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Key Points:

- The latest generation of coupled climate models project an increase in severity and frequency of very wet Indian summer monsoon seasons
- Very wet monsoon seasons are projected to occur 8 times more often in 2050–2100 compared to 1965–2015 under unabated climate change
- On the subseasonal scale, there is a shift from days with light rainfall to days with moderate or heavy rainfall

Supporting Information:

Supporting Information may be found in the online version of this article.

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Intensification of Very Wet Monsoon Seasons in India Under Global Warming

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Abstract Rainfall-intense summer monsoon seasons on the Indian subcontinent that are exceeding long-term averages cause widespread floods and landslides. Here we show that the latest generation of coupled climate models robustly project an intensification of very rainfall-intense seasons (June–September). Under the shared socioeconomic pathway SSP5-8.5, very wet monsoon seasons as observed in only 5 years in the period 1965–2015 are projected to occur 8 times more often in 2050–2100 in the multi-model average. Under SSP2-4.5, these seasons become only a factor of 6 times more frequent, showing that even modest efforts to mitigate climate change can have a strong impact on the frequency of very strong rainfall seasons. Besides, we find that the increasing risk of extreme seasonal rainfall is accompanied by a shift from days with light rainfall to days with moderate or heavy rainfall. Additionally, the number of wet days is projected to increase.

Plain Language Summary The South Asian monsoon affects the life of more than one billion people. In the past, summer monsoon seasons (June–September) with very intense rainfall have been associated with widespread floods and an increased number of landslides. Here, we set the focus on the question how the probability of these very wet monsoon seasons will change in the 21st century under climate change. For this purpose, we use the latest generation of climate models with improved performance regarding the Indian monsoon as well as reduced uncertainties compared to the previous model generation. Under the strongest emission scenario, very wet monsoon seasons that used to be observed in 5 out of 50 years in the period 1965–2015 are projected to occur 8 times more frequently in 2050–2100 on multi-model average. With modest mitigation efforts, this is reduced to a factor of 6 in the future period. Besides, this increase in frequency and intensity of extreme monsoon seasons is accompanied by a shift from days with light rainfall to days with moderate or heavy rainfall. Additionally, the number of wet days is projected to increase. The particular character of the change depends on the determination of humankind to reduce carbon emissions and implement mitigation measures.

1. Introduction

There have been numerous floods in recent years associated with the Indian summer monsoon (ISM) as a component of the South Asian monsoon, for example, the Mumbai floods in 2005 (Bohra et al., 2006), floods in Northwest India and Pakistan in 2010 as a response to a strong La Niña event (Mujumdar et al., 2012) or those in Kerala in 2018 (Vishnu et al., 2019). Since the 1980s, there have been more than 95,000 deaths associated with floods and landslides in the countries of the Indian subcontinent (Guha-Sapir et al., 2018). Hunt and Menon (2020) found that the Kerala flooding event in 2018 could be 36% more rainfall-intense under a RCP8.5 climate. Almazroui et al. (2021) projected an increase in the annual maximum consecutive 5-day precipitation in the Asian monsoon regions and derived a higher risk for extreme flooding in the Asian monsoon regions. Given the agricultural yield's sensitivity to the monsoon rainfall variability and associated extremes (DeFries et al., 2016; Prasanna, 2014; Revadekar & Preethi, 2012), understanding how the ISM responds to global warming is also crucial for crop yields and food security in the region as well as for numerous other aspects of public and individual life, like water management or the country's economy.

The data from various phases of Coupled Model Intercomparison projects (CMIPs) has been widely used to examine the projected changes in the global climate as well as its different components such as the ISM. In the last generation of climate models - which were the basis of earlier studies on seasonal extremes – studies identified monsoon rainfall features that were not yet well represented in the CMIP5 models (Tayler et al., 2012).

Recently, the data from the latest phase 6 of CMIP (CMIP6) (Eyring et al., 2016) has become available and it was confirmed that they bring relevant improvements regarding the ISM's characteristics (Dong & Dong, 2021; Gusain et al., 2020; Rajendran et al., 2021). By updating deep convective schemes, by modifying indirect effects of aerosols in cloud formation as well as by implementing finer resolutions the models have undergone further improvements (Gusain et al., 2020; Rajendran et al., 2021). The improved model capacity in capturing the meridional moisture flux convergence might have contributed to the reduction in dry and wet biases in the Asian monsoon region as well as to the models capacity in reproducing extreme precipitation (Dong & Dong, 2021). Nevertheless, other dynamics as the relationship between the ISM rainfall and the Equatorial Indian Ocean Oscillation are not yet fully captured adequately in many models. Given this relationship's crucial impact on the interannual variability of the ISM, also in this generation of CMIP, there still remains potential for further improvements (Rajendran et al., 2021).

There is a widespread agreement among global climate models that the rainfall during the ISM will increase throughout the 21st century (Almazroui et al., 2020; Chaturvedi et al., 2012; Katzenberger et al., 2021; Lee & Wang, 2014; Mei et al., 2015; Menon et al., 2013; Sharmila et al., 2015). Using 32 models of the latest climate model generation (CMIP6), Katzenberger et al. (2021) quantified the projected summer monsoon rainfall increase to be between 9.7% and 24.3% by the end of the 21st century depending on the underlying emission scenario. Also a linear dependence of the ISM rainfall and the global temperature independent of the scenarios was found and estimated to be 0.33 mm/day per degree Celsius which corresponds to 5.4% of the current annual rainfall (Ha et al., 2020; Katzenberger et al., 2021). Thus, the rainfall of the ISM domain is more sensitive to rising global temperatures than global precipitation (1%–3% per degree Celsius, Ha et al. (2020)). In addition, an increase of the interannual variability of seasonal rainfall is projected (Jayasankar et al., 2015; Katzenberger et al., 2021; Kitoh, 2017; Menon et al., 2013) raising the amount of rainfall in some seasons even further.

While the literature on the projections of the ISM's interannual variability has been converging toward an intensifying tendency, the particular outcome for wet seasonal extremes had only drawn limited attention until recent years, which was the motivation for Kamizawa and Takahashi (2018) to use 22 CMIP5 models to address this research question. In their study, the changes in the wettest (driest) and second wettest (driest) season between 2007–2031 and 2076–2100 were examined under the Representative Concentration Pathway 4.5 (RCP4.5). Most of the CMIP5 models projected that the wet seasonal extremes expand over the Indian subcontinent, but it has to be noted, that focusing on the maxima is a method highly susceptible to the bias of outliers. These results coincide with the earlier study by Sharmila et al. (2015), who found that the years with strong monsoon rainfall are expected to increase in frequency as well as severity by the end of the 21st century but the results still had a very strong inter-model spread. Against this background and given the improvements in CMIP6 compared to CMIP5 as explained before, the results of CMIP6 regarding the seasonal extremes are of particular interest. Additionally, Dong and Dong (2021) point out the improvements between CMIP5 and CMIP6 regarding the daily rainfall amount (exceeding 10 and 20 mm) which was additional motivation for this study to also analyze the question how the changes in seasonal rainfall translate to selected indices on the subseasonal scale.

Here, we use the data of 32 CMIP6 models in order to quantify the changes in seasonal rainfall extremes in India under different emission scenarios. We also analyze how these changes translate to the subseasonal scale, particularly changes of daily rainfall. In order to do so, we select six models with a better monsoon performance in the historical simulations in order to get an insight about their projections following the detailed evaluation provided by Rajendran et al. (2021). Section 2 gives an overview about the underlying scenarios, the CMIP6 data, the definition of seasonal extremes and the characterization of daily rainfall as well as the selection criteria for the models. Section 3 gives a detailed insight about our results and in Section 4 these results are discussed in the context of similar studies.

2. Methods

2.1. CMIP6 Data

For our analysis we include all models that were available for the historic period (1850–2015) as well as the future period (2015–2100) under SSP5-8.5 in ScenarioMIP (O'Neill et al., 2016) which is the combination of the socio-economic scenario pathway 5 (SSP5) and the RCP8.5 (Van Vuuren et al., 2014). We also conduct the analysis for the SSP2-4.5 (SSP2, RCP4.5) and SSP1-2.6 (SSP1, RCP2.6) scenario. Even if for some models several realizations were available, we only used one ensemble member. We select the area of India and neighboring areas (longitude 67°–98°E and latitude 6°–36°N; see Figure S1 in Supporting Information S1) as ISM region and focus on the land area. The analysis of the wet seasons is performed using the individual grids of each model (For native model resolution, see Table S3 in Supporting Information S1), and for further spatial analysis, the grids of the models with the better ISM performance in the historical simulations are standardized to a 1° × 1° latitude/longitude grid by first order conservative remapping. In this context, it has to be noted that the native spatial resolution strongly differs between the models ranging from 100 to 500 km over land. For the analysis of the ISM seasons we use monthly data, for the research questions on subseasonal we analyze data on a daily scale. For each model and each summer season, we calculate the mean monsoon rainfall by averaging the monthly rainfall data from June-September (JJAS) over the region of interest to obtain the mean daily precipitation (units: mm/day; please note that e.g., a total rainfall amount of 880 mm per season is equivalent to 880 mm/122 days in season = 7.2 mm/day). In order to compare the rainfall in 2050–2100 to a baseline period, we decided to use 1965–2015 in accordance with the Intergovernmental Panel on Climate Change Assessment Report 6 guidelines (Masson-Delmotte et al., 2021). It has to be noted that the baseline period is not a stationary period since it includes for example, the strong trend observed in the second half of the 20th century due to the significant influence of aerosols. For further insight in the timeseries of mean ISM rainfall refer to Katzenberger et al. (2021). The 50-years period is chosen in order to obtain statistically robust results. The results for the stationary preindustrial baseline period 1900–1950 as well as the shorter period 1985–2015 provide comparable results (See Tables S2 in Supporting Information S1).

2.2. Definitions

Observations have shown that even in seasons that exceed the longterm rainfall averages by 10% (which corresponds to one standard deviation of longterm seasonal precipitation; Singh et al. (2019)), severe floods on large scales with significant impact on the Indian food production and the Gross Domestic Product occur (Gadgil & Gadgil, 2006; Wang et al., 2015). Thus, some studies define surplus/excess/flood/wet years as the longterm average ISM rainfall plus 10% of the mean (Mohanty et al., 2002; Parthasarathy et al., 1994; Singh et al., 2019). To focus on the even more extreme monsoon seasons, we define very wet monsoons seasons by the 90%-percentile in this study. This means that we classify a monsoon season as very wet if the seasonal rainfall falls within the range of rainfall during the five wettest seasons in 1965–2015, thus what corresponds to a 1-in-10-years monsoon season. These very wet seasons can be considered as years with a very high risk for severe floods and socioeconomic impacts. For the analysis on the subseasonal scale, we classify the daily rainfall amount following the definitions applied by Sharmila et al. (2015): Wet days are defined as days with rainfall of at least 0.1 mm/day and light rainfall as precipitation between 0.1 and 10 mm/day. Moderate rainfall ranges from 10 to 40 mm/day and heavy rainfall is defined as precipitation exceeding 40 mm/day. We also calculated the Simple Daily Intensity Index (SDII) in order to get an insight on the mean precipitation amount at rainy days (>1 mm).

2.3. Model Comparison

Rajendran et al. (2021) provide a detailed study about the evaluation of the CMIP6 models in the context of the ISM. The selection criteria are based on the seasonal monsoon rainfall, the interannual variability but also aspects like the spatial distribution. Applying these criteria for 1951–2010 and using gridded rainfall data of the Indian Meteorological Department (Pai et al., 2014), six of the 32 models available for this study are classified to have the best historic monsoon performance in their study. These models are considered with particular focus in our study.

3. Results

In order to understand the changes in the seasonal precipitation between 1965 and 2015 and the second half of the 21st century, we analyze the former and future distribution of yearly JJAS mean precipitation (Figure 1). Under the SSP5-8.5 scenario, the multi-model average shows an increase in the seasonal mean precipitation (6.8 mm/day) as compared to the historical period (5.6 mm/day). Taking only the models with a reasonably good representation of the ISM into consideration, the increase is from 6.2 mm/day to 7.3 mm/day. In the modest mitigation scenario (SSP2-4.5), the historic seasonal mean increases to 6.3 mm/day averaging over all models and

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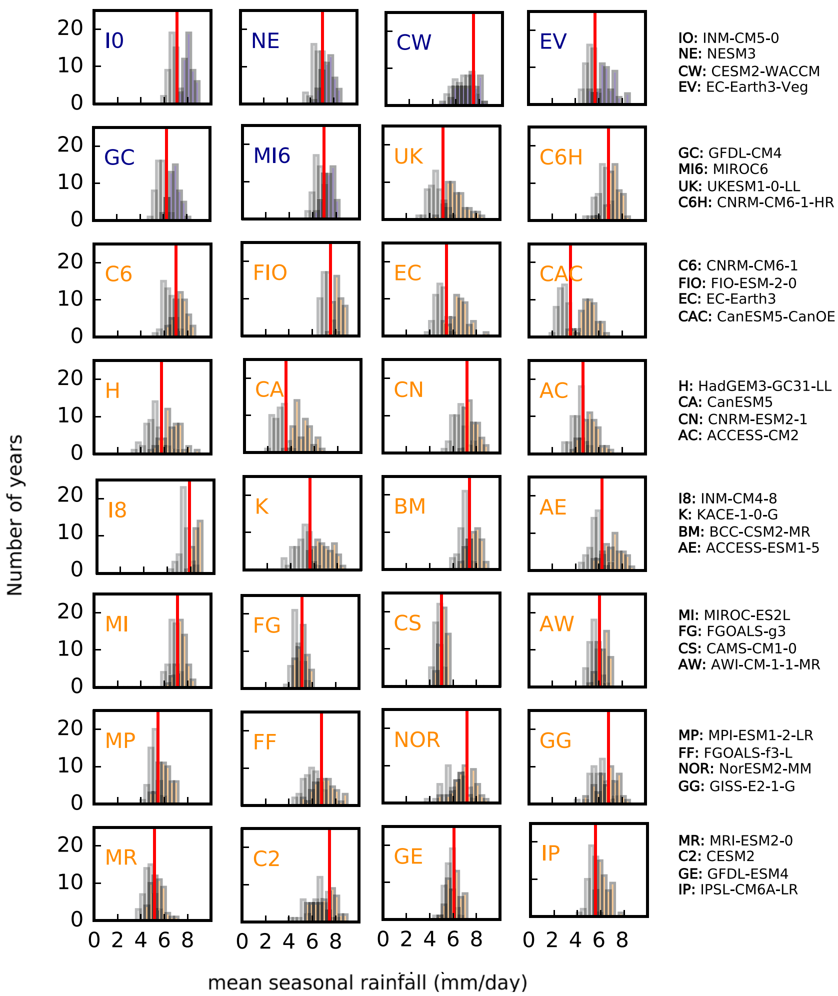

Figure 1. General increase from mean seasonal summer rainfall [mm/day] of the Indian monsoon toward wetter years between the historical (1965–2015) and the future period (2050–2100) in the Indian monsoon region under unabated climate change (SSP5-8.5). The historic monsoon rainfall distribution is presented in gray, the future distribution in colors: The blue bars represent the models with the best representation of the Indian summer monsoon, orange the remaining models. The vertical red line represents the 90%-percentile of 1965–2015, thus it marks the threshold of the 5 wettest seasons in the historic period. The abbreviations refer to CMIP6 models.

in SSP1-2.6 the increase is to 6.2 mm/day. This change is accompanied by an increase in variation of seasonal monsoon precipitation: For all models, the standard deviation increases in SSP5-8.5, which is associated with an increase of the year-to-year (interannual) variability.

By definition of the 90%-percentile with regard to the baseline period 1965–2015, five extraordinary wet seasons have exceeded the threshold in this past period. For the future period 2050–2100, the general shift of the precipitation distribution toward wetter seasons is accompanied by more seasons exceeding this threshold. Accordingly, dry seasons are projected to be rarer in the 21st century (only taking into account rainfall; for water availability the role of evaporation is also crucial which was beyond the focus of this study). The temporal development toward more severely wet seasons is displayed in Figure 2a. The variation is within multi-model mean plus one standard deviation (based on the historical CMIP6 data ranging from 1950 to 2015) for 1950–2027, but a significant increase beyond the observed natural variability emerges in 2027, which accelerates non-linearly. The spatial distribution of the 90th-percentile of the mean seasonal rainfall in 1965–2015 is displayed in Figure 2b. The regions in which the monsoon seasonal rainfall is projected to intensify most is shown in Figure 2c. Particularly the Himalayan region, Bangladesh, the west coast and central India are projected to intensify most. The number of seasons in the period of 2050–2100 that are classified as very wet according to our definition, can be seen at

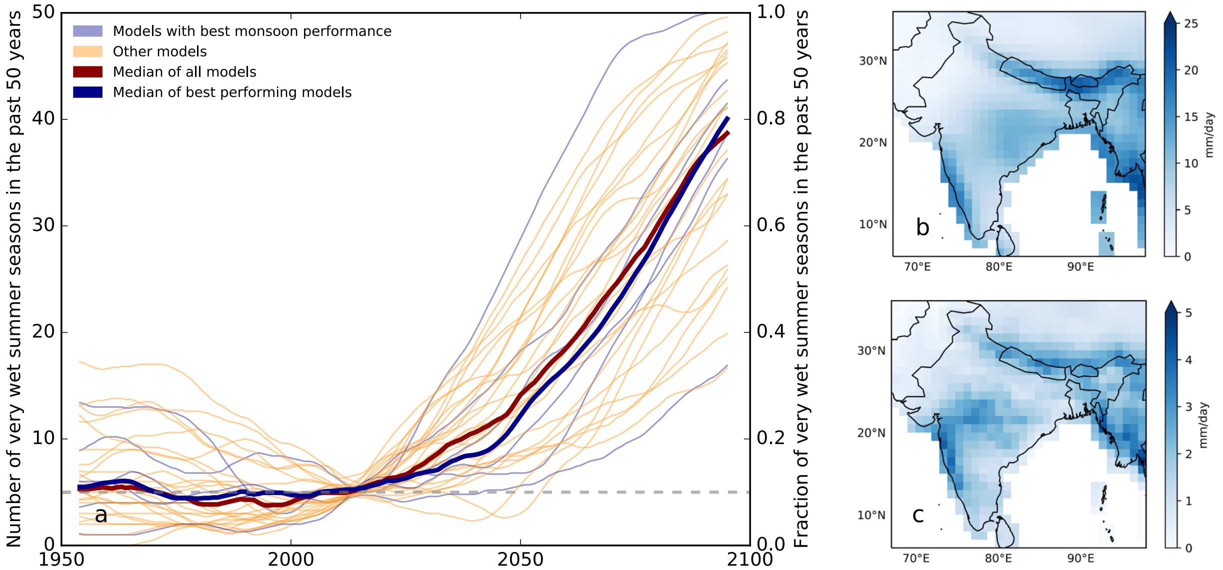

Figure 2. (a.) Increase of very wet Indian summer monsoon (ISM) seasons (JJAS) in the 21st century under unabated climate change (SSP5-8.5). For each of the 32 models in our study, the number of very wet seasons in the preceding 50-year period is calculated (1965–2015, 1966–2016, …, 2051–2100), and the resulting timeseries are smoothed with a 10 years moving average. For color explanation refer to Figure 1. The red curve marks the median of all models. The blue curve marks the median of the models with better ISM representation. The horizontal gray line marks the reference from 1965 to 2015 when per definition 5 out of 50 seasons were very wet. 90th-percentile based on mean seasonal rainfall in 1965–2015 (b.) and projected change in the 90th-percentile between 1965–2015 and 2050–2100 under SSP5-8.5 (c.) for the multi-model mean of six models with best monsoon performance.

the very right of the Figure 2a and in the circular bar plot in Figure 3. The multi-model mean of very wet seasons in 2050–2100 is 38.9 under SSP5-8.5 (thus 7.8 times more than in 1965–2015), 29.1 under SSP2-4.5 (factor 5.8) and 25.1 under SSP1-2.6 (factor 5.0). Results for individual models are given in Table S1 of Supporting Information S1. The models with a better representation of the ISM in the historical simulations project 39.5 very wet seasons in 2050–2100 under SSP5-8.5, 24.1 seasons under SSP2-4.5 and 22.1 seasons under SSP1-2.6.

The relationship between the increase in very wet seasons under SSP5-8.5 and the increase in global mean temperature is - apart from some few outliers - relatively linear (see Figure S2 in Supporting Information S1; with outliers: correlation coefficient = 0.12). The slope is 9.6 seasons/K, which means that per degree of global warming, it is projected that within 50-year-periods, 9.6 more summer monsoon seasons are to be very wet.

The results for the changes in the amount of daily precipitation are displayed in Figure 4. The spatial distribution for the individual models can be found in the Figures S3 and S4 of Supporting Information S1. The number of wet days (>0.1 mm) is projected to increase in most of the Indian monsoon region. Interestingly, most of the general circulation models coincide in an increase of wet days particularly in the Northwest of India. Nevertheless, there still remains a considerable range between the intensity of the change in this area. The number of days with light rainfall (10 mm $> x >$ 0.1 mm) in each season is projected to decrease in multi-model average, particularly in Bangladesh and North of the Himalayan mountains as well as the West coast of India. In Pakistan, the number is projected to increase. Regarding moderate rainfall days (40 mm $> x >$ 10 mm), the multi-model mean suggests an increase in most areas, while in Bhutan and South Pakistan a decrease is projected. However, the individual models show a broad range of different patterns with limited overlap between the models. For heavy rainfall days (>40 mm), an increase in the order of 0–2.5 days per season is projected, specially in the Westen Ghats, the South coast of Bangladesh and the Himalayan region. These results coincide with the results for the SDII that show an intensification of the mean precipitation amount on rainy days (Figure S5 in Supporting Information S1).

4. Discussion

In this study, we use 32 CMIP6 models to analyze the future frequency of very strong rainfall seasons under climate change. We found a clear, general increase of the yearly ISM rainfall between 1965-2015 and 2050–2100 toward wetter seasons. Under SSP5-8.5, the increasing trend becomes significant in 2027. Similar intensifying

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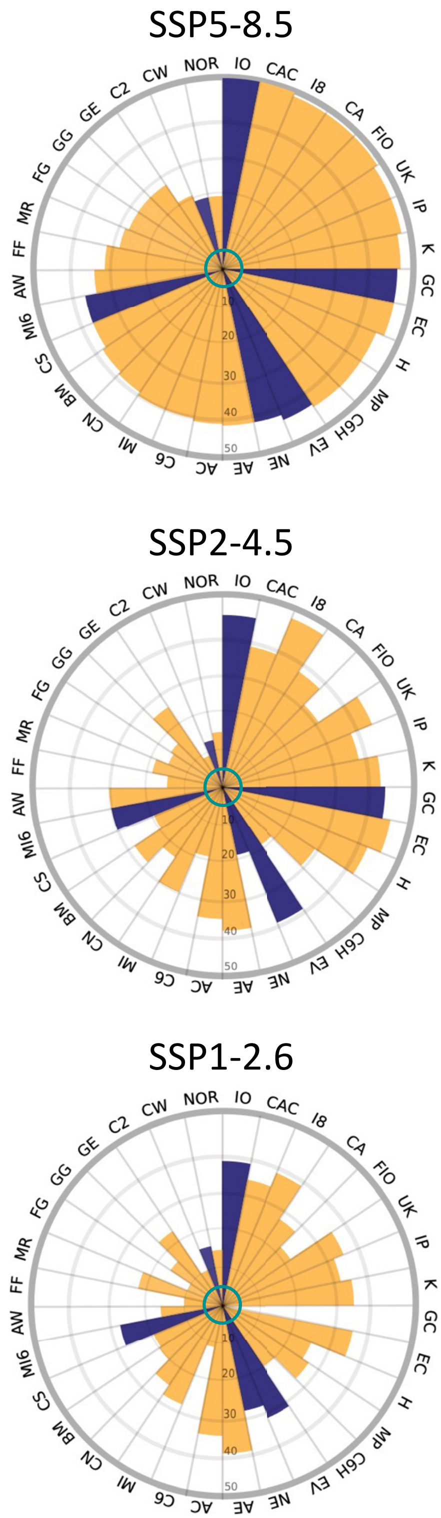

Figure 3. Increase in the number of very wet Indian summer monsoon (ISM) seasons by the second half of the 21st century in comparison to 1965–2015 in the Indian monsoon region under sustainable development (SSP1-2.6), modest mitigation (SSP2-4.5) and unabated climate change (SSP5-8.5). Each circle segment represents the result for one model. A full segment means that 50 out of 50 seasons in the future period of 2050–2100 are projected to be very wet (compared to the 1965–2015 baseline period). Blue bars represent models with a better representation of the ISM in the historical simulations, while orange bars belong to the models with less ability of simulating the ISM in historical simulations. The cyan circle represents the reference period of 1965–2015, in which by definition 5 seasons exceed the 90%-percentile of that period. For GFDL-CM4 (GC) in SSP1-2.6 no data was available. For model abbreviations refer to Figure 1.

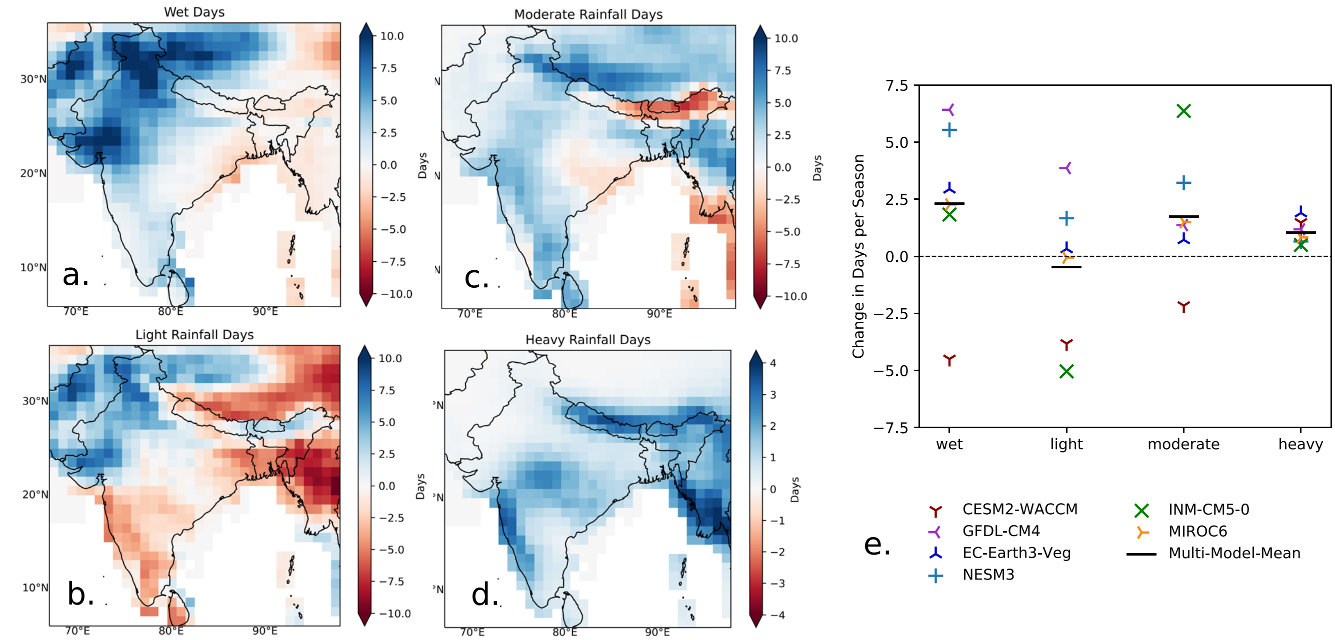

Figure 4. Change in (a.) wet days (>0.1 mm) and days with (b.) light (10 mm > x > 0.1 mm), (c.) moderate (10 mm > x > 40 mm) and (d.) heavy (>40 mm) rainfall between 1965–2015 and 2050–2100 under SSP5-8.5. The change is shown as number of days per season that change in average between the two periods. The multi-model mean of the six models with best monsoon performance in the historical simulations is displayed. In (e.) the results for the single models as well as the multi-model mean are summarized (mean from monsoon region). More details regarding the spatial distribution of the change are displayed in the Figures S3 and S4 of Supporting Information S1.

tendencies of very wet seasons were found by other studies, but partly were not yet able to provide statistically robust results (Kamizawa & Takahashi, 2018) or still had a large spread between the models selected (Sharmila et al., 2015; Turner & Annamalai, 2012). Sharmila et al. (2015) used the 4 CMIP5 models that captured monsoon rainfall features best and found that strong monsoons might get wetter under the strongest emission scenario. This might be due to a projected increase in persistent wet spells and a decrease in dry spells in strong monsoon years (Sharmila et al., 2015). In the literature, these terms are commonly referred to as active and break spells (Singh et al., 2014). The spells of the Indian monsoon have their origin in the interaction between multiple modes of propagating intraseasoal oscillations consisting of 10–20 days and 30–50 days fluctuations (Krishnamurthy & Shukla, 2007). In observations, an increase of the intensity of wet spells between 1951-1980 and 1981–2011 was found by a previous study (Singh et al., 2014). However, changes in frequency, duration and extent are still under scientific debate (Singh et al., 2019).

The increasing tendency of very wet seasons is linked to the projected increase of the mean ISM rainfall amount examined and confirmed by several studies (Chaturvedi et al., 2012; Katzenberger et al., 2021; Lee & Wang, 2014; Mei et al., 2015; Menon et al., 2013; Sharmila et al., 2015). There is a widespread agreement (Singh et al., 2019) that this trend is the consequence of the Indian Ocean's rising temperature increasing atmospheric moisture content and thus moisture convergence (Cherchi et al., 2011; Mei et al., 2015; Seth et al., 2013; Sooraj et al., 2015). In addition to this increased amount of precipitation in June-September, an increase in interannual variability of seasonal rainfall is projected (Jayasankar et al., 2015; Katzenberger et al., 2021; Kitoh, 2017; Menon et al., 2013). Since the occurrence of El-Niño and La-Niña years are linked to weak and strong ISM years (Kumar et al., 2006), the El Niño Southern Oscillation (ENSO) might contribute to this trend in interannual variability. Nevertheless, no consensus regarding the future of ENSO activity, for example, regarding frequency and amplitude has been reached (Cai et al., 2015; Chen et al., 2017; Collins et al., 2010).

Given that Dong and Dong (2021) found an improvement of the representation of daily rainfall with more than 10 mm and more than 20 mm, the results of CMIP6 regarding the daily amount of rainfall are of particular interest. In multi-model mean, we found a decrease of light rainfall and an increase of heavy rainfall days in a large area of the Indian monsoon region confirming the results of a previous study based on CMIP5 models (Sharmila et al., 2015). While the results of Sharmila et al. (2015) indicate a rather decrease of days with moderate rainfall, the CMIP6 models in our study tend to project an increase in moderate rainfall days. Simultaneously, the spatial pattern of the projected changes is quite similar in CMIP6 and CMIP5. However, particularly regarding the light rainfall days, there also remains a disparity between models in CMIP6. These differences are also a result of different wet or dry bias in the individual models, in both Sharmila et al. (2015) as well as this study.

Regarding the number of wet days during a monsoon season, we found an increasing tendency toward future monsoon seasons. This result is opposing the result of Sharmila et al. (2015) who reported a decrease in the multi-model mean. But as the authors of this study also pointed out, this result is based on the spatial pattern of four CMIP5 models with a rather limited overlap between the tendencies in the individual models. In comparison, the results from the CMIP6 models show less spread between the individual models and coincide also regarding the strong increasing tendency in the Northwest of the monsoon region. The difference between CMIP6 and CMIP5 might be due to the different climate models underlying the analysis, but could also be a result of the improvements between the model generations.

By using only one ensemble member per model in this study, we neglected the possible contribution of internal model variability to the uncertainty of the model's projection. Besides, as some model centers provide several models and certain model components are used among different modeling groups, the models cannot be regarded independent from each other (Knutti et al., 2017).

5. Conclusion

We used 32 of the latest generation of climate models in CMIP6 to update the findings on very wet seasons from CMIP5. For this purpose, we analyze the change in very wet ISM seasons between 1965–2015 and 2050–2100 under unabated (SSP5-8.5), modestly abated (SSP2-4.5) as well as strongly abated (SSP1-2.6) climate change. Under all scenarios, we found a clear change toward wetter seasons between the two periods which is associated with an increase in severity as well as frequency of very strong rainfall seasons. This increase is less clear under SSP2-4.5 and SSP1-2.6. Under the same scenario, very wet seasons that used to occur in 5 out of 50 years in 1965–2015 are projected on average to appear in 39 out of 50 years in 2050–2100. Under SSP2-4.5, they are projected to occur in 29 out of 50 years. Thus, even modest efforts to mitigate climate change can have a strong impact on the frequency of very strong rainfall seasons.

In this study, we also set the focus on the question how this intensification of very wet ISM seasons translates to the subseasonal scale, in particular the amount of daily rainfall. In this context, we found that the CMIP6 models project a shift from days with light rainfall days toward days with moderate or heavy rainfall. This intensification of daily rainfall can also be seen in the increase of the SDII. However, the CMIP6 models remain with a considerable multi-model spread for some regions. Regarding the number of wet days, the models largely coincide in projecting an increasing tendency, particularly for the Northwest of the monsoon region.

While an increase (decrease) in summer monsoon rainfall is associated with an increase (decrease) in crop yields, this relationship is not valid for precipitation rainfalls exceeding or falling below a certain threshold (Kumar et al., 2004; Prasanna, 2014). Varghese et al. (2020) projected a decrease in future rice yields in Kerala as a result of a rise in temperature and a decrease in rainfall in the region that in combination reduces the maturity time of the crop as well as the total biomass production. Revadekar and Preethi (2012) found that fluctuations in various indices of precipitation extremes of the ISM are related to foodgrain yields. Considering additionally the fact that the population of India is expected to further grow and to reach 1.5 billion in the mid 21st century (Dyson et al., 2005), the increased frequency of very strong ISM rainfall seasons found in this study has to remain object of further studies in order to implement adaptions strategies in agriculture and not to become a serious threat to food security in India.

Data Availability Statement

The datasets from CMIP6 simulations are available via the CMIP6 Search Interface: https://esgf-node.llnl.gov/search/cmip6/ (last access: 31 March 2022) (WCRP, 2022). The codes for this study are permanently available: https://doi.org/10.5281/zenodo.6973330 (Katzenberger, 2022).

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