Earth Syst. Dynam. Discuss., 4, 1–24, 2013
www.earth-syst-dynam-discuss.net/4/1/2013/
doi:10.5194/esdd-4-1-2013

Earth System Dynamics Discussions

Consistent increase in Indian monsoon rainfall and its variability across CMIP-5 models

A. Menon[1,2], A. Levermann[1,2], J. Schewe[1], J. Lehmann[1,2], and K. Frieler[1]

[1]Potsdam Institute for Climate Impact Research, 14473 Potsdam, Germany
[2]Institute of Physics, University of Potsdam, 14476 Potsdam, Germany

Received: 3 December 2012 – Accepted: 20 December 2012 – Published: 7 January 2013

Correspondence to: A. Menon (menon@pik-potsdam.de)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The possibility of an impact of global warming on the Indian monsoon is of critical importance for the large population of this region. Future projections within the Coupled Model Intercomparison Project Phase 3 (CMIP-3) showed a wide range of trends with varying magnitude and sign across models. Here the Indian summer monsoon rainfall is evaluated in 20 CMIP-5 models for the period 1850 to 2100. In the new generation of climate models a consistent increase in seasonal mean rainfall during the summer monsoon periods arises. All models simulate stronger seasonal mean rainfall in the future compared to the historic period under the strongest warming scenario RCP-8.5. Increase in seasonal mean rainfall is the largest for the RCP-8.5 scenario compared to other RCPs. The interannual variability of the Indian monsoon rainfall also shows a consistent positive trend under unabated global warming. Since both the long-term increase in monsoon rainfall as well as the increase in interannual variability in the future is robust across a wide range of models, some confidence can be attributed to these projected trends.

1 Introduction

Indian summer monsoon rainfall affects the lives of the large population of India by determining its water availability as well as food security (Parthasarathy et al., 1988; Auffhammer et al., 2006). About 80 % of the annual precipitation over India occurs during the monsoon months from June to September (Kripalani et al., 2003; Turner and Annamalai, 2012) and the released latent heat plays an important role in the atmospheric circulations as well as the radiative heat budget of the region (Webster, 1972). Even after achieving growth in service and industrial sectors, agriculture plays a vital role in the economy of the country as it is the predominant occupation in the rural regions of India. Extreme rainfall events and crop failure have adverse effects on the millions of inhabitants as well as the national economy. Hence it is of critical importance

ESDD
4, 1–24, 2013

to understand how the monsoon will change under future warming, in order to take sufficient adaptation measures.

Changes in the Indian monsoon under global warming are still a matter of intense scientific debate (e.g. Turner and Annamalai, 2012; Sabade et al., 2011). An analysis of observational data for the past 130 yr shows no clear evidence of the effect of global warming on Indian monsoon rainfall strength and its interannual variability (Kripalani et al., 2003; Mooley and Parthasarathy, 1984; Guhathakurta and Rajeevan, 2008). While no clear trend can be found for monsoon rainfall averaged over India as a whole (Mooley and Parthasarathy, 1984; Guhathakurta and Rajeevan, 2008), observations show significant trends in rainfall over several smaller regions of the country (Jagannathan and Parthasarathy, 1973; Kumar et al., 1992; Guhathakurta and Rajeevan, 2008). Some subdivisions of India show a positive trend in monsoon rainfall, some show a significant negative trend where as there are some small regions that do not show any significant trend (Kumar et al., 1992; Guhathakurta and Rajeevan, 2008). Observations based on a $1^{\circ} \times 1^{\circ}$ gridded daily dataset suggests that monsoon rainfall in a homogeneous region over central India shows no significant long term trend during the past few decades (Goswami et al., 2006). Even though the frequency and magnitude of extreme events show a rising trend over central India (Rajeevan et al., 2006; Goswami et al., 2006), a significant trend is absent in seasonal mean rainfall. This is attributed to a decrease in the frequency of moderate events (Goswami et al., 2006). A study by Fu et al. (1999) shows an increase in the Indian monsoon rainfall in relation to an abrupt warming around the year 1920.

By contrast several ice core records and speleothem records show a decreasing trend in the Indian summer monsoon (ISM) rainfall in the last century. ISM rainfall intensity measured from the Dasuopu ice core shows a decreasing trend during the past century (Duan et al., 2004; Thompson et al., 2000). ISM intensity from speleothem record over southern Arabia also shows a decreasing trend over the past century which is attributed to the increase in sea surface temperature over the Indian Ocean (Burns

ESDD
4, 1–24, 2013

et al., 2002). The ISM intensity reconstructed from a tree ring record over Tibetan Plateau also shows a decreasing trend from 1860 to present (Xu et al., 2012).

Models have their own limitations in capturing the regional rainfall accurately (Turner and Annamalai, 2012). While some model studies find very little impact on the all India monsoon rainfall in transient and time-slice climate change experiments (Mahfouf et al., 1994; Timbal et al., 1995; Lal et al., 1994, 1995), some others suggest an increase in the mean Indian monsoon precipitation as well as the interannual variability under enhanced warming (Meehl and Washington, 1993; Kitoh et al., 1997; Hu et al., 2000; Lal et al., 2001; Cubasch et al., 2001; May, 2002; Fan et al., 2012). The Hamburg COSMOS model shows a complex behavior with changing skewness of the rainfall distribution and an associated increase in monsoon failure events (Schewe and Levermann, 2012). A subset of the IPCC AR4 models suggest an increase in the strength of the monsoon precipitation (Kripalani et al., 2007), whereas the monsoon circulation is projected to weaken (Tanaka et al., 2005; Ueda et al., 2006), while earlier studies using slab ocean models suggest a strengthening of monsoon precipitation as well as the circulation (Zhao and Kellogg, 1988). The projected precipitation from few CMIP-3 models which are considered more realistic show a range of trends including negative trends in monsoon rainfall by 2100 (Turner and Annamalai, 2012) under the SRES A1B scenario. More recent studies consider the effect of black carbon aerosols on south Asian monsoon (Meehl et al., 2008; Ramanathan et al., 2005) and suggest that a "business as usual" black carbon scenario can result in about 25 % decrease in mean monsoon rainfall by the mid-21st century. Some of the models also show a projected increase in the rainfall interannual variability. However, the seasonal projection of interannual variability of South Asian monsoon rainfall is a major challenge (Sperber and Palmer, 1996; Goswami, 1998).

In order to capture the full range of possible future scenarios, including mitigation strategies, the Representative Concentration Pathways (RCP) have been developed as a basis for the IPCC fifth assessment report. There are four RCPs categorized according to their approximate radiative forcing in the year 2100. We use data from RCP

ESDD
4, 1–24, 2013

model simulations in order to study the projected changes in the mean and variability of ISM rainfall in future. In this study, we examine the mid-nineteenth century to the end of the twenty-first century variability of ISM rainfall simulated by twenty of the models that participated in the CMIP-5. Section 2.1 shows a brief model evaluation of the Indian summer monsoon mean rainfall. Section 2.2 gives the trend in all India mean monsoon rainfall and Sect. 2.3 its interannual variability in the RCP based simulations. The results are discussed in Sect. 3.

2 Results

2.1 Model evaluation

In this study, we use simulated rainfall obtained from 20 of the models that participated in the CMIP-5. Models are chosen according to the availability of the data: only those models are analyzed for which data for historic period (1850–2005), RCP-8.5 and at least one more scenario were available at the time of the study. The model information is summarized in Table 1. The range in global mean temperature as constrained by past climate observations allow for a wide range of responses within an RCP (Schewe et al., 2011). Historical simulations are based on observed concentrations of green house gases and reconstructed aerosol emissions. Future projections are based on the four Representative Concentration Pathways (RCP) (Moss et al., 2010). RCP-8.5 is the pathway for which radiative forcing reaches 8.5 $W m^{-2}$ by 2100. Similarly RCP-4.5 and RCP-6.0 represent the pathways for which radiative forcing reach 4.5 and 6 $W m^{-2}$ in 2100. RCP-2.6 peaks in radiative forcing at 3 $W m^{-2}$ before 2100 and declines afterwards reaching 2.6 $W m^{-2}$ in 2100. India as a whole (all-India) is selected for the study and data is masked over all-India region. Mean rainfall is obtained by averaging the June-September (JJAS) rainfall over the all-India land region and denoted as all-India summer monsoon rainfall (AISMR). The all-India rainfall dataset from Parthasarathy et al. (1994) is used to compare the seasonal mean rainfall from models

ESDD
4, 1–24, 2013

during historical periods with observations. The observational data covers a period from 1871 to 2004.

In order to identify models with a potentially realistic representation of the monsoon rainfall, we compare their long-term seasonal mean with the observed precipitation (Parthasarathy et al., 1994) for the period 1871 to 2004 (Fig. 1). The climatological mean rainfall from observations is 7.1 mm day^{-1}, with a standard deviation of 0.7 mm day^{-1}. About half of the models capture seasonal mean rainfall within twice the standard deviation (vertical dashed lines in Fig. 1) of the observed mean for the period 1871 to 2004. Models like MIROC-ESM and MIROC-ESM-CHEM show a slight overestimation of seasonal mean rainfall, while models like CSIRO-Mk3 and MRI-CGCM3 show an underestimation. The error bars in Fig. 1 represent long-term standard deviations for each of the models under consideration and the values vary from 0.4 to 0.7 for various models. NorESM1-M and GFDL-CM3 capture the mean rainfall closest to the observed mean. The spatial patterns of rainfall during the monsoon season as simulated by all the models are shown in Fig. 2. The models which underestimate the climatological rainfall do not capture the spatial pattern of monsoon well. CSIRO-Mk3.6.0 and MRI-CGCM3 model more rainfall over the east coast of Bay of Bengal and the tropical Indian Ocean. They show very low rainfall over the all-India region. Similarly, the Hadley Centre models (HadGEM2-CC and HadGEM2-ES) and the Institute Pierre Simon Laplace models (IPSL-CM5A-LR and IPSL-CM5A-MR) capture very little rainfall over the all-India region with comparatively higher rainfall over the Himalayan mountains and the Bay of Bengal.

As discussed by Levermann et al. (2009) the monsoon region can enter a climatic regime in which latent heat transport towards land is insufficient to sustain a monsoon circulation which may lead to abrupt monsoon transition (Zickfeld et al., 2005) as observed in the past (Schewe et al., 2012; Cook et al., 2010; Sinha et al., 2011). While observations clearly show that the ISM is currently within the active monsoon regime it is possible that the CMIP-5 models which exhibit a very weak ISM are outside this regime. In this study, we decide to interpret the results of the future monsoon evolution

ESDD
4, 1–24, 2013

from models with historical mean precipitation below the observed mean minus twice its standard deviation (5.7 mm day^{-1}) as well as the ones with an unrealistic spatial pattern, with care as they are less likely to provide a good approximation of the real evolution. Full information is, however, provided for all models.

2.2 Long term trend in Indian monsoon rainfall under various RCP warming scenarios

AISMR is analyzed for the four RCPs (Figs. 3 and 4). AISMR shows a clear positive long-term trend in all the models under the RCP-8.5 scenario whereas the long term trend is small under RCP-2.6 scenario (Fig. 3). And even for the lowest concentration scenario RCP-2.6, only three out of twenty models show a small decreasing trend in rainfall. The percentage changes in the AISMR (δmean) by the end of the 21st century (2070–2100) with respect to the pre-industrial period (1870–1900) under all the RCPs are summarized in Fig. 5. Models listed in the upper panel of Fig. 5 are those that capture the AISMR well with mean rainfall for the historic period (1871–2004) falling within twice the standard deviation (0.7 mm day^{-1}) of the observed mean (7.1 mm day^{-1}). The relative increase in mean monsoon rainfall is less (up to < 15 %) for these models compared to the ones with a much lower historic mean. The significance of δmean values are obtained from a Student's t-test and it shows that 19 out of the 20 models show a significant increase in δmean under the RCP-8.5 scenario at a 95 % confidence level. MPI-ESM-LR shows a slight increase in the AISMR during the end of the twenty first century compared to the pre-industrial period under RCP-8.5 scenario, which is not significant at a 95 % confidence level. MRI-CGCM3 shows the maximum increase in AISMR of about 60 % by the end of the twenty-first century compared to the end of the nineteenth century for RCP-8.5 and RCP-6.0 scenarios. But as shown in Fig. 2, MRI-CGCM3 does not capture the spatial pattern of AISMR realistically. All the models show a consistent increase in δ mean at 95 % confidence level under all the scenarios. None of the negative values of δmean are significant at a 95 % confidence level.

ESDD
4, 1–24, 2013

In summary, a consistent picture of an increasing seasonal mean rainfall under global warming arises from the CMIP-5 intercomparison.

Due to the relatively fast adjustment time of the atmosphere, most models show little path-dependence of the ISM change, in the sense that changes are very similar for the same increase in global mean temperature compared to pre-industrial period independent of which scenario was followed. Therefore it is possible to provide the percentage change in AISMR as a function of global mean temperature change or AISMR-change per degree of warming. It is given in Fig. 6. RCP-2.6 scenario is not considered here as the temperature changes are very low under this scenario. Considering only trends which are significant at a 95 % confidence level, all models project an increase in the AISMR with an increase in temperature. The trends are comparatively smaller for the more realistic models. Figure 7 shows the histogram of the trends per degree Kelvin. The relative changes in AISMR per degree of warming range from 1–19 % K^{-1}. 66.5 % of the trends for an ensemble of all models lies in the range of 1–9 % K^{-1} with a median increase of 3.2 % K^{-1}. While considering only the more realistic models in the upper panel of Fig. 6, 66.5 % of the relative changes in AISMR per degree of warming is in the range 1.3–3 % K^{-1}. These models show a median increase of 2.3 % K^{-1}. This value is closer to the projected increase in global mean precipitation per degree of warming (2.2 ± 0.52 % K^{-1}) given by Frieler et al. (2011) for CMIP-3.

2.3 Future evolution of interannual variability

The percentage changes in long-term standard deviation for the period 2050–2100 with respect to 1900–1950 are used to analyze how the interannual variability evolves under global warming. The standard deviation of seasonal mean rainfall shows a positive trend in most of the models under the RCP-8.5 scenario (Fig. 8) indicating an increase in interannual variability in the future. Out of the 20 models under consideration, 17 models show an increase in interannual variability under this scenario. MIROC-ESM-CHEM, HadGEM2-CC and IPSL-CM5A-LR show a slight decrease (< 10 %) in standard deviation by the second half of the twenty first century compared to the

ESDD
4, 1–24, 2013

first half of the twentieth century. It has to be noted that most models show an increase in interannual variability in the future under various concentration pathways. The largest increase is simulated by FGOALS-s2, BCC-CSM1.1 and HadGEM2-ES under the RCP-8.5 scenario. CCSM4 shows a decrease in variability under all the scenarios except RCP-8.5. GFDL-ESM2G, GFDL-ESM2M, FGOALS-s2, HadGEM2-ES and MRI-CGCM3 show an increase in interannual variability under all the four RCPs. While HadGEM2-ES captures an increase in interannual variability under all the four scenarios, HadGEM2-CC captures a decrease in interannual variability in the two available scenarios at the time of the study. But as shown earlier in Fig. 2 these two models did not capture the spatial pattern of monsoon rainfall reasonably well. Out of the few negative trends of interannual variability, most of them are under the RCP-2.6 and RCP-4.5 scenarios. The interannual variability has a clear positive trend in most of the models under the higher scenarios RCP-6.0 and RCP-8.5.

3 Discussion and conclusions

The future evolution of Indian summer monsoon rainfall and its interannual variability have been analyzed based on global coupled model simulations under the RCP scenarios. This study analyzes whether previous inconsistency between models regarding the long term trend in the Indian summer monsoon rainfall under transient warming scenarios still exists in the CMIP-5 generation of climate models. By comparison of the models' performance with the all-India mean monsoon rainfall for historic period from observations and examination of the spatial patterns of rainfall, we consider some models as more realistic and put more emphasis on them compared to the ones with a very weak monsoon rainfall. For these models a consistent picture arises: Indian summer monsoon rainfall increases under future warming. All models except MPI-ESM-LR simulate the maximum positive trend in mean monsoon rainfall under the highest concentration pathway RCP-8.5. This result agrees with Fu et al. (1999) who

ESDD
4, 1–24, 2013

find an increase in the Indian monsoon rainfall during abrupt warming and suggests a relationship between global temperature increase and the Indian monsoon rainfall.

An increase in seasonal mean precipitation can occur due to changes in the intertropical convergence zone (Hu et al., 2000). In coupled models under global warming it has been attributed predominantly to an increase in the water holding capacity of the atmosphere with increase in surface temperature (Trenberth, 1998). For example, Meehl et al. (2005) suggest the increase in water vapor content associated with an increase in sea surface temperature in a warmer climate as the reason for enhanced precipitation in the tropics in some IPCC AR4 models. The atmospheric water vapor is projected to increase by 12–16 % over large parts of India (Kripalani et al., 2007) at the time of CO_2 doubling. This increased moisture content can lead to enhanced precipitation. In this study, we see that the increase in AISMR per degree change in temperature is about 2.3 % K^{-1} which is similar to the projected increase in global mean precipitation per degree change in temperature in CMIP-3 (Frieler et al., 2011).

A second trend that emerges consistently across models in CMIP-5 is an increase in interannual variability. The monsoon variability shows a general increasing trend under various RCPs in most of the models. Rainfall variability is particularly important for societal and economic adaptation strategies, defining the required year-to-year flexibility for agricultural management, disaster preparedness, etc. Further studies are needed to understand the physical reasons behind the increase in interannual variability. One of the reasons attributed to the increase is the increase in ENSO variability in future which is transmitted to south Asian monsoon rainfall through the Walker cell (Hu et al., 2000; Schewe and Levermann, 2012). Another possibility is that the enhanced variability is attributed to the increase in tropical Indian Ocean and Pacific sea surface temperatures, irrespective of the ENSO variability (Meehl and Arblaster, 2003). According to Meehl and Arblaster (2003) the Pacific Ocean SST plays the dominant role where as the Indian Ocean plays a secondary role in monsoon interannual variability. Also an observations-based study suggests that the increase in interannual variability of Indian summer monsoon is associated with warmer land and ocean temperatures

ESDD
4, 1–24, 2013

(Meehl and Washington, 1993). We do not aim for a consistent physical understanding across all climate models here, but concluded that most of the models that participated in the CMIP-5 show a positive trend in monsoon mean rainfall as well as its interannual variability under future warming. It can be noted that all the trends in AISMR which are significant at a 95 % confidence level are positive. The long-term intensification of monsoon rainfall, but even more so the intensification of monsoon variability, require long-term adaptation strategies in coping with future climate change in India.

Acknowledgements. This work was funded by the BMBF PROGRESS project (support code 03IS2191B). We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups (listed in Table 1) for producing and making available their model output. For CMIP the US Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

References

Auffhammer, M., Ramanathan, V., and Vincent, J. R.: Integrated model shows that atmospheric brown clouds and greenhouse gases have reduced rice harvests in India, P. Natl. Acad. Sci., 103, 19668–19672, 2006. 2

Burns, S., Fleitmann, D., Mudelsee, M., Neff, U., Matter, A., and Mangini, A.: A 780-year annually resolved record of Indian Ocean monsoon precipitation from a speleothem from south Oman, J. Geophys. Res., 107, 4434, doi:10.1029/2001JD001281, 2002. 3

Cook, E. R., Anchukaitis, K. J., Buckley, B. M., Di Arrigo, R. D., Jacoby, G. C., and Wright, W. E.: Asian Monsoon Failure and Megadrought During the Last Millennium, Science, 328, 486–439, 2010. 6

Cubasch, U., Meehl, G., Boer, G., Stouffer, R., Dix, M., Noda, A., Senior, C., Raper, S., and Yap, K.: Projections of future climate change, in: Climate Change 2001: The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel, edited by: Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., Van der Linden, P. J., Dai, X., Maskell, K., and Johnson, C. A., Cambridge University Press, UK, 526–582, 2001. 4

Duan, K., Yao, T., and Thompson, L.: Low-frequency of southern Asian monsoon variability using a 295-year record from the Dasuopu ice core in the central Himalayas, Geophysical Research Letters, 31, L16 209, 2004. 3

Fan, F., Mann, M. E., Lee, S., and Evans, J. L: Future changes in the south Asian summer monsoon: An analysis of the CMIP3 multi-model projections, J. Climate, 25, 3909–3928, 2012. 4

Frieler, K., Meinshausen, M., von Deimling, T., Andrews, T., and Forster, P.: Changes in global-mean precipitation in response to warming, greenhouse gas forcing and black carbon, Geophys. Res. Lett., 38, L04702, doi:10.1029/2010GL045953, 2011. 8, 10

Fu, C., Diaz, H., Dong, D., and Fletcher, J.: Changes in atmospheric circulation over Northern Hemisphere oceans associated with the rapid warming of the 1920s, Int. J. Climatol., 19, 581–606, 1999. 3, 9

Goswami, B. N.: Interannual variations of Indian summer monsoon in a GCM: External conditions versus internal feedbacks, J. Climate, 11, 501–522, 1998. 4

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, 314, 1442–1445, 2006. 3

Guhathakurta, P. and Rajeevan, M.: Trends in the rainfall pattern over India, Int. J. Climatol., 28, 1453–1469, 2008. 3

Hu, Z., Latif, M., Roeckner, E., and Bengtsson, L.: Intensified Asian summer monsoon and its variability in a coupled model forced by increasing greenhouse gas concentrations, Geophys. Res. Lett., 27, 2681, doi:10.1029/2000GL011550, 2000. 4, 10

Jagannathan, P. and Parthasarathy, B.: Trends and periodicities of rainfall over India, Monthly Weather Review, 101, 371–375, 1973. 3

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., 75, 1019–1031, 1997. 4

Kripalani, R., Kulkarni, A., Sabade, S., and Khandekar, M.: Indian monsoon variability in a global warming scenario, Nat. Hazards, 29, 189–206, 2003. 2, 3

Kripalani, R. H., Oh, J. H., Kulkarni, A., Sabade, S. S., and Chaudhari, H. S.: South Asian summer monsoon precipitation variability: Coupled climate model simulations and projections under IPCC AR4, Theor. Appl. Climatol., 90, 133–159, doi:10.1007/s00704-006-0282-0, 2007. 4, 10

ESDD
4, 1–24, 2013

Kumar, K., Pant, G., Parthasarathy, B., and Sontakke, N.: Spatial and subseasonal patterns of the long-term trends of Indian summer monsoon rainfall, Int. J. Climatol., 12, 257–268, 1992. 3

Lal, M., Cubasch, U., and Santer, B.: Effect of global warming on Indian monsoon simulated with a coupled ocean-atmosphere general circulation model, Current Sci., 66, 430–438, 1994. 4

Lal, M., Cubasch, U., Voss, R., and Waszkewitz, J.: Effect of transient increase in greenhouse gases and sulphate aerosols on monsoon climate, Current Sci., 69, 752–763, 1995. 4

Lal, M., Nozawa, T., Emori, S., Harasawa, H., Takahashi, K., Kimoto, M., Abe-Ouchi, A., Nakajima, T., Takemura, T., and Numaguti, A.: Future climate change: Implications for Indian summer monsoon and its variability, Current Sci., 81, 1196–1207, 2001. 4

Levermann, A., Schewe, J., Petoukhov, V., and Held, H.: Basic mechanism for abrupt monsoon transitions, P. Natl. Acad. Sci., 106, 20572–20577, 2009. 6

Mahfouf, J., Cariolle, D., Royer, J., Geleyn, J., and Timbal, B.: Response of the Meteo-France climate model to changes in CO_2 and sea surface temperature, Clim. Dynam., 9, 345–362, 1994. 4

May, W.: Simulated changes of the Indian summer monsoon under enhanced greenhouse gas conditions in a global time-slice experiment, Geophys. Res. Lett., 29, 1118, doi:10.1029/2001GL013808, 2002. 4

Meehl, G. A. and Arblaster, J. M.: Mechanisms for projected future changes in south Asian monsoon precipitation, Clim. Dynam., 21, 659–675, 2003. 10

Meehl, G. A., Arblaster, J. M., and Tebaldi, C.: Understanding future patterns of increased precipitation intensity in climate model simulations, Geophys. Res. Lett., 32, L18719, doi:10.1029/2005GL023680, 2005. 10

Meehl, G. A., Arblaster, J. M., and Collins, W. D: Effects of black carbon aerosols on the Indian monsoon, J. Climate, 21, 2869–2882, 2008. 4

Meehl, G. A. and Washington, W. M.: South Asian Summer Monsoon Variability in a Model with Doubled Atmospheric Carbon Dioxide Concentration, Science, 260, 1101–1104, 1993. 4, 11

Mooley, D. and Parthasarathy, B.: Fluctuations in All-India summer monsoon rainfall during 1871–1978, Climatic Change, 6, 287–301, 1984. 3

Moore, J., Grinsted, A., and Jevrejeva, S.: New tools for analyzing time series relationships and trends, EOS Trans. Am. Geophys. Union, 86, 226, 2005. 19

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., van Vuuren, D. P., Carter, T. R., Emori, S., Kainuma, M., Kram, T., Meehl, G. A., Mitchell, J. F. B., Nakicenovic, N., Riahi, K., Smith, S. J., Stouffer, R. J., Thomson, A. M., Weyant, J. P., and Wilbanks, T. J.: The next generation of scenarios for climate change research and assessment, Nature, 463, 747–756, 2010. 5

Parthasarathy, B., Munot, A., and Kothawale, D.: Regression model for estimation of Indian foodgrain production from summer monsoon rainfall, Agr. Forest Meteorol., 42, 167–182, doi:10.1016/0168-1923(88)90075-5, 1988. 2

Parthasarathy, B., Munot, A., and Kothawale, D.: All-India monthly and seasonal rainfall series: 1871–1993, Theor. Appl. Climatol., 49, 217–224, 1994. 5, 6

Rajeevan, M., Bhate, J., Kale, J. A., and Lal, B.: High resolution daily gridded rainfall data for the Indian region: Analysis of break and active monsoon spells, Current Sci., 91, 296–306, 2006. 3

Ramanathan, V., Chung, C., Kim, D., Bettge, T., Kiehl, J. T., Washington, W. M., Fu, Q., Sikka, D. R., and Wild, M.: Atmospheric brown clouds: Impacts on South Asian climate and hydrological cycle, P. Natl. Acad. Sci., 102, 5326–5333, 2005. 4

Sabade, S., Kulkarni, A., and Kripalani, R.: Projected changes in South Asian summer monsoon by multi-model global warming experiments, Theor. Appl. Climatol., 103, 543–565, 2011. 3

Schewe, J. and Levermann, A.: A statistically predictive model for future monsoon failure in India, Environ. Res. Lett., 7, 044023, doi:10.1088/1748-9326/7/4/044023, 2012. 4, 10

Schewe, J., Levermann, A., and Meinshausen, M.: Climate change under a scenario near 1.5 °C of global warming: monsoon intensification, ocean warming and steric sea level rise, Earth Syst. Dynam., 2, 25–35, doi:10.5194/esd-2-25-2011, 2011. 5

Schewe, J., Levermann, A., and Cheng, H.: A critical humidity threshold for monsoon transitions, Clim. Past, 8, 535–544, doi:10.5194/cp-8-535-2012, 2012. 6

Sinha, A., Berkelhammer, M., Stott, L., Mudelsee, M., Cheng, H., and Biswas, J.: The leading mode of Indian Summer Monsoon precipitation variability during the last millennium, Geophys. Res. Lett., 38, L15703, doi:10.1029/2011GL047713, 2011. 6

Sperber, K. and Palmer, T.: Interannual tropical rainfall variability in general circulation model simulations associated with the Atmospheric Model Intercomparison Project, J. Climate, 9, 2727–2750, 1996. 4

ESDD
4, 1–24, 2013

Tanaka, H., Ishizaki, N., and Nohara, D.: Intercomparison of the intensities and trends of Hadley, Walker and monsoon circulations in the global warming projections, SOLA, 1, 77–80, 2005. 4

Thompson, L., Yao, T., Mosley-Thompson, E., Davis, M., Henderson, K., and Lin, P.: A high-resolution millennial record of the South Asian monsoon from Himalayan ice cores, Science, 289, 1916–1919, 2000. 3

Timbal, B., Mahfouf, J., Royer, J., and Cariolle, D.: Sensitivity to prescribed changes in sea surface temperature and sea ice in doubled carbon dioxide experiments, Clim. Dynam., 12, 1–20, 1995. 4

Trenberth, K.: Atmospheric moisture residence times and cycling: Implications for rainfall rates and climate change, Climatic Change, 39, 667–694, 1998. 10

Turner, A. and Annamalai, H.: Climate change and the South Asian summer monsoon, Nat. Climate Change, 2, 587–595, 2012. 2, 3, 4

Ueda, H., Iwai, A., Kuwako, K., and Hori, M.: Impact of anthropogenic forcing on the Asian summer monsoon as simulated by eight GCMs, Geophys. Res. Lett., 33, L06703, doi:10.1029/2005GL025336, 2006. 4

Webster, P.: Response of the tropical atmosphere to local, steady forcing, Mon. Weather Rev., 100, 518–541, 1972. 2

Xu, H., Hong, Y., and Hong, B.: Decreasing Asian summer monsoon intensity after 1860 AD in the global warming epoch, Clim. Dynam., 39, 2079–2088, doi:10.1007/s00382-012-1378-0, 2012. 4

Zhao, Z. and Kellogg, W.: Sensitivity of soil moisture to doubling of carbon dioxide in climate model experiments, Part II: The Asian monsoon region, J. Climte, 1, 367–378, 1988. 4

Zickfeld, K., Knopf, B., Petoukhov, V., and Schellnhuber, H. J.: Is the Indian summer monsoon stable against global change?, Geophys. Res. Lett., 32, L15707, doi:10.1029/2005GL022771, 2005. 6

ESDD

4, 1–24, 2013

Table 1. Details of the data availability for the 20 comprehensive models used in the study. Only those models are selected for which data for historic period, RCP-8.5 and at least one more scenario is available at the time of the study.

Modeling Center (Group)	Model	RCP-8.5	RCP-6.0	RCP-4.5	RCP-2.6
Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia	ACCESS1.0	Y	N	Y	N
Beijing Climate Center,China Meteorological Administration	BCC-CSM1.1	Y	Y	Y	Y
Canadian Centre for Climate Modelling and Analysis	CanESM2	Y	N	Y	Y
National Center for Atmospheric Research	CCSM4	Y	Y	Y	Y
Centre National de Recherches Meteorologiques/ Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique	CNRM-CM5	Y	N	Y	Y
Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	CSIRO-Mk3.6.0	Y	Y	Y	Y
LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences	FGOALS-s2	Y	Y	Y	Y
NOAA Geophysical Fluid Dynamics Laboratory	GFDL-CM3	Y	Y	N	Y
	GFDL-ESM2G	Y	Y	Y	Y
	GFDL-ESM2M	Y	Y	Y	Y
Met Office Hadley Centre	HadGEM2-CC	Y	N	Y	N
	HadGEM2-ES	Y	Y	Y	Y
Institute for Numerical Mathematics	INM-CM4	Y	N	Y	N
Institut Pierre-Simon Laplace	IPSL-CM5A-LR	Y	Y	Y	Y
	IPSL-CM5A-MR	Y	N	Y	Y
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC-ESM	Y	Y	Y	Y
	MIROC-ESM-CHEM	Y	Y	Y	Y
Max Planck Institute for Meteorology	MPI-ESM-LR	Y	N	Y	Y
Meteorological Research Institute	MRI-CGCM3	Y	Y	Y	Y
Norwegian Climate Centre	NorESM1-M	Y	Y	Y	Y

ESDD
4, 1–24, 2013

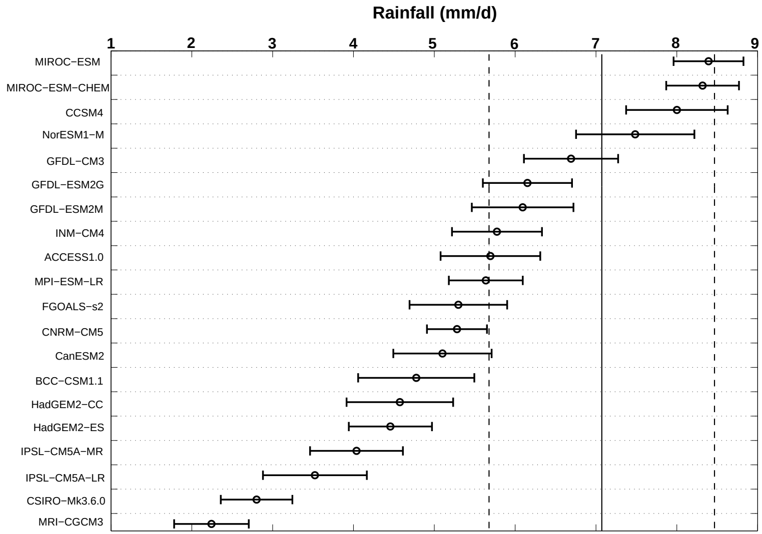

Fig. 1. JJAS mean rainfall over all India region from different models for the historic period. The black vertical line shows the all India mean monsoon rainfall from observations for the period 1871–2004 and the dashed lines show mean plus/minus twice the standard deviation of all India mean rain. Circles with error bars represent mean and mean plus/minus one standard deviation for the 20 comprehensive models from 1871 to 2004.

ESDD
4, 1–24, 2013

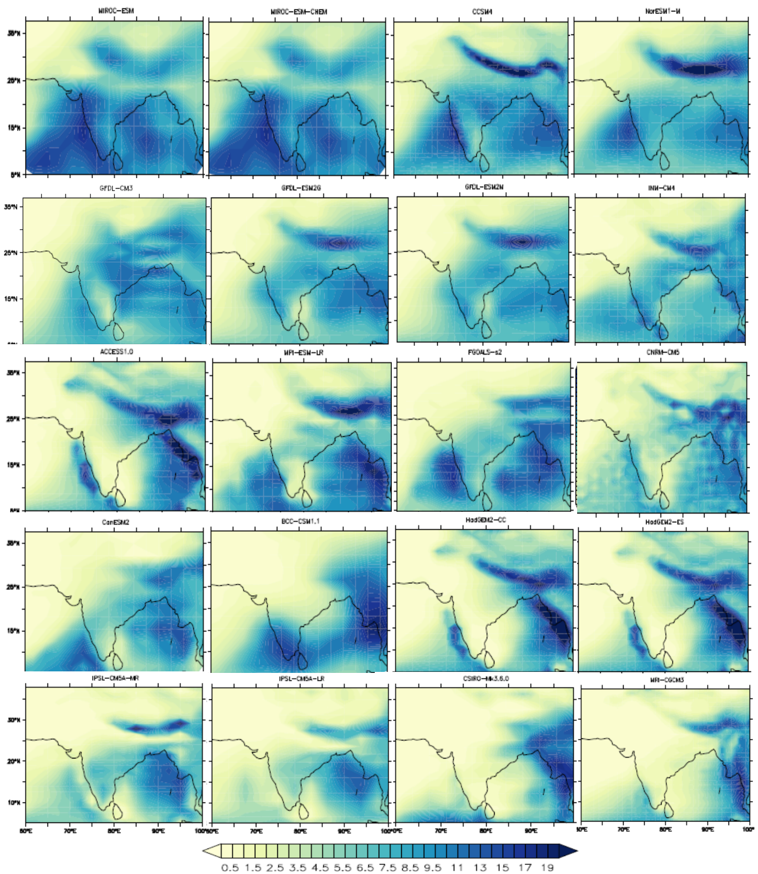

Fig. 2. June–September (JJAS) rainfall climatology (mm day^{-1}) during the period 1871–2004 for all the 20 models. Models with lowest seasonal mean rainfall do not capture the spatial pattern realistically. The models are shown in the same order as in Fig. 1.

ESDD
4, 1–24, 2013

Consistent increase in Indian monsoon rainfall

A. Menon et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

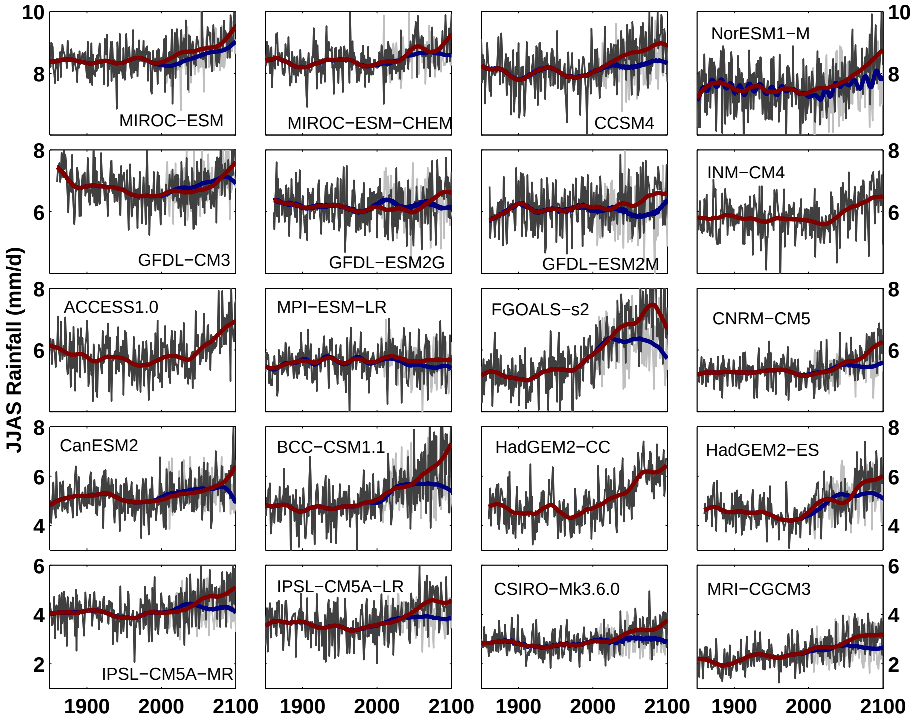

Fig. 3. Indian summer monsoon seasonal (June–September) mean rainfall for the period 1850–2100 from the 20 comprehensive climate models. Gray shadings represent the yearly values and red and blue lines represent the nonlinear trend in seasonal mean rain obtained from a singular spectrum analysis with a window width of 21 yr for RCP-8.5 and RCP-2.6 respectively. The non-linear trends are calculated using a routine from Aslak Grinsted and the method is discussed in Moore et al. (2005).

ESDD
4, 1–24, 2013

Consistent increase in Indian monsoon rainfall

A. Menon et al.

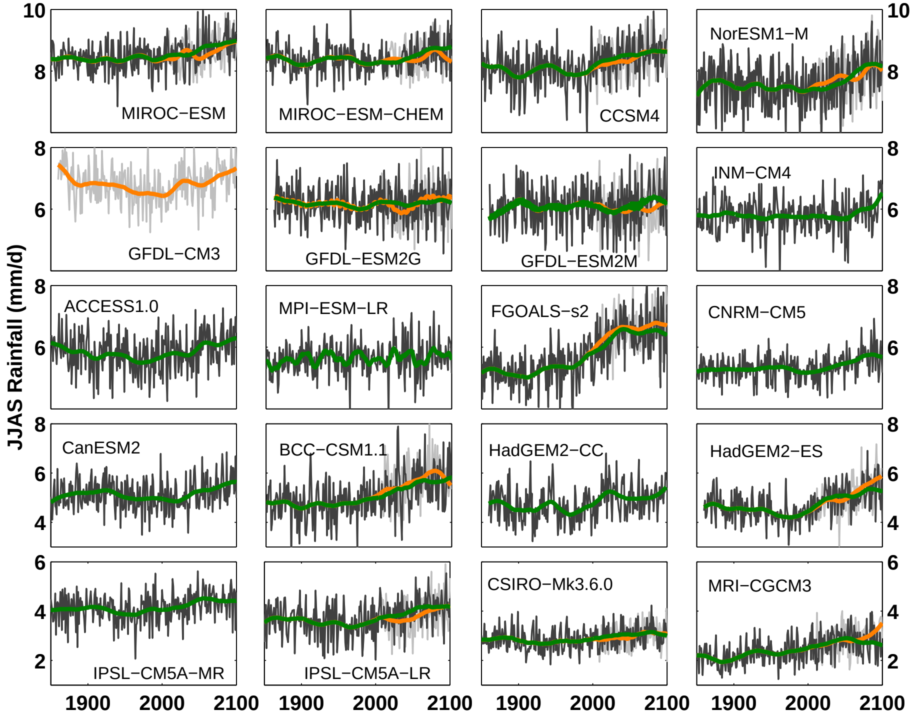

Fig. 4. Longterm trend in seasonal mean rainfall, same as in Fig. 3, but for RCP-4.5 (green) and RCP-6.0 (orange) scenarios. Please refer Table 1 for the data availability for Figs. 3 and 4.

ESDD
4, 1–24, 2013

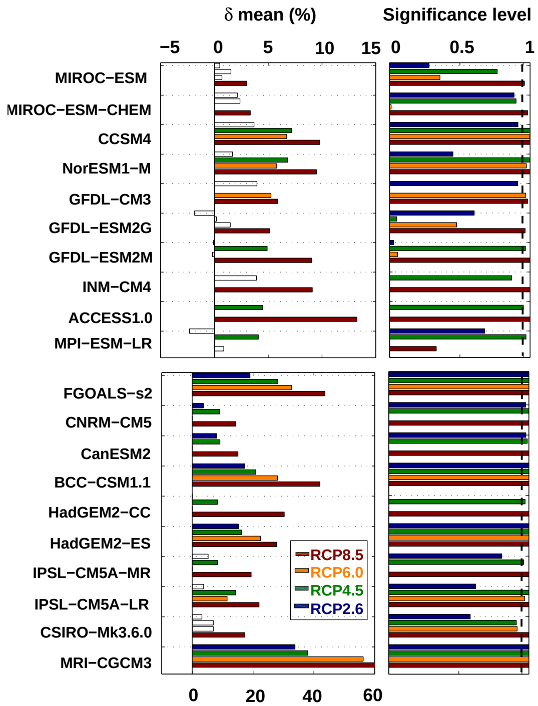

Fig. 5. Percentage change in mean rainfall for RCP-8.5 (red), RCP-6.0 (orange), RCP-4.5 (green) and RCP-2.6 (blue) for all the models under consideration. Relative change is calculated as the change in seasonal (JJAS) mean rainfall for the period 2070–2100 with respect to the period 1870–1900, i.e. $\left(\frac{\overline{\text{JJASrain}_{2070-2100}}}{\overline{\text{JJASrain}_{1870-1900}}}\cdot 100\right)-100$. The gap separates models with rainfall values for 1871–2004 lying within and outside twice the standard deviation of the observed mean as per Fig. 1. Two panels on the right hand side show the significance levels and the vertical dashed line marks 95 % confidence level. Bars on the left side panels are transparent if the δmean values are not significant at 95 % confidence level.

ESDD
4, 1–24, 2013

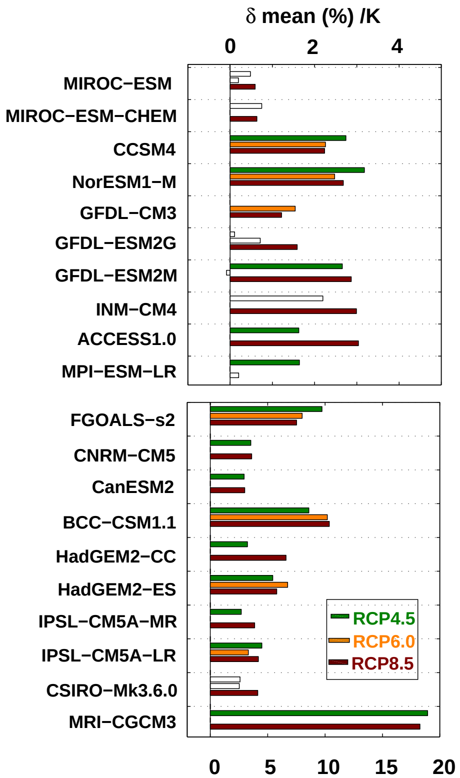

Fig. 6. Percentage change in mean rainfall per degree change in temperature for RCP-8.5 (red), RCP-6.0 (orange) and RCP-4.5 (green) for all the models. As the temperature change in RCP-2.6 is very small, it is not taken into consideration. Transparent bars are the values which are not significant at 95 % confidence level.

ESDD
4, 1–24, 2013

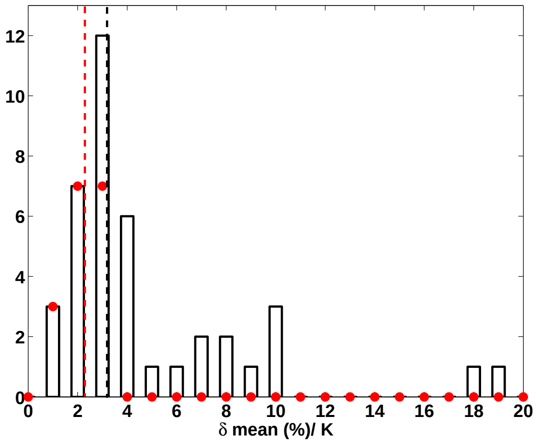

Fig. 7. Histogram of the percentage changes in mean rainfall per degree change in temperature for all the significant scenarios of all models as in Fig. 6. Red dots represent the values for the models in the upper panel of Fig. 6. Black dashed line shows the median value for the ensemble of all models and red dashed line shows the median value for the most realistic models, i.e. the ones in the upper panel of Fig. 6.

ESDD
4, 1–24, 2013

ESDD
4, 1–24, 2013

Consistent increase in Indian monsoon rainfall

A. Menon et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

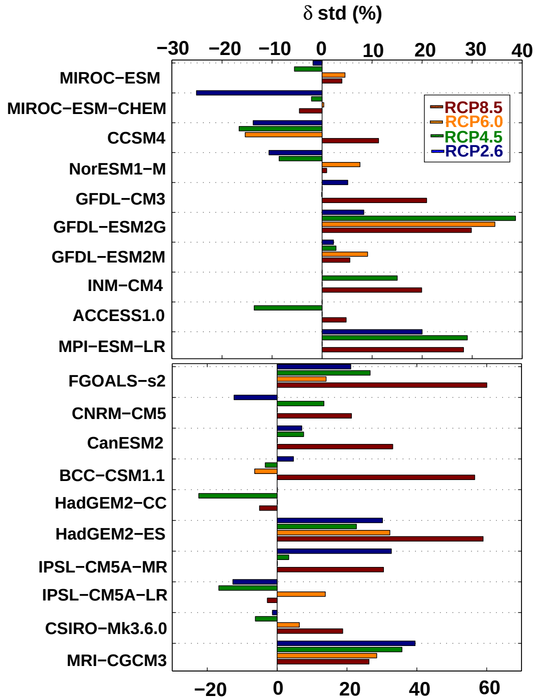

Fig. 8. The percentage change of standard deviation (STD) during the second half of 21st century to the standard deviation during the first half of the 20th century under RCP-8.5 (red), RCP-6.0 (orange), RCP-4.5 (green)and RCP-2.6 (blue) for all the models under consideration. All values greater than 0 shows an increase in variability. The percentage change is given as $\left(\frac{\mathrm{STD}_{2050-2100}}{\mathrm{STD}_{1900-1950}} \cdot 100\right) - 100$. The upper and lower panels are separated as in Figs. 5 and 6.