Future Changes of Summer Monsoon Characteristics and Evaporative Demand Over Asia in CMIP6 Simulations

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Abstract Future greenhouse warming is expected to influence the characteristics of global monsoon systems. However, large regional uncertainties still remain. Here we use 16 Coupled Model Intercomparison Project Phase 6 (CMIP6) models to determine how the length of the summer rainy season and precipitation extremes over the Asian summer monsoon domain will change in response to greenhouse warming. Over East Asia the models simulate on average on the earlier onset and later retreat; whereas over India, the retreat will occur later. The model simulations also show an intensification of extreme rainfall events, as well as an increase of seasonal drought conditions. These results demonstrate the high volatility of the Asian summer monsoon systems and further highlight the need for improved water management strategies in this densely populated part of the world.

Plain Language Summary Future climate change is expected to influence the characteristics of the global monsoon system. However, large regional uncertainties still remain. Using 16 Coupled Model Intercomparison Project Phase 6 models, we determine the impact of greenhouse warming on the length of the summer rainy season and precipitation extremes over the Asian subregional monsoon domains (East Asia, western North Pacific, India, and Indo-China Peninsula). Over East Asia the models simulate on average an earlier inception and a later termination of the summer rainy season, whereas over India, the termination will occur later. The model simulations also show an intensification of extreme rainfall events, as well as an increase of seasonal drought conditions. Our results demonstrate the high volatility of the Asian summer monsoon system and further highlight the need for improved water management strategies in this densely populated part of the world.

1. Introduction

Monsoon systems experience a strong seasonal contrast between land and ocean temperatures, which in turn triggers wind reversals, changes in moisture supply and resulting precipitation shifts (Liu et al., 2015; Wang & LinHo, 2002). The Asian summer monsoon (ASM) is the most extensive and influential monsoon system since large populations depend on monsoonal rainfall to sustain agricultural, municipal and industrial water demands (Intergovernmental Panel on Climate Change, 2014; Turner & Annamalai, 2012). The ASM brings not only necessary water resources but also associated with extreme contrasts in precipitation and drought (Freychet et al., 2015). The Intergovernmental Panel on Climate Change provided an indication in their fifth assessment report that recent climate changes have exerted significant influences on biogeophysical systems (Intergovernmental Panel on Climate Change, 2014). Since global warming is likely to continue in the coming decades (Kim & Ha, 2018; Tariku & Gan, 2018), monsoon seasons are expected to change in terms of mean state, duration, frequency of climate extremes, and altered hydrologic conditions. Therefore, to implement sustainable water management plans, it is essential to understand the response of monsoon systems to greenhouse warming.

Previous studies demonstrated that future climate change will alter the statistical properties of extreme rainfall events (Dong et al., 2016; Kripalani et al., 2007; Lee & Wang, 2014). According to some studies, the ASM onset would occur earlier in response to rising land surface temperatures (Zhang & Qian, 2002), ocean heat content (Li & Yanai, 1996), and moisture content of the atmosphere (Hsu et al., 2012). Other authors have suggested a delayed monsoon onset as a result of weakened upper tropospheric thermal contrasts (Ueda...
et al., 2006) and an overall weaker monsoon circulation (Zhang et al., 2012). Several studies also discuss the future length of ASM under the global warming scenario. The length of ASM will increase due to future earlier onset and delayed retreat (Kitoh et al., 2013; Lee & Wang, 2014; Moon & Ha, 2017). On the contrary, some studies have suggested that the weakening of the meridional gradient in upper tropospheric temperature induces the delayed onset and earlier retreat (Saberaali & Ajayamohan, 2018; Saberaali et al., 2012). Those contrasting features simulated by general circulation models (GCMs) from the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Kitoh et al., 2013; Lee & Wang, 2014; Moon & Ha, 2017) suggest uncertain changes in the monsoon characteristics under global warming and necessitate timely updates of relevant analyses. Nonetheless, despite the incongruity GCM simulations, the Clausius-Clapeyron (C-C) relationship provides a plausible indication that the precipitation extremes are expected to occur more frequently in a warming climate (Min et al., 2011; Scoccimarro et al., 2013). This can have profound implications for the Asian monsoon domain (Scoccimarro et al., 2013; Sillmann et al., 2013; Zhang et al., 2018). To further improve future climate model projections, the scientific community—under the auspices of the World Climate Research Programme—has conducted the CMIP6 (Eyring et al., 2016). Current state-of-the-art GCMs in the CMIP6 archive have shown their advanced ability to capture large-scale patterns of the ASM precipitation (Gusain et al., 2019). We, therefore, use the latest subset of CMIP6 projections to further document the sensitivity of the ASM to greenhouse warming (Riahi et al., 2017). Despite the vital roles of the regional monsoon systems, subregional future changes have not been analyzed in detail. Here, we focus on local changes in four subregions of the Asian monsoon domain.

2. Data and Method

2.1. Data Collection From the CMIP6 Archive

We first analyze daily precipitation, 2-m air temperature, and runoff for the historical period (1979–2014) and a future period from 2065–2100 using climate projections under the Shared Socioeconomic Pathway (SSP) 2–4.5 scenario (hereafter SSP2–4.5) in the CMIP6 archive. The SSP scenarios of the CMIP6 framework were developed to facilitate integrative analyses of future climate impacts, vulnerabilities, adaptation, and mitigation (Riahi et al., 2017). The SSP2–4.5 scenario updates the Representative Concentration Pathway 4.5 (RCP 4.5) of CMIP5, assuming the same medium level of greenhouse gas emission scenario. The land use and aerosol pathways hypothesized in SSP2–4.5 are not extreme relative to other SSP scenarios and are combined with an intermediate level of societal vulnerability (O’Neill et al., 2016). More details about the SSP scenarios can be found in O’Neill et al. (2016). For our analysis, we produced CMIP6 pentad data with the nonoverlapping 5-day averages of a subset of 16 CMIP6 models available for analysis. For our analysis, we use the historical simulations and SSP2–4.5 experiments of these 16 models as well as reanalysis data (Table S1 in the supporting information).

To study changes of terrestrial evapotranspiration, we additionally collected monthly future projections of the near-surface upward and downward short radiations, upward and downward longwave radiations, mean air temperature, relative humidity, and wind speed available from the seven GCMs (the bold texts in Table S1).

The overall performance of the CMIP6 GCM historical simulations is evaluated against the pentad precipitation from the Global Precipitation Climatology Project data set (Xie et al., 2003) and the ERA-Interim data (Dee et al., 2011) from the European Centre for Medium-Range Weather Forecasts. To quantify the fidelity of the 16 CMIP6 models in terms of representing key features of the ASM climate, we use the Taylor diagram over the Asian domain [0–60°N, 60–160°E] (Figure S1a). The spatial correlation coefficients between the simulated precipitation and the reference data ranges between 0.65 and 0.9. In the case of air temperature, the pattern correlation coefficients were above 0.95 (Figure S1a). The 16-member multimodel ensemble (16MME) reproduces the reanalysis data reasonably well.

2.2. Definition of Summer Monsoon Domain and Rainy Season

The most distinctive characteristic of monsoon systems is the annual cycle of precipitation fields. Previous studies have defined the global monsoon (GM) domain by comparing rainfall ranges of summer and winter-time (Kitoh et al., 2013; J. Liu et al., 2009; Wang & Ding, 2006). To define the ASM domain in the context of the annual cycle, we carry out a harmonic analysis at each grid point. Since the harmonic analysis is...
relatively insensitive to noise, we can get useful signal regardless of the noise. The harmonic analysis is performed as

\[ \text{AmpR}(n) = \text{AMP}_0 + \sum_{t=\text{Jun}}^{t=\text{Aug}} \text{AMP}(n) \times \cos \left( \frac{2\pi n}{T} (t - \text{PHA}(n)) \right) \]

where \( n, t, \text{AMP}(n), \text{PHA}(n) \) denote the harmonic order, time, amplitude, and phase of \( n \)-th harmonic, respectively. \( \text{AMP}_0 \) is the mean of Fourier amplitude. As a conceptual definition of the Northern Hemisphere summer, June to August \( \text{AmpR}(n) \) is investigated. We suggest the new monsoon domain is defined with two conditions: (1) \( \log(\text{AmpR}(2)/\text{AmpR}(1)) < -0.1 \) and (2) \( \text{AMP}(1) > 2 \text{ mm/day} \) (Figure 1a). It is noted that this new definition well agrees with previously suggested ones (Figure S2). Furthermore, the harmonic analysis definition excludes parts of northern America, which were previously included in monsoon domain definitions. The main advantage of our new definition of the GM domain is its robustness, as it does not consider precipitation in mesoscale and smaller scales by using harmonic analysis. We study the simulated future change over the ASM domain, which is defined by Kitoh et al. (2013 hereafter K13; Figure S2). In addition, our study targets four subregional monsoon domains during the summer period (May-September) focusing on the onset time of monsoons (Figure S3a) over India (IND; 60°-90°E, 5°-30°N), the Indo-China Peninsula (ICP; 90°-120°E, 5°-30°N), East Asia (EA; 110°-140°E, 30°-55°N), and the western North Pacific (WNP) region (135°-160°E, 5°-25°N), using the new ASM domain definition presented above (Figure 1a).

Our methodology for analyzing rainy seasons is similar to that used by Wang and LinHo (2002) who defined the onset and retreat of monsoon using the sum of the first 12 harmonics of precipitation. This monsoon definition is advantageous because the same threshold of onset and retreat can be used irrespective of locations. We have modified Wang and LinHo’s (2002) definition by adding the duration condition (that the precipitation higher than criteria should last more than two pentads after the onset date). As a guide, the simulation skill for the rainy season using MME in the concept of the spatial distribution is reasonable with a high pattern correlation coefficient (Figure S3). In this study, the area-averaged precipitation over the monsoon sub-region domain is used for the representative rainfall. It is a useful way not only to identify the characteristics but also to capture the subregional rainfall well. The climatological onset date of the summer monsoon is early May over ICP, early June over IND, mid-June over EA, and late July over WNP. The withdrawal occurs in late July over EA, late September over IND and WNP, and early October over ICP. These climatological onset and retreat dates are quite sensible compared to previous studies. The present index is well matched with other definitions of monsoon onset and retreat (Table S2, Moon & Ha, 2019). Since most of the models tend to underestimate the precipitation amounts over Asia, the onset criteria for model projection is modulated from 5 to 3.5 mm/day, which is the mean difference between the reanalysis data and model outputs. The model performance skills for onset and retreat are shown in Figure S1b.

2.3. Extreme Rainfall Index

A 20-year return value of precipitation (P20) suggested by Zwiers and Kharin (1998) is investigated to study the extreme climate changes in precipitation. The P20 index is the daily rainfall intensity of a 20-year return period using a generalized extreme value distribution. The changes in P20 between the reference period (1995–2014) and the future (2081–2100) (Figure 3) document how daily rainfall is projected to change in the Asian subregional monsoon system. As another approach, we have also examined the changes in the extreme indices that are taken from the Expert Team on Climate Change Detection and Indices. The maximum 1-day precipitation (RX1day) and extremely wet day total amount when the daily precipitation exceeds the 95th percentile of the wet-day precipitation (R95p) are investigated during the summertime (May to September).

2.4. Complementary Principle of Evapotranspiration

Despite the ability of GCMs to simulate near-surface latent heat fluxes, the energy fluxes modeled by GCMs are often biased, even in reanalysis data sets (Ma & Szilagyi, 2019; Ma et al., 2019). Instead of direct use of the latent heat fluxes projected by GCMs, we employed the generalized complementary relationship (GCR) of Szilagyi et al. (2017).

The GCR is based on the complementarity between atmospheric evaporative potential \( (E_p) \) and actual evapotranspiration on a land surface \( (E) \). In this theory, the potential evaporation under wet surface conditions
Figure 1. (a) Global monsoon (GM) domain defined by the present study (blue shaded) and Wang and Ding (2006) (black contour). (b) Percentage changes (2065–2100 minus 1979–2014) in the precipitation per global mean precipitation by 16MME. The cross symbol indicates the region where summer precipitation is above 4 mm/day, and the black line shows the GM domain. (c) Percentage changes (2065–2100 minus 1979–2014) in the last decades of the 21st century precipitation per 1 °C of global warming in CMIP6 SSP2–4.5 scenarios during the summertime (e.g., MJJAS) over East Asia (EA), western North Pacific (WNP), India (IND), and Indo-China Peninsula (ICP).
is separately defined as the wet-environment evapotranspiration \((E_w)\). When a surface is wet, \(E\) would be limited by the atmospheric evaporative potential only (i.e., \(E = E_p = E_w\)). However, if water availability on the surface does not sustain \(E_w\), \(E\) should not reach \(E_w\), and the energy surplus \((E_w - E)\) heats the overlying atmosphere, raising its evaporative potential beyond \(E_w\) (i.e., \(E < E_w < E_p\)). Since a smaller \(E\) results in a larger difference between \(E_p\) and \(E_w\). This land-atmosphere feedback mechanism results in an inverse relation between \(E_p\) and \(E\).

By modifying the definitive derivation of Brutsaert (2015), Szilagyi et al. (2017) generalized this principle with a polynomial approximation. The following studies have confirmed the superior performance of the GCR to sophisticated land surface models, reanalysis climate data, and even a state-of-the-art spatial interpolation of flux observations (D. Kim et al., 2019; Ma & Szilagyi, 2019; Ma et al., 2019). More details about the GCR are given in Szilagyi et al. (2017). By applying the MME of the collected energy, humidity, and wind speed projections to the GCR, we produced monthly \(E\), \(E_w\), and \(E_p\) time series for the same historical and future periods.

3. Results

3.1. Changes in Precipitation Rate and Rainy Season

Based on the C–C relation, the saturation global water vapor pressure will increase approximately by 7% per 1 °C rise in global temperature (Boer, 1993; Held & Soden, 2006). This physical basis suggests that global warming would enhance precipitation on the land surface. The summertime “wet-get-wetter” response is shown as the climate warms (Figure 1b). The summer rainfall over the domain where has 4 mm/day in the present climate will amplify at about 20% in the future climate. According to the previous studies using CMIP5 (Hsu et al., 2013; K13; Lee & Wang, 2014), monsoon precipitation is likely to strengthen in the future with its intensity due to increased moisture convergence by the surface evaporation. Our analysis of the MME climate projections under the SSP2–4.5 scenario shows that global precipitation during the last decades of the 21st century is expected to rise at about +2% per 1 °C, being consistent with Boer (1993), indicating that the mean precipitation rise is not only controlled by the C–C relation. The Intergovernmental Panel on Climate Change fifth assessment report provided a similar implication that the global precipitation sensitivity to the temperature rise is about 1%/°C to 3%/°C which is based on CMIP5 climate projections using the RCP4.5 scenario (Stocker et al., 2013). The GM region has a lower sensitivity of precipitation than the global region by about 1%/°C (with a median value of 0.5%/°C) during the summertime. It seems that the global water cycle is amplifying at less than the global mean C–C rate and regional precipitation sensitivity gets distinct over the monsoon domain in the future.

Our analysis for the four Asian subregional monsoon domains shows a stronger precipitation sensitivity to rising temperatures as compared to the GM domain (Figure 1c). The largest precipitation sensitivity is found over IND and EA with the 5.4%/°C and 4.6%/°C (with a median value of 6%/°C and 4.1%/°C), respectively. The increases in summer precipitation to global temperature rise in WNP (3.3%/°C) and ICP (2.9%/°C) are less than those over EA and IND. Even though a few models projected decreasing rainfall in the future, both the median and MME increase significantly over all the regions. The precipitation sensitivity in the Asian summer subregional monsoon systems increases considerably more than for the GM and global domains (Wang et al., 2014). We will further study the determining factors for the pattern of regional rainfall trends relative to 1° global warming. Note that the length of the rainy season is directly linked to the seasonal mean rainfall (Goswami & Xavier, 2005; Sabeerali & Ajayamohan, 2018).

Figure 2 shows the simulated future changes in the onset, retreat, and length of the rainy season. The natural variability shown as the green box in Figure 2 is estimated with the change of decadal-onset date. The MME represents well the summer monsoon rainy season with a high correlation coefficient (Figure S1b). We have considered “likely” as a likelihood of future changes if MME and the median value of model simulation tend toward both delayed or both advanced rainy season. For example, the onset of the summer monsoon in EA and WNP is likely to occur earlier by up to 1 pentad. Those are distinctive changes in onset date compared with GM and other subregional domains. For the retreat phase, we find a delay by 1 to 3 pentads over all regions. However, only the EA shows a high confidence with both mean and median shifting in the same direction and outside of the decadal null hypothesis. Here the length of the monsoon season increases overall submonsoon regions. We find that both MME mean and median have shown a lengthening of the rainy
season over EA (Figure 2c). This implies that the duration of the summer monsoon over EA would increase by more than 5 pentads in the future. This change further exceeds the value derived from the decadal changes in the observations. Interestingly, the MME shows a prolonged rainy season, whereas the median shows a shorter season over WNP and ICP and little changed over IND. For these regions, we assign a “low confidence” to the projections of the rainy season length. We also note here that MME changes in ICP length are consistent with the range of decadal variability in the observations.

Overall, the future duration of the rainy season is mostly modified by changes in retreat. Among the four subregional monsoon domains, the EA will be lengthened very likely by 5 pentads due to the delayed end of monsoon season. In the majority of Asian subregional monsoon, the future changes of the rainy season are larger than those over GM. The most consistent projections are that (1) EA will have a longer rainy season due to the advanced onset and delayed retreat, (2) the monsoon onset over WNP will occur earlier, (3) IND will experience a longer rainy season due to the delayed retreat, and (4) there is a slightly delayed onset over ICP. Using the K13 monsoon region definition, the only difference to our definition is that the median retreat is projected to advance over EA (Figure S4). Both advanced onset and delayed retreat over ASM are mostly consistent with the future projection based on the CMIP5 concentration-driven projections for the RCP4.5 scenario (Kitoh et al., 2013; Lee & Wang, 2014; Moon & Ha, 2017; Oh et al., 2018).

3.2. Changes in Extreme Rainfall

Monsoon rainfalls are becoming more intense and future projections show that greenhouse warming will further increase the occurrence of extreme rainfall events (Kitoh et al., 2013; Scoccimarro et al., 2013; Zhang et al., 2018). Here we highlight the projected changes in extreme rainfall from the subset of CMIP6 models. Figure 3 shows in all four subregions massive and consistent future changes in P20, RX1day, and R95p relative to the reference period, in accordance with earlier CMIP5-based studies (Sillmann et al., 2013). In the case of extremes, we only consider the median of the ensemble, not the multimodel mean value. The
extreme rainfall metrics chosen here are more suitable compared to fixed threshold indices because they account for climatological changes in precipitation over Asian submonsoon regions, as well as model biases. The CMIP6 still exhibit a relatively large spread (Figure 3a). The Asian subregional monsoon shows a large increasing rate of extremes in precipitation compared to GM. The strong increase in P20 toward the end of the 21st century is projected for EA (69%) and IND (57%), whereas P20 increase a little increase in other regions with under 37%. In the case of RX1day and R95p, the extreme change over EA is the largest among the Asian subregional monsoon domain with 68% and 42% (Figures 3b and 3c).

According to dividing South Asia into IND and ICP, we have shown that the increasing rate of RX1day over IND (57%) is larger than ICP (45%). It indicates that the different mechanisms in South Asia might play a role in the future change of extremes. Most models project increasing extreme rainfall for RX1day and R95p, but the increasing rate is larger in RX1day than R95p over all subregional monsoon domain. It is noted that future warming increases the extremes over the Asian monsoon subregions more than in other monsoon systems. Independent of the monsoon definition, the EA region is will experience the largest change in extremes (Figure S5).

3.3. Changes in Runoff and Evapotranspiration

Many previous studies have demonstrated that precipitation will be increased in response to greenhouse warming, as a result of an acceleration of the hydrological cycle (Hsu et al., 2012; Lee & Wang, 2014) (Figures 4a–4c). While both summer precipitation and runoff increase (Figures 4a–4c), the trend of precipitation is considerably higher than the runoff variations. This implies that increasing $E$ could balance the impacts of growing precipitation on runoff generation. Thus, the enhanced precipitation enhanced does not necessarily yield increases in surface water availability. The application of the GCR to the CMIP6 projections provides a consistent insight that $E$ will increase together with the enhance precipitation. The less trends of runoffs thus could be attributed to the rising $E$.

However, considering the relative drought definition, the upward $E$ trend is not a signal of wetting land surfaces owing to more rapidly rising $E_w$ (Figure 4d). The steeper $E_w$ trend implies that atmospheric water...
demands increasingly deviate from the land surface water consumption, gradually amplifying water deficit (i.e., $E_w - E$) by the end of the 21st century. The trend differences between $E$ and $E_p$ will become even more severe the “business as usual” SSP5–8.5 scenario (Figure 4e).

Hence, despite growing precipitation, future droughts will become more intense due to more rapidly rising atmospheric water demands. In particular, drought risks seem to be high across IND, ICP, and western part of EA.

4. Summary and Discussion

We studied the response of Asian regional monsoon systems to greenhouse warming using the current subset of released CMIP6 models. Regional changes in the characteristics of the rainy season are substantial across the Asian subregional monsoon domains. We find evidence for longer rainy seasons in the future associated with a delayed retreat. Here, we emphasize that both earlier onsets and delayed retreats are projected to extend the duration of the EA monsoon by up to 4 pentads. These changes in monsoon durations might be attributed to increasing seasonal precipitation rates with the global temperature rise (Goswami & Xavier, 2005). Most of the models also reveal a considerable increase in the probability of extreme precipitation events. The increasing rate of summer precipitation (Figure 1c) is larger over IND than EA, whereas the rainy season and precipitation extremes are large in EA. The relationship between the lengthening and intensification of the summer monsoon will be further studied in the future.
We also highlight that drought risks over EA could increase with rapidly rising evaporative demands. The land surfaces are likely to become drier based on the fact that the evaporative demand was projected to rise more rapidly than land surface evaporation. IND, ICP, and the western part of EA are expected to experience increasing drought risk. In other words, the evaporative demand increases swiftly over those domains. Especially, the western part of EA is expected to exhibit an increased drought risk as compared to the eastern part. Furthermore, the variability of summer monsoon precipitation enlarges, suggesting that higher probabilities of flooding and drought occurrence in the future (Figures 4a–4c; Ni & Hsu, 2018). Our study of future changes in the length of the rainy season, extreme rainfall, and evaporative demand highlights the urgency to consider changes in the hydrological cycle as a means to improve water management in one of the densest populated regions of our planet.

Author Contributions

K.-J. H. and A. T. designed the study, S. M., K.-J. H., and D. K. performed the analysis. All authors contributed to writing the manuscript.

Competing Interests

The authors declare no competing financial interests.

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