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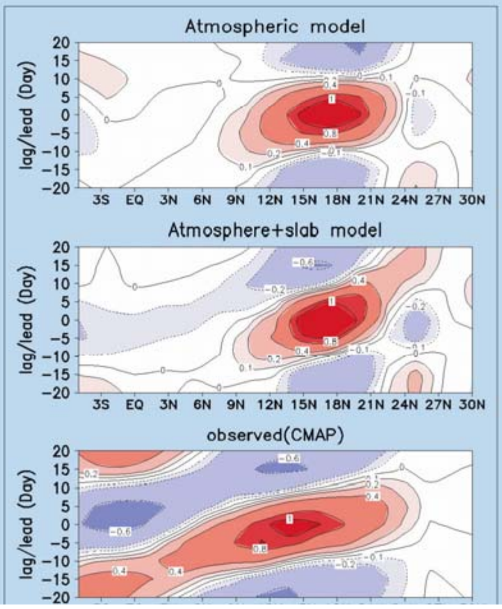

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Content

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by

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Abstract

The ability of the atmosphere-slab ocean coupled model in simulating the northward propagation associated with 30-60 day mode of intraseasonal oscillation (ISO) during summer monsoon season is examined and, compared with the performance of the atmosphere-only component of the same model. Portable Unified Model (PUM) developed by Hadley centre for climate prediction and research, U.K. is used for the purpose. Pair of identical experiments are performed with the atmosphere-slab ocean coupled model and its atmosphere-only counterpart of PUM. Each experiment is comprised of single realization for the 11-years period with the respective model. The standalone atmospheric model is forced with monthly mean observed sea surface temperatures (SST). In an experiment with coupled model, SSTs evolve according to mutual interaction of atmosphere with the mixed layer slab ocean model.

The 30-60day mode of ISO simulated by the model in both experiments during summer monsoon season is compared with corresponding observations. Atmosphere-slab ocean coupled model is better able to simulate meridional propagation of 30-60 day mode of ISO from Equatorial Indian ocean to Indian subcontinent than its atmosphere only counterpart. SST forcing is monthly mean and modification of SST by atmosphere is neglected in an experiment with atmospheric model. Consequence is the poor simulation of northward propagation of 30-60 day mode of monsoon ISO. It is concluded that interactive SST along with its variations on daily scale in coupled model setup facilitates the improved simulation with respect to northward movement of 30-60 day mode of ISO during summer monsoon over India.

1. Introduction

a. Boreal summer intraseasonal oscillations

Asian Summer Monsoon (ASM) exhibits substantial intraseasonal variability (ISV) in the form of active and break spells with enhanced and reduced rainfall respectively over the Indian subcontinent. The ISV over ASM region consist of oscillations with two period ranges broadly falling in the range of 10-20days (Murakami 1976; Krishnamurthy and Bhalme 1976) and 30-60days (Dakshinamurthy and Keshavamurthy 1976; Yasunari 1979, 1980; Sikka and Gadgil 1980). Together, westward propagating 10-20day mode in the northwestern tropical Pacific and northward propagating 30-60day mode, are referred as **Boreal Summer Intraseasonal Oscillation** (BSISO) (Wang and Xie, 1997 and Annamalai and Sperber, 2005). From early 1980's, the evidence of south to north progression of rainfall and circulation anomalies across India during the summer monsoon months with a recurrence period of about 40 days using the observed data was noted (Singh and Kripalani,1985,1986, Kripalani et.al.,1991). Several authors (Yasunari 1979; Sikka and Gadgil 1980; Krishnamurti and Subrahmanyan 1982; Murakami et al. 1984; Lau and Chen 1986; Gadgil, 1990; Wang and Rui 1990) have shown that the 30-60day mode of BSISO is dominated by organized convective events that form in the equatorial Indian Ocean and then exhibit northward movement. Thus the prominent feature of this mode is the meridional propagation from about 5 ^{o}S to 25^{o}N with an approximate speed of about 1^{0}-2^{0} latitude day $^{-1}$ over south Asian monsoon region (Gadgil, 1990; Lawrence and Webster, 2002, Webster and Hoyos, 2004). The convection in Eastern Equatorial Indian Ocean is anticorrelated with that over India (Annamalai and Sperber, 2005, Klingaman et.al.2008a). The structure of 30-60day mode of ISO is described in detail by previous researchers. (Annamalai and Slingo 2001, Kemball-Cook and Wang 2001, Goswami 2006, and Klingaman et.al.2008a). Significant progress has been achieved using observations and numerical experiments in understanding the physical processes, feedbacks and mechanisms underlying complex interactions governing 30-60 day mode of ISO (Goswami,2006,Wang, 2006, Slingo, Inness and Spereber, 2006 and references therein). The studies have confirmed the contributions of air-sea coupling in enhancing the northward propagation of boreal summer ISOs (Fu and Wang, 2004, Goswami, 2006, Hendon, 2006 and the references therein), that is described in the following section.

b. Role of atmosphere-ocean coupling in the BSISO

The limited ability is exhibited by the Atmospheric General Circulation Models (AGCMs) to represent observed monsoon ISV in tropics (Rajendran et.al. 2002, Waliser et.al.2003 b, and c). A recent study (Klingaman et. al. 2008b) has demonstrated that SST variability at frequencies higher than 5 days contributes to better representation of 30-60day mode of ISO in an AGCM. Hadley Centre atmospheric model used in their study when forced with observed daily SST forcing displayed stronger ISV (in convection), which is more consistent with observation than 5-day means and monthly mean SST forcing. However, off late many researchers have recognized the deficient simulation by AGCMs that prompted them to use coupled Atmosphere-Ocean General Circulation Models (AOGCMs) for tropical ISV simulation (Fu and Wang, 2004, Zheng et.al. 2004, Jiang et.al. 2004, Rajendran and Kitoh, 2006, Klingaman et. al. 2011). Still the fact that the AGCMs generated weak monsoon BSISO suggests that basic oscillation and northward propagation may be of atmospheric origin that probably results from internal atmospheric variability. Air-sea interaction can only modulate amplitude, frequency domain and northward propagation characteristics of BSISO (Fu et.al.2003, Rajendran and Kitoh, 2006, Fu et. al. 2007, Wang et.al.2009). However, there are limitations with AOGCMs also as indicated by significant problems in representation of BSISO by several AOGCMs that participated in different model intercomparison studies. All models from the Intergovernmental Panel on Climate Change (IPCC) Fourth assessment Report (AR4) (Lin et.al.2008) and the Development of a European Multimodel Ensemble System for Seasonal-to-Interannual Prediction (DEMTER) project have confirmed this deficiency in simulation of summertime ISV (Xavier et.al. 2008).

The presence of active air-sea interactions during summer ISO's is also demonstrated by various observations. Evidence of air-sea interaction is suggested from coherent space-time evolution of atmospheric convection, SST and surface fluxes associated with monsoon ISO using in-situ (Krishnamurti, et.al.,1988, Bhat et. al. 2001, Sengupta and Ravichandran, 2001) and remote observations (Sengupta et.al.2001, Webster et.al.2002, Klingaman et.al. 2008a).

c. The purpose of the present study

The focus of the present study is to investigate the impact of atmosphere-ocean coupling along with higher frequency SST variability in the atmosphere-slab ocean model on the simulated northward propagating 30-60day mode of ISO. While it is not possible to isolate the role of air-sea interaction from observation, models can be used for the purpose. The authors use Portable Unified Model (PUM) to address this issue. Single ensemble integration using atmosphere-only (AGCM) and atmosphere-slab ocean coupled version (referred hereafter as AGCM+Slab) of PUM is conducted to study the problem.

Brief description of model used [(PUM -AGCM and AGCM+slab)] is given in section 2a, followed by section 2b providing the details of model experiments. The model/observed comparison of SST climatology is described in section 3a and precipitation in section 3b. The intraseasonal variability of precipitation simulated by the standalone atmospheric model, atmosphere-slab ocean coupled model and corresponding observation is presented in section 4. Section 5 is reserved for Summary and discussion of results.

2. Model description and experimental design

a. Model description

A numerical model known as ‘Portable Unified Model (PUM)’, version 4.5, is used in the present study. The Unified Model (UM) is the name given to the suite of atmospheric and oceanic numerical modeling software developed and used at the Hadley centre, U.K., for climate prediction and research. PUM is one of the world’s leading numerical prediction models. The design of PUM modeling system is such that it can be run in atmosphere-only, ocean-only or in coupled mode. In the present study, atmosphere-only and Atmosphere-slab ocean coupled mode of PUM are utilized.

PUM applies grid-point scheme on regular latitude-longitude grid in the horizontal with the resolution of 2.5^o latitude x 3.75^o longitude. The atmospheric component of the model is documented earlier (Gordon et. al. 2000), which is the same as atmospheric component of the coupled ocean-atmosphere model referred as ‘HadCM3’.

The slab model is coupled to the atmospheric model. The slab model consists of a simple thermodynamic mixed layer ocean model of fixed depth. In the slab ocean model, the ocean is represented by a single layer of water (of constant thickness for which standard value of 50m is selected), that is assumed to be perfectly mixed. At sea points, the atmosphere model requires the sea surface temperature, together with an ice depth and concentration when sea-ice is present. In an atmosphere only run, the data for these surface conditions is provided from ancillary files. When the slab model is included, the SST and ice parameters are computed interactively during the run. The atmosphere model is run for one coupling period, typically 1 day, during which the driving fluxes for the slab model are averaged. Then the slab model is called (typically with a 1 day timestep) to update the SST, ice depth and concentration, which are passed back to the atmosphere model for use over the next coupling period. The detail description of slab ocean component of PUM is reported by William et al., 2000.

The slab ocean model does not include ocean currents. Thus a representation of the heat flux from the surrounding ocean must be applied in order to provide a realistic SST distribution. This is known as ‘heat convergence’.

b. Model experimental design

Prior to conduct experiments for the objective of the study, calibration experiment is required to calculate heat convergence. Slab ocean model is coupled to atmospheric model and SST and ice parameters are computed in calibration run, but after every five days SSTs are restored to climatological reference values provided by an ancillary file. The corrective heat flux required for resetting computed SSTs to climatology is stored, which will also correct for errors in the surface fluxes. At sea-ice points, SST under the ice is reset but no correction is applied to the ice depth. If a grid-point which is open ocean during calibration experiment becomes ice covered during subsequent slab model integration and possesses a large negative heat convergence, then ice can grow rapidly through an unwanted feedback. This will take the model away from the climatological open ocean. Thus at the start of the time step in control runs, heat convergence less than a user-specified value (recommended to be 40 wm^{-2}) are reset to the specified value with the excess being distributed evenly over all the open ocean points in the same hemisphere.

A calibration experiment is made for the period of 10-years. Monthly mean heat convergence fluxes averaged over 10-years of calibration run is used in control experiments performed with atmosphere-slab ocean model.

Two parallel sets of integration for the period 1985-1995 with PUM are made; one with atmosphere only model and another set with AGCM+slab ocean coupled model. Both set of experiments start from the same initial condition of 1st April 1985, created from NCEP reanalysis data. The details of NCEP reanalysis data are given in Kalnay et. al. (1996). The only difference between the two experiments is that one experiment is carried with uncoupled atmospheric model, in which known ocean conditions are specified from observed SST. In this particular experiment, atmospheric model is driven by monthly observed Optimum Interpolated SST (OISST) data. The other experiment is performed with atmosphere-slab ocean coupled model that interactively computes SST and sea ice during the model integration.

Experiment made with AGCM + slab Ocean includes both the atmosphere-slab ocean coupling and the higher frequency (daily) SST variability. On the other hand, in atmosphere only model experiment specified monthly mean SST forces atmosphere which responds passively to the forcing.

3. Model climatology

For GCMs to be useful for monsoon diagnostic and prediction studies, it is important that prime features of the mean summer monsoon are simulated with moderate skill. It is unlikely that models with large errors in simulating the mean climate will be able to simulate and predict its variability. Thus mean summer monsoon simulated by the atmosphereonly and atmosphere-slab ocean coupled configuration of PUM is assessed. Monsoon simulated in coupled model is related to SST and thus SST climatology is also examined.

a. JJAS mean SST

SST climatology is based on single realization of the AGCM+slab ocean model for the period (1984-2003). JJAS mean SST climatology simulated by the model is illustrated in Figure 1a and corresponding OISST observation in Figure 1b.

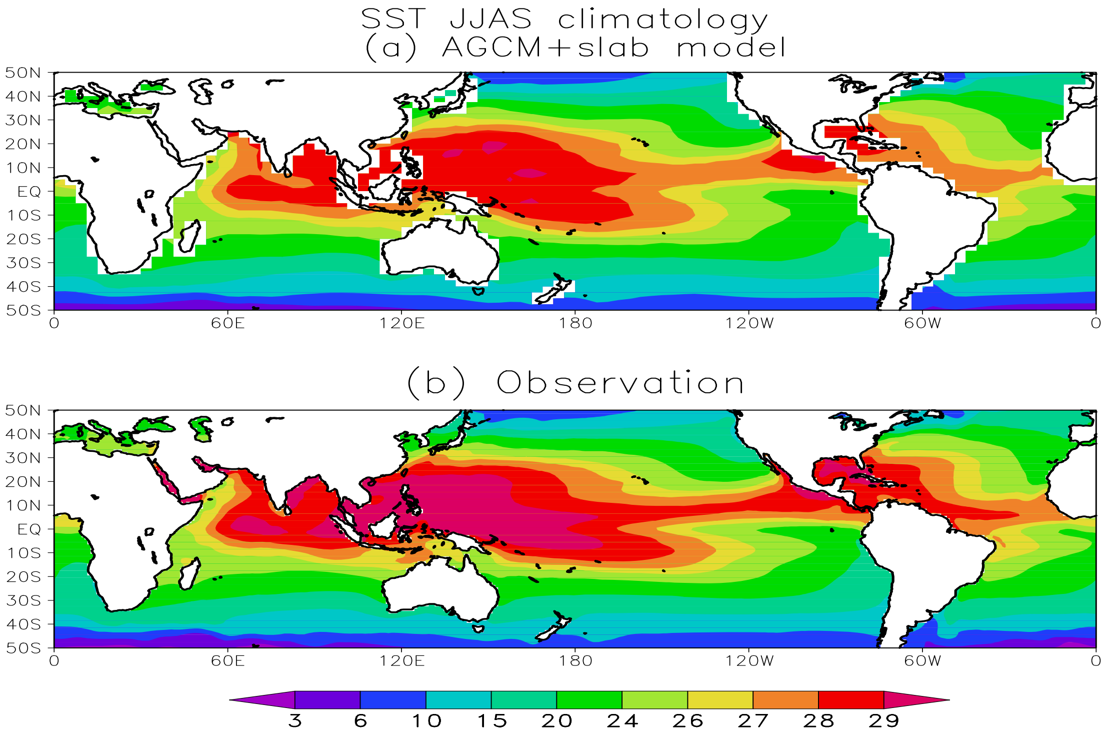


Figure 1: JJAS SST (^{o}C) climatology based on 1984-2003 (a) AGCM+slab model (b) observation

Chief features of observed climatology are the warmest temperature in tropics and northern hemisphere subtropics with temperature decreasing towards poles. Model captured the prime aspects of mean SST except for difference in magnitude of tropical SST from observation. Figure 3 shows that the simulated SST over tropical Indian ocean, west and central Pacific ocean and tropical Atlantic Ocean are underestimated.

b. JJAS mean Precipitation

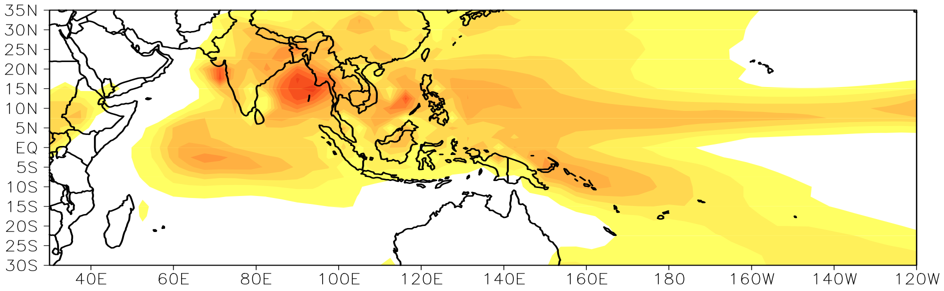
The relative performance of mean summer monsoon in AGCM and AGCM+slab ocean model simulation is appraised. The atmospheric model climatology is based on the sample of 126 monsoon seasons (21 seasons /6members). PUM AGCM is integrated in hindcast mode for 21 summer monsoon seasons from 1984-2004. Set of six ensemble members are run for each monsoon season. Members of ensemble for particular monsoon season differ in starting atmospheric states while forced with the same boundary forcing of SST. Six ensemble members are initiated from consecutive analysis one day apart. Ensemble run provides a measure of the AGCM's sensitivity to small differences in initial conditions. The atmospheric initial states for ensemble members are created from daily NCEP reanalysis data corresponding to zero GMT of 25-30th April of corresponding season. The model is integrated till end of September. The initial conditions are selected about a month in advance of monsoon season so as to allow GCM to spin up. Monthly observed Optimum Interpolated Sea surface temperature (OISST) (version v2) data is used as boundary forcing for the model. The data is downloaded from http://www.ncep.noaa.gov. OISST data is available on 1^0 long x 1^0 lat resolution. Detail description of OISST is described by (Reynolds et. al. (2002)). AGCM+slab ocean coupled model climatology is estimated from single realization for the period (1984-2003).

Summer monsoon precipitation climatology in two model setups namely atmosphere only and AGCM + slab Ocean are shown in figures 2a and 2b respectively and their difference (AGCM-[AGCM +slab]) in figure 2c. Observed climatology from Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) is shown in figure 2d. CMAP data is available on 2.5^o long x 2.5^o lat grid over 88.75^o N-88.75^o S and 1.25^o E-358.75^o E. It is downloaded from http://www.cdc.noaa.gov. Xie and Arkin (1997) provide the details of CMAP data set.

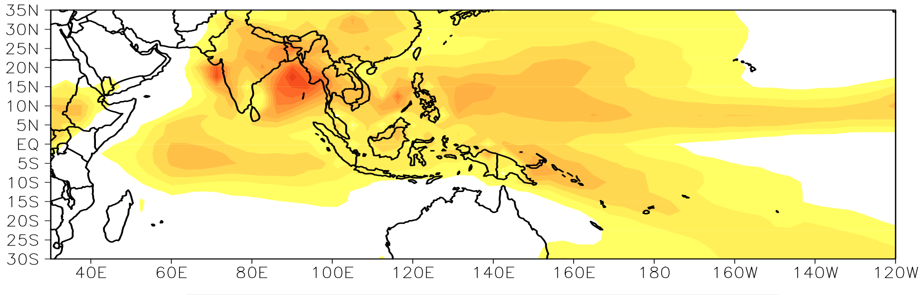
Indian region is characterized by precipitation maxima over west coast and head Bay of Bengal and the rain shadow over northeast peninsula as illustrated in CMAP observation (Figure 2d). These prime precipitation centers and major large scale features in model are reasonably close to observation. However, locations of the certain precipitation centers in model deviates from observation such as the west coast of India, head Bay of Bengal and equatorial Indian ocean. Besides, model overestimates precipitation over majority of Indian land region and Bay of Bengal. There is resemblance in two setups (standalone atmospheric and coupled model) over Indian land region except for small departure over northeast peninsula. There are larger differences over Indian ocean (large positive) and North Pacific Ocean (large negative) (Figure 2c). The western Equatorial Indian Ocean maximum is diminished in the coupled setup. AGCM underestimates precipitation over north Pacific ocean with respect to AGCM+slab ocean model.

JJAS Precipitation Climatology

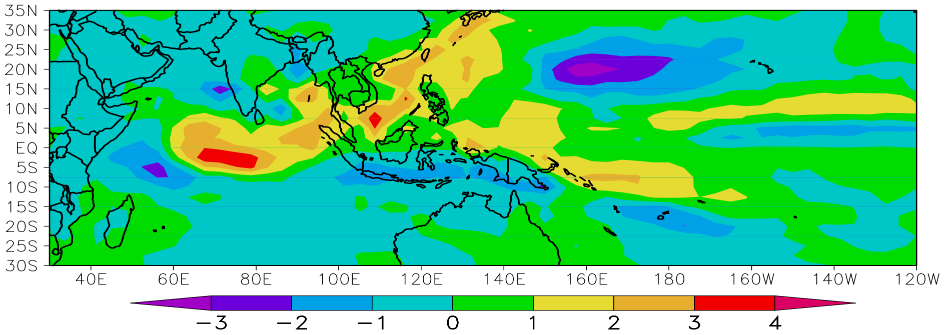
(a)AGCM



(b)AGCM+Slab



(c) Difference (a−b)



(d) CMAP

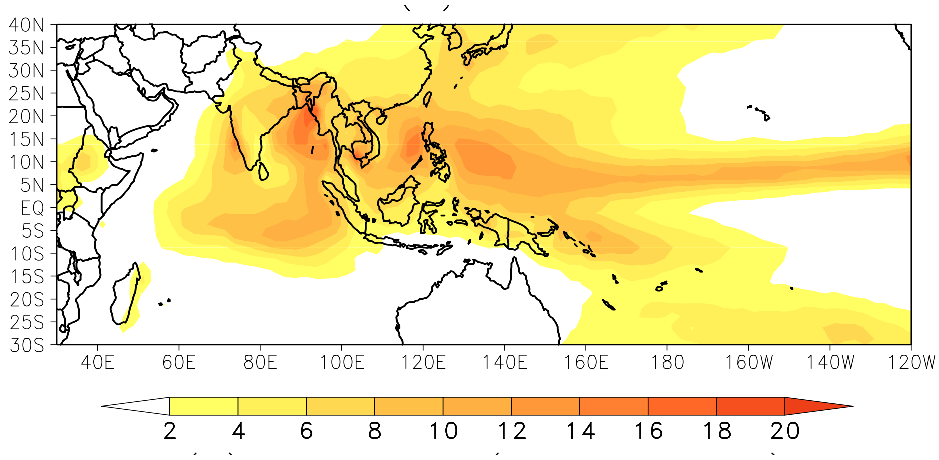


Figure 2. JJAS precipitation (mm day^{-1}) climatology (a) AGCM (b) AGCM+slab ocean model (c) Difference (AGCM-(AGCM+slab)) (d) CMAP

c. Temporal variation of precipitation

The temporal evolution of precipitation climatology averaged over Indian land region from 1st May-30th September in AGCM, AGCM+slab coupled model and corresponding observation is illustrated in Figure 3. High resolution (1^0x1^0) daily gridded rainfall data prepared by India Meteorological Department (IMD), Pune (Rajeevan et al. 2005), is used as observation. This dataset is prepared by National Climate centre (NCC) of IMD, Pune. Atmosphere only and AGCM+slab ocean model climatology matches well with observation (Figure 3), although with fewl differences. During onset, peak and withdrawal phases of monsoon, climatology of coupled model is closer to observation than AGCM.

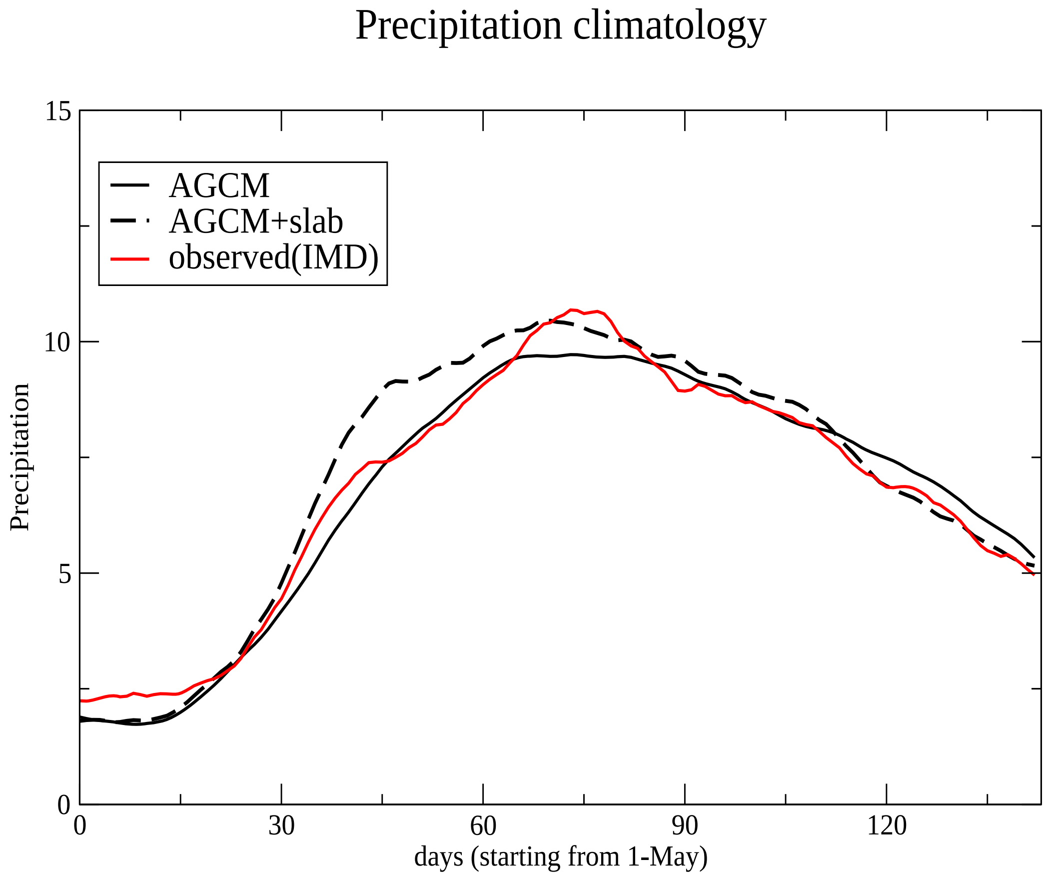


Figure 3. **Precipitation climatology (mm day^{-1}) during 1st May-30tn September averaged over Indian land region from AGCM (Solid line), AGCM+slab model (Dashed line) and IMD observation (red solid line).**

d. Meridional movement of precipitation

The meridional movement of precipitation climatology averaged over Indian longitudes from equatorial Indian ocean to Indian subcontinent simulated by the model is examined. Temporal evolution of pentad precipitation climatology averaged over 70^{o}E-85^{o}E during 1st June-30th September is illustrated for latitudinal belt extending from Equtor-35^{o}N, simulated by the AGCM in figure 4a and AGCM+slab model in figure 4b. Observed CMAP counterpart is shown in figure 4c. The northward migration of precipitation is noticed starting from 1st June near 5^{0}N in AGCM and observation, while the movement is observed from 12^{0}N in AGCM+slab model. The maxima in CMAP is located at about 20^{0}N from end of July to beginning of August. Model/observed comparison suggests deviation of model simulation in some aspects. Both model experiments (standalone atmospheric and coupled) have two maxima, one near 20^{0}N from July beginning to mid-July and other at 30^{0}N latter in July-August. The two model experiments simulates much larger precipitation north of 15^{0}N from mid-June till September compared to observation (Figures 4a,b and c).

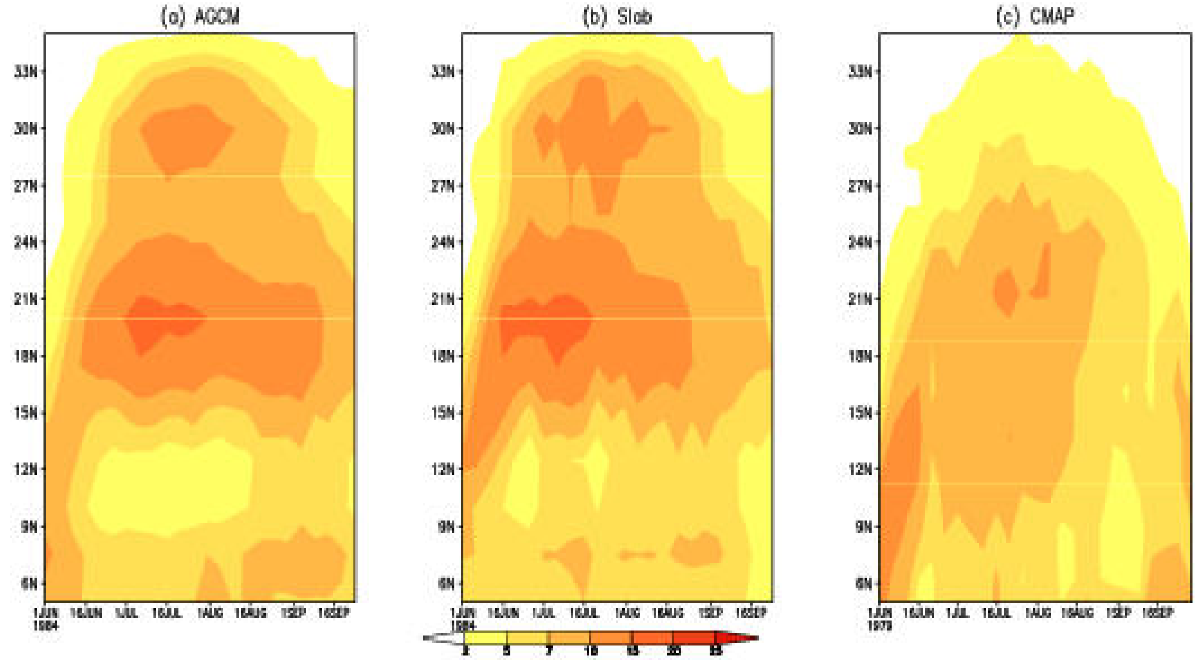


Figure 4: **Pentad precipitation climatology (mm day-1) averaged over 70^{o}-85^{o}E, 1st June-30th September (Latitude-time section). (a) AGCM (b) AGCM+slab ocean (c) CMAP.**

4. Intraseasonal variability of precipitation

The evidence of significant influence of ISO on seasonal mean monsoon and its predictability have been suggested by number of researchers (Sperber et al. 2000; Goswami and Ajaymohan 2001; Waliser et al. 2003a; Ajaymohan and Goswami 2007; Ajaymohan 2007). This motivated us to gain deeper insight into the possible role of air-sea interaction in BSISO simulation. For this purpose, BSISO simulation with AGCM and AGCM+slab ocean model is compared with corresponding CMAP observations. Details of CMAP data are given in previous section 3b.

Intraseasonal variance of 20-100 day filtered JJAS precipitation anomalies simulated by AGCM and AGCM+slab ocean model are shown in figures 5 (a and b) respectively and corresponding CMAP observation in figure 5 c. Two zones of maximum precipitation with primary zone over the Indian subcontinent and the secondary over the warm waters of the Indian Ocean are identified in both observation as well as model simulation. These two zones coincide with the movement of the tropical convergence zone (TCZ). The corresponding model/observation differences are also shown in Figure 5d and 5e respectively for AGCM and AGCM+slab ocean coupled model. Difference between two model simulations (AGCM-(AGCM+slab)) is illustrated in Figure 5f. The zone of maximum precipitation over Indian subcontinent is much stronger and that over Indian ocean is much weaker in model simulation compared to observation. Over the region separated by the two zones of maximum precipitation, the ISO variance is weaker in model than observation. The difference between model simulation in AGCM and AGCM+slab ocean coupled model suggests that the model/observed difference is reduced in coupled model compared to standalone atmospheric model, particularly over head BB, north Arabian sea and western Indian ocean.

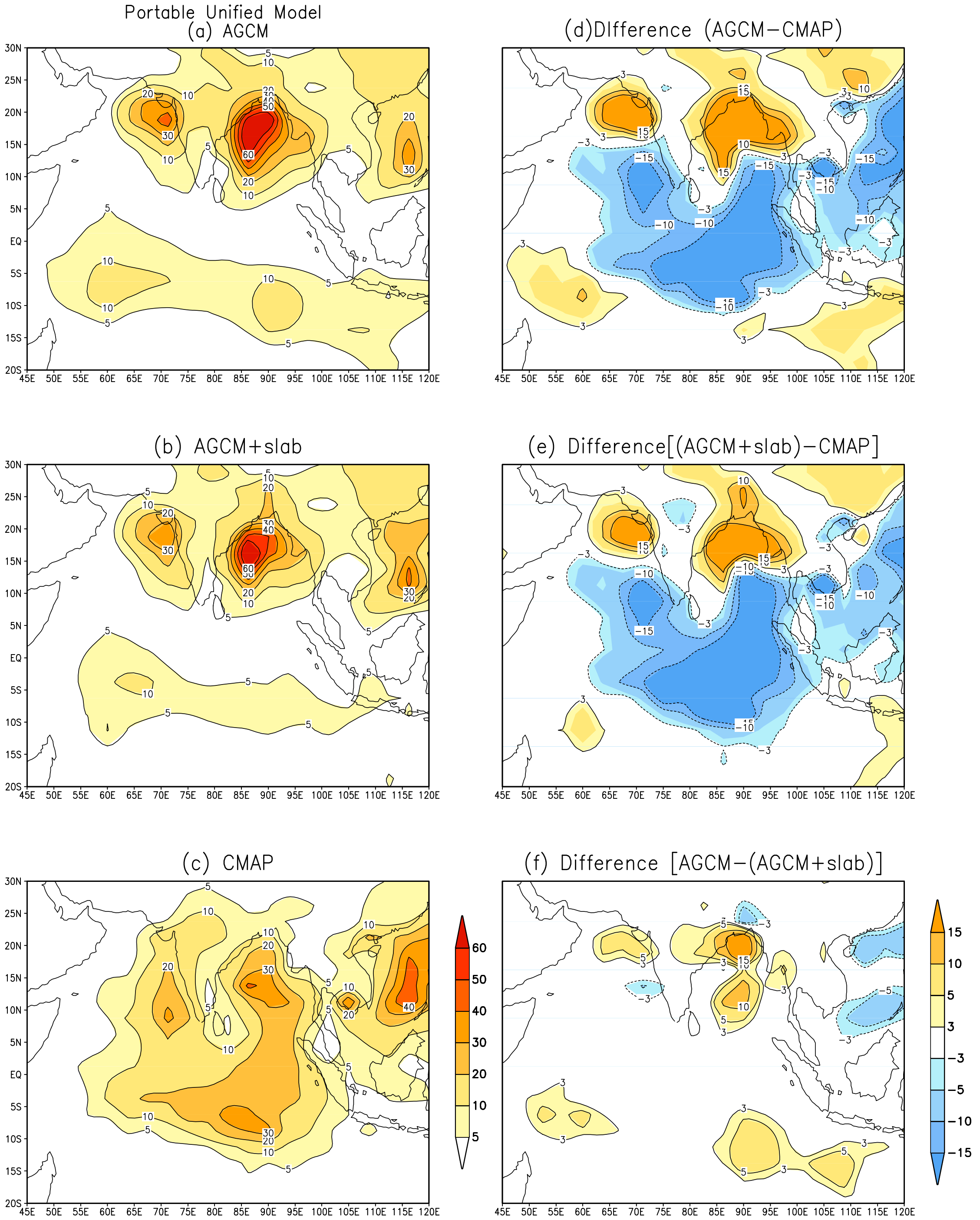


Figure 5: Variance of 20-100 day filtered JJAS precipitation (mm^2 day^{-2}) anomalies (1985-1995) (a) AGCM (b) AGCM+slab model (c)CMAP (d) Difference (AGCM-CMAP) (e) Difference ((AGCM+slab)-CMAP) (f) Difference (AGCM-(AGCM+slab))

Cloud bands exhibit coherent northward propagation from south equatorial Indian ocean (~5^{o} S) to about 25^{o} N on intraseasonal time scales during summer monsoon season (Yasunari 1979; Sikka and Gadgil 1980). To study the northward propagation characteristics of BSISO, 20-100 day filtered JJAS precipitation anomalies are regressed at different time lags with respect to reference time series. This lag regression is estimated for the simulations of atmosphere only model and AGCM+slab ocean coupled model. Reference time series is calculated based on the filtered precipitation anomalies averaged over a box in the monsoon trough region spanning 70^{o}-95^{o}E; 12^{o}-22^{o}N from 1st June-30th September. Lag-regression of observed CMAP precipitation is also estimated based on the data for the same period (1985-1995) as the model simulation. Statistically significant values at significance level of 0.1 are considered using T-statistic. The lag- regression plots corresponding to lag of 10-days to lead of 15-days with a difference of 5-days are shown in Figures 6(a-f) for AGCM and 7(a-f) for AGCM+slab ocean model. Similar illustration for CMAP observation is given in Figure 8(a-f). Coherent northward movement of filtered precipitation anomalies on intraseasonal time scale is clearly noticed in observation (Figure 8(a-f)). Precipitation anomalies (positive) over equatorial Indian Ocean (Figure 8a) are observed to move poleward in a coherent manner to form an active monsoon season with increased precipitation (Figure 8c) over the Indian subcontinent. Meanwhile reduced precipitation anomalies build up over the equatorial Indian ocean (Figure 8d) which moves northward to form a break monsoon (Figure 8f) after 15 days. The northward movement of filtered precipitation anomalies is better simulated in AGCM+slab model (Figure 7(a-f)). AGCM is unable to simulate the meridional movement (Figure 6(a-f)). Though AGCM+slab model exhibit some differences from observation such as anomalies are weaker in all lag-lead situations (Figure 7(a-f)). The negative precipitation anomalies do not strengthen from lag 5-day (Figure 7b) as in observation (Figure 8b). The initiation of positive anomalies in the equatorial Indian ocean concurrent with break phase (large negative anomalies over Indian peninsula) for lead 15-day (Figure 8f) is also absent in coupled model (Figure 7f).

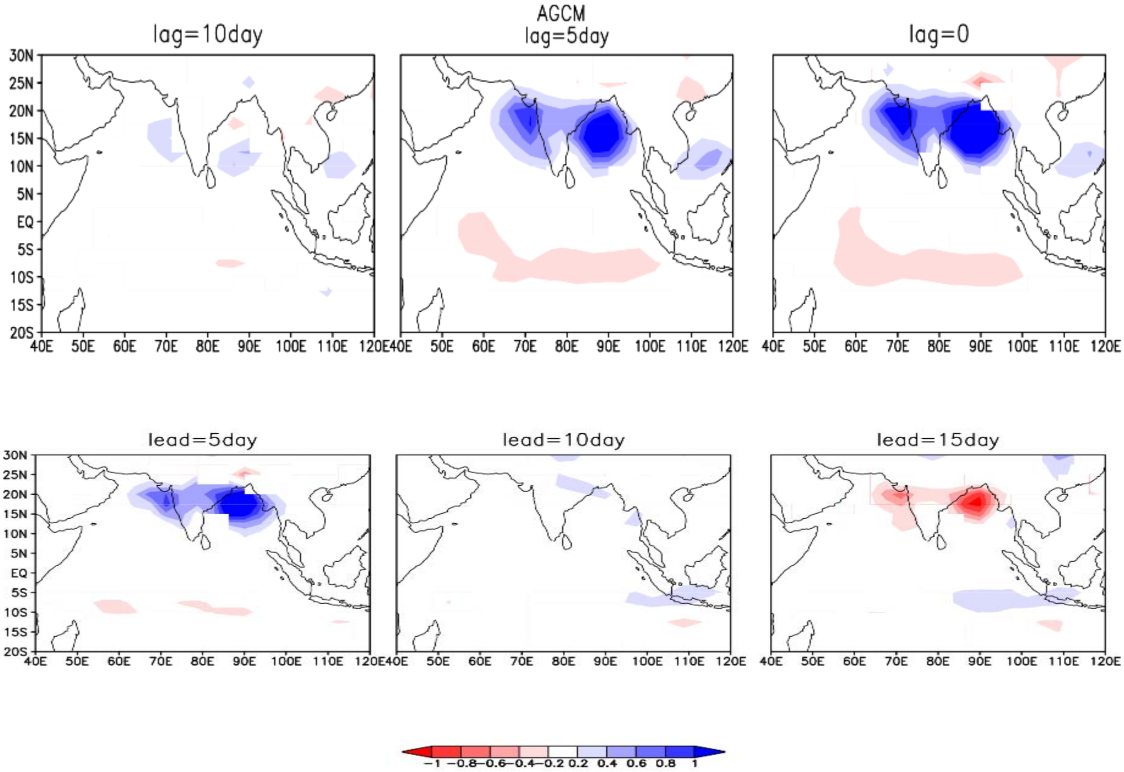


Figure 6. Regressed 20-100 day filtered precipitation (mm day^{-1}) anomalies from AGCM for different lags. Only statistically significant (0.1 significance level using t-test) values are plotted.

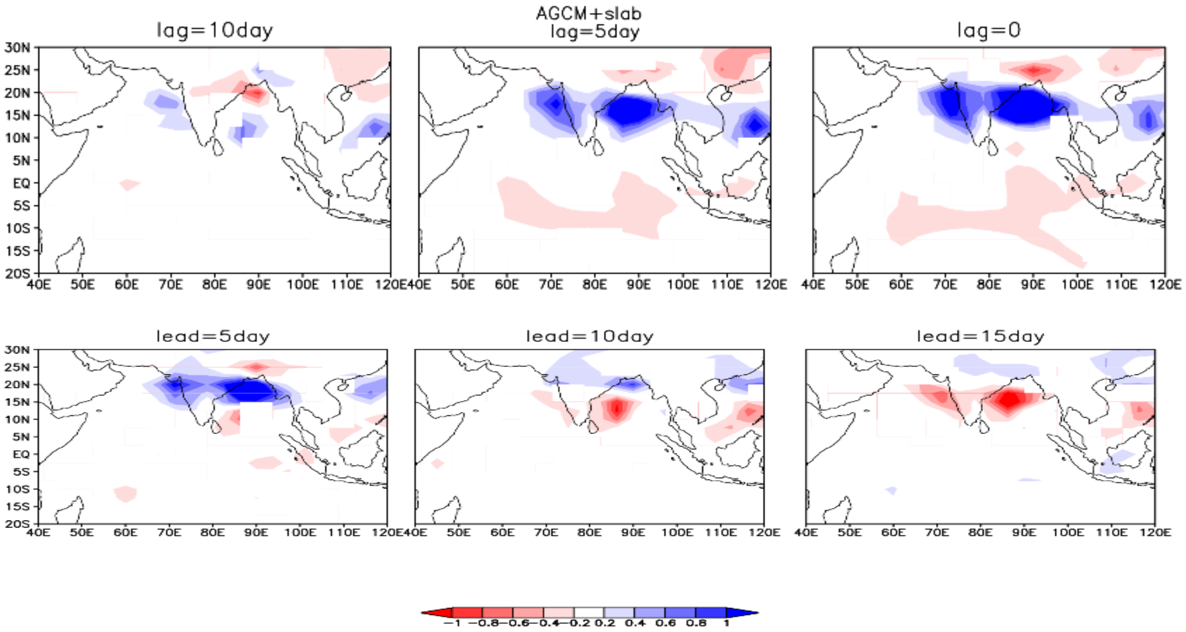


Figure 7: As in figure 6 but for AGCM+slab model

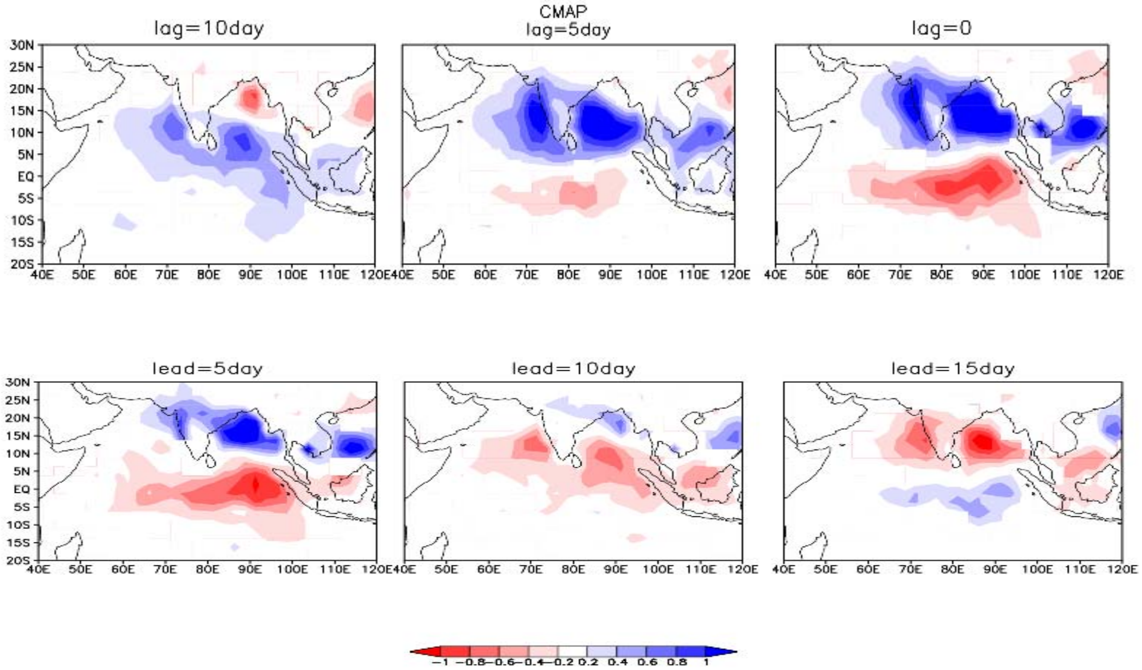


Figure 8: Same as in figure 6 except for CMAP observation

Northward propagation characteristics of precipitation anomalies are summarized in latitude-time plot of regressed precipitation anomalies during summer monsoon season averaged over the longitude 70^0-95^0E. Regression map of precipitation is illustrated for AGCM, AGCM+slab ocean coupled model and CMAP observation in Figures (9 a, b and c) respectively. Observation (Figure 9c) shows coherent propagation from ~ 5^oS to 25^o N. Coherent northward propagation is also noticed in AGCM+slab model. Large precipitation anomalies are located over latitude belt 12^o-22^o N throughout the period AGCM (Figure 9a), while the northward propagation is missing in AGCM (Figure 9a). Thus an important characteristic of BSISO is different in the uncoupled (standalone atmospheric model) and the coupled simulation (AGCM+slab ocean model). Organized meridional propagation is observed in AGCM+slab ocean model (Figure 9b). This suggests an improvement in the key feature of BSISO in coupled model setup. Klingaman et.al. (2008b) have demonstrated that HadAM3 AGCM forced with high frequency SST (daily) is better able to simulate northward propagating BSISO than the same AGCM forced with monthly mean SSTs. The important role of atmosphere-ocean coupling in BSISO is discussed in the introduction of the study. The question of whether the atmosphere-ocean coupling or higher frequency SST forcing influence ISO simulation remains unresolved. Thus the improvement in simulation of meridional propagation of BSISO in the AGCM+slab ocean coupled model used in the present study may be attributed to the combined role of inclusion of air-sea interaction and higher frequency (daily) SST variability.

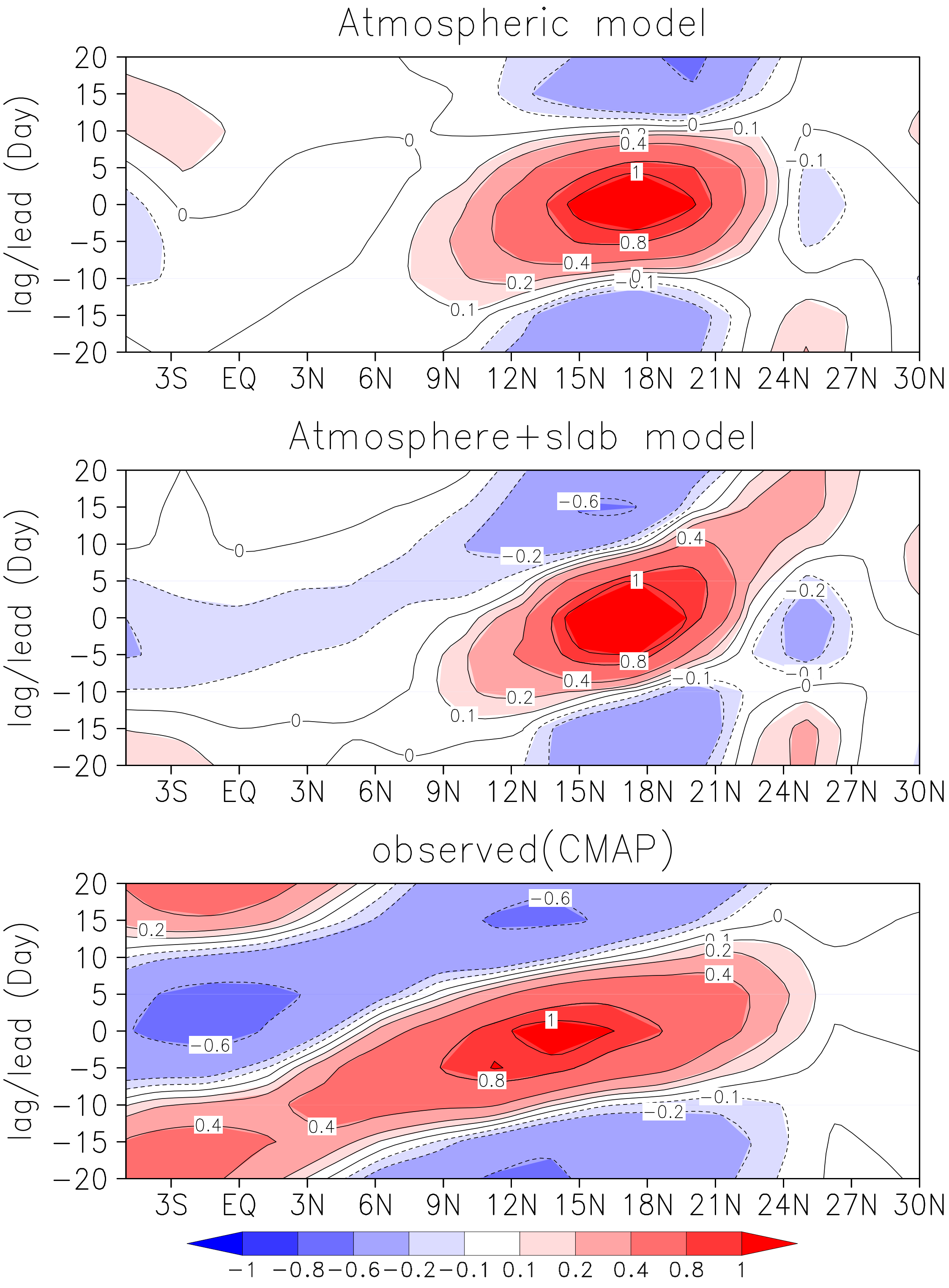


Figure 9. Regressed filtered precipitation (mm day-1) anomalies averaged over 70^o-95^{o}E latitude –time (days). (a) AGCM (b) AGCM + slab ocean (c) CMAP. Only statistically significant (0.1 significance level using t-test) anomalies are plotted.

5. Summary and discussion

The role of air-sea interaction in ISO has been noted using observations in the Indian ocean region (Sengupta and Ravichandran 2001, Sengupta et al. 2001) and using coupled models in the simulation (Fu et al. 2002; Fu et al. 2003; Rajendran et al. 2004; Zheng et al. 2004) and in the northward propagation (Jiang et al. 2004). The inadequacy of AGCMs to sufficiently represent the ISO in tropics (Slingo et al. 1996; Waliser et al. 2003b,c) and better representation of 30-60day mode of ISO in an AGCM forced with SST at frequencies higher than 5 days (Klingaman et. al. 2008b) has also been indicated. With this view, we had studied the role of simple atmosphere-slab ocean coupling along with higher frequency SST (daily in atmosphere-slab coupled model experiment) in the northward movement of 30-60day mode of BSISO simulation.

To examine this problem, we made two identical sets of model experiments, each comprising of single realization of the model integration for long period (11-years). The first set of experiment is made with atmospheric model prescribed with observed monthly mean SST as boundary forcing and a companion experiment with AGCM+slab ocean. The results from the two model experiments are compared with corresponding observations from CMAP. Statistically significant lag-regressed precipitation anomalies suggest that there is more organized meridional propagation in AGCM+slab ocean coupled model . The northward propagation characteristics of BSISO in atmosphere-slab ocean coupled model agree more closely with observation than AGCM. Better simulation of northward propagation of BSISO is a result of inclusion of air-sea coupled interaction and higher frequency SST variability. However, modeling studies are constrained by the shortcoming of the model and hence are highly model dependent.

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