipitation climatology of models with CMAP shows that precipitation does not progresses sufficiently northward till Indian core region in four out of ten models. Thus the monsoon response to altered CO_2 is studied for six out of ten models as the criteria used in the present study for identification of active/break spells is based on precipitation over Indian core region. Following are the results :

(i) Mean daily cycle of precipitation in MIROC3.2 (medres) model compares well with observation in spite of medium resolution T42. However there is underestimation in MRI-CGCM2.3.2 and very late peak at the end of August. Other models (GFDL-CM2.0, GFDL-CM2.1, CGCM3.1 and ECHAM5/MPI-OM) have either problem of double peak or underestimation/ absence (GISS-ER, IPSL-CM4) of precipitation or time of peak much latter than observation (INM-CM3.0 and ECHO-G).

(ii) Validation of daily variability of precipitation in control experiment of models with observation suggests fairly realistic simulation in ECHO-G, INM-CM3.0 and CGCM3.1 and ECHAM5/MPI-OM models. In some of the models (GFDL-CM2.0, GFDL-CM2.1, ECHAM5/MPI-OM and MIROC3.2 (medres) peak is much prior to observation. Variability is too low in GISS-ER, MRI-CGCM2.3.2 and absent in IPSL-CM4.

(iii) Future projections of both doubled and quadrupled CO_2 scenarios indicate significant increase in mean and moderate increase in S.D. throughout the summer monsoon season in MRI-CGCM2.3.2 model. The change is either small or is not consistent in the two climate change experiments in rest of the models.

(iv) Estimation of the impact of climate change on frequency and duration of active spells, short, long and total break spells in various models suggest that:

- There is little change in active/break spells and duration in most of the models.

- Results are not consistent among the models. In few models, the results of the two enhanced CO_2 experiments are not uniform.

- There is a decrease in active, short and total break spells/days and long break spells in CGCM3.1 model in both climate change experiments. The decrease is large for short break spells, total break spells and duration of total breaks, more in quadrupled $CO_{2.}$

(v) Gross features of break/active composite precipitation anomaly in control experiment is captured by majority of the models. The active/break composite precipitation anomaly is seen to intensify and enlarge in future climate change projections of majority of models, more significantly (moderately) in quadrupled (doubled) CO_2 experiment. This is clear from strengthening of precipitation minima (maxima) over central India and maxima (minima) over northeast India during break (active) composite.

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Table-1: Brief description of the models

S.No	Institution	Model	Resolution		Model Description
			Atmosphere	Ocean	
1	Geophysical Fluid Dynamics Laboratory	GFDL - CM2.0	2.5^o lon x 2.0^0 lat	1^o lon x 1^0 lat with enhanced tropical resolution (1/3 on equator)	Delworth, T.L. et. al., 2004
2	Geophysical Fluid Dynamics Laboratory	GFDL - CM2.1	2.5^o lon x 2.0^0 lat	1^o lon x 1^0lat with enhanced tropical resolution (1/3 on equator)	Delworth, T.L. et. al., 2004
3	Goddard Institute for Space Studies(GISS), NASA,USA	GISS-ER	5^0 lon x 4^0 lat	5^0 lon x 4^0 lat	Schmidt, G. A., et. al.,2005
4	CCSR/NIES/FRCGC, Japan	MIROC3.2 (medres)	T42 L20	1.4^0 lon x 1.4^0 lat	K-1 model developers (http://www.ccsr.u-tokyo.ac.jp /kyosei/hasumi/MIROC/ tech-repo.pdf)
5	Meteorological Research Institute, Japan Meteorological Agency, Japan	MRI-CGCM 2.3.2	T42 (~2.8^0)	2.5^0 lon x 2.0^0 lat (poleward of 12S and 12N) ~0.5 (4S-4N)	Yukimoto et. al., 2001
6	Institut Pierre Simon Laplace (IPSL), France	IPSL-CM4	2.5° x 3.75° (i.e. 96x71 grid points). Vertical: 19 levels	quasi-isotrope tri-polar grid (2 poles in the northern hemisphere, on over Canada and the other over Siberia. 2° resolution Mercator grid with enhanced meridional resolution in the vicinity of the equator and in Med and Red seas (1°)	Marti O., et. al. 2005

S.No	Institution	Model	Resolution		Model Description
			Atmosphere	Ocean	
7	Canadian Centre for Climate Modelling & Analysis, Canada	CGCM3.1(T47)	3.75 degrees lat/lon and 31 levels in the vertical.	1.85 degrees, with 29 levels in the vertical.	Kim, S.-J., G.M. Flato, G.J. Boer and N.A. McFarlane, 2002
8	Institute for Numerical Mathematic, Russia Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, and Model and	INM-CM3.0	5x4 in longitude and latitude, 21 levels in vertical.	2.5x2 degrees in longitude and latitude, 33 sigma-levels in vertical.	Alekseev et al. 1998. Diansky et al. 2002. Diansky, Volodin 2002.
9	Data group. Germany / Korea.	ECHO-G	T30 L19	even grid rows (E/W) correspond to a T42 Gaussian grid in high and mid latitudes; towards the equator the meridonal distances decrease (min = 0.5 deg); 20 levels;	Legutke, S. and E. Maier-Reimer, 1999. Legutke, S. and R. Voss, 1999
10	Max Planck Institute for Meteorology	ECHAM 5/MPI-OM	T63 L31	1.5 deg 40 vertical levels	Jungclaus, J.H., et.al., 2005

Table 2 : Details of model integration period considered for analysis

Sr. No.	***Model***	***1pctto2x***		***1pctto4x***	
		20-years centered at the time of doubling	Last 20-years	20-years centered at the time of quadrupling	Last 20-years
1.	GFDL-CM2.0	-	2061-2080	-	2131-2150
2.	GFDL-CM2.1	-	2061-2080	-	2131-2150
3.	GISS-ER	2101-2120	-	2171-2190	-
4.	MIROC3.2 (medres)	-	2051-2070	-	2121-2140
5.	MRI-CGCM2.3.2	2001-2020	-	2071-2090	-
6.	IPSL-CM4	-	2061-2080	-	-
7.	CGCM3.1(T47)	-	2050-2069	-	2120-2139
8.	INM-CM3.0	-	2071-2090	2001-2020	2141-2160
9.	ECHO-G	2051-2070	2261-2280	2121-2140	2261-2280
10.	ECHAM5/MPI-OM	-	2061-2080	-	2131-2150

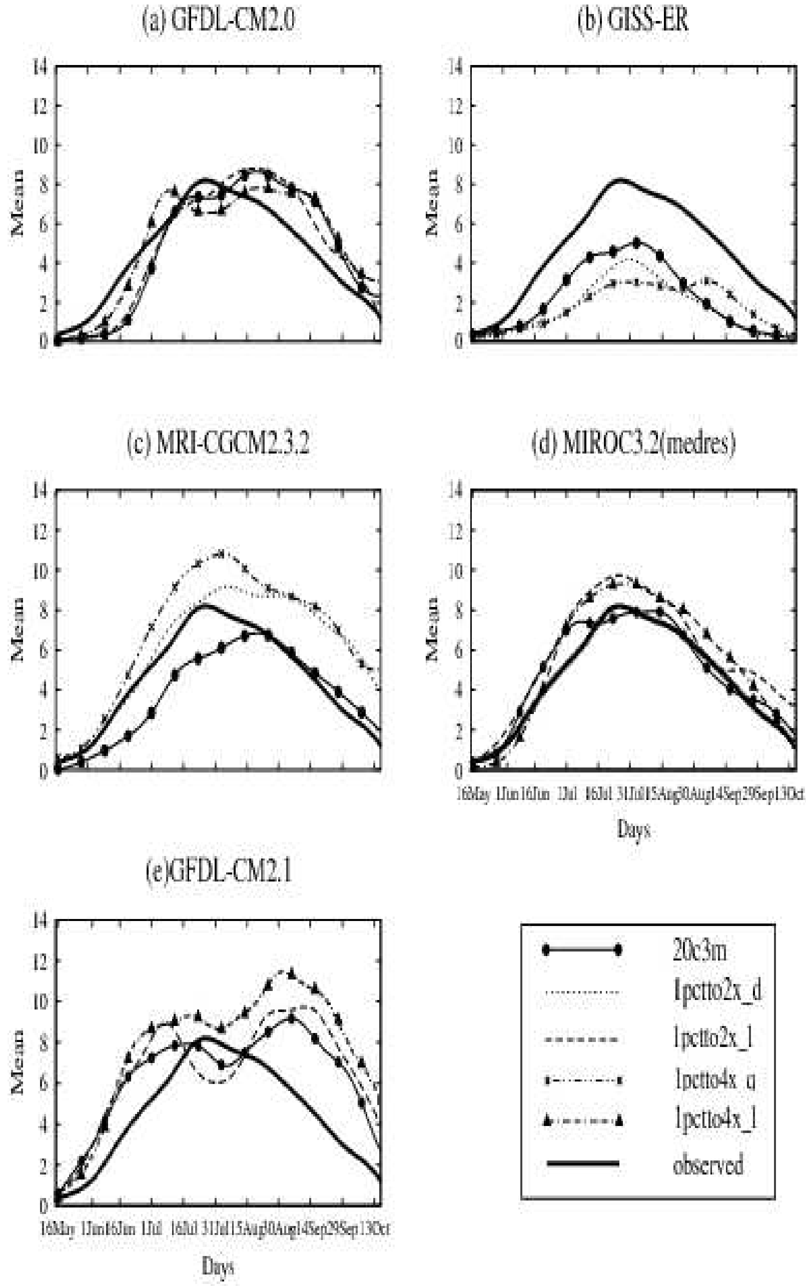

Fig1a: Daily precipitation climatology averaged over 73^0 - 82^0 E; 18^0 - 28^{0}N from 16 May -15 Oct based on 20-year periods of three experiments for 20c3M, 1pctto2x_d (20-years centered at the time of doubling), 1pctto2x_l (last 20-years), 1pctto4x_q (20- years centered at the time of quadrupling), 1pctto4x_l(last 20-years), IITM observations.

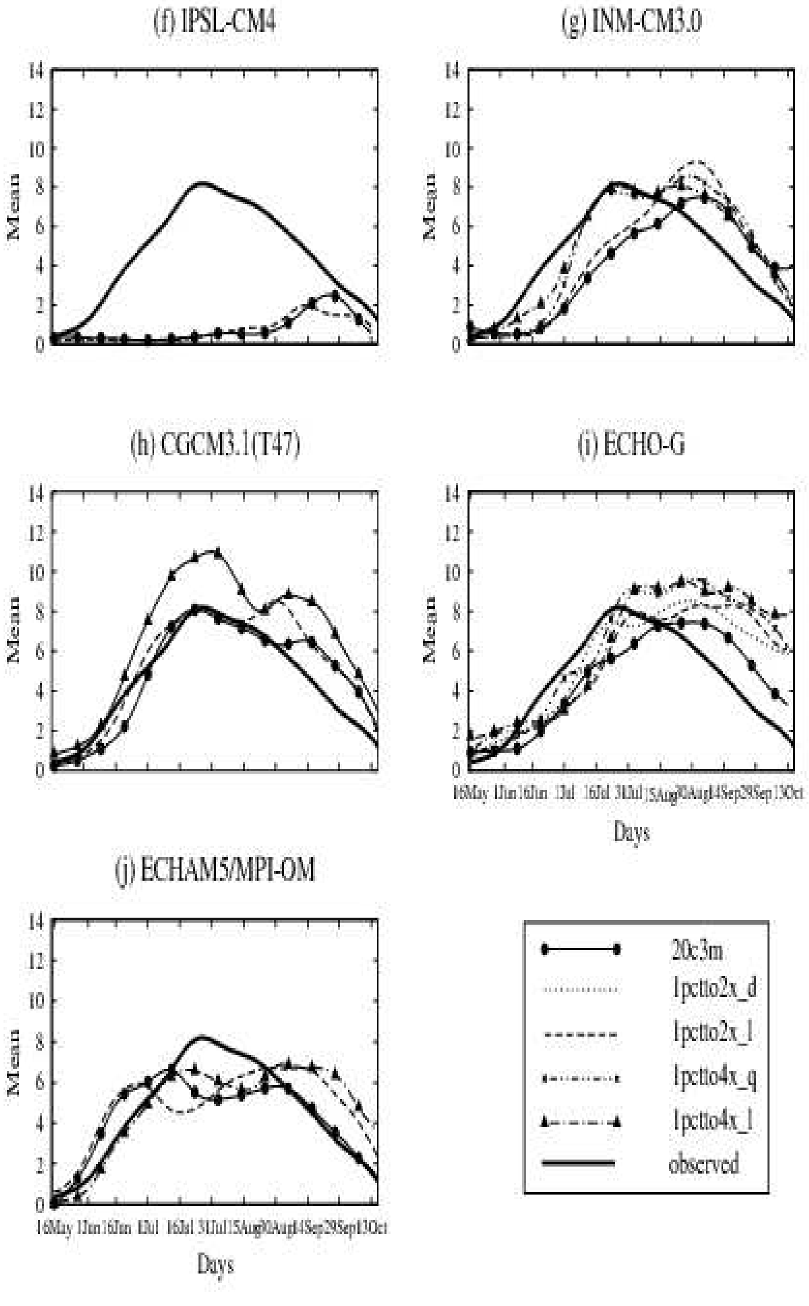

Figure 1b: Same as in figure 1a.

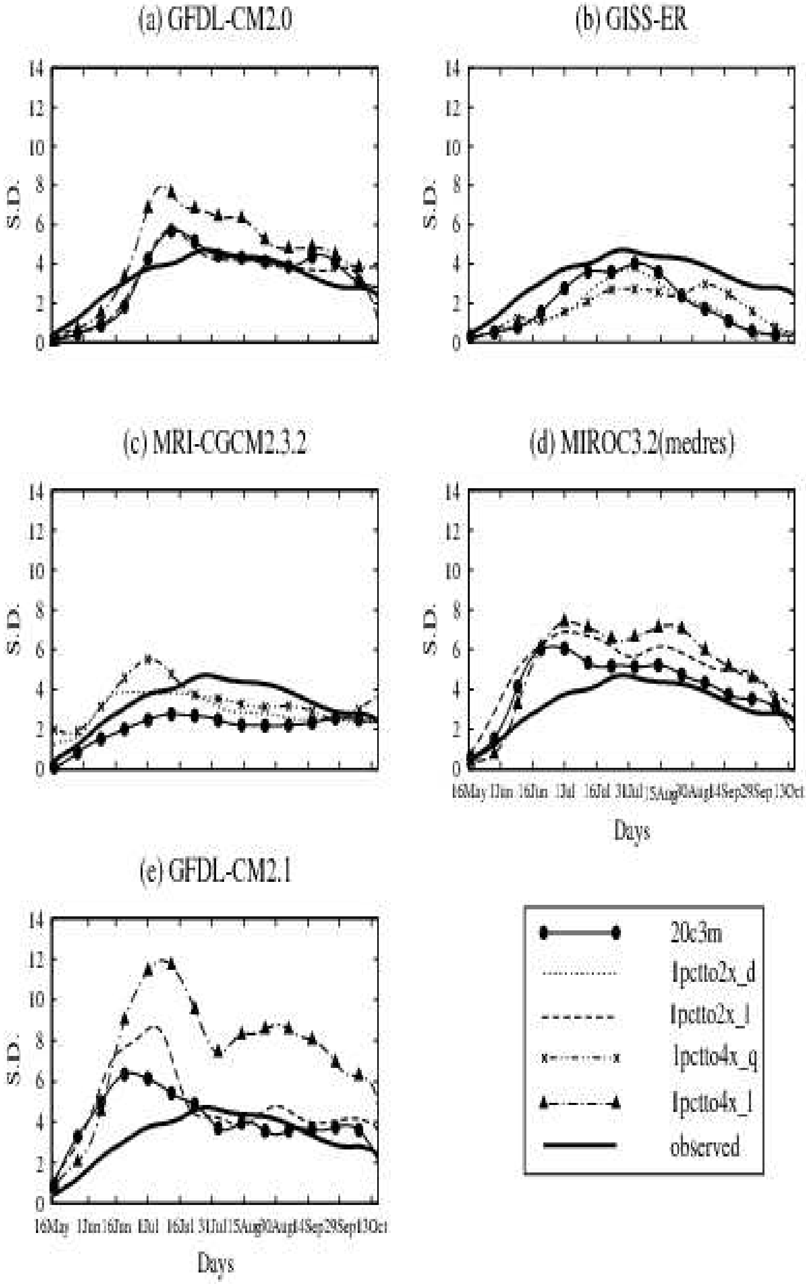

Figure 2a: Same as in figure 1a except for daily standard deviation of precipitation.

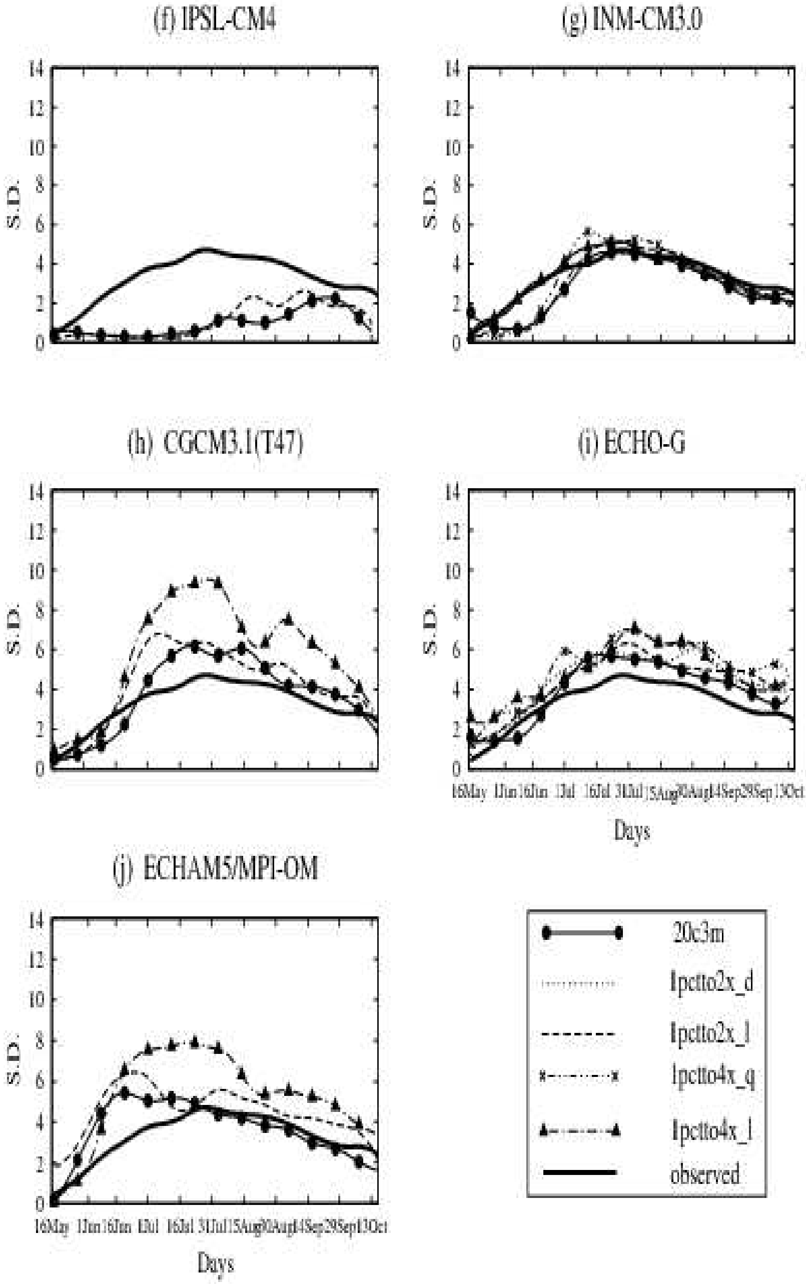

Figure 2a: Same as in figure 2a .

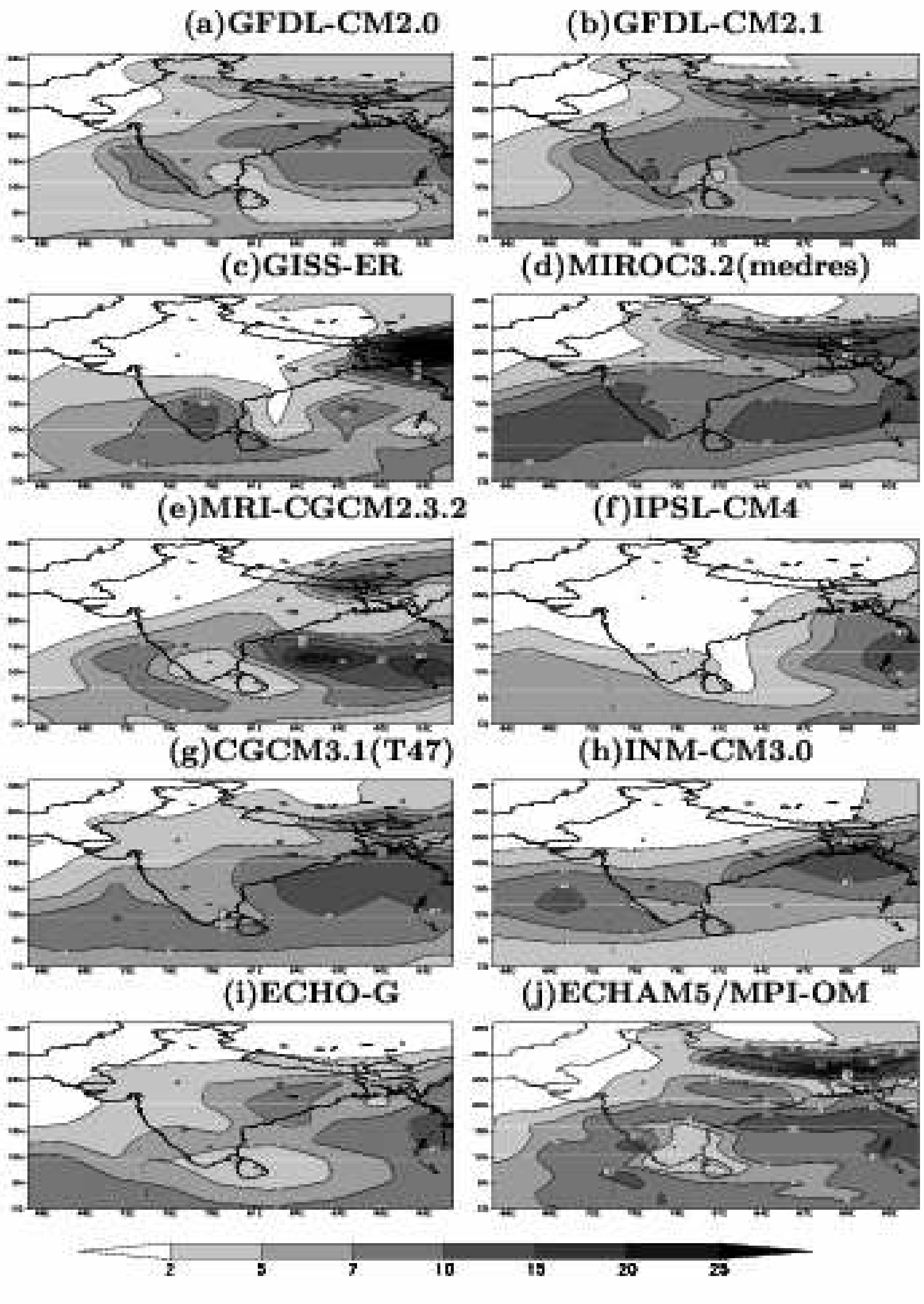

Figure 3: Precipitation (mm/day) summer monsoon season (June-September) climatology over region (65^0E-95^0E; Eq.-35^0N)

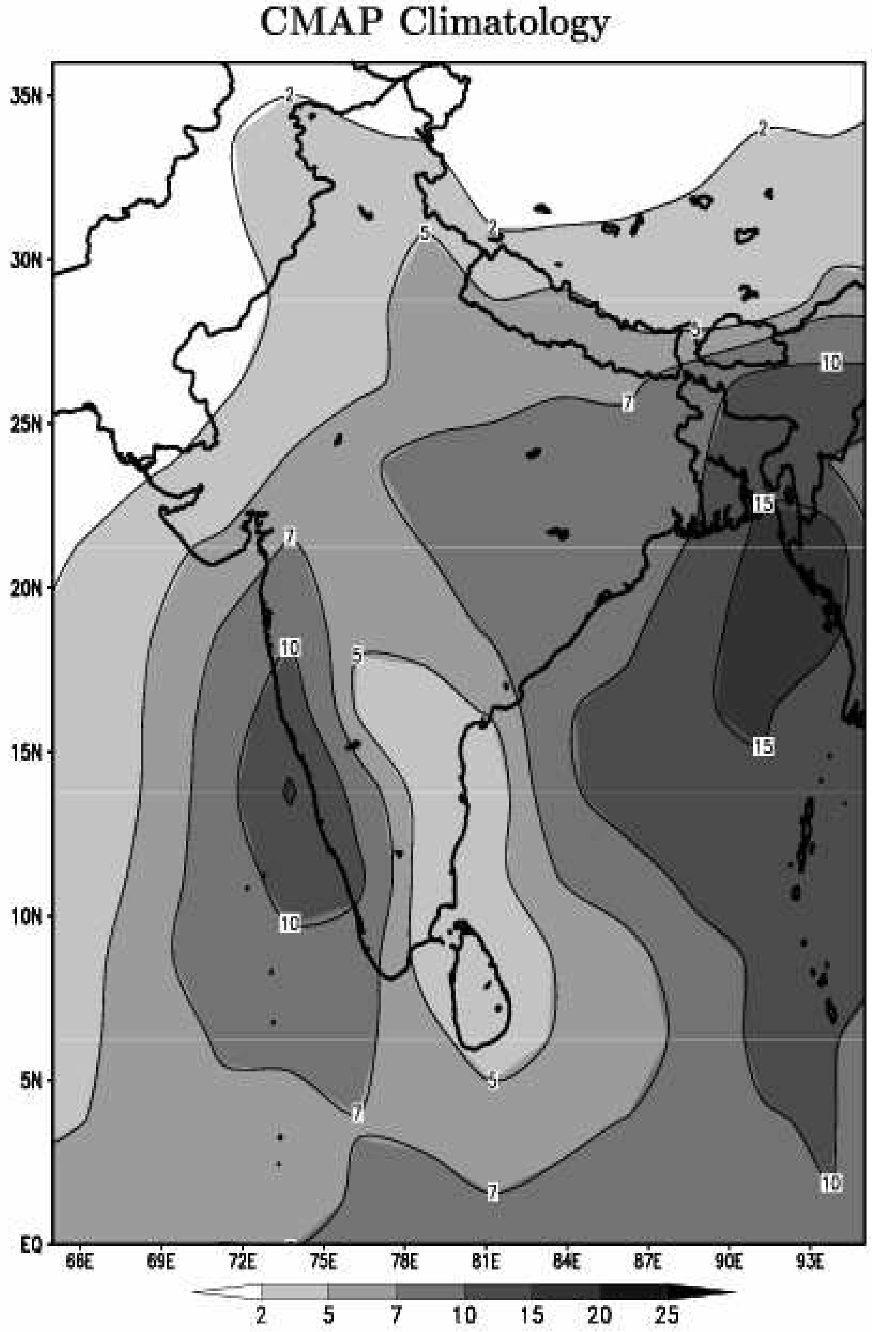

Figure 4: CMAP precipitation (mm/day) summer monsoon season (June-September) climatology over region (65^0E-95^0E; Eq.-35^0N)

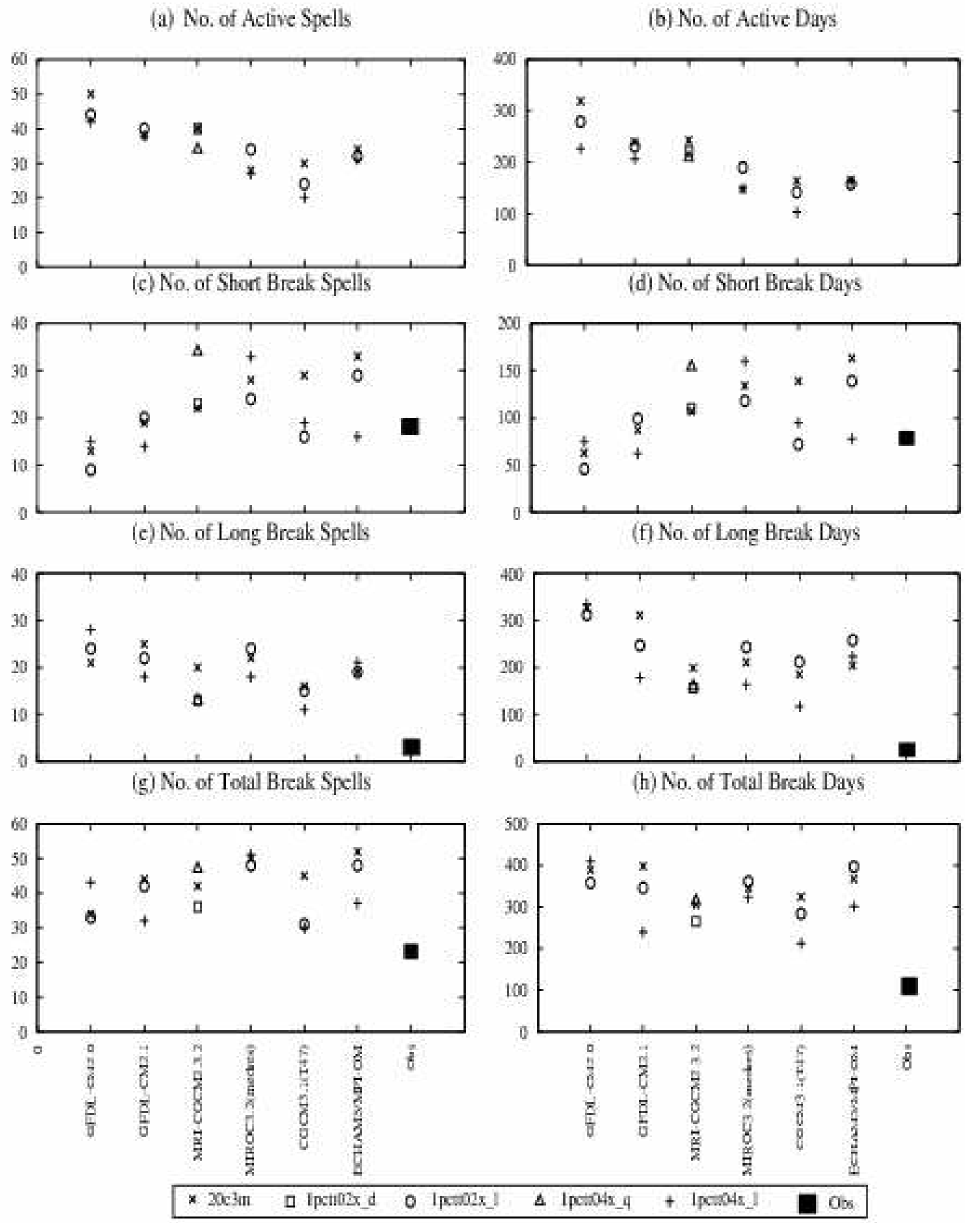

Figure 5 : (a) Number of active spells in 20C3M,1pctto2x and 1pctto4x experiments of six models viz,GFDL-CM2.0 , GFDL-CM2.1, MRI-CGCM2.3.2, MIROC3.2 (medres), CGCM3.1 and ECHAM5/MPI-OM.

(b) Same as in 5(a) except for number of active days.
(c) Same as 5(a) except for number of short break spells
(d) Same as 5(a) except for number of short break days
(e) Same as 5(a) except for number of long break spells
(f) Same as 5(a) except for number of long break days
(g) Same as 5(a) except for number of total break spells
(h) Same as 5(a) except for number of total break days.

(a)

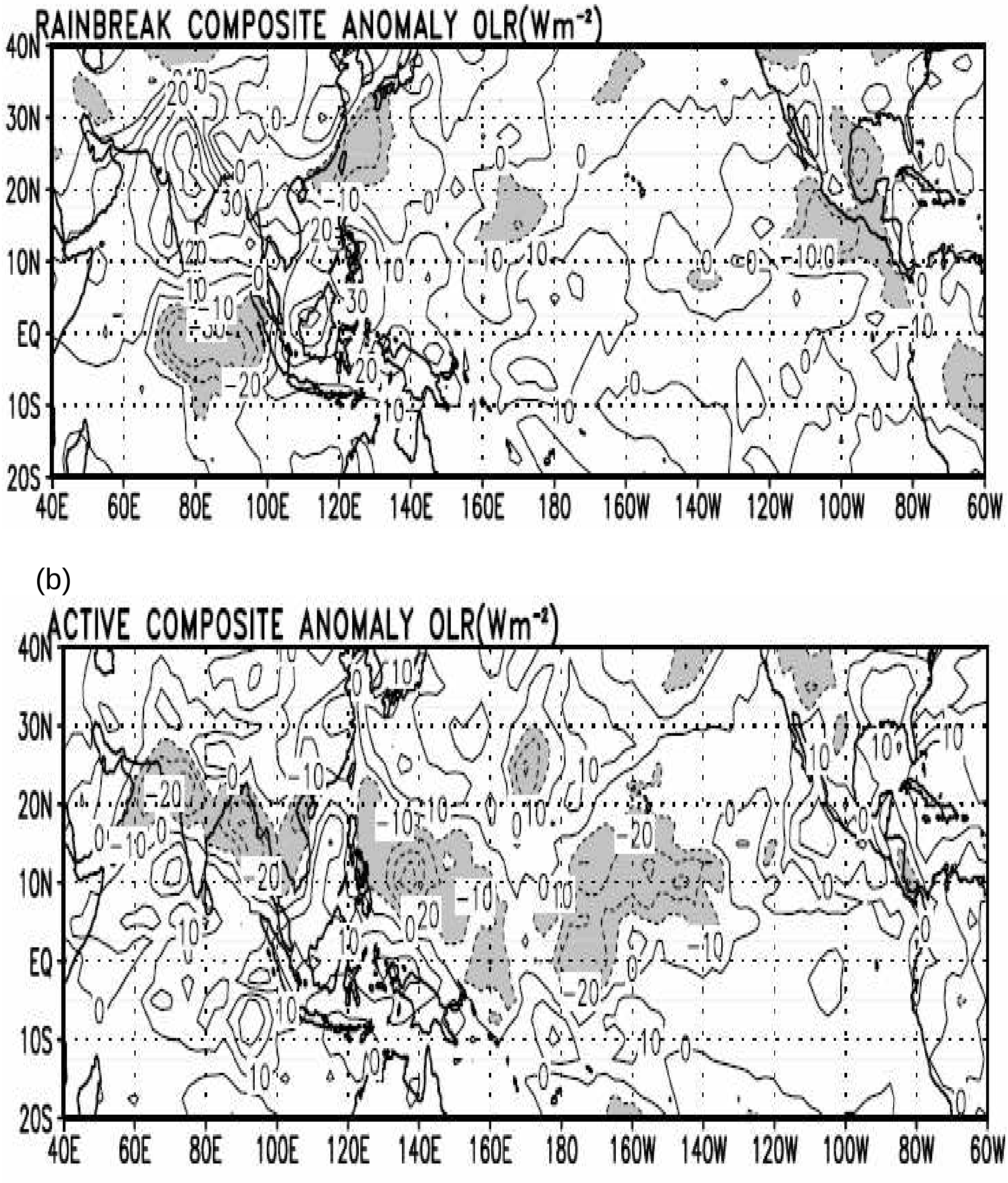

Figure 6: OLR anomaly patterns (a) Break composite (b) Active composite (Reproduced with permission from Gadgil and Joseph, 2003.)

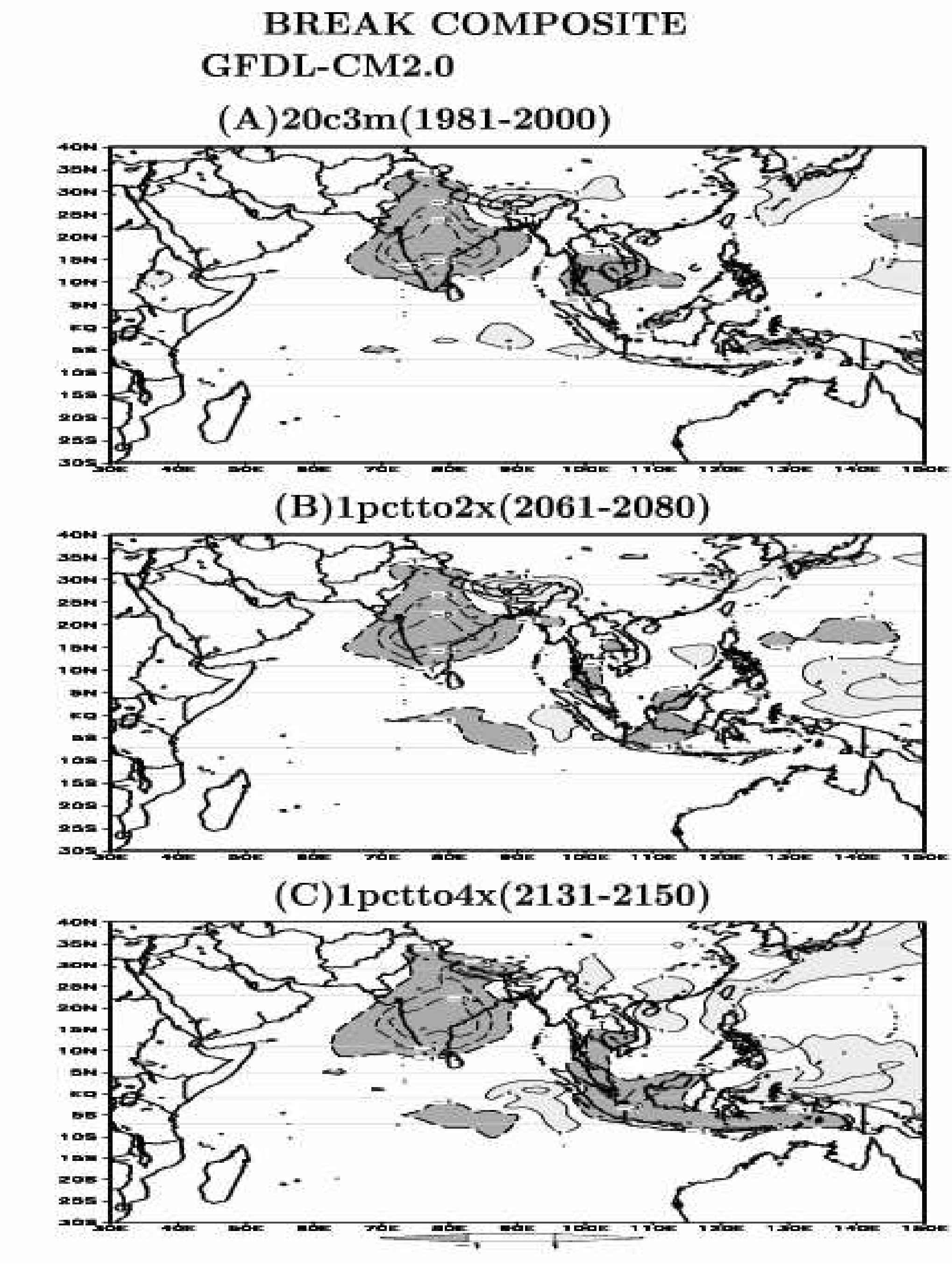

Figure 7: Break composite precipitation anomaly for GFDL-CM2.0 model (Anomalies less than -1 are shaded dark and anomalies greater than +1 are shaded light. Contour intervals are -13, -11,-9, -7, -5, -3,-1, 1, 3, 5, 7. Negative contours are dashed. Positive contours are solid.) (a) 20c3M (1981-2000) (b) 1pctto2x (2061-2080) (c) 1pctto4x(2131-2150)

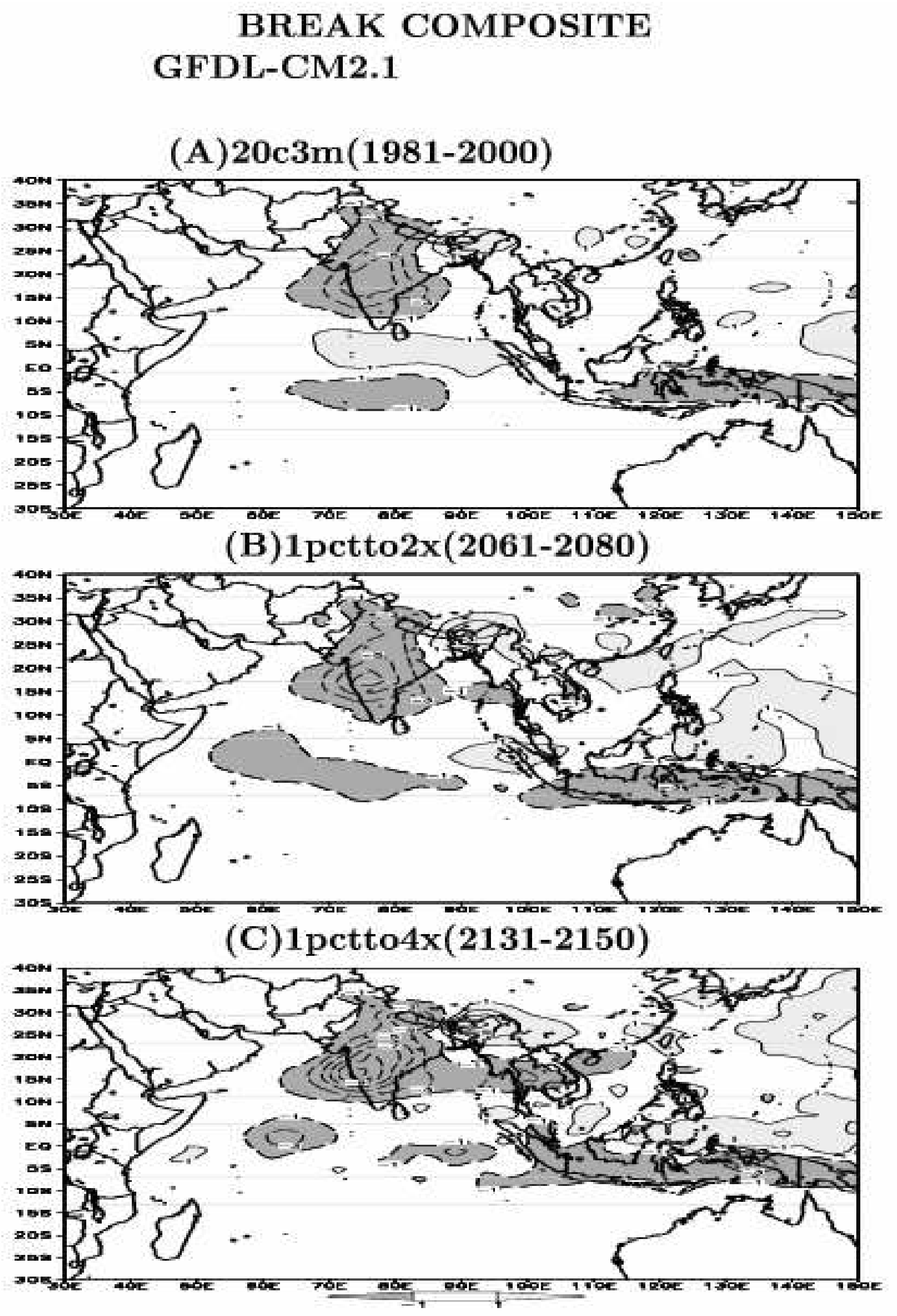

Figure 8: Same as figure 7 except for GFDL-CM2.1 model

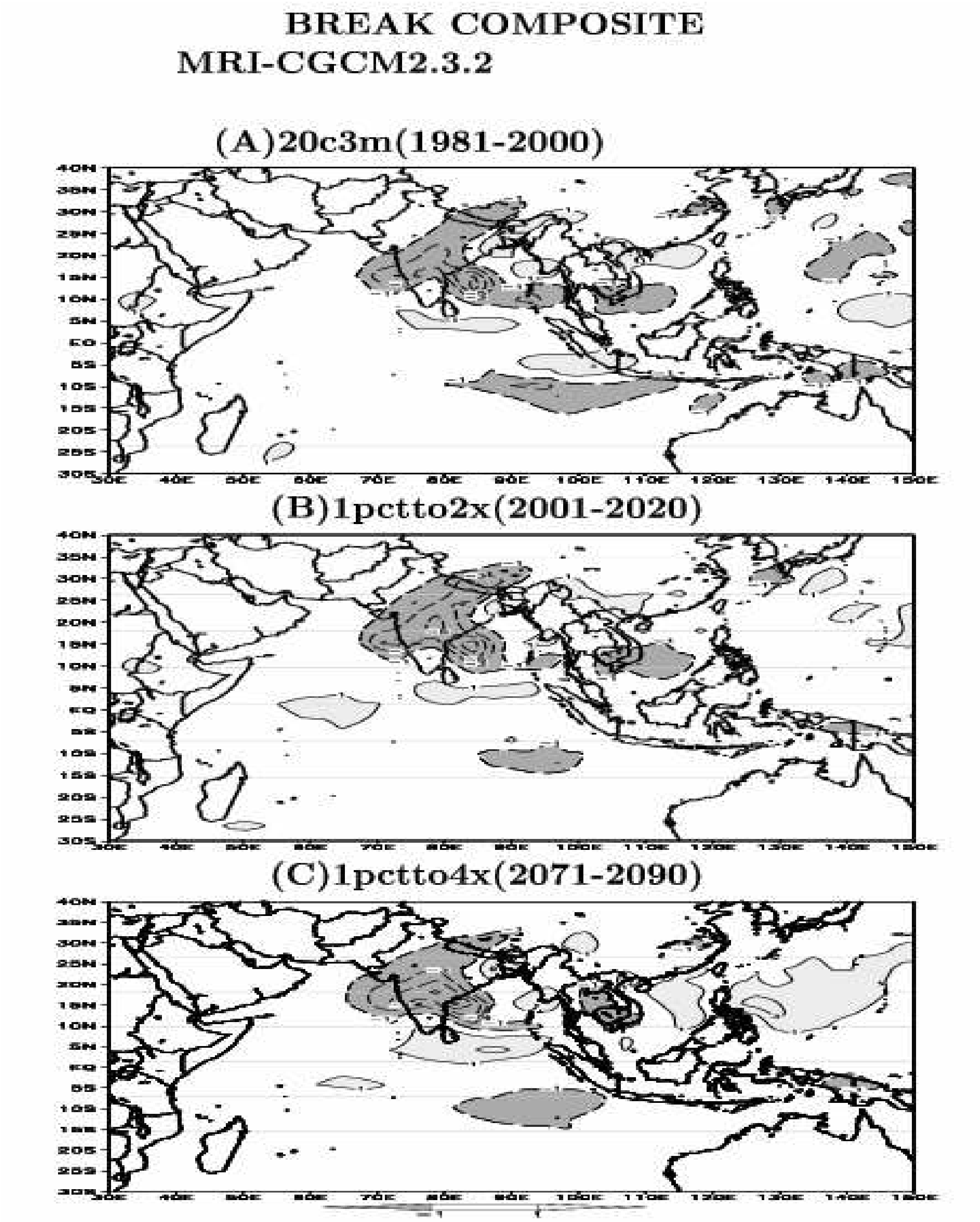

Figure 9: Same as figure 7 except for MRI-CGCM2.3.2

BREAK COMPOSITE
MIROC3.2(medres)

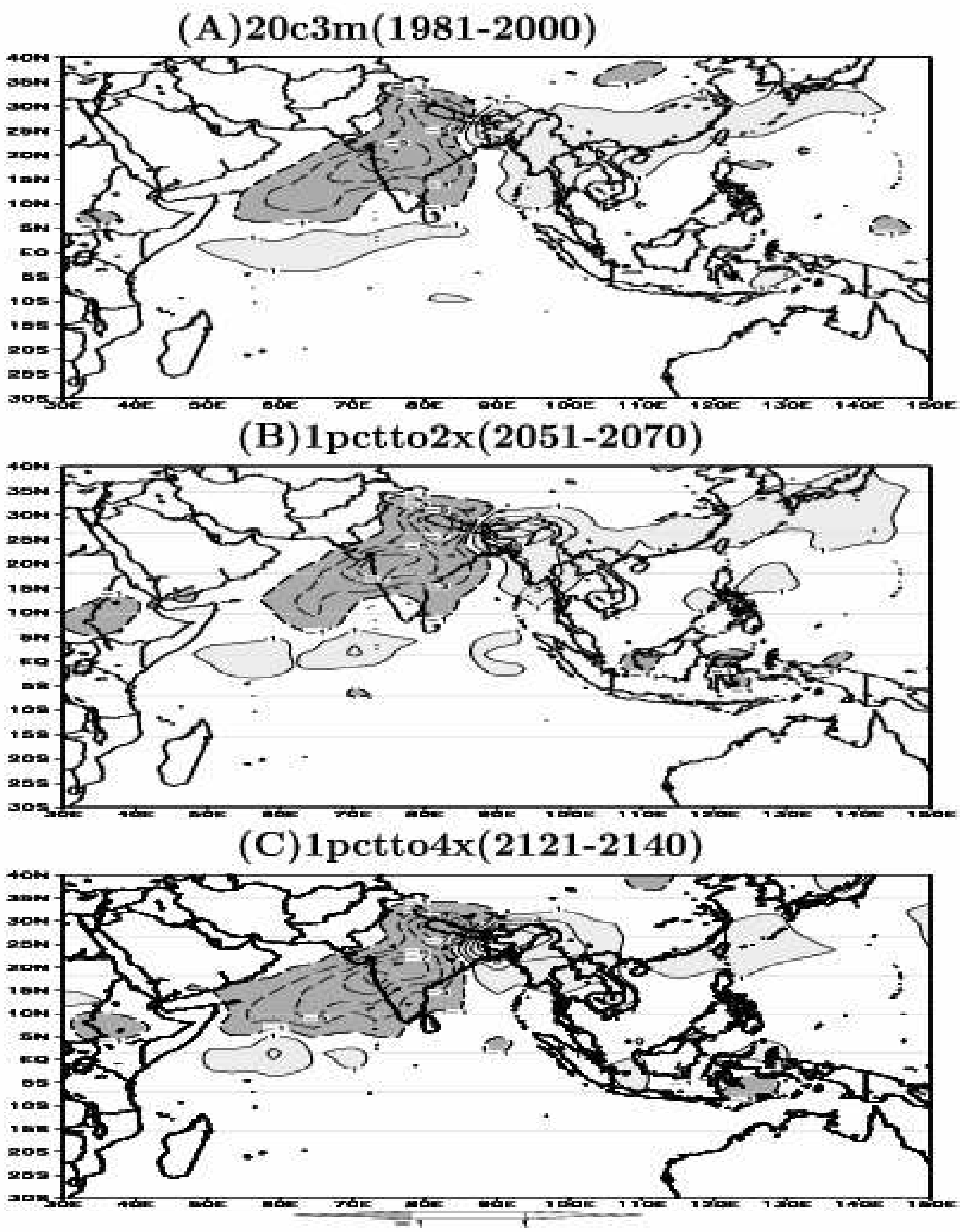

Figure 10: Same as figure 7 except for MIROC3.2 (medres)

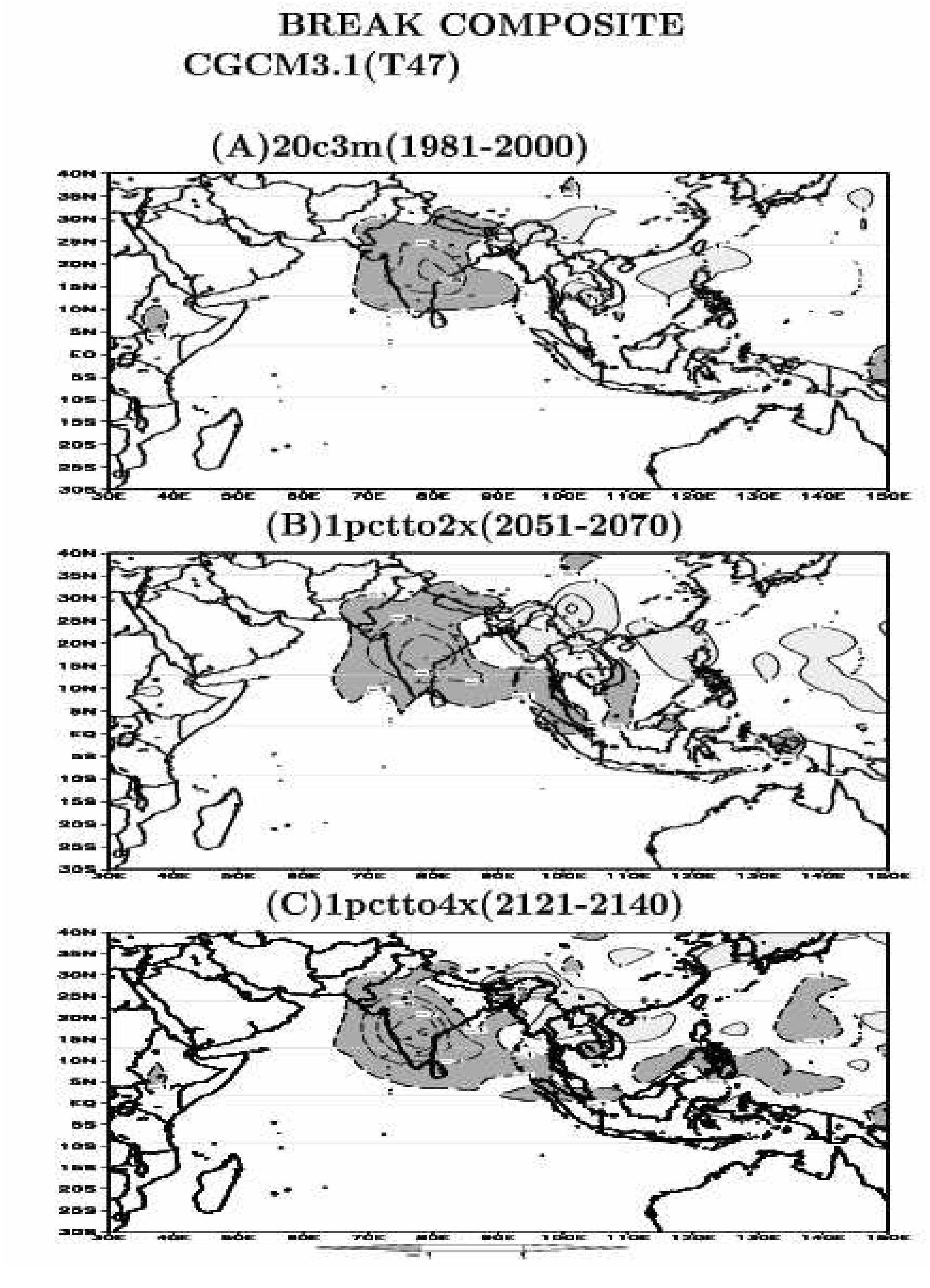

Figure 11: Same as figure 7except for CGCM3.1

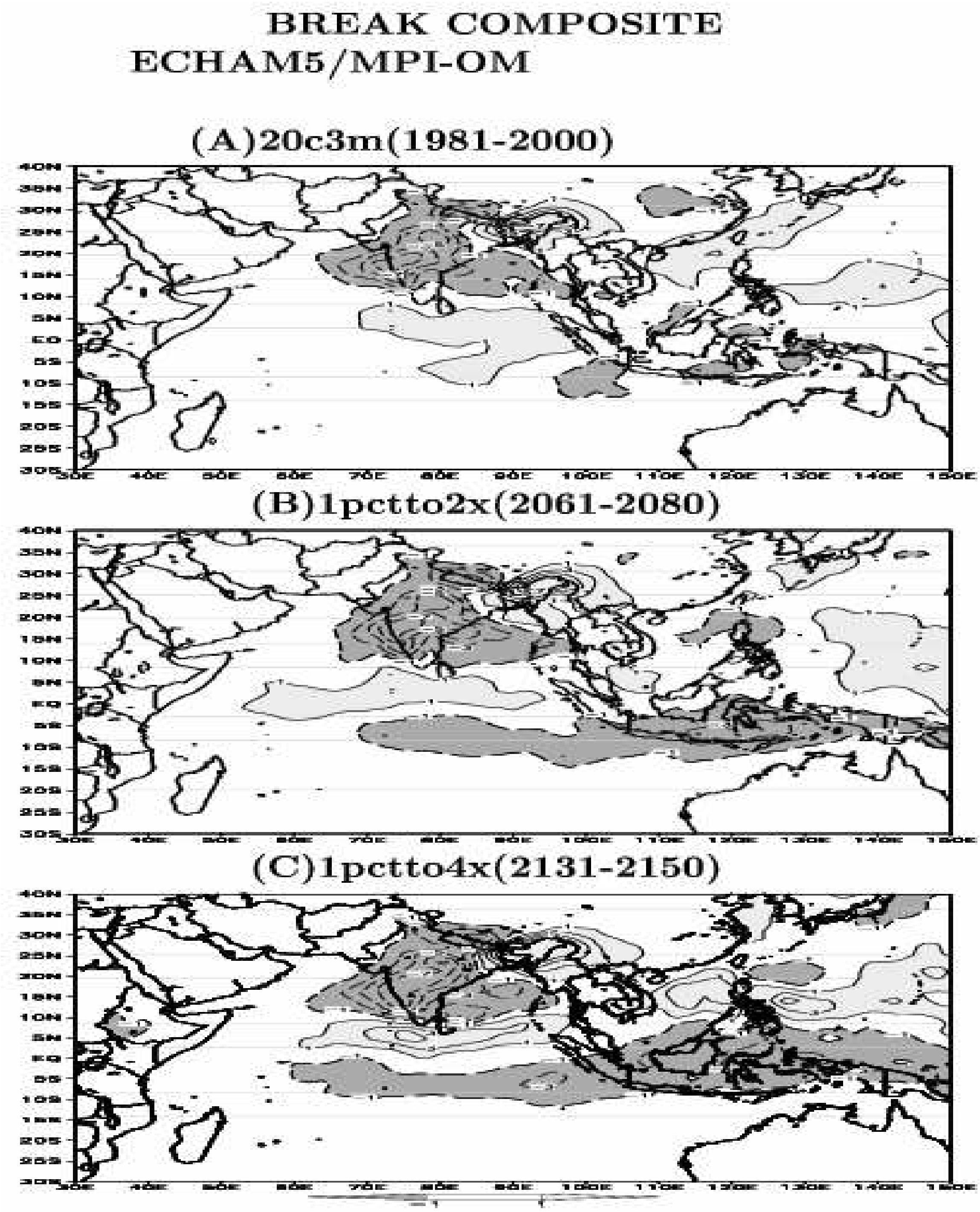

Figure 12: Same as figure 7 except for ECHAM5/MPI-OM

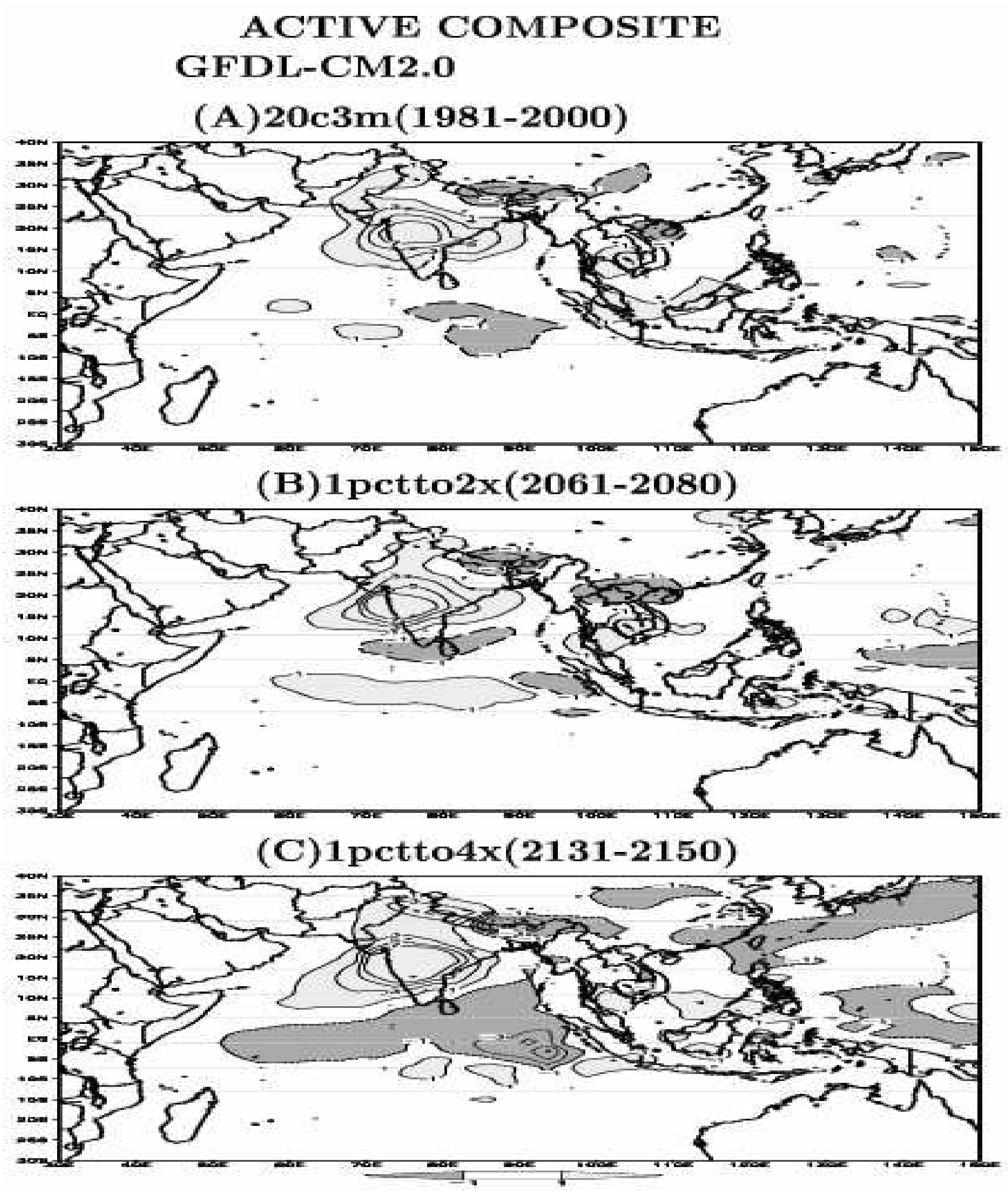

Figure 13: Active composite precipitation anomaly for GFDL-CM2.0 model (Anomalies less than -1 are shaded dark and anomalies greater than +1 are shaded light. Contour intervals are -13, -11, -9,-7, -5, -3, -1, 1, 3, 5, 7. Negative contours are dashed. Positive contours are solid.) (a) 20c3M (1981-2000) (b) 1pctto2x (2061-2080) (c) 1pctto4x (2131-2150)

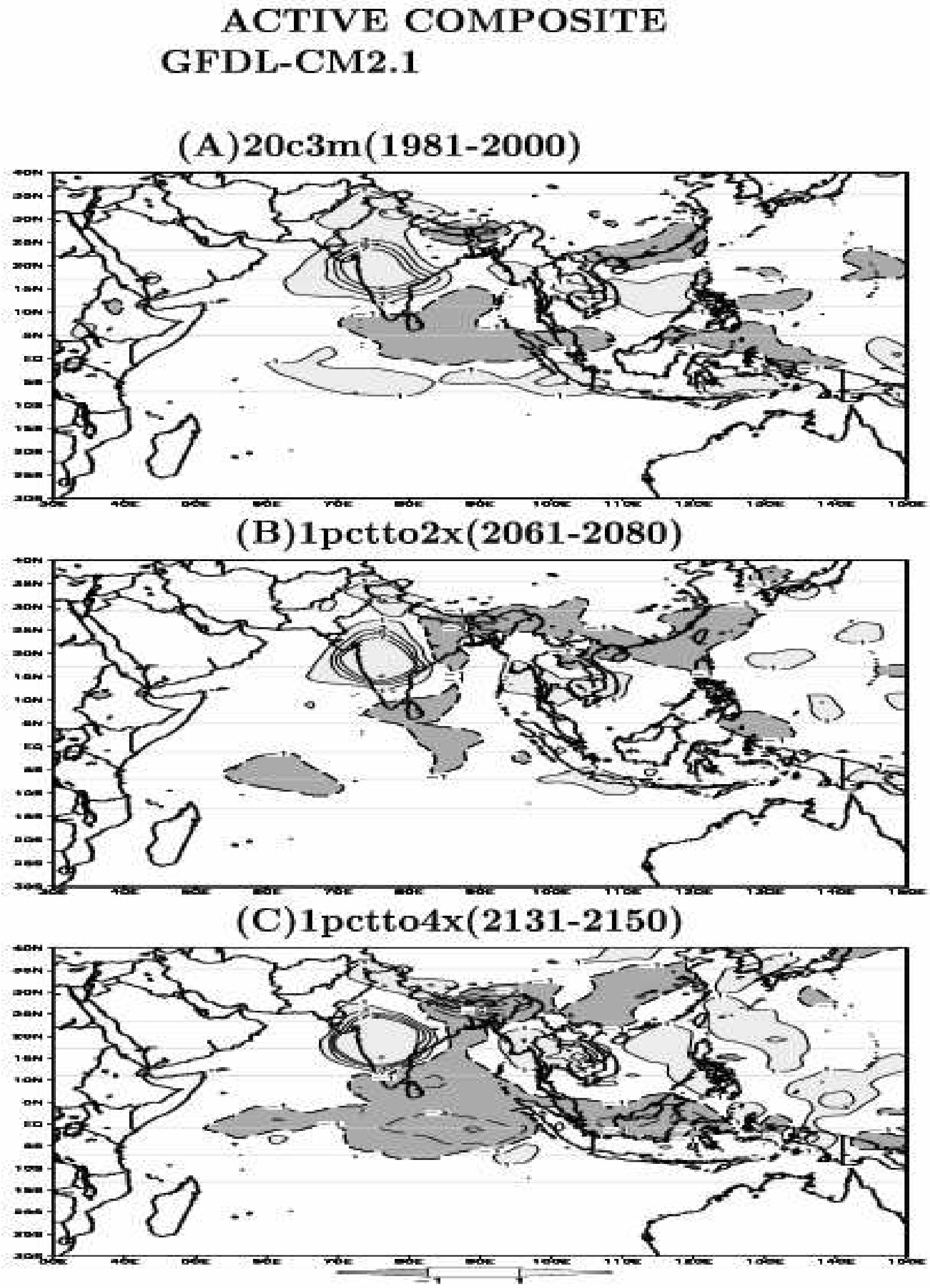

Figure14: Same as figure 13 except for GFDL-CM2.1 model

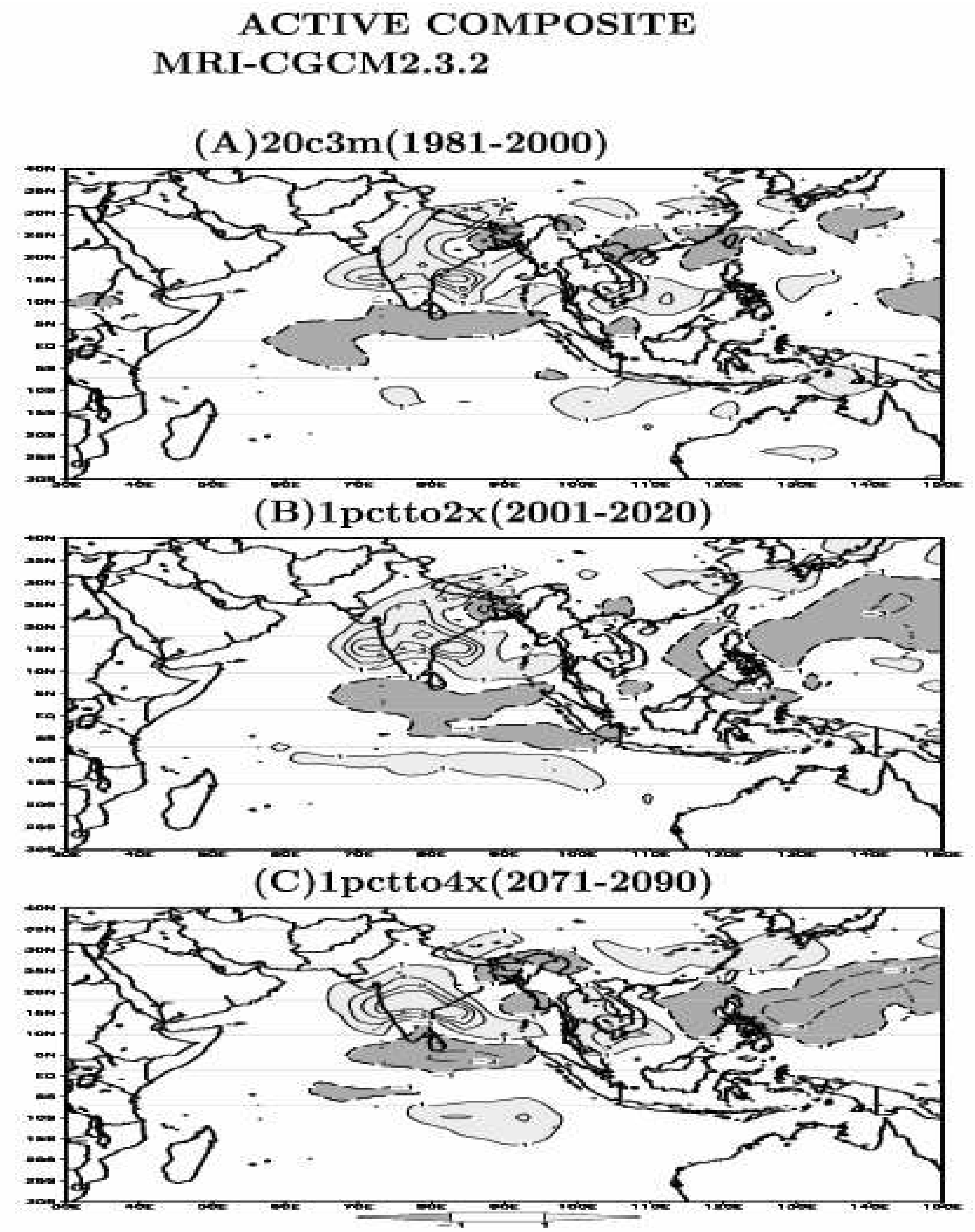

Figure 15: Same as figure 13 except for MRI-CGCM2.3.2

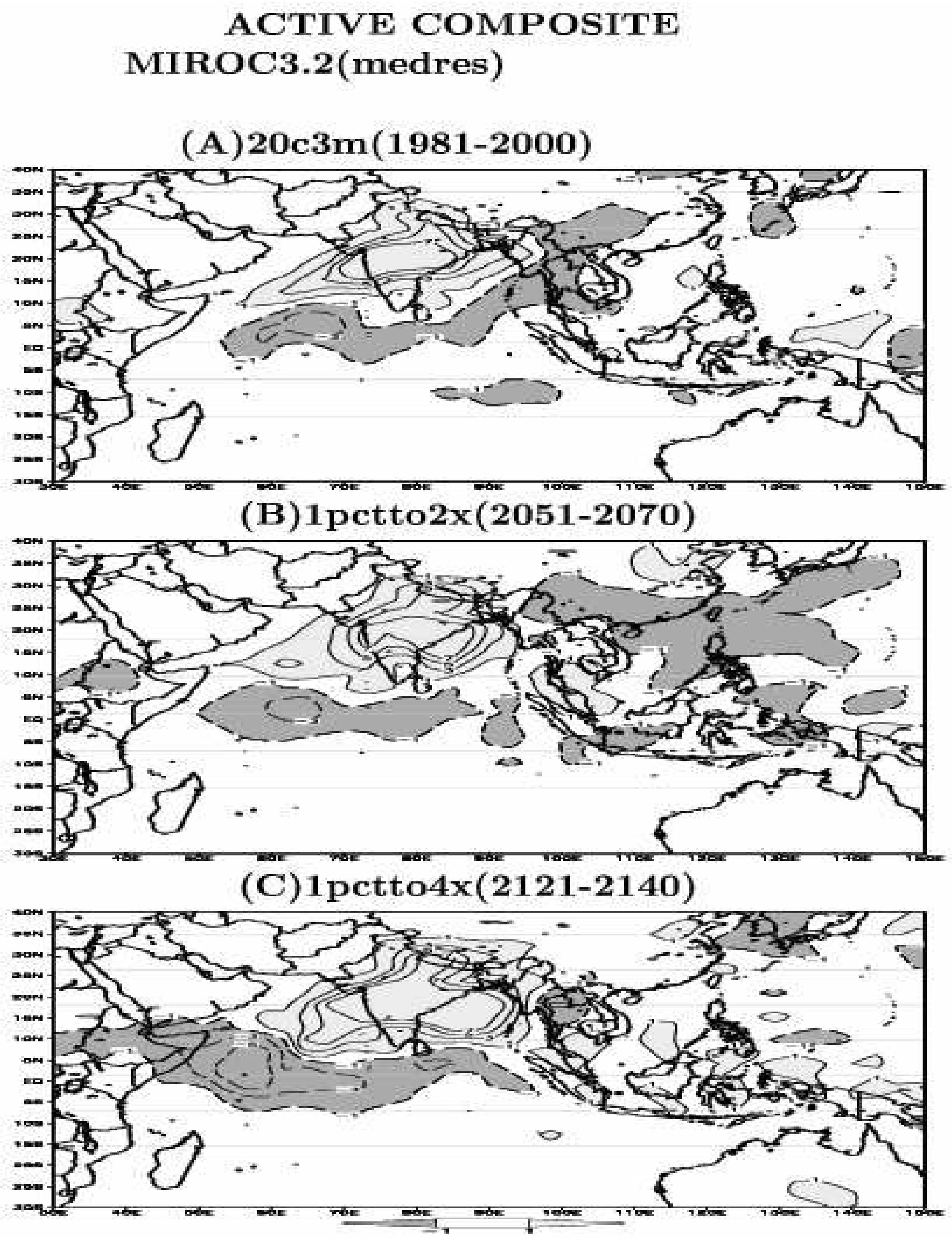

Figure 16: Same as figure 13 except for MIROC3.2(medres)

ACTIVE COMPOSITE
CGCM3.1(T47)

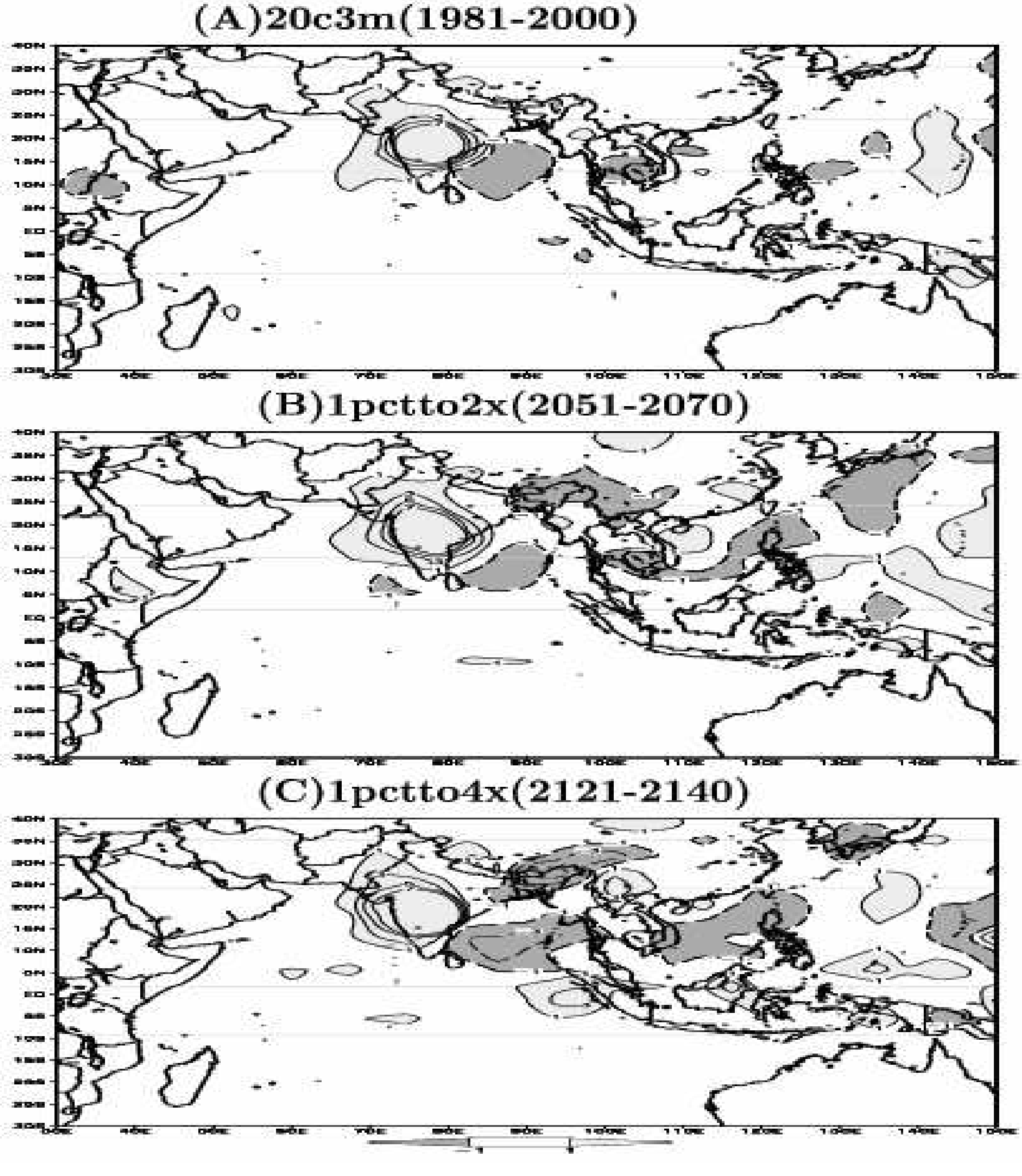

Figure 17: Same as figure 13 except for CGCM3.1

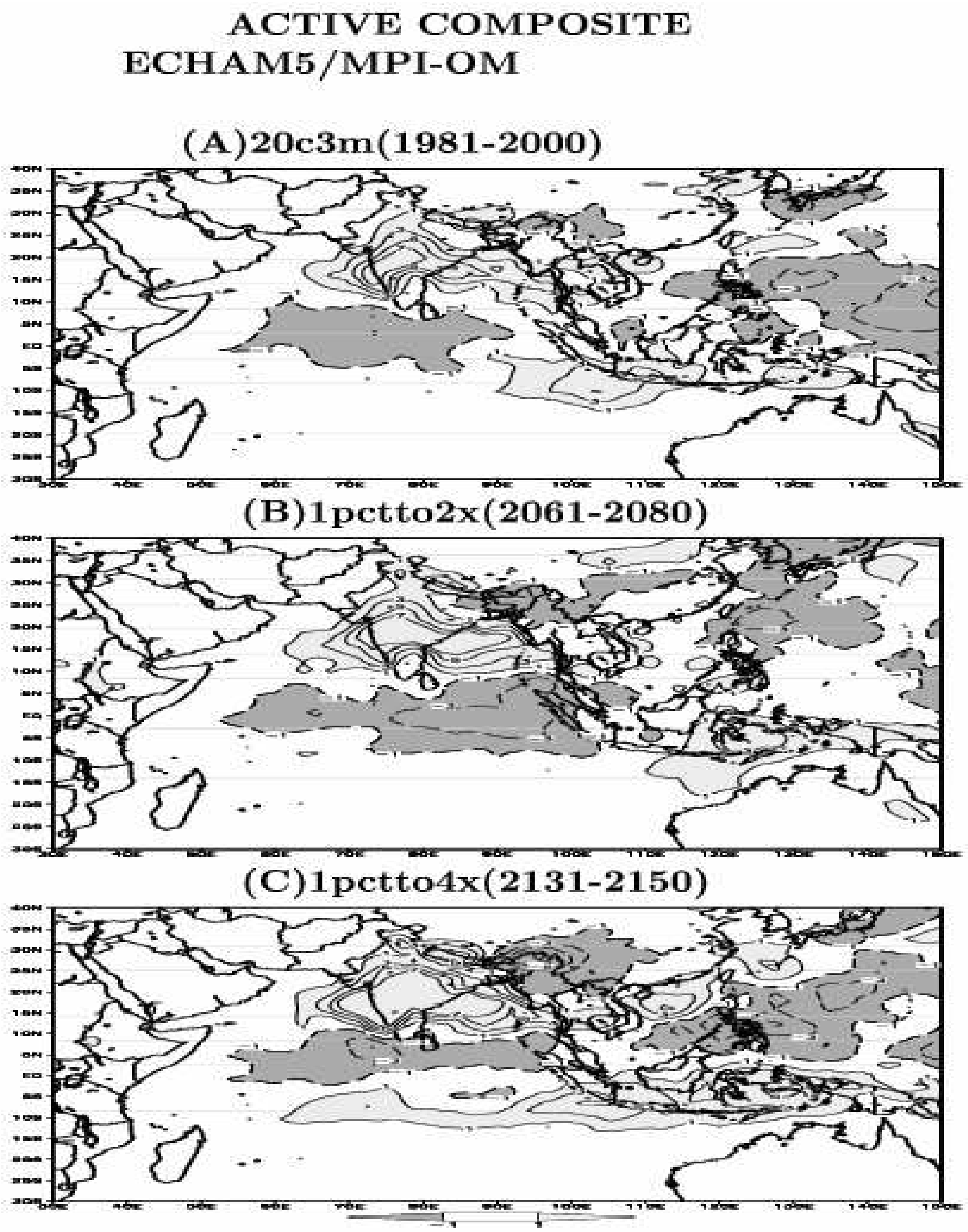

Figure 18: Same as figure 13 except for ECHAM5/MPI-OM