Simulation of regional features of the Indian summer monsoon in a GCM

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ABSTRACT

Major characteristics of South Asian summer monsoon climate are analyzed using simulations from the upgraded version of Florida State University Global Spectral Model (FSUGSM). The south Asian monsoon has been studied in terms of mean precipitation and low-level and upper-level circulation patterns and compared with observations. In addition, models fidelity in simulating monsoon intraseasonal and interannual variability and the teleconnection patterns associated with the monsoon interannual variability is examined.

The model is successful in simulating the major rainbelts over the Indian monsoon region. However, the model exhibits bias in simulating the precipitation bands over South China Sea and West Pacific region. Seasonal mean circulation patterns of low-level and upper-level winds are consistent with the models precipitation pattern. Basic features like onset and peak phase of monsoon is realistically simulated by the model. However, model simulation indicates an early withdrawal of monsoon. Northward propagation of rainbelts over the Indian continent is simulated fairly well, but over the ocean propagation is week. Model is able to simulate the meridional dipole structure associated with the monsoon intraseasonal variability realistically, though the equatorial component is bit week. Model is unable to capture the observed interannual variability of monsoon. Analysis of teleconnection patterns reveal that, in the model, eastern equatorial Pacific SST anomalies influence the Indian summer monsoon.

1. Introduction

The Indian summer monsoon (June-September, JJAS) precipitation is closely related to the annual evolution of the tropical convergence zone (TCZ, Gadgil 2003; Ramage 1971; Shukla 1987) and is characterized by some unique regional features. It includes, existence of two bands of maximum precipitation, one over the continent and north Bay of Bengal and the other over the Indian ocean between the equator and 10°S, the narrow maximum along the western Ghat with a rain shadow over the south eastern continent and the maximum over the head Bay of Bengal. Active and break spells of the Indian monsoon are unique regional features of monsoon intraseasonal oscillations (ISOs). The monsoon ISOs comprise of the 10-20 day westward propagating mode (Chen and Chen 1993; Goswami and Xavier 2004; Krishnamurti and Bhalme 1976) and the northward propagating 30-60 day mode (Goswami and Ajayamohan 2001; Sikka and Gadgil 1980; Webster et al. 1998; Yasunari 1979). The dominant monsoon ISO has large spatial scale similar to that of the seasonal mean and its interannual variability (Goswami and Ajayamohan 2001; Sperber et al. 2001). The evolution of the annual cycle of the monsoon and the monsoon ISOs are, therefore, intimately linked (Gadgil 2003; Goswami and Ajayamohan 2001; Waliser et al. 2003).

Prediction of the seasonal monsoon precipitation assumes great importance as the agricultural production and water resources depend crucially on the precipitation during the rainy summer season (Gadgil 2003; LinHo and Wang 2002; Webster et al. 1998). However, almost all climate models have insignificant (nearly zero) skill in simulating the observed interannual variability of the summer seasonal mean precipitation over the Asian monsoon region (Brankovic and Palmer 2000; Kang et al. 2002; Wang et al. 2004). Ability of a climate model to simulate and predict the seasonal mean precipitation anomalies depends on three factors, namely its ability simulate the observed climatological distribution of summer precipitation (systematic bias), its ability to simulate the forced mode of interannual variability associated with slow sea surface temperature (SST) variability

(ENSO) and the model's ability to correctly simulate the internal low frequency (LF) variability. The internal LF variability, in turn, appears to be generated by the intraseasonal oscillations (Ajayamohan and Goswami 2003; Goswami 1998; Goswami and Ajayamohan 2001). Therefore, the ability of a model to simulate the regional features of summer mean precipitation and the climatology of the monsoon ISOs with an acceptable degree of fidelity is essential for it to be useful for prediction of the seasonal mean.

Although the climate models have improved over the last couple of decades in simulating the global climate in general, almost all climate models still have serious problem in simulating the regional features of the Indian summer monsoon climate and its interannual variability Gadgil and Sajani (1998); Kang et al. (2002); Sperber and Palmer (1996). Gadgil and Sajani (1998) carried out a detailed analysis of monsoon precipitation simulation in over thirty models that participated in the Atmospheric Model Intercomparison Project (AMIP, Gates 1992). They find that a large number of models simulate exceptionally high precipitation over equatorial Indian Ocean (IO) and exceptionally low rainfall over the Indian continent. Even within the oceanic rainbelt, maximum precipitation is often simulated in the western IO rather than over the eastern IO as observed. Even when some models simulate continental rainbelt, they do so between 10°N and 15°N, much southward compared to the observed to the observed position of about 25°N. Poor simulation of the climatological mean precipitation may also influence the model's ability to simulate the teleconnection pattern associated with ENSO SST variability and hence in simulating the global forced mode. Recently, Waliser et al. (2003) assessed the intraseasonal variability associated with the Asian summer monsoon for 10 GCMs. They have shown that many models lack in representing the intraseasonal variability in the equatorial Indian ocean. Double convergence zone about the equator, lack of eastward propagation are some of the major problems identified in the simulation of intraseasonal oscillations. Unrealistically high (low) ISO activity in a model can give rise to unrealistic simulation of internal LF variability and influence simulation of seasonal mean anomaly.

In the present study we investigate the ability of the recently upgraded FSUGSM (Cocke and LaRow 2000; LaRow and Krishnamurti 1998) in simulating the complex regional features of climatological mean Indian summer monsoon. In this context, we will explore in detail how the model simulates the seasonal mean monsoon precipitation, intraseasonal and interannual monsoon variability and the associated teleconnection patterns and compare with the observations. Section.2 gives a brief description of the model, design of the numerical experiments and the data sets used for the study. Section.3 shows the the NH summer and winter climatology of the model and discusses its merits and demerits compared to observed climatologies. Section.4 considers the description on the model simulation of monsoon intraseasonal variability. Section.5 is the analysis of interannual variability of monsoon and it's teleconnection patterns. Main conclusions of this work is summarized in Section.6.

2. Experimental framework and data sources

FSUGSM is a global spectral model at horizontal resolution of T63 ($\sim 1.86^\circ$) with 17 unevenly spaced σ-levels. Brief description of the model is listed in LaRow and Krishnamurti (1998). The physical parameterizations include fourth order horizontal diffusion (Kanamitsu et al. 1983), modified KUO-type cumulus scheme (Krishnamurti et al. 1983), shallow convection (Tiedke 1984), large scale condensation (Kanamitsu 1975). Long and shortwave radiative fluxes are based on a band model (Harshvardhan and Corsetti 1984; Lacis and Hansen 1974), surface energy balance is coupled to similarity theory (Krishnamurti et al. 1991) with surface fluxes calculated via similarity theory (Businger et al. 1971). The parameterization of the low, middle and high clouds are based on threshold relative humidity values. Vertical turbulent transport for heat, momentum and moisture within the atmosphere are parameterized based on exchange coefficients that are functions of the Richardson number (Louis 1981). Details of the model's physical parameterizations can be found in Krishnamurti et al. (1991).

Since snow is not yet forecasted in the atmospheric model, the European Centre for Medium Range Weather Forecasts (ECMWF) analysis of monthly snow depth are used to determine the snow coverage. Snow depths greater than 20cm were assumed to completely cover the ground with an increased ground albedo. Linear interpolation between months were used to modify the snow cover and the resulting albedo field. The snow depth fields were used during the initialization and free forecast phase.

Observed pentad and monthly precipitation datasets based on Climate Prediction Centre Merged Analysis of Precipitation (CMAP; Xie and Arkin 1997) were used for validation of simulated precipitation. The National Centre for Environmental Prediction/National Centre for Atmospheric Research (NCEP/NCAR) daily and monthly reanalysis products (Kalnay et al. 1996) were used for validation of the circulation fields.

FSUGSM has recently been equipped with five different state-of-the-art cumulus parametrization schemes. They are (1) NCEP/SAS (National Centre for Environmental Prediction/Simplified Arakawa-Schubert; Pan and Wu 1994); (2) NCAR/ZM (National Center for Atmospheric Research; Zhang and McFarlane 1995); (3) NRL/RAS (Naval Research Laboratory/Relaxed Arakawa-Schubert; Rosmond 1992); (4) MIT (Massachusetts Institute of Technology; Emanuel and Zivkovic-Rothman 1999); and (5) GSFC/RAS (Goddard Space Flight Center/Relaxed Arakawa-Schubert; Moorthi and Suarez 1992). We first examined, how the south Asian monsoon is simulated by the model with these different schemes. For that purpose five five-month ensemble simulations with different initial conditions were carried out for two years (1987 and 1988). Initial conditions differ from each other by one day starting May 1. Fig.1 shows the ensemble mean of 10 realizations (5 each for 1987 and 1988) for each scheme compared with the observations. Observed precipitation shown in Fig.1(g) is based on CMAP. Main drawback in most schemes is the the inability of the model to simulate both the primary monsoon precipitation zone over the Indian continent and the secondary monsoon precipitation zone over the equatorial Indian ocean together. KUO scheme (Fig.1(e)), NCAR (Fig.1(b)), NRL (Fig.1(c)) overestimates precipitation over the Indian Ocean while NCEP (Fig.1(a)) and GSFC (Fig.1(d)) underestimates the precipitation over the Indian Ocean. NCEP, NCAR and NRL schemes simulates the two zones of precipitation as one zone resulting in above normal rainfall over the equator. Apart from that, all the five schemes except MIT (Fig.1(f)) fails to simulate the rain shadow region over the southern tip of the Indian peninsula. Position of the two major zones of precipitation is realistic in the MIT scheme, though there is too much rainfall over the foothills of Himalayas. We find that FSUGSM with MIT scheme is able to simulate the unique regional features of the south Asian monsoon region realistically and hence select this scheme for further analysis. Shin et al. (2003) also find that FSUGSM with MIT scheme produce better seasonal forecast over the Indian region. They have also shown that the MIT scheme is less sensitive to model resolution than any other scheme. We carry out a long integration (21 years;1982-2002) of the FSUGSM with the MIT convection scheme with observed weekly mean SST forcing. Weekly mean SST data is derived from Reynolds and Smith (1994).

3. Simulation of Seasonal Mean

In this section, we investigate the fidelity of FSUGSM in simulating the observed seasonal mean precipitation and circulation climatology. Fig.2(a,b) shows the seasonal mean precipitation simulated by the model in Northern-Hemisphere (NH) summer (JJAS) and winter (DJF) respectively. Fig.2(c,d) shows the corresponding observed precipitation from CMAP. The simulation of precipitation maxima over the Bay-of-Bengal (around 20°N) and west coast of India precipitation are remarkable when compared to the observations. FSUGSM succeeds in simulating the secondary precipitation maxima over the Indian Ocean whereas the model overestimates precipitation over Africa and Central America. Systematic error in simulation of JJAS climatological mean summer precipitation, however, occurs, over the south China Sea and the western north equatorial Pacific (110°E to 140°E) where the model climate is too dry compared to the observed. Also the south Pacific Convergence zone extends a bit too far to the east in the model. The pattern correlation between simulated and observed precipitation climatology in the tropics (0°-360° and 40°S-40°N) is 0.6. In winter, FSUGSM tend to simulate excess rainfall over the North Indian Ocean, Australia, South America and Africa. We note that the model's skill in simulating winter climatology is poor with all convection schemes. Model captures the precipitation zones in summer months reasonably well and shows systematic bias in simulating the observed precipitation zones realistically in the winter months.

The mean JJAS climatology of the Indian summer monsoon constructed from the 21-year simulations in terms of lower and upper level circulation is shown in Fig.3(a,b) while similar climatology of observed winds from NCEP/NCAR reanalysis are shown in Fig.3(c,d). The model simulates the geographical position of the low level jet, cross equatorial flow and the south equatorial easterlies realistically (Fig.3a and c). Consistent with the weaker simulated monsoon precipitation over the south China Sea region, the strength of the low-level winds are also weak than the observed. The pattern correlation between simulated and observed zonal and meridional wind climatology at 850 hPa over the domain 40°-140°E;20°S-35°N are 0.88 and 0.64 respectively. FSUGSM underestimates the strength of the upper level easterly jet. The Tibetan anticyclone is simulated bit too far to the north and the easterly jet is weaker than observed in general and maximum around 10°N rather than close to equator as in observations (see Fig.3b and d). The pattern correlation between simulated and observed zonal and meridional wind climatology at 200 hPa over the domain 40°-140°E;20°S-35°N are 0.94 and 0.56 respectively.

The model's ability in simulating the annual evolution of the Indian monsoon is tested in Figure 4. We select two indices to test models climatological annual evolution, one based on precipitation an the other that is directly linked to the dynamics. Goswami et al. (1999) demonstrated that an 'extended range Indian monsoon' rainfall index (EIMR) might yield a more comprehensive definition of the Indian summer monsoon. They defined EIMR as the mean JJAS precipitation averaged over 70°-110°E and 10°-30°N, taking into account the fact that the oceans and nearby regions of India play an important role in the Indian summer monsoon variability. An index based on the surface kinetic energy ($\frac{1}{2}$ ($u^2 + v^2$)) in the region 50°-65°E and 5°-15°N can be linked to the dynamics (Goswami et al. 1999; Ju and Slingo 1995). Since the low level winds over the Arabian Sea are strongly related to the precipitation over the monsoon region (Joseph and Sijikumar 2004), we constructed an index to represent kinetic energy (KE) of low-level jet (KELLJ) defined as the seasonal mean KE of winds at 850hPa averaged over 50°-65°E and 5°-15°N. Solid line in Fig.4 indicates the annual evolution of EIMR calculated from the 21-year climatology of FSUGSM while the dashed line line indicates the corresponding observed EIMR from CMAP. A first look at the plot suggests that the model is able to capture the annual evolution of monsoon except that the model amplitude of precipitation is higher than the observed. It is bit puzzling to note that the model simulation of august precipitation is weaker than the observed. Dashed dot line in Fig.4 indicates model KELLJ where as dotted line indicates the corresponding KELLJ from observations (NCEP). Sudden increase in Kinetic energy associated with the onset of monsoon in early May is well captured by the model. Kinetic energy decreases in mid August, indicating an early withdrawal of monsoon. This discrepancy which reflects in both the monsoon indices (EIMR and KELLJ) may be due to models soil moisture parametrization. Though the model simulates the onset of monsoon realistically, it has a systematic error in simulating the withdrawal phase of the monsoon in September. Fig.5a shows the north-south gradient of the vertically averaged (600hPa-200hPa) temperature from the model and Fig.5b shows the corresponding plot from the observations (NCEP). Solid line indicates the vertically averaged temperature over the northern latitudes (30°-130°E,10°S-40°N) and the dotted line represents vertically averaged temperature over the southern latitudes (30°-130°E,30°S-10°N). Early withdrawal of monsoon is also reflected here as the temperature gradient in the northern domain increases in mid August and

September. The reversal of the large scale temperature gradient is responsible for the onset and withdrawal phases of monsoon.

4. Simulation of Monsoon Intraseasonal Variability

Here we examine the characteristics of monsoon intraseasonal variability simulated by FSUGSM during the summer monsoon season (June-September) and validate it with the corresponding observed monsoon ISO characteristics. For this purpose, we have constructed daily anomalies of some fields (Precipitation, Zonal and meridional winds at 850hPa and 200hPa) by removing the mean and sum of annual and semiannual harmonics. To examine the intraseasonal temporal characteristics of simulated precipitation anomalies, a precipitation time series is created with daily anomalies between June 1 and September 30 for all 21 years averaged over a small region in the Bay-of-Bengal. Similar time series for zonal wind at 850hpa (U_{850}) averaged over a small region in the Arabian Sea is also created and a power spectrum analysis is carried out on these two time series (Fig.6). The model simulated precipitation and U_{850} show a statistically significant peak around 30-60 days which is consistent with the observations (Goswami and Ajayamohan 2001; Krishnamurti and Bhalme 1976; Yasunari 1980). In order to study the spatial characteristics of the monsoon intraseasonal oscillations which include both these preferred periodicities in detail, all the selected field anomalies are bandpass filtered using a Lanczos filter (Duchon 1979) to retain periodicities between 10 and 90 days for the period June 1 to September 30 for all the 21 years considered for the study. Intraseasonal precipitation variance simulated by the model during the northern summer monsoon season is shown in Fig.7a and the corresponding variance from observations is shown in Fig.7b. Model is able to simulate intraseasonal precipitation variance over the Arabian Sea, Bay-of-Bengal and equatorial Indian Ocean which are preferred locations of TCZ. However, model simulated intraseasonal variance over Arabia and some parts of Africa are in contrast with the observations. Model simulation of intraseasonal variance is poor over west Pacific which is consistent with the systematic bias of the model's summer monsoon rainfall climatology. Simulation of U_{850} intraseasonal variance is realistic over the Indian monsoon region (Fig.7). For low level zonal winds, intraseasonal variance simulated over the Bay-of-Bengal is deficient compared to observations. Systematic bias of the model in simulating the western Pacific winds reflects in the simulation of intraseasonal variance.

To evaluate models fidelity in simulating the propagation characteristics of monsoon ISO, a reference time series is created by averaging 10-90 day filtered precipitation over EIMR (70°-110°E;10°-25°N) during the summer monsoon season (1 June to 30 September) for all the simulated 21 years (1982-2002). Lag regression of 10-90 day filtered precipitation anomalies are then constructed with respect to the reference time series both for the model simulations as well as for observations. Regressed precipitation averaged over 70°-95°E is plotted as a function of latitude is shown in Fig.8a. Fig.8b represents a similar plot from observations. It is clear that the model simulates the northward propagation of monsoon ISO over the northern latitudes. However, model shows a bias in simulating the propagation characteristics over the southern latitudes. Model propagation starts from the tip of the Indian peninsula (north of 8°N). This may be due to problems associated with the models boundary layer formulation over the ocean to produce less rainfall over the ocean. Observations usually show a clean northward propagation of monsoon in the U_{850} field (Fig.8d). Model simulated U_{850} also show some northward propagation (Fig.8c) but it is weaker compared to observations.

The phase composite analysis (Murakami and Nakazawa 1985) is used to find the large-scale spatial structure associated with the monsoon ISOs. We calculated daily precipitation composites for all active and break days for the period 1982-2002 from 1 June to 30 September. Active and break days are defined using a reference time series created based on EIMR, active days are those for which filtered precipitation anomalies are greater than +1 standard deviation, while those less than -1 standard deviation are termed as break days. Fig.9 shows the climatological mean of all active and break days respectively for the 21-year period. When compared with the corresponding observed composites (Fig.9c,d), it is clear that the model simulates the meridional dipole structure associated with the Indian summer monsoon intraseasonal variability realistically (Fig.9a,b). However, it may be noted that the simulated intraseasonal variability over the warm waters of equatorial Indian Ocean is weak compared to observations. Similar phase composite analysis carried out on 850hPa winds is shown in Fig.10(a,b) and the corresponding analysis on observations is shown in Fig.10(c,d). Classic picture of spatial pattern of monsoon ISO involves enhancement (decrease) of monsoon low level winds in the active (break) phases of Indian summer monsoon. It is noteworthy that the model simulates the spatial pattern associated with the monsoon ISO for low-level winds fairly similar to that of the observed except that the amplitude of model simulated winds are weak. Also, consistent with bias in the model climatology, model fails to capture the intraseasonal variability over the west Pacific. Similar composite plot for upper-level winds is shown in Fig.11. Easterlies over the continent and location of the Tibetan anticyclone is simulated realistically by the model.

Thus, the model is successful in simulating the temporal and spatial characteristics of observed monsoon ISO during the northern summer over the Indian region reasonably well. In the next section, we examine model's fidelity in simulating the monsoon interannual variability.

5. Simulation of Monsoon Interannual Variability

Different monsoon indices are used to evaluate the strength of the monsoon rainfall over India and its interannual variability. Most commonly used index is the IMR (Indian Monsoon Rainfall index) defined as the precipitation averaged from June to September over India (Parthasarathy et al. 1994). This index is calculated based on data from 306 raingauge stations distributed uniformly through out India. It might be difficult to compare it directly with the simulated JJAS climatological mean precipitation averaged over the subcontinent. Hence, we use EIMR, precipitation averaged over 70°-110°E;10°-25°N as the rainfall index. Other indices used include kinetic energy of low-level jet (KELLJ, defined in section.3) and Monsoon Hadley-Circulation Index, an index based on meridional wind shear (MH; Goswami et al. 1999). This broad-scale index represents the monsoon variability as V_{850}-V_{200}, where V_{850} and V_{200} are the meridional anomalies of 850hPa and 200hPa wind anomalies averaged for the JJAS season over 70°-110°E and 10°-25°N. To compute these indices based on observations, CMAP data set is used calculate observed EIMR, NCEP winds are used to calculate KELLJ and MH. Fig.12 shows how these indices are simulated by the model. Fig.12a compares the Model EIMR with CMAP EIMR. A first look at this plot suggests that the model simulation of precipitation amplitude is generally high. Model simulation of interannual variability is poor as it is unable to simulate the amplitudes of the dry and wet years correctly. Fig.12b shows the different monsoon indices simulated by the model normalized by their own standard deviation. It is clear that there is a good correspondence between the indices within the model. Models fidelity in simulating interannual variability of monsoon precipitation is shown Fig.12c, where the normalized model-EIMR and CMAP-EIMR are plotted. Though the model simulates the dry and wet years of 1987 and 1988 correctly, it fails to capture the dry years of 2001 and 2002. In general, model simulation of interannual variability of monsoon is not reliable. Cross correlation between the different monsoon indices within the model and with the observations are summarized in Table-I. The correlation coefficient between EIMR and KELLJ is 0.85, while that of EIMR and MH is 0.5 and that between KELLJ and and MH is 0.59. This indicates that both the dynamical indices have good correlation with EIMR for FSUGSM. While comparing the model monsoon indices with the observed monsoon indices, it is seen that EIMR correlates poorly with MH but have moderate positive correlation with KELLJ. The correlation coefficient between model KELLJ and observed KELLJ is 0.43. Model KELLJ also have moderate positive correlation with model EIMR.

We evaluate the interannual variance simulated by FSUGSM for the 21-year period taken for the study. Fig.13a shows the interannual precipitation variance simulated by the model for the northern summer monsoon season (JJAS) while Fig.13b shows the corresponding interannual variance seen in the CMAP data set. Model simulation of interannual variance over the Indian monsoon region is reasonable when contrasted with the CMAP variance. Model succeeds in simulating interannual variance over the preferred zones of precipitation. However, the large interannual variance over western and central equatorial Pacific seen in the observations are not captured by the model. Fig.13c shows the interannual variance associated with the zonal winds at 850hPa simulated by the model for the northern summer monsoon season (JJAS) while Fig.13d shows the corresponding interannual variance seen in the observed data set. Model overestimates interannual variance over the equatorial Indian Ocean and underestimates variance over the west Pacific.

To find the large scale spatial structure associated with the simulated IAV of the summer monsoon, composite of precipitation and lower and upper level winds corresponding to strong and weak monsoon are calculated. Strong (weak) monsoons are identified based on normalized EIMR form model simulations and observed datasets. Strong (weak) monsoon years are identified as those years where the normalized EIMR is greater than 1 standard deviation (less than -1 std). Such strong monsoon composites of simulated precipitation and lower and upper level winds are shown in Fig.14. We can identify some similarities in the spatial structure of IAV of precipitation from model simulations and observations over the continent. Model simulates the west coast rainfall, maxima over the Bay-of-Bengal and the rainshadow region over the southeast India realistically. Systematic error of the model in simulating the west Pacific rainfall reflects in the simulation of IAV also. In the Indian Ocean region, model simulates the rainbelt as an elongated patch from 40°E to 120°E. Observations show and east-west dipole structure in this region. This bias is reflected in the simulation of IAV of 850hPa winds (see Fig.14c,d) as the south easterlies over the equatorial Indian Ocean is not captured by the model. Model simulates the 200hPa easterlies over the Indian Ocean region but fails to simulate it over the Indian continent when compared to observations.

It is clear from the above analysis that the model exhibits poor skill in the simulation of IAV of Indian summer monsoon. The question is whether the poor skill of simulation of IAV of monsoon is due to the systematic problem of the model or due to problems inherent with the IAV of monsoon system. Simulation of IAV of Indian monsoon is one of the most intriguing problems (Gadgil 2003; Gadgil et al. 2002). In this context, it might be interesting to look into how the model responds to observed forced variability associated with the SST variations.

6. Teleconnections

Impact of air-sea interaction associated with the changes in the Walker circulation induced by changes in the convection between Indian and Pacific Oceans are well known. Several studies have shown the significant ENSO-monsoon relationship on interannual time scales (Ju and Slingo 1995; Webster et al. 1998). Most of these studies indicate a close relationship between droughts of the Indian monsoon and El $\tilde{N}$ino. However, there seems to be a break down in this relationship in the recent decade (Krishakumar et al. 1995). To assess models performance in simulating interannual variations of Indian summer monsoon, it is important to ascertain some of models teleconnection patterns. Moreover, teleconnection analysis is used here as a measure of models ability to correctly simulate the component of interannual variability forced by the imposed boundary conditions. To start with, we examine the correlation coefficients between simulated northern summer monsoon precipitation and NINO-3 sea surface temperature anomalies (SSTA), a popular index used to quantify strength of ENSO signal. Fig.15a shows the lag-zero correlation map of JJAS NINO-3 SSTA with the simulated JJAS precipitation and Fig.15b shows the corresponding plot where NINO-3 SSTA is correlated with CMAP precipitation. Model simulates the ENSO related precipitation variability realistically. Precipitation over the Indian continent and NINO-3 SSTA are negatively correlated indicating a strong ENSO-Monsoon signal in the model simulations. However, observed correlation map (Fig.15b) does not show such a relationship, possibly due to the break down of ENSO-Monsoon relationship in the recent decade. Another interesting difference to note when contrasted with observations is the positive correlation of equatorial Indian Ocean precipitation with NINO-3 SSTA. This means that the convection over eastern Indian Ocean in model simulations seems to respond much more strongly on interannual time scales to interannual changes in SST than observed.

Relationship between various monsoon indices and ENSO is examined in terms of the teleconnection patterns revealed by lag-zero correlations between the indices and SST (similar to Sperber and Palmer 1996). The correlations between JJAS SST and the three monsoon indices (EIMR,KELLJ and MH) based on the 21-year simulation period (1982-2002) are shown in Fig.16. The patterns are similar in all three cases. Eastern equatorial Pacific is negatively correlated with the Indian summer monsoon, while the western Pacific and parts of Indian Ocean are positively correlated. The pattern of correlation in the equatorial Pacific is not El Niño like, as the negative correlation area is not equatorially confined. Negative correlation of monsoon indices with SST in the Arabian Sea along the coast of Africa and Arabia may be due to strong winds along this route in monsoon time. Stronger winds causes higher evaporation resulting in upwelling and mixing would cool SST. For MH (Fig.16c) negative correlation band is wider over the Indian Ocean.

Next, we examine how the Walker and Hadley circulation associated with ENSO is simulated by FSUGSM. For this purpose, JJAS averaged zonal, meridional and vertical wind anomalies were regressed with NINO-3 SST. Fig.17a shows the anomalous Hadley circulation pattern associated with ENSO simulated by FSUGSM averaged over 70°-

90°E and Fig.17c shows the anomalous Walker circulation pattern simulated averaged over a domain 5°S-5°N. Fig.17c,d shows the corresponding Walker and Hadley circulation pattern from NCEP. Associated with shift of the Walker circulation during El Niño (La Niña), there is large increase in convergence (divergence) over the equatorial Pacific Ocean enhancing (decreasing) convection over equatorial Indian Ocean and thereby strengthening (weakening) the monsoon Hadley circulation. Ascending motion associated with warm SST over equatorial Pacific is simulated realistically. However, the strength of the descending cell over 120°E is weak in the model and hence underestimates the strength of Hadley cell.

7. Summary and Discussion

Using simulations from the upgraded version of FSUGSM, major characteristics of south Asian summer monsoon climate is studied and validated with the observed data sets. In addition to assessing the simulation of mean summer monsoon rainfall and it's associated circulation patterns, the fidelity of the model in reproducing the monsoon seasonal cycle, intraseasonal variability, interannual variability and associated teleconnection patterns are also investigated.

FSUGSM is able to simulate the unique regional features associated with the Indian summer monsoon realistically. The model produces a reasonable representation of the seasonal mean monsoon precipitation and circulation features although the amplitude of simulated precipitation and monsoon flow is higher than the observed. The major precipitation bands over the monsoon domain, one over the continent and Bay-of-Bengal and the other over the warm waters of the Indian Ocean is realistically simulated. The rainshadow region over the southeastern tip of the peninsula and the narrow maximum along the western ghats is simulated correctly. However, the model shows systematic bias in simulating the rainbands over south China Sea region and western north Pacific. These model biases reflects in the simulated lower and upper level winds. Though the model succeeds in simulating the onset phase of Indian summer monsoon correctly, the withdrawal phase is simulated 30 days earlier than observed.

Model simulates the temporal and spatial characteristics associated with the intraseasonal variability of the Indian monsoon with reasonable accuracy. Power spectrum analysis carried out on model simulated precipitation and low level zonal wind anomalies show statistically significant peaks between 30 and 60 days similar to observations. Spatial structure of active and break phases of Indian summer monsoon simulated by the model are similar to that seen in observations. However, the low level winds simulated by the model is too zonal over the equatorial Indian Ocean compared to observations. This discrepancy is reflected in the simulation of precipitation and 200hPa winds also. Northward propagation of intraseasonal anomalies are restricted over the land in the model simulations unlike the observations. Some characteristics of the monsoon intraseasonal oscillations are related to ocean-atmosphere coupling in the Indian Ocean and hence the intraseasonal variability of the model may be improved by coupling the model with ocean. Recently Rajendran et al. (2004) have shown that coupling over the Indian Ocean improves the simulation of monsoon intraseasonal oscillations.

Model shows poor skill in simulating the interannual variability of Indian summer monsoon. We examined the spatial structure associated with the interannual variability of monsoon. Model simulates the rainbelt over the equatorial Indian Ocean as an elongated patch and fails to capture the east-west dipole structure of precipitation seen in observations over this region. It is to be noted that most dynamical models fail to capture the interannual variability associated with the Indian summer monsoon. This may be due to the fact that the predictability of the Indian summer monsoon is limited by internal variability whose amplitude over this region is comparable to that of the forced variability arising from slowly varying boundary forcings. Teleconnection analysis of the IAV of the Indian summer monsoon reveal models fidelity is simulating the component of IAV forced by sea surface temperature. Model simulates the ENSO related precipitation variability reasonably well. ENSO-monsoon relationship is bit stronger in the model than observed. Ascending cell of Walker circulation due to warming of equatorial Pacific is simulated well. However, the descending cell over 120°E is weak in the model and hence the strengthening of the Hadley cell is not simulated realistically.

FSUGSM is able to simulate the complex and unique regional features associated with the Indian summer monsoon with a fair amount of success. Model shows systematic bias in simulating western north Pacific rainband. Northward propagation associated with the monsoon intraseasonal seasonal oscillation are not simulated realistically over the Indian Ocean. Model shows poor skill in simulating the interannual variability of monsoon. Model needs considerable improvement to eliminate these biases to simulate the interannual variability associated with the Indian summer monsoon. Incorporating a new land surface scheme and coupling the model with ocean may help in eliminating some of these biases.

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Figure Captions

FIG. 1. Ensemble mean JJAS seasonal mean precipitation (mm.day^{-1}) simulated by FSUGSM using different convection schemes. Seasonal mean precipitation is calculated as the mean of ten ensembles for 1987 amd 1988 with different initial conditions.

FIG. 2. (a,b) 21-year climatology of JJAS and DJF seasonal mean precipitation (mm.day^{-1}) (c,d) Same as in (a,b) but from observations (CMAP).

FIG. 3. (a,b) 21-year climatology of JJAS seasonal mean 850hPa and 200hPa winds (ms^{-1}). (c,d) shows the corresponding observed winds from NCEP/NCAR Reanalysis.

FIG. 4. Climatological annual mean evolution of monsoon indices. Indices are defined in section.3

FIG. 5. Vertically averaged (600hPa to 200hPa) temperature over the northern latitudes (30°-130°E,10°-40°N, solid line) annd over the southern latitudes (30°-130°E,30°S-10°N, dotted line).

FIG. 6. An example showing power spectrum of precipitation and zonal winds at 850hPa (U_{850}). Precipitation anomalies are averaged over 85°-95°E and 10°-15°N and U_{850} anomalies are averaged over 55°-65°E and 5°-10°N. Dashed line indicates 95% confidence limit.

FIG. 7. (a) Intraseasonal Variance of 10-90 day filtered June-September precipitation anomalies (mm.day^{-1}) from the model. (b) Same as (a) but from CMAP. (c) Intraseasonal Variance of 10-90 day filtered June-September zonal wind anomalies at 850hPa (ms^{-1}) from the model. (d) Same as (c) but from NCEP/NCAR Reanalysis.

Fig. 8. (a) Latitude versus lags (days) plot of 70°-95°E averaged filtered precipitation anomalies (mm.day^{-1}). (b) Same as (a) but for CMAP. (c) for zonal wind anomalies at 850hPa (ms^{-1}). (d) Same as (c) but from NCEP/NCAR Reanalysis.

Fig. 9. (a) Active minus break precipitation composites (mm.day^{-1}) from the model and (b) from CMAP. Composites are calculated from 10-90 day filtered precipitation anomalies based on normalized EIMR.

Fig. 10. Same as Fig.9 but for 850hPa winds (ms^{-1}).

Fig. 11. Same as Fig.9 but for 200hPa winds (ms^{-1}).

Fig. 12. Different indices of monsoon interannual variability. (a) EIMR from model and CMAP and IMR. (b) Normalized EIMR, MH and KELLJ.

Fig. 13. (a) Interannual variance of JJAS seasonal mean precipitation anomalies (mm.day^{-1}) from model (b) Same as in (a) but for CMAP (c) for zonal wind anomalies at 850hPa (ms^{-1}) (d) Same as in (a) but from NCEP/NCAR Reanalysis.

Fig. 14. Strong minus weak composites of seasonal mean precipitation and wind anomalies. (a) Model Precipitation (b) CMAP Precipitation (c) 850hPa winds from model (d) 850hPa winds from NCEP (e) 850hPa winds from model (f) 850hPa winds from NCEP. Strong/Weak monsoon years are identified based on normalized EIMR.

Fig. 15. (a) Correlation coefficients between JJAS NINO-3 sea surface temperature anomalies (SSTA) and JJAS model precipitation (b) Same as (a) but with respect to CMAP precipitation.

Fig. 16. Correlation coefficients (r) between different monsoon indices calculated from model simulations versus JJAS/DJF sea surface temperature. (a) r between model EIMR and JJAS SST (b) r between CMAP EIMR and JJAS SST (c) r between model EIMR and DJF SST (d) r between CMAP EIMR and DJF SST

Fig. 17. Hadley and Walker circulation changes associated with ENSO. Simulated zonal (u) and meridional (v) and vertical (w) winds were regressed at zero lag at all grid points with JJAS NINO-3 SSTA. (a) JJAS 70°-95°E averaged u,v and w (x 0.5×10^4) anomalies at different levels plotted as a function of latitude. (b) Same as (a) but from NCEP (w x 0.1×10^3) (c)JJAS 5°S-5°N averaged u,v and w (x 0.2×10^5) anomalies at different levels plotted as a function of longitude. Unit vector for vertical velocity corresponds to 0.5×10^4 hPas^{-1} in plot (a) and 0.2×10^5 hPas^{-1} in plot (b). (d) Same as (c) but from NCEP (w x 0.14×10^3).

Fig. 18. Table:1 (left panel) Cross correlation between the different monsoon indices calculated from model. (right panel) Cross correlation beteen the different monsoon indices calculated from model simulations with that calculated from observed data sets.