Experimental Seasonal Forecast of Monsoon 2005 Using T170L42 AGCM on PARAM Padma

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ABSTRACT

As a part of the Experimental Extended Range Monsoon Prediction Experiment, ensemble mode seasonal runs for the monsoon season of 2005 were made using the National Centre for Environmental Prediction (NCEP), T170L42 AGCM. The seasonal runs were made using six initial atmospheric conditions based on the NCEP operational analysis and with forecast monthly sea surface temperature (SST) of the NCEP Coupled forecast system (CFS). These simulations were carried out on the PARAM Padma supercomputer of Centre for Development of Advanced Computing (C-DAC), India. The model climatology was prepared by integrating the model for ten years using climatological SST as the lower boundary. The climatology of the model compares well with the observed, in terms of the spatial distribution of rainfall over the Indian land mass.

The model-simulated rainfall compares well with the Tropical Rainfall Measuring Mission (TRMM) estimates for the 2005 monsoon season. Compared to the model climatology (7.81mm/day), the model had simulated a normal rainfall (7.75 mm/day) for the year 2005 which is in agreement with the observations (99 % of long term mean). However, the model could not capture the observed increase in September rainfall from that of a low value in August 2005. The circulation patterns simulated by the model are also comparable to the observed patterns. The ensemble mean onset is found to be nearer to the observed onset date within one pentad.

Key Words: Monsoon Seasonal forecast, PARAM Padma, T170L42, CFS SST

1.0 Introduction

The long-range forecasting of the Indian Summer Monsoon, using dynamical models, is a challenge faced by the meteorological community as research has shown that the simulation of the monsoon rainfall of India is a very tough problem. The dynamical seasonal forecasting, if successful, would provide a wonderful tool for the researchers and the operational meteorologists to forecast the Indian Summer Monsoon Rainfall (ISMR) which is of value to the applications community and national agencies. There have been many notable studies to understand the dynamical processes of the Indian Monsoon (Ramage, 1971; Rao, 1976; Sikka and Gadgil, 1980; Yasunari, 1980; Chang and Krishnamurti, 1987) and to improve the forecast skill of the dynamical models (Krishnamurti *et al*. 2000a, 2000b, 2001, 2005 and others). The relatively poor skills of the numerical models can be attributed to the limitations of the physical parameterizations schemes in the models and also to the low resolution of the models used in several earlier attempts for the monsoon simulation. Sperber *et al*. (1994) found that an increase in resolution had a positive impact on the simulation of the Indian Monsoon. Jha *et al*. (2000), using Florida State University Atmospheric General Circulation Model (AGCM) at resolutions of T42 and T170 for the month of July, found that the higher resolution model simulated the monsoon features more realistically. The improvement in the monsoon precipitation in the high-resolution models is attributed to the improvement of the regional rainfall resulting from better resolution of the topographical features of the Indian region.

This paper presents an ensemble forecast of ISMR 2005, carried out experimentally by the Centre for Development of Advanced Computing (C-DAC) under the Extended Range Monsoon Prediction (ERMP) initiative of the Indian Climate Research Program (ICRP) of the Department of Science and Technology (DST), India. The main objectives of this program are to evaluate and to improve upon the AGCMs being used by the research community in India for the long-range monsoon forecasting. The simulations reported here, were carried out on C-DAC's supercomputer PARAM Padma using the NCEP T170L42 AGCM. PARAM Padma is a distributed memory supercomputer with 256 IBM processors connected with an indigenously developed PARAMNet switch. The computer has a peak performance of one Teraflop. More details about the machine are available at http://www.cdac.in/html/ctsf/ctsfidx.asp. The primary aim of this attempt was to test the use of a high resolution AGCM for foreshadowing the monsoon season (June-September) rainfall over India in advance through SST forcing and to evaluate its performance at the end of the season. Therefore, it necessitated using initial conditions at the beginning of May with the forecast SST provided by a coupled ocean-atmosphere climate model. The option used in this study for the forecast SST for May, June, July, August and September 2005 was the data provided by the NCEP Coupled Forecast System (CFS) (Saha *et al.* 2006) and the initial conditions used were those provided by the operational NCEP analysis for the six member ensemble.

The observed monsoon of 2005 showed some interesting features with regard to its evolution on sub-seasonal scale. The onset of the monsoon over the southwestern coast of India (Kerala state) took place on 5-6 June 2005. Its progress along the West Coast was arrested between 7 - 17 June, followed by a rapid progress to 23^0 N in the next week. It advanced over the Gangetic Plain rather rapidly between 20 - 27 June such that the entire country was in its sweep by 30 June. The performance of the monsoon on the monthly scale in terms of the observed rainfall for India as a whole was below normal for June (-12%) and August (-28%) but for July and September it was above normal by 14% and 17% respectively. For the season as a whole the observed rainfall of the country was 99% of the long-period normal. On the sub-seasonal scale the All India rainfall for 2005 was above normal between 17 June to 6 August and it was mostly below normal for the month of August 2005 (Lal *et al*. 2006). The mid-season deficit in rainfall between 6 August to 3 September was made up by the revival of the monsoon, resulting in excess rainfall between 5 – 23 September. These were the most conspicuous features of the observed performance of the monsoon 2005 in terms of rainfall. In all one cyclonic storm, five monsoon depressions and six low pressure areas formed in the season, which is close to normal for the season. Of these, three depressions and three low pressures areas formed in June and July 2005 and one cyclonic storm, two depressions and two low pressure areas formed during 7 to 24 September in an overlapping manner. Hence June, July and September witnessed good cyclogenic activity while in August the situation remained rather quiet and weak monsoon conditions prevailed.

In section 2 the model description in brief and the data used for the model initialization are presented. A discussion of the model precipitation climatology, forecast of monsoon 2005 and the simulation of the large scale episodes of the monsoon are presented in section 3. Summary and concluding remarks are given in section 4.

2. Model Description and Initialization

The NCEP T170L42 AGCM was used for making the seasonal forecasts of monsoon for the year 2005. The model has 512 X 256 horizontal gaussian grid points and 42 vertical sigma levels. The physics used in the model was the Simplified Arakawa Schubert scheme (Pan and Wu, 1995) for convection, Rapid Radiation Transfer Model (RRTM) (Mlawer *et al.* 1997) for the long wave radiation, and the parameterization of Hou *et al*. (2002) for the short wave radiation. Detailed model documentation can be found at http://www.emc.ncep.noaa.gov/gmb/moorthi/gam.html.

An ensemble of the model seasonal runs was made using six initial conditions of the 1st, 2nd, 3rd, 5th, 6th and the 7th May 2005. The model was integrated from the above six initial conditions up to 30 September. The analysis files of the NCEP Global Forecast System (of T254L64resolution converted to T170L42) were used for the initial data. The monthly forecast sea surface temperature (SST) of the NCEP Coupled Forecast System (CFS) was used as the lower boundary. We followed the methodology suggested by Saha (2004) for removing the biases, if any, in preparing the ensemble mean CFS SST data from the member ensembles of 1 May 2005. Our purpose in this study is not to determine the impact of SST bias on the monsoon rainfall simulation vis-à-vis the simulations under the climatological SST. We use the CFS forecast SST merely to provide viable values at the lower boundary prior to the season (with May initial conditions) to be utilized for operational long-range forecasting needs. Therefore, we believe that biases, if any, in the evolution of the monthly SST in the CFS forecasts would not be a serious handicap in our results. However, we ran the same ensemble with the observed SST, which were available after the hindcast and also with the climatological SST to understand the role played by the SST on the ensemble mean rain simulation for the 2005 monsoon season. Table 1 gives the comparison of the rainfall simulation for the monthly and seasonal rainfall with these three sets of SSTs. It is observed that there are differences in the monthly average rainfall such that the rainfall for climate SST is the lowest of the three in June and July. It is highest of the three in August and September. The rainfall simulated by the CFS SST showed the reverse behavior in June and July. We shall revert back to it in section 3. Hence the SST bias, if any, in the CFS SST apparently did not play a major role in the rainfall simulation over India. We show in Figure 1 the difference between the Reynolds (Reynolds et al. 1994) observed SST and the CFS forecast SST for the months of May - Sep 2005. From the figure it is seen that the CFS SST is cooler over most parts of the equatorial ocean throughout the season. However, the CFS forecasts underestimated the SST by 1 - 2^{o} K over parts of the Indian Ocean at isolated places. Comparison of the CFS SST with the climatological SST showed that the CFS SST was warmer by 0.5^{o} K over most parts of the Indian Ocean.

The climatology of the model was generated by integrating the model for ten years using the climatological SST. Work is planned to obtain climatology of the model with observed SST. The discussion on ensemble forecast of monsoon 2005, precipitation climatology of the model and the inter-ensemble variability is based on simulated five day averaged model outputs. The model simulated monthly and seasonal precipitation for the year 2005 is also compared with the Tropical Rainfall Measuring Mission (TRMM) (Simpson *et al*. 1988) 3 hourly rainfall (3B42 V6) estimates averaged for the whole monsoon season. The climatological rainfall is also compared with the monthly long-term mean Xie-Arkin (1997) (XA) precipitation. The simulated winds are compared with the NCEP-NCAR Reanalysis by interpolating the model output to the reanalysis grid.

3. Results and Discussion

a) Model Climatology

The long-term mean monthly XA precipitation and the model climatological precipitation based on ten year average is shown in Figure 2. The seasonal XA precipitation shows two maxima in the rainfall distribution, one over the West Coast of India and the other near northeast India and the head Bay of Bengal. Qualitatively the model is able to capture these two maxima realistically. The rain shadow zone in the leeward side of the Western Ghats of India is also well captured in the model simulated climatological rainfall. The model-simulated mean monthly rainfall and the mean monthly XA rainfall show similar patterns of spatial distribution for the four months season (JJAS) and for individual months too. However along the West Coast of India the model precipitation is comparatively higher than the XA precipitation. Over the Indian landmass, the area-weighted rainfall climatology computed from the XA precipitation is found to be 6.07, 5.04, 7.62, 6.93 and 4.69 mm/day for the southwest monsoon season (JJAS) and for the months of June, July, August and September respectively. The model ensemble mean simulated rainfall climatology for the season and rainfall for the respective four months are 7.75, 9.02, 9.00, 7.91 and 5.06 mm/day respectively (Table 2). The comparison of both showed an overestimation of the simulated climatological rainfall compared to the XA rainfall especially in the months of June and July which together resulted in higher seasonal rainfall by the model simulated climatology. The overestimation in the rainfall, in the model climatology, compared to the XA climatology could be attributed to the simulated higher climatological precipitation along the West Coast of India. Also, note that the rainfall in the climatology of the model for August and September showed rainfall maximum in the Bay of Bengal with slightly southward shift from those of June and July.

To have a better representation of the southwest monsoon, the lower tropospheric cross-equatorial flow should be properly simulated by the AGCMs. The winds at 850hPa, obtained from the model simulations and those from the Reanalysis data are shown in Figure 3. The magnitudes of the mean cross-equatorial flow, obtained from the model outputs and those from the Reanalysis, are comparable for the monsoon season and for the individual months of June to September. However, the model simulated winds, particularly in June, are stronger in magnitude than the Reanalysis winds both over the Arabian Sea and the Bay of Bengal which would account for the high rainfall simulated in the model for June climatology. The model simulated 200 hPa (figure not shown) easterly jet is somewhat weaker than that in the Reanalysis for August and September. The seasonal position of the jet is properly located in the model simulated outputs and the flow across the equator between 80 - 100^o E is from the NE in agreement with the observations. The monsoon trough location is fairly well simulated in July, both in position and strength, whereas it shows more intensity in June and less intensity in August and September compared to the observations. These differences would support the higher intensity of the model simulated rain in June and slight weakening of the rainfall from August to September as compared to the observations. Overall the model-simulated rainfall and the large scale circulation features are satisfactory on the seasonal basis. However on monthly basis the model is biased towards considerably (+75%) higher rainfall and stronger circulation in June and lower rainfall in September (-12%) (Table 2). For July, the model climatology agrees within 5% of the observed rainfall on All India basis.

b) Forecast of the Monsoon 2005

The ensemble monsoon rainfall forecast by the model and as observed in the TRMM rainfall estimates are shown in Figure 4. Table 2 shows different features of the observed and the model forecast rainfall. The monthly averaged and the ensemble averaged model simulated rainfall over the Indian landmass for the months of June, July, August and September is 8.71, 10.60, 7.10 and 4.76 mm/day and 7.81 mm/day for the season. The corresponding TRMM estimated rainfall over the Indian landmass is 6.90, 4.63, 10.22, 5.90 and 6.79 mm/day for the whole season and for the months of June, July, August and September respectively. Thus, it can be seen that compared to the TRMM estimates over India, the model simulated comparatively higher rainfall in the months of June (+95%) and August (+34%) and comparatively less rainfall in the months of July (-12%) and September (-25%). The maximum rainfall, simulated by the model, is seen to be near the eastern equatorial Indian Ocean in these months of August and September. The equatorial Indian Ocean rainfall is seen to be higher than the TRMM estimated rainfall in the months of July, August and September 2005. This could be taken as a bias of the model with respect to the TRMM estimates. The simulated ensemble average seasonal forecast rainfall for the monsoon 2005 (7.81 mm/day) is slightly above (0.8%) the seasonal model climatological rainfall (7.75 mm/day) indicating very close to normal rainfall for the monsoon season 2005. The observed rainfall for the season, as per the India Meteorological Department (IMD) estimates, is 99% of the normal (Lal *et al*. 2006). Hence the model simulated seasonal anomaly (+0.8%) was very close to the observed seasonal anomaly (-1%) and viewed in that perspective the model simulated seasonal forecast can be considered as very good for the season of 2005. Table 2 also shows the area weighted ISMR (mm/day) for the ensemble mean and for each member of the ensemble with respective initial conditions. The departure of the area weighted summer monsoon rainfall for the ensemble mean for each member of the ensemble for the 2005 season are given in Table 2, which also gives the figures for the model and observed climatologies of rainfall. The signs of the ensemble mean monthly departures are in agreement with the observed departures for the season (columns 8 and 9 of Table 2) 2005. The magnitudes of the ensemble mean rainfall for different months are within one standard deviation of the observed values. These features show that the ensemble mean gave a satisfactory measure of model rainfall on the monthly scale.

The 850hpa winds (Figure 5) for the year 2005, as seen in the Reanalysis and as simulated by the model, show that the model simulated wind speeds are somewhat smaller than that in the Reanalysis. The model winds are reversed (easterly flow) over the central Bay of Bengal in the months of August and September. This reversal is due to high amounts of rainfall in the equatorial Indian Ocean, as seen in Figure 4, which resulted in the building up of subsidence and consequent ridge over the central Bay of Bengal extending up to the South China Sea. The simulated 200 hPa winds also showed that the easterly jet weakened in the months of August and September. Also there was a development of a southeasterly flow at 200 hPa across the equator in the model simulations instead of the normally observed northeasterly flow. Thus, the major model bias with respect to the observations for 2005 monsoon is the excess rain over the near-equatorial belt along 80^o - 120^o E and the correspondingly less rainfall over the central Bay of Bengal which extended even up to the South China Sea.

To understand the intra-seasonal variability in the ISMR 2005 within the ensemble forecasts we calculated the pentad rainfall for the whole season for the region 8^o - 32^o N, 70^o – 90^o E (Figure 6) for all the individual members of the ensemble. From the figure it is seen that there is a large variation in the simulated rainfall within the members of the ensembles but all the members show an increase of rainfall in the month of July and reduction of rainfall in the months of August and September. The intra-ensemble differences in the pentad rainfall are expected but the consensus about the reduction of rainfall in the individual members would indicate a bias in the model, as the model simulations show an increase in rainfall along 80^o - 120^o E near the equatorial belt in August and September with decrease over the Bay of Bengal. It is difficult to explain this bias with regard to increase in rainfall in the near-equatorial belt which leads to the corresponding drying up of the monsoon over the Bay of Bengal due to subsidence on the flanks of a region of highly organized near-equatorial convection. We suspect that the model convection scheme may be responsible for this behavior.

c) Simulated features of main phases of the monsoon 2005

The use of AGCMs for simulating the inter-annual variability of the seasonal climate in the tropics rests on the premise (Charney and Shukla, 1981 and several others since then) that while the atmospheric predictability of the large scale weather in the tropics may be restricted to 10-15 days due to dynamical reasons there may be some signal in the seasonal climate prediction in the tropics in a statistical sense on long -enough time basis (say a month or a season) and on large areal basis (such as the size of India). This signal is considered to result from the influence of the slowly changing boundary conditions such as SSTs. Several attempts, so far made, with regard to using AGCM for seasonal monsoon predictions have given mixed results (Kang *et al*. 2002 and others too). This is perhaps due to the complexities introduced by the coupled land-ocean-atmosphere monsoon system as the monsoon has strong intraseasonal oscillations on two prominent scales 10-20 days (Krishnamurti and Arduney 1980) and 30-50 day (Sikka and Gadgil, 1980; Yasunari, 1980), which result due to a combination of internal and coupled ocean–atmosphere dynamics. While the 10-20 day mode propagates westward, the 30-50 day mode moves northward from equator to 30^o N in the Indian longitudes. Hence in the study of simulating the monsoon performance in a particular year, such as

2005 in our case, it is pertinent to compare the simulations as a result of SST forcings for the monthly and seasonal performance of monsoon rains and circulation and not to compare the simulations against observations on daily basis in detail. We have done this on the monthly scale for All India rainfall as discussed above. However we felt that it would also be interesting to study the simulations with respect to the main phases in the evolution of the regional monsoon and its sub-seasonal variability. It is expected that a good simulation would show all the major observed features in the evolution of the monsoon. This was done on the 5-day (pentad) average basis. We discuss the results of our study with regard to the simulations of the main phases of the monsoon in the following paragraphs.

(i) *The Monsoon Onset*

The onset of the monsoon in the observations is characterized by a sudden spell of increased precipitation over Kerala and its persistence for at least a few days or so. To determine the monsoon onset in the model simulation, an area-weighted average of the model forecast precipitation over Kerala (8^o - 12^o N and 75^o – 77^o E) was computed for each initial condition and for the ensemble mean (Figure 7a). We note that before 25 May simulated precipitation amounts, based on all the initial conditions and their ensemble mean, were below 1 cm. The sudden rise in the simulated rainfall, based on the 2nd and the 7th May initial conditions, is observed on 27 May and 28 May respectively. With the 2nd May initial conditions the simulated rainfall was about 5 cm and with that of the 7th May initial conditions, it was 4 cm. The 3rd May initial condition showed a gradual rise in the amount of precipitation to about 2 cm from 27 May to 2 June. The simulated rainfall, based on the 1st, 5th and the 6th May initial conditions showed less precipitation activity during the last week of May and the 1st week of June. The sudden rise in the simulated precipitation amounts was observed on 8 June, 9 June and 16 June for the initial conditions of the 1st, 5th and the 6th May respectively. Thus it can be seen that, the initial conditions of the 2nd, 3rd and the 7th May showed an early onset whereas the other three initial conditions showed a delayed onset as compared to the date of onset of the 5th June declared by the IMD. The ensemble mean predicted rainfall of all the initial conditions showed a sudden rise in rainfall on 30 May and its persistence up to 25 June. From this it could be concluded that the dispersion of date of onset, simulated by the initial conditions of the 2nd, 3rd, 5th, 6th, and the 7th May 2005 and that of the ensemble mean is in the range of one pentad with respect to the observed onset date of IMD. However, the initial conditions of the 1st May showed a large dispersion of about 11 days from the observed date of onset. It is a priori difficult to diagnose the probable cause for the delayed onset simulated with the initial condition of the 1st May 2005. The initial conditions of a particular date may not be found good for a skillful forecast. Since there is a scatter in the monsoon onset date simulations among different initial conditions, an ensemble mean would provide a better guidance for this purpose.

Some investigators have used other methods for determining the date of monsoon onset. For example Vernekar and Ji (1999) calculated the onset of the monsoon by computing an area-weighted average rainfall over the region 8° N - 28° N, 65° E - 85° E (figure not shown). Judged in this perspective, the calculated area-weighted average for the ensemble mean over this region in our study showed that the model simulated onset date was 28 May 2005. This is one week ahead of the onset declared by the IMD but only two days earlier from our ensemble mean date of 30 May 2005. However, the application of the Vernekar and Ji (1999) methodology on the individual ensemble member simulations gave the onset dates as 11 June, 26 May, 6 June, 2 June and 6 June for the members with initial conditions of the 1st, 2nd , 5th, 6th and the 7th May 2005, respectively. This shows large intra-member dispersion compared to one pentad as per the criterion applied by us for the onset date to be fixed with respect to rainfall increase over the Kerala grid. The initial conditions with the 3rd May did not show any sudden increase in rainfall. Based on this limited study, it is suggested that it would be good to stick to the criterion of sudden increase in pentad rainfall over Kerala for determining the pentad in which the monsoon would set over Kerala region. The analysis of the pentad precipitation (Figure 8) showed an increase in precipitation by large amount and its persistence thereafter over Kerala region from pentad corresponding to 28 May to 2 June. The first day of our pentads corresponds to 8 May 2005.

It is also well known that the onset of the monsoon is characterized by an increase in the wind speed and changes in its direction in the lower troposphere by at least 120° over the Arabian Sea

(Ananthakrishanan *et al*. 1967) and hence the Kinetic Energy (KE) over the oceanic region near the equator (Krishnamurti and Ramanathan, 1982). The analysis of the pentad mean wind at 850 hPa in our simulations showed the gradual setting of Somali-Jet in the pentad of 11 – 15 days (19-23 May), and the monsoonal winds sweeping over the Arabian Sea in the pentad of 16 – 20 days (24-28 May).

The model simulated area-average (50^o – 70^o E and 0^o – 10^o N) KE per unit mass at 850 hPa for all the initial conditions and for the ensemble mean are shown in Figure 7b. A gradual increase in the KE for all the initial conditions and their ensemble mean is seen from 28 May. Also from the figure it can be seen that the simulated KE in the first week of June showed a persistent increase of more than 25 Joule, which corresponds to winds of more than 5 m/s. This can be treated as an indication of the setting of the monsoonal winds over the Arabian Sea off the coast of Kerala. The analysis of the increase in KE also indicated that the probable onset of the monsoon over Kerala is in the first week of June 2005. Thus, from the different analyses carried out for determining the date of onset of the monsoon, using AGCM simulations in our study, we can conclude that the model was capable of indicating the date of onset in a satisfactory way with a dispersion of only one pentad in five out of six different individual members of the ensemble used.

(ii) Advance of Monsoon over India in 2005

The establishment of the monsoonal flow over the southeast Bay of Bengal and the adjoining landmass could be observed from the ensemble mean winds at 850 hPa to have occurred on 27 May. The averaged ensemble winds at 850 hPa on 29 May showed the establishment of the southwesterly winds over the entire Andaman Sea and over the central Bay of Bengal on 31 May. The establishment of the Somali Jet, cross-equatorial flow over the African coast and the onset of the monsoon over the entire Bay of Bengal could be observed from the ensemble mean winds at 850 hPa during the first three days of June. The onset of the monsoon over Sri Lanka and parts of Kerala was observed from the model output to have occurred on 5 and 6 June, respectively. This is in agreement with the observed date of onset of the monsoon over Kerala by IMD as 5 June. The simulated precipitation of 10 mm / day over Kerala coast can be seen in the pentad corresponding to 21 – 25 May (Figure 8). Further increase in the pentad precipitation over the southern Peninsular India, the central India and parts of the east central India can be seen in Figure 8, in the pentads corresponding to 26 - 30 days (4-8 June), 31 – 35 days (9-13 June) and 36-40 days (10-14 June) respectively from 8 May. Examination of the daily ensemble averaged winds show that progress of the monsoon over the southern parts of the South Peninsular India occurred by 8 June; over entire peninsular India by 22 June, central India and parts of east central India by 25 June and the entire India by 30 June. This progress of the monsoon is in good agreement with the observed progress of monsoon provided by the IMD. The establishment of the monsoon trough could also be seen in the ensemble mean winds at 850 hPa. Thus the model could simulate the advance of the monsoon over different parts of India in a satisfactory manner.

(iii) Mid-Season Active-Break Spell and Revival of the Monsoon 2005

The simulated monsoon, after its full establishment by the end of June, showed a good activity during the whole of July with a small south-north fluctuations in the monsoon trough and formation of synoptic scale disturbances which looked like monsoon lows/depressions. Also we noticed the pulsatory strengthening of the low level south westerly flow over the Arabian Sea and the Bay of Bengal. Tropical easterly jet at 200 hPa also showed fluctuation in its strength and position. All these features, simulated by the model, resemble the transient fluctuations in the monsoon. Hence the model has simulated the transient behavior of the monsoon rather realistically.

The weakening of the monsoon is characterized by the migration of the monsoon trough from its normal position to the foothills of Himalayas. This behavior of the monsoon trough is also seen from the model simulated outputs. During the last week of July model 5-day averaged outputs of 850 hPa winds showed the migration of the monsoon trough from its normal position to the foothills of the Himalayas. From the end of July till the end of August, the simulated location of the monsoon trough was seen near the foothills of the Himalayas which is by and large close to the observed behavior in August 2005. However the model was unable to simulate the revival of the monsoon which was observed in the beginning of September 2005 from the near-equatorial region in the Bay of Bengal. Associated with this development in the early September 2005, the rainfall over the Peninsular and the central India remained high up to the 4th week of September over the Bay of Bengal. In the observations this had happened due to the overlapping formation of four low pressure systems (one cyclone, 1 depression and two low pressure areas) which moved over the region as a result of the northward moving intra-seasonal oscillation (ISO) of the monsoon and formation of a depression in the northeast Arabian Sea. However the model simulations did not show these observed features. We noticed that the model monsoon tended to revive from the formation of a low in the monsoon trough in-situ by activation of the monsoon trough over north Bay of Bengal and adjoining land rather than from the influence of northward propagating mode of the ISO from the near-equatorial zone to the monsoon trough zone. It is hard to know whether such a feature is a general characteristic of the model or if it occured only for September 2005. This would need examination of the details of individual years of the twenty years model climatology being made with observed SST as lower boundary. However the monthly mean 850 hPa and 200 hPa circulations did not suggest any specific biases with regard to the increase in the near-equatorial rains and the decrease in the Bay of Bengal rains with the mean SST climatology as shown in Figure 2. This deficiency in the model maybe due to it being stand-alone AGCM and without any explicit feedback from the ocean and also may be due to the deficiencies in the cumulus parameterization of the model. For the northward propagating modes to be properly simulated the coupling of the atmosphere with ocean is essential. The model convective parameterization is perhaps oversensitive to the prescribed SST's as the climatological SST pattern is quite smooth and slightly cooler than CFS SST and the observed SST.

(iv)Withdrawal of the Monsoon

The start of the weakening of the southwesterlies over the central and north India and the setting of the northeasterly winds over the northeast India is observed in the ensemble pentad averaged winds from early September onward. The withdrawal of the monsoon from central India and setting of northeast monsoon is seen from the model outputs as early as 15 September. However in actual observations withdrawal was delayed due to the prevalence of circulation patterns associated with the overlapping formation of the low pressure systems discussed above, as a result of strong ISO's, which caused rainfall over central India and even over northwest India till the last week of September. The model was unable to simulate this feature. The monsoon had weakened in the model in mid-August 2005. This is brought out in a striking manner by the build-up of an anticyclonic circulation along 10^o – 15^o N from 70^o – 110^o E from mid-August. This was responsible for the persistence of the easterly low-level flow along this belt, in the model simulations from mid-August. We also noticed the development of a strong convergence zone between the lower tropospheric monsoonal westerlies between 70^o – 80^o E and easterlies between 80^o - 120^o E in the near-equatorial belt. This obviously enhanced the rainfall in this belt during August and September in the model simulations and the corresponding sinking motion on the northern flank in the central Bay of Bengal, which dried up the monsoon rains in the Bay of Bengal and up to even the South China Sea. Figure 9 shows a comparison of the pentad averaged relative vorticity along 88 - 92^o E over the Bay of Bengal from early August to end of September 2005 as simulated by the model and as in the Reanalysis. There is an episode of the northward migration as seen in the observation which began in early September and mid-September near 3 - 6^o N and continued up to September end. Positive relative vorticity persisted in the observations under the influence of the northward moving ISO's. These features are missing in the model simulations. Figure 9b shows a belt of positive vorticity in the mid-September prevailing in the belt 5-10^oN and occasional appearance of positive vorticity near 18-20^o N but no regional characteristic northward propagating ISO as seen in the observations (Figure 9a). This explains the lack of agreement in the revival of the monsoon between the observations and the simulations.

4. Summary and Concluding Remarks

In this study we simulated the Indian monsoon using the high resolution T170L42 NCEP global model. As the study was done in May 2005 to foreshadow the long-range seasonal performance of the monsoon 2005, as such CFS SST forecast for individual months of May to September were used with the belief that the biases, if any, in the CFS forecast SST had been corrected by the methodology followed in adopting CFS SST after Saha (2004). The climatology of the model showed that the model was able to capture the main features of the monsoon rainfall quite well. However, it is seen that the model has a positive bias in simulating heavy rainfall off the Western Ghats in June. The analysis of the large-scale circulation patterns in the lower and the upper troposphere showed that the model was able to simulate the Somali Jet in the lower troposphere and the tropical easterly Jet in the upper troposphere realistically well. Some broad conclusions are given below.

i) Compared with the model's rainfall climatology, the model simulated ensemble mean rains, for India as a whole, were near-normal for June, August and September 2005 while it was above normal for July. In actual observations the rainfall on the country's scale was below the normal in June and August 2005 and quite above the normal in September 2005. Another major difference of the model simulations with respect to observations occurred for September 2005 rainfall which showed considerable negative departure from its climatology whereas the observed September 2005 rainfall was in good excess. This together with the excess rainfall of July 2005 wiped off the major deficit of the observed rainfall in June and August 2005.

ii) The model has shown a good performance in foreshadowing the onset of the monsoon and its advance over the country. It also simulated higher than normal rainfall in July for the ensemble mean as well as for the individual members of the ensemble. The model could well simulate the onset of the monsoon through the build-up of cross equatorial flow. The dispersion of the predicted date of onset from the observed one is found to be one pentad for five out of six individual members of the ensemble. The model also simulated the mid-season weakening of the monsoon and the shift of the monsoon trough close to the Himalaya which led to a deficit from the normal rainfall over the country's scale in the month of August. In the model simulation this was also associated with the development of an anticyclonic regime at 850 hPa in the central Bay of Bengal. However, the model was unable to simulate the very strong revival of the southwest monsoon which was witnessed in the observations. Some revival in the rainfall activity did occur in the model simulation toward the end August to early September 2005 and up to mid September 2005 resulting from the activation of the monsoon trough in-situ over north Bay of Bengal and the adjoining landmass of India. On the contrary, in actual observations the strong revival had taken place due to the activation of a northward moving convective organization mode of the ISO from the near-equatorial central and the eastern Indian Ocean. During this phase five overlapping monsoon low pressure systems (one cyclonic storm, 2 depressions and one low pressure area) had formed between 7-24 September 2005, some of which moved over the Peninsular India towards Northwest India. The simulation of such a northward moving convective organization is not observed in this AGCM in 2005 as they result in observations from the coupling of the ocean – atmospheric processes on the intra-seasonal scale for whose simulations a good coupled ocean-atmosphere model is needed. Even several of the presently available coupled models are not able to capture ISO's of the monsoon realistically both in intensity and phase propagation (Inness and Slingo, 2003). However some investigators like Fu *et al*. (2002) and others have shown that coupled processes help in simulating the correct phase and structure of monsoon ISOs. Besides coupled processes, physical parameterization and other physical processes are also important in the models. Our opinion which agrees with the opinion of several others is that long-range monsoon forecasting could be only partially successful through the application of AGCMs and the hope of better success is only through the use of coupled models, provided they could realistically simulate both the intensity and the northward phase propagation of the ISO.

iii) Our results for the monsoon season of 2005 showed that the model did forecast normal seasonal rainfall compared to the model climatology (+0.7 % anomaly). Compared to the TRMM estimates, the model had simulated a higher seasonal rainfall (23% of the TRMM) than the observed which was as a result of the very strong monsoon simulated by the model for June with high rainfall particularly over the Western Coast of India. This may be mainly due to the bias in the model of simulating heavy rainfall on the windward side of the Western Ghats.

iv)Even though the model seasonal rainfall agreed rather well with the observed performance of the seasonal rainfall on the All-India basis for 2005, however on the monthly scale it occurred due to wrong reasons. The model simulated rainfall for June 2005 was much higher than the observed in quantitative basis but it was lower than the observed for September 2005. The model had simulated the good performance of the monsoon from June to mid-July and weakening of monsoon from mid-August to the end of September. The model simulated a weakening of the monsoon and suppression of rainfall over the Bay of Bengal from mid-August itself. This was due to the development of a large-scale convergence in the model simulations in the lower tropospheric winds along 80^o – 120^o E near the equator (6^o S -6^o N) and the build-up of a ridge at 850 hPa with easterly flow over most of the Bay of Bengal. The persistence of the subsidence over the central Bay of Bengal, resulted from the near-equatorial convective organization. This in turn was responsible for the development of the anticyclonic flow in the Bay of Bengal at 850 hPa. It is difficult to pinpoint the specific causes for this. We suspect that it could result in the model's convective parameterization being sensitive to prescribed SST.

Several years of monsoon simulations, in multi-member ensemble mode, with different initial forecast and observed SST conditions, are needed to determine biases, if any, in the model simulations. Such a study is underway and the results would be presented in another paper. One aspect which is clear in the model simulations as well as in observations for the season 2005 is that, the seasonal rainfall may become normal as a result of compensation taking place on the sub-seasonal scale. Hence, a good monsoon forecast should also have a good skill for the monthly performance of the rains over India. This appears to be a tough problem and only the future holds the answer to as to the capability of an AGCM for such a purpose.

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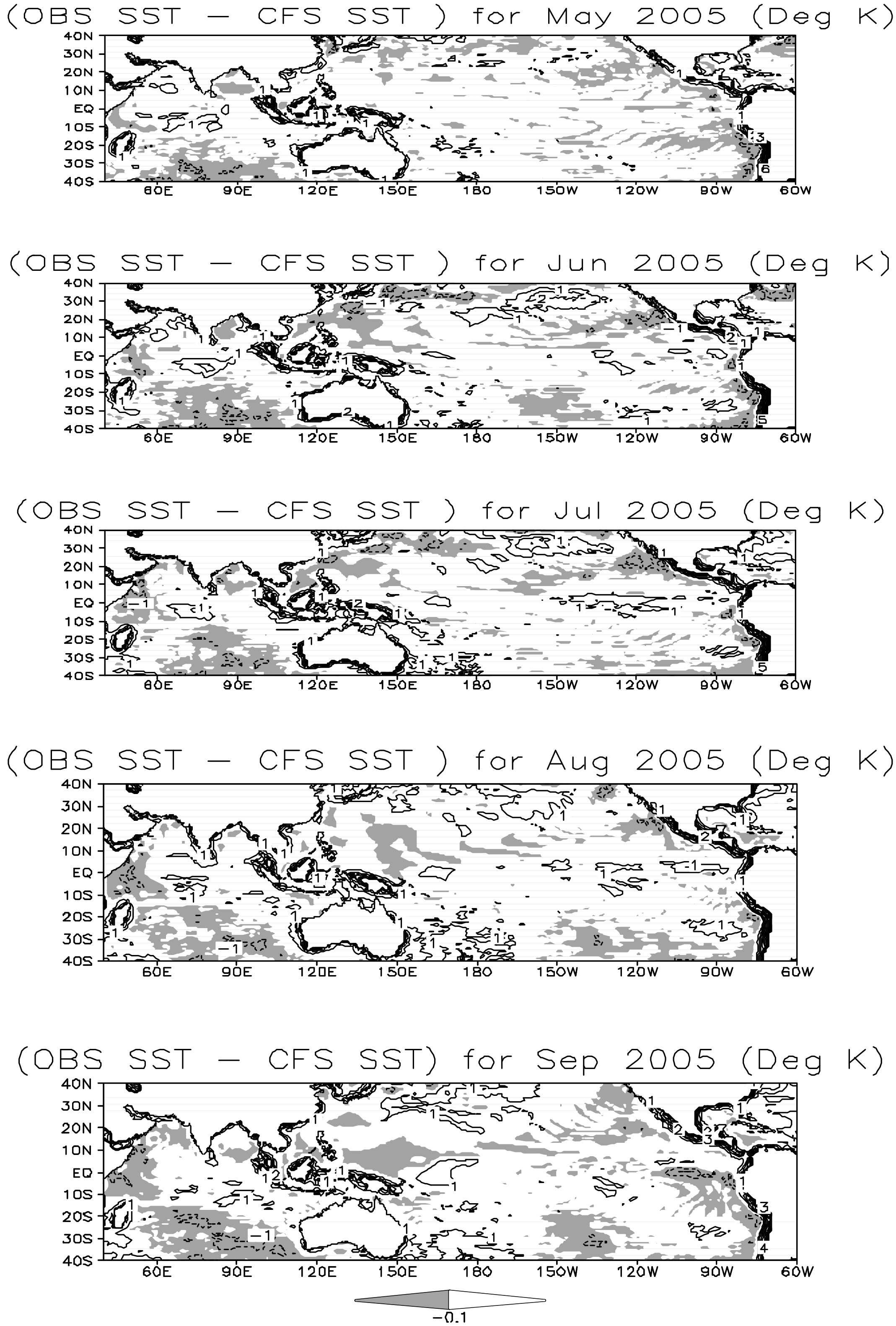

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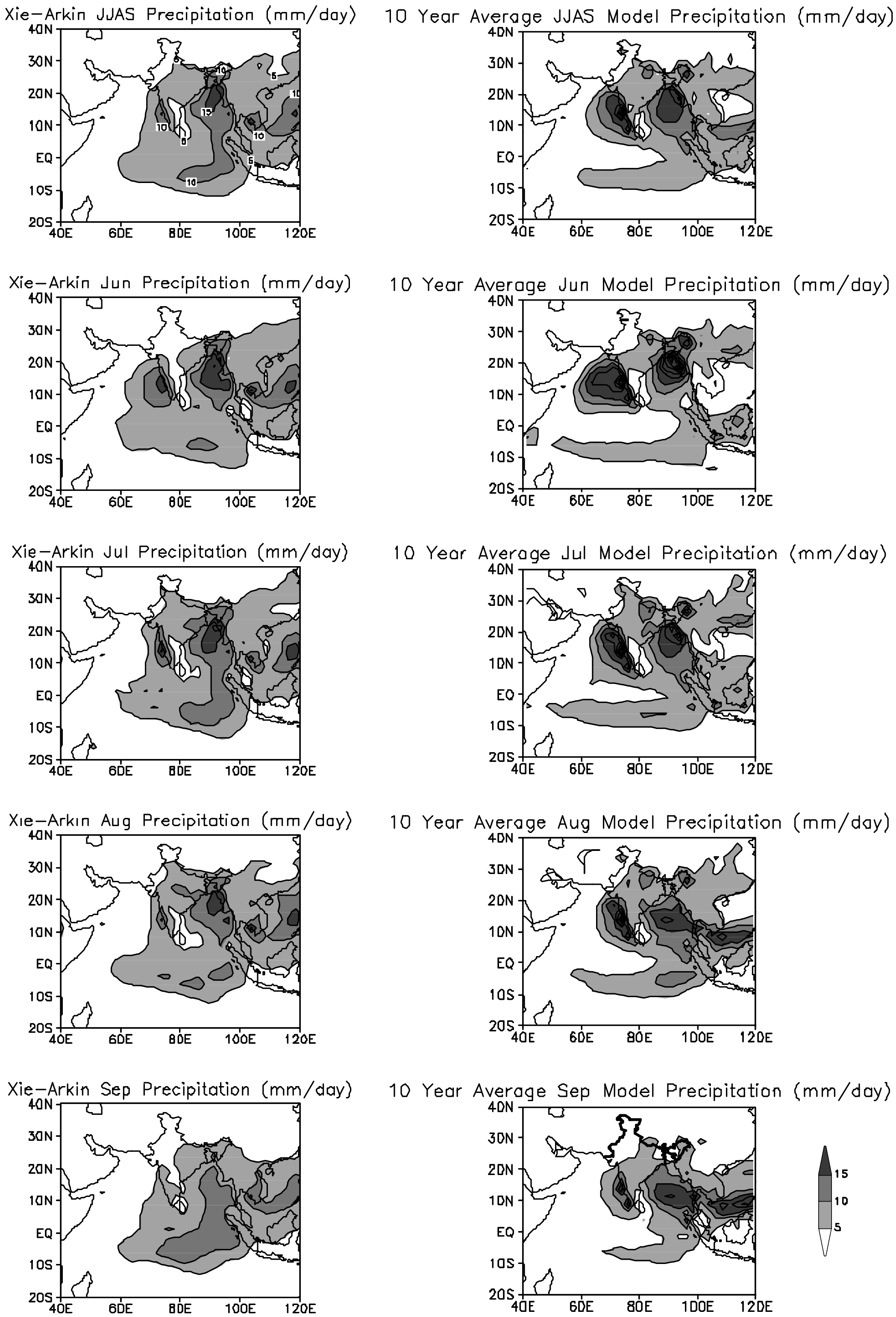

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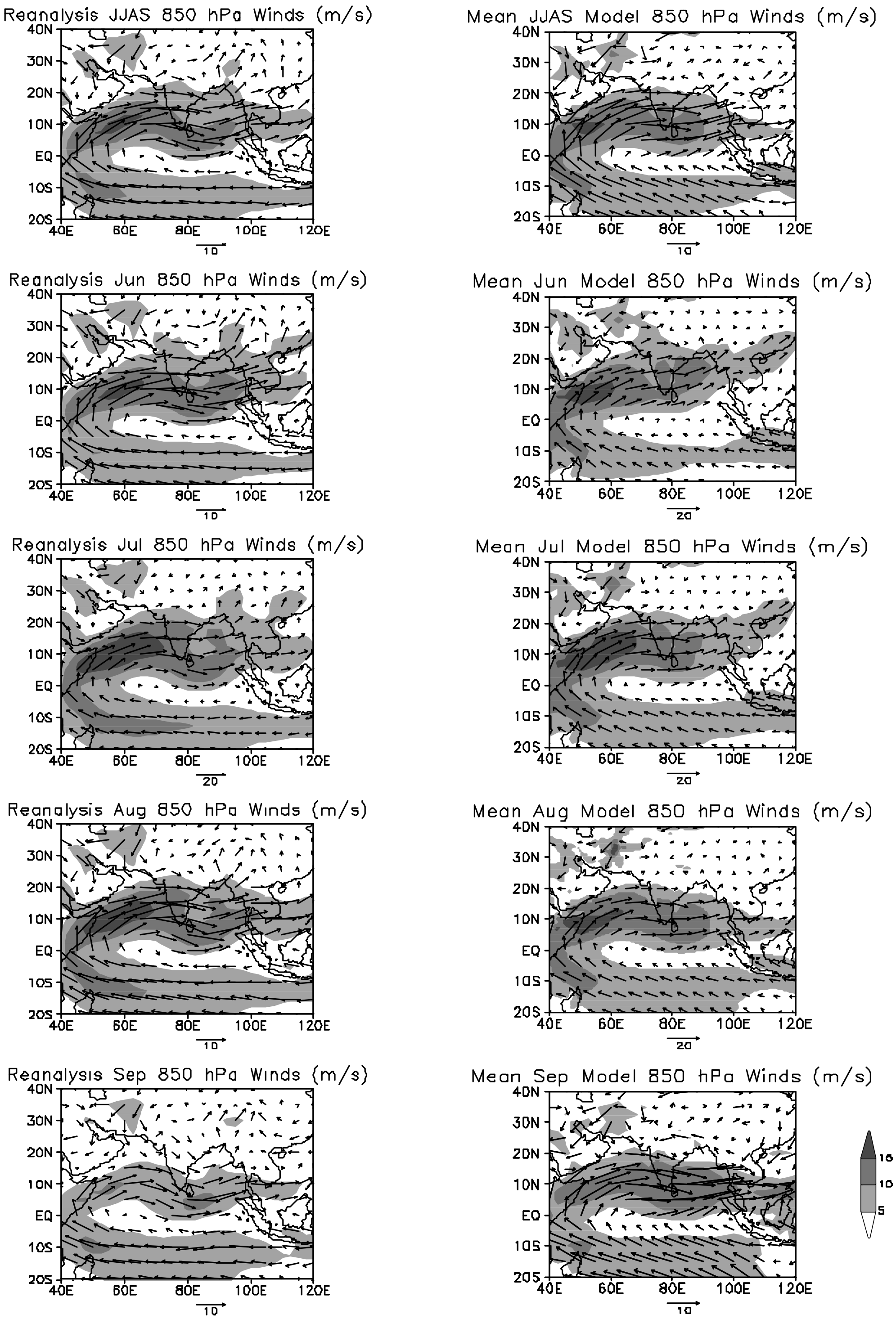

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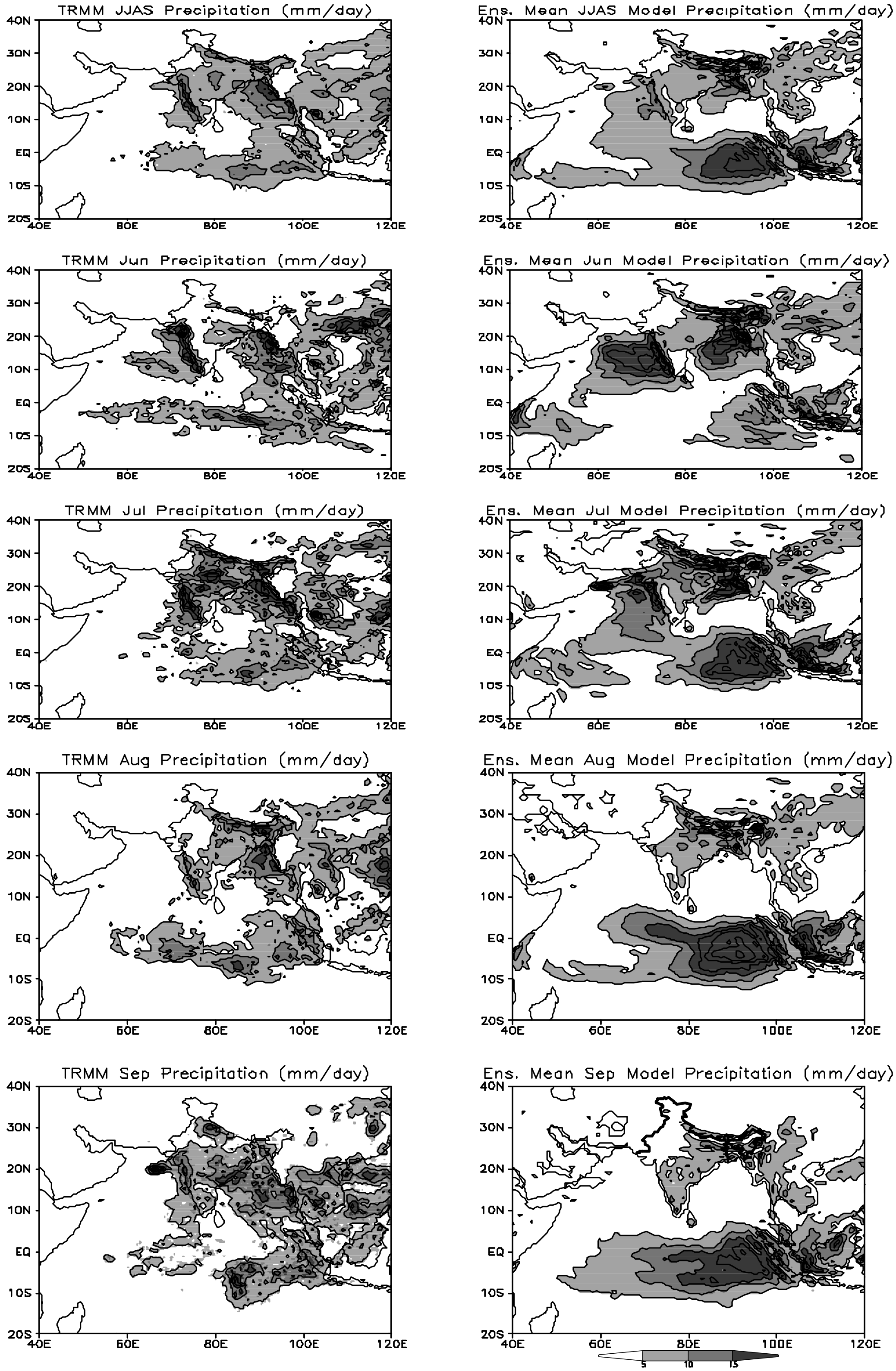

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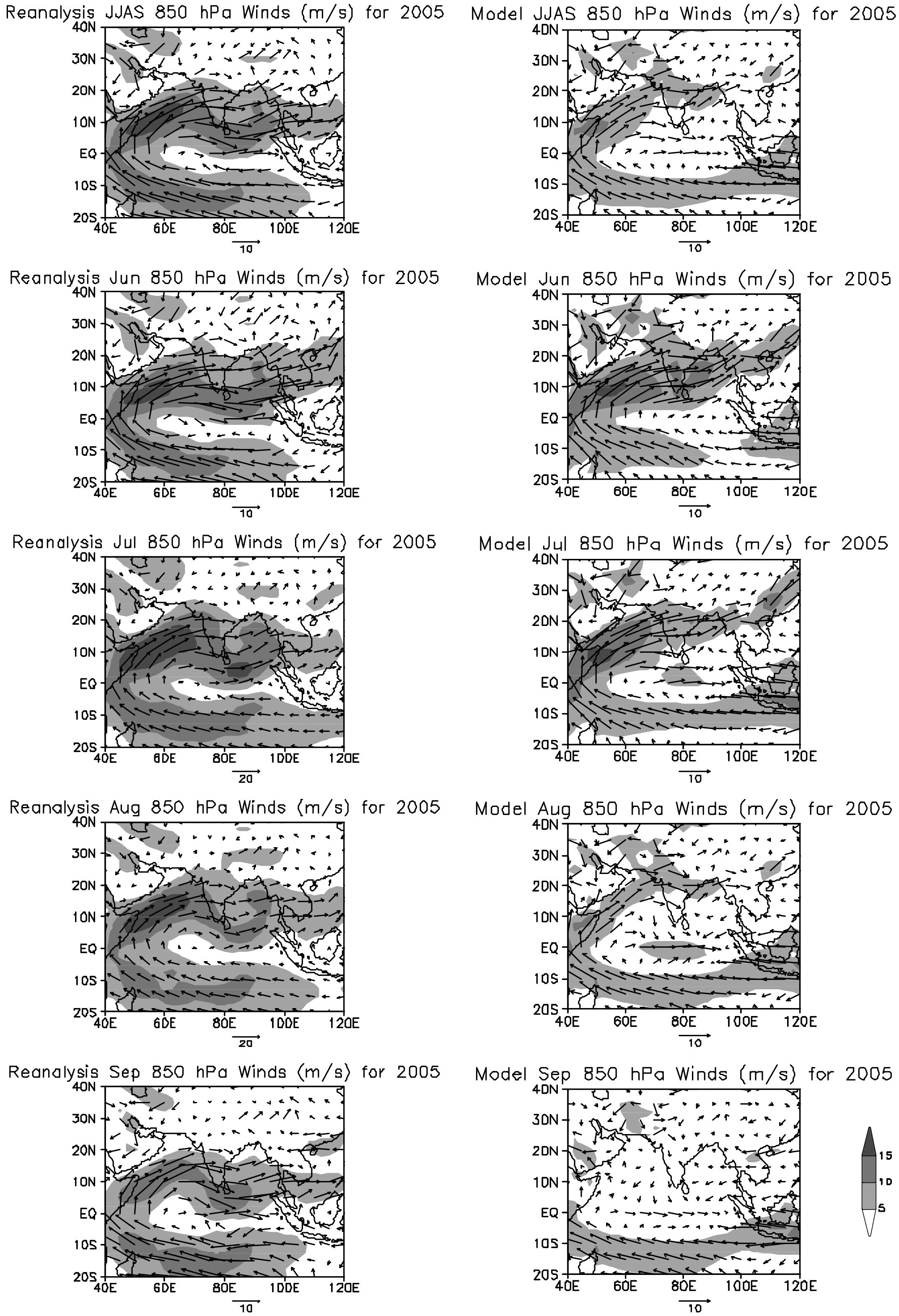

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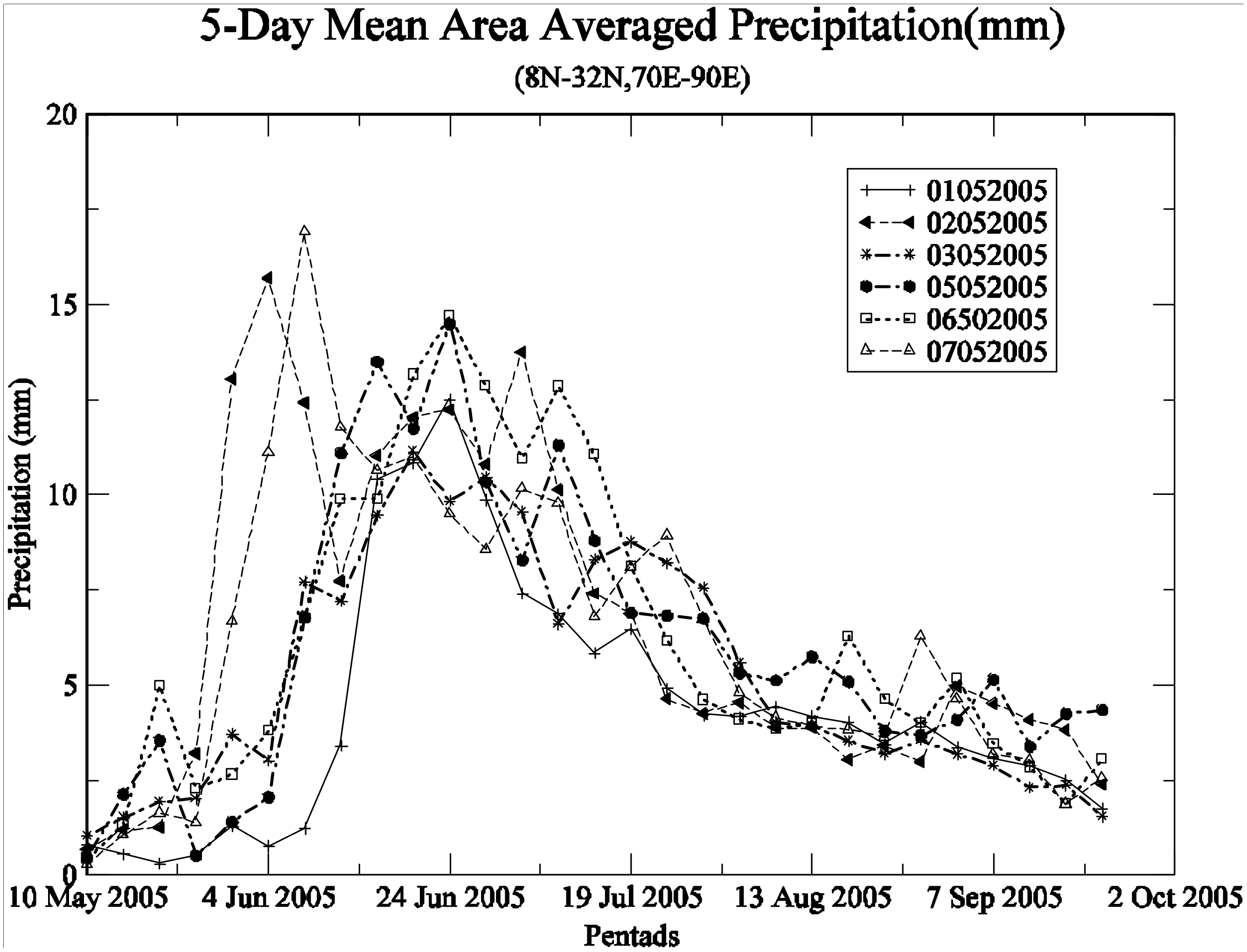

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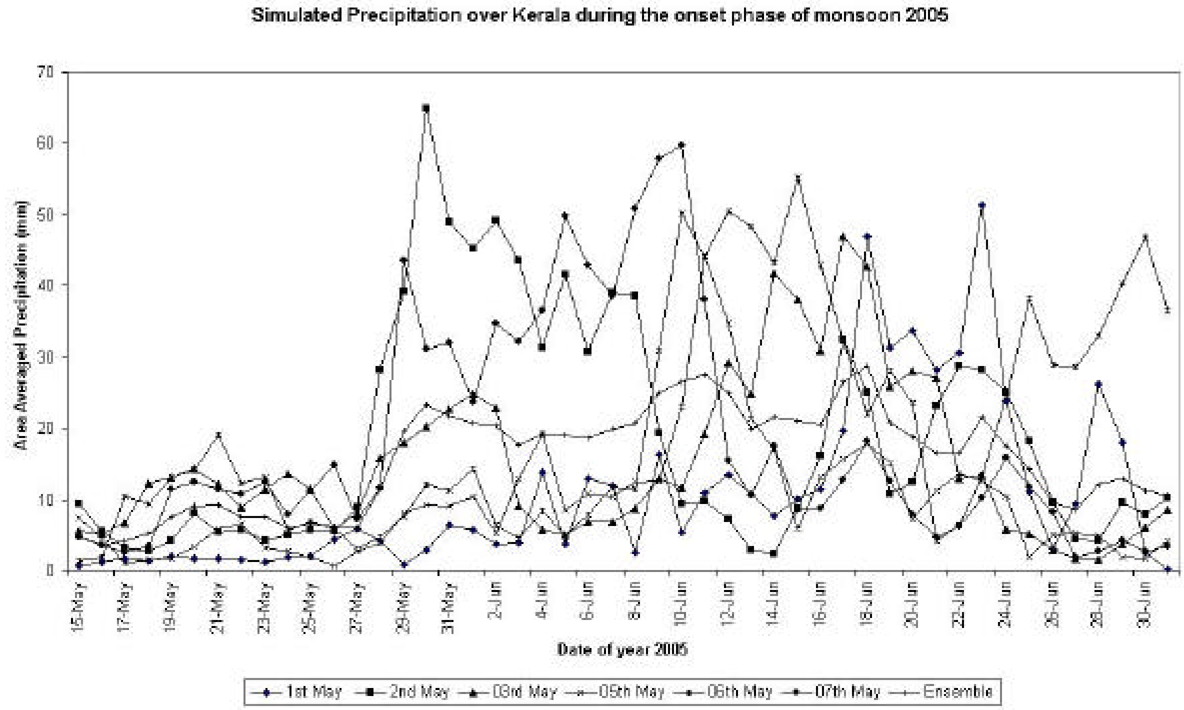

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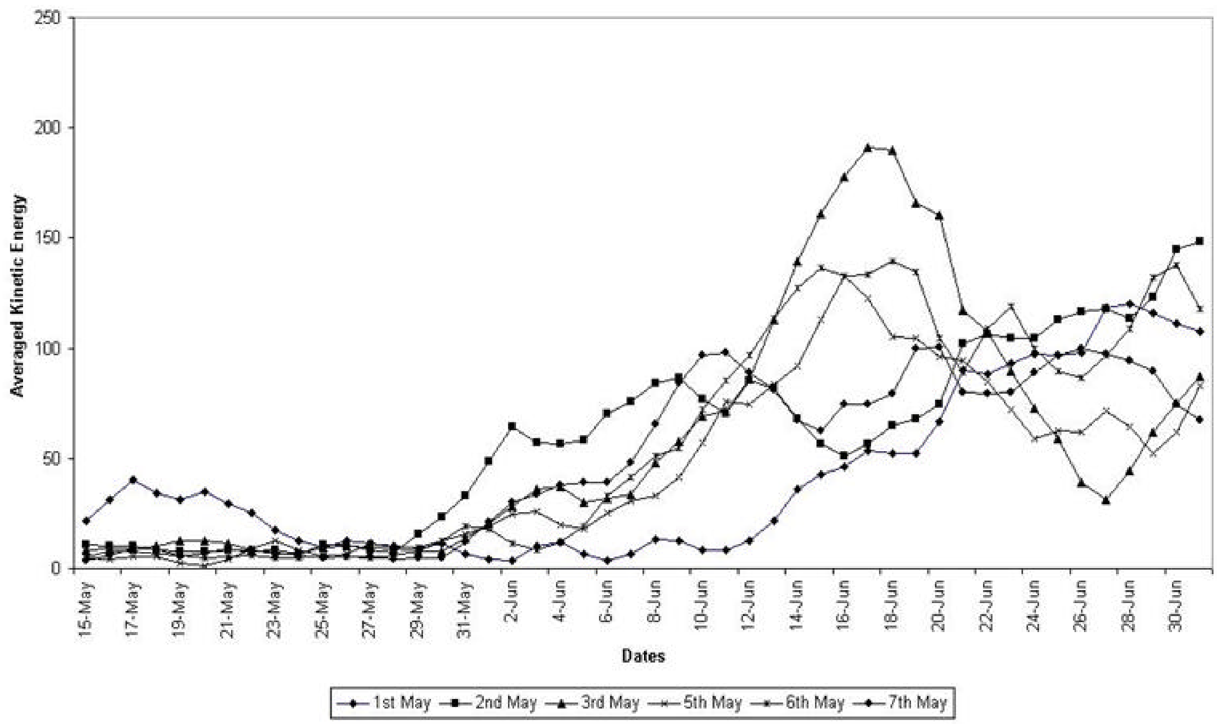

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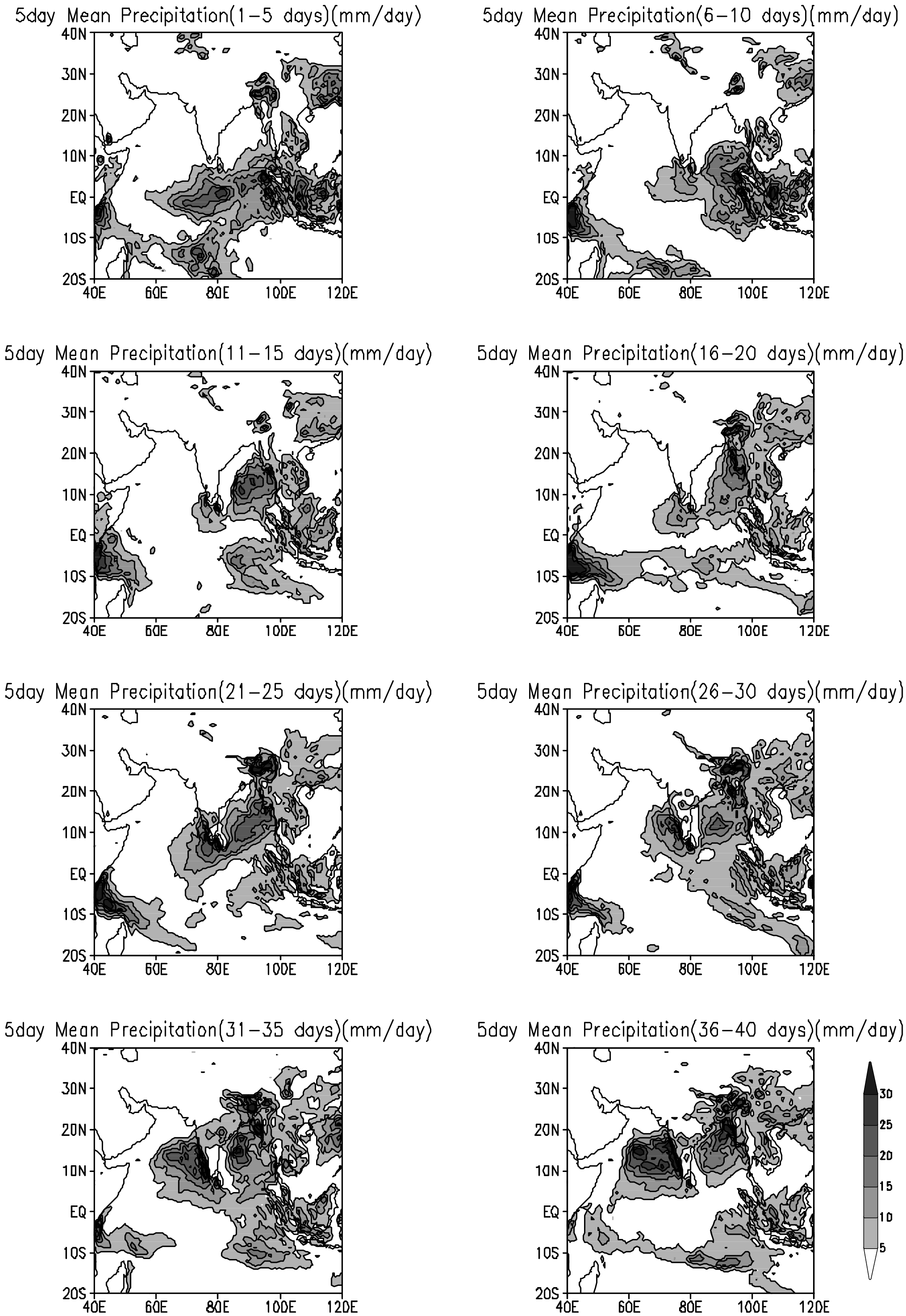

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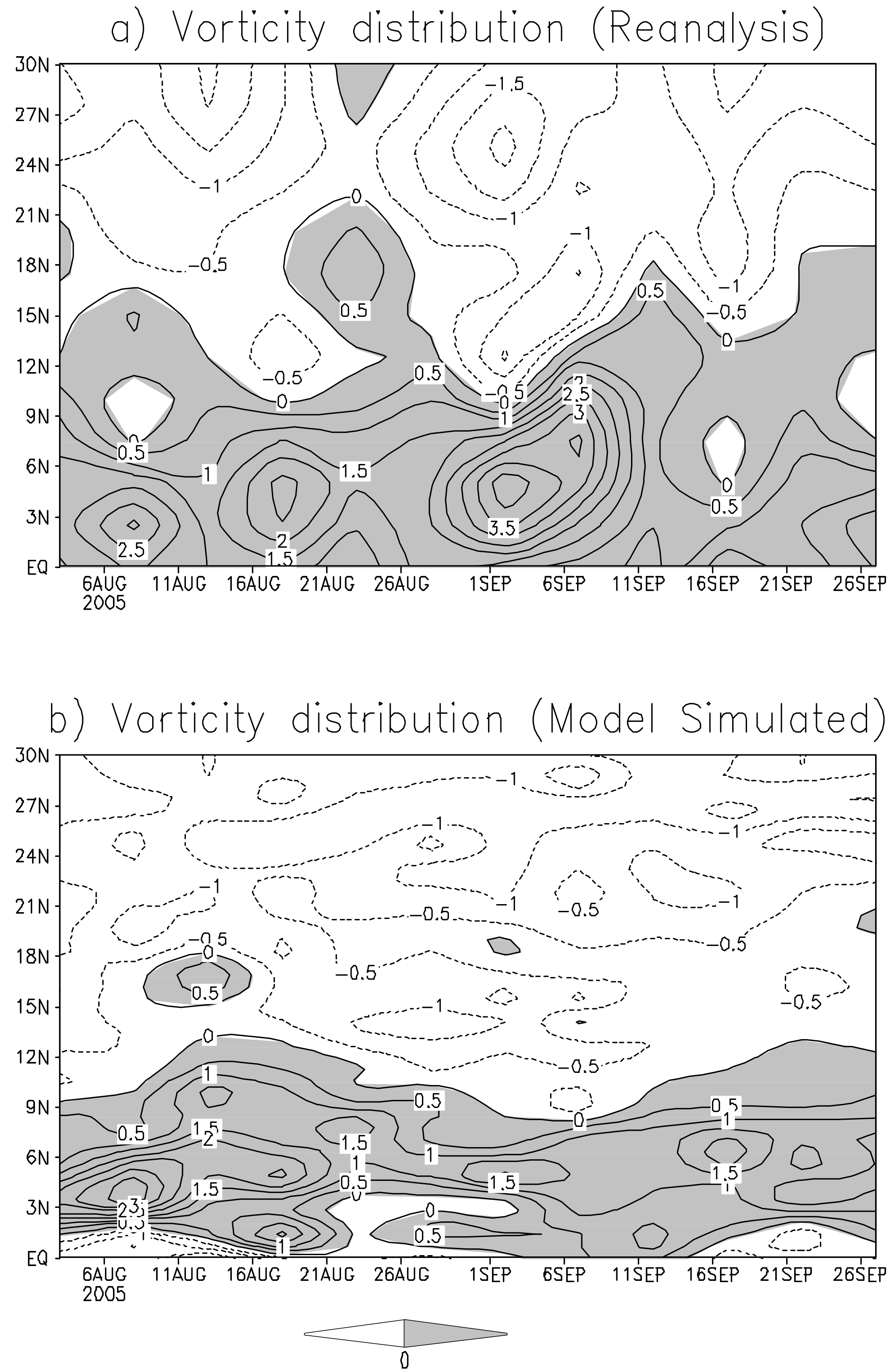

Figure 9. Vorticity (x10e-5 s^{-1}) variations along 90^{o} E from 3rd August to 30th September 2005. a) Reanalysis, b) Model simulated ensemble mean. Positive Vorticity is shaded

Table 1: Monthly and Seasonal ensemble mean rainfall (mm/day) as simulated for 2005 monsoon with CFS SST, Climate SST and Observed SST.

	June	July	August	September	Seasonal
CFS SST	8.71	10.60	7.10	4.76	7.81
Climate SST	6.68	9.47	7.73	5.18	7.29
Observed SST	7.51	9.58	7.59	4.32	7.27

Table 2: Area weighted all India Summer Monsoon Rainfall (mm / day). Departure of area weighted summer monsoon rainfall from model climatological precipitation given in bracket.

Months /Season	Initial Conditions							Observed 2005 Season		**Seasonal rainfall Climatology**	
	1st May	2nd May	3rd May	5th May	6th May	7th May	Ensemble Mean	IMD	TRMM	Model	Obs.
June	7.12 (-21.1)	8.68 (-3.8)	10.42 (15.5)	9.12 (1.1)	7.01 (-22.3)	9.93 (10.1)	8.71 (-3.4)	**4.55 (-12)**	**4.63**	**9.02**	**5.18**
July	9.3 (3.3)	12.16 (35.1)	9.81 (9.0)	10.82 (20.3)	12.08 (34.3)	9.45 (5.0)	10.60 (17.9)	**10.82 (+14)**	**10.22**	**9.0**	**9.49**
August	7.01 (-11.3)	6.7 (-15.3)	7.38 (-6.7)	8.14 (3.0)	6.86 (-13.3)	6.53 (-17.4)	7.10 (-10.2)	**6.02 (-28)**	**5.90**	**7.91**	**8.35**
Sept.	3.86 (-23.6)	5.03 (-0.5)	4.17 (-17.5)	5.9 (16.8)	4.97 (-1.6)	4.6 (-9.06)	4.76 (-5.9)	**6.7 (+14)**	**6.79**	**5.06**	**5.73**
Season	6.84 (-11.7)	8.16 (5.3)	7.96 (2.6)	7.96 (2.6)	7.76 (0.0)	7.63 (-1.5)	**7.81 (0.7)**	**7.15 (-0.9)**	**6.90**	**7.75**	**7.22**