Detailed response to reviewer comments on the manuscript "Consistent increase in Indian monsoon rainfall and its variability across CMIP-5 models" by Menon et al. submitted to Earth Syst. Dynam. Discuss.

We would like to thank both of the anonymous reviewers for taking time and effort to read the manuscript and suggest these comments to improve the manuscript. Please find below our detailed responses to the comments.

Reviewer#1

Major points:

* The major weak point is that I find the analysis too simplistic: the manuscript does not investigate the mechanism responsible for the increased trends, especially the links with the changing circulation. This would add depth to the findings.
Response:- We have included an analysis of the changes in monsoon circulation under global warming using 19 of the CMIP-5 models. We couldn't include results from HadGEM2-ES as wind data for historic period is not available. Figures corresponding to monsoon circulation are added to the manuscript. (Please see additional figs 3-6) . We find that the monsoon circulation weakens over the south peninsular India, but strengthens over northern parts of India in majority of the models by the end of the twenty-first century (2070-2100) compared to the historic period (1970-2000) under RCP-8.5 scenario. Most of the models also show a northward shift in the monsoon circulation in future under RCP-8.5 scenario (Fig. 5). A new section is added in the manuscript (Section 2.4) to show the results on monsoon circulation.

* The analysis is carried out only in terms of area-average quantities, I wonder also how are the spatial patterns of the changes.
Response:- We have now included a figure to show the composite differences in rainfall pattern for the 20 models to see how rainfall spatial pattern changes in future with respect to the past under RCP-8.5 scenario (please refer additional fig. 2). All models show an increase in rainfall under global warming in most parts of India, especially over the Northeastern parts near the Himalayas .

* I suggest the authors to consider some recently published works, such as Lee and Wang (2012, Climate Dynamics), Hsu et al. (2012, JGR), Cherchi et al. (2011, CD). How are the findings of this work different from these others?
Response:- We have added the following sentences in the introduction section in order to include the main results from these studies (Page 4, Lines 75-81) : " Cherchi et al., 2011 analyze global monsoons based on a fully coupled atmosphere-ocean general circulation model and suggest that the Indian summer monsoon intensifies in future, mainly in response to the increased moisture content under various CO2 forcings. Studies based on CMIP-5 models under RCP-4.5 scenario project an increase in global mean precipitation of around 3.2\%/K (Hsu et l., 2013) and a larger increase in annual mean precipitation over the entire Asian monsoon region with less uncertainty as compared to CMIP-3 models (Lee and Wang, 2012)."

We have concentrated more on the regional Indian monsoon and analysed the changes in mean monsoon rainfall as well as inter annual variability under all the four RCP scenarios. We find that all these scenarios consistently project an increase in Indian monsoon mean rainfall for 20 of the CMIP-5 models and the increase is of the order of 2.3%/K.

Minor points:

* Did you use multiple ensemble members or one realization for each model?
Response:- We have used only one realization for each model in the analysis. Data from only one realization are available for some of the models. Also, there is not much difference between each realization for the same model.

* Page 3: mention also multi-decadal fluctuations, not only linear trends. See for example, Krishna Kumar et al. (2010, Climate Dynamics). Furthermore, why aerosols are not mentioned in the discussion? A number of recent studies have suggested they have played a very important role in the last decades, most likely dominating GHGs.
Response:- We added these additional lines into the introduction (Page 5, Lines 91-97)- "Multi-decadal fluctuations are also present in the Indian summer monsoon rainfall and are forced mainly by the tropical sea surface temperatures, and partly by extra-tropical oscillations like Atlantic multidecadal oscillation (Kucharski et al., 2009). Indian monsoon rainfall shows considerable decrease from late 1950s to 1990s. Kucharski et al., 2009 uses CMIP-3 models to show that the increase in GHGs in the twentieth century has not contributed significantly to the observed Indian summer monsoon decadal variability."

A line is already included in the manuscript mentioning the role of black carbon (Page 5, lines 86-89). We have now added additional sentences on the role of sulphate aerosols (Page 4, Lines 81-85):- "Aerosols play an important role in shaping monsoon over South Asia. IPCC Fourth Assessment Report (Meehl et al., 2007) examined the role of scattering aerosols like sulphate aerosols in monsoon. The presence of sulphate aerosols over south Asia mask the effect of increased temperature gradient by green house gases by reflecting the solar radiation and thereby reducing the land warming and hence the thermal contrast."

* Page 5, line 16: they also include the natural forcings, such as volcanoes and solar variations.
Response:- We have modified the sentence as (Page 6, Lines 116-118):-"Historical simulations are based on solar and volcanic forcing, land use, observed concentrations of green house gases, and reconstructed aerosol emissions."

* Page 6, line 27: what do you mean by active regime? The monsoon has been found to have been declining in the last few decades. The paragraph is not clear.
Response:-Active monsoon regime here represents the climatic regime during which monsoon is functioning normally and not like the paleo period during which there were abrupt monsoon transitions.

* Fig 2: is view of the discussion (e.g., pag. 6, lines 15-20) you should show observations. The comparison is also qualitative. Use some measure to quantify the overall discrepancy in the patterns.
Response:- One figure showing the spatial pattern of Indian monsoon rainfall JJAS climatology from IMD observational data for the period 1970-2000 is included (Please see additional fig. 1). We quantify the overall area-averaged rainfall (please see Fig. 1), but not the spatial pattern as we think that it is not relevant for this paper. This paper concentrates mainly on the changes in the overall Indian summer monsoon rainfall.

*Fig. 5: merge is some way the 2 figures, highlighting only critical values of the significance (e.g.90%, 95%).
Response:- We have removed the panels showing significance levels. Only those bars are coloured which are above 95% significance level. Others are left transparent.

Reviwer#2

1) A case regarding the more reliability of the simulated South Asian summer monsoon response in CMIP5 GCMs than that in CMIP3 GCMs cannot be made unless authors quantify that CMIP5 GCMs have more skill in the simulation of South Asian summer monsoon dynamics compared to the skill exhibited by CMIP3 GCMs.
Response:- A review paper by Turner and Annamalai (2012) shows that projected precipitation from some CMIP-3 models show wide range of trends in Indian monsoon rainfall in future including negative trends. Also Lee and Wang (2012) compares CMIP-5 and CMIP-3 models and suggest that the CMIP-5 models capture larger increase in annual mean precipitation over the Asian monsoon region with less uncertainity as compared to CMIP-3 models (Please see page 4, Lines 78-81) . Our study shows a consistent increasing trend in Indian monsoon mean rainfall in future under all RCPs and in 20 of the CMIP-5 models. So based on the past literature and our results we come to a conclusion that CMIP-5 models are more consistent in capturing Indian monsoon rainfall compared to CMIP-3 models.

2) CMIP3 GCMs showed a weakening of monsoon circulations, it is important to know the similarities/dissimilarities in the simulated circulations response in CMIP5 GCMs.
Response:- We have now included an analysis of monsoon circulation in CMIP-5 models under RCP-8.5 scenario. It was not done before because the wind data was not available to us during the time of the study. We find that most of the CMIP-5 models show a weakening of the monsoon circulation over southern peninsular India, where as the circulation strengthens in the northern part by the end of the twenty-first century compared to the end of the twentieth century. We find that there is a northward shift in the monsoon circulation by about 2 degrees in future in response to global warming in majority of the models under consideration (Please see additional figs 3-6). An additional section is added in the manuscript (Section 2.4) to show the results on monsoon circulation.

3) Most of the GCMs in CMIP5 ensemble are significantly drier than observations; it is imperative to quantify whether this dry bias has any influence on their simulated response in the 21st century period.
Response:- Models are sorted according to their dryness (as per Fig. 1) in figures 5,6,7 and 8 in the manuscript. From these figures, we can see that the scales for percentage changes in mean rainfall are different for wet and dry models. This shows that the dry bias has an influence on the simulated response.

4) Authors must provide details of the driving mechanisms that are responsible for increase in rainfall in future under all RCPs and that whether the cause of positive precipitation response is consistent across the CMIP5 ensemble.
Response:- When we analysed 20 models under all four RCPs, our intention was to just see how monsoon responds in CMIP-5 models. It is difficult to come to a conclusion regarding mechanisms as these models have varying initial conditions. Moreover, already the manuscript has 14 figures now after the revision and inclusion of more analysis might be out of scope of this study.

5) Authors should also show grid based model results in addition to the area averaged time series. Time-series analysis cannot be helpful if reader wants to know whether or not a spatial robustness in rainfall response also exists across the models.
Response:- We have included a composite difference analysis to show how the spatial distribution of rainfall changes under global warming with respect to past in all the 20 models (Please see additional fig. 2).

6) This study didn't discuss a single high-resolution regional model based study over South Asia. There

is more than one high-resolution study from recent past that simulates suppression in South Asian summer monsoon in response to increase in greenhouse forcing (e.g. Ashfaq et al, GRL).
Response:- We have included the following sentence in the introduction (Page 4, Lines 62-65)- “A study (Ashfaq et al., 2009) based on a high resolution nested model suggests a suppression in the Indian monsoon rainfall in future which is attributed to a weakening of the monsoon circulation and a suppression of the intraseasonal modes.”

7) It will be useful to know that how many of these models simulate rainfall response that is outside of the envelope of the baseline variability and that when this happens during the 21st century period. Perhaps, one can also look across the models to see how consistent models are in the simulation of the climate state where monsoon rainfall is permanently beyond the natural climate variability if that at all happens in CMIP5 GCMs in their 21st century rainfall projections.
Response:- In order to answer this, we have reproduced figures 3 and 4 in the manuscript with horizontal lines showing mean+/- standard deviation during the historic period (1871-2004) for each of the models (Please see figures 7 and 8 in this response file). The following sentences are added to the manuscript (Page 7-8, Lines 164-168):- “Under RCP-8.5 scenario, majority of the models simulate rainfall response outside the envelope of the baseline variability (black horizontal lines) towards the end of the twenty-first century. FGOALS-s2 shows a rainfall response beyond the baseline variability from the beginning of the twenty-first century onwards under all the RCP scenarios.”

8) In addition to the analysis of mean and inter-annual variability, authors should also add analysis of extremes and intra-seasonal variability. It is important to know that how fine- and intra-seasonal time-scale climate variations shape the mean simulated response in the GCMs and that how consistent the fine-temporal scale variations are across the CMIP5 ensemble.
Response:- We have analysed how sub-seasonal variability have changed under global warming in CMIP-5 models. But we have already submitted it as a separate paper (Menon et al., 2013) and is accepted for publication now. It is now cited in the manuscript as (Page 4, Lines 65-66):-”CMIP-5 models consistently project significant increase in Indian summer monsoon rainfall sub-seasonal variability under unmitigated climate change (Menon et al., 2013).”

References:-

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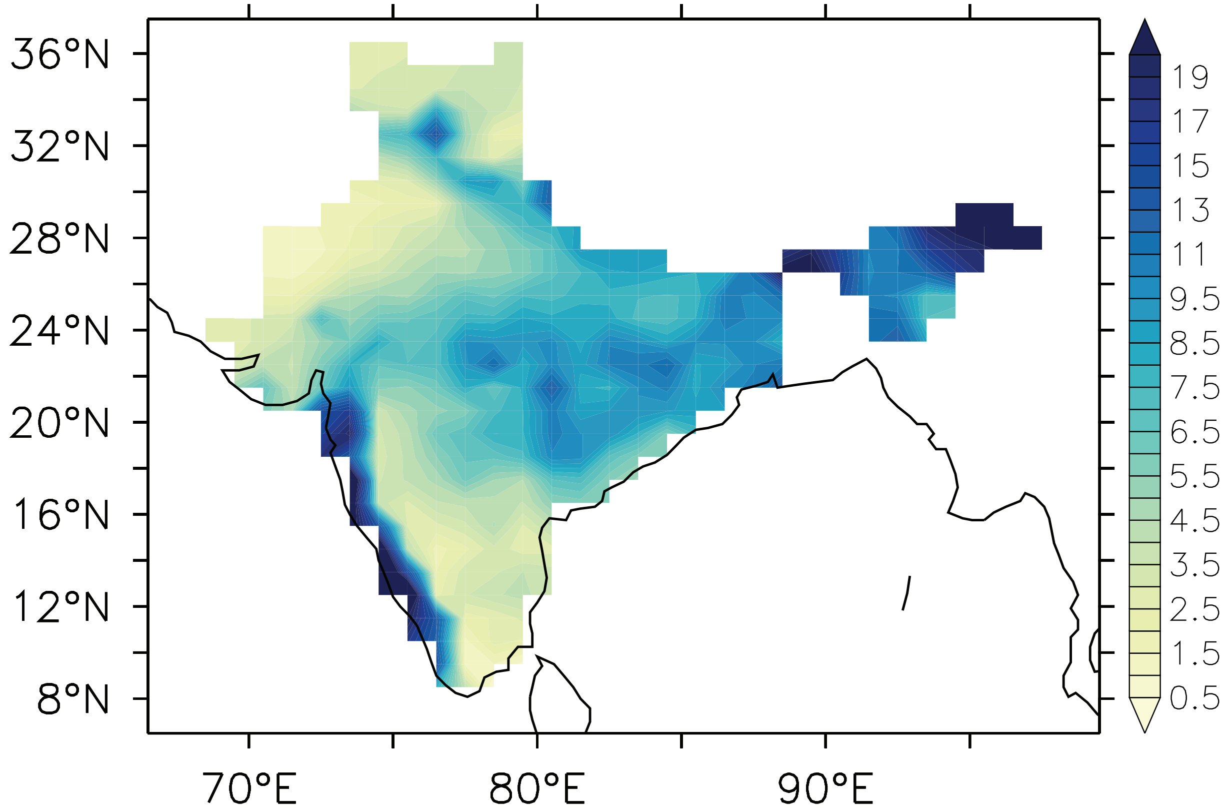

Figure 1: June-September (JJAS) rainfall climatology (mm/day) during the period 1970-2000 from the India Meteorological Department (IMD) daily gridded observational dataset. Mean precipitation is highest over south-west peninsular India, north-east India and central India.

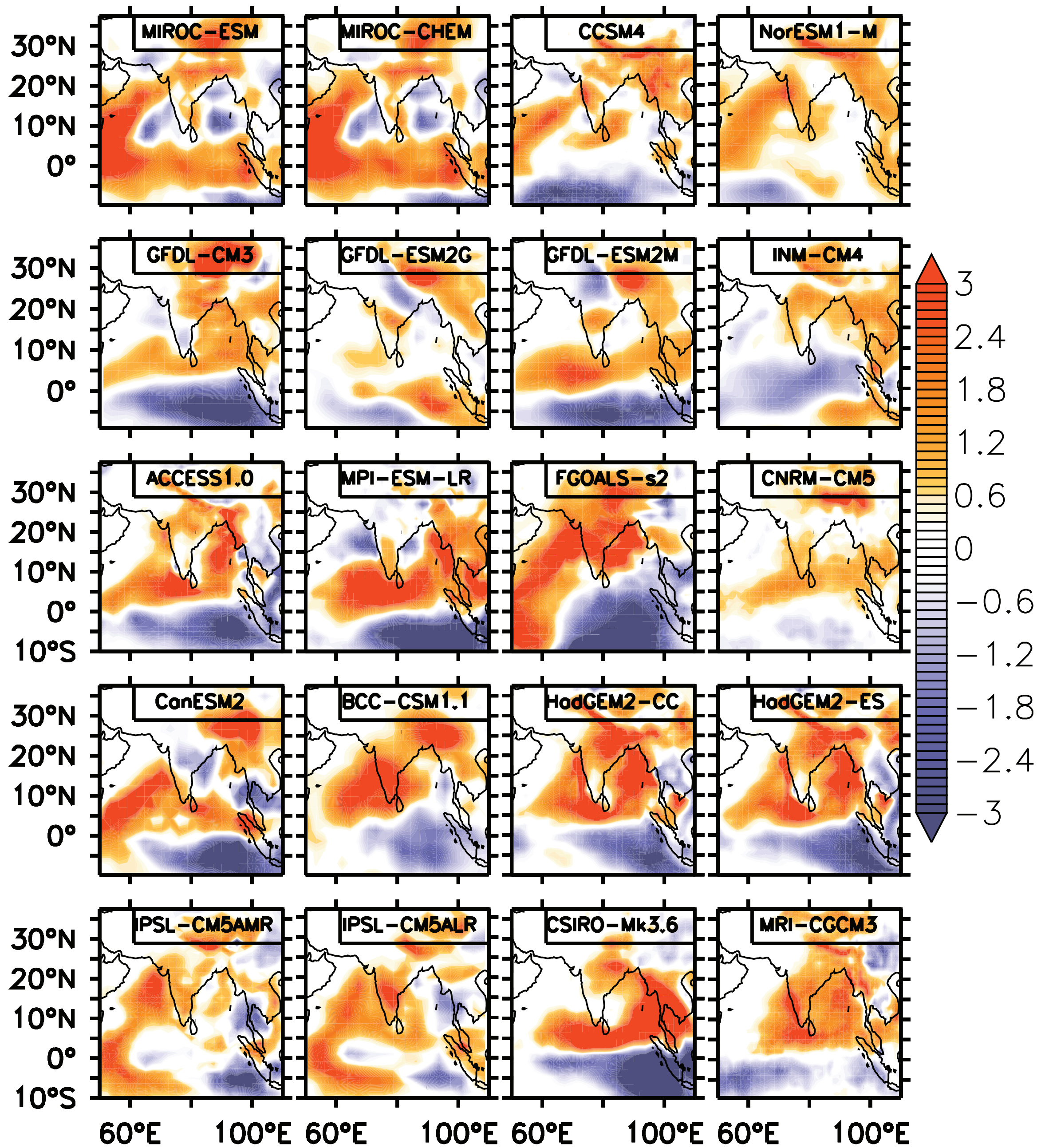

Figure 2: JJAS rainfall composite difference (mm/d) for the period 2070-2100 under RCP8.5 scenario and for the period 1970-2000. Majority of the models capture an increase in summer monsoon mean rainfall by about 0-3 mm/day in most parts of India.

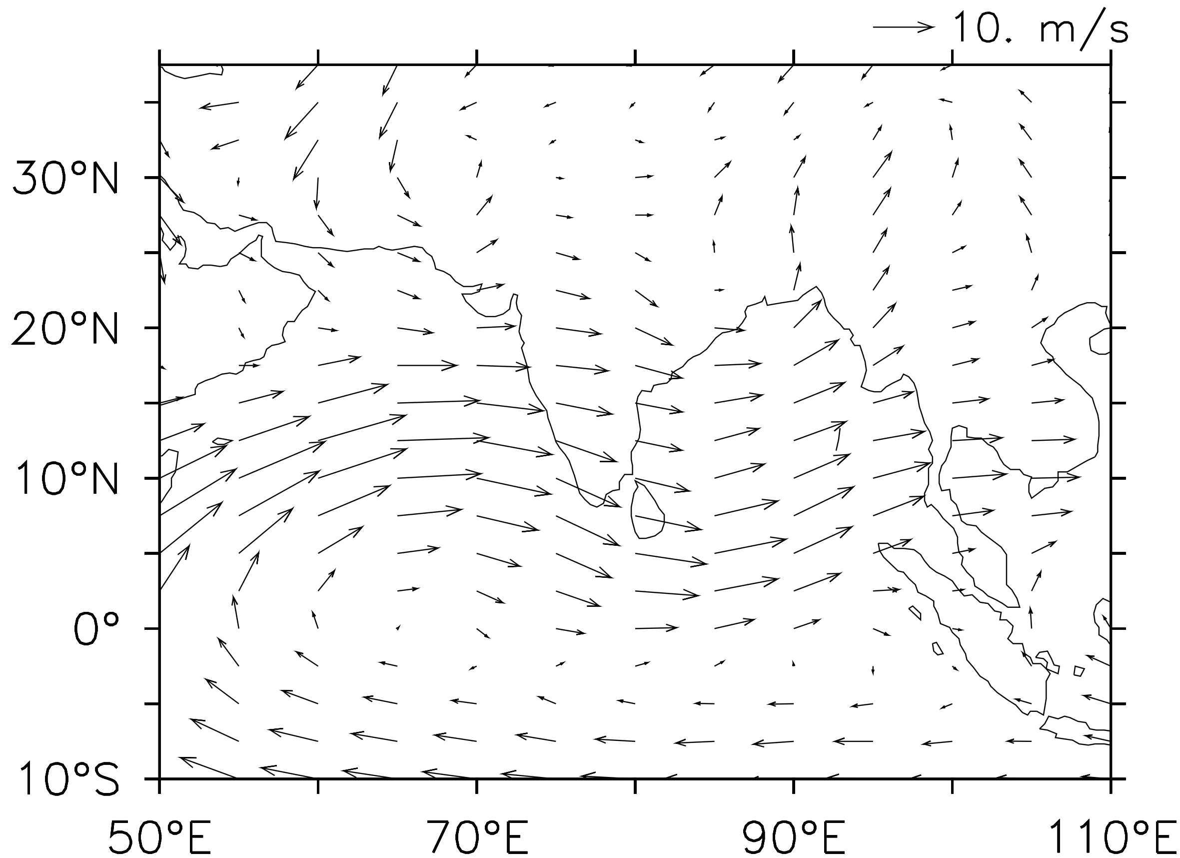

Figure 3: June-September 850 hPa wind (m/s) climatology for the period 1970-2000 from NCEP/NCAR reanalysis data.

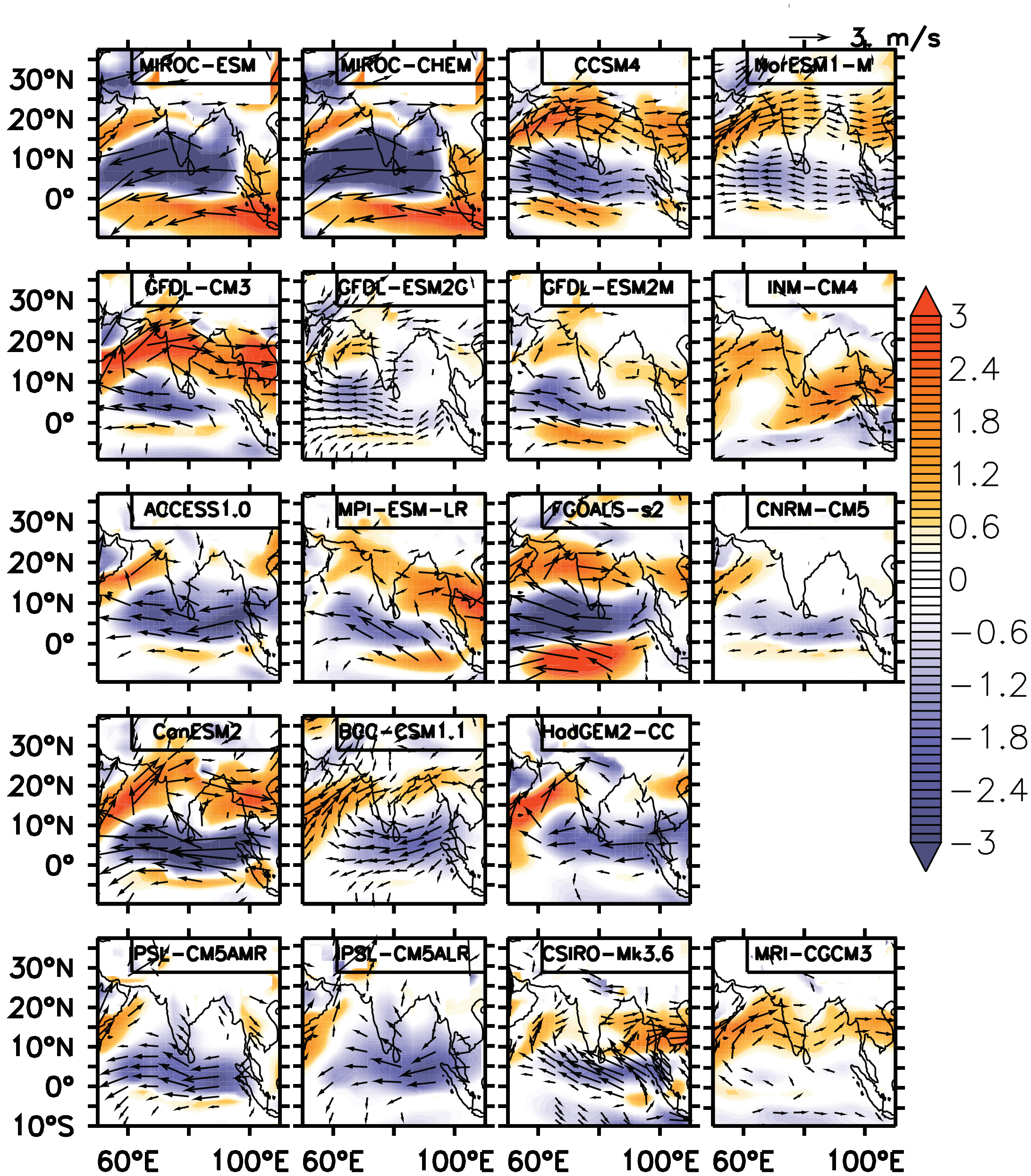

Figure 4: Difference in wind speed (shaded) and vectors (m/s) during June-September for the period 2070-2100 under RCP8.5 and 1970-2000 for 19 models under consideration. HadGEM2-ES is not shown as wind data for historic period is not available at the time of the study. Wind vector anomalies are in the direction of the mean flow over the northern parts of India and are opposite to the mean flow over the southern parts of India in most of the models.

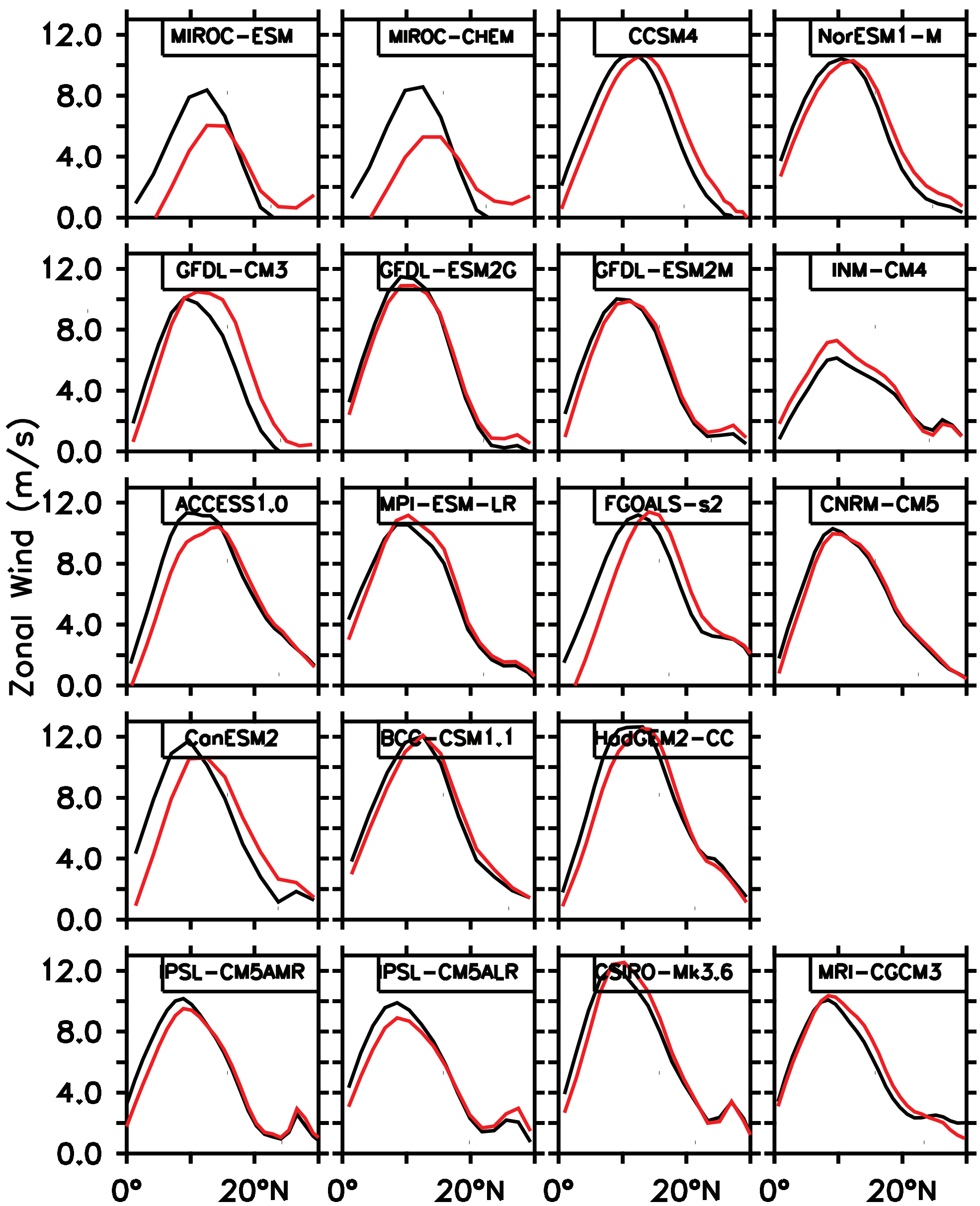

Figure 5: Meridional pattern of zonal wind (m/s) averaged over the region 50E-110E for the 19 CMIP-5 models during June-September. Black lines represent JJAS mean zonal wind for the period 1970-2000 and red lines represent JJAS mean zonal wind for the period 2070-2100.

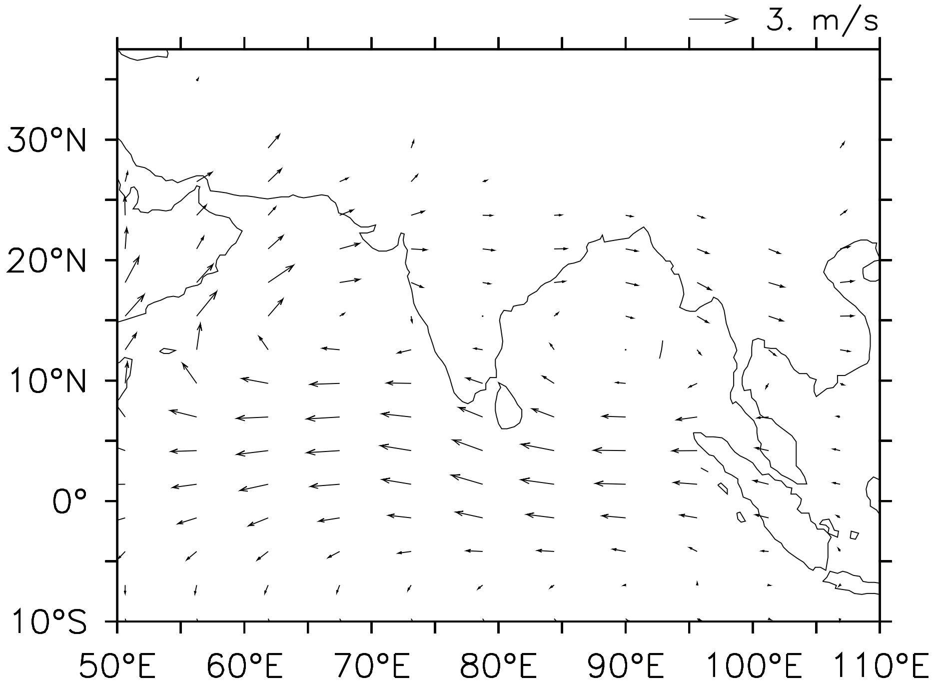

Figure 6: Differences in June-September 850 hPa winds (m/s) for the period 2070-2000 (under RCP8.5) compared to the historic period (1970-2000) for the ensemble mean of all 19 models under consideration.

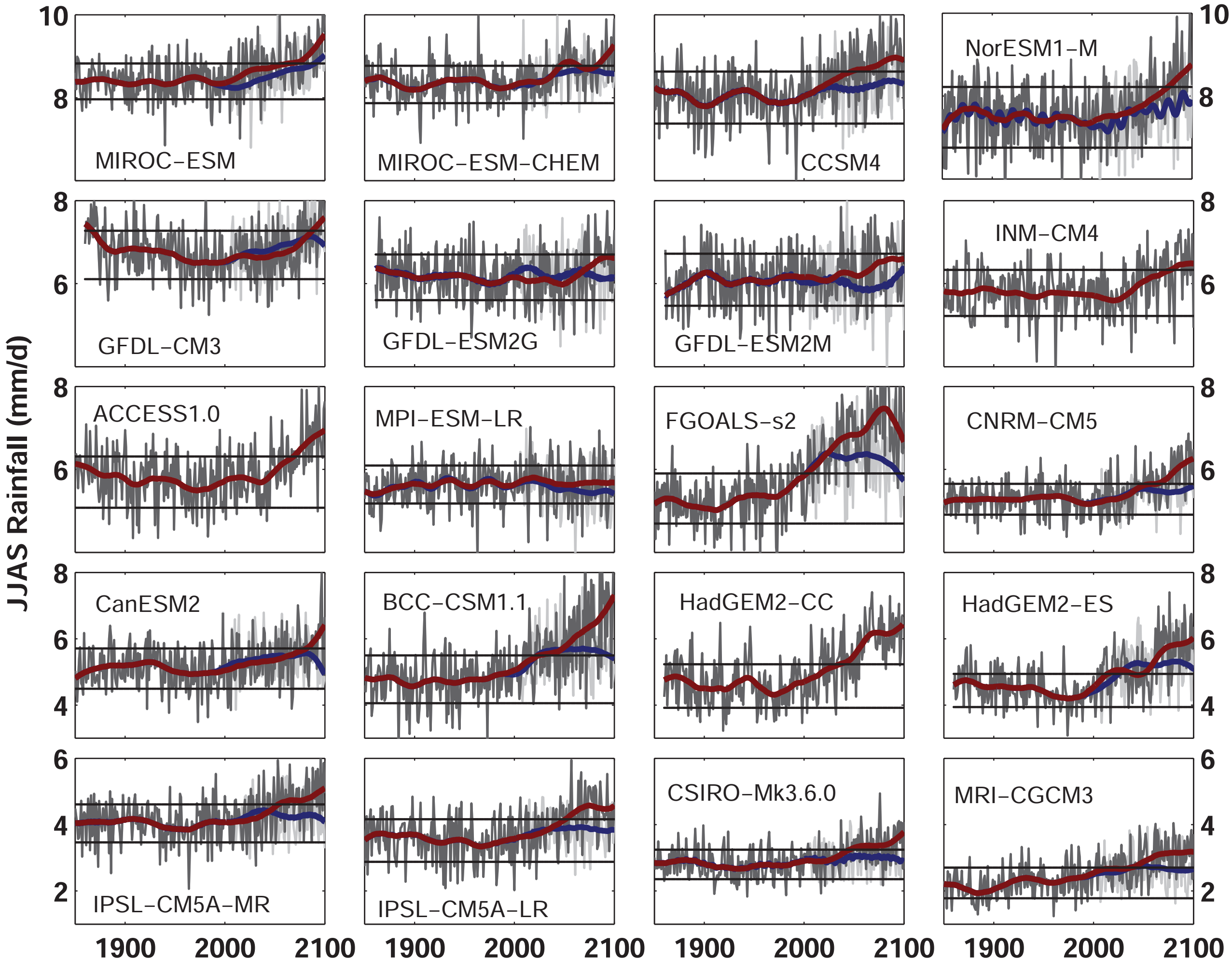

Figure 7: Indian summer monsoon seasonal (June–September) mean rainfall for the period 1850–2100 from the 20 comprehensive climate models. Gray shadings represent the yearly values and red and blue lines represent the nonlinear trend in seasonal mean rain obtained from a singular spectrum analysis with 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). The horizontal black lines represents mean ± standard deviation for each model for the period 1871-2004 which shows the range of baseline variability.

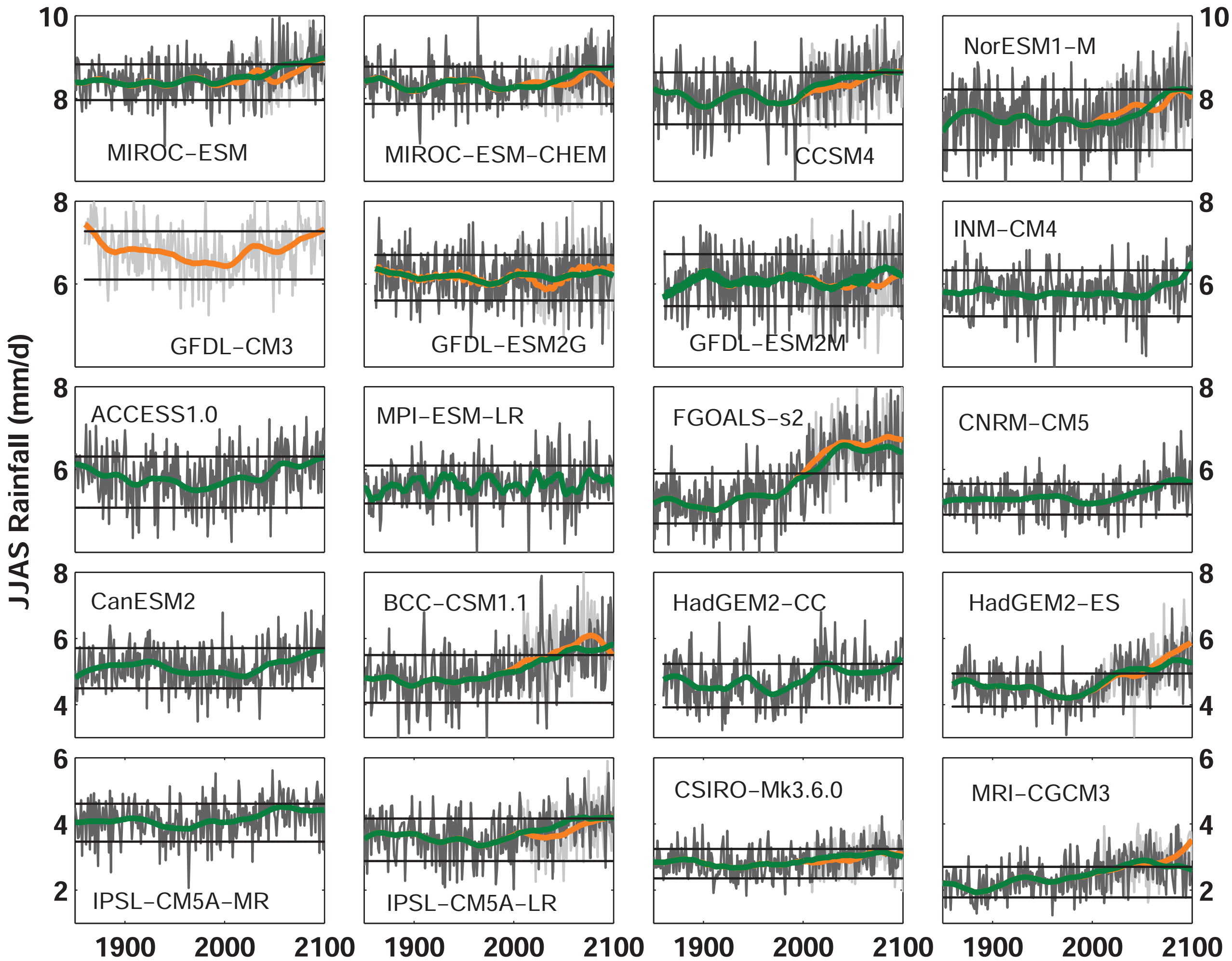

Figure 8: Longterm trend in seasonal mean rainfall, same as in Fig. 7, but for RCP-4.5 (green) and RCP-6.0 (orange) scenarios. Horizontal black lines represent the range of baseline variability as in Fig. 7.