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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. NH 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 GHGs 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), and decrease in North America and unchanged in Southern Hemisphere. Over 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.

Capsule Summary

This paper reviews the current knowledge on detection, attribution and projection of global and regional monsoons (South Asian, East Asian, Australian, South American, North American, and African) under climate change.

1. Introduction

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 six 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 2004).

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.

2. Global monsoon

2.1. 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) has intensified due to a significant upward trend in the NH summer monsoon (Wang et al., 2012). Extended analysis of the whole 20th 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, South and East Asia during the second half of the 20th 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 multi-decadal 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.

2.2. 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 21st 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 Socio-economic Pathways (SSPs) (Fig. 2; Lee et al. 2019). The projected GMP increase over land by the end of the 21st century relative to 1995-2014 in CMIP6 is about 50% larger than in CMIP5. Models with high (>4.2°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, which is consistent with the CMIP5 results (Lee and Wang, 2014). During 1950-1990, 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 GHG since the pre-industrial period (1850-1900) is three 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 SST (Wang et al. 2018). Lee et al. (2019) found that land monsoon precipitation sensitivity (precipitation change per degree of global warming) slightly increases with the level of GHG forcing, whereas the ocean monsoon precipitation has almost no sensitivity (Fig. 2). The GM land precipitation sensitivity has a median of 0.8 %/°C in SSP2-4.5, and a median of 1.4%/°C in SSP5-8.5. The latter is slightly higher than that simulated by CMIP5 models under RCP 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%/°C in contrast to little change in the southern hemisphere (SH; -0.3%/°C). In both hemispheres, the annual range of land monsoon rainfall will increase by about 2.6%/°C, with wetter summers and drier winters. In addition, the projected land monsoon rainy season will be lengthened in the NH (by about ten 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). GHG-induced horizontally differential heating results in a robust "NH-warmer-than-SH" pattern (Fig. 4c), which enhances NH monsoon rainfall (Liu et al. 2009, Mohtadi et al. 2016), 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 inter-hemispheric 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 (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%/°C, and 3.9%/°C, 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).

2.3. 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 20th-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.

3. Regional monsoon changes

3.1 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., Salzmann 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, Salzmann and Cherian, 2015, Jiang and Zhou 2019). The processes by which aerosols affect monsoons were reviewed by Li et al. (2015). Aerosols can also have a remote impact on regional monsoons (Shaeki et al., 2018).

CMIP models consistently project increases in the mean and variability of SASM precipitation, despite weakened circulation at the end of the 21st century relative to the present (e.g., Kitoh et al. 2013; 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., 2019). However, this is not the case in CMIP6 projections (Fig. 3).

3.2 East Asian monsoon

During the 20th century, East Asian summer monsoon (EASM) exhibited considerable multi-decadal variability with a weakened circulation and a south flood-north drought pattern since the late 1970s (Zhou 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, 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 sea-surface temperature (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 %/°C (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 five 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).

3.3 African monsoon

West Africa rainfall totals in the Sahel have been increasing since the 1980s, which helped regreening (Taylor et al. 2017; Brandt et al. 2019). Much of the increase in seasonal rainfall is owed to positive trends in mean intensity (Lodoun et al. 2013, Sarr et 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 towards a wetter late season and delayed cessation of the rains (Lodoun et al. 2013, Brandt et al. 2019). All the above changes are qualitatively consistent with the CMIP5 response to GHG (Marvel et al., 2019). Preliminary results from CMIP6 confirm that the Sahel will become wetter, except for the west coast, and the rainy season will extend later (Supplementary Fig. S1). 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 (supplementary Fig. S2), while some regional models suggest enhanced rainfall during the short rains and a curtailed long-rains season (Cook and Vizy 2013; Han et al. 2019). In the Congo Basin, observed precipitation trends are inconclusive (Zhou et al. 2014; Cook and Vizy 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. (Supplementary Fig. S3).

The CMIP6 models project that under SSP2-4.5 scenario and by the latter part of 21st 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)

3.4 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 20th and early 21st 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%/°C 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, Joudain et al. (2013) found that seven of ten "good" CMIP5 models indicate a 5-20% increase in monsoon rainfall over northern (20°S) Australian land by the latter part of the 21st century, but trends over a much larger region of the Maritime Continent are more uncertain. Narsey et al. (2019) found that 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 21st century, the Madden-Julian Oscillation (MJO) is anticipated to have stronger amplitude rainfall variability (Maloney et al. 2018), but the impact on Australian summer monsoon intraseasonal variability is uncertain (Moise et al. 2019).

3.5 North American monsoon

Observed long-term 20th 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 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 2013, Cook and Seager, 2013), and a more substantial reduction for Central American precipitation (Colorado-Ruiz et al., 2019). However, there is low confidence in these projections, since both local biases (the models' representation of vegetation dynamics, land cover and 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 are shown, 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.

3.6 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 the central-east 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 total precipitation (Figs. 3 and 4). This is consistent with El Niño impacts (Grimm 2011) and CMIP5 projections (Seth et al. 2013). CMIP5 also projected reduction of early monsoon rainfall while peak season rainfall increases, a delay and shortening of the monsoon season (Seth et al. 2013), and prolonged dry spells between the rainy events (Christensen et al., 2013). However, inter-model 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 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 rainforest die-back in the future remains real.

4. Extreme precipitation events in summer monsoons

4. 1. 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 in the southern part of the South African monsoon, about 8%/°C in the South Asian monsoon, 6-11%/°C in the NAM, and 15-25%/°C in the eastern part of the South American monsoon (Zhang and Zhou 2019). At Seoul, 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 towards heavier precipitation in shorter duration spells occurred from 1950–2015 (Fig. 7) (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-20th Century. An optimal fingerprinting analysis shows that anthropogenic forcing has made a detectable contribution to the observed shift towards 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 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. 2019). 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).

Land-falling 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.

4.2. 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, 2013, 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 five-day GM rainfall responds approximately linearly to global temperature increase at a rate of 5.17 (4.14–5.75)%/°C 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 three-fold increase in the frequency of rainfall extremes over the Indian subcontinent under future projections for global warming of 1.5°C–2.5°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 Australian, South Asian, and East Asian monsoon domains (Fig. 8). The largest fractional increases in monsoon rainfall variability occur for South Asian at all sub-annual 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. 2019b) 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 Korea 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).

5. Model Issues and Future Outlook

5.1 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 (Willetts 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. 2019; Marvel et al, 2019) 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 under-developed parametrizations and a paucity of observations of land-atmosphere exchanges that can only be improved through field observation programs (e.g. Turner et al., 2019). 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 meter/day, 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).

5.2 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 ~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, Chen et al. 2019). 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. (2019) 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; Sori 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 CO2-raditiative impacts (Cui et al., 2019). While CMIP6 models are more advanced in terms of physical processes included and resolution, the inter-model spread in projection of monsoons in CMIP6 models has remained as large (or became larger) compared to CMIP5 models (Fig 2).

5.3 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 modelling centers and a focus on the key processes that need to be improved.

Traditional future assessments of the global monsoon continue to rely on multi-model approaches. However, a small multi-model ensemble such as CMIP5 or CMIP6 may not represent the full extent of uncertainty introduced by internal (multi-decadal) 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, 2017) or by MPI-ESM (Maher et al., 2019) – with tens to a hundred 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 20th 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 sub-cloud 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 towards 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 Nina-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.

6. 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.

1. 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 towards the recurvature type. If this trend continues, it may cause an increase in the ratio of TC-related extreme rainfall in Korea 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 scale 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 ground water 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.

2. 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-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-high confidence).

CMIP6 models project a larger increase in monsoon rainfall over land than over ocean (Fig. 2). Land monsoon rainfall will likely increase in the NH, but change little in the SH (Figs. 2 and 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 GHGs-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 21st century in CMIP6 is *likely* about 50% larger than in corresponding scenarios of CMIP5.

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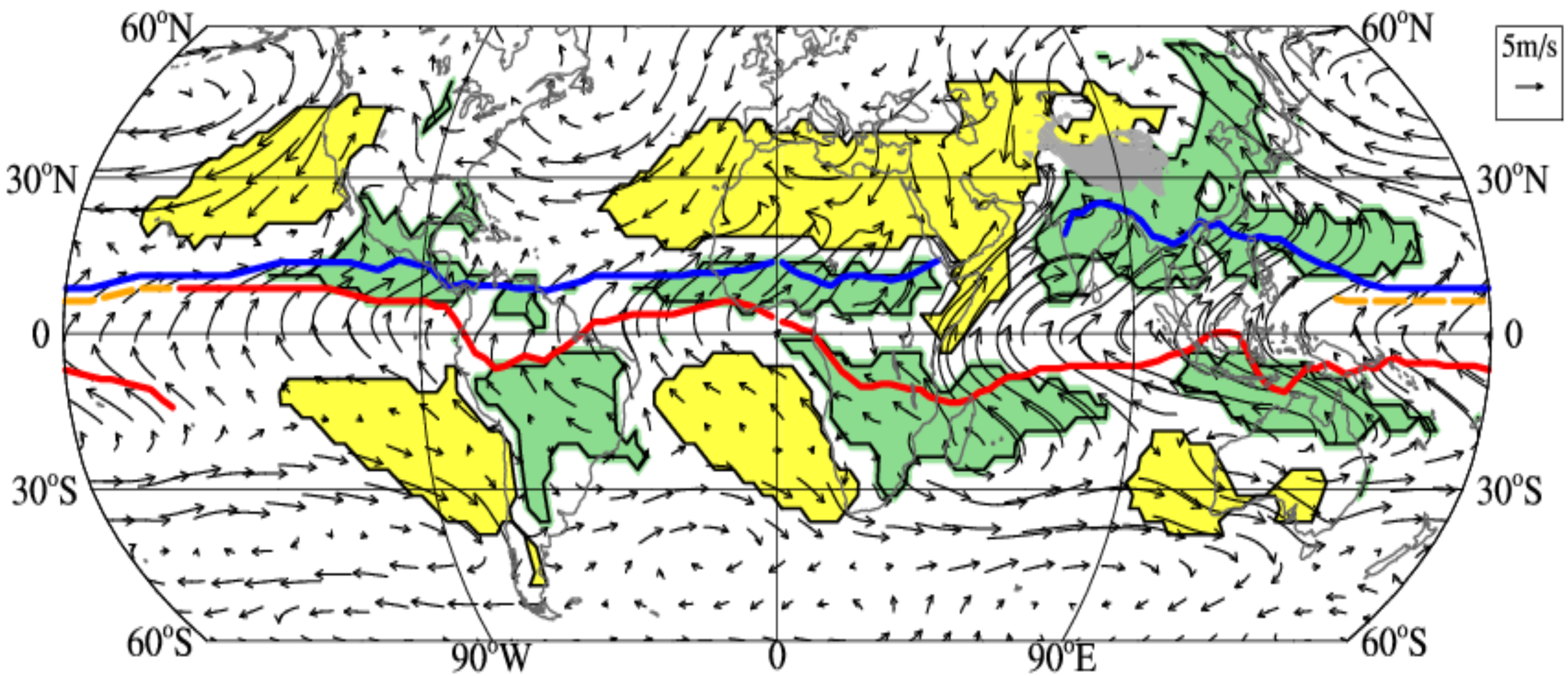


Figure 1. The GM precipitation domain (in Green) defined by the local summer-minus-winter precipitation rate exceeds 2 mm day^{-1}, and the local summer precipitation exceeds 55 % of the annual total (Wang and Ding 2008). Summer denotes May through September for the North ern Hemisphere and November through March for the Southern Hemisphere. The dry regions (in yellow) is 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).

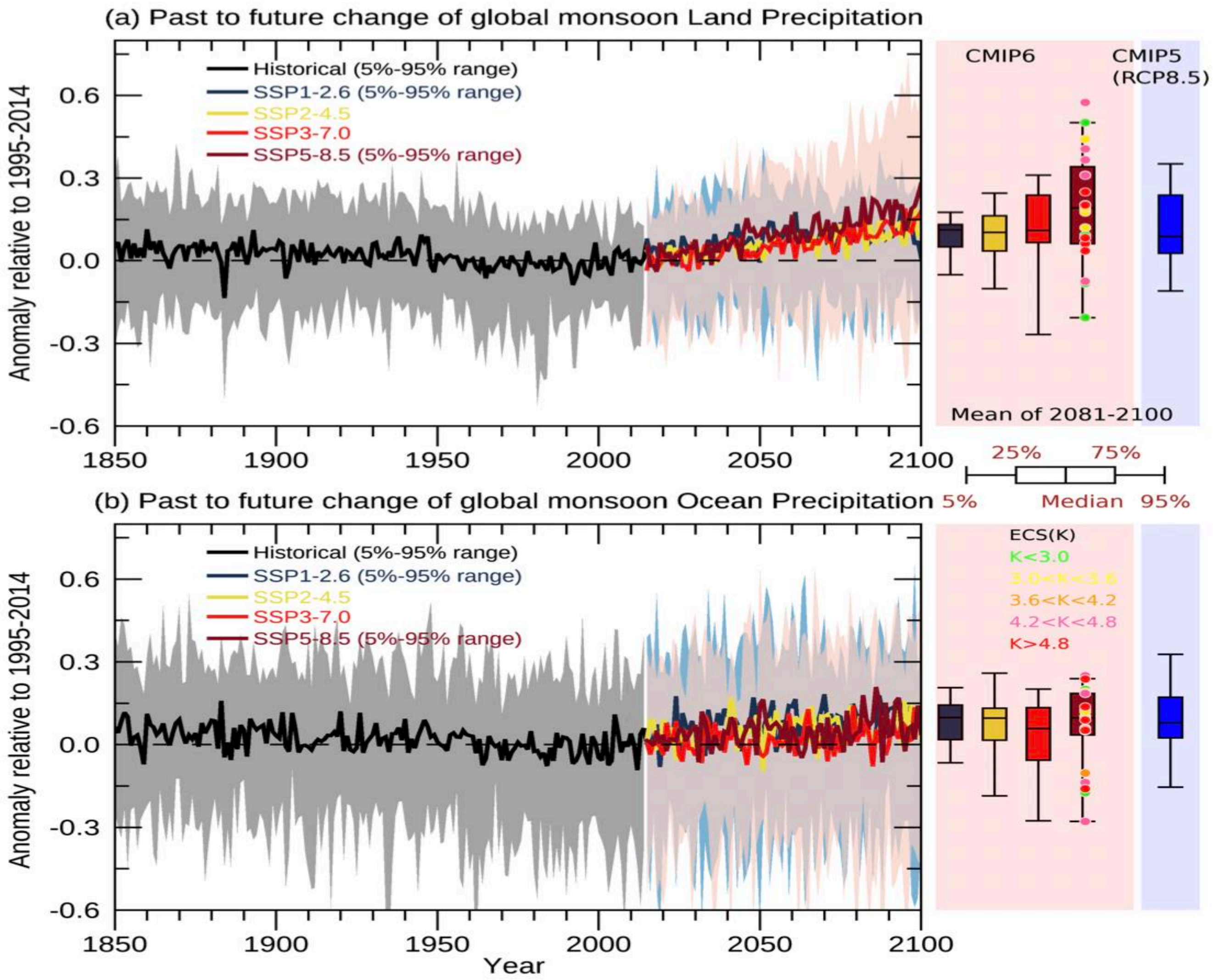


Fig. 2 Past to future changes of annual-mean global monsoon precipitation (mm/day) over (a) land and (b) ocean relative to the recent past (1995-2014) in historical simulation (1850-2014) and four core SSPs (2015-2100) obtained from 34 CMIP6 models. Pink and mid-blue shading indicate 5%-95% likely range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

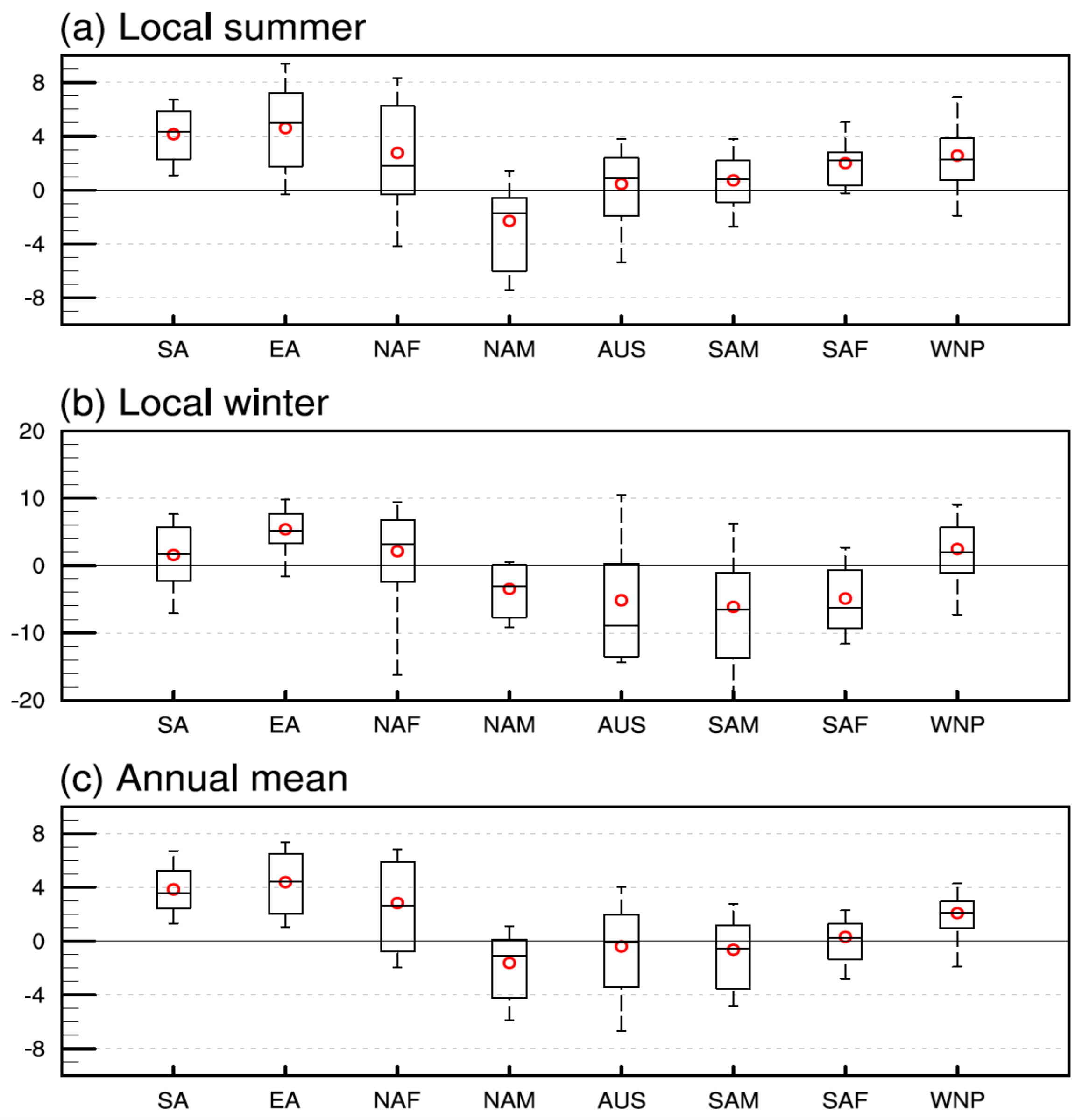


Fig. 3 Projected regional land monsoon precipitation sensitivity under the SSP2-4.5, i. e., the percentage change (2065–2099 relative to 1979–2013) per 1°C global warming, in units of %/°C) derived from 24 CMIP6 models for (a) local summer, (b) local winter, and (c) annual mean land monsoon precipitation 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 83th 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 dash line segments represent the range of nonoutliers (5%-95%).

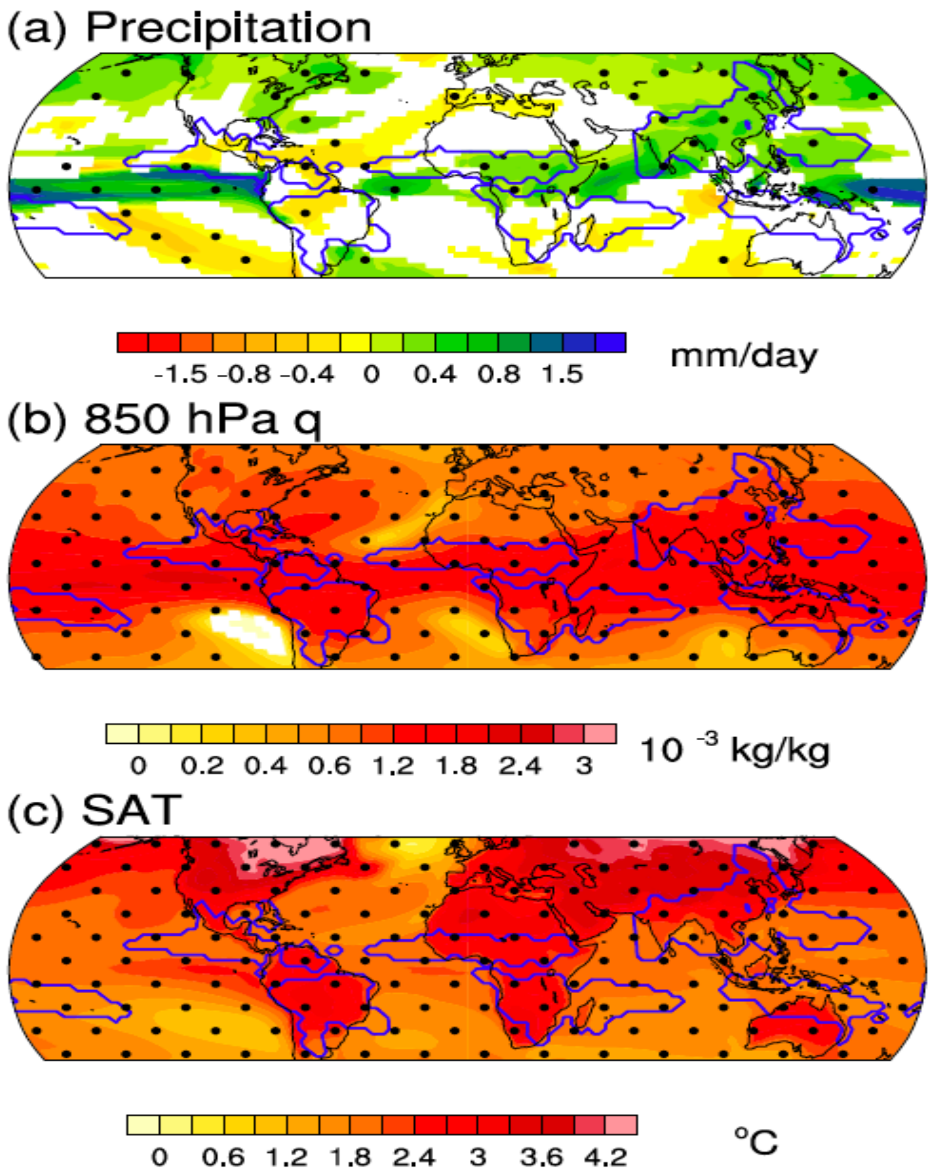


Fig. 4 Changes in the annual mean (a) precipitation, (b) 850 hPa specific humidity, and (c) surface air temperature. Changes are measured by the SSP2-4.5 projection (2065–2099) relative to the historical simulation (1979–2013) in the 15 models' MME. The color shaded region denotes the changes are statistically significant at 66% confidence level (likely change). Stippling denotes areas where the significance exceeds 95% confidence level (very likely) by student t-test.

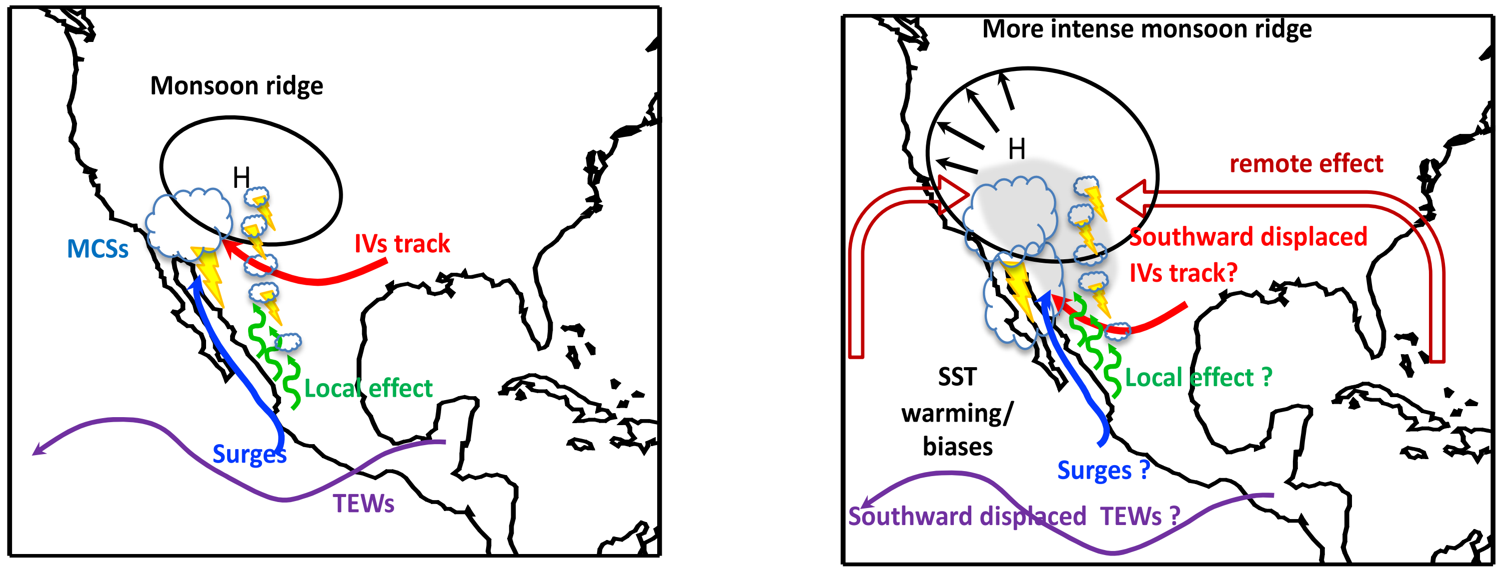


Fig. 5: Schematic main features related to present (left panel) and future (right panel) changes for the North American Monsoon (left). The expansion and northwestward shift of the NAM ridge, the southward shift of the upper-level inverted troughs (IVs) track, and the strengthening of the remote stabilizing effect due to SST warming are shown. Red and blue shading indicates drying and wettening respectively due to the large- scale shifts. Larger clouds in the lower panel is suggestive of more intense MCS-type convection. A question mark (?) on the lower panels indicates uncertainty in the response, as it is the case, for example, for the local mechanisms associated with atmosphere-land interaction, NAM moisture surges and southward shift the tropical easterly waves (TEWs) track.

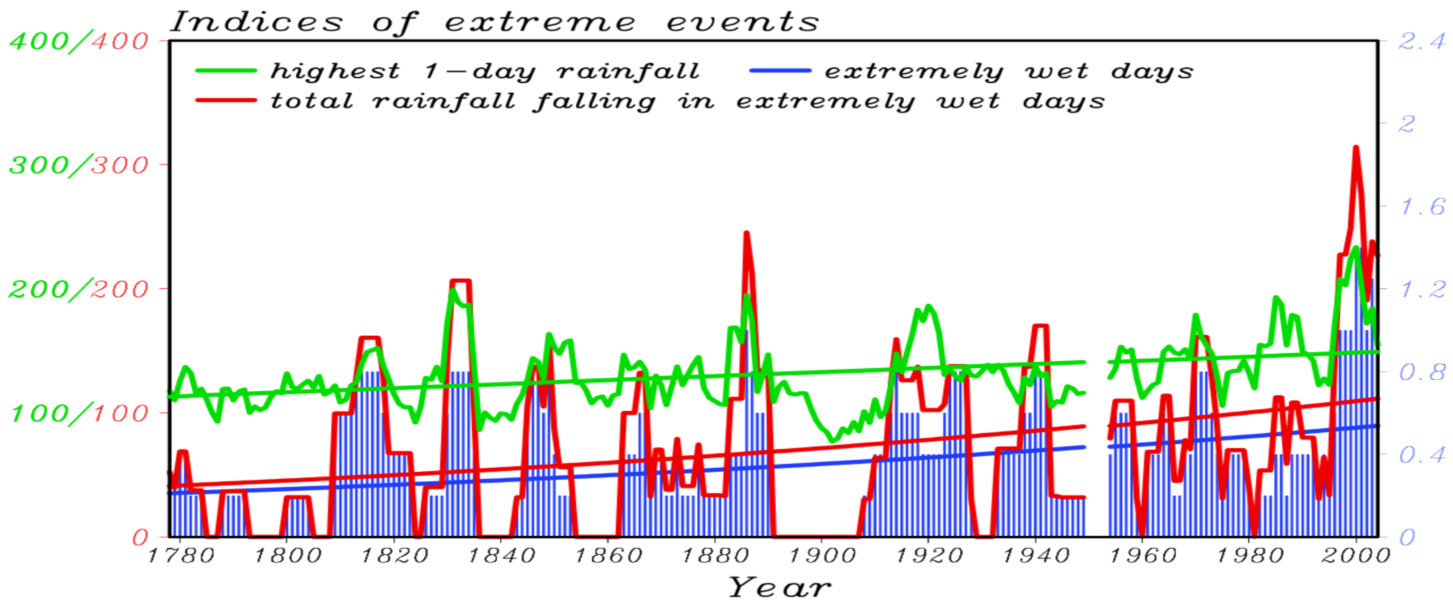


Figure 6. Time series of extreme precipitation events observed at Seoul, Korea since 1778. Running five-year means of the summer highest one-day precipitation amount (green, mm/day in the left y-axis), the number of extremely wet days (blue, right y-axis) and the precipitation amount falling in the extremely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

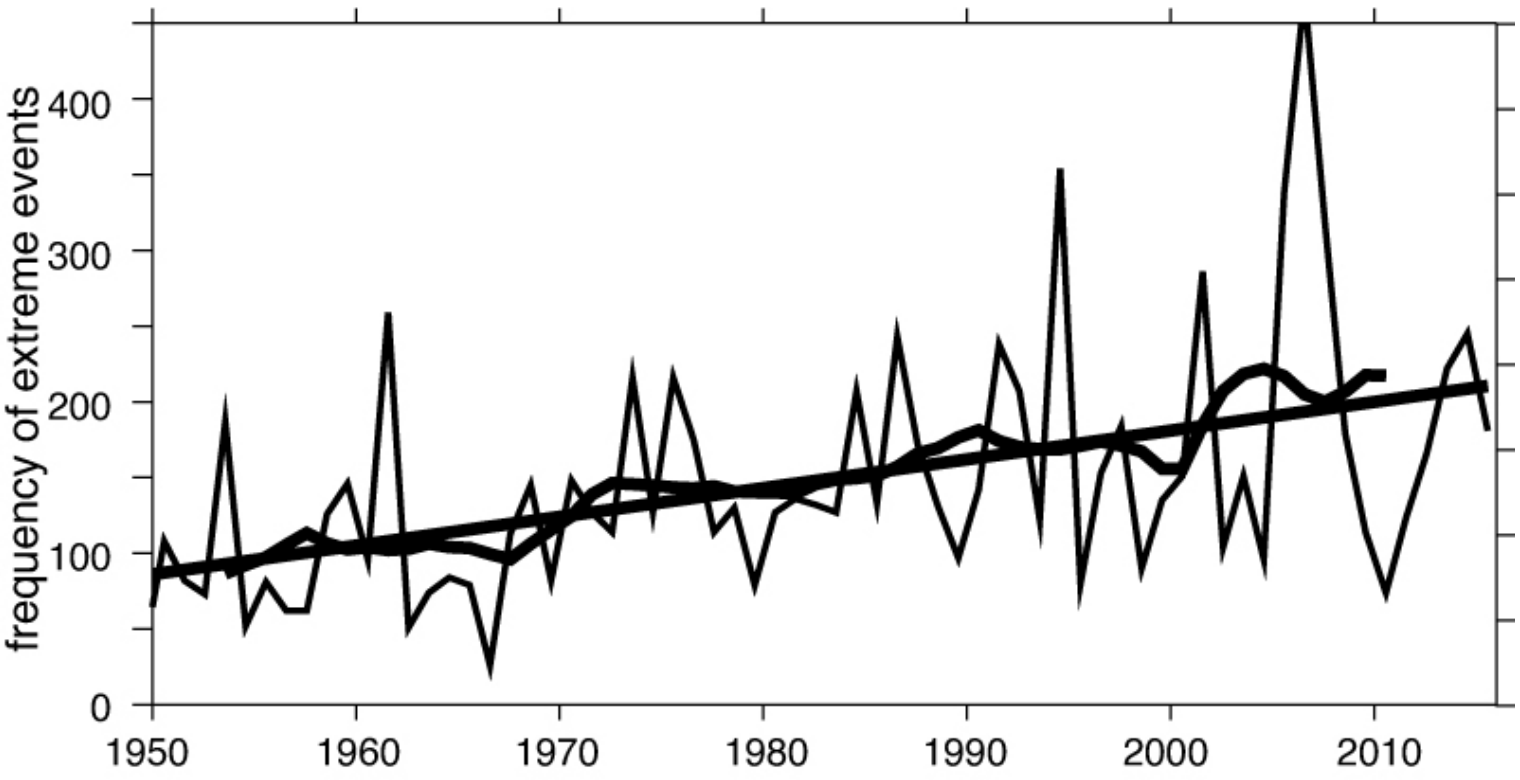
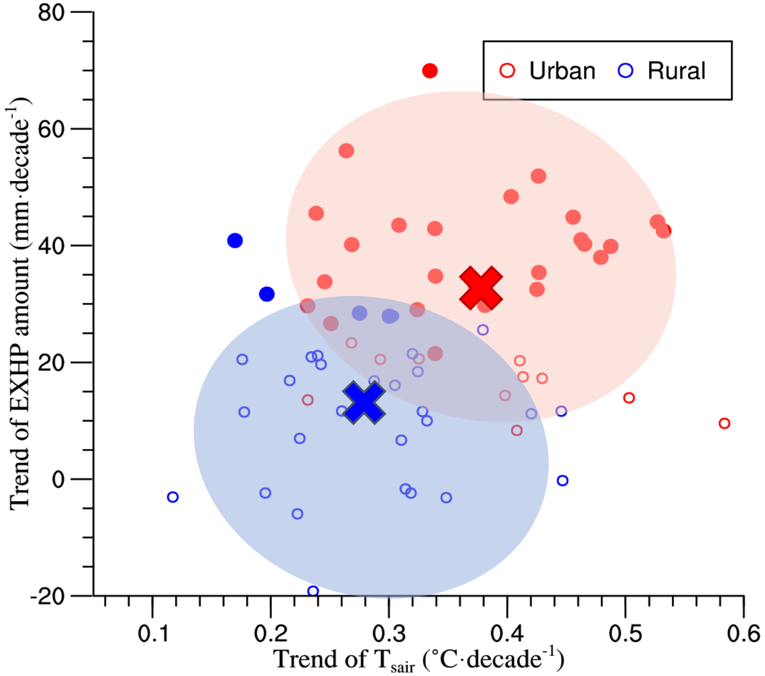
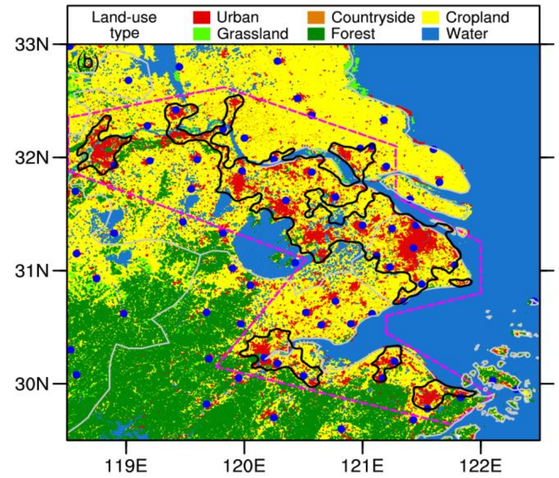


Figure 7. Frequency of extreme rain events (number of grid cells exceeding 150 mm/day per year) over central Indian subcontinent (75°–85° E, 19°–26° N) for the summer monsoon (June-September) during 1950–2015. The trend lines shown in the figures are significant at 95% confidence level. The smoothed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





Mean trends	T_{sair} (°C·decade^{-1})	EXHP amount (mm·decade^{-1})
Rural	0.28	12.8
Urban	0.38	32.6

Figure 8 The surface air temperature and extremely hourly rainfall trends for urban stations (red) and rural stations (blue) in the Yangzi River Delta, calculated from changes from 1975-1996 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)

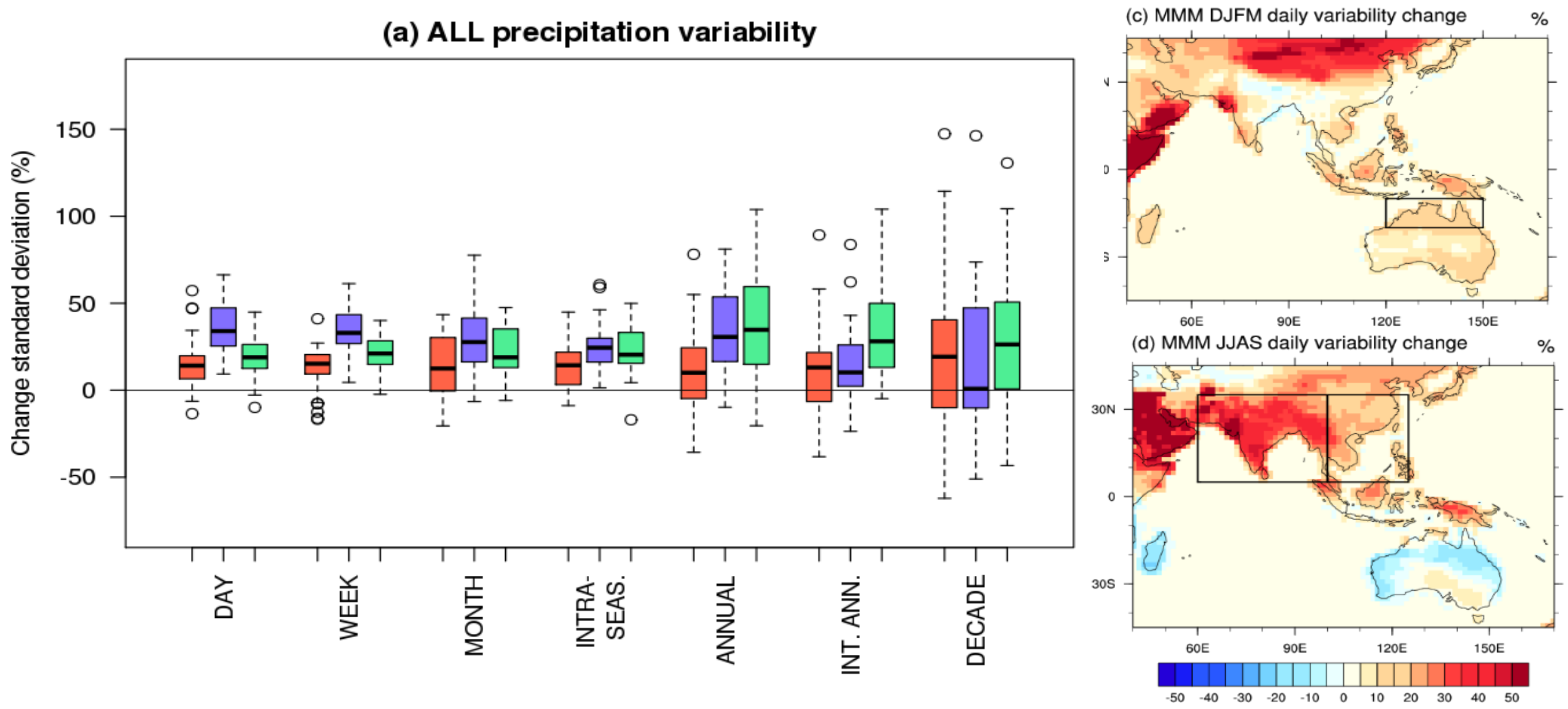


Fig. 9 (a) RCP8.5 (2050-2100) minus HIST (1950-2000) differences in band-pass-filtered daily rainfall standard deviation (%) for Australian (red, left boxes), South Asian (purple, center boxes) and East Asian (green, right boxes) monsoon domain. Data are DJFM months for AUS and JJAS months for SA and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