Projected precipitation changes over the south Asian region for every 0.5 °C increase in global warming

Mansi Bhowmick, Sandeep Sahany and Saroj K Mishra
Centre for Atmospheric Sciences, IIT Delhi, India
E-mail: mansibhowmick@gmail.com

Keywords: south Asia, extreme rainfall, annual precipitation, global warming

Abstract
Using all ensemble members of NCAR CCSM4 for historical natural, RCP4.5 and RCP8.5 scenarios from CMIP5, we analyse changes in mean and extreme precipitation over the south Asian region for every 0.5 °C increase in global warming. An increase in mean annual precipitation is projected over majority of the south Asian region with increased levels of warming. Over Indian land, the spatially-averaged annual mean precipitation shows an increase in the range of ~2–14 % based on the RCP scenario and level of warming. However, a decrease in mean annual precipitation is projected over northwest parts of the Indian sub-continent and the equatorial Indian Ocean with increased levels of warming. In general, we find multifold increase in the frequency of occurrence of daily precipitation extremes over the Indian subcontinent and surrounding oceans. Over Indian land, frequency of occurrence of daily precipitation extremes show up to three-fold increase under both RCP scenarios for global warming levels in the range of 1.5–2.5 °C. With further increase in warming we find that the frequency of occurrence of daily precipitation extremes could show a massive four- to six-fold increase over majority of Indian land. Notably, unlike the projected increase in the frequency of occurrence of daily precipitation extremes, the projected change in annual mean precipitation is found to be insignificant in a 1.5 °C warmer world, over majority of the south Asian region, under both RCP scenarios. Given the projected large increase in frequency of daily precipitation extremes with increased levels of warming, our study provides scientific support to the recommendations of the Paris Agreement of 2015.

1. Introduction
Under the Paris agreement in 2015, United Nations Framework Convention of climate change proposed an ambitious climate change mitigation target on limiting global temperature increase above preindustrial levels to below 2 °C or even further limit it to below 1.5 °C. Since then few studies have conducted numerical experiments (e.g. Mitchell et al 2017) and investigated global (Mitchell et al 2016, Liu et al 2018) and regional (King et al 2017, Chevuturi et al 2018) impacts of 1.5 °C warming as well as an additional half degree warming to 2 °C. However, the short-term interest among the signatory countries, technological lock-ins in energy systems and socio-economic constraints questions the feasibility of such an objective. Hence, climate change projections need to be assessed not only at specific warming levels, but for a range of levels that the climate system is likely to undergo in the ongoing century.

Considering an overwhelming portion (86%) of weather and climate related disaster affected population lives in the storm and flood-prone Asia (according to the International disaster database https://emdat.be/publications), the focused region of study here is south Asia. Summer monsoon season being the dominating period in terms of precipitation, majority of the climate change studies over the Indian subcontinent and Asia focus on this period (June–September months). Using numerical modelling approach, response of increased radiative forcing to the monsoon variability (e.g. Meehl and Wahrson 1993, Kripalani et al 2003,
Sharmila et al (2015), active and break spells (e.g. Mandke et al 2007, Turner and Slingo 2009), mean summer monsoon precipitation (e.g. Kitoh et al 1997, Lal et al 2001, Ueda et al 2006, Turner et al 2007, Ashfaq et al 2009, Sabade et al 2011, Lau et al 2013), synoptic systems (e.g. Stowasser et al 2009), extreme events (e.g. Turner and Slingo 2009, Sahany et al 2018) have been studied extensively in the past and reviewed by Turner and Annamalai (2012). Apart from investigating specific characteristics of the monsoon, most of the above mentioned studies analysed the mean monsoon state and projected a significant increase in monsoon precipitation with increased levels of greenhouse forcing. Furthermore, Chaturvedi et al (2012) shows converging tendency of models towards the wetter summer monsoon when going from the low to high radiative forcing scenario. However, at odds, Ashfaq et al (2009) found suppression of the monsoon rainfall, increased frequency of break periods and delay in the monsoon onset under the enhanced greenhouse forcing scenario.

Based on the multiple observational dataset, Jin and Wang (2017) observed a significant reduction in the rainfall over Central India during the monsoon season in the second half of the twentieth century, but since 2002 onwards a significant wetter trend is observed. Dash et al (2009), using the daily gridded rainfall data showed that the long wet spells and the frequency of moderate to low precipitation days have significantly decreased over India in the last half of the 20th century, whereas, dry spells show a significant increase. Goswami et al (2006) found the increase in magnitude and frequency of extreme rainfall over Central India using a fixed threshold to define extremes. Similarly, Roxy et al (2017) reported a threefold increase in the extreme precipitation events over central India between 1950 and 2015. Rajeevan et al (2008) reached a similar conclusion for entire India. On the other hand, Ghosh et al (2012) highlighted the increasing spatial variability in the extreme precipitation over India.

Acknowledging the dominance and significance of summer monsoon season precipitation, it is also important to highlight that the southeast part of India receives majority of rainfall from northeast monsoon during the post monsoon months (e.g. Singh and Sontakke 1999, Rajeevan et al 2012). On the other hand, extreme north and northwest of India receives significant precipitation during the winter months. Changes in the winter precipitation over northwest India can have significant socio-economic impacts including agriculture (e.g. Krishna Kumar et al 2004, Jayaraman 2011). Recent occurrence of Chennai floods (southeast India) in December 2015 (e.g. Van Oldenborgh et al 2016) significantly highlights the importance of the study of precipitation in the months other than summer monsoon season.

Thus in this work we analyse the annual distribution of the precipitation and extreme precipitation over south Asia for a wide range of global warming levels. This paper is structured as follows: section 2 describes data used and methodology, section 3 presents the results showing projections under different levels of global warming and section 4 provides conclusions.

2. Data and method

In this study, we have considered extended Coupled Model Inter-comparison Project 5 (CMIP 5) experiments for RCP4.5, RCP8.5 and HistoricalNat scenario from the NCAR CCSM4 model. The NCAR CCSM4 model is chosen for this study because a recent study by Anand et al (2018), carried out a systematic evaluation of various CMIP5 models for the Indian summer monsoon season and found that overall this model compared quite well with reanalysis and observations, as compared to other CMIP5 models. The available six ensemble members for each RCP scenario and four ensemble members for historical natural experiment are taken into consideration. The time period of RCP simulations is 2006 to 2100. The warming is computed from the natural baseline period of 1850–2005 from HistoricalNat simulation. For each RCP scenario, and for each ensemble member, first, the period corresponding to 1.5 °C of global warming is extracted. In order to extract the period for 1.5 °C of global warming, we compute the global mean surface temperature difference (ΔT) from the baseline period for moving (at 1 year interval) 10 year periods starting from 2006 to 2100 (e.g. 2006–2015, 2007–2016, etc). The 10 year running means are used in order to eliminate inter-annual variability in the global warming signal. The entire period for which the 10 year mean ΔT lies in the range of 1.3 °C–1.7 °C is considered to be the period representative of an average 1.5 °C warmer world. For example, if the ΔT lies in the range of 1.3–1.7 for the first 10 year (2006–2015) to the 8th 10 year period (2013–2022), the period 2006–2022 is considered to be representative of a 1.5 °C warmer world for the given ensemble member. This procedure is used to extract periods representative of warming levels at 0.5 °C increments (e.g. 1.8–2.2, 2.3–2.7, and so on). It is to be noted that a given year may contribute to two warming levels (e.g. 1.5° and 2°), since we do not assume independence between the two worlds. Since the two scenarios have different rates of warming, for a given level of warming the sample size could be different under RCP4.5 and RCP8.5. Figure 1 shows this range of the number of decades contributing to specific levels of warming for the RCP4.5 and RCP8.5 scenarios. Using the extracted time periods corresponding to different levels of warming, changes in precipitation characteristics (including extremes) are analysed over our domain of interest spanning 10°S–40°N and 60°–100°E. The precipitation changes relative to the baseline from the natural world are calculated for various levels of
warming, and annual mean changes are presented in figure 2. Regions with statistically significant changes are computed using standard t-test and are stippled for 99% confidence level. In figure 3, using box and whiskers diagram, annual cycle of monthly mean precipitation over Indian land is presented for various levels of warming. Similarly, using all ensemble members the probability distribution of daily rainfall over Indian land is shown in figure 4. In figure 5, the frequency of occurrence of extreme daily rainfall events (defined using the natural world 99.9 percentile threshold value for each grid point) is shown.

3. Results

Annual mean precipitation over the globe (supplementary figure 1 is available online: stacks.iop.org/ERL/14/054005/mmedia) shows positive and negative changes (from the baseline period of historical natural simulations described in section 2) for different levels of global warming (ranging from 1.5°C to 4.5°C) under RCP4.5 and RCP8.5 scenarios. Stippling shows changes significant at 99% confidence level. Under both RCP scenarios, majority of the equatorial region is projected to have increased precipitation with increased levels of global warming. However, in deep tropics and parts of subtropics over the Atlantic Ocean, Pacific Ocean, Central America and maritime continent regions in east Asia, decreased precipitation is projected at various levels of global warming under both RCP scenarios. Majority of Africa and south Asian subcontinent are projected to have increase in precipitation with increase in levels of global warming. Polar regions in both hemispheres are projected to have significant increase in precipitation for different levels of global warming under both RCP4.5 and RCP8.5 scenarios. The respective changes over globe get progressively intensified and significant at higher levels of warming. While it is worthwhile to do a detailed analysis on global scale, we focus on the south Asian region in this paper, since it is a densely populated region with more than one sixth of global population living under vulnerable conditions to climate and weather related disasters (as described in introduction). Hence, rest of the study is focused on mean and extreme precipitation changes over the south Asian region for various levels of global warming, using various ensemble members of the NCAR CCSM4 from the CMIP5 archive.

3.1. Projected spatial changes in mean precipitation

In figure 2 we show the projected changes in the annual mean precipitation under the RCP4.5 and RCP8.5 global warming scenarios for every 0.5°C increase in the global average near-surface air temperature (see section 2 for details). Over Arabian Sea the precipitation is projected to increase under RCP4.5 for various levels of global warming ranging from 1.5°C to 2.5°C. Similarly, under the RCP8.5 scenario (see...
Figure 2(b), an almost monotonic increase in the precipitation is projected over Arabian Sea for increase in global warming from 1.5 °C through 4.5 °C. Under RCP4.5, the Bay of Bengal does not show any significant change in the 1.5 °C warmer world, however, with increased warming significant increase in precipitation is seen, starting from the southern parts gradually moving to the central bay. Similar to RCP4.5, under RCP8.5, precipitation changes over the Bay are insignificant in a 1.5 °C warmer world, but with increased levels of warming, increase in precipitation is seen starting from the southern Bay and gradually moving towards the central and north Bay. In contrast, the equatorial Indian Ocean shows a decrease in precipitation with the increased levels of warming for both RCP scenarios, and the spatial extent of significant decrease increases with increase in warming.

Over Indian land changes are grossly insignificant in both 1.5 °C and 2 °C warmer worlds under both RCP scenarios, except over some parts of extreme north-east India. In a 2.5 °C warmer world, a significant increase in the precipitation is projected over majority of the Indian land (except over northwest India) under RCP4.5 scenario, however, no significant increase is projected under RCP8.5 scenario. The exact reason behind this is not obvious, but one should note that the number of years contributing to the 2.5 °C warmer world under the RCP4.5 scenario is around 2–3 times of that contributing under the RCP8.5 scenario. For increased levels of warming beyond 2.5 °C under RCP8.5 scenario, a significant monotonic increase in the precipitation is projected over Indian land.

The heavy precipitation zones, such as the foothills of Himalaya, show significant increase in precipitation under the RCP4.5 scenario, with the spatial extent and amplitude of increase gradually increasing with increased levels of warming. A large increase in the precipitation is projected over foothills of Himalaya.
with an increase in global warming from 2 °C through 4.5 °C under the RCP8.5 scenario. Significant increase in the precipitation is projected over the Tibetan Highland region under all levels of warming under both scenarios. Notably, unlike the Himalayan foothills, the amplitude of projected precipitation does not
show a monotonic increase under the increased levels of warming. Annual mean precipitation over the Myanmar region is projected to increase under both the RCP4.5 and RCP8.5 scenario, with the projected amplitude of change progressively increasing with increased levels of warming. On the other hand, northwest part of the Indian-sub continent (including Jammu and Kashmir, Pakistan and Afghanistan) shows a decrease in the precipitation in both RCP scenarios, however, the results are significant only for the higher levels of warming, like 2.5 °C in the RCP4.5 scenario, and 3 °C and higher in the RCP8.5 scenario.

3.2. Projected annual cycle of precipitation

Figure 3 shows the annual cycle of precipitation averaged over Indian land for the Historical Natural world, and for different levels of global warming under the RCP4.5 and RCP8.5 scenarios. The box depicts 25th percentile, median and 75th percentile value of the monthly mean precipitation, and the whiskers show maximum and minimum precipitation for the month, considering all ensemble members. For pre-monsoon months (March–May), under the RCP4.5 scenario, the maximum monthly mean precipitation is within the variability observed in natural world except for the 1.5 °C warming in the month of April. Similarly, under the RCP8.5 scenario, the maximum monthly mean precipitation in pre-monsoon months is within the natural world variability, but a noteworthy decrease in the maximum value is projected with an increase in levels of warming in the month of May. The projected median values in this season, under both RCP scenarios, do not show any noteworthy increase or decrease. Minimum monthly mean precipitation values are, in general, within the natural variability in this season under both the RCP scenarios.

The projected maximum monthly mean precipitation during the first two months of summer monsoon season (June–September) show an increase only for some levels of warming, however, in August and September it shows an increase for most levels of
warming, under both the RCP scenarios. The median values in the monsoon season under both the RCP scenarios are projected to increase with increased levels of warming, except for the month of June. The minimum monthly mean precipitation in warmer worlds is projected to have higher values in monsoon season under both RCP scenarios.

In the post-monsoon months (October–November), under the RCP4.5 scenario, unprecedented values of the maximum monthly mean precipitation is projected in some but not all levels of warming. Similarly, under the RCP8.5 scenario, an increase in the maximum monthly mean precipitation is projected during the post-monsoon months for some levels of warming. A monotonic increase in the median value of the monthly mean precipitation is projected for increase in the levels of warming for these months under both RCP scenarios. The minimum monthly mean precipitation values for the post monsoon months in warmer worlds are, in general, projected to increase under both the RCP scenarios.

For winter months (December–February), the maximum monthly mean precipitation in warmer worlds is mostly within the natural variability under the RCP4.5 scenario. However, the month of December in the RCP8.5 scenario is projected to have unprecedented values of the maximum monthly mean precipitation for some warmer worlds. The projected median values of the precipitation in this season, under both scenarios, do not show any notable increase or decrease. In general, this season, under both RCP scenarios, is projected to have minimum monthly mean precipitation values within natural variability, except for the month of December, where the projected values in some warmer worlds are lower than natural world minimum.

### 3.3. Probability distribution of daily extreme precipitation

The probability distribution function (PDF) of the annual daily precipitation is derived for different levels of warming under the RCP4.5 and RCP8.5 scenarios, and shown in figure 4. Daily precipitation for all grid points (over Indian land) from all the ensemble members is collectively used (without any averaging) to compute the PDF. Under the RCP4.5 scenario (see figure 4(a)) the frequency of occurrence of the daily rainfall values < 50 mm d⁻¹ is very high (nearly 80%), due to the fact that non-rainy days are also considered in the computation. For daily heavy precipitation values (> 100 mm d⁻¹) a systematic increase in the frequency of the occurrence is projected with the increase in levels of warming. Likewise, the projected frequency of occurrence of the extreme precipitation (tail of the distribution), in general, increases with increased levels of warming. Notably, the magnitude of the extreme daily precipitation in warmer worlds is ∼100–150 mm d⁻¹ higher than the natural world extremes.

Similarly in the RCP8.5 scenario (figure 4(b)), maximum frequency of occurrence is between 0–50 mm d⁻¹. The PDFs start to diverge after ∼50 mm d⁻¹ and the frequency of occurrence for the higher daily rainfall bins increases with the increase in warming. A sizeable fraction of this increase is likely to be contributed from the sharp increase in the precipitation over foothills of Himalayas (discussed in section 3.1). A significant peak with a sharp increase in frequency is projected near the tail of the PDF in a 4 °C warmer world. The magnitude of extreme precipitation value in the 4.5 °C warmer world is projected to be around 200 mm d⁻¹ higher compared to the natural world extremes.

### 3.4. Spatial distribution of the frequency of extreme precipitation

Figure 5 shows the spatial distribution of the frequency of occurrence of extreme precipitation under both RCP scenarios. Over Arabian Sea, (i) under RCP4.5 scenario the frequency of extreme precipitation is projected to increase with the increase in the levels of warming, (ii) under RCP8.5 scenario frequency of extreme precipitation is projected to increase from 3 days/decade to 15 days/decade with increase in warming from 1.5 °C to 4.5 °C. Over Bay of Bengal, (i) the increase in levels of warming from 1.5 °C to 2 °C, under both the RCP scenarios do not show any notable increase or decrease in frequency of extreme precipitation, (ii) in a 2.5 °C warmer world, compared to the uniform increase in the frequency of extreme precipitation under the RCP4.5 scenario, increase in frequency is fragmented under RCP8.5 scenario, and (iii) for 3 °C warming and higher, a monotonic increase in the frequency of extreme precipitation is projected. Notably, the south Indian Ocean shows a gradual increase in the frequency of occurrence of the extreme precipitation, appearing as a distinct belt with growing levels of greenhouse forcing under both the RCP scenarios. Over Indian land, in general, an increase in frequency is projected with the increase in levels of warming under both the RCP scenarios, but the increase in frequency is not uniform. Relatively high frequency of occurrence of extreme precipitation is projected over the southern peninsula and central India compared to the Indo-Gangetic plain.

For increase in levels of warming from 1.5 °C to 2 °C, the Himalayan foothills and Himalayan range do not show any noteworthy change under both scenarios. However, over the Himalayan range, for warmer worlds beyond 2 °C, a distinct belt of the high frequency of occurrence of extreme precipitation is projected that gets progressively more frequent with the increase in levels of warming. Over some parts of Tibetan plateau, under the RCP4.5 scenario, an increase in the frequency is projected with the
increased levels of warming (1.5°C–2.5°C). Under the RCP8.5 scenario, beyond 2.5°C a monotonic increase in the frequency of extreme precipitation is projected over the Tibetan plateau. The Myanmar region shows similar characteristics as south and central India with the maximum frequency of extreme precipitation reaching 18 days/decade (as compared to ~3 days/decade in a natural world) with increased levels of warming under the RCP8.5 scenario, however, under RCP4.5 scenario there is 2–3 fold increase in the frequency of the extreme precipitation. North-west parts of the Indian subcontinent (including Jammu and Kashmir, Pakistan and Afghanistan) do not show any notable increase in the frequency of occurrence of the extreme precipitation with the increase in the levels of warming under the RCP4.5 scenario. However, under the RCP8.5 scenario, with the increase in levels of warming beyond 2°C, an increase in the frequency of extreme precipitation is projected.

4. Conclusions

This study evaluates the impact of every 0.5°C increment in global mean warming (under RCP4.5 and RCP8.5 scenarios) with respect to Natural Historical simulation on the mean and extreme precipitation over the south Asian region using all the available ensembles of NCAR CCSM4 from CMIP5. We find that with increased levels of warming there is an increase in the mean annual precipitation over majority of the south Asian region, except over northwest parts of the Indian sub-continent and equatorial Indian Ocean, where it is projected to decrease. In most of the monsoon and post monsoon months, an increase in maximum and median values of the monthly mean precipitation is projected over Indian land for a wide range of warming levels, under both the RCP scenarios. Frequency and intensity of extreme precipitation is also projected to increase with increase in the global mean temperature.

In general, dry regions are projected to get drier and wet to get wetter with increase in warming, except over Bay of Bengal (gets drier up to 2.5°C of warming and gradually gets wetter at higher warming levels). Despite the uncertainties attached to the projections, warming beyond ~2°C, shows significant changes in the magnitude of precipitation under both RCP scenarios.

Daily rainfall extremes over Indian land are projected to increase up to three times in both the RCP scenarios for 1.5°C–2.5°C levels of global warming. For higher levels of warming (found only under RCP8.5 scenario) a four to six fold increase in the frequency of occurrence of daily precipitation extremes is projected over majority of the Indian land. The Himalayan range, parts of the northeast India, and southern equatorial Indian Ocean show frequent increase in the frequency of extremes with each 0.5°C increase in the levels of warming under both the RCP scenarios. The projected increase in the frequency of extremes is found to be lowest for the northwest parts of Indian subcontinent for all levels of warming and under both the RCP scenarios.

Keeping the 2015 Paris Agreement in perspective, in regard to daily precipitation extremes, we find an increase in the frequency of occurrence over Indian land to be around 2 times under 1.5°C warming, 2–3 times under 2°C warming, and ~3 times and higher under higher levels of warming. Thus, our study provides strong evidence to support the suggestion of limiting global warming to around 1.5°C, in order to restrict the increase in occurrence of precipitation extremes, and its associated impacts.

Acknowledgments

Authors sincerely acknowledge the World Climate Research Program’s Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate-modelling group of NCAR CCSM for producing and making available their model output. This research is partially supported by DST Centre of Excellence in Climate Modeling at IIT Delhi (RP03350), and DST Science and Engineering Research Board (SERB) Project (ECR/2015/000229).

Competing interests

The authors declare no competing financial interests.

ORCID iDs

Mansi Bhowmick https://orcid.org/0000-0002-6985-2493

References

Anand A, Mishra S K, Sahany S, Bhowmick M, Rawat J S and Dash S K 2018 Indian summer monsoon simulations: usefulness of increasing horizontal resolution, manual tuning, and semi-automatic tuning in reducing present-day model biases Sci. Rep. 8 3522
Ashfaq M, Shi Y, Tung W, Trapp R J, Gao X, Pal J S and Diffenbaugh 2009 Suppression of south Asian summer monsoon precipitation in the 21st century Geophys. Res. Lett. 36 L01704
Chaturvedi R K, Joshi J, Jayaraman M, Bala G and Ravindranath N H 2012 Multi-model climate change projections for India under representative concentration pathways (RCPs): a preliminary analysis Curr. Sci. 103 791–802
Chevuturi A, Klingaman N P, Turner A G and Hannah S 2018 Projected changes in the Asian–Australian monsoon region in 1.5°C and 2.0°C global-warming scenarios Earth’s Future 6 339–58
