

Monsoons Climate Change Assessment

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ABSTRACT: Monsoon rainfall has profound economic and societal impacts for more than two-thirds of the global population. Here we provide a review on past monsoon changes and their primary drivers, the projected future changes, and key physical processes, and discuss challenges of the present and future modeling and outlooks. Continued global warming and urbanization over the past century has already caused a significant rise in the intensity and frequency of extreme rainfall events in all monsoon regions (high confidence). Observed changes in the mean monsoon rainfall vary by region with significant decadal variations. Northern Hemisphere land monsoon rainfall as a whole declined from 1950 to 1980 and rebounded after the 1980s, due to the competing influences of internal climate variability and radiative forcing from greenhouse gases and aerosol forcing (high confidence); however, it remains a challenge to quantify their relative contributions. The CMIP6 models simulate better global monsoon intensity and precipitation over CMIP5 models, but common biases and large intermodal spreads persist. Nevertheless, there is high confidence that the frequency and intensity of monsoon extreme rainfall events will increase, alongside an increasing risk of drought over some regions. Also, land monsoon rainfall will increase in South Asia and East Asia (high confidence) and northern Africa (medium confidence), decrease in North America, and be unchanged in the Southern Hemisphere. Over the Asian–Australian monsoon region, the rainfall variability is projected to increase on daily to decadal scales. The rainy season will likely be lengthened in the Northern Hemisphere due to late retreat (especially over East Asia), but shortened in the Southern Hemisphere due to delayed onset.

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Many parts of the Earth's surface and two-thirds of the global population are influenced by the monsoon. This paper reviews the current state of knowledge of climate change and its impacts on the global monsoon and its regional components, including recent results from phase 6 of the Coupled Model Intercomparison Project (CMIP6) that were reported at a World Meteorological Organization/World Weather Research Programme workshop held in Zhuhai in early December 2019. The review's primary focus is on monsoon rainfall, both mean and extremes, whose variability has tremendous economic and societal impacts. Due to the large body of literature on this broad topic, only a fraction can be cited in this concise review.

The global monsoon (GM) is a defining feature of the Earth's climate and a forced response of the coupled climate system to the annual cycle of solar insolation. For clarity, we define the monsoon domain primarily based on rainfall contrast in the solstice seasons (Fig. 1). The North American monsoon (NAM) domain covers western Mexico and Arizona but also Central America and Venezuela, and is larger than that traditionally recognized by many scientists working on the NAM. We aim to encompass the range of literature marrying together global monsoon, regional monsoon, and paleoclimate monsoon perspectives and therefore reach a compromise. Equatorial Africa and the Maritime Continent also feature annual reversal of surface winds, although the former has a double peak in the equinoctial seasons and the latter is heavily influenced by complex terrain (Chang et al. 2005).

Our goal is to outline past changes of the monsoon and identify the key drivers of these changes, assess the roles and impacts of natural and anthropogenic forcings and regional

variability, and discuss the limitations and difficulties of current climate models in representing monsoon variability. We will also attempt to summarize projected future changes both globally and in various monsoon regions using recent model results. Due to the inherent uncertainties and model limitations, the degree of confidence in the results varies. A section on model issues and outlook is devoted to discussing challenges of present and future monsoon modeling.

Global monsoon

Detection and attribution of observed changes.

Wang and Ding (2006) found a decreasing trend of global land monsoon precipitation from the 1950s to 1980, mainly due to the declining monsoon in the Northern Hemisphere (NH). After 1980, GM precipitation (GMP) intensified due to a significant upward trend in the NH summer monsoon (Wang et al. 2012). Extended analysis of the whole twentieth-century NH land monsoon rainfall indicates that short-period trends may be part of multidecadal variability, which is primarily driven by forcing from the Atlantic [Atlantic multidecadal variation (AMV)] and the Pacific [interdecadal Pacific oscillation (IPO)] (Zhou et al. 2008; Wang et al. 2013, 2018; Huang et al. 2020a). On the other hand, there is evidence that anthropogenic aerosols have influenced decreases of NH land monsoon precipitation in the Sahel and South and East Asia during the second half of the twentieth century (Polson et al. 2014; Giannini and Kaplan 2019; Zhou et al. 2020b). It should be noted that this long-term decrease in precipitation could be, in part, due to natural multidecadal variations of the regional monsoon precipitation (Sontakke et al. 2008; Jin and Wang 2017; Huang et al. 2020b). It remains a major challenge, however, to quantify the relative contributions of internal modes of variability versus anthropogenic forcing on the global scale.

Projected long-term changes. The CMIP5 results suggest that GM area, annual range, and mean precipitation are likely to increase by the end of the twenty-first century (Kitoh et al. 2013; Hsu et al. 2013; Christensen et al. 2013). The increase will be stronger in the NH, and the NH rainy season is likely to lengthen due to earlier or unchanged onset dates and a delayed retreat (Lee and Wang 2014). The increase in GM precipitation was primarily attributed to temperature-driven increases in specific humidity, resulting in the “wet get wetter” pattern (Held and Soden 2006).

Analysis of 34 CMIP6 models indicates a larger increase in monsoon rainfall over land than over ocean in all four core shared socioeconomic pathways (SSPs) (Fig. 2; Lee et al. 2019). The projected GMP increase over land by the end of the twenty-first century relative to 1995–2014 in CMIP6 is about 50% larger than in CMIP5. Models with high ($>4.2^{\circ}\text{C}$) equilibrium climate sensitivity (ECS) account for this larger projection. The causes of CMIP6 models' high ECS has been discussed in Zelinka et al. (2020). Note that the forced signal of GMP over land shows a decreasing trend from 1950 to the 1980s, but the trend reversed around 1990,

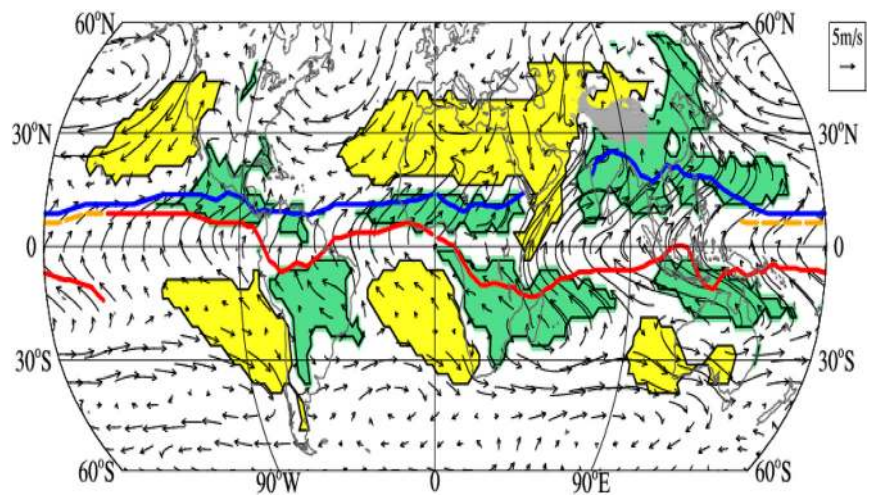


Fig. 1. The GM precipitation domain (green) defined by the local summer minus winter precipitation rate exceeding 2 mm day^{-1} , and the local summer precipitation exceeding 55% of the annual total (Wang and Ding 2008). Summer denotes May–September for the NH and November–March for the SH. The dry regions (yellow) are defined by local summer precipitation being less than 1 mm day^{-1} . The arrows show August minus February 925-hPa winds. The blue (red) lines indicate the ITCZ position in August (February). Adopted from P.-X. Wang et al. (2014).

which is consistent with the CMIP5 results (Lee and Wang 2014). During 1950–90, the temperature-driven intensification of precipitation was likely masked by a fast precipitation response to anthropogenic sulfate and volcanic forcing, even though the warming trend due to greenhouse gas (GHG) since the preindustrial period (1850–1900) is 3 times larger than the cooling due to aerosol forcing (Lau and Kim 2017; Richardson et al. 2018). The recent upward trend may signify the emergence of the greenhouse gas signal against the rainfall reduction due to aerosol emissions. However, the trend during recent decades can be influenced by the leading modes of multidecadal variability of global sea surface temperature (SST) (Wang et al. 2018). The GM land precipitation sensitivity has a median of $0.8\% \text{ }^{\circ}\text{C}^{-1}$ in SSP2–4.5, and a median of $1.4\% \text{ }^{\circ}\text{C}^{-1}$ in SSP5–8.5. The latter is slightly higher than that simulated by CMIP5 models under RCP8.5 (Fig. 2). Z. Chen et al. (2020) estimated that in the long-term (2080–2099) relative to 1995–2014, the GM land precipitation will increase by 3.52% ($0.47 \sim 6.58\%$ for the 10th–90th ensemble range) in SSP2–4.5 and 5.75% ($-0.17 \sim 11.68\%$) in SSP5–8.5.

Wang et al. (2020) examined the ensemble-mean projection from 15 early-released CMIP6 models, which estimates that under SSP2–4.5 the total NH land monsoon precipitation will increase by about $2.8\% \text{ }^{\circ}\text{C}^{-1}$ in contrast to little change in the Southern Hemisphere (SH; $-0.3\% \text{ }^{\circ}\text{C}^{-1}$). In both hemispheres, the annual range of land monsoon rainfall will increase by about $2.6\% \text{ }^{\circ}\text{C}^{-1}$, with wetter summers and drier winters (Zhang et al. 2019). In addition, the projected land monsoon rainy season will be lengthened in the NH (by about 10 days) due to late retreat, but will be shortened in the SH due to delayed onset; the interannual variations of GMP will be more strongly controlled by ENSO variability (Wang et al. 2020). In monsoon regions, increases in specific humidity are spatially uniform (Fig. 4b), but the rainfall change features a robust NH–SH asymmetry and an east–west asymmetry between enhanced Asian–African monsoons and weakened NAM (Fig. 4a), suggesting that circulation changes play a crucial role in shaping the spatial patterns and intensity of GM rainfall changes (Wang et al. 2020; Jin et al. 2020). GHG-induced horizontally differential heating

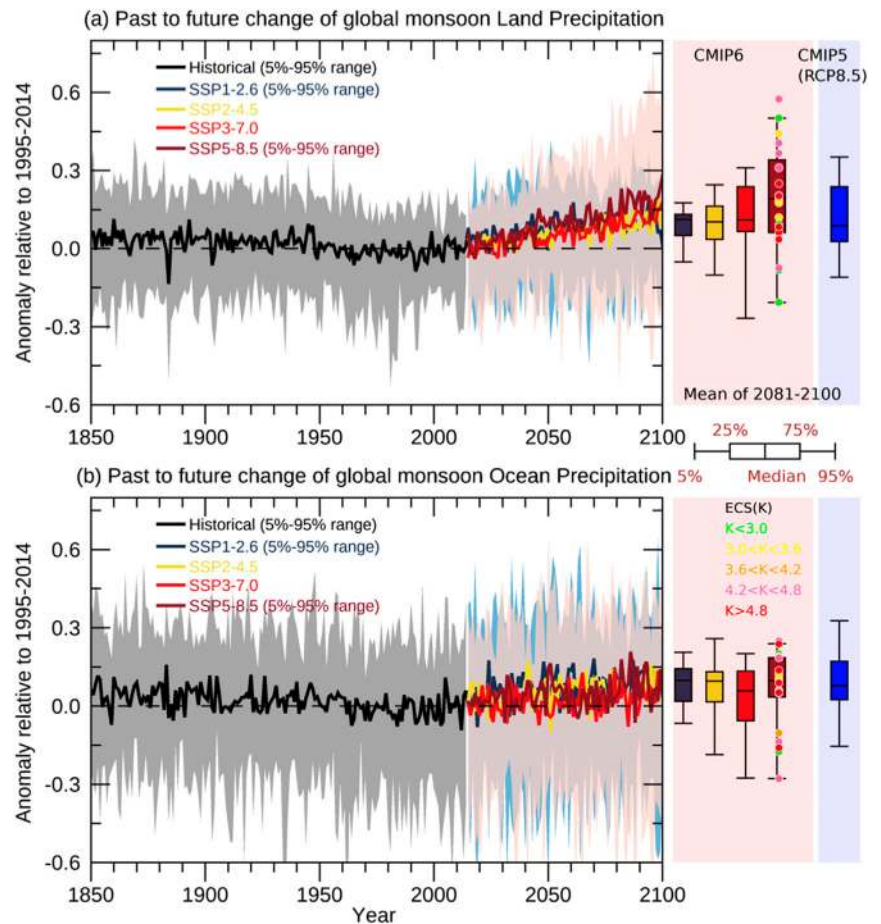


Fig. 2. Past to future changes of annual-mean global monsoon precipitation (mm day^{-1}) over (a) land and (b) ocean relative to the recent past (1995–2014) in the historical simulation (1850–2014) and four core SSPs (2015–2100) obtained from 34 CMIP6 models. Pink and blue shading indicate the 5%–95% likely range of precipitation change in the low-emission (SSP1–2.6) and high-emission (SSP5–8.5) scenarios, respectively. The mean change during 2081–2100 relative to the recent past is also shown, with the boxplot on the right-hand side obtained from four SSPs in 34 CMIP6 models compared to RCP8.5 in 40 CMIP5 models. The solid dot in the boxplot for SSP5–8.5 indicates individual model's ECS.

results in a robust “NH warmer than SH” pattern (Fig. 4c), which enhances NH monsoon rainfall (Liu et al. 2009), especially in Asia and northern Africa, due to an enhanced thermal contrast between the large Eurasia–Africa landmass and adjacent oceans (Endo et al. 2018). Those CMIP models that project a stronger interhemispheric thermal contrast generate stronger Hadley circulations, more northward positions of the ITCZ, and enhanced NH monsoon precipitation (Wang et al. 2020). The GHG forcing also induces a warmer equatorial eastern Pacific (Fig. 4c), which reduces NAM rainfall by shifting the ITCZ equatorward (Huang et al. 2013; Wang et al. 2020). Climate models on average predict weakening ascent under global warming (Endo and Kitoh 2014), which tends to dry monsoon regions. Weakening monsoon ascent has been linked to the slowdown of the global overturning circulation (Held and Soden 2006). However, a definitive theory for why monsoon circulations broadly weaken with warming remains elusive.

Land monsoon rainfall (LMR) provides water resources for billions of people; an accurate prediction of its change is vital for the sustainable future of the planet. Regional land monsoon rainfall exhibits very different sensitivities to climate change (Fig. 3). The annual mean LMR in the East Asian and South Asian monsoons shows large positive sensitivities with means of $4.6\% \text{ }^{\circ}\text{C}^{-1}$, and $3.9\% \text{ }^{\circ}\text{C}^{-1}$, respectively, under SSP2–4.5. The LMR likely increases in NAF, but decreases in NAM, and remains unchanged in the Southern Hemisphere monsoons (Jin et al. 2020).

Projected near-term change. The interplay between internal modes of variability, such as IPO, AMV, and SH annular mode (Zheng et al. 2014), and anthropogenic forcing is important in the historical record and for the near-term future (Chang et al. 2014). Huang et al. (2020a) used two sets of initial condition large ensembles to suggest that internal variability linked to the IPO could overcome the forced upward trend in the South Asian monsoon rainfall up to 2045. Using twentieth-century observations and numerical experiments, Wang et al. (2018) showed that the hemispheric thermal contrast in the Atlantic and Indian Oceans and the IPO can be used to predict the NH land monsoon rainfall change a decade in advance. The significant decadal variability of monsoon rainfall leads to considerable uncertainties in climate projections for the next 30 years; thus, improvements in predicting internal modes of variability could reduce uncertainties in near-term climate projections.

Regional monsoon changes

South Asian monsoon. The South Asian summer monsoon (SASM) circulation experienced a significant declining trend from the 1950s together with a weakening local meridional circulation and notable precipitation decreases over north-central India and the west coast that are associated with a reduced meridional temperature gradient (e.g., Krishnan et al. 2013; Roxy et al. 2015). This trend was attributed to effects of anthropogenic aerosol forcing (e.g., Bollasina et al. 2011; Salzmänn et al. 2014; Krishnan et al. 2016) and equatorial Indian Ocean warming due to increased GHG (e.g., Sabeerali and Ajayamohan 2017). However, it could potentially be altered by multidecadal variations (Shi et al. 2018) arising from internal modes of climate variability such as the IPO and AMV (e.g., Krishnan and Sugi 2003; Salzmänn and Cherian 2015; Jiang and Zhou 2019). The processes by which aerosols affect monsoons were reviewed by Li et al. (2016). Aerosols can also have a remote impact on regional monsoons (Shawki et al. 2018).

CMIP models consistently project increases in the mean and variability of SASM precipitation, despite weakened circulation at the end of the twenty-first century relative to the present (e.g., Kitoh et al. 2013; B. Wang et al. 2014), though some models disagree (Sabeerali and Ajayamohan 2017). The uncertainty in radiative forcing from aerosol emissions in CMIP5 causes a large spread in the response of SASM rainfall (Shonk et al. 2020). However, this is not the case in CMIP6 projections (Fig. 3).

East Asian monsoon. During the twentieth century, East Asian summer monsoon (EASM) exhibited considerable multidecadal variability with a weakened circulation and a south flood–north drought pattern since the late 1970s (Zhou et al. 2009; Ding et al. 2009). The south flood–north drought pattern has been predominantly attributed to internal variability, especially the phase change of the IPO (Li et al. 2010; Nigam et al. 2015; Li and Wang 2018; Ha et al. 2020a), and aided by GHG-induced warming (Zhu et al. 2012), and increased Asian aerosols emissions from the 1970s to 2000s (Dong et al. 2019). Since 1979, both SST and atmospheric heating over Southeast Asia and adjacent seas have increased significantly (Li et al. 2016), which may have led to decreased rainfall over East Asia, South Asia, (Annamalai et al. 2013) and the Sahel region (He et al. 2017).

Analysis of 16 CMIP6 models indicates that, under the SSP2–4.5 scenario, EASM precipitation will increase at $4.7\% \text{ }^{\circ}\text{C}^{-1}$ (Ha et al. 2020b), with dynamic effects more important than thermodynamic effects (Oh et al. 2018; Li et al. 2019). EASM duration is projected to lengthen by about 5 pentads due to earlier onset and delayed retreat (Ha et al. 2020b), which is comparable to previous assessment results (Endo et al. 2012; Kitoh et al. 2013; Moon and Ha 2017).

African monsoon. West Africa rainfall totals in the Sahel have been increasing since the 1980s, which helped greening (Taylor et al. 2017). Much of the increase in seasonal rainfall is owed to positive trends in mean intensity (Lodoun et al. 2013; Sarret al. 2013), rainfall extremes (Panthou et al. 2014; Sanogo et al. 2015), and the frequency of intense mesoscale convective systems (Taylor et al. 2017). Several West African countries have experienced trends toward a wetter late season and delayed cessation of the rains (Lodoun et al. 2013). All the above changes are qualitatively consistent with the CMIP5 response to GHG (Marvel et al. 2020). Preliminary results from CMIP6 confirm that the Sahel will become wetter, except for the west coast, and the rainy season will extend later (Fig. ES1 in the online supplemental material). Yet, the range of simulated variability has not improved, and large quantitative uncertainties in the projections persist. In spite of the large spread, the CMIP6 models project that NAF land monsoon rainfall will likely increase (Fig. 3).

In East Africa, observed increases in the boreal fall short rains are more robust (e.g., Cattani et al. 2018) than negative trends in the spring long rains (e.g., Maidment et al. 2015). Regionality is pronounced, and there is sensitivity to Indian Ocean SSTs and Pacific variability (Liebmann et al. 2014; Omondi et al. 2013). Selected CMIP6 models project little agreement on how East African rainfall will change (Fig. ES2), while some regional models suggest enhanced rainfall during the short rains and a curtailed long-rains season

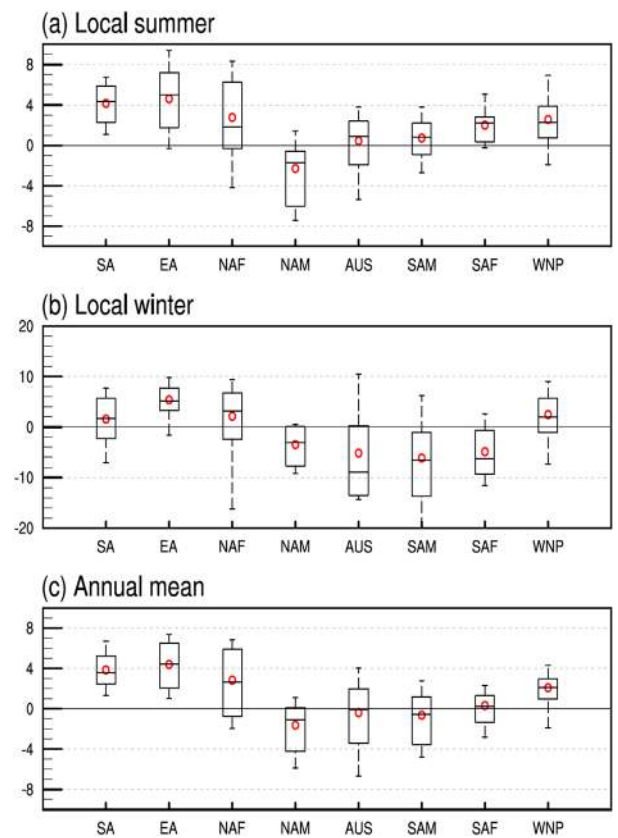


Fig. 3. Projected regional land monsoon precipitation sensitivity under the SSP2–4.5, i.e., the percentage change (2065–99 relative to 1979–2013) per 1°C global warming ($\% \text{ }^{\circ}\text{C}^{-1}$), derived from 24 CMIP6 models for (a) local summer, (b) local winter, and (c) annual mean land monsoon precipitation for each region. Local summer means JJAS in NH and DJFM for SH, and local winter means the opposite. The upper edge of the box represents the 83rd percentile and the lower edge is the 17th percentile, the box contains 66% of the data. The horizontal line within the box is the median. Red circle is the mean. The vertical dashed line segments represent the range of non-outliers (5%–95%).

(Cook and Vizzy 2013; Han et al. 2019). In the Congo Basin, observed precipitation trends are inconclusive (Zhou et al. 2014; Cook and Vizzy 2019), but one study reports earlier onset of the spring rains (Taylor et al. 2018). A preliminary analysis finds overall improvement in CMIP6 models in the overestimation of Congo Basin rainfall, though projections of changes under the SSP2–4.5 scenario are inconsistent (Fig. ES3).

The CMIP6 models project that under SSP2–4.5 scenario and by the latter part of twenty-first century, the SAF land monsoon rainfall will likely increase in summer but considerably reduce in winter, so that the annual range will amplify but the annual mean rainfall will not change significantly (Fig. 3)

Australian monsoon. Observations show increasing trends in mean and extreme rainfall over northern, especially northwestern Australia since the early 1970s (Dey et al. 2019). Although Australian summer monsoon rainfall has exhibited strong decadal variations during the twentieth and early twenty-first century, making detection and attribution of trends challenging, the recent upward trend since 1970s has been attributed to direct thermal forcing by increasing SST in the tropical western Pacific (Li et al. 2013) and to aerosol and GHG forcing (Rotstayn et al. 2007; Salzmann 2016).

Australian monsoon rainfall is projected to increase by an average of $0.4\% \text{ }^{\circ}\text{C}^{-1}$ in 33 CMIP5 models (Dey et al. 2019), although there is a large spread in the magnitude and even the direction of the projected change. By selecting the best-performing models for the Australian monsoon, Jourdain et al. (2013) found that 7 of 10 “good” CMIP5 models indicate a 5%–20% increase in monsoon rainfall over northern (20°S) Australian land by the latter part of the twenty-first century, but trends over a much larger region of the Maritime Continent are more uncertain. The range in Australian monsoon projections from the available CMIP6 ensemble is substantially reduced compared to CMIP5, however, models continue to disagree on the magnitude and direction of change. The CMIP6 models project that summer and annual mean LMR changes are insignificant under SSP2–4.5; but the winter LMR will likely decrease (Fig. 3) due to the enhanced Asian summer monsoon. By the end of the twenty-first century, the Madden–Julian oscillation (MJO) is anticipated to have stronger-amplitude rainfall variability (Maloney et al. 2019), but the impact on Australian summer monsoon intraseasonal variability is uncertain (Moise et al. 2020).

North American monsoon. Observed long-term twentieth-century rainfall trends are either negative or null, but the trends can vary substantially within this region (Pascale et al. 2019). During the period of 1950–2010 the monsoonal ridge was strengthened and shifted the

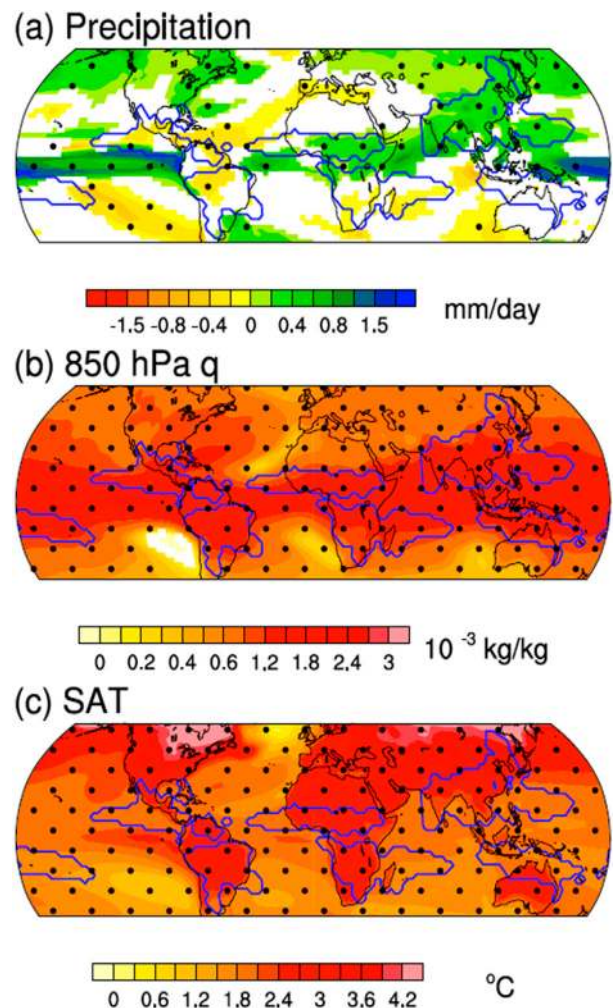


Fig. 4. Changes in the annual mean (a) precipitation, (b) 850-hPa specific humidity, and (c) surface air temperature. Changes are measured by the SSP2–4.5 projection (2065–99) relative to the historical simulation (1979–2013) in the 15 models’ MME. The color-shaded region denotes the changes are statistically significant at 66% confidence level (likely change). Stippling denotes areas where the significance exceeds 95% confidence level (very likely) by Student’s *t* test.

patterns of transient inverted troughs making them less frequent in triggering severe weather (Lahmers et al. 2016). Recent observational and modeling studies show an increase in the magnitude of extreme events in NAM and Central American rainfall under anthropogenic global warming (Aguilar et al. 2005; Luong et al. 2017).

Climate models suggest an early-to-late redistribution of the mean NAM precipitation with no overall reduction (Seth et al. 2013; Cook and Seager 2013), and a more substantial reduction for Central American precipitation (Colorado-Ruiz et al. 2018). However, there is low confidence in these projections, since both local biases (the models' representation of vegetation dynamics, land cover and land use, soil moisture hydrology) and remote biases (current and future SST) may lead to large uncertainties (Bukovsky et al. 2015; Pascale et al. 2017). Confidence in mean precipitation changes is lower than in the projection that precipitation extremes are likely to increase due to the changing thermodynamic environment (Luong et al. 2017; Prein et al. 2016).

Figure 5 schematically sums up the factors that are likely to be determinant in the future behavior of the NAM: the expansion and northwestward shift of the NAM ridge, and the strengthening of the remote stabilizing effect due to SST warming, and more intense MCS-type convection. More uncertain remains the future of the NAM moisture surges and the track of the upper-level inverted troughs, which are key synoptic processes controlling convective activity.

South American monsoon. A significant positive precipitation trend since the 1950s till the 1990s was observed in southeast South America, and has been related to interdecadal variability (Grimm and Saboia 2015), ozone depletion and increasing GHG (Gonzalez et al. 2014; Vera and Diaz 2015). The trend in the tropical South American monsoon is less coherent due to the influence of the tropical Atlantic and the tendency to reverse rainfall anomalies from spring to summer in central and eastern South America due to land–atmosphere interactions (Grimm et al. 2007). In recent decades the dry season has been lengthened and become drier, especially over the southern Amazonia, which has significant influences on vegetation and moisture transport to the SAM core region (Fu et al. 2013).

The CMIP6 models-projected future precipitation changes resemble the anomalies expected for El Niño: little change of annual

mean precipitation, with drier winter/spring and increased peak monsoon rainfall (Figs. 3 and 4). This is consistent with El Niño impacts (Grimm 2011) and CMIP5 projections, which show delay and shortening of the monsoon season, but intensification in its peak (Seth et al. 2013), and prolonged dry spells between the rainy events (Christensen et al. 2013). However, intermodel discrepancies are large (Yin et al. 2013). CMIP5 models also likely underestimate the climate variability of the South American monsoon and its sensitivity to climate forcing (Fu et al. 2013). Bias-corrected

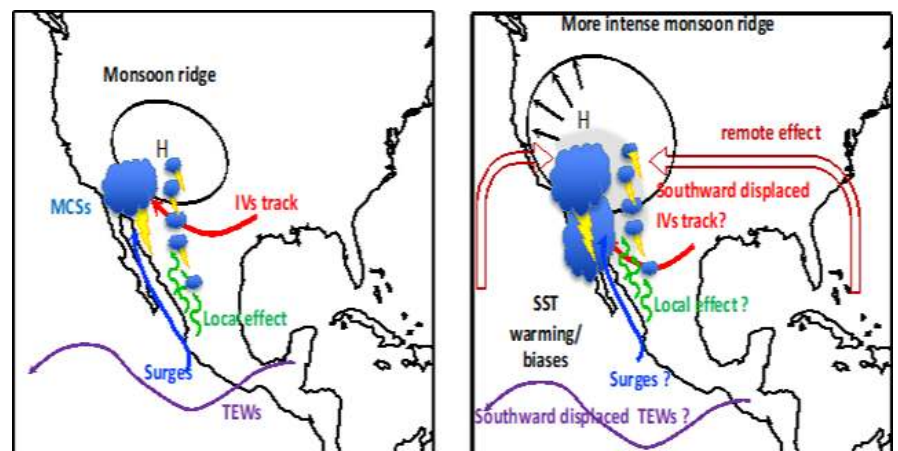


Fig. 5. Schematic main features related to (left) present and (right) future changes for the NAM. The expansion and northwestward shift of the NAM ridge, the southward shift of the upper-level inverted troughs (IVs) track, and the strengthening of the remote stabilizing effect due to SST warming are shown. Larger clouds in the right panel are suggestive of more intense MCS-type convection. The question marks in the right panel indicate uncertainty in the response, as is the case, for example, for the local mechanisms associated with atmosphere–land interaction, NAM moisture surges, and a southward shift the tropical easterly waves (TEWs) track.

projections generally show a drier climate over eastern Amazonia (e.g., Duffy et al. 2015; Malhi et al. 2008). Thus, the risk of strong climatic drying and potential rain forest die-back in the future remains real.

Extreme precipitation events in summer monsoons

Past changes and attribution.

Over the past century, significant increases in extreme precipitation in association with global warming have emerged over the global land monsoon region as a whole, and annual maximum daily rainfall has increased at the rate of about 10%–14% °C⁻¹ in the southern part of the South African monsoon, about 8% °C⁻¹ in the South Asian monsoon, 6%–11% °C⁻¹ in the NAM, and 15%–25% °C⁻¹ in the eastern part of the South American monsoon (Zhang and Zhou 2019). At Seoul, South Korea, one of the world's longest instrumental measurements of daily precipitation since 1778 shows that the annual maximum daily rainfall and the number of extremely wet days, defined as the 99th percentile of daily precipitation distribution, all have an increasing trend significant at the 99% confidence level (Fig. 6). In the central Indian subcontinent, a significant shift toward heavier precipitation in shorter duration spells occurred from 1950 to 2015 (Fig. 7) (Goswami et al. 2006; Roxy et al. 2017; Singh et al. 2019). In East Asia, the average extreme rainfall trend increased from 1958 to 2010, with a decreasing trend in northern China that was offset by a much larger increasing trend in southern China (Chang et al. 2012). Over tropical South America, extreme indices such as annual total precipitation above the 99th percentile and the maximum number of consecutive dry days display more significant and extensive trends (Skansi et al. 2013; Hilker et al. 2014).

Attribution studies show that global warming has already increased the frequency of heavy precipitation since the mid-twentieth century. An optimal fingerprinting analysis shows that anthropogenic forcing has made a detectable contribution to the observed shift toward heavy precipitation in eastern China (Ma et al. 2017). Simulations with all and natural-only forcing show that global warming increased the probability of the 2016 Yangtze River extreme summer rainfall by 17%–59% (Yuan et al. 2018). A large ensemble experiment also

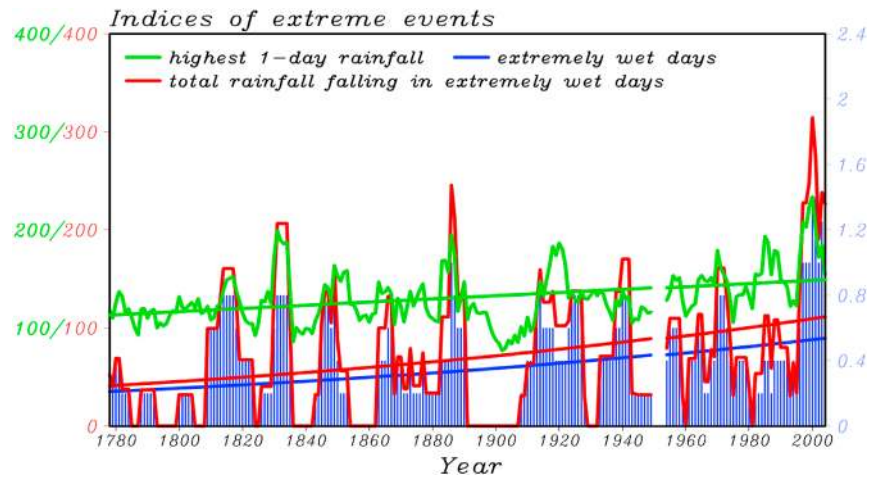


Fig. 6. Time series of extreme precipitation events observed at Seoul, South Korea, since 1778. Running 5-yr means of the summer highest 1-day precipitation amount (green, mm day⁻¹ on the left y axis), the number of extremely wet days (blue, right y axis), and the precipitation amount falling in the extremely wet days (red, mm day⁻¹ on the left y axis). The extremely wet days are calculated as the 99th percentile of the distribution of the summer daily precipitation amount in the 227-yr period. Also shown are the corresponding trends obtained by least squares regression for the green curve and by logistic regression for the blue and red curves. Adopted from Wang et al. (2006).

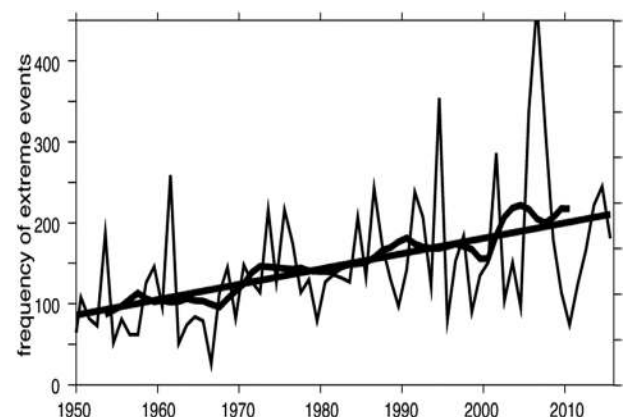


Fig. 7. Frequency of extreme rain events (number of grid cells exceeding 150 mm day⁻¹ yr⁻¹) over the central Indian subcontinent (19°–26°N, 75°–85°E) for the summer monsoon (June–September) during 1950–2015. The trend lines are significant at 95% confidence level. The smoothed curves on the time series analyses represent 10-yr moving averages. Adopted from Roxy et al. (2017).

showed that historical global warming has increased July maximum daily precipitation in western Japan (Kawase et al. 2019).

Another anthropogenic forcing is urbanization. A significant correlation between rapid urbanization and increased extreme hourly rainfall has been detected in the Pearl River Delta and Yangtze River Delta of coastal China (Fig. 8) (Wu et al. 2019; Jiang et al. 2020). The increasing trends are larger in both extreme hourly rainfall and surface temperature at urban stations than those at nearby rural stations. The correlation of urbanization and extreme rainfall is due to the urban heat island effect, which increases instability and facilitates deep convection. Large spatial variability in the trends of extreme rainfall in India due to urbanization and changes in land use and land cover has also been detected (Ali and Mishra 2017).

Landfalling tropical cyclones (TCs) make large contributions to heavy precipitation in coastal East Asia. In the last 50 years, the decreasing frequency of incoming western North Pacific (WNP) TCs more than offsets the increasing TC rainfall intensity, resulting in reduced TC-induced extreme rainfall in southern coastal China, so the actual increase in non-TC extreme rainfall is even larger than observed (Chang et al. 2012). Evidence in the WNP, and declining TC landfall in eastern Australia (Nicholls et al. 1998), suggest that this poleward movement reflects greater poleward TC recurvature.

Future projection. One of the most robust signals of projected future change is the increased occurrence of heavy rainfall on daily-to-multiday time scales and intense rainfall on hourly time scales. Heavy rainfall will increase at a much larger rate than the mean precipitation, especially in Asia (Kitoh et al. 2013; Kitoh 2017). Unlike mean precipitation changes, heavy and intense rainfall is more tightly controlled by the environmental moisture content related to the Clausius–Clapeyron relationship and convective-scale circulation changes. On average, extreme 5-day GM rainfall responds approximately linearly to global temperature increase at a rate of $5.17\% \text{ }^{\circ}\text{C}^{-1}$ ($4.14\% \text{--} 5.75\% \text{ }^{\circ}\text{C}^{-1}$) under RCP8.5 with a high signal-to-noise ratio (Zhang et al. 2018). Regionally, extreme precipitation in the Asian monsoon region exhibits the highest sensitivity to warming, while changes in the North American and Australian monsoon regions are moderate with low signal-to-noise ratio (Zhang et al. 2018). CMIP6 models project changes of extreme 1-day rainfall of +58% over South Asia and +68% over East Asia in 2065–2100 compared to 1979–2014 under the SSP2–4.5 scenario (Ha et al. 2020b). Model experiments also indicate a threefold increase in the frequency of rainfall extremes over the Indian subcontinent under future projections for global warming of $1.5^{\circ}\text{--}2.5^{\circ}\text{C}$ (Bhowmick et al. 2019). Meanwhile, light-to-moderate rain events may become less frequent (Sooraj et al. 2016).

Changes in the variability of monsoon rainfall may occur on a range of time scales. Brown et al. (2017) found increased rainfall variability under RCP8.5 for each time scale from daily to decadal over the

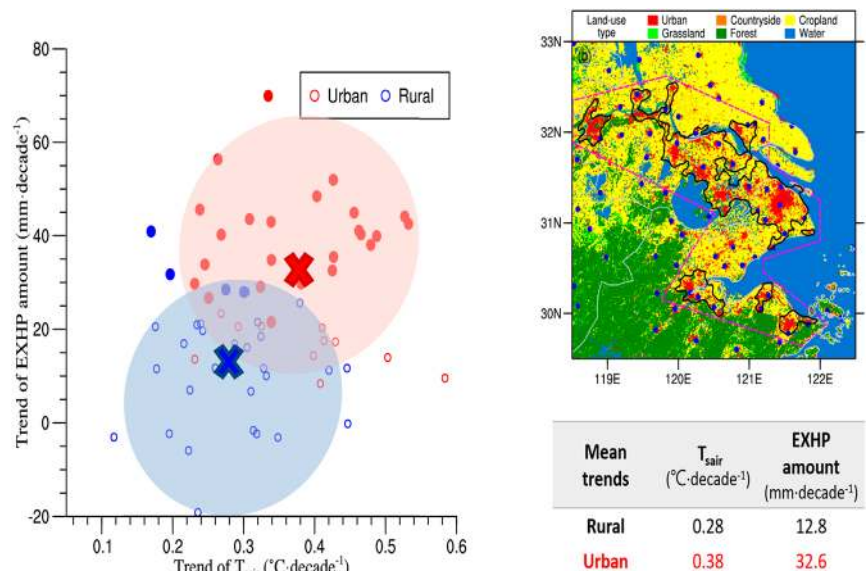


Fig. 8. The surface air temperature and extreme hourly rainfall trends for urban stations (red) and rural stations (blue) in the Yangtze River Delta, calculated from changes from 1975–96 to 1997–2018, during MJJAS. The thick crosses are averages of the station values. Adapted from Figs. 1 and 11 in Jiang et al. (2020).

Australian, South Asian, and East Asian monsoon domains (Fig. 8). The largest fractional increases in monsoon rainfall variability occur for the South Asian monsoon at all subannual time scales and for the East Asian monsoon at annual-to-decadal time scales. Future changes in rainfall variability are significantly positively correlated with changes in mean wet season rainfall for each of the monsoon domains and for most time scales.

Selected CMIP5 models project more severe floods and droughts in the future climate over South Asia (Sharmila et al. 2015; Singh et al. 2019). Due to more rapidly rising evaporation, the projections for 2015–2100 under CMIP6 SSP2–4.5 and SSP5–8.5 scenarios indicate that the western part of East Asia will confront more rapidly increasing drought severity and risks than the eastern part (Ha et al. 2020b).

Projections of future extreme rainfall change in the densely populated and fast-growing coastal zones are particularly important for several reasons. First, in fast-growing urban areas, extreme rainfall will likely intensify in the future, depending on the economic growth of the affected areas. Second, future extreme rainfall changes in coastal areas will be affected by future changes in landfalling TCs. For instance, TC projections (Knutson et al. 2019) suggest a continued (albeit with lower confidence) northward trend. Assuming this means more recurvature cases, it would lead to extreme rainfall increases in coastal regions of the Korean peninsula and Japan and decreases in China. Third, the increase in monsoon extreme rains and TCs, together with rising sea level will lead to aggravated impacts, for instance, along coastal regions of the Indian subcontinent (Collins et al. 2019).

Model issues and future outlook

Major common issues and missing processes. CMIP6 models improve the simulation of present-day solstice season precipitation climatology and the GM precipitation domain and intensity over the CMIP5 models, and CMIP6 models reproduce well the annual cycle of the NH monsoon and the leading mode of GM interannual variability and its relationship with ENSO (Wang et al. 2020). However, the models have major common biases in equatorial oceanic rainfall and SH monsoon rainfall, including overproduction of annual mean SH monsoon precipitation by more than 20%, and the simulated onset is early by two pentads while the withdrawal is late by 4–5 pentads (Wang et al. 2020). Systematic model biases in monsoon climates have persisted through generations of CMIP (e.g., Sperber et al. 2013). In particular, the poor representation of precipitation climatology is seen in many regional monsoons, such as Africa (Creese and Washington 2016; Han et al. 2019) and North America (Geil et al. 2013). These biases are often related to SST biases in adjacent oceans (Cook and Vizy 2013; Pascale et al. 2017). There are additional outstanding common issues for regional monsoon simulations, which are not immediately apparent in quick-look analyses. A major one is the diurnal cycle, which is poorly simulated in the tropics, due to failures in convective parameterization (Willettts et al. 2017). Biases in evapotranspiration also affect the Bowen ratio (Yin et al. 2013), and thus atmospheric boundary layer humidity and height. Biases in variability emerge in historical monsoon simulations, hampering accurate attribution of present-day monsoon changes (Herman et al. 2020; Marvel et al. 2020) and amplifying uncertainties in future projections.

While there are subtle improvements from CMIP3 to CMIP5 and to CMIP6 due to steady increases in horizontal resolution and improved parameterizations, simulation of monsoon rainfall is still hampered by missing or poorly resolved processes. These include the lack of organized convection (e.g., mesoscale convective systems or monsoon depressions) at coarse model resolutions, poorly simulated orographic processes, and imperfect land–atmosphere coupling due to underdeveloped parameterizations and a paucity of observations of land–atmosphere exchanges that can only be improved through field observation programs (e.g., Turner et al. 2020). Further, proper simulation of how aerosols modify monsoon rainfall requires improved cloud microphysics schemes (Yang et al. 2017; Chu et al. 2018). Finally,

some features of monsoon meteorology that are crucial to climate projection and adaptation, such as extreme rainfall accumulations exceeding 1 m day^{-1} , are nearly impossible to simulate in coupled climate models. High-resolution regional simulations can potentially ameliorate biases, but they still must rely on GCM-generated boundary conditions in their projections. Convection-permitting regional simulations have been suggested to more realistically represent short time scale rainfall processes and their responses to forcing (e.g., in future simulations for Africa; Kendon et al. 2019).

Sources of model uncertainty in future projection of monsoons. The major sources of projection uncertainty include model uncertainty, scenario uncertainty, and internal variability. Contributions from internal variability decrease with time, while those from scenario uncertainty increase. Model uncertainty dominates near-term projections of GM mean and extreme precipitation with a contribution of $\sim 90\%$ (Zhou et al. 2020a). Model uncertainty often arises from divergent circulation changes. In particular, circulation changes caused by regional SST warming and land–sea thermal contrast can generally contribute to uncertainty in monsoon rainfall changes (Chen and Zhou 2015; Pascale et al. 2017). Uncertainty in projected surface warming patterns is closely related to present-day model biases, including the cold-tongue bias in the tropical eastern Pacific (Chen and Zhou 2015; Ying et al. 2019) and a cold bias beneath underestimated marine stratocumulus, which can induce a large land–sea thermal contrast in the future (Nam et al. 2012; X. Chen et al. 2020). Monsoons are strongly influenced by cloud and water vapor feedbacks (Jalihal et al. 2019; Byrne and Zanna 2020), yet how the large variations in these feedbacks across climate models impact monsoon uncertainties is unknown. Another factor affecting future monsoon changes are vegetation feedbacks. Cui et al. (2020) showed that they may exacerbate the effects of CO_2 -induced radiative forcing, especially in the North and South American and Australian monsoons via reduced stomatal conductance and transpiration. Vegetation is an important water vapor provider and can affect monsoon onsets (Wright et al. 2017), yet current climate models have limited capability in representing how vegetation responds to climate and elevated CO_2 , and how land use and fires affect future vegetation distribution and functions. The extent to which these model limitations contribute to the uncertainty of future monsoon rainfall projections is virtually unknown, although plant physiological effects may exacerbate CO_2 radiative impacts (Cui et al. 2020). While CMIP6 models are more advanced in terms of physical processes included and resolution, the intermodel spread in projection of monsoons in CMIP6 models has remained as large (or became larger) compared to CMIP5 models (Fig. 2).

Future outlook. Future models might improve by explicitly resolving deep convection to address common problems across monsoon systems. In attribution, controversies remain over the relative roles of natural multidecadal variability and anthropogenic forcing, especially of aerosol effects on the observed historical monsoon evolution in Asia and West Africa. Quantification of the roles of multidecadal variability in biasing the transient climate sensitivity in observations as well as in model simulations is encouraged.

There is an urgent need to better understand sources of uncertainty in future rainfall projections. Such sources encompass but are not limited to structural uncertainty, uncertainties in aerosol processes and radiative forcing, the roles of internal modes of variability and their potential changes in the future, ecosystem feedbacks to climate change and elevated CO_2 , and land-use impacts. To have more confidence in future projections, we need to quantify the causes of spread in future climate signals at the process level: the relative magnitudes of forcing uncertainty versus mean-state biases and feedback uncertainties. This type of error quantification requires specially designed, coordinated simulations across modeling centers and a focus on the key processes that need to be improved.

Traditional future assessments of the global monsoon continue to rely on multimodel approaches. However, a small multimodel ensemble such as CMIP5 or CMIP6 may not represent the full extent of uncertainty introduced by internal (multidecadal) variability. More recently, large ensembles are being employed to help understand the spread or degree of uncertainty in a climate signal, and, at the regional level, the interplay between internal variability and anthropogenic external forcing in determining a climate anomaly. Such large ensembles are either perturbed parameter ensembles (PPE) (Murphy et al. 2014) or alternatively, traditional initial-condition ensembles—e.g., by CanESM2 (Sigmond and Fyfe 2016; Kirchmeier-Young et al. 2017) or by MPI-ESM (Maher et al. 2019)—with tens of members to 100 members. Large-ensemble methods should be applied to the global monsoon in order to determine the extent to which internal variability can explain its declining rainfall in the late twentieth century. We suggest that an additional pathway to more reliable monsoon projections would be to develop emergent constraints applicable to monsoons, and this should be a focus for the research community.

Recent theoretical advances in tropical atmospheric dynamics offer new avenues to further our understanding of monsoon circulations in a changing climate. Monsoon locations have been shown to coincide with maxima in subcloud moist static energy (MSE) (Privé and Plumb 2007), with MSE budgets likely to be useful for understanding the response of monsoons to external forcing (Hill 2019). Recent studies of the ITCZ may also provide new insights into the strength and spatial extent of monsoons. Theoretical work has identified energetic (Sobel and Neelin 2006; Byrne and Schneider 2016) and dynamical constraints (Byrne and Thomas 2019) on the width of the ITCZ, with implications for its strength (Byrne et al. 2018). Additionally, Singh et al. (2017) have linked the strength of the Hadley circulation to meridional gradients in moist entropy. The extent to which these theories can explain CMIP6 changes in monsoon strength and spatial extent is an open question that should be prioritized.

Understanding past monsoon responses to external forcings may shed light on future climate change. The NH monsoon future response is shown to be weaker than in simulations of the mid-Holocene, although future warming is larger (D'Agostino et al. 2019). This occurs because both thermodynamic and dynamic responses act in concert and cross-equatorial energy fluxes shift the ITCZ toward the warmer NH during the mid-Holocene, but in the future, they partially cancel. The centennial–millennial variations of GM precipitation before the industrial period are mainly attributable to solar and volcanic (SV) forcing (Liu et al. 2009). For the same degree of warming, GHG forcing induces less rainfall increase than SV forcing because the former increases stability, favoring a weakened Walker circulation and El Niño–like warming, while the latter warms tropical Pacific SSTs in the west more than the east, favoring a La Niña–like warming through the ocean thermostat mechanism (Liu et al. 2013). An El Niño–like warming reduces GM precipitation (Wang et al. 2012). Jalihal et al. (2019), by examining responses of tropical precipitation to orbital forcing, find that the changes in precipitation over land are mainly driven by changes in insolation, but over the oceans, surface fluxes and vertical stability play an important role in precipitation changes.

Summary

We have reviewed past monsoon changes and their primary drivers, summarized projected future changes and key physical processes, and discussed challenges of the present and future modeling and outlooks. In this section we will assign a level of confidence to the main conclusions wherever feasible.

Extreme rainfall events. Continued global warming over the past century has already caused a significant rise in the intensity and frequency of extreme rainfall events in all

monsoon regions (e.g., Figs. 6 and 7; high confidence). Urbanization presents additional anthropogenic forcing that significantly increases localized extreme rainfall events in areas of rapid economic growth due to the urban heat island effect (Fig. 8, high confidence). This urban effect is expected to expand to more locations with the growing economy, especially in Asia. There is some indication that TC tracks in the western North Pacific have been shifting more toward the recurvature type. If this trend continues, it may cause an increase in the ratio of TC-related extreme rainfall in the Korea Peninsula and Japan versus China (low confidence).

Almost all future projections agree that the frequency and intensity of extreme rainfall events will increase. The occurrence of heavy rainfall will increase on daily to multiday time scales and intense rainfall on hourly time scales. The increased extreme rainfall is largely due to an increase in available moisture supply and convective-scale circulation changes. Meanwhile, models also project prolonged dry spells between the heavy rainy events, which, along with enhanced evaporation and runoff of groundwater during heavy rainfall, will lead to an increased risk of droughts over many monsoon regions (high confidence). Notably, the enhanced extreme rain events will *likely* contribute to compound events—where increasing tropical cyclones, rising sea level, and changing land conditions—may aggravate the impact of floods over the heavily populated coastal regions.

Mean monsoon rainfall and its variability. Observed changes in the mean monsoon rainfall vary by region with significant decadal variations that have been related to internal modes of natural variability. Since the 1950s, NH anthropogenic aerosols may be a significant driver in the Sahel drought and decline of monsoon rainfall in South Asia (medium to high confidence). NH land monsoon rainfall as a whole declined from 1950 to 1980 and rebounded after the 1980s, due to the competing influence of internal climate variability, radiative forcing from GHGs and aerosol forcing (high confidence); however, it remains a challenge to quantify their relative contributions. CMIP6 historical simulations suggest that anthropogenic sulfate and volcanic forcing likely masked the effect of GHG forcing and caused the downward trend from 1950 to 1990 (Fig. 2); however, the recent upward trend may signify the emergence of the greenhouse gas signal against the rainfall reduction due to aerosol emissions (medium to high confidence).

CMIP6 models project a larger increase in monsoon rainfall over land than over the ocean (Fig. 2). Land monsoon rainfall will likely increase in the NH, but change little in the SH (Figs. 2, 4). Regionally, land monsoon rainfall will increase in South Asia and East Asia (high confidence), and northern Africa (medium confidence), but decrease over North American monsoon region (high confidence) (Fig. 3). The projected mean rainfall changes (either neutral or slightly decreasing) over SH (American, Australian, and southern African) monsoons have low confidence due to a large spread. The future change of GM precipitation pattern and intensity is determined by increased specific humidity and circulation changes forced by the vertically and horizontally inhomogeneous heating induced by GHG radiative forcing. Under GHG-induced warming, the land monsoon rainy season changes considerably from region to region; yet, as a whole, the rainy season will likely be lengthened in the NH due to late retreat (with most significant change over East Asia), but shortened in the SH due to delayed onset. The variability of monsoon rainfall is projected to increase on daily to decadal time scales over the Asian–Australian monsoon region (Fig. 9). Models generally underestimate the magnitude of observed precipitation changes, which poses a major challenge for quantitative attributions of regional monsoon changes. The range of projected change of annual-mean global land monsoon precipitation by the end of the twenty-first century in CMIP6 is *likely* about 50% larger than in corresponding scenarios of CMIP5.

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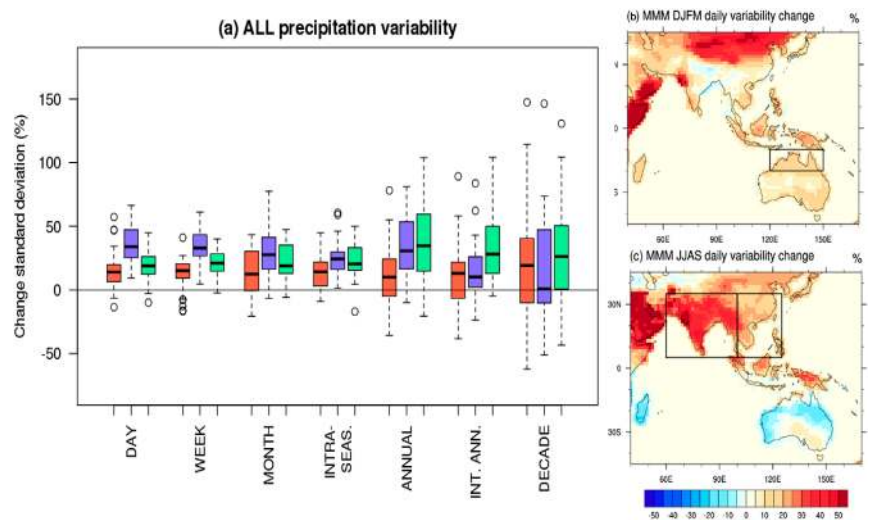


Fig. 9. (a) RCP8.5 (2050–2100) minus HIST (1950–2000) differences in bandpass-filtered daily rainfall standard deviation (%) for the Australian (red, left boxes), South Asian (purple, center boxes), and East Asian (green, right boxes) monsoon domains. Data cover DJFM for the Australian monsoon and JJAS for the South and East Asian monsoon. Daily data are bandpass filtered for the set of bands indicated on the x axis. The multimodel mean change in standard deviation of *daily* rainfall (%) from HIST (1950–2000) to RCP8.5 (2050–2100) is shown in (b) DJFM and (c) JJAS. The South Asian, East Asian, and Australian monsoon domains are shown in the relevant wet season (from Brown et al. 2017).

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