

Simulation of characteristic features of Asian summer monsoon using a regional climate model

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सार – इस शोध-पत्र में भूमंडलीय जलवायु परिवर्तन के परिणामस्वरूप शताब्दी के मध्य (2041–60) के दौरान एशियाई ग्रीष्मकालीन मानसून के विशिष्ट लक्षणों का पूर्वानुमान करने के उद्देश्य से अनुकरण प्रयोगों के परिणाम प्रस्तुत किए गए हैं। इसके लिए हैडले जलवायु पूर्वानुमान और अनुसंधान केन्द्र, यू. के. का क्षेत्रीय जलवायु मॉडल हैड आर. एम. 2 का उपयोग किया गया है। एशियाई क्षेत्र के लिए 20 वर्षों की अवधि के दो अनुकरण प्रयोग किए गए हैं नामतः पहला, 1990 स्तरों के अनुरूप ग्रीन हाउस गैस सांद्रण की निर्धारित मात्रा, जिसे कंट्रोल (सी. टी. एल.) प्रयोग कहा गया है और दूसरा 1990 से लेकर 2041–60 तक के लिए ग्रीन हाउस गैस सांद्रण के वार्षिक मिश्रण में 1 प्रतिशत की वृद्धि समेत जिसे आगे ग्रीन हाउस गैस (जी. एच. जी.) प्रयोग कहा गया है। ग्रीन हाउस गैस सांद्रण में वार्षिक मिश्रण में 1 प्रतिशत की वृद्धि जलवायु परिवर्तन के अंतः सरकारी पैनल आई. पी. सी. द्वारा तैयार की गई योजना से ली गई है।

इन प्रयोगों से शताब्दी के मध्य के दौरान एशियाई ग्रीष्मकालीन मानसून में पाए जाने वाले विशिष्ट लक्षणों में होने वाले कुछ परिवर्तनों का पता चला है जिनका बढ़े हुए मानवजनित उत्सर्जकों के कारण होना स्वाभावित है। समूची मानसून ऋतु के दौरान भारतीय क्षेत्र पर निम्न क्षोभ मंडल (850 हैक्टापास्कल) में मानसून द्रोणी (एम. टी.) का उत्तर की ओर सामान्य रूप से बढ़ना सबसे अधिक महत्वपूर्ण परिवर्तन प्रतीत होता है। अनुकरण परिणामों से मानसून ऋतु के दौरान अरब सागर में समुद्र स्तर दाब (एस. एल. पी.) में लगभग 1–2 है. पा. की वृद्धि का पता चला है जिसके परिणामस्वरूप निम्न क्षोभ मंडल में असामान्य प्रतिचक्रवात होते हैं। इसका अर्थ यह हुआ कि निम्न स्तरीय जेट (एल. एल. जे.) और अरब सागर में मानसून की धारा कमजोर पड़ जाती है।

यह मॉडल उष्णतर समुद्र सतह की स्थितियों में हिंद महासागर के उत्तर में मानसूनी चक्रवातीय विक्षोभों की आवृत्ति में कमी को अनुकरित करता है जो हाल ही के दशकों में मानसून के अवदाबों की आवृत्ति में कमी की प्रवृत्तियों के अनुरूप पाई गई है।

इन प्रयोगों से यह पता चलता है कि पाकिस्तान और उसके समीपवर्ती उत्तरी पश्चिमी भारत के ऊपर ऊष्मा निम्नदाब तीव्र हो सकता है और मानसून ऋतु के दौरान थोड़ा पूर्व की ओर बढ़ सकती है। यह मॉडल, भारतीय समुद्र के दक्षिणी भागों में 8° – 10° उ. के बीच 100 है. पा. (टी. ई. जे. कोर का स्तर) पर विशेषकर मानसून के पूर्वार्द्ध के दौरान उष्णकटिबंधीय पूर्वाभिमुखी जेट(टी. ई. जे.) को प्रभावित करता है।

ABSTRACT. The paper presents the results of simulation experiments aimed at predicting the characteristic features of Asian Summer Monsoon during the middle of the century (2041-60) resulting from global climate change. The model used is HadRM2 regional climate model of the Hadley Centre for Climate Prediction and Research, UK. Two simulation experiments of 20 years length have been performed for the Asian domain, namely, one with a fixed amount of greenhouse gas concentration corresponding to 1990 levels called the 'control' (CTL) experiment and the other with the annual compound increase of 1 % in the greenhouse gas concentration for 2041-60 from 1990 onwards called the 'greenhouse gas' (GHG) experiment. The annual compound increment of 1 %, in the greenhouse gas concentration has been adopted from the projection given by the Intergovernmental Panel for Climate Change (IPCC).

The experiments have brought out some of the changes in the characteristic features of mid-century Asian summer monsoons that are expected to occur due to increased anthropogenic emissions. The most significant change seems to be a general northward shift of the monsoon trough (MT) in the lower troposphere (850 hPa) throughout the monsoon season over the Indian region. The simulation results have shown an increase of about 1-2 hPa in the sea level pressure (SLP) over the Arabian Sea during the monsoon resulting in an anomalous anticyclone over there in the lower troposphere. This would mean the weakening of Low Level Jet (LLJ) and the Arabian sea branch of the monsoon current.

The model has simulated a decrease in the frequency of the monsoonal cyclonic disturbances over the north Indian Ocean under the warmer sea surface conditions which conforms to the observed decreasing trends in the frequency of monsoon depressions in recent decades.

The experiments have shown that the Heat Low over Pakistan and adjoining northwest India, may intensify and shift slightly eastward during the monsoon. The model has simulated the strengthening of Tropical Easterly Jet (TEJ) at 100 hPa (the location of TEJ core) over the southern parts of Indian sea between 8° - 10° N, especially during the first half of the monsoon season.

Key words – Simulation, Asian summer monsoon, Monsoon trough, Heat low, Tropical easterly jet, Greenhouse emission, Monsoonal cyclonic disturbance, Climate model.

1. Introduction

There is a strong need for the proper assessment of various consequences of climate changes resulting from an increase in the global mean temperature due to anthropogenic emissions. According to an existing evidence, the increase in the greenhouse gases could warm the earth's atmosphere by 1.5° C to 4.5° C by the middle of the 21st century (IPCC, 2001). Greenhouse warming not only increases the air temperature but also increases SST (Manabe and Stouffer, 1980). The impact of global climate change may be different for different regions of the world. The Asian summer monsoon region due to its agrarian economy's dependence on the quantity and distribution of monsoon rains is highly vulnerable to any change in the monsoonal rainfall pattern. In recent decades, there have been some significant changes in the monsoonal cyclogenesis pattern over the north Indian Ocean which have been extensively studied by Singh 2001a. There seems to be an intriguing relationship between the observed trends in the frequency of the monsoonal cyclonic disturbances and the SST in the north Indian Ocean. Singh, 2001a has shown that the frequency of monsoon depressions and cyclones has decreased considerably during recent decades. The frequency has almost halved from the beginning to the end of the 20th century. Recently Patwardhan and Bhalme, 2001 have also reported the decreasing trend in the frequency of monsoonal disturbances. On the other hand the SSTs have registered an uptrend over the north Indian ocean. Using reliable satellite derived SST data, Singh and Sarker, 2003 have found that mean annual SSTs have increased over the north Indian ocean at the rate of about 0.2° C / decade during the period 1985-1998. The increasing trend during the summer monsoon season is even more pronounced (~ 0.4° - 0.6° C / decade).

The main objective of present study is to simulate different characteristic features of Asian summer monsoon using a reliable regional climate model that can capture the monsoonal features due to its high resolution. The general circulation models (GCMs) have successfully simulated the large scale climatological features and have

been able to predict the global climate changes but on regional scale these models have had only limited success, particularly over the Asian summer monsoon region. Thus a regional climate model (RCM) with high resolution is most suitable for simulating the characteristic features of Asian summer monsoon. The present work attempts to simulate some of the important components of monsoon like, Monsoon Trough (MT), Heat Low (HL), Low Level Jet (LLJ), Tropical Easterly Jet (TEJ) using the HadRM2 regional climate model of the Hadley Centre for Climate Prediction and Research, UK. The impact of warmer sea conditions on the monsoonal cyclogenesis has also been simulated.

The results of control experiment presented in section 3 show that HadRM2 has been able to simulate various components of southwest monsoon reasonably well. The simulations of rainfall and temperature distributions over the Indian subcontinent have been extensively studied by earlier investigators (Bhaskaran and Mitchell, 1998 and Rupa Kumar and Ashrit 2001) and therefore this aspect has not been repeated in the present work. However, the consistency of simulated changes in the monsoon components with respect to rainfall distribution has been discussed in the text whenever necessary.

2. Model and experiments

HadRM2 is a second generation regional climate model of the Hadley Centre for Climate Prediction and Research, UK. It is a high resolution climate model that covers a limited area of 5000 km × 5000 km. The horizontal resolution is 50 km × 50 km with 19 hybrid vertical levels. The initial conditions to start HadRM2 are taken from the second generation Hadley Centre coupled atmosphere-ocean general circulation model HadCM2. The higher resolution of HadRM2 enables the simulation of finer features of monsoon including the monsoonal system like monsoon depression.

The atmospheric component of HadRM2 is a hydrostatic primitive equation model. There are 19 hybrid

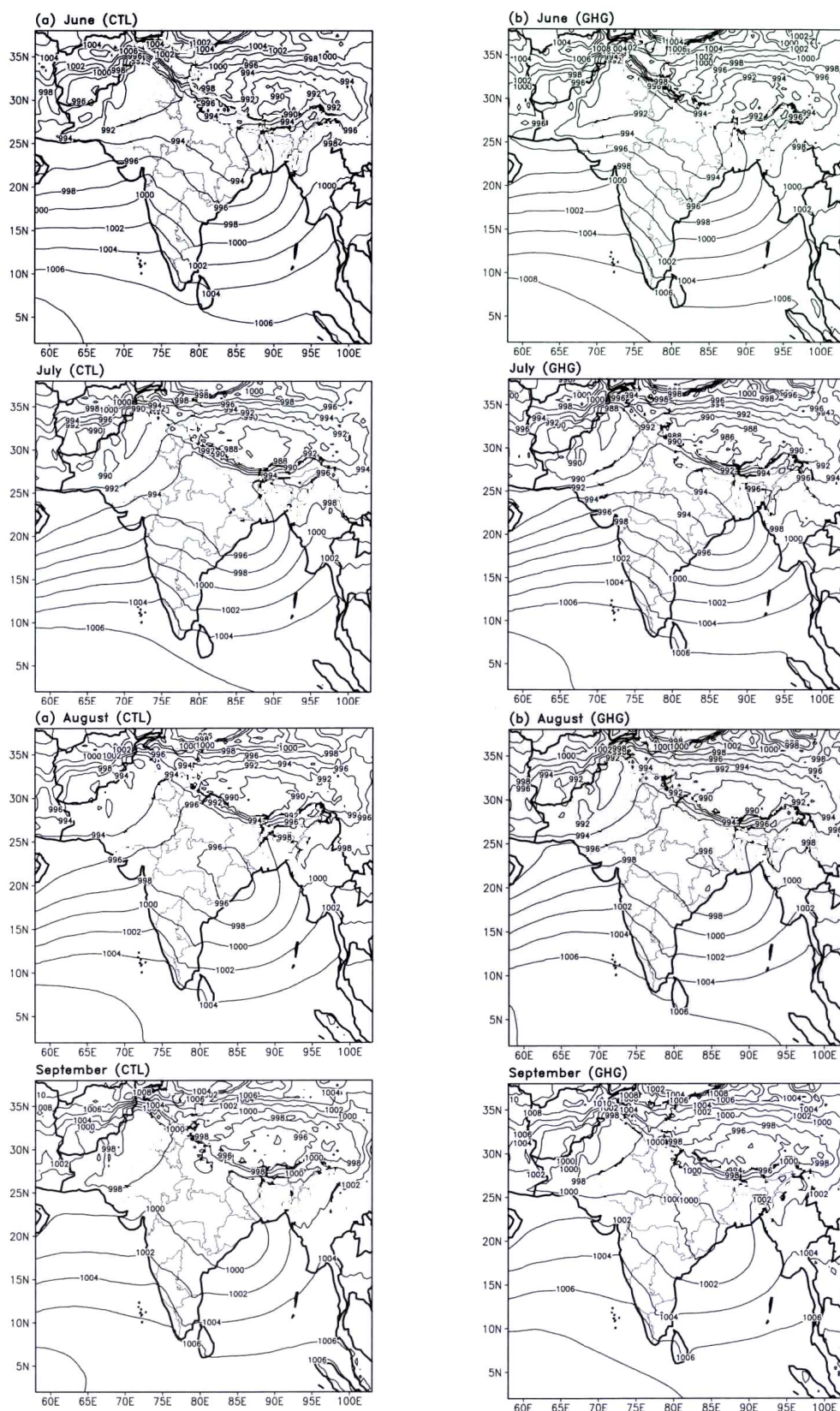


Fig. 1. Mean monthly sea level pressure distribution over the Asian summer monsoon domain for June-September during 2041-60 (a) CTL and (b) GHG

coordinate vertical levels, lowest at about 50 m and highest at 0.5 hPa (Cullen, 1993). The model equations are solved in the spherical coordinates. The horizontal resolution of HadRM2 is $0.44^\circ \times 0.44^\circ$ *i.e.*, a minimum resolution of 50 km \times 50 km at the equator. The HadRM2 needs a time step of 5 minutes to maintain numerical stability (Jones *et al.*, 1995). The radiation scheme includes seasonal and diurnal cycles of insolation, computing short-wave and long-wave fluxes which depend upon temperature, water vapour, O₃, CO₂ and clouds (Jones *et al.*, 1995).

Bhaskaran *et al.* (1996) used HadRM2 to simulate the climate over India during the monsoons of the years 1984, 1985, 1987 and 1988. The purpose of selection of these years was to have normal, weak and strong monsoons in the set. The intensity of the simulated monsoon was found to be influenced by the northwest and north propagating modes of the monsoon which were almost similar to the observed modes of the monsoon. However, the simulated intensity of MT was stronger in the experiments conducted by Bhaskaran *et al.*, (1996).

In the present experiments HadRM2 has been driven by the lateral boundary conditions obtained from coupled atmospheric ocean GCM HadCM2. HadCM2 has shown good skill in capturing broad features of monsoon (Bhaskaran and Mitchell, 1998; Lal and Harasawa, 2001; Rupa Kumar and Ashrit, 2001). Two simulation experiments of 20 years length have been conducted for the Asian summer monsoon domain namely, one with a fixed amount of greenhouse gas concentration corresponding to 1990 levels (CTL) and the other with an annual increase of 1% in the greenhouse gas concentration (GHG) for 2041-60 from 1990 onwards. The impacts of increased emissions and the resulting global warming on the main features of monsoon, *i.e.*, Monsoon Trough, Heat Low, Low Level Jet, Tropical Easterly Jet and the monsoonal cyclogenesis have been simulated which will be presented in the following section.

It may be pointed out that the changes in monsoon components are very slow and therefore it is necessary to consider a sufficiently long period of about 50 years to bring out the differences between the CTL and GHG experiments. However, the simulated changes after every 20 years period have been examined and the consistent changes only are being reported in the present work. For instance, a northwest shift of about 2° in Monsoon Trough axis position at 850 hPa in GHG experiment as compared to the CTL experiment is discernible after 50 years. The simulated changes after 20 years are too small. As mentioned earlier the initial conditions to start HadRM2 have been taken from the ocean-atmosphere GCM HadCM2.

3. Results and discussion

The sea level pressure distribution over the monsoon domain is an important feature of monsoon which determines the pressure gradients and resulting strength of monsoon in the lower troposphere. The intensities of Heat Low and the Monsoon Trough are intimately linked to the SLP distribution during the monsoon. The simulated SLP distributions during each monsoon month (June-September) in control and GHG experiments for the period 2041-60 have been presented in Fig. 1. The difference between GHG-CTL is the anomaly in SLP which is due to increased greenhouse gas emissions. The SLP anomaly at each grid point has been computed by subtracting the surface pressure value at that grid point obtained in control experiment from the corresponding value obtained in GHG experiment.

The circulation pattern at 850 hPa determines the strength of monsoon current. The strength of westerlies over the Arabian Sea is a measure of the intensity of Low Level Jet and the cross equatorial flow. In the Indo-Gangetic planes and over the Head Bay of Bengal the flow pattern determines the intensity and location of monsoon trough. Thus the circulation at 850 hPa has been simulated in the above-mentioned experiments separately and the results have been presented in Fig. 2 to facilitate the comparison.

The upper level winds at 100 hPa determine the upper tropospheric divergence in the monsoon region. The core of tropical easterly jet being at 100 hPa, its intensity and location could be inferred from the 100 hPa circulation pattern. The simulated circulation patterns at 100 hPa in CTL and GHG experiments have been shown in Fig. 3.

Before we discuss the changes in the monsoon components due to increased GHG emissions it is necessary to examine whether HadRM2 is able to capture the salient features of southwest monsoon in control experiment or not. An examination of Figs. 1 and 2 shows that the sea level pressure distribution and the circulation pattern in the lower troposphere (*i.e.*, at 850 hPa) are simulated well. The position and intensity of Heat Low match with the climatology. Similarly the core of TEJ at 100 hPa is also simulated well (Fig. 3). The simulated slope of Monsoon Trough axis in the Bay of Bengal *i.e.*, the tilt of the axis toward south is more as compared with the climatological slope but the positions match over the land areas.

Undoubtedly, the rainfall is most important parameter which needs to be simulated in climate change assessments. But the simulations of monsoon rainfall and

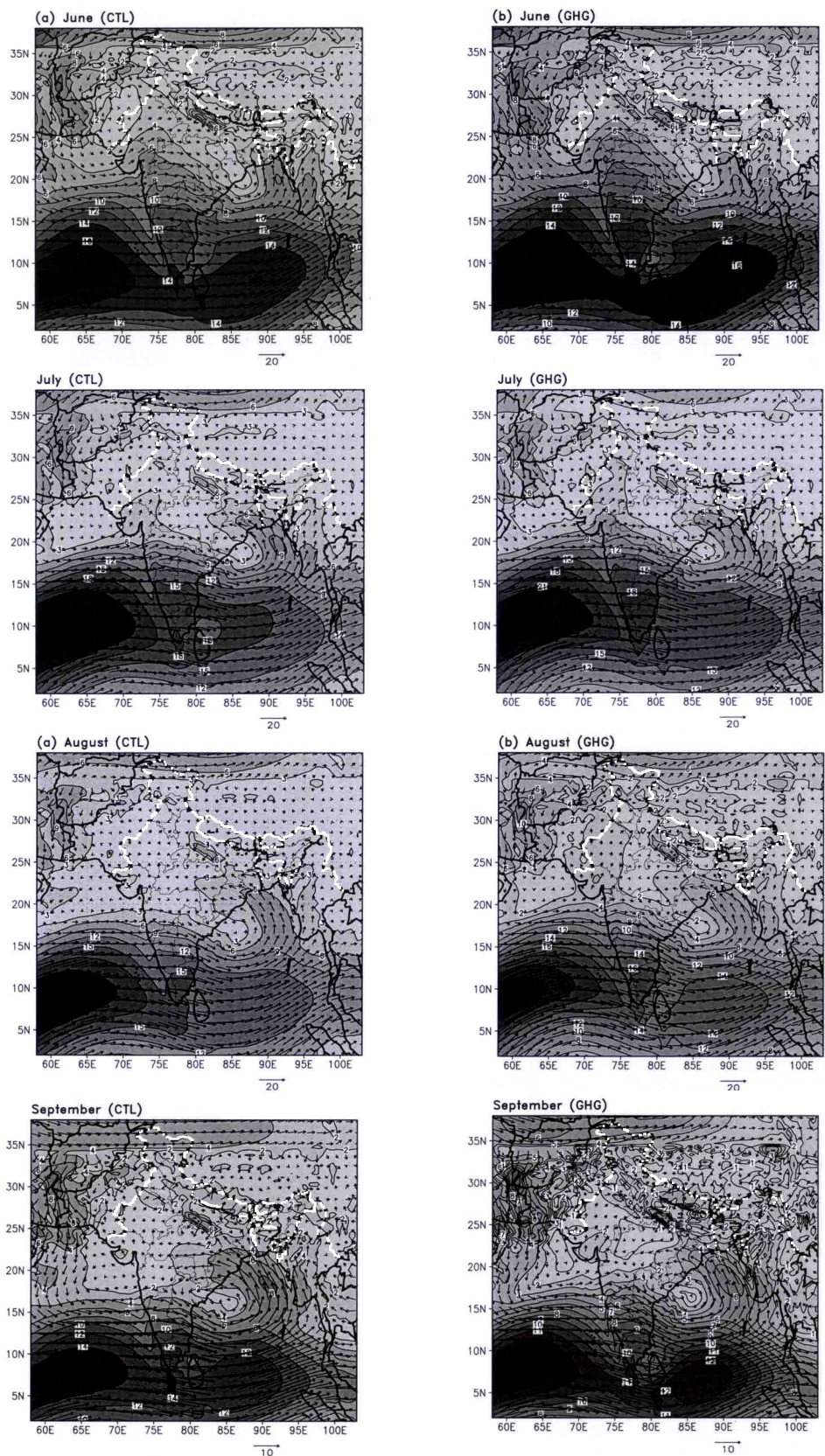


Fig. 2. Mean monthly circulation pattern at 850 hPa for June-September during 2041-60 (a) CTL and (b) GHG

its spatial distribution in quantitative terms may be misleading. For instance HadCM2 seems to underestimate the rainfall over Indo-Gangetic plains and overestimate over the Himalayan region. The all India monsoon rainfall (June-September) simulated by HadCM2 in control experiment is 755.50 mm against the observed value of 966.90 mm showing a departure of 211.40 mm (Rupa Kumar and Ashrit, 2001). Similarly, the standard deviation of all India monsoon rainfall in HadCM2 control experiment is 71.10 mm against the observed value of 86.20 mm. It is desirable to give more emphasis on the likely changes in the monsoon circulation pattern and then infer the expected changes in monsoon rainfall distribution qualitatively which is precisely the objective of present work. The monsoon trough position, intensity of heat low, distribution of sea level pressure and vorticity along the west coast of India, cross equatorial flow and intensity of low level jet can provide good indications of monsoon rainfall distribution over India. However, mean monthly circulation/rainfall patterns cannot give any indication of active/break monsoon conditions, which have a time scale of few days only.

3.1. Heat Low and the SLP distribution over the Arabian Sea

It is seen from Fig. 1 that the minimum isobar of 992 hPa is found in the central region of the HL in the month of June in CTL experiment which covers extreme western part of Rajasthan, Punjab, some parts of western Haryana and adjoining areas of Pakistan. But in GHG experiment there is an eastward shift and the 992 hPa isobar expands up to west UP covering entire Haryana. Thus HL zone has shifted up to western UP causing slight intensification of low pressure east-west trough zone over that area. During July, the 992 hPa isobar over Rajasthan and adjoining Punjab in CTL experiment is completely replaced by 990 hPa isobar. Thus in July there is a clear indication of intensification of HL over Pakistan and adjoining areas of Rajasthan and Punjab. During August also the SLP in the central region of HL is lower in GHG as compared to CTL experiment. During September however, there is no difference in the intensities of HL in the two experiments. Thus it is concluded that there is an indication of intensification and eastward shift of HL due to increased green house emissions during the monsoon months June to August by the middle of the century.

The most striking difference in the SLP distributions in the two experiments is observed over the Arabian Sea. This is clearly brought out by Fig. 2 which shows that the SLPs over the Arabian Sea will be higher by 1-1.5 hPa during June, 1.5-2 hPa during July and August and 1-2 hPa during September by the middle of the 21st century as a result of increased green house gas

concentration in the atmosphere. This change in the SLP distribution over the Arabian Sea is capable of causing certain imbalances in the monsoon climate. For instance, the higher SLP anomalies over the Arabian Sea may weaken the Arabian Sea branch of monsoon current and the low level jet and suppress the cross-equatorial flow. The cyclogenesis over the Arabian Sea during monsoon will be reduced. The onset of southwest monsoon through the 'onset vortex' may also become infrequent. The weakening of Arabian Sea branch of monsoon would certainly cause reduction in the monsoon precipitation over northwest India and Pakistan. The appearance of an anomalous high pressure over the Arabian Sea in GHG experiment is an indication of increased subsidence over that area. This is likely to strengthen the low level inversion over the Arabian Sea and reduce the monsoon precipitation over the sea. The major implication of these changes may be the complete absence of monsoon current over Pakistan in some years.

3.2. Monsoon trough

The monsoon trough is a significant component of summer monsoon. Any change in its intensity and location may affect the observed rainfall distribution during the monsoon. In order to bring out likely changes in MT intensity and location due to anthropogenic emissions we have presented in Fig. 2 the 850 hPa circulation pattern as simulated in CTL and GHG experiments.

The presence of westerly anomalies in the monsoon trough axis region at 850 hPa is an indication of northward shift of MT. Fig. 4 depicts the axis of MT at 850hPa during each monsoon month as simulated in CTL and GHG experiments. There is an evident northward shift of about 2° in the mean position of MT axis during July and August which account for major amount of monsoon precipitation. During June there seems to be slight northward shift of MT axis over the Bay of Bengal. During September also except extreme southwest Bay of Bengal there is a general northward shift in the MT axis. The northward shift of MT axis especially during July-August may increase the monsoon precipitation over northeast India and Bangladesh. There is an indication of more frequent monsoon floods in Bangladesh due to global warming as the run-off in Meghna-Ganges-Brahmaputra rivers system is expected to increase considerably as a result of increased monsoon rainfall over northeastern states of India and Bangladesh. This conforms to the observed increasing trends in the monsoon rainfall over Bangladesh in recent decades (Singh, 2001 b). It is not surprising that the observed sea-level trend along Bangladesh coast is about 6 mm/year which is almost six times higher than the global mean rate (Singh 2001b). The simulated changes in sea level

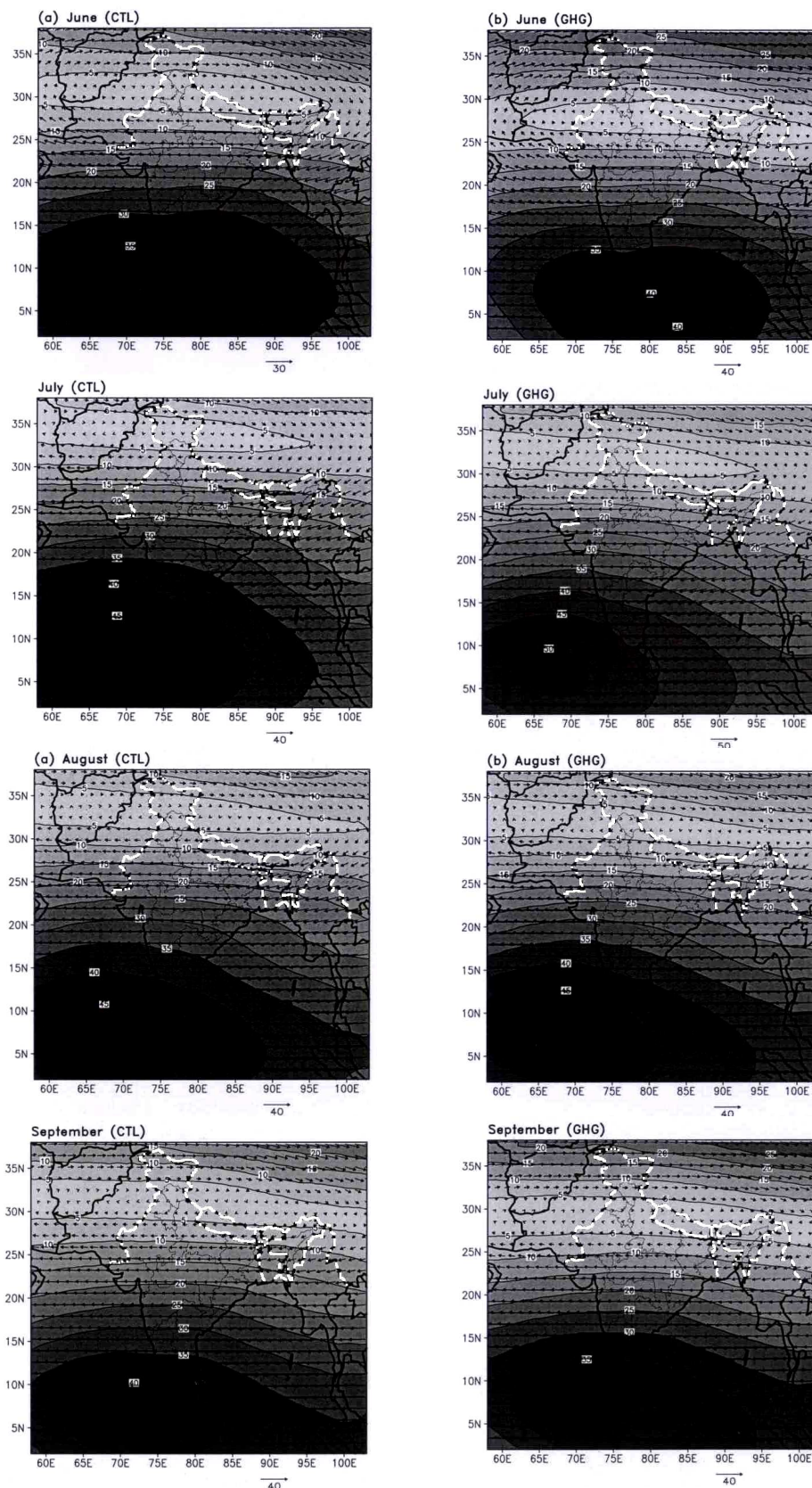


Fig. 3. Mean monthly circulation pattern at 100 hPa for June-September during 2041-60 (a) CTL (b) GHG

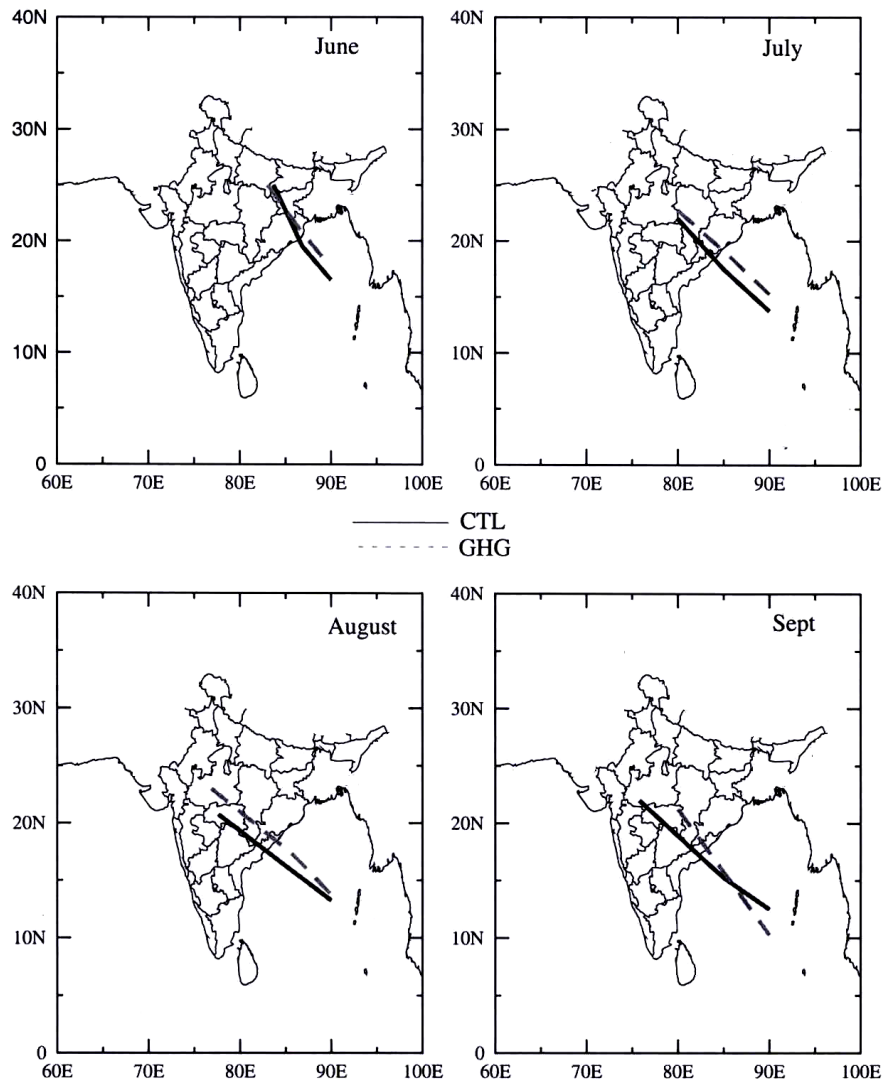


Fig. 4. Mean monthly locations of monsoon trough axis during 2041-60 in CTL and GHG experiments

pressure distribution and Monsoon Trough position agree well with the simulated changes in the precipitation distribution over the Indian subcontinent which have projected an increase in the monsoon precipitation over northeast India and Bangladesh during the period 2041-60.

Another interesting aspect of simulated winds at 850 hPa is a general reduction in the positive vorticity along the south west coast of India due to anthropogenic emissions. This feature is again unfavourable for the strength of Arabian sea branch of monsoon current. On the other hand, there seems to be a general intensification of monsoon current over the south Bay of Bengal in GHG

experiment. Due to this the monsoon flow in the lower troposphere shows signs of strengthening there. This is likely to increase the monsoon precipitation over that region. Therefore, the simulation experiments indicate a general enhancement in the monsoon precipitation over the northeastern belt of the Asian monsoon domain and a general reduction in the rainfall over western side due to increased anthropogenic emissions.

3.3. Upper tropospheric (100 hPa) circulation pattern and Tropical Easterly Jet

The intensity and location of TEJ is another factor that is linked to the monsoon performance. A comparative

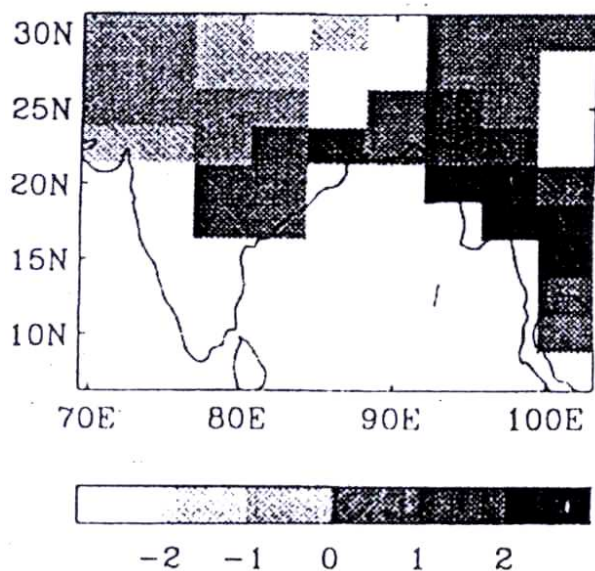


Fig. 5. Projected changes (GHG-CTL) in the Asian summer monsoon rainfall (June-September) pattern (in units of mm/day)

examination of 100 hPa circulation feature Fig. 3 in GHG and CTL experiments reveals that the easterlies over extreme southern peninsula, Sri Lanka and adjoining areas of the south Bay of Bengal during June are stronger in GHG as compared to the CTL experiment where a 40 ms^{-1} isotach appears in place of the 35 ms^{-1} isotach. In July, the maxima (50 ms^{-1}) appears over the south Arabian Sea in GHG in place of 45 ms^{-1} in CTL. During August, the easterlies are slightly stronger over the central region of south Bay of Bengal. But in September, there is not much difference in the strength of easterlies over the Indian peninsula or over the Bay of Bengal. Over the south Arabian Sea the easterlies are slightly weaker in GHG experiment. Therefore, in the first half of the monsoon, there is a strengthening of 100 hPa easterlies over the southern part of Indian Seas in GHG experiment.

3.4. Frequency of monsoonal cyclonic disturbances

As mentioned earlier the monsoonal cyclogenesis has been very much subdued over the north Indian ocean in recent decades inspite of increasing SSTs (Singh, 2001a and Singh and Sarker, 2003). It is an interesting relationship that needed to be simulated in order to firmly establish the impact of increasing SSTs on the monsoonal cyclogenesis. An attempt was made to identify all monsoonal cyclonic disturbances during the 20 year period from 2041-60 by examining the daily distribution of SLP and 850 hPa winds in CTL and GHG experiments.

There was a need to adopt an objective criteria for the identification of cyclonic disturbances. As a preliminary exercise the disturbances were identified by considering the maximum wind speed at 850 hPa $> 15 \text{ m/s}$ and a local minimum in SLP with SLP departure $< -5 \text{ hPa}$. The duration of the disturbances were taken to be atleast two days in order to filter out unimportant ones. It may be remarked that the quantitative criteria used to determine the number of cyclonic disturbances is very close to the IMD's synoptic criteria in terms of wind speed and pressure departure. However, IMD's criteria which is based on satellite information in addition to synoptic charts is not feasible to be applied in totality in numerical simulations. The simulation yielded about five monsoonal cyclonic disturbances per season over the north Indian ocean in control and about four disturbances per season in GHG experiment indicating a 20% reduction in the frequency of monsoonal cyclonic disturbances in 50 years from now. The statistical extrapolations based on actual observations estimate even steeper decreasing trends in the monsoonal cyclogenesis over the north Indian Ocean. Thus the reduction in the frequency of monsoon depressions and cyclones under warmer sea surface conditions over the north Indian Ocean is common in simulations and the observed trends.

3.5. Simulated changes in monsoon rainfall

The projected changes in summer monsoon rainfall pattern by the middle of 21st century are presented in Fig. 5. The model has simulated a decrease in monsoon rainfall (June-September) over the western parts of India. Over the northeastern region the monsoon rainfall is likely to increase. Therefore, the northwestern and peninsular India which are prone to large interannual and intraseasonal variabilities of monsoon rainfall are likely to receive less precipitation by the middle of the Century due to increased greenhouse gas emission. On the other hand the northeastern region which is less prone to monsoon rainfall variability is likely to receive more monsoon precipitation. An implication of these changes would be a more frequent occurrence of extreme events of precipitation, especially over the northeastern India and Bangladesh. Over northwestern parts of India and Pakistan the frequency of droughts may increase due to overall reduction in monsoon precipitation.

As revealed by Fig. 5 over the west coast of India and central parts of the country the monsoon precipitation is likely to decrease by 1-2 mm/day which may result in more frequent monsoon breaks. The increased rainfall over Bangladesh and the northeast India is also an indication of more frequent monsoon breaks.

4. Conclusions

The experiments conducted to simulate some of the characteristic features of mid-century Asian Summer monsoons have shown that:

(i) By the middle of 21st century, the sea level pressure over the Arabian sea is expected to be higher by 1-2 hPa throughout the monsoon season due to an increase in green house gas concentration in the atmosphere. This is likely to weaken the low level jet and the Arabian Sea branch of the monsoon.

(ii) The heat low over Pakistan and adjoining northwest India may intensify and shift slightly eastward, especially, during June to August.

(iii) The axis of Monsoon Trough at 850 hPa may shift northward by about 2° during July-August which is indicative of enhanced monsoon rainfall over Bangladesh and northeast India. Northward shift of Monsoon Trough may cause reduction in monsoon precipitation over the central parts, a situation conducive for increased number of monsoon breaks.

(iv) The upper tropospheric easterlies at 100 hPa may strengthen over the southern region of the Indian Seas during the first half of the monsoon season.

(v) The model has simulated a reduction in the frequency of the monsoonal cyclonic disturbances over the north Indian Ocean under warmer sea surface conditions.

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