Indian summer monsoon in future climate projection by a super high-resolution global model

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The impact of future climate change on the Indian summer monsoon has been investigated using a super high-resolution global general circulation model. The model with approximately 20-km mesh horizontal resolution can resolve features on finer spatial scales, which were till now resolved by employing high-resolution regional models. Regional models are known to have high dependency on the lateral boundary forcing and significant inability to represent regional-global scale interactions comprehensively. Another advantage of the 20-km global model is its fidelity in representing the regional distribution of the present-day monsoon rainfall. Super high-resolution future scenario for the Indian summer monsoon shows widespread but spatially varying increase in rainfall over the interior regions and significant reduction in orographic rainfall over the west coasts of Kerala and Karnataka and the eastern hilly regions around Assam. Over these regions, the drastic reduction of wind by steep orography predominates over the moisture build-up effect (that causes enhanced rainfall over other parts) in reducing the rainfall. This indicates that monsoon rainfall is strongly controlled by parameterized physics and high-resolution processes which need to be resolved with adequately high resolution. The model projects substantial, spatially heterogeneous increase in both extreme hot and heavy rainfall events over most parts of India by the end of the century. While fine-scale surface moisture feedbacks influence the response of extreme hot events, extreme precipitation is influenced by fine-scale orography, evaporation, moisture content and circulation. Thus, the results indicate that consideration of fine-scale processes is critical for accurate assessment of local and regional-scale vulnerability to climate change.

Keywords: Climate change, general circulation model, Indian summer monsoon, super high-resolution.

GLOBAL concentrations of greenhouse gases (GHGs) have increased exponentially since the industrial revolution[1]. The increase in radiative forcing of the atmosphere due to the increasing GHG concentration results in the warming of the earth's surface[2] and may have significant impact on the large-scale circulation patterns. Over the tropics, the Indian monsoon is one of the most dominant circulation systems that plays an important role in the general circulation of the atmosphere through its transport of heat and moisture from the tropics. More importantly, monsoon has great importance for the agrarian economy of India[3,4]. Therefore, it is essential to understand the potential changes in monsoon caused by an increase in atmospheric GHGs. But the large inter-model difference in the simulation of Indian summer monsoon by the current global general circulation models (GCMs) and their low skill in representing the present-day Indian summer monsoon climate were found to be the major detrimental factors[5].

Several recent studies have focused on the possible influence of increasing emissions of GHGs on the Asian summer monsoon. For example, NCAR-coupled GCM simulation with doubled CO_2, showed an intensification of the Asian summer monsoon and its variability[6]. Significant increase in monsoon rainfall was suggested to occur due to increased CO_2 in a coupled GCM despite the weakening of the low-level circulation over the Arabian Sea[7]. The increased rainfall was found to be due to larger moisture content in the warmer troposphere[7], or intensification of moisture transport into the region[8], or increased moisture source from the warmer Indian Ocean[9]. The large-scale aspects of the Indian summer monsoon were also found to be weakening[10]. Current projection studies indicate that summer precipitation is likely to increase in South Asia on a broader scale[11]. An increase in the frequency of intense precipitation events in parts of South Asia, and in East Asia, is also likely. However, it is still not clear how the regional distribution of the Indian summer monsoon rainfall responds to global warming under the A1B scenario[12] in greenhouse warming experiments. Thus, it is meaningful to study the response of the Indian monsoon rainfall and circulation with a major focus on their regional distribution.

GCMs often fail to capture the fine-scale structures that affect regional climate due to their coarse resolution. This aspect partially accounts for the deficiencies shown by GCMs in reproducing important aspects of the regional

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distribution of the Indian summer monsoon meteorological parameters. For example, using a coupled model of T106 resolution for the atmosphere[13], the projected increase in the Indian summer monsoon rainfall in 2080s is 10–15%. But this model appeared to have significant shortcomings in simulating the present-day summer monsoon rainfall. Similarly, the highest resolution simulation among IPCC AR4 coupled models[11] also showed lack of reasonable fidelity in capturing important features of present-day summer monsoon rainfall. Increasing the resolution of a global GCM can resolve features on finer spatial scales, which were till now resolved by employing nested high-resolution regional models. In a study using a regional climate model[14] with reasonable skill in representing the spatial distribution of summer monsoon rainfall over India, the climate change impact under A2 and B2 scenarios[12] was found to increase the monsoon precipitation over the entire country, with some regional variation. However, nesting of high-resolution regional model is known to have high dependency on the lateral boundary forcing and significant inability to represent regional–global-scale interaction comprehensively due to lack of two-way nesting for feedback with the forcing GCM input. Alternately, enhancing the global GCM resolution considerably, the regional–global-scale interactions can be incorporated comprehensively and regional climate information such as land–sea distribution, lakes, soil characteristics and orography can be better represented, so that the simulation will be useful for local impact assessments.

In this article, we present the future climate change scenario for the Indian summer monsoon using a super high-resolution global GCM simulation. As increase in resolution can possibly lead to both improvement and reduction in the quality of the monsoon simulation[15], an assessment of the present-day rainfall simulation of the model has been made by comparing with the observed rainfall over India. This model was found to have a realistic simulation of boreal winter climate over the tropics[16]. In this study, we address the climate change impact on the regional distribution of the Indian summer monsoon rainfall towards the end of the 21st century.

Super high-resolution model and time-slice experiment

A global super high-resolution GCM with a spatial grid size of about 20 km and 60 vertical levels, jointly developed by Japan Meteorological Agency (JMA) and Meteorological Research Institute (MRI), Japan has been used for global warming projection[17]. The model corresponds to triangular truncation 959 with linear Gaussian grid in the horizontal comprising 1920×960 grid cells of about 20 km. The model is hereafter referred to as the 20-km model. This has been the operational global model for short-time numerical weather prediction of JMA since November 2007.

The dynamical framework of the model consists of a full primitive equation system[18]. The cumulus parameterization scheme used in this hydrostatic model is the Arakawa–Schubert scheme with Randall and Pan-type closure[19]. The effect of entrainment and detrainment between the cloud top and cloud base in convective downdraft instead of re-evaporation of convective precipitation has been included. Introduction of a two-level semi-Lagrangian scheme[20] made possible the use of a long time-step in time integration. The model integrations were performed in the Earth Simulator, a massively parallel vector supercomputer.

For the present-day climate simulation, observed historical sea surface temperature (SST) by HadISST[21] from 1979 to 1988 was prescribed. A 'time-slice experiment' was performed for the future climate simulation towards the end of the 21st century from 2075 to 2084. The boundary SST dataset was prepared by superposing, (i) the trend in the Multi-Model Ensemble (MME) of SST projected by the World Climate Research Programme (WCRP) Coupled Model Inter-comparison Project (CMIP3) multi-model dataset, (ii) future change in MME of SST (ΔSST) and (iii) the detrended observed SST anomalies for the period 1979–88. Future change in MME of SST was evaluated by the difference between the 20th century simulations and future simulation under IPCC A1B emission scenario[12]. Linear trend for future climate by the CGCMs was also taken into account. Figure 1 is a schematic diagram of the boundary SST set-up for the time-slice experiment. The design retains observed year-to-year variability and El Nino and Southern Oscillation (ENSO) events in future climate, but with a higher mean and clear increasing trend in SST.

The validation data for the present-day rainfall simulation of the 20-km model was taken from the daily gridded rainfall data in $1° \times 1°$ grid from India Meteorological Department (IMD)[22] for the period 1979–88. This dataset is based on 1803 stations with a minimum 90% data availability during the period 1951–2003. For rainfall validation over the global tropics, we have used the TRMM 3B43 precipitation dataset from 1998 to 2008. The gridded estimates were on a calendar-month temporal resolution at a 0.25° lat. × 0.25° long. spacing (40N–40S)[23].

Present-day climate simulation

The fidelity of the model in representing the present-day climatological features of tropical monsoons is crucial for building confidence in its future projections of tropical climate, including the Indian summer monsoon. Figure 2 shows the seasonal (June, July, August, September mean, hereafter referred to as the JJAS mean) rainfall over the global tropics from TRMM 3B43 observation and super high-resolution simulation. The model shows a realistic representation of the inter tropical convergence zone

(ITCZ) and tropical monsoons in terms of the location and spatial extent of high rainfall. For example, the orientation of major rainbelts and distribution of rainfall associated with the African monsoon, North and South American monsoons, and Indian and East Asian monsoons are well simulated by the model. Mean rainfall over Japan and East Pacific are also close to observation.

Indian summer monsoon

The most important aspect of the Indian summer monsoon and the most difficult parameter for the GCMs to simulate is the rainfall occurring in the season[5]. Over the Indian region, in addition to the continental rainfall, the rainfall over equatorial Indian Ocean is also simulated realistically by the model. However, rainfall over the Indian land mass is modulated by the orographic features. Figure 3 reveals numerous regional details of the observed seasonal mean (JJAS mean) monsoon rainfall pattern over India, illustrating the importance of the super high resolution of the GCM for providing important regional climate information, particularly the orographic nature of the seasonal precipitation. The 20-km simulation captures many aspects of the regional distribution of observed monsoon rainfall. These include meridionally oriented orographic maximum along the west coast of the Indian Peninsula, relative

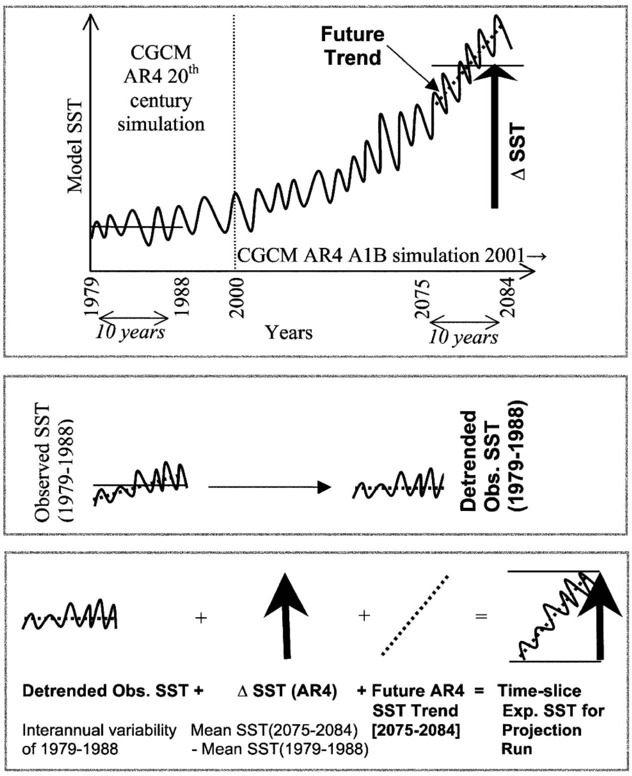

Figure 1. Schematic diagram of the sea surface temperature (SST) setting used for the end of the 21st century simulation under IPCC–AR4 A1B scenario.

maxima over the central Indian region, parts of the Indo-Gangetic plain and the northeast region. On the south-eastern part of the Indian peninsula, precipitation is relatively weak as in observation. However, there is a slight rainfall underestimation over the West Bengal region.

The primary manifestation of the Indian monsoon which is also crucial for an accurate simulation of the mean monsoon and its variability[5], is the distinct seasonality in precipitation. On all-India average, the simulated rainfall annual cycle has been compared with the corresponding variation in observed IMD rainfall in Figure 4. The model shows marked skill in capturing the phases of rainfall variation with minor quantitative differences. Simulation shows small reduction in the mean rainfall during the peak monsoon months of July and August, and slight overestimation for other months. The sudden enhancement in monthly precipitation associated with the onset phase, persistence of intense rainfall during June–September and the sharp reduction after the withdrawal in September are well captured.

Future climate change scenario for India

At the end of the 21st century, the model predicts an increase in precipitation significant at 95% level (Figure 5), in most of the areas where rainfall is rather strong during the monsoon season (Figure 3). However, in the southern half of the west coast of the peninsula, parts of eastern India and the Jammu–Kashmir region, future decrease in rainfall has been projected. So far, future scenarios for the Indian summer monsoon rainfall even using high-resolution regional climate models have projected relatively uniform climate change[14]. In summary, the projected changes indicate an overall intensification of the all-India monsoon rainfall with strong regional modulations, in the future, in response to the anticipated increase in GHG concentration and resultant widespread warming of the surface temperature (not shown).

Consistent with the projected strengthening of the seasonal mean monsoon rainfall over most parts of the country, the mean annual variations of the all-India rainfall in the present and future climatic conditions (Figure 6) also clearly show the intensification of the rainfall not only during the summer monsoon season but during an extended period from April to November. The variations in both climates are in phase with a systematic quantitative future enhancement, except during the winter season of December–February. This is consistent with the current understanding that the rainfall over South Asia will decrease during the December–February season and will increase during the rest of the months under global warming[11]. This difference in rainfall annual cycle is associated with a corresponding systematic intensification of the annual cycle of surface temperature in future (Figure 6). An average projected change of approximately 2 mm/day appears

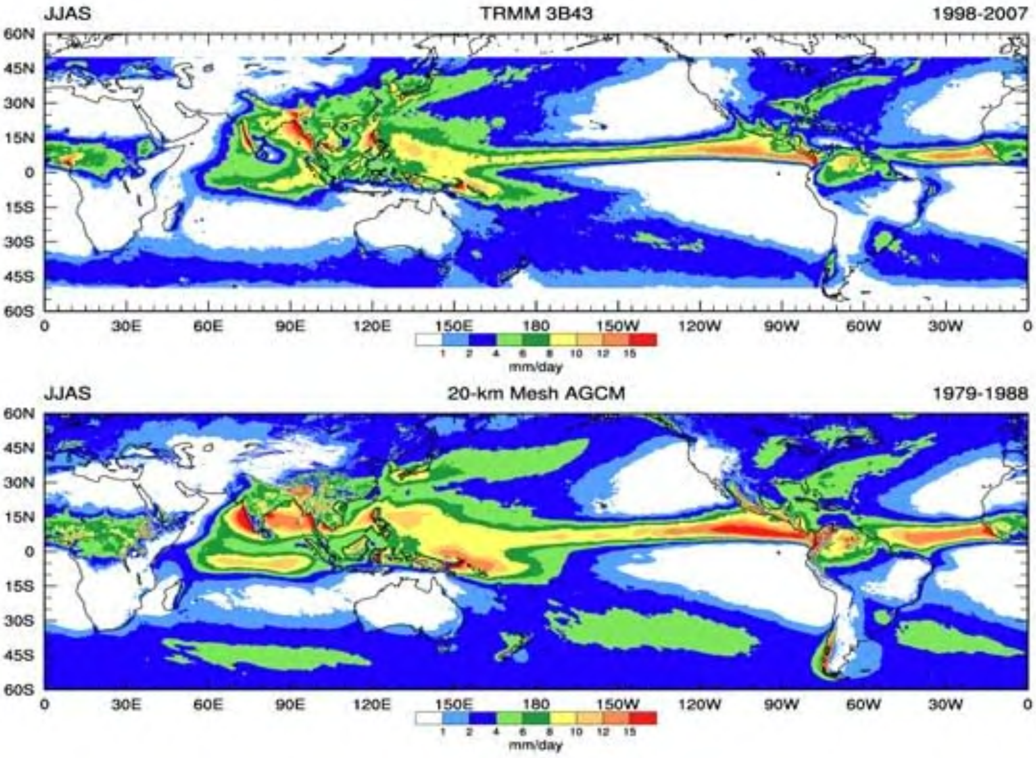

Figure 2. Seasonal (JJAS) mean rainfall from TRMM 3B43 observation and 20-km AGCM simulation.

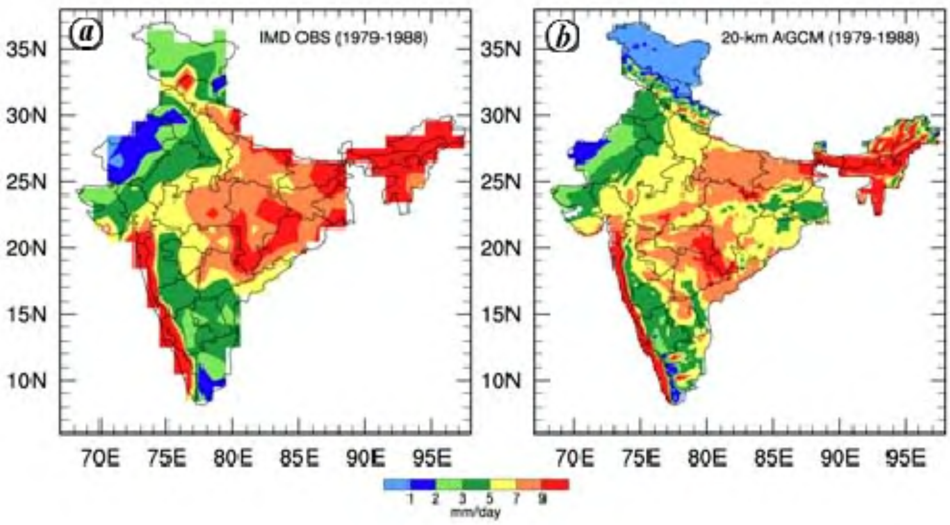

Figure 3. JJAS mean rainfall from IMD observation (***a***) and present-day simulation of the 20-km model (***b***).

to have been caused in response to a mean warming of about 3°C.

However, the manner of change of precipitation is uneven with distinct spatial inhomogeneity (Figure 5). Different factors can contribute to the change in the hydrological cycle due to climate warming. Increase in the saturation-specific humidity or the capacity to hold water vapour with rise in temperature can increase the actual water vapour content in the atmosphere. Thus, if the mean residence time of water vapour in the atmosphere does not change, both precipitation and evaporation would increase with exponential dependence on temperature. But, regional factors which are resolvable with 20-km resolution, like the availability of surface moisture, horizontal convergence/divergence of air flow in the lower atmosphere and orography modulate the concentration of water vapour evaporated from the surface or transported into the area. Thus, the resultant spatial distribution of atmospheric moisture and the precipitation changes can be uneven.

Figure 7 shows high-resolution orography and the seasonal mean changes in horizontal wind and moisture convergence at 850 hPa, evaporation, precipitable water (PWAT) and column integrated moisture transport projected by the model in response to future warming. Associated with the increased specific humidity due to future warming, there is a widespread increase in PWAT over the entire country, but with strong quantitative spatial variation (Figure 7 *d*). Strong future increase in evaporation occurs over most of the regions due to enhanced precipitation over India (Figure 7 *c*). Evaporation is enhanced over these regions since the soil moisture content also increases in these areas (not shown) as a consequence of the increased rainfall. In contrast, comparatively weaker enhancement is seen over regions with reduced future rainfall, such as Rajasthan, Jammu–Kashmir and parts of Assam, Arunachal Pradesh, Manipur, Meghalaya and Mizoram. Rainfall reduction in Jammu–Kashmir, parts of Himachal Pradesh and Uttarakhand is associated with low PWAT, reduced evaporation, lack of inflow of low-level moist air (Figure 7 *a*) or transport of dry air from the Arabian region. Enhanced rainfall in Uttar Pradesh, Bihar, parts of Madhya Pradesh, Chhattisgarh, Orissa, Andhra Pradesh, Karnataka, Tamil Nadu and Maharashtra is due to increased low-level inflow of oceanic air from the Arabian Sea or Bay of Bengal, increased PWAT and stronger column-integrated moisture transport (Figure 7 *d*). A northward shift of monsoon circulation in changed climate scenario[7] can be responsible for the anticyclonic anomalous flow over the Arabian Sea and resultant precipitation changes over southwest India. Insignificant rainfall change over Jharkhand and surrounding parts of Bihar, Orissa and Chhattisgarh is associated with weak PWAT changes.

In contrast, reduction in future orographic rainfall over the west coast of Goa, Karnataka and Kerala is associated with positive changes in PWAT and evaporation. Over this region, the effect of steep orography (Figure 7 *a*) on the circulation in the region appears to play a dominant role. Major features of mountain effect are found to be the rapid and systematic changes in climatic parameters such as temperature and precipitation over short distances[24] due to the complexity of their topography and associated

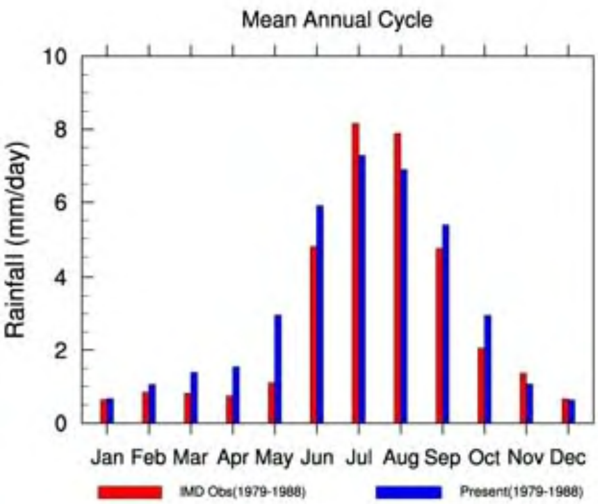

Figure 4. Climatological annual cycle of all-India (70–85°E; 0–35°N) rainfall from IMD data and 20-km simulation.

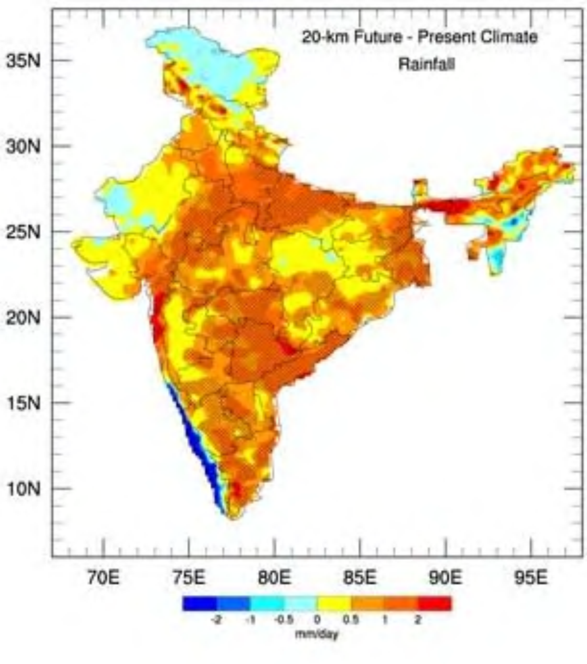

Figure 5. JJAS mean difference in rainfall between future projection and present-day simulation of the 20-km model. Differences significant at 95% level are stippled.

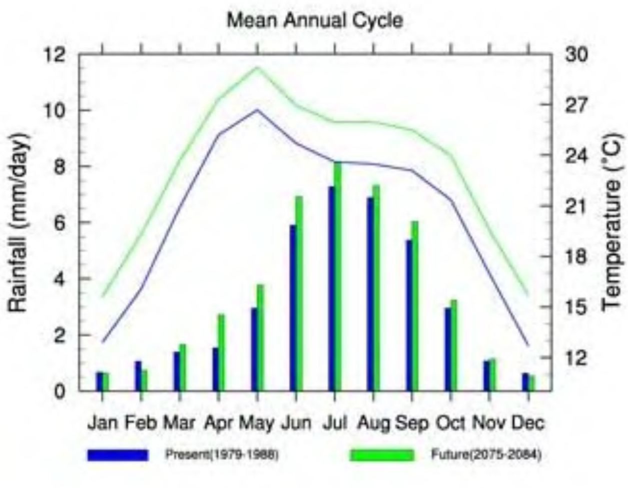

Figure 6. Climatological annual cycles of rainfall and surface temperature from the present-day simulation and the 21st century projection of the 20-km model.

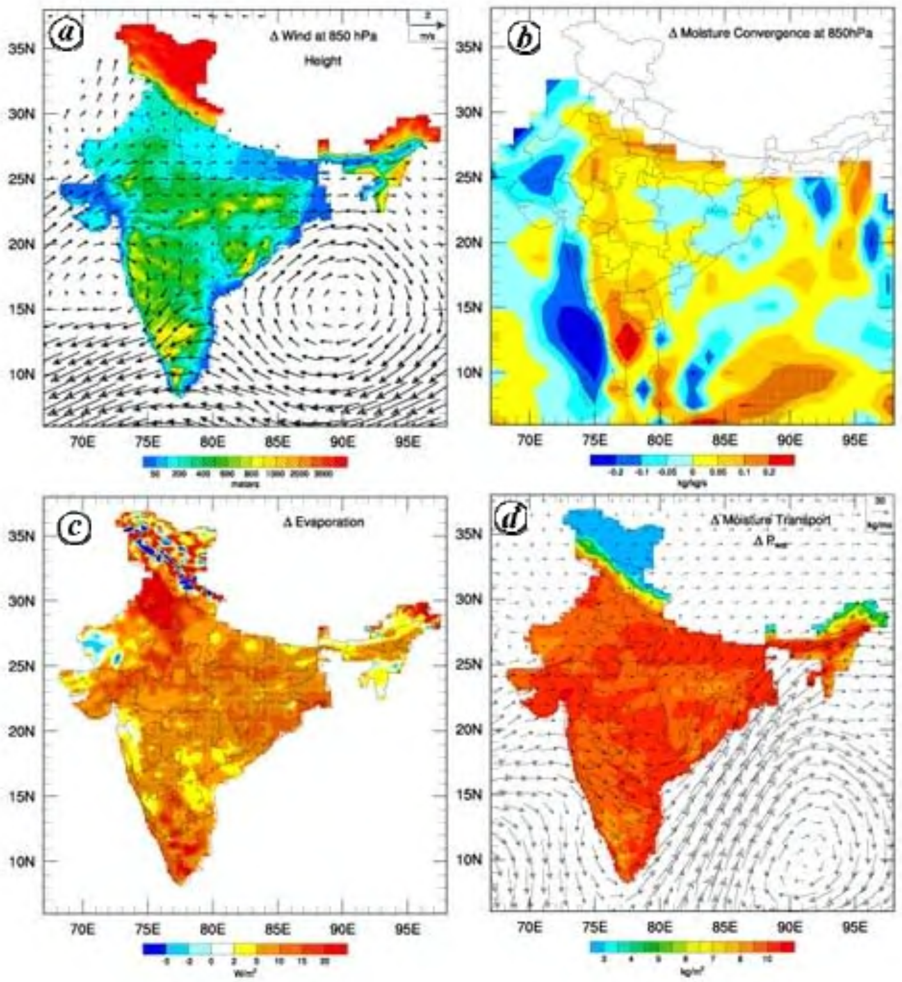

Figure 7. JJAS mean difference between future projection and present-day simulation of the 20-km model for (***a***) background orography overlain with 850 hPa wind vectors, (***b***) moisture convergence at 850 hPa, (***c***) evaporation (differences significant at 95% are stippled), and (***d***) precipitable water overlain with column-integrated moisture transport.

systematic variation of radiation and soil types. The 20-km model, unlike projections using models which are generally too crude to adequately represent the topographic details, projects spatially varying global warming impact over orographic regions, particularly over the Western Ghats and Northeast India. Height and zonal extent of orography are the largest in the southern half of the Western Ghats. Drastic reduction of westerly winds (Figure 7 *a*), local moisture convergence at 850 hPa (Figure 7 *b*) and increased northerly and easterly components in moisture transport (Figure 7 *d*) along the steep mountains dominate over the increased moisture effect in reducing local rainfall. The influence of the Western Ghats on upstream summer monsoon circulation was found to induce a southward component at all levels above the meridionally-oriented ridge, in a study using a quasi-geostrophic model for rotating stratified flow over obstacles[25].

As the atmospheric moisture content is the largest in the lower troposphere, the pattern of the vertically integrated atmospheric moisture transport (Figure 7 *d*) and low-level moisture convergence (Figure 7 *b*) resemble to a large extent, the wind pattern in the lower troposphere (Figure 7 *a*). In the source regions of atmospheric moisture, i.e. the southern subtropical Indian Ocean, the western Indian Ocean, the Arabian Sea, and the area east of Sri Lanka, the atmosphere takes up moisture, and the prevailing winds transport most of this moisture to the Indian subcontinent and further eastward. Over the Indian region, atmospheric moisture is thus transported eastward to the north. The westerly moisture transport continues over the Arabian Sea (except the Kerala and Karnataka coasts) and the Indian subcontinent, extending further into the central Indian region. Although the westerly wind changes at 850 hPa in the Indian region are only slightly enhanced in the future (Figure 7 *a*), the westerly atmospheric moisture transport in the total column is considerably increased in this region (Figure 7 *d*). Apparently, over central India, the Indian peninsula and some

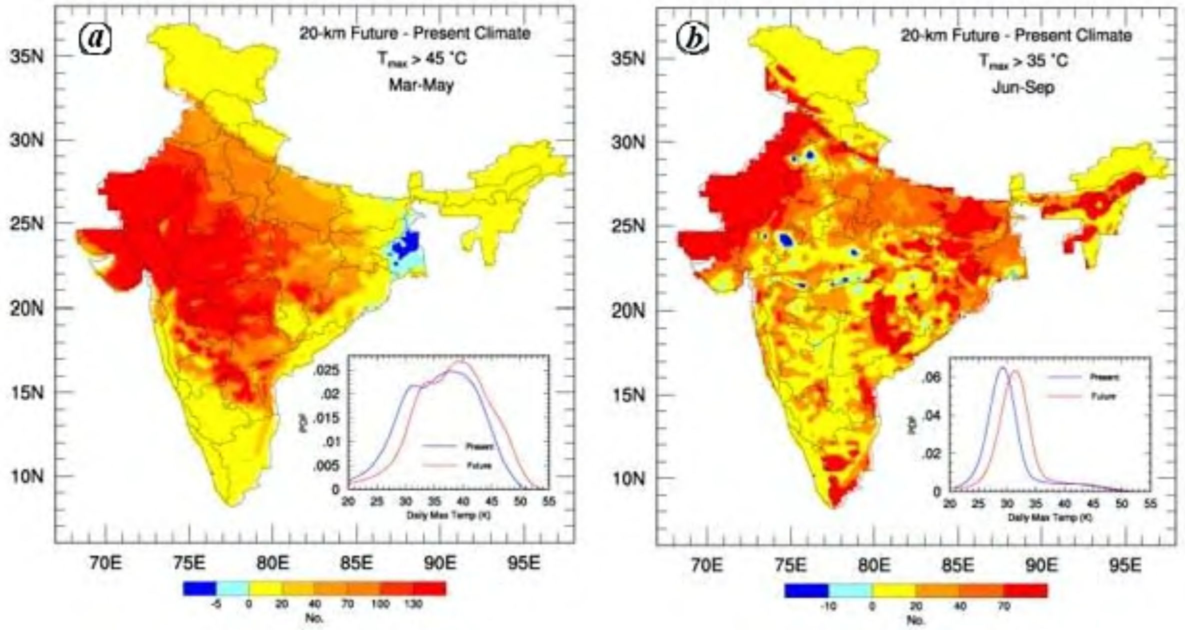

Figure 8. Difference in the number of days with maximum temperature greater than (***a***) 45°C in March–May and (***b***) 35°C in JJAS, between the future climate simulation and present-day simulation of the 20-km model. (Inset) Probability density functions (PDFs) of daily maximum temperature for the corresponding season. PDF bin size is 0.5°C.

parts of east India, the westerly changes of winds above the boundary layer contribute to the strengthening of the vertically integrated atmospheric moisture transport (not shown). Obviously, the future increase in the monsoon rainfall is due to the intensification of the atmosphere moisture flux into the central Indian region, which in turn is related to an additional increase in future atmospheric moisture content other than the increase due to increased specific humidity (and PWAT) under general warming.

Extreme events

Global warming can affect severe precipitation in a number of ways, including changing its frequency, intensity and timing of occurrence. Heavy precipitation episodes with subsequent surface run-off can inflict catastrophic property damage and loss of human life. Thus, it is important to determine how the character of such events could change in response to GHG-induced global warming in future. Recent studies[26] have shown that there are positive trends in the frequency of hot events[27] and heavy[28–30] or in some places reduced[31] precipitation events. However, it is not currently clear in what ways fine-scale feedbacks will modulate the regional and local responses to such large-scale changes. Therefore, the impact of climate warming on the regional distribution of extreme hot and severe precipitation events in India was investigated using the 20-km simulation.

As seen in the case of the annual cycle of monthly mean temperature, at the end of the 21st century, the 20-km simulation predicts an increase in both maximum and minimum temperature throughout the year by 3°C (not shown). In the peak summer months of March–May (before the heavy rainfall occurrence in the model), the number of extreme hot events (during the 10-year period) with temperature greater than 45°C will be increased in future (Figure 8 *a*). A pocket of reduced future occurrence of extreme hot events is seen in the West Bengal region. The orographic ascent of moisture-laden upstream wind will cause future increase in May rainfall, which can cause anomalous cooling of the surface over this region. During the monsoon season, increase in hot events is not as strong as in March/April, due to the feedback of widespread increased future rainfall. The pattern of number of extreme hot events with temperatures greater than 35°C in JJAS (Figure 8 *b*), appears to have been caused in part by the summer surface–moisture–precipitation feedback in the time-slice experiment. JJAS evaporation anomalies were weak or negative over northwest India and parts of the foothills and Northeast India (Figure 7 *c*), amplifying direct radiative heating by decreasing latent cooling over these areas. Conversely, JJAS precipitation and evaporation anomalies were positive over the north-central Indian region, muting direct radiative heating by increasing latent cooling. Also, the high orography over these regions acts as a barrier to the moisture-laden low-level winds from the Arabian Sea on the wind-ward side, which can contribute to a future increase in rainfall (Figure 7). These fine-scale precipitation–surface–moisture effects likely interacted with larger-scale climate processes. For instance, upper-level cyclonic flow was enhanced over the regions

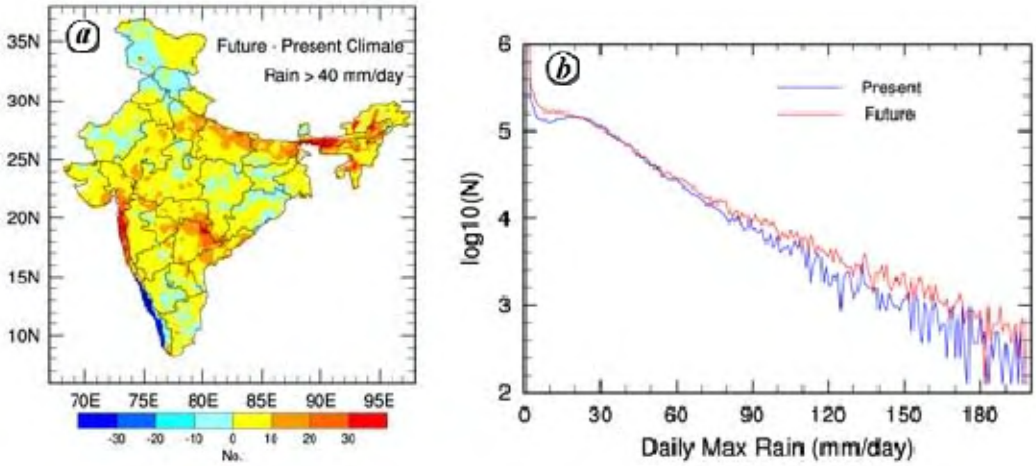

Figure 9. ***a***, Difference in the number of days with precipitation in JJAS greater than 40 mm/day between the future climate simulation and present-day simulation of the 20-km model. ***b***, Frequency distribution of daily maximum precipitation over India during JJAS.

with higher extreme hot events in future (not shown). Although such changes could have initiated the precipitation–soil moisture–evaporation feedback to enhance extreme hot events by increasing the surface temperature and reducing clouds and precipitation, it is also possible that the larger-scale changes resulted from the changes in surface moisture balance[32]. Although further studies are required to ascertain the full nature of these multiscale climate system interactions, this experiment indicates that such interactions could exert critical control on the regional response of extreme temperature events to anthropogenically elevated GHG concentrations.

Figure 8 also shows the probability density functions (PDFs) for the daily maximum temperature (T_{max}) for each of the two seasons. PDFs were produced by binning daily maximum temperature during a season for the 10-year period. The 1979–88 PDF is different (for mean and standard deviation) from the 2075–84 PDF for both seasons, indicating a clear shift towards warmer conditions at the end of the century. Differences between the distributions for the occurrence of warm days in the present-day climate and future warming climate, suggest that there will be warming of extreme maximum temperatures in future. Further, while there is no change in the high tail of the T_{max} PDF in future warming climate for June–September season (Figure 8 *b*), there exists an overall shift in the T_{max} PDF in future climate, for the pre-monsoon hot season of March–May (Figure 8 *a*).

For severe precipitation, many coastal areas also exhibited substantial increase in extreme event contribution, with peak positive anomalies of up to 30 days occurring over the west coast around Mumbai (Figure 9). The changes in extreme precipitation over this region were related to changes in large-scale atmospheric flow during summer (Figure 7). Enhanced anticyclonic flow at the upper levels increases when coupled with positive anomalies in tropospheric moisture and moisture transport (Figure 7). This suggests enhanced forcing of synoptic-scale ascent, and hence clouds and precipitation. The patterns of anomalies in extreme precipitation event frequency (Figure 9) were similar to those of seasonal mean precipitation (Figure 5), including peak anomalies in extreme precipitation event frequency of up to 30 days over the northern parts of the west coast, central India and the foothills of the Himalayas, extending up to eastern India. Frequency distributions of daily maximum rainfall from the present-day and future climate simulations are shown in Figure 9 *b*. Intensification of strong (>50 mm/day) and extreme (>100 mm/day) rainfall events occurs in the projected future climate. The pattern of precipitation anomalies (Figure 5) suggests a weakening of the orographic rain, due in large part to the changes in the extreme precipitation regime. For instance, positive anomalies in mean precipitation on the northern half of the west-coast regions were associated with large changes in extreme-event frequency (Figures 5 and 9). In contrast, over the northeast peninsular region, positive anomalies in seasonal mean precipitation were associated with negative changes in the frequency of extreme rainy days (Figure 9). In either case, mean precipitation increase could have resulted from GHG-related increases in the moisture content of air being carried across mountain ranges or from increases in up-slope flow on the lee side of those ranges.

Changes in precipitation extremes over the northeast peninsula also appeared to have been related to large-scale dynamics. Extreme-event anomalies were associated with positive anomalies in lower tropospheric moisture transport across the region (Figure 7). Such increase in moisture content can contribute to increase in convective available potential energy and therefore to enhanced convective precipitation. Over the east coast of the peninsula, strong positive anomalies of evaporation (Figure 7 *c*) and peak positive anomalies in moisture transport (Figure 7 *d*) likely contributed to the strong positive anomalies in extreme event frequency in future.

Concluding remarks

The super high-resolution present-day simulation reveals to a large extent the regional details of the Indian summer monsoon, which compares well with the distribution of observed precipitation. This indicates that the simulation of local aspects of the Indian summer monsoon benefits from the high resolution. Therefore, we can have better confidence in the validity of the prediction of future changes in the Indian summer monsoon on the basis of time-slice experiment.

Super high-resolution future scenario for the Indian summer monsoon shows spatially varying rainfall projection, with widespread increase in rainfall over the interior regions and significant reduction in orographic rainfall over the west coasts of Kerala and Karnataka, and the eastern hilly regions around Assam. Over orographic regions, the drastic reduction of wind by steep orography predominates over the moisture build-up effect (that causes enhanced rainfall over other parts) in reducing the rainfall. This indicates that monsoon rainfall is strongly controlled by parameterized physics and high-resolution processes which need to be resolved with adequately high resolution.

In some parts, rainfall changes appeared to be related to the enhancement of the atmospheric moisture content, which on the other hand, can be due to two reasons. First, general warming leads to an increase in the specific humidity in the atmosphere. And secondly, the 20-km simulation predicts an increase in evaporation over most of India, in particular in the central Indian region, over the northeast region as well as parts of the peninsula. Another factor contributing to the increase in monsoon precipitation may be an increase in precipitation efficiency, i.e. the rate at which precipitation is formed, in moist and warmer environment.

The model projects substantial spatially heterogeneous increase in both extreme hot and heavy rainfall events over most parts of India by the end of the century. While fine-scale surface moisture feedback influences the response of extreme hot events, extreme precipitation is influenced by fine-scale orography, evaporation, moisture content and circulation. Thus, the results indicate that consideration of fine-scale processes is critical for accurate assessment of local and regional-scale vulnerability to climate change.

The future changes in the seasonal mean monsoon and extremes of daily rainfall predicted by the 20-km simulation are plausible because of the capability of the model in simulating these aspects of the Indian summer monsoon quite realistically. However, it is to be noted that this is one of several possibilities to be expected in the future. For example, the projected results can be sensitive to the particular scenario for the atmospheric concentrations of the important GHGs in the future. Further, the projection can be sensitive to the initial and boundary conditions used. In order to assess the effects of these uncertainties, an ensemble of global time-slice simulations would have to be performed, with different climate models, initial and boundary forcings and different GHG scenarios prescribed.

1. Dentener, F. *et al.*, *Climate Change 2001: The Scientific Basis*, IPCC W.G.I., Cambridge University Press, New York, 2001, p. 50.
2. Meehl, G. A. *et al.*, How much more global warming and sea level rise? *Science*, 2005, **307**, 1769–1772.
3. Gadgil, S., Abrol, Y. P. and Rao, S., On growth and fluctuation of Indian food grain production. *Curr. Sci.*, 1999, **76**, 548–556.
4. Gadgil, S. and Gadgil, S., The Indian Monsoon, GDP and Agriculture. *Econ. Polit. Wkly*, 2006, **11**, 4887–4895.
5. Gadgil, S. and Sajani, S., Monsoon simulation in AMIP runs. *Climate Dyn.*, 1998, **14**, 659–689.
6. Meehl, G. A. and Washington, W. M., South Asian summer monsoon variability in a model with a doubled atmospheric carbon dioxide concentration. *Science*, 1993, **260**, 1101–1104.
7. Kitoh, A., Yukimoto, S., Noda, A. and Motoi, T., Simulated changes in the Asian summer monsoon at times of increased atmospheric CO_2. *J. Meteorol. Soc. Jpn.*, 1997, **75**, 1019–1031.
8. May, W., Simulated changes of the Indian summer monsoon under enhanced greenhouse gas conditions in a global time-slice experiment. *Geophys. Res. Lett.*, 2002, **29**, 1118.
9. Meehl, G. A. and Arblaster, J. M., Mechanisms for projected future changes in South Asian monsoon precipitation. *Climate Dyn.*, 2003, **21**, 659–675.
10. Stephenson, D. B., Douville, H. and Rupa Kumar, K., Searching for a fingerprint of global warming in the Asian summer monsoon. *Mausam*, 2001, **52**, 213–220.
11. Solomon, S. *et al.*, *Climate Change 2007: The Physical Science Basis*, IPCC W.G.I., Cambridge University Press, New York, 2007, p. 996.
12. Nakicenovic, N. *et al.*, IPCC special report on emission scenarios. IPCC W.G.I., Cambridge University Press, Cambridge, 2000, p. 599.
13. Lal, M. *et al.*, Future climate change: implications for Indian summer monsoon and its variability. *Curr. Sci.*, 2001, **81**, 1196–1207.
14. Rupakumar, K. *et al.*, High-resolution climate change scenarios for India for the 21st century. *Curr. Sci.*, 2005, **90**, 1–12.
15. Stephenson, D. B., Chauvin, F. and Royer, J.-F., Simulation of the Asian summer monsoon and its dependence on model horizontal resolution. *J. Meteorol. Soc. Jpn.*, 1998, **76**, 237–265.
16. Rajendran, K., Kitoh, A., Mizuta, R., Sajani, S. and Nakazawa, T., High resolution simulation of mean convection and its intraseasonal variability over the tropics in MRI/JMA 20-km mesh AGCM. *J. Climate*, 2008, **21**, 3722–3739.
17. Mizuta, R. *et al.*, 20-km-Mesh global climate simulations using JMA–GSM model: mean climate states. *J. Meteorol. Soc. Jpn.*, 2006, **84**, 165–185.
18. Kanamitsu, T., Tada, T., Kudo, T., Sato, N. and Isa, S., Description of the JMA operational spectral model. *J. Meteorol. Soc. Jpn.*, 1983, **61**, 812–828.
19. Randall, D. and Pan, D. M., Implementation of the Arakawa–Schubert cumulus parameterization with a prognostic closure. *Meteorol. Monogr.*, 1993, **46**, 145–150.

20. Yoshimura, H. and Matsumura, T., A two-time-level vertically conservative semi-Lagrangian semi-implicit double Fourier series AGCM. CAS/JSC WGNE Research Activities in Atm. and Oce. Modeling, 2005, **35**, 3.27–3.28.
21. Rayner, N. A. *et al.*, Global analyses of SST, sea ice and night marine air temperature since the late nineteenth century. *J. Geophys. Res. Atmos.*, 2003, **108**, 4407.
22. Rajeevan, M., Bhate, J., Kale, J. D. and Lal, B., High resolution daily gridded rainfall data for Indian region: analysis of break and active monsoon spells. *Curr. Sci.*, 2006, **91**, 296–306.
23. Huffman, G. J. *et al.*, The TRMM multisatellite precipitation analysis (TMPA): quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. *J. Hydrol. Meteorol.*, 2007, **8**, 38–55.
24. Becker, A. and Bugmann, H., Predicting global change impacts on mountain hydrology and ecology: integrated catchment hydrology/altitudinal gradient studies. IGBP Report 43, International Geosphere–Biosphere Programme, Stockholm, 1997.
25. Gadgil, S., Orographic effects on the southwest monsoon: a review. *Pure Appl. Geophys.*, 1977, **115**, 1413–1430.
26. Meehl, G. A. *et al.*, Global Climate Projections. In *Climate Change 2007: The Physical Science Basis*, IPCC (AR4), W.G.I., Cambridge University Press, New York, 2007, pp. 747–843.
27. Uchiyama, T., Mizuta, R., Kamiguchi, K., Kitoh, A. and Noda, A., Changes in temperature-based extremes indices due to global warming projected by a global 20-km-mesh atmospheric model. *SOLA*, *Meteorol. Soc. Jpn.*, 2006, **2**, 68–71.
28. Kamiguchi, K., Kitoh, A., Uchiyama, T., Mizuta, R. and Noda, A., Changes in precipitation-based extremes indices due to global warming projected by a global 20-km-mesh atmospheric model. *SOLA*, *Meteorol. Soc. Jpn.*, 2006, **2**, 64–67.
29. Palmer, T. N. and Raisanen, J., Quantifying the risk of extreme seasonal precipitation events in a changing climate. *Nature*, 2002, **415**, 512–514.
30. Goswami, B. N., Venugopal, V., Sengupta, D., Madhusoodanan, M. S. and Xavier, P. K., Increasing trend of extreme rain events over India in a warming environment. *Science*, 2006, **314**, 1442–1445.
31. Kitoh, A., Yatagai, A. and Alpert, P., First super-high-resolution model projection that the ancient 'Fertile Crescent' will disappear in this century. *Hydrol. Res. Lett.*, 2008, **2**, 1–4.
32. Pal, J. S. and Eltahir, E. A. B., A feedback mechanism between soil-moisture distribution and storm tracks. *Q. J. R. Meterol. Soc.*, 2003, **129**, 2279–2297.

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