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# DYNAMICAL SEASONAL PREDICTION EXPERIMENTS OF THE INDIAN SUMMER MONSOON

by

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# Dynamical seasonal prediction experiments of the Indian summer monsoon.

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## ABSTRACT

An atmospheric general circulation model (AGCM) is used to explore its potential for ensemble seasonal prediction and simulation of the Indian summer monsoon. In this study we have examined the prediction and simulation of the boreal summer monsoon anomalies using Center for Ocean Land Atmospher studies (COLA) AGCM during 1997-2002. Two sets of AGCM experiments are presented here. The global SST anomalies of May are superposed on the monthly (June-September) climatological SSTs and were used for GCM integrations of the first set. The second set uses the observed global SST during June-September as the boundary forcing. Both the hindcast and May SST persistence forecast experiments are initiated using the observed initial conditions corresponding to the last week of May. The hindcast experiments show reasonable skill in simulating the monsoon rainfall and circulation anomalies during 1997-2002. On the other hand, the May SST persistence experiments indicate that the behavior of the summer monsoon anomalies depend on the manner in which the SST anomalies evolve spatially and temporally during the monsoon season. It is seen that the simulated monsoon rainfall is rather sensitive to remote and regional boundary forcings. Based on the results of our studies it is suggested that accurate SST information during the summer monsoon season is necessary for improving the seasonal forecasting of the Indian summer monsoon.

# 1 Introduction

The monsoon system over South and East Asia is perhaps one of the most fascinating phenomena in the world. It affects the lives of more than half of the world population living in the Asian continent. Year-to-year variations in the monsoon rainfall exerts profound impact on the agriculture, water availability, livestock, economy, power generation, industry and various social aspects in these countries. Given the inherent complexities associated with the monsoon system, accurate prediction of the monsoon has remained a challenge to the research community. Nevertheless, considerable research has been conducted in recent years towards understanding the factors that give rise to the monsoon interannual variability and for improving our capabilities in predicting the monsoon variability (e.g., WCRP 1993). India has had a long tradition of long-range prediction of seasonal monsoon rainfall (Gowarikar *et al.*, 1989), primarily using various statistical methods (Krishna Kumar *et al.*, 1995). For the first time during early 70s, Manabe with his modelling group simulated boreal summer monsoon with AGCM (Manabe *et al.*, 1974; Hahn and Manabe 1975). Later significant improvements in the treatment of dynamical and physical processes in GCM have prompted a renewed effort in simulating monsoon features, reasonably well (Miller *et al.*, 1992; Sud and Walker 1992). The Atmospheric Model Intercomparison Project (AMIP), of the World Climate Research Program was an ambitious attempt to validate the simulations against the observed climate and intercompare performance of GCMs developed by research groups all over the globe (Gates, 1990, 1992; Boer *et al.*, 1992; Mujumdar and Kulkarni 1999a). Recently an international project titled 'CLIVAR Asian/Australian monsoon Atmospheric General Circulation Model intercomparison' was carried out to study the impact of El Niño on Asian summer monsoon of 1997. IITM participated in this project for which Hadley centre climate model (HadAM2b) has been used (Mandke et al. 2001; Kang et al. 2002). A number of focussed attempts have been made in last decade in order to achieve accurate dynamical seasonal forecast (Mo 1992; Palmer et al. 1992; Webster and Yang 1992, Brankovic et.al. 1994; Palmer and Anderson 1994; Brankovic and Palmer 1997; Brankovic and Palmer 2000). Various issues like impact of boundary conditions, initial conditions, physical parameterization schemes, size of ensemble and model formulation have been addressed by the above researchers. The General Circulation Model (GCM) simulations were initiated in research mode by Climate Modelling group at IITM, Pune, India, during 1997 (Mujumdar and Kulkarni, 1999; Mandke *et al.*, 1999, Soman *et al.*, 2000, Satyan *et al.*, 2000, Mujumdar *et al.*, 2001; Krishnan *et al.*, 2001). These forecasts are being communicated to IMD.

The physical basis for atmospheric predictability on seasonal time scales resides primarily on the notion that slowly varying anomalous lower boundary forcing tends to exert significant influence on the atmospheric development. Such forcing is generally thought to be associated with anomalies of sea surface temperature (SST), soil moisture and snow cover. The study of Charney and Shukla (1981), revealed that the effect of such slowly varying lower boundary conditions dominate the year-to-year variability in the tropics. However, in the extra-tropics the effects of lower boundary forcing must compete with variability due to internal dynamics comprising of flow instabilities and nonlinear interactions among various scales of motions. Therefore seasonal time-scale anomalies are considered to be potentially more predictable in the tropics than in the mid-latitudes (Mujumdar and Krishnan 2001). There is an alternative idea that seasonal time-scale anomalies in the tropics are not only dependent on boundary forcing, but are also sensitive to random weather perturbations. Brankovic and Palmer (1997) performed nine-member seasonal ensemble integrations for 120-days starting from nine different initial conditions using the same boundary forcing. Their results suggested that the seasonal mean monsoon rainfall and circulation showed significant variation among the ensemble members although the boundary forcing was same for all the experiments. A mathematical basis for inferring this sensitive dependence of the atmospheric state to the initial conditions is described by the classical study of Lorenz (1963). According to Palmer (1994), atmospheric seasonal prediction has to be necessarily probabilistic and needs to be tackled using ensemble integrations, (*i.e.,* to integrate a model many times starting from different initial conditions), of dynamically based forecast models. The main constraint for seasonal prediction with an atmospheric GCM is to have the boundary conditions like SST of the coming season. We have adopted the persistent anomaly method (Soman *et al.*, 1999; Mujumdar *et al.*, 2000) to obtain SST boundary forcing for long-lead dynamic forecast. Thus the persistence method provides an opportunity to understand the role of slowly varying remote as well as regional boundary forcings in contributing to the generation and maintenance of anomalous circulation patterns over the monsoon region. Results from past studies suggest that the regional-scale summer monsoon variability over India is significantly associated with the intraseasonal fluctuations of monsoon activity over the subcontinent (Rao, 1976; Yasunari, 1979,80; Sikka and Gadgil, 1980; Gadgil and Asha, 1992; Ferranti *et.al.*, 1997; Krishnamurthy and Shukla, 1999; Annamalai *et.al.*, 1999; Krishnan *et.al.*, 2000, Goswami and Ajaya Mohan, 2000). The monsoon intraseasonal fluctuations manifest in the form of prominent active/break monsoon cycles. The impact of boundary forcings in regulating the intraseasonal variability over the Indian monsoon region is presented in our earlier studies (Mujumdar and Krishnan, 2001 and Krishnan *et al.*, 2001). The present study deals with modelling studies undertaken to examine the important aspects concerning ensemble monsoon prediction. The primary objective of this research work is to understand the factors that contributed to the maintenance of anomalous features associated with the monsoon systems over Indian sub-continent during 1997-2002. One of the key issues in this context, is concerning the influence of regional and remote boundary forcing both on the large-scale and regional-scale monsoon circulation.

## 2 Model experiments and Data

Though we have carried out dynamical seasonal prediction experiments using two state of art models viz. Center for Ocean-Land-Atmosphere (COLA) GCM and Hadley Center Climate GCM. Here we restrict our discussion to dynamical seasonal prediction experiments using COLA GCM. A series of ensemble simulations is being carried out for the seasonal forecasting (in research mode). The COLA T30L18 spectral model has a resolution of triangular truncation at wave number 30 which is approximately equivalent to 3.75 X 3.75 lat-lon grid resolution on the earth surface with a vertical resolution of 18 unevenly spaced sigma levels. The complete model documentation has been presented by Kinter *et.al.*, (1997) and Mujumdar 2002. This GCM has been extensively used for monsoon studies (e.g. Fennessy *et al.*, 1994; Krishnan *et al.*, 1998; Pattnaik *et al.*, 1999; Mujumdar and Krishnan 2001; Krishnan *et al.*, 2001; Mujumdar 2002). Two sets of ensemble experiments of 6 members each are being carried out since 1997 for the seasonal simulation (Mujumdar and Kulkarni 1999b). The observed initial conditions used in our study were obtained from NCEP. The NCEP initial conditions containing the spectral coefficients of temperature, divergence, vorticity and moisture at 18 sigma levels and surface pressure were processed so that they become compatible with the COLA T30L18 GCM. The experiments (EM97, EM98, EM99, EM2k, EM2k1, EM2k2) were run using latest available May mean SST anomalies persisted over the climatological SSTs of June to September (JJAS) and near season initial conditions at 00Z on 26th - 31st May, every year during 1997 to 2002. For the second set, experiments (E97, E98, E99, E2k, E2k1, E2k2) were integrated with observed JJAS SSTs and similar initial conditions described above. Each member of ensemble was integrated for monsoon season. The details of the SST forcing and initial conditions used for the ensemble seasonal integrations are presented in Table.1. In this study we have presented the analysis of simulated rainfall, wind and velocity potential. Further analysis will be carried out for various simulated atmospheric variables in our future studies.

The ensemble forecasts are validated using diagnostic analysis of observations. Datasets from multiple sources have been employed for the present diagnostic analysis. They consist of the sub-divisional and all India rainfall prepared by Indian Institute of Tropical Meteorology (IITM), based on daily and weekly weather report obtained from the India Meteorological Department (IMD) (see *http://www.imd.ernet.in* and *http://www.tropmet.res.in*); the grided rainfall dataset both over land and oceanic areas from the Climate Prediction Center (CPC) - which is commonly referred to as the CPC Merged Analysis of Precipitation (CMAP). The CMAP dataset is a product of merging rainguage observations and precipitation estimates from satellites (Xie and Arkin, 1997). Atmospheric parameters such as (winds, velocity potential, etc) were obtained from the National Center for Environmental Prediction (NCEP) reanalysis dataset (Kalnay *et al.*, 1996). In addition, we have gathered reports of rainfall departures from Monthly Climate Data for the World. Also we have used the monthly Climate Diagnostic bulletins produced by the National Oceanic Atmospheric Administration (NOAA), Climate Diagnostic Center, Boulder, Colorado and IMD. The SST data used for our analysis is based on the Optimum Interpolated SST (OI SST) (Reynolds and Smith, 1994).

## 3 Seasonal predictions and simulations

The various aspects of climatological features of monsoon, both observed and simulated by COLA AGCM, are amply discussed by Pattnaik *et al.*, 1999; Mujumdar and Krishnan, 2001; Krishnan *et al.*, 2001 and Mujumdar 2002. Here we will describe the anomaly patterns in order to study the performance of the seasonal simulation by COLA GCM. The ensemble seasonal simulation started with century's strongest El Niño event during 1997 described by warm SST anomalies in the equatorial central-eastern Pacific Ocean. Fig.1a and Fig.2a show the spatial distribution of the global SST anomalies during May and JJAS 1997 respectively. It can be noted from the Fig.1b and Fig.2b that the warm SST anomalies during unique El Niño of 1997, persisted even during boreal summer of 1998 over the eastern Pacific Ocean. The May SST anomalies over parts of Indian Ocean and western Pacific Ocean persisted during JJAS 1998. Fig.1c-Fig.1e and Fig.2c-Fig.2e show that the years 1999 to 2001 were non-ENSO years, however it is important to note that the Indian Ocean has been anomalously warm during these three years. The year 2002 is peculiar which didn't indicate clear sign of El Niño during the month of May (Fig.1f) however by July warming over the equatorial central-east Pacific was significant and continued during the monsoon season of 2002 (Fig.2f). Fig.1 and Fig.2 reveal that the pattern of May SST anomalies have generally persisted during June to September except for the year 1999.

The observed monthly rainfall anomalies, prepared using the rainfall climatology over the period starting from 1979 to 1995, during boreal summer monsoon of 1997 exhibits that the convective activity over Indian Monsoon region (Fig.3a- Fig.3d) has gradually increased. Whereas over equatorial central-eastern Pacific (hereafter Pacific sector) the convective activity has gradually increased in response to the strongest El Niño. Further August 1997 observed significant large scale positive rainfall anomalies over Pacific sector and the Indian monsoon region. It is interesting to note that during the strongest El Niño event of 1997, the monthly rainfall anomalies over Indian subcontinent and neighborhood are not in contrast to the Pacific sector (as was observed during past El Niño events see *http : //www.tropmet.res.in*. The strengthening (weakening) of the lower tropospheric wind anomalies at 850 hPa support the enhancement (suppression) of the convection over Pacific sector (Indian monsoon region) on the monthly scale. The seasonal rainfall pattern exhibits very weak negative anomalies over Indian subcontinent and significantly strong positive anomalies over Pacific sector (Fig.3e). The seasonal scale rainfall anomalies are dynamically consistent with lower tropospheric wind anomalies over Indian monsoon region and Pacific sector. The upper tropospheric (200 hPa) velocity potential anomalies (Fig.3f) exhibit the anomalous outflow over the strong convective zone (Pacific sector) and anomalous inflow over the weak convective zone (summer monsoon region). The anomalous inflow induces vertical subsidence (Mujumdar and Krishnan, 2001 and Krishnan *et al.*, 2001) suppressing the convection over Indian monsoon region. During 1998 monthly as well as seasonal scale rainfall and lower tropospheric wind anomalies exhibit suppressed convection over Pacific sector, whereas over Indian monsoon region the features are similar to that of 1997 except the rainfall anomalies are positive (Fig.4a-Fig.4e). The upper level velocity potential anomaly (Fig.4f) shows anomalous moderate inflow over monsoon region and strong anomalsous outflow over Pacific sector. The Pacific sector exhibits weak anomalous convective activity associated with anomalous upper tropospheric inflow during 1999 to 2001 on monthly as well as seasonal scale (Fig.5-Fig.7). Thus the Pacific sector depict very weak intra-annual variability during 1999 to 2001 in response to the non-ENSO episode. It should be noted that the upper tropospheric features over Indian monsoon region, in particular over Indian sub-continent also observed weak anomalous outflow during 1999 to 2001 in response to the anomalously warm Indian Ocean SSTs and overlying observed weak anomalous outflow. While the anomalous circulation features over the Indian monsoon region are similar to that of 1998, the rainfall anomalies are significantly negative (Fig.5a-Fig.5e). The anomalous velocity potential (Fig.5f) shows weak anomalous outflow over the south-western Indian Ocean and strong anomalous inflow over Pacific sector similar to that of 1998. The case of abnormally low Indian monsoon rainfall (Fig.6) during 2000 is presented in detail in our recent study (Krishnan *et al.*, 2001). The occurrence of prolonged break spells over the Indian subcontinent during 2000 summer monsoon season is an important feature which was diagnosed in the above mentioned study. The upper tropospheric anomalies of velocity potential over Indian Ocean shows weak outflow and strong inflow over Pacific sector similar to that of 1999 (Fig.6f). The summer monsoon over Indian sub-continent during 2001 also turns out to be weak (Fig.7). The occurrence of frequent break spells (*http ://www.tropmet.res.in*) over Indian region is note worthy. The velocity potential anomalies at 200 hPa shows that (Fig.7f) the anomalous outflow over Indian monsoon region and anomalous inflow over central Pacific region is very weak during JJAS-2001. The summer monsoon of the year 2002 turns out to be peculiar, as the convective activity started developing over Pacific sector in contrast to the previous four years (1998-2001) (Fig.8). The July 2002 observed century's lowest rainfall over Indian subcontinent (*http ://www.tropmet.res.in*). The convection over Tropical Indian ocean was anomalously active during June and July 2002 (Fig.8a and Fig.8b). The anomalous tropospheric circulation was weak over Indian monsoon region throughout the season. The anomalous velocity potential at 200 hPa is similar to that of 1997 (Fig.3f) with the anomalous inflow over Indian monsoon region and anomalous outflow over Pacific sector during JJAS 2002 (Fig.8f). The detail diagnostic and ensemble simulations, with COLA AGCM, studies are in progress to understand the abnormal summer monsoon 2002.

In this preliminary analysis of seasonal prediction with COLA AGCM, seventy two seasonal integrations have been performed during (JJAS) 1997 to 2002. Out of seventy two, half of the integrations were performed with May persisted SST and half with observed SST. The summer ensemble seasonal mean simulation of rainfall and circulation anomalies are compared with the corresponding anomalies of the observed fields. The anomalies for the GCM simulated fields are calculated with respect to the model climatology based on a 13-year integration of the same model using observed SSTs (1982-1994) (Pattnaik it et al., 1999). The experiments EM97 and E97 reveal that the ensemble mean on the monthly as well as seasonal scale of rainfall and wind anomalies at 850 hPa (Fig.10 and Fig.11) exhibit good agreement between both the simulations, also they have good resemblance to observed features (Fig.3 and Fig.4a) over Indian monsoon region and Pacific Ocean, except the direction of the wind anomalies are not comparable. The 200 hPa velocity potential anomaly fields as simulated by E97 (Fig.11e) is very close to that of observation (Fig.3e), where as the EM97 simulation (Fig.10e) shows west-ward shift of centers of inflow and outflow over Indian Ocean and Pacific Ocean respectively. Also the Fig.9 brings out the consistency in simulating anomalous features among the members of the ensemble experiment EM97. The rainfall anomalies simulated by EM98 and E98 experiments exhibit (Fig.12 and Fig.13) positive anomalies over Indian monsoon region and negative anomalies over Pacific Ocean, similar to that observed during JJAS 1998 (Fig.4). The monthly as well as seasonal scale wind anomalies in EM98 and E98 are as weak (in strength) as seen from observed anomalies, however they differ in direction. It is interesting to note that upper tropospheric velocity potential anomalies simulated by E98 (Fig.13e) has close resemblance with the observation (Fig.4e), whereas EM98 shows weak outflow over Indian monsoon region and strong outflow over Pacific region (Fig.12e). The strong convection over the Pacific region simulated by the EM98 experiment may be because of the presence of the El Niño signal which subsequently weakened during JJAS 1998. The simulated features discussed above are consistent in all the members of the ensemble experiments of EM98 and E98 (Figures not shown). The experiments (EM99, E99, EM2k, E2k, EM2k1, E2k1) for the non-ENSO years 1999 to 2001 shows (Fig.14 to Fig.19) weak rainfall and wind anomalies over Indian subcontinent and central-eastern Pacific Ocean. The weakening of the monsoon circulation was qualitatively reflected in the rainfall simulations clearly indicating decrease of monsoon precipitation over India, northern Arabian Sea and Bay of Bengal; and increased precipitation over the equatorial oceanic region. The Pacific region during these non-ENSO years exhibit the close resemblance between simulation and the observed (JJAS) anomalous features. The upper level regions of anomalous outflow over the Indian monsoon region in both the experiments during 1999-2001 agrees well with the observations. The anomalous inflow as simulated by both the experiments during 1999-2001 over the Pacific region also agrees well with the observations. The ensemble mean simulation during 2000 is analyzed in detail in our recent study (Krishnan *et al.*, 2001). The dynamical features simulated by AGCM revealed weakening of the monsoon Hadley cell and the associated moisture transport anomalies during 2000. It is essential to mention that the simulations with the observed SST exhibit close resemblance to the observations. The ensemble simulations, on monthly as well as seasonal scale, by EM2k2 clearly brings out the suppressed anomalous convection over Indian sub-continent and neighbourhood during 2002 (Fig.20a-Fig.20e). The enhanced convective activity over western Pacific Ocean extending into the central Pacific Ocean is noteworthy. The anomalous monsoon circulation and rainfall simulated by EM2k2 ensemble experiments indicate the significant weakening over Indian subcontinent and neighborhood. While the anomalous increase in monsoon precipitation associated with strong anomalous circulation over the equatorial Indian Ocean can be prominently seen in the EM2k2 ensemble simulations (Fig.20a-Fig.20e). The simulated anomalous upper level outflow over the Indian monsoon region seems to be confined to the southern latitudes. It is interesting to note that the extreme Eastern Pacific region shows anomalous inflow during JJAS 2002 (Fig.20f). The ensemble simulation in case of E2k2 confirms the strong suppression of convection over Indian monsoon region (Fig.21a-Fig.21e) on monthly as well as seasonal scale as simulated by EM2k2 experiment. The convection associated with lower tropospheric anomalous inflow is mostly lying over Indian Ocean and extends in the central Pacific and adjoining regions (Fig.21e). The anomalous features over Pacific Ocean differ in case of EM2k2 (Fig.20) and E2k2 (Fig.21). The upper troposhperic outflow pattern (Fig.21e) differ from the observed one (Fig.8e). However over Indian monsoon region the simulation has good resemblance to the observations. All the members of the EM2k2 and E2k2 experiments show consistency in simulating the anomalous features discussed above (Figures not shown).

# 4 Conclusion

Diagnostic analysis of observations and a series of ensemble seasonal integrations have been carried out using the COLA T30L18 GCM since 1997 to examine the performance of the monsoon over Indian monsoon region. Twelve sets (EM97, E97, EM98, E98, EM99, E99, EM2k, E2k, EM2k1, E2k1, EM2k2 and E2k2), each having 6 ensemble members, of seasonal integrations were carried out. The SST forcing and the observed initial conditions used for the above experiments are described in Table.1. The model simulations are validated by comparing with NCEP reanalysis, CMAP rainfall and datasets from multiple sources described in section 2. The simulated rainfall and circulation, over the Indian and south Asian monsoon regions and also over the tropical Pacific Ocean, during JJAS of 1997-2002 are found to be consistent with the observations. In our previous studies we have shown that the ensemble simulations of the JJAS rainfall anomalies are found to exceed the 95% confidence level, obtained from a statistical t-test, over the tropical Pacific Ocean and the Indian monsoon region (Mujumdar and Krishnan, 2001; Krishnan et al. 2001). The simulated and observed percentage departure of the area averaged (over Indian subcontinent, 5-30$^0$N and 60-90$^0$E) rainfall during JJAS of 1997-2002 are shown in (Fig.22). The simulations based on the observed June-September SST boundary forcing produce more realistic monsoon rainfall and circulation features as compared to the May persisted SST experiments. As is to be expected, some of the smaller-scale monsoon features are not as well simulated. For instance the anomalous rainfall and circulation features over west coast of India and over the Bay of Bengal show a southward shift as compared to the observed positions.

It is noteworthy that the ensemble simulations consistently show the enhancement of the convection over equatorial Indian Ocean and neighborhood during the non-ENSO years 1999 to 2001. The upper tropospheric anomalous outflow seems to be confined to the Indian Ocean rather than Indian subcontinent. We have also examined the influence of the remote and regional boundary forcings on the regional scale variability over the Indian monsoon region (Mujumdar and Krishnan, 2001; Krishnan *et al.*, 2001). The GCM simulated daily monsoon rainfall variations over the Indian subcontinent were generally found to be associated with more number of break spells during 1999 to 2002 (Figures not shown). It is worth mentioning that the above experimental simulations also yielded consistent support for the variation of the monsoon rainfall and circulation anomalies, on the monthly and seasonal scale, in response to the remote and regional boundary forcings during 1997-2002.

These results suggest that information of the SST evolution during the summer monsoon months is necessary for improving the seasonal forecasting of the Indian summer monsoon. Predictability due to the month to month persistence of SST within the monsoon season also needs to be explored.

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# 6 Figure captions

Fig. 1. Maps of SST anomalies for month of May (a) 1997 (b) 1998 (c) 1999 (d) 2000 (e) 2001 (f) 2002. Contour interval 0.5$^o$K; zero contour is suppressed; positive contours are shaded and broken lines indicate negative values. Anomalies are with respect to the OISST climatology (Smith and Reynolds, 1998) for the base period (1961-90).

Fig. 2 Same as Fig.1 except for June-September mean anomalies.

Fig. 3 The monthly distribution of the rainfall anomalies (mm day$^{-1}$) superimposed on 850 hPa wind anomalies (ms$^{-1}$) for 1997 (a) June (b) July (c) August (d) September. The rainfall anomaly contour interval is 3 ; positive contours are shaded in dark and light shading with the contours of broken lines indicate negative values. The wind is computed from NCEP reanalysis dataset. The orographic mask is left blank. The observed rainfall is based on Xie and Arkin (1997). (e) Same as Fig.3a but for 1997 JJAS anomalies. (e) JJAS mean velocity potential anomalies ($\chi$) field $10^6 m^2 s^{-1}$ at 200 hPa for 1997. Contour interval is 1 unit; zero contour is suppressed and broken lines indicate negative values.

Fig. 4 Same as Fig.3 except for 1998.
Fig. 5 Same as Fig.3 except for 1999.
Fig. 6 Same as Fig.3 except for 2000.
Fig. 7 Same as Fig.3 except for 2001.
Fig. 8 Same as Fig.3 except for 2002.

Fig. 9 JJAS mean rainfall anomalies superimposed on 850 hPa wind anomalies for various ensemble members of EM97 GCM experiment (a) member-1 (b) member-2 (c) member-3 (d) member-4 (e) member-5 (f) member-6. The contour interval is 2 units; broken lines indicate negative values; positive contours are shaded and zero contour is suppressed.

Fig. 10 Same as Fig.3 except for EM97 GCM experiment.
Fig. 11 Same as Fig.10 except for E97 GCM experiment.
Fig. 12 same as Fig.10 except for EM98 GCM experiment.
Fig. 13 same as Fig.10 except for E98 GCM experiment.
Fig. 14 same as Fig.10 except for EM99 GCM experiment.
Fig. 15 Same as Fig.10 except for E99 GCM experiment.
Fig. 16 same as Fig.10 except for EM2k GCM experiment.
Fig. 17 same as Fig.10 except for E2k GCM experiment.
Fig. 18 Same as Fig.10 except for EM2k1 GCM experiment.
Fig. 19 same as Fig.10 except for E2k1 GCM experiment.
Fig. 20 same as Fig.10 except for EM2k2 GCM experiment.
Fig. 21 Same as Fig.10 except for E2k2 GCM experiment.

Fig. 22 The simulated and observed percentage departure of area averaged rainfall during JJAS of 1997-2002.

## Table 1. GCM Experiments

| Ensemble Experiment {6 members (01,02,03,...,06)} | SST Boundary Condition (June – September) | Initial Condition {Six ICs corresponding to} |
|---|---|---|
| **EM97** | Observed Climatological SST + Anomalies of May 1997 | (26, 27, 28, ... 31) May 1997 |
| E97 | Observed SST of 1997 | |
| **EM98** | Observed Climatological SST + Anomalies of May 1998 | (26, 27, 28, ... 31) May 1998 |
| **E98** | Observed SST of 1998 | |
| **EM99** | Observed Climatological SST + Anomalies of May 1999 | (26, 27, 28, ... 31) May 1999 |
| **E99** | Observed SST of 1999 | |
| **EM2k** | Observed Climatological SST + Anomalies of May 2000 | (26, 27, 28, ... 31) May 2000 |
| **E2k** | Observed SST of 2000 | |
| **EM2k1** | Observed Climatological SST + Anomalies of May 2001 | (26, 27, 28, ... 31) May 2001 |
| **E2k1** | Observed SST of 2001 | |
| **EM2k2** | Observed Climatological SST + Anomalies of May 2002 | (26, 27, 28, ... 31) May 2002 |
| **E2k2** | Observed SST of 2002 | |

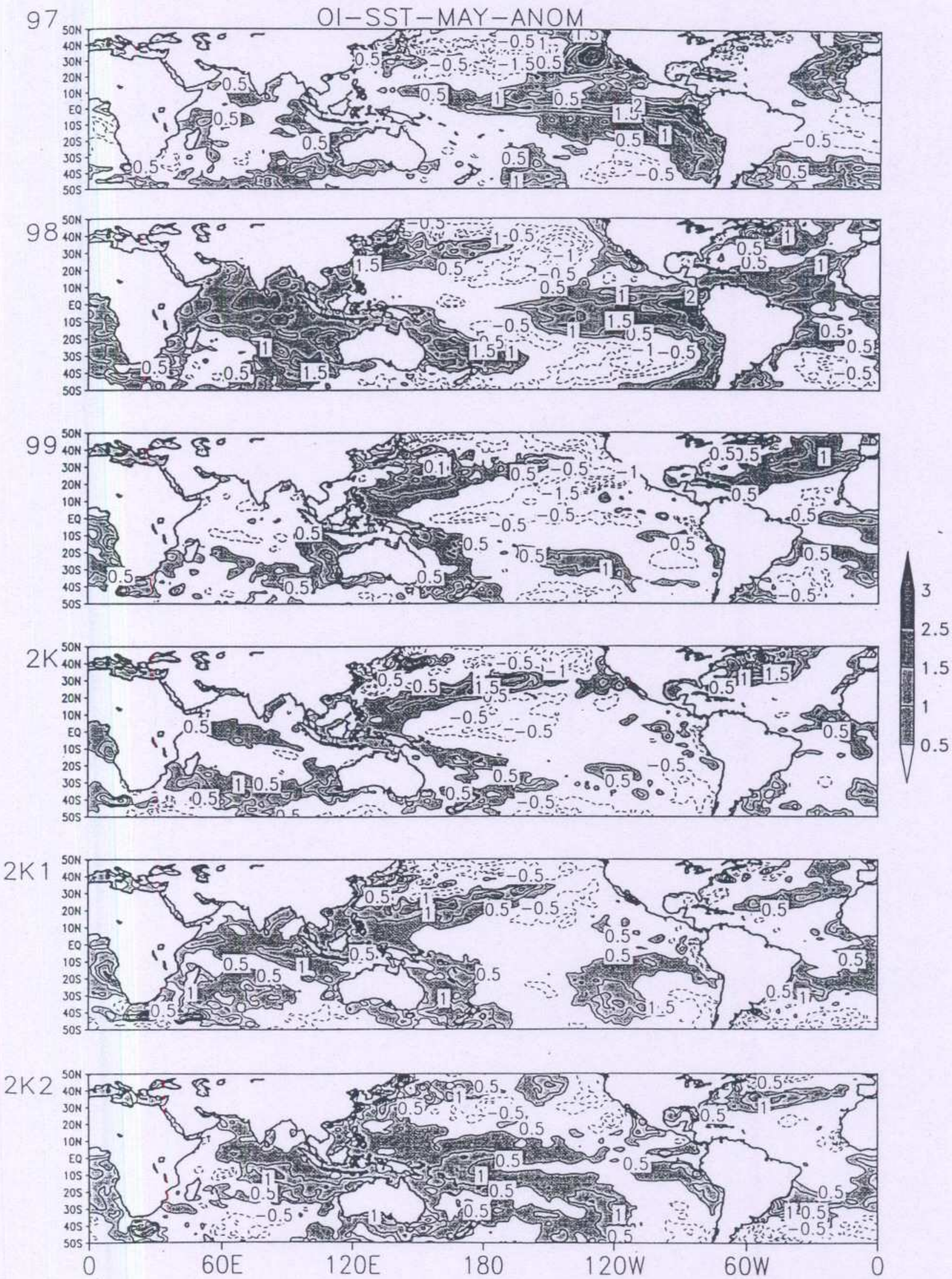

OI-SST-MAY-ANOM
97
98
99
2K
2K1
2K2
50N
40N
30N
20N
10N
EQ
10S
20S
30S
40S
50S
0
60E
120E
180
120W
60W
0
3
2.5
1.5
1
0.5

Fig.1

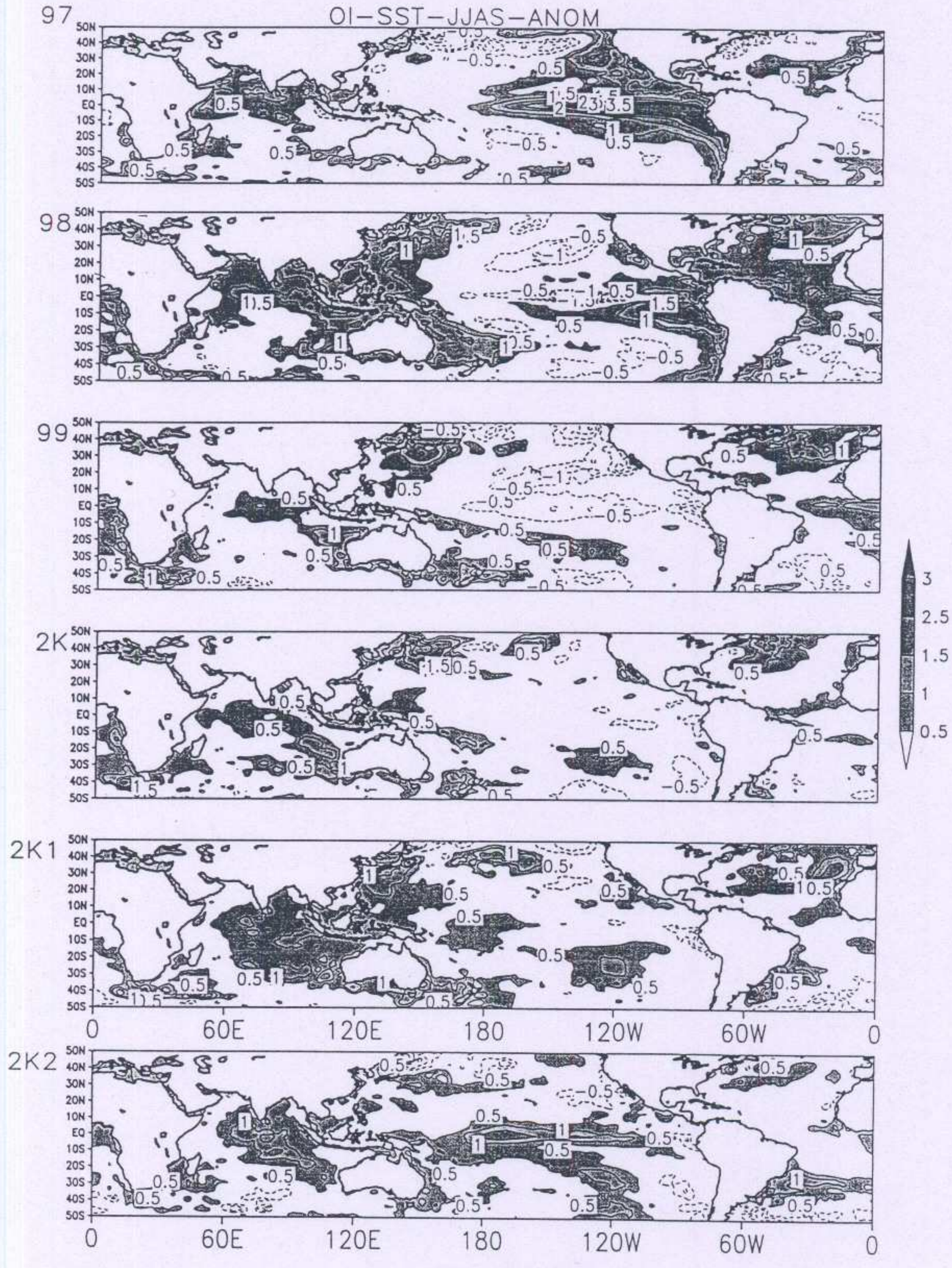

OI-SST-JJAS-ANOM
97
98
99
2K
2K1
2K2
0
60E
120E
180
120W
60W
0
3
2.5
1.5
1
0.5

Fig. 2

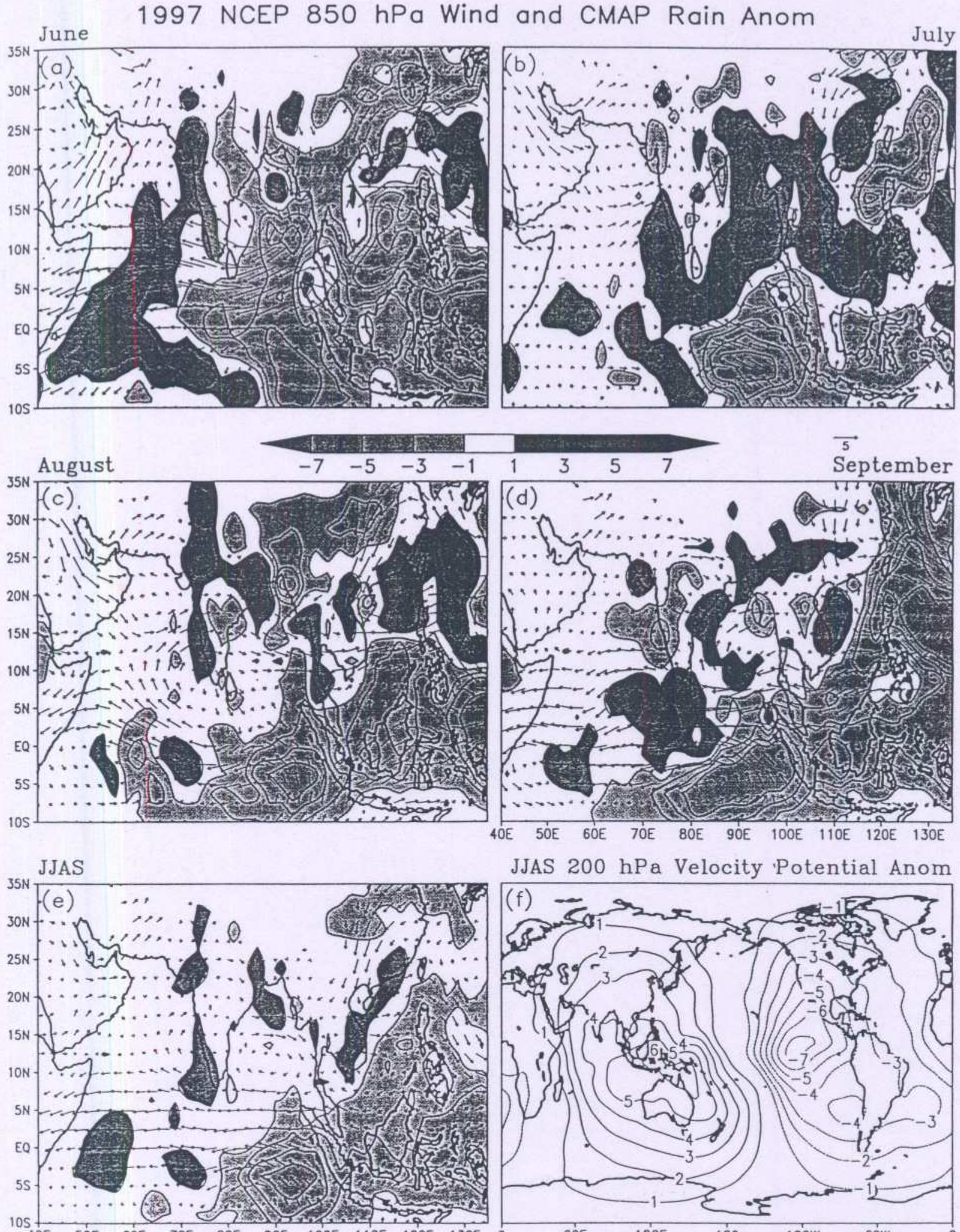

1997 NCEP 850 hPa Wind and CMAP Rain Anom
June
July
(a)
(b)
August
September
(c)
(d)
-7 -5 -3 -1 1 3 5 7
5
JJAS
(e)
JJAS 200 hPa Velocity Potential Anom
(f)
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
40E 50E 60E 70E 80E 90E 100E 110E 120E 130E
0 60E 120E 180 120W 60W 0

Fig.3

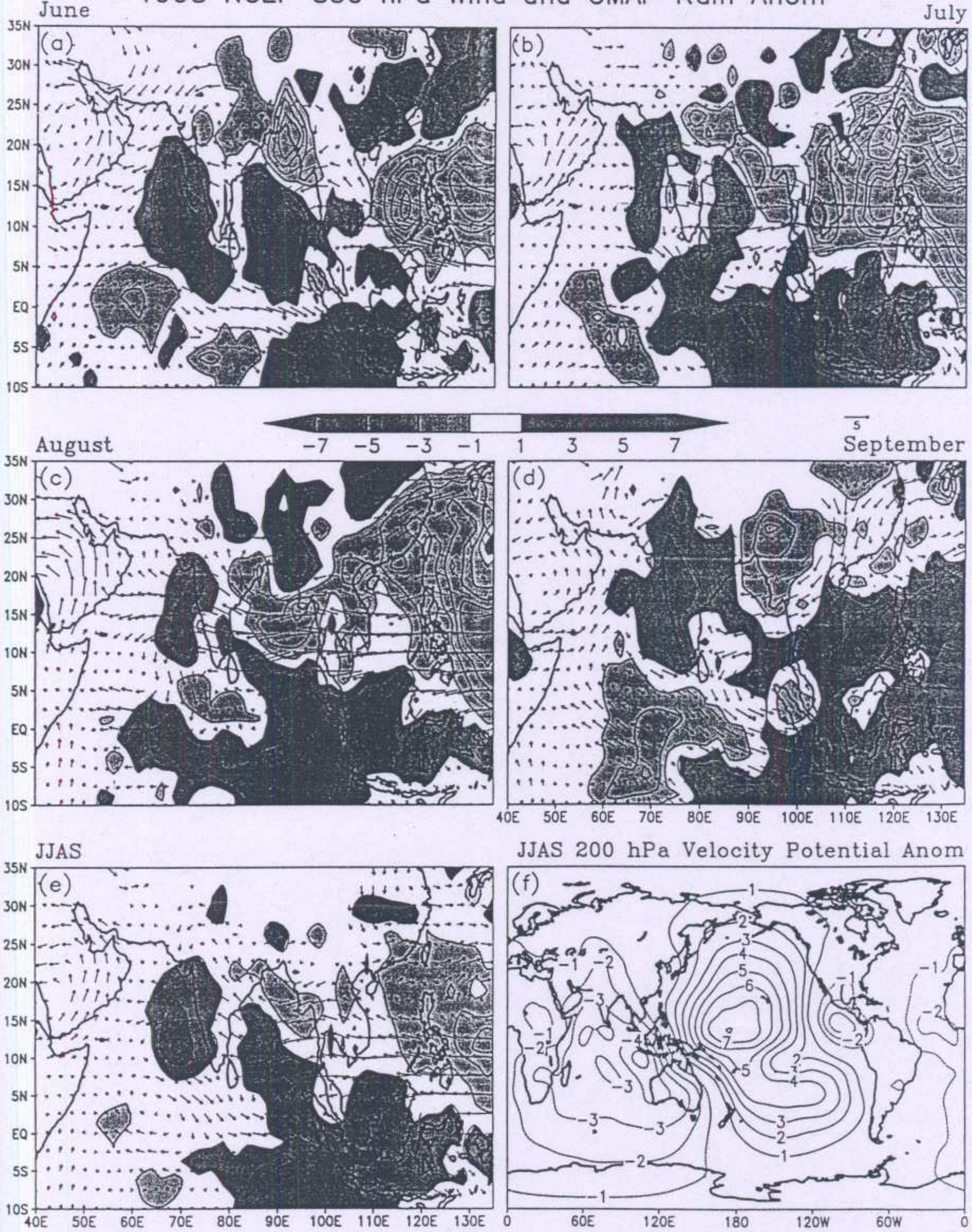
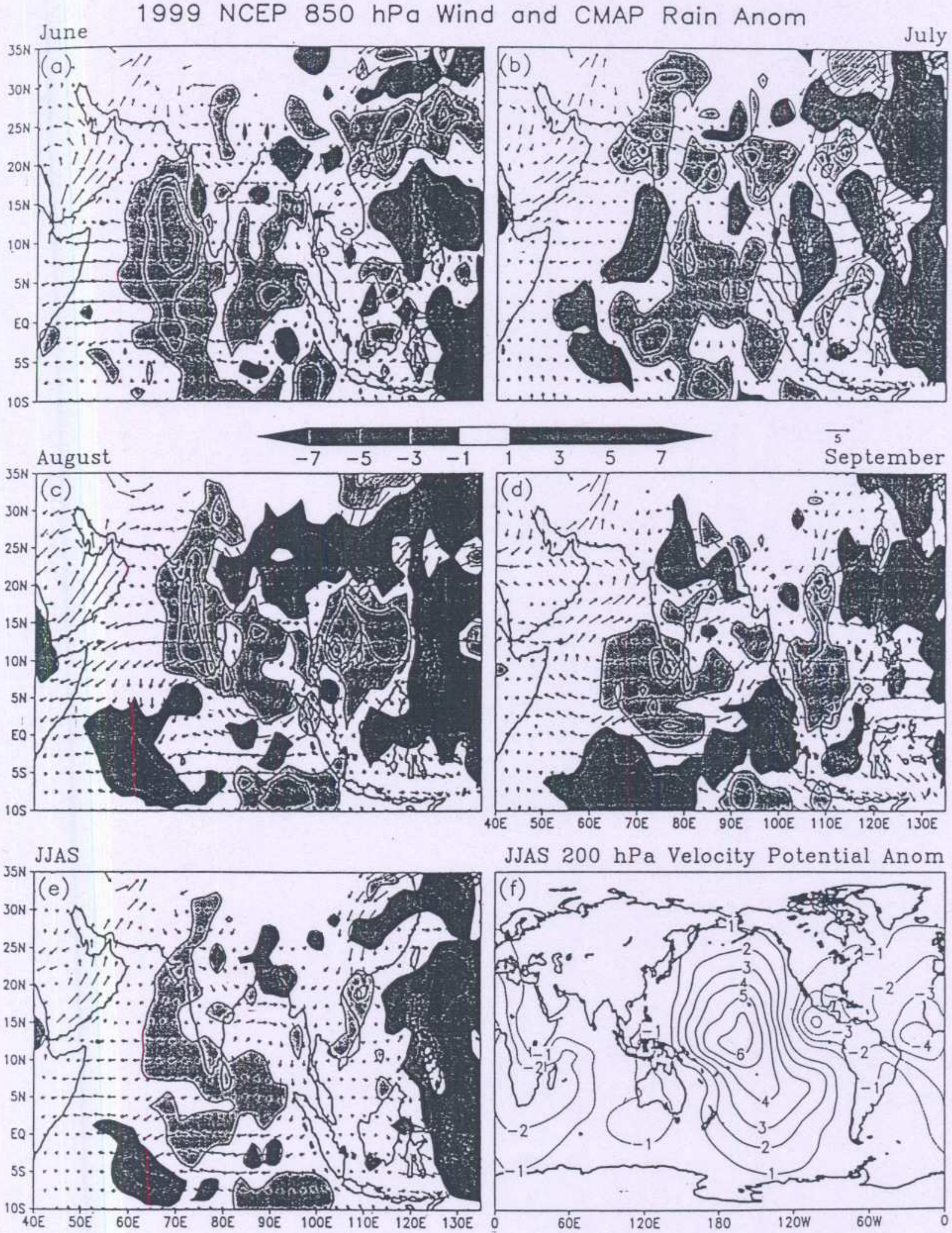

1998 NCEP 850 hPa Wind and CMAP Rain Anom
June
July
(a)
(b)
August
September
(c)
(d)
-7 -5 -3 -1 1 3 5 7
5
JJAS
(e)
JJAS 200 hPa Velocity Potential Anom
(f)
35N 30N 25N 20N 15N 10N 5N EQ 5S 10S
40E 50E 60E 70E 80E 90E 100E 110E 120E 130E
0 60E 120E 180 120W 60W 0

Fig. 4



1999 NCEP 850 hPa Wind and CMAP Rain Anom
June
July
(a)
(b)
August
September
(c)
(d)
-7 -5 -3 -1 1 3 5 7
5
JJAS
JJAS 200 hPa Velocity Potential Anom
(e)
(f)
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
40E 50E 60E 70E 80E 90E 100E 110E 120E 130E
0 60E 120E 180 120W 60W 0


Fig.5

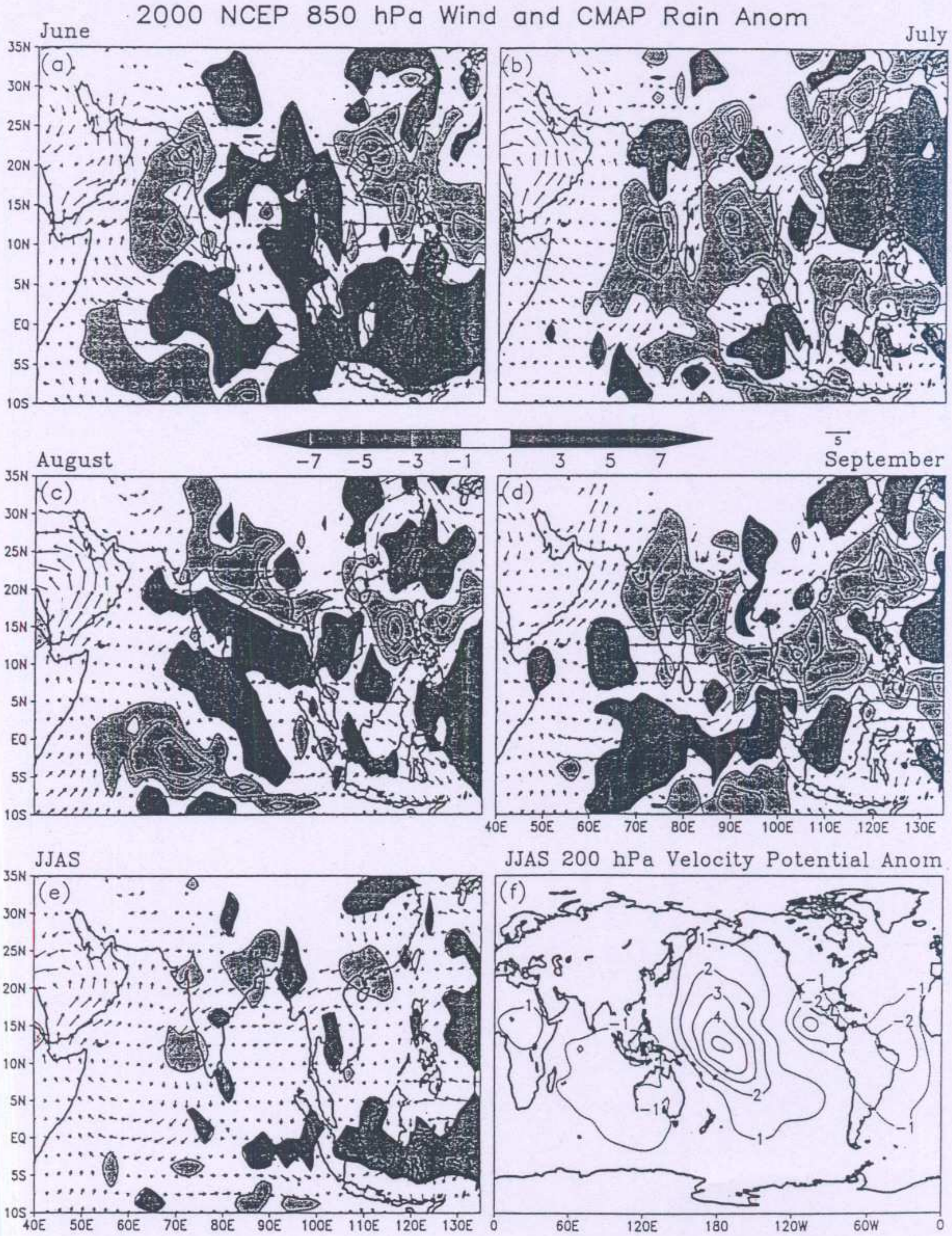
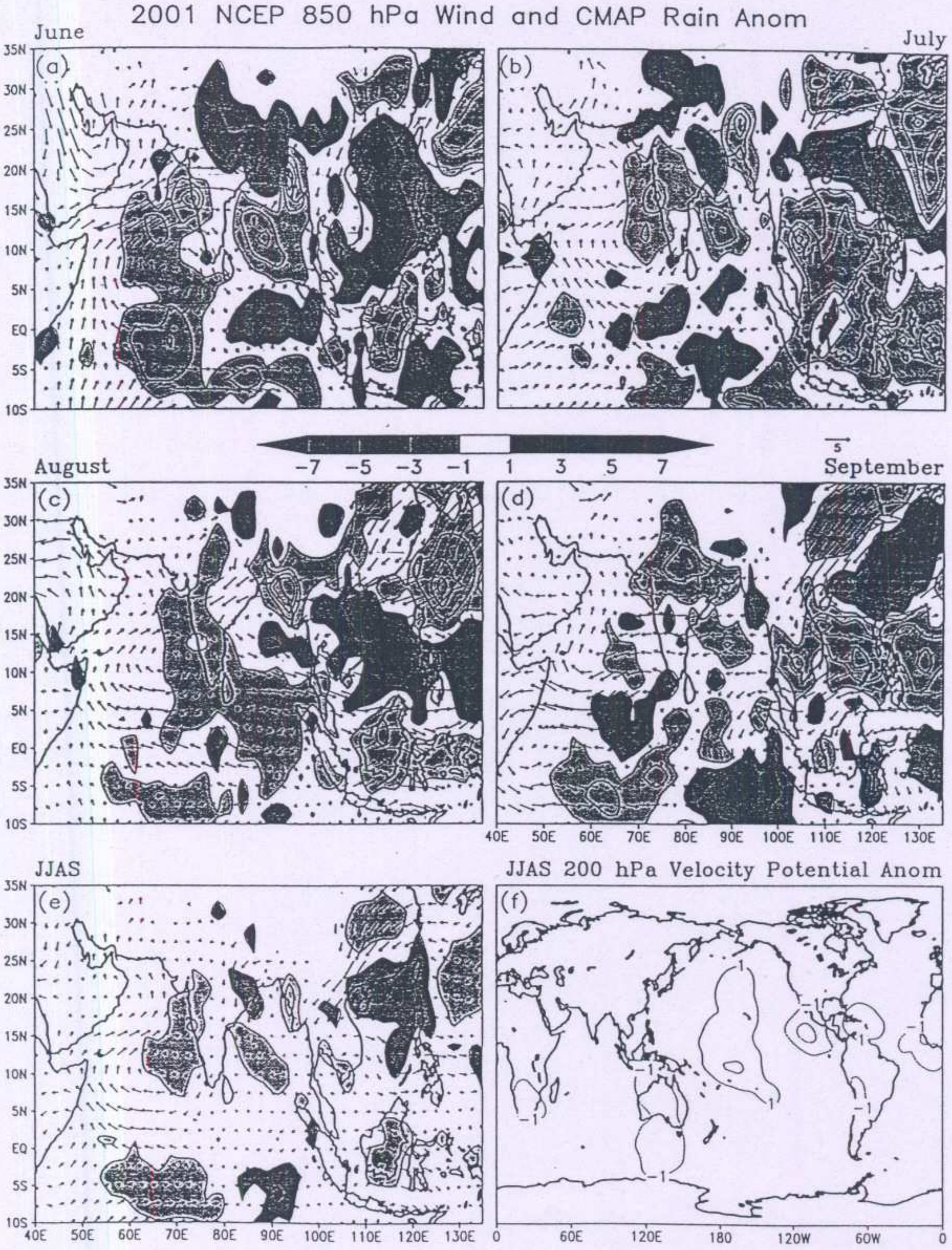
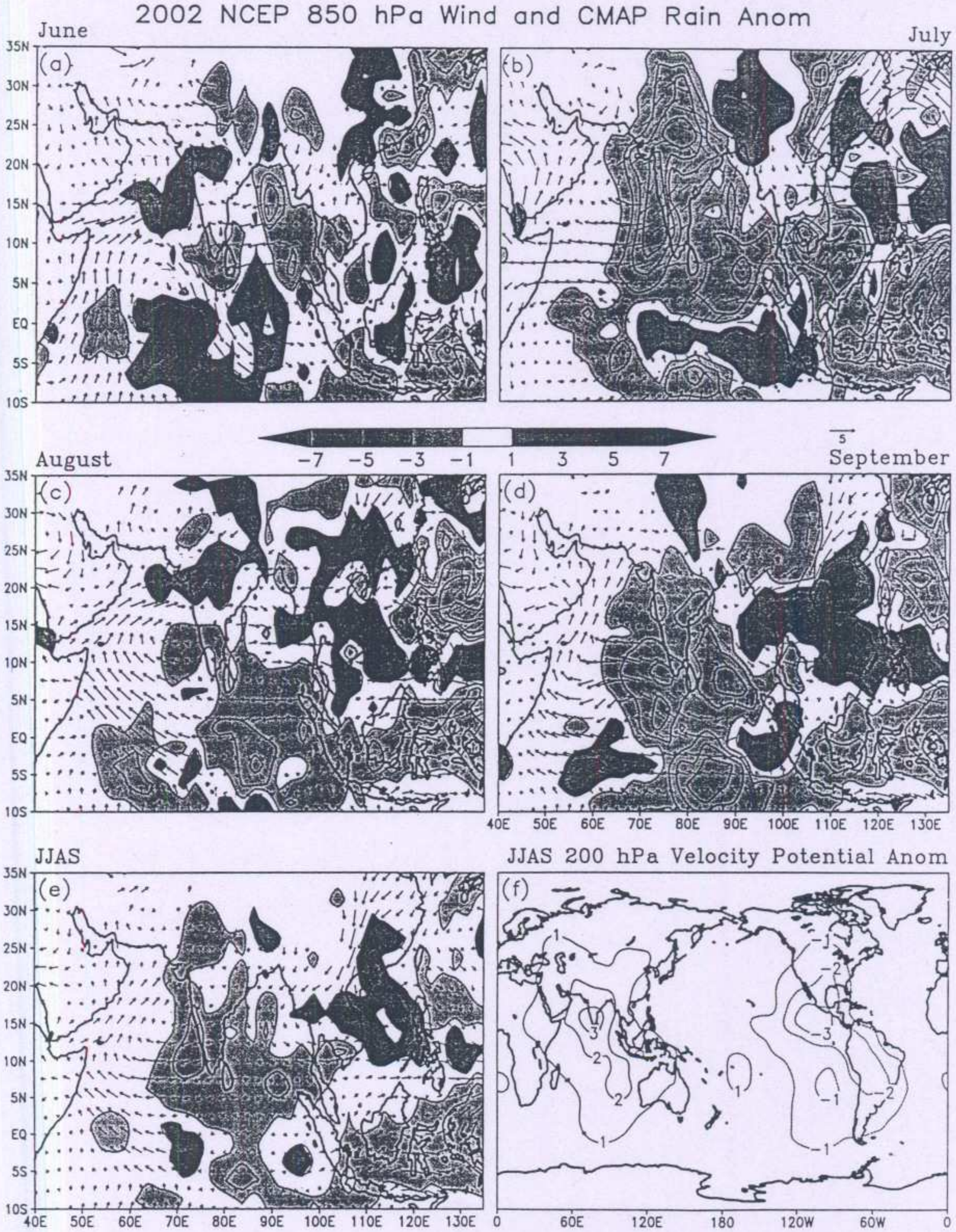

2000 NCEP 850 hPa Wind and CMAP Rain Anom
June
July
(a)
(b)
August
September
(c)
(d)
-7 -5 -3 -1 1 3 5 7
5
JJAS
JJAS 200 hPa Velocity Potential Anom
(e)
(f)
35N 30N 25N 20N 15N 10N 5N EQ 5S 10S
40E 50E 60E 70E 80E 90E 100E 110E 120E 130E
0 60E 120E 180 120W 60W 0

Fig.6



2001 NCEP 850 hPa Wind and CMAP Rain Anom
June
July
(a)
(b)
August
September
(c)
(d)
-7 -5 -3 -1 1 3 5 7
5
JJAS
JJAS 200 hPa Velocity Potential Anom
(e)
(f)
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
40E 50E 60E 70E 80E 90E 100E 110E 120E 130E
0 60E 120E 180 120W 60W 0


Fig.7



2002 NCEP 850 hPa Wind and CMAP Rain Anom
June
July
(a)
(b)
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
-7 -5 -3 -1 1 3 5 7
5
August
September
(c)
(d)
40E 50E 60E 70E 80E 90E 100E 110E 120E 130E
JJAS
JJAS 200 hPa Velocity Potential Anom
(e)
(f)
0 60E 120E 180 120W 60W 0


Fig.8

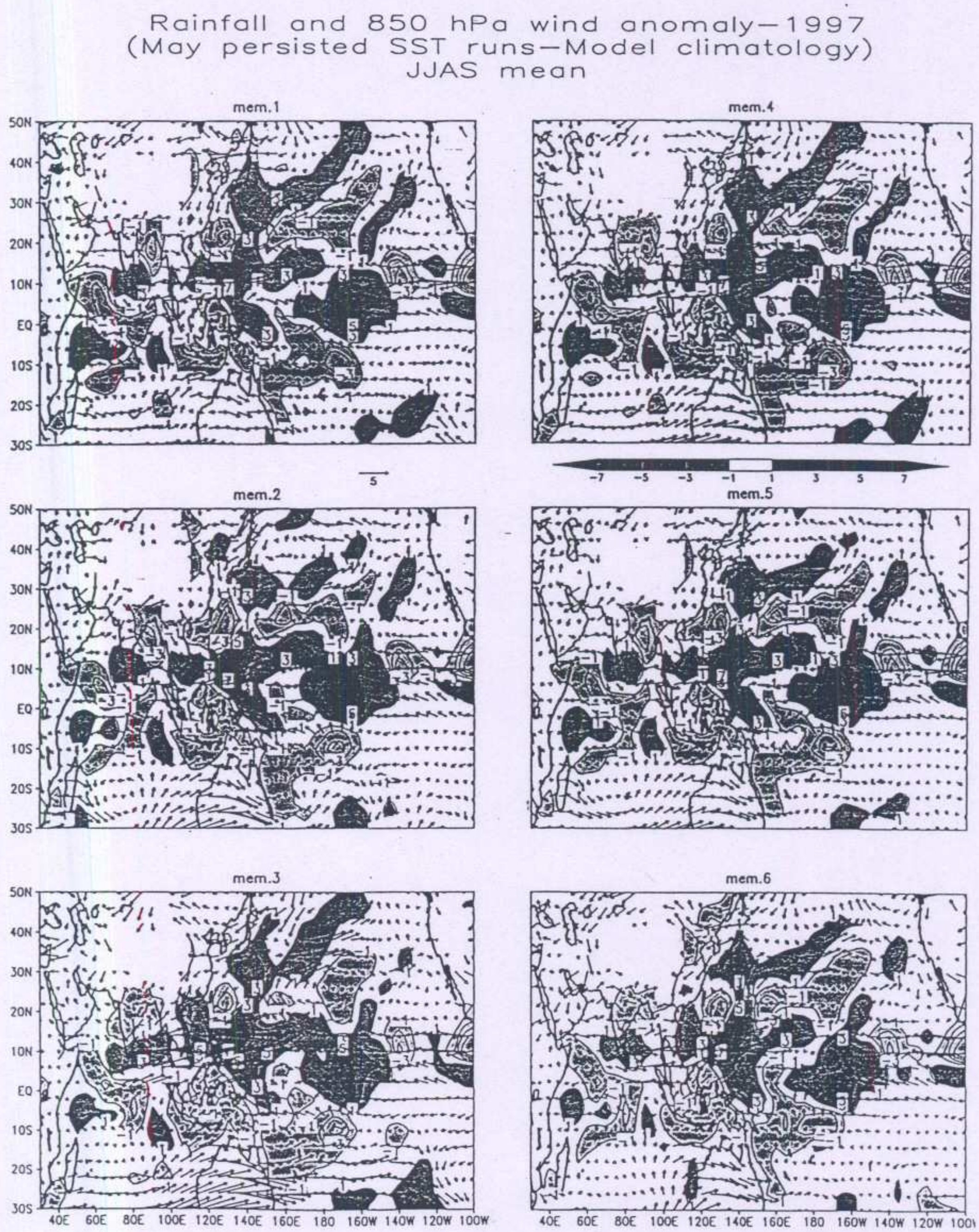

Rainfall and 850 hPa wind anomaly−1997
(May persisted SST runs−Model climatology)
JJAS mean
mem.1
mem.4
mem.2
mem.5
mem.3
mem.6
50N
40N
30N
20N
10N
EQ
10S
20S
30S
40E 60E 80E 100E 120E 140E 160E 180 160W 140W 120W 100W
-7 -5 -3 -1 1 3 5 7
5

Fig. 9

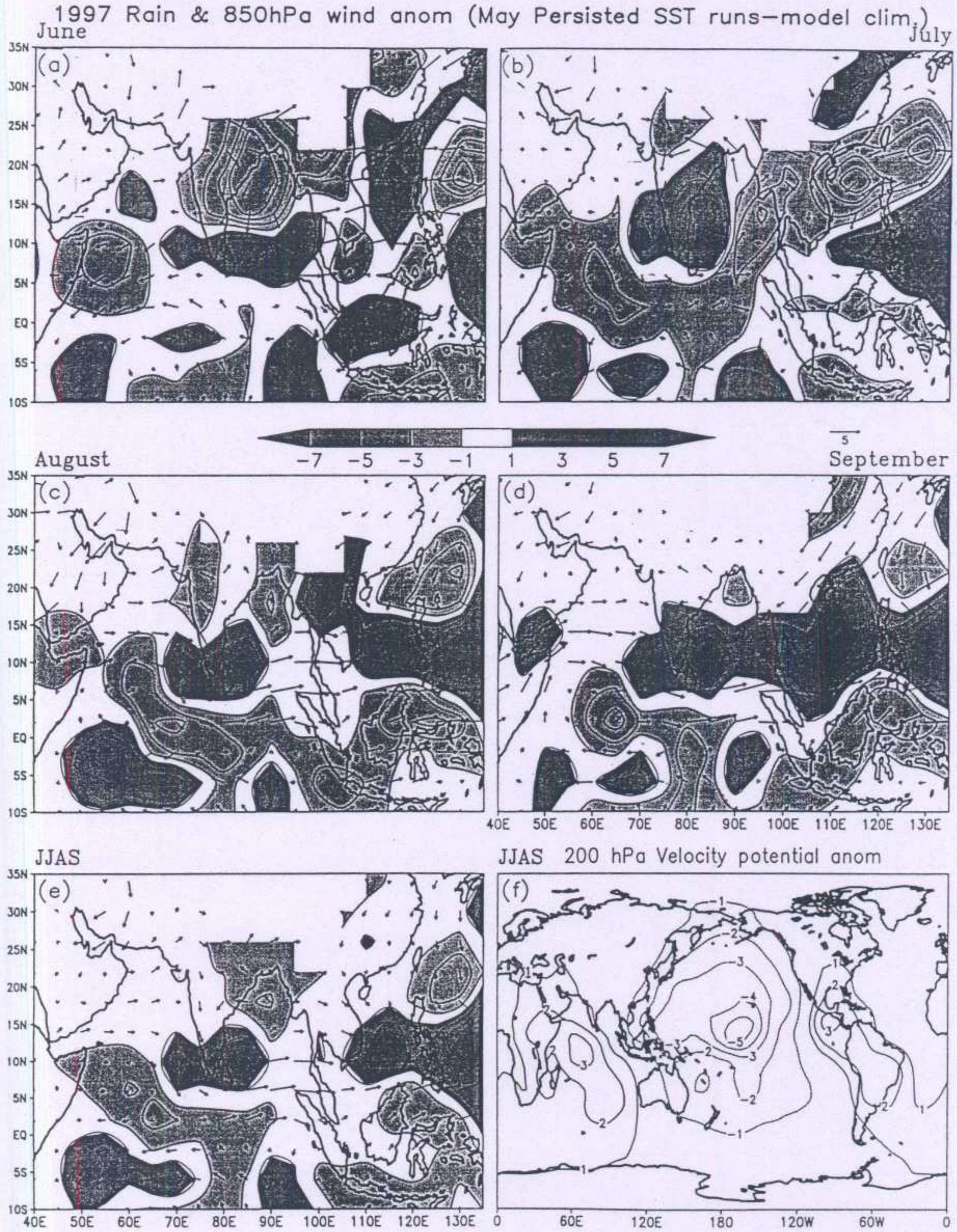

1997 Rain & 850hPa wind anom (May Persisted SST runs—model clim.)
June
July
(a)
(b)
August
September
(c)
(d)
-7 -5 -3 -1 1 3 5 7
5
JJAS
JJAS 200 hPa Velocity potential anom
(e)
(f)
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
40E 50E 60E 70E 80E 90E 100E 110E 120E 130E
0 60E 120E 180 120W 60W 0

Fig.10

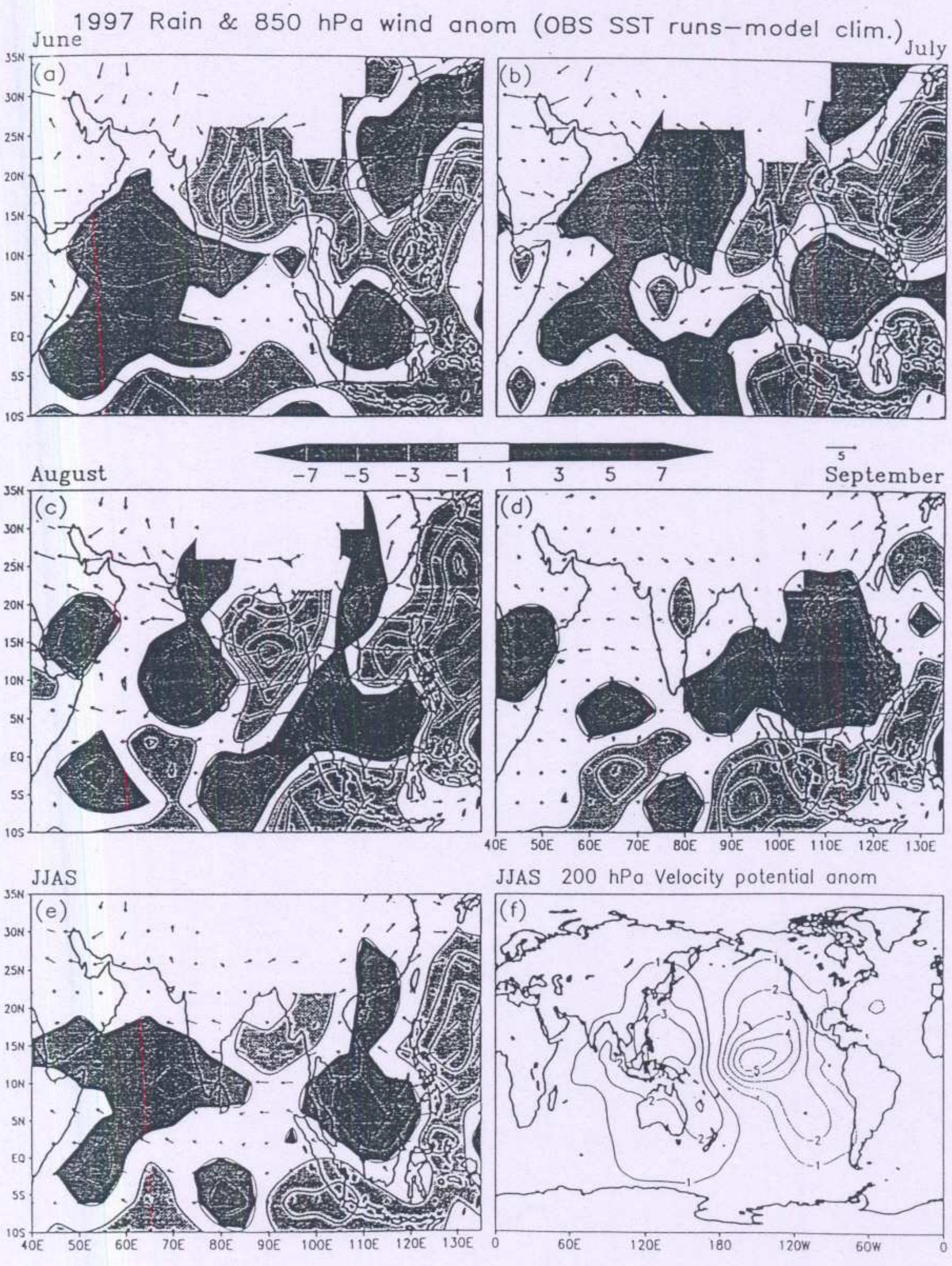

1997 Rain & 850 hPa wind anom (OBS SST runs—model clim.)
June
July
August
September
JJAS
JJAS 200 hPa Velocity potential anom
(a)
(b)
(c)
(d)
(e)
(f)
-7 -5 -3 -1 1 3 5 7
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
40E 50E 60E 70E 80E 90E 100E 110E 120E 130E
0 60E 120E 180 120W 60W 0

Fig.11

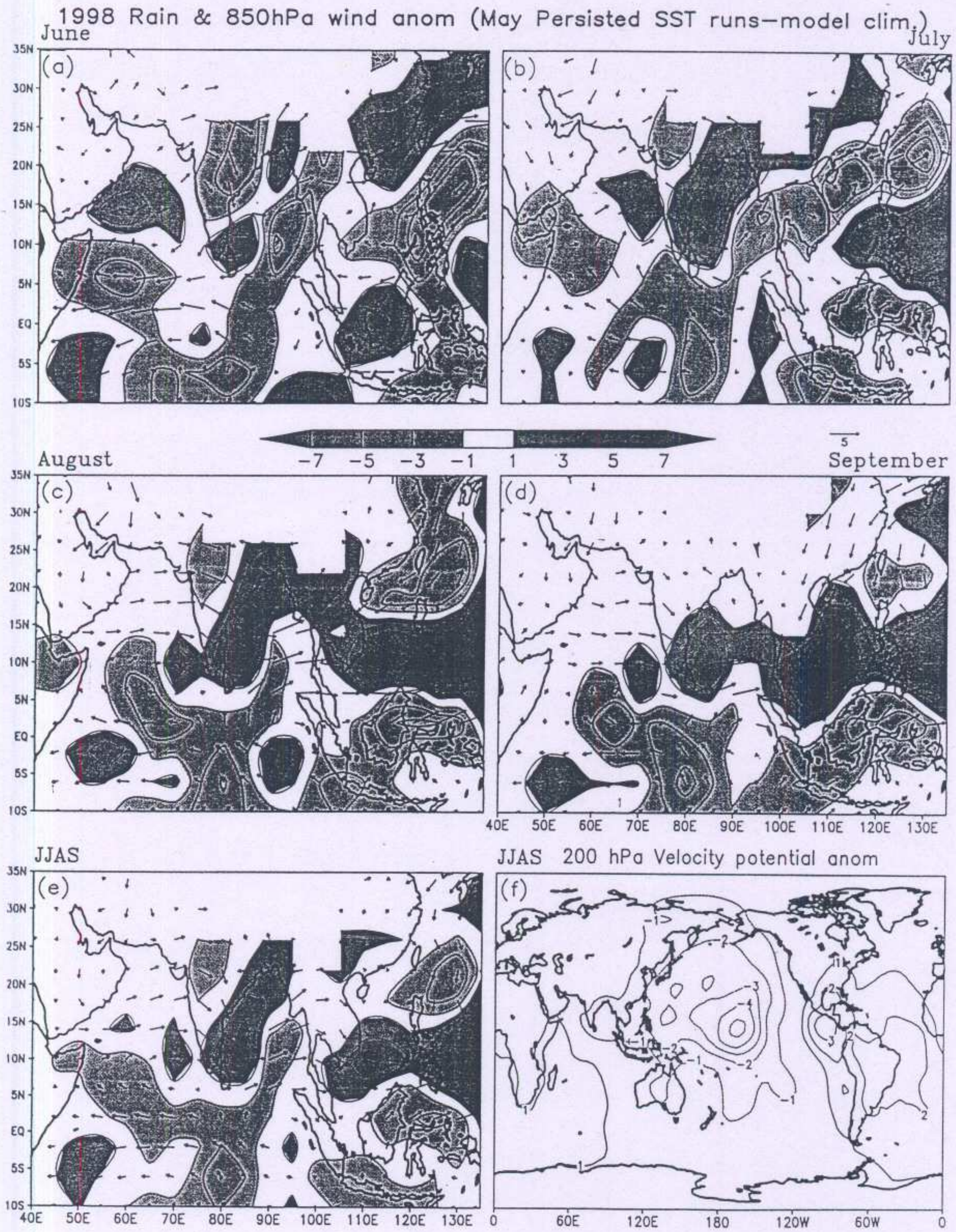

1998 Rain & 850hPa wind anom (May Persisted SST runs—model clim.)
June
July
(a)
(b)
-7 -5 -3 -1 1 3 5 7
5
August
September
(c)
(d)
JJAS
JJAS 200 hPa Velocity potential anom
(e)
(f)
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
40E 50E 60E 70E 80E 90E 100E 110E 120E 130E
0 60E 120E 180 120W 60W 0

Fig. 12

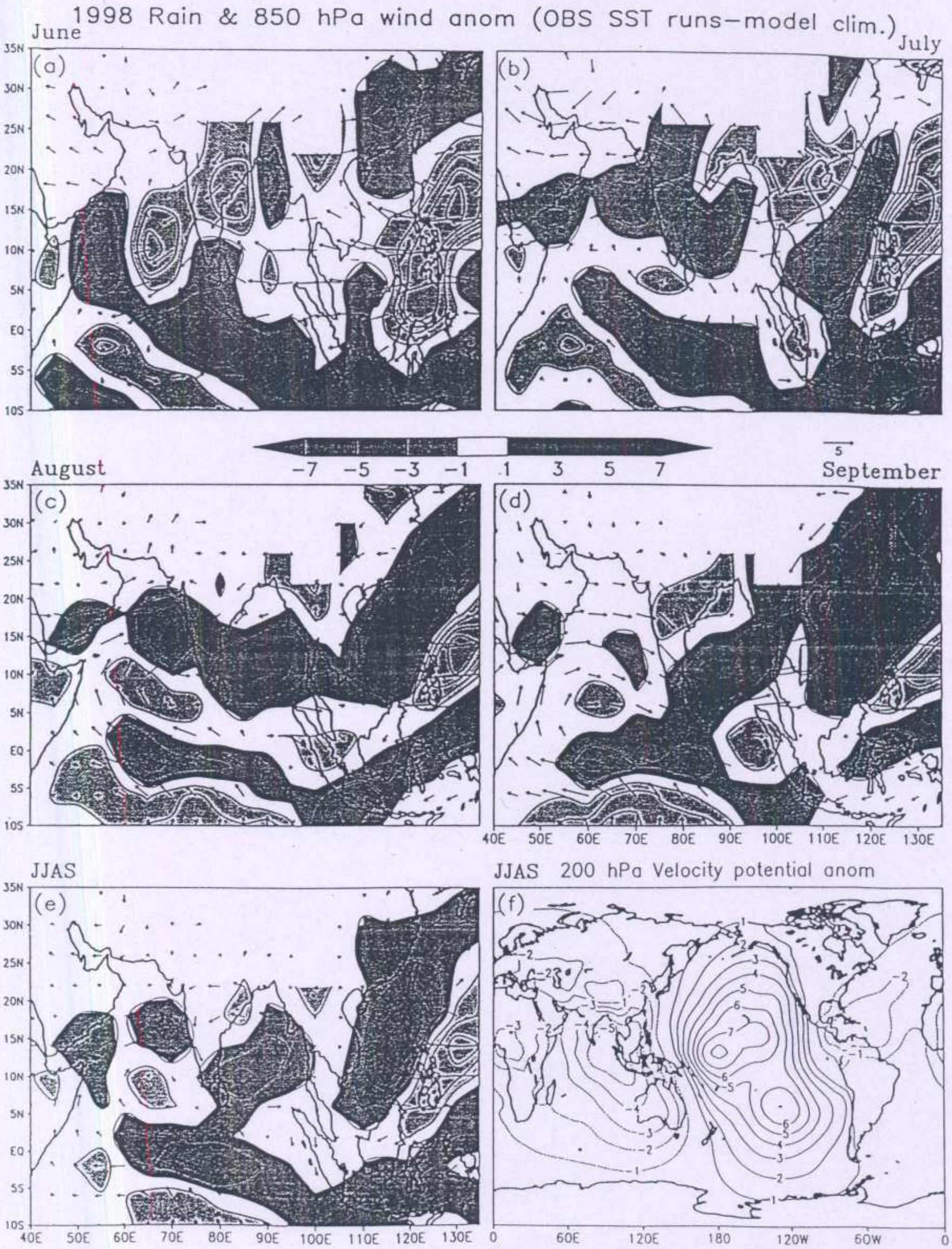
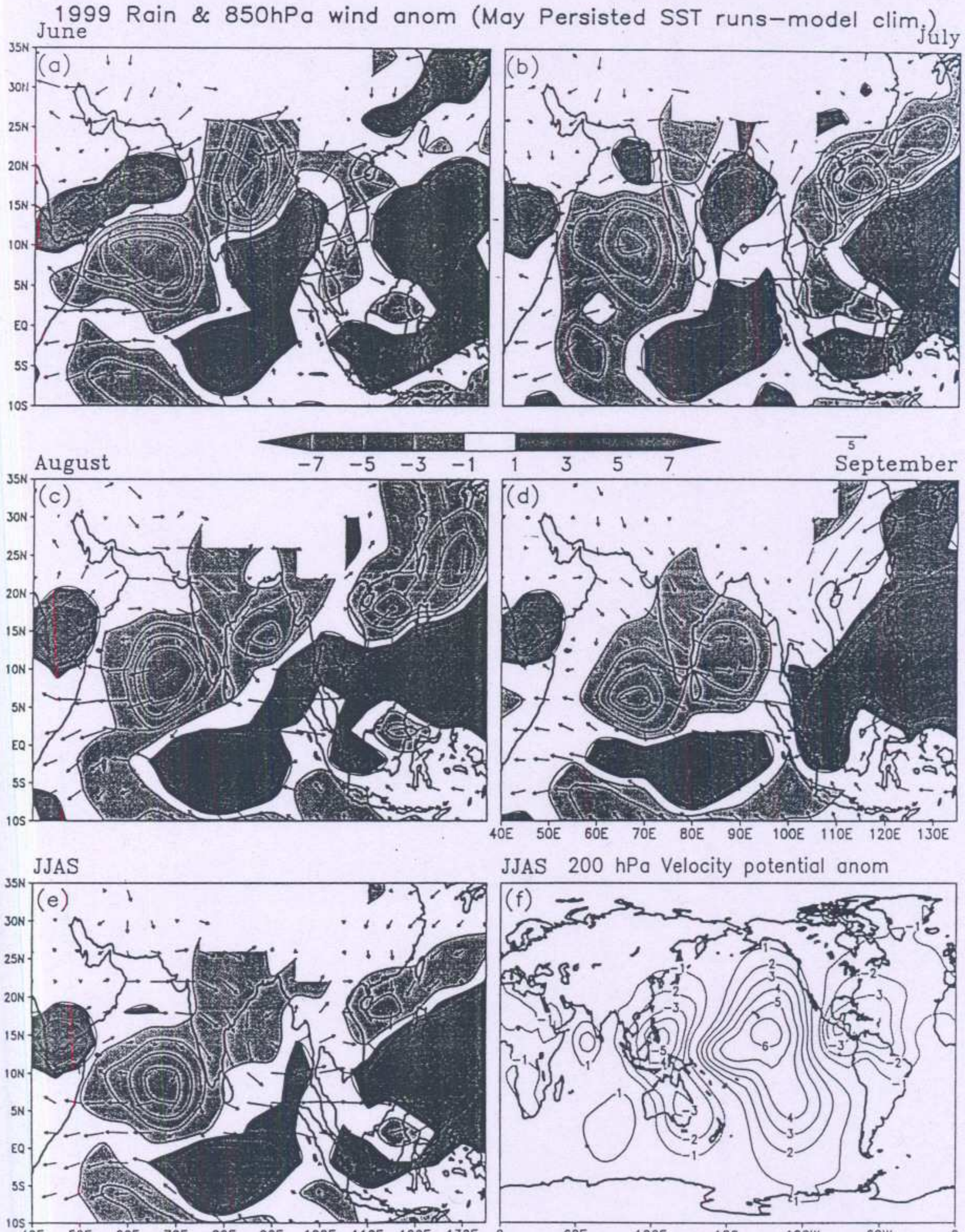

1998 Rain & 850 hPa wind anom (OBS SST runs—model clim.)
June
July
(a)
(b)
-7 -5 -3 -1 .1 3 5 7
August
September
(c)
(d)
JJAS
JJAS 200 hPa Velocity potential anom
(e)
(f)
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
40E 50E 60E 70E 80E 90E 100E 110E 120E 130E
0 60E 120E 180 120W 60W 0

Fig.13



1999 Rain & 850hPa wind anom (May Persisted SST runs−model clim.)
June
July
(a)
(b)
August
September
(c)
(d)
-7 -5 -3 -1 1 3 5 7
5
JJAS
(e)
JJAS 200 hPa Velocity potential anom
(f)
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
40E 50E 60E 70E 80E 90E 100E 110E 120E 130E
0 60E 120E 180 120W 60W 0


Fig.14

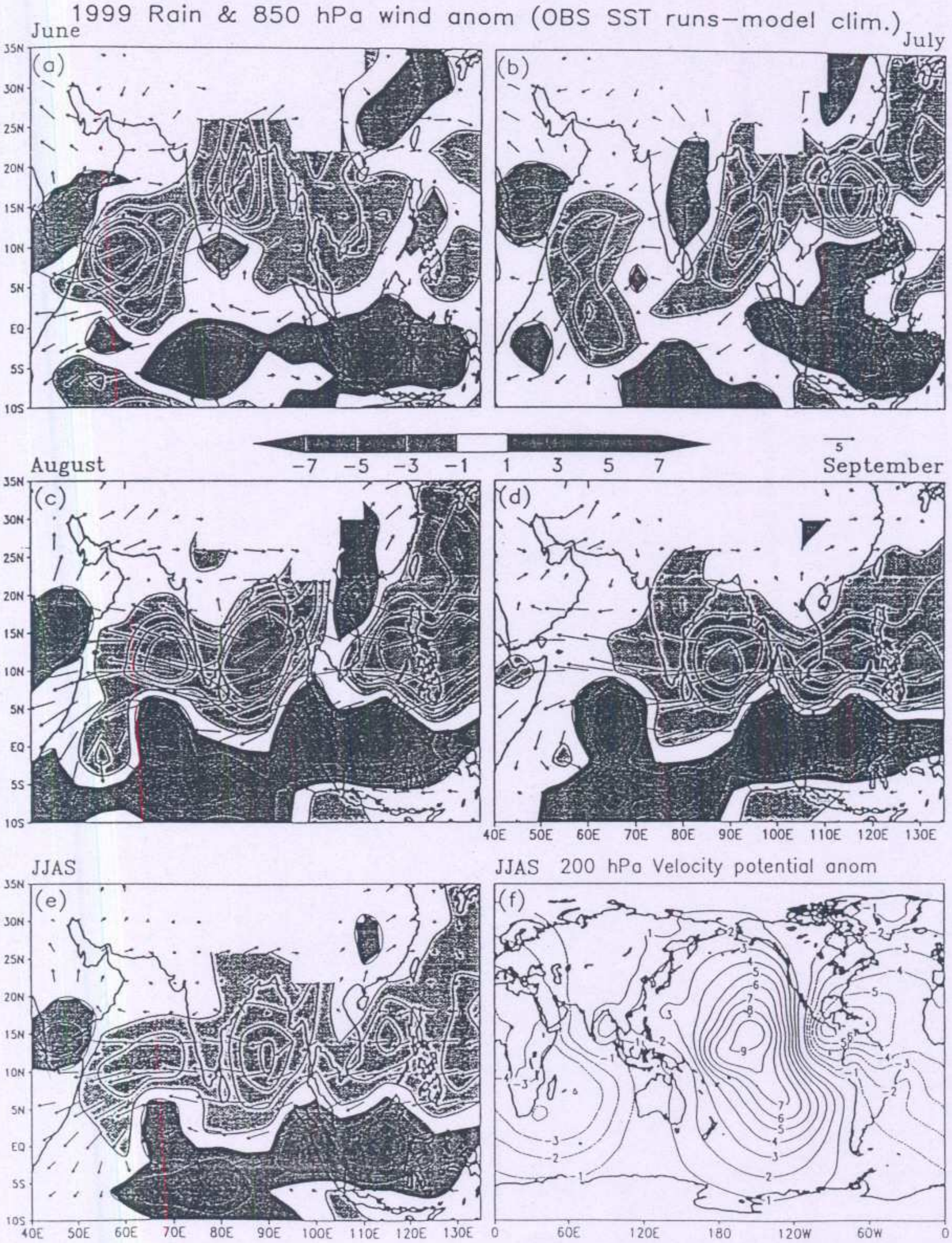

1999 Rain & 850 hPa wind anom (OBS SST runs−model clim.)
June
July
August
September
JJAS
JJAS 200 hPa Velocity potential anom
(a)
(b)
(c)
(d)
(e)
(f)
−7 −5 −3 −1 1 3 5 7
5
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
40E 50E 60E 70E 80E 90E 100E 110E 120E 130E
0 60E 120E 180 120W 60W 0

Fig. 15

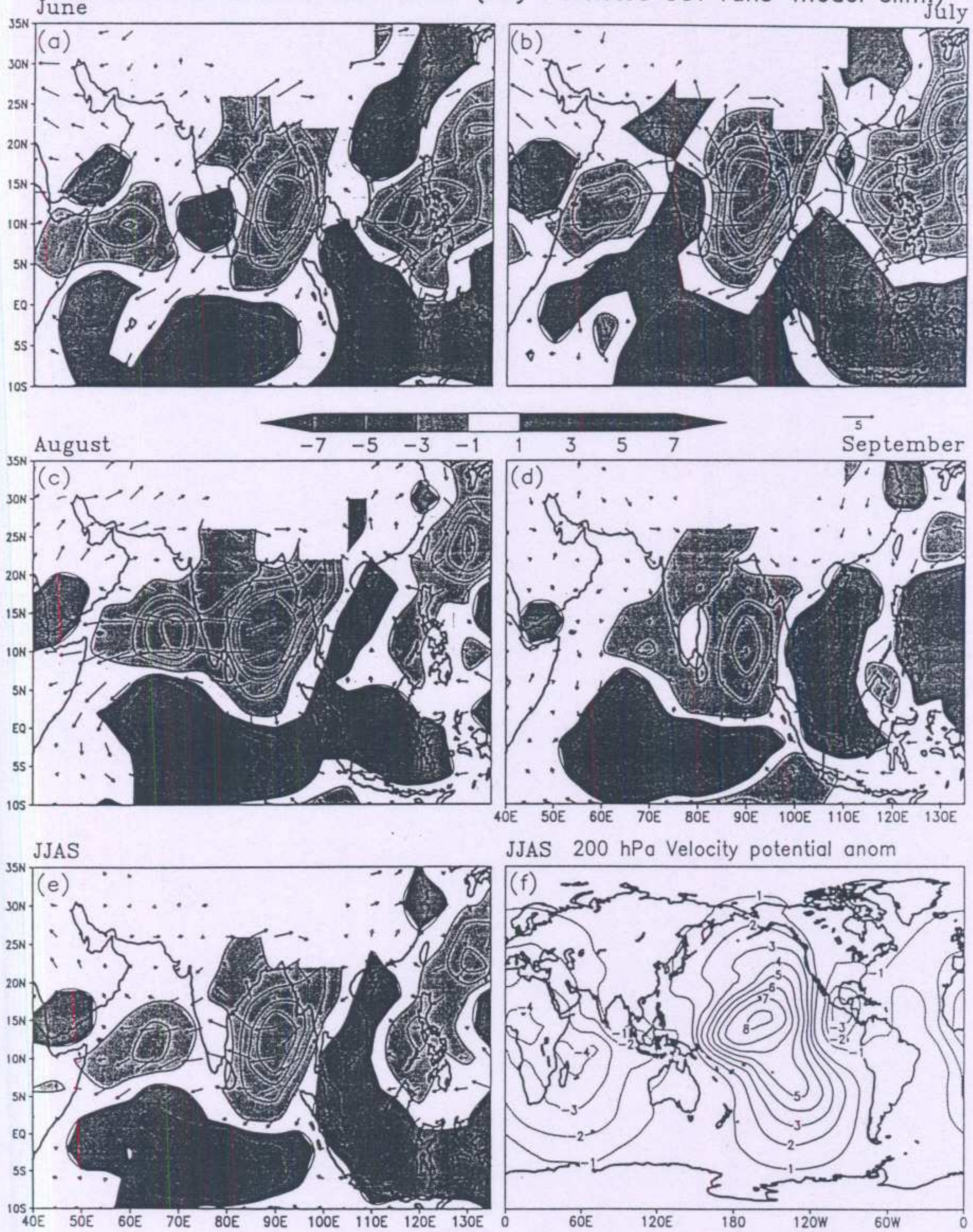

2000 Rain & 850hPa wind anom (May Persisted SST runs—model clim.)
June
July
August
September
JJAS
JJAS 200 hPa Velocity potential anom
(a)
(b)
(c)
(d)
(e)
(f)
-7 -5 -3 -1 1 3 5 7
5

Fig.16

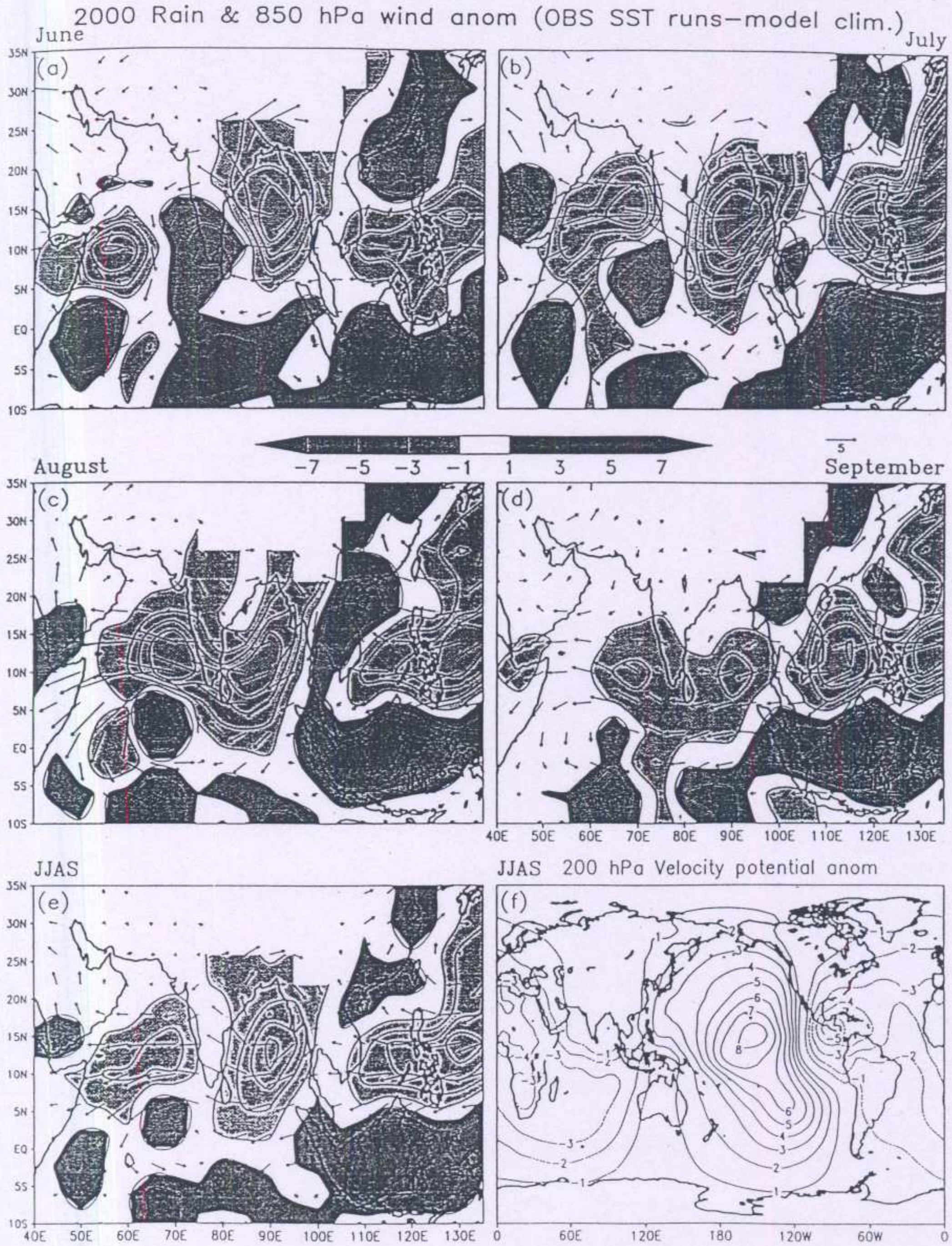

2000 Rain & 850 hPa wind anom (OBS SST runs−model clim.)
June
July
(a)
(b)
August
September
(c)
(d)
−7 −5 −3 −1 1 3 5 7
5
JJAS
(e)
JJAS 200 hPa Velocity potential anom
(f)
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
40E 50E 60E 70E 80E 90E 100E 110E 120E 130E
0 60E 120E 180 120W 60W 0

Fig. 17

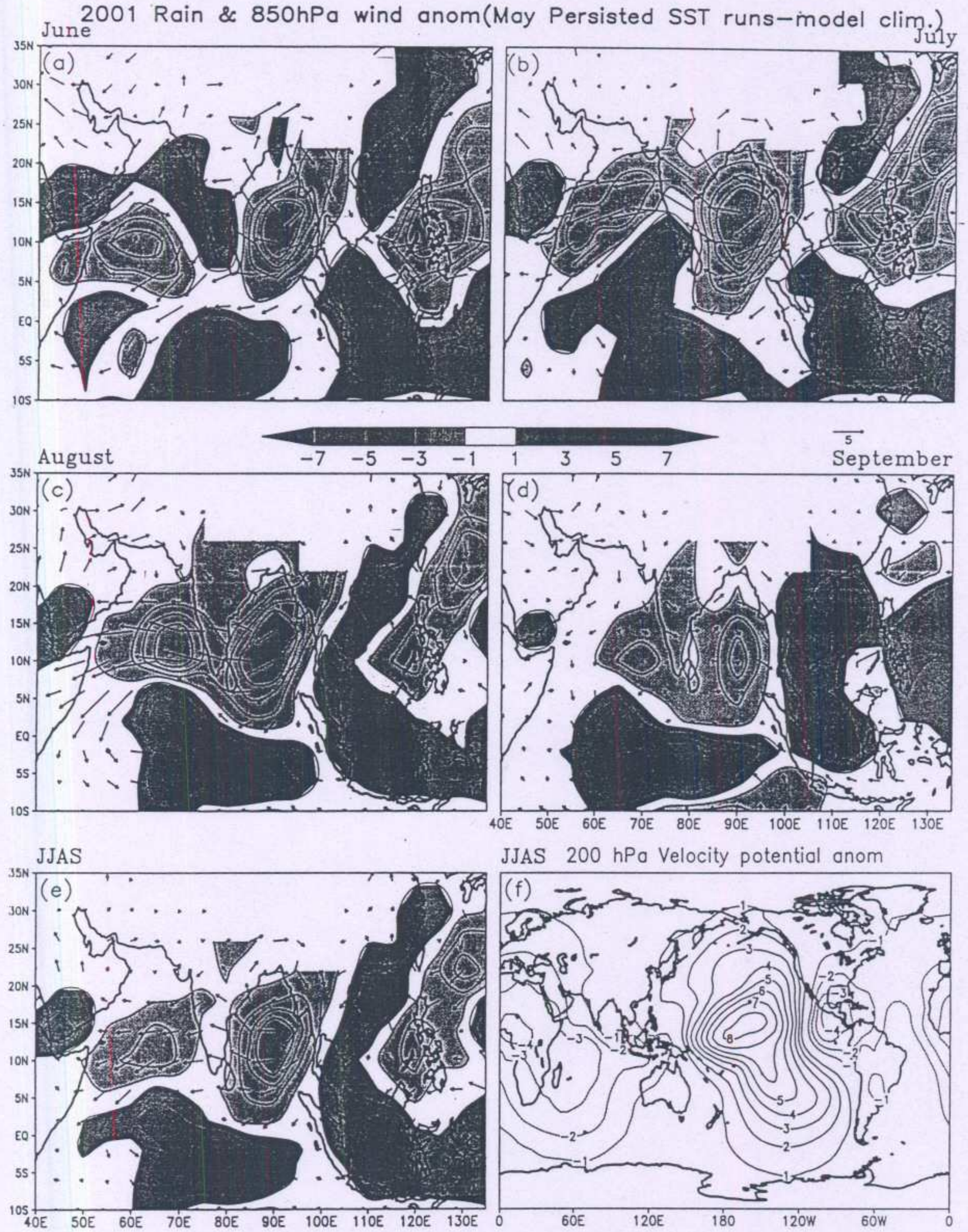
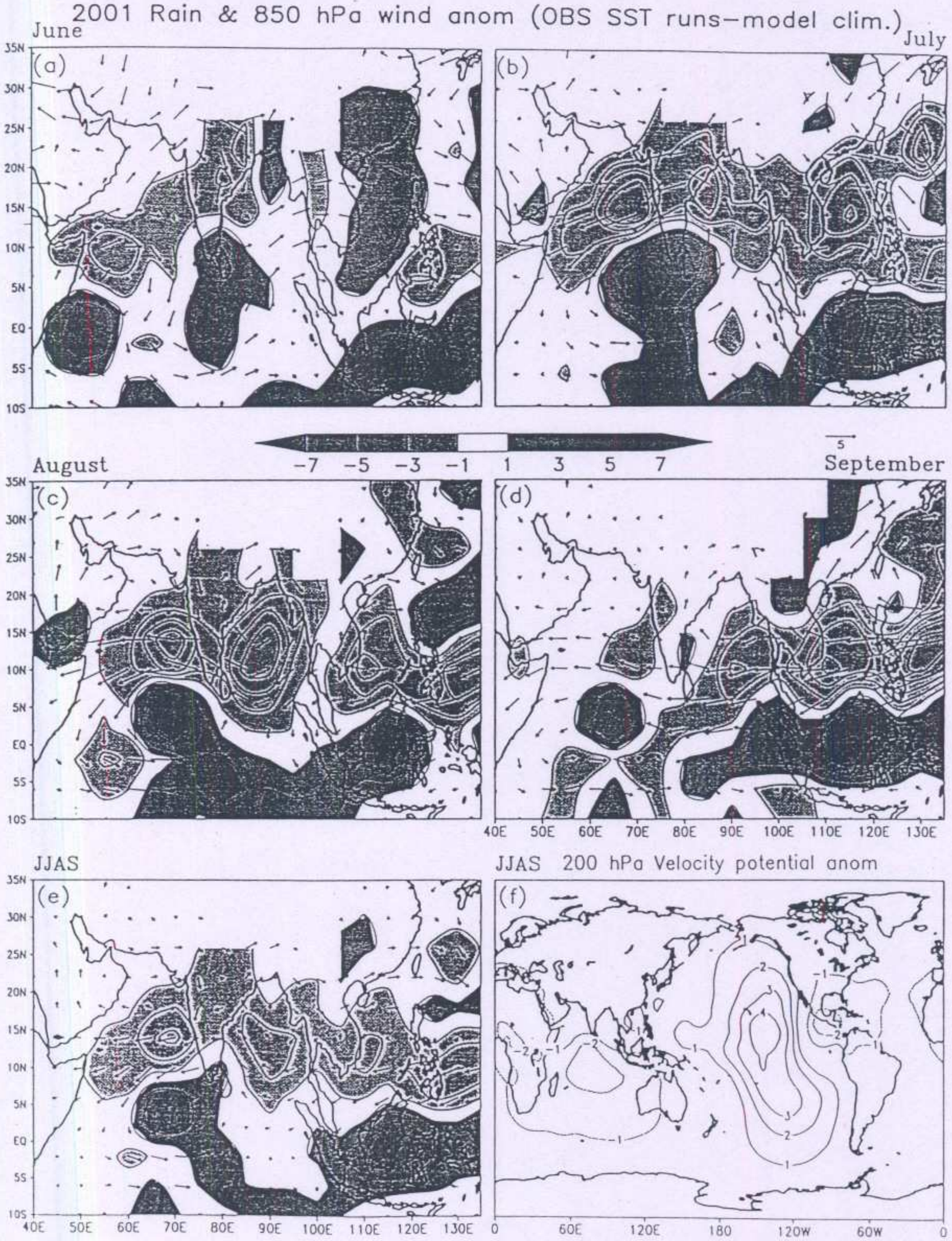

2001 Rain & 850hPa wind anom(May Persisted SST runs−model clim.)
June
July
(a)
(b)
(c)
(d)
(e)
(f)
August
September
-7 -5 -3 -1 1 3 5 7
5
JJAS
JJAS 200 hPa Velocity potential anom
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
40E 50E 60E 70E 80E 90E 100E 110E 120E 130E
0 60E 120E 180 120W 60W 0

Fig.18



2001 Rain & 850 hPa wind anom (OBS SST runs−model clim.)
June
July
August
September
JJAS
JJAS 200 hPa Velocity potential anom
(a)
(b)
(c)
(d)
(e)
(f)
−7 −5 −3 −1 1 3 5 7
5
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
40E 50E 60E 70E 80E 90E 100E 110E 120E 130E
0 60E 120E 180 120W 60W 0


Fig. 19

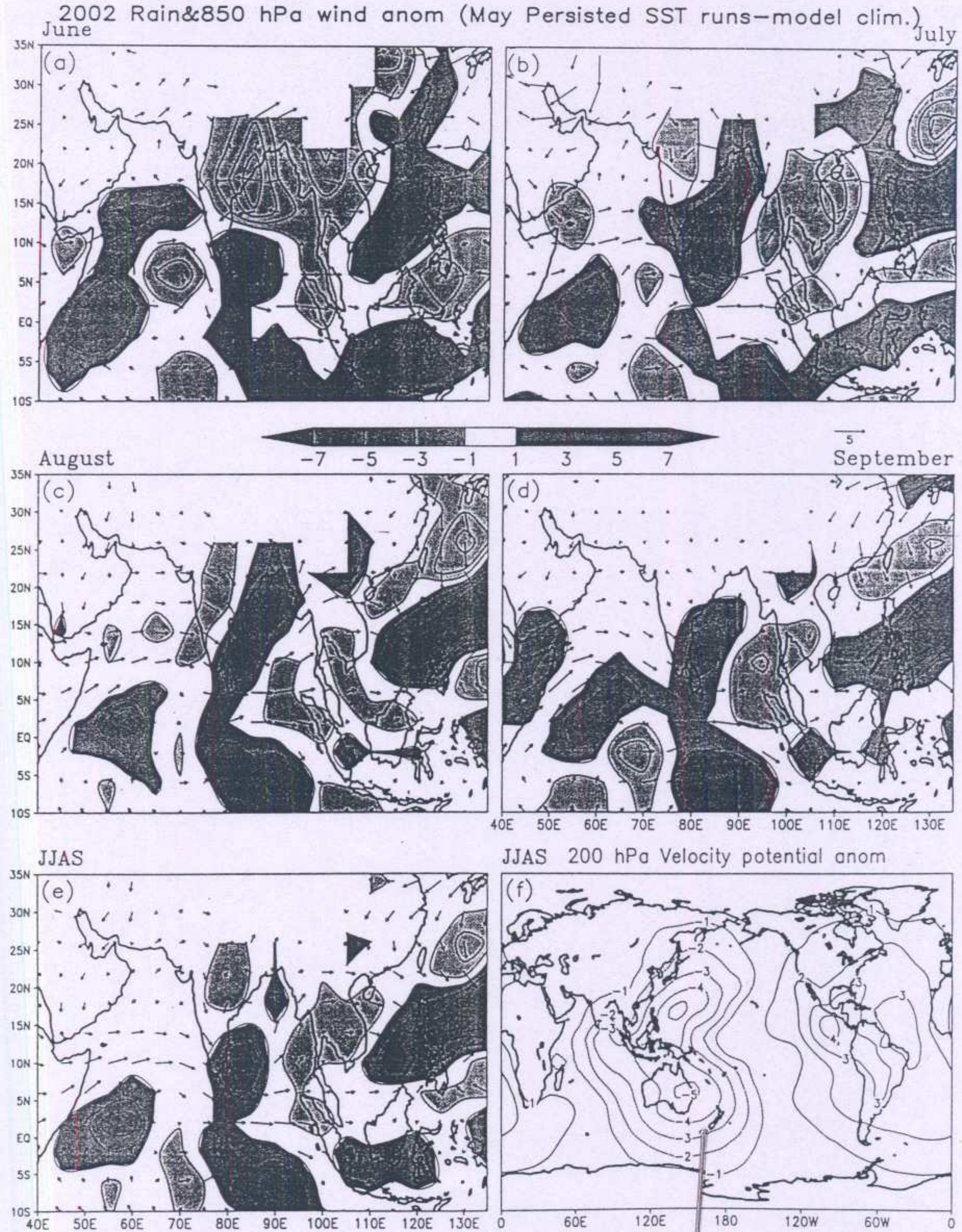

2002 Rain&850 hPa wind anom (May Persisted SST runs–model clim.)
June
July
(a)
(b)
−7 −5 −3 −1 1 3 5 7
5
August
September
(c)
(d)
JJAS
JJAS 200 hPa Velocity potential anom
(e)
(f)
35N 30N 25N 20N 15N 10N 5N EQ 5S 10S
40E 50E 60E 70E 80E 90E 100E 110E 120E 130E
0 60E 120E 180 120W 60W 0

Fig. 20

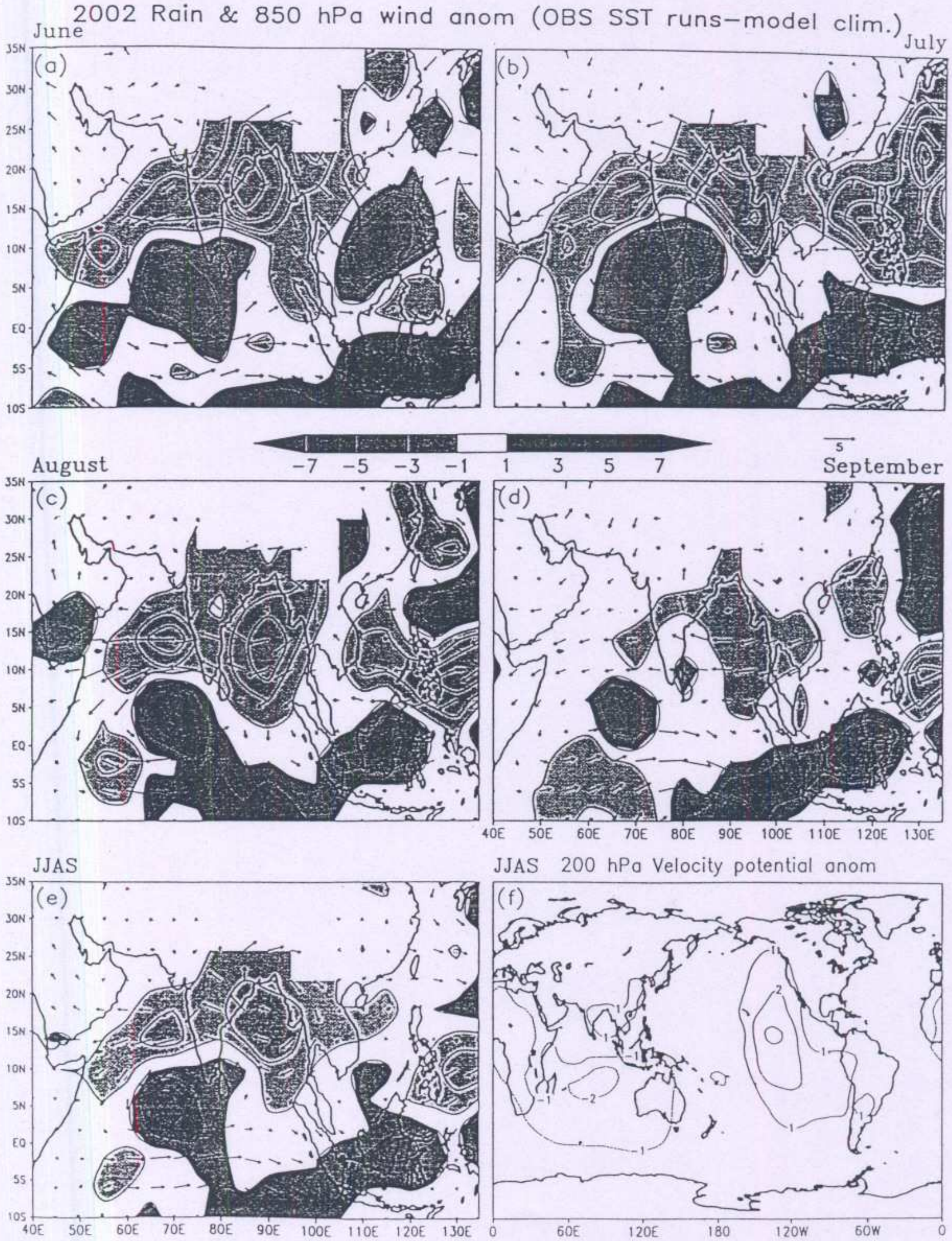
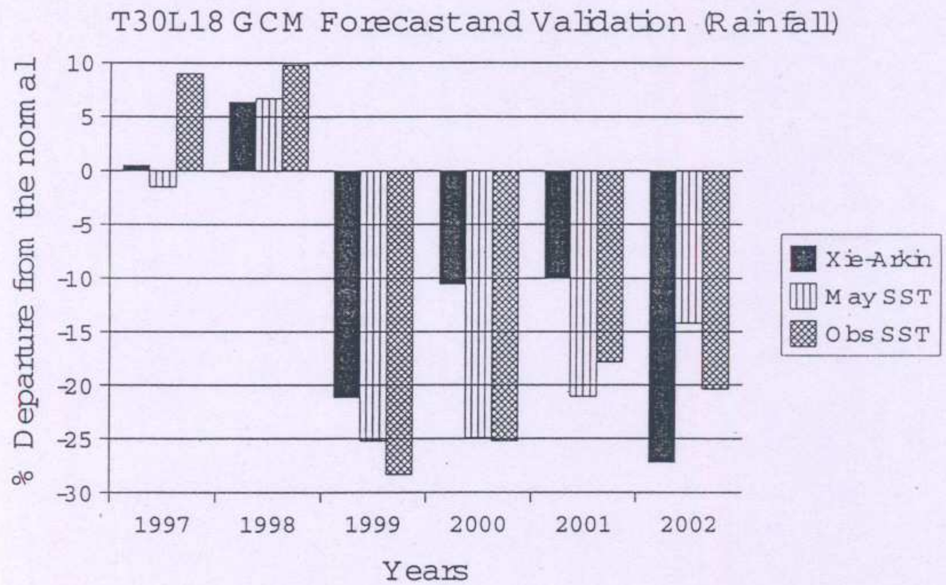

2002 Rain & 850 hPa wind anom (OBS SST runs−model clim.)
June
July
August
September
JJAS
JJAS 200 hPa Velocity potential anom
(a)
(b)
(c)
(d)
(e)
(f)
−7 −5 −3 −1 1 3 5 7
5
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
40E 50E 60E 70E 80E 90E 100E 110E 120E 130E
0 60E 120E 180 120W 60W 0

Fig. 21



T30L18 GCM Forecast and Validation (Rainfall)
% Departure from the normal
10
5
0
-5
-10
-15
-20
-25
-30
1997
1998
1999
2000
2001
2002
Years
Xie-Arkin
May SST
Obs SST


Fig. 22

# I. I. T. M. RESEARCH REPORTS

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- Study of potential evapo-transpiration over Andhra Pradesh, *Rakhecha P.R.*, September 1971, RR-004.
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- Theoretical study of mountain waves in Assam, *De U.S.*, February 1973, RR-007.
- Local fallout of radioactive debris from nuclear explosion in a monsoon atmosphere, *Saha K.R. and Sinha S.*, December 1972, RR-008.
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- Note on "Applicability of quasi-geostrophic barotropic model in the tropics", *Asnani G.C.*, February 1973, RR-010.
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- Southern hemisphere influence on Indian rainfall, *Raghavan K.., Paul D.K. and Upasani P.U.*, February 1976, RR-024.

- Climatic fluctuations over Indian region - Rainfall : A review, *Parthasarathy B. and Dhar O.N.*, May 1978, RR-025.

- Annual variation of meridional flux of sensible heat, *Verma R.K. and Asnani G.C.*, December 1978, RR-026.

- Poisson distribution and years of bad monsoon over India, *Mooley D.A and Parthasarathy B.*, April 1980, RR-027.

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