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"My interest in monsoon climate starts from questioning its definition. Monsoon was defined by the annual reversal of surface winds over the past three centuries. However, land monsoon rainfall has the most significant impact on human life. Since monsoon climate features a contrasting rainy summer and dry winter, I attempted to define the monsoon by rainfall characteristics in 1994, which suggests monsoon is a global phenomenon. Since then, I have been interested in regional (especially Asian) and global monsoon dynamics."

—Bin Wang, University of Hawaiʻi at Mānoa

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"In college I spent most my time competing in premier league bridge and seemed to be destined to become a professional bridge player. When I learned that heavy rainfall in the South China Sea can occur a couple days following cold air outbreaks from far away Siberia, I thought weather forecasting can be as fun as bridge. Instead of counting cards, I just have to count the cold air outbreaks and rainfall. And my father would be happier with me if I did not make a living playing cards."

—Chih-Pei Chang, Naval Postgraduate School and National Taiwan University

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Chih-Pei Chang (second from right) in 1978, then of the Department of Meteorology, Naval Postgraduate School, attending the Winter Monsoon Experiment with colleagues in Kuala Lumpur, Malaysia.

Monsoons in Climate Change

Adapted from "Monsoons Climate Change Assessment," by **Bin Wang** (University of Hawaiʻi at Mānoa), **Michela Biasutti, Michael P. Byrne, Christopher Castro, Chih-Pei Chang, Kerry Cook, Rong Fu, Alice M. Grimm, Kyung-Ja Ha, Harry Hendon, Akio Kitoh, R. Krishnan, June-Yi Lee, Jianping Li, Jian Liu, Aurel Moise, Salvatore Pascale, M. K. Roxy, Anji Seth, Chung-Hsiung Sui, Andrew Turner, Song Yang, Kyung-Sook Yun, Lixia Zhang**, and **Tianjun Zhou**. Published online in *BAMS*, January 2021. For the full, citable article, see **DOI:10.1175/BAMS-D-19-0335.1**.

Editors' note: *In BAMS online, the authors review "the current state of knowledge of climate change and its impacts on the global monsoon and its regional components," including "past monsoon changes and their primary drivers, the projected future changes, and key physical processes," and they "discuss challenges of the present and future modeling and outlooks." The article includes recent results from the Coupled Model Intercomparison Project Phase 6 (CMIP6) reported at a World Weather Research Programme workshop hosted by Sun Yat-Sen University in Zhuhai, China, in December 2019. The article focuses on monsoon rainfall over land. Consider these pages to be a quick-look dashboard of key points of the review. Note: On these pages, "high-confidence" results from the article are in italics. This does not imply the confidence levels for other statements.*

Monsoon rainfall on land (LMR) provides water resources for more than two–thirds of the global population. Monsoonal variability has tremendous societal impact. Accurate prediction of its change is vital.

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 will increase on hourly time scales. Heavy rainfall will increase at a much larger rate than the mean precipitation, especially in Asia.

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. 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 heavy rains, which, along with enhanced evaporation and runoff, will lead to an increased risk of droughts in many monsoon regions. 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 in heavily populated coastal regions.

An ensemble of 15 CMIP6 models estimates that under (shared socioeconomic pathways) SSP2–4.5, the total Northern Hemisphere (NH) LMR will increase by about 2.8% °C^{-1} in contrast to little change in the Southern Hemisphere (SH; −0.3% °C^{-1}). In both hemispheres, the annual range of LMR will increase by about 2.6% °C^{-1}, with wetter summers and drier winters. In addition, the projected rainy season in the NH will be lengthened by about 10 days due to late retreat, but will be shortened in the SH due to delayed onset. In addition to this robust NH–SH asymmetry there is an east–west asymmetry between enhanced Asian–African monsoons and weakened North American monsoon (NAM), suggesting that circulation changes play a crucial role in shaping the spatial patterns and intensity of global monsoon rainfall changes. Also, interannual variations of global monsoon precipitation (GMP) will be more strongly controlled by ENSO variability.

The greenhouse-gas (GHG)-induced robust "NH warmer than SH" pattern enhances NH LMR, especially in Asia and northern Africa, which have enhanced thermal contrast between large landmasses and adjacent oceans. The models that project a stronger interhemispheric thermal contrast generate stronger Hadley circulations, a further–north ITCZ, and enhanced NH LMR. Meanwhile, the increase in GMP (noted especially in the NH) is primarily attributed to temperature-driven increases in specific humidity, resulting in a "wet get wetter" pattern.

Climate models on average predict weakening ascent under global warming, which tends to dry monsoon regions. Weakening monsoon ascent has been linked to the slowdown of the global overturning circulation. However, a definitive theory for why monsoon circulations broadly weaken with warming remains elusive.

Past monsoon responses to external forcing may shed light on future climate change. The future NH monsoon response to GHG warming is projected to be weaker than the response in simulations of the mid-Holocene, although future warming is larger. This is because thermodynamic and dynamic responses act in concert during the mid-Holocene, but in simulations of the future, they partially cancel.

Future GHG-induced changes in monsoon rains differ region to region, and variability changes on a range of time scales. Globally decadal variability has been related to natural (internal) variability.

Another anthropogenic forcing, the urban heat island, increases convection and significantly increases localized extreme rainfalls.

Uncertainties

There is an urgent need to better understand uncertainty in rainfall projections. We need to quantify the causes of spread in future climate signals at the process level. For example, monsoons are strongly influenced by cloud and water vapor feedbacks, but these feedbacks vary greatly across climate models. Also, vegetation feedbacks may exacerbate the effects of CO_2-induced radiative forcing, especially in American and Australian monsoons. Water vapor from vegetation can affect monsoon onset, yet current climate models have limited capability in representing vegetation response to elevated CO_2, as well as land use and fire. The effect of these limitations on uncertainties in monsoon rainfall projections is virtually unknown.

it remains a major challenge to quantify the relative contributions of internal modes of variability versus anthropogenic forcing. A small multimodel ensemble such as CMIP5 or CMIP6 may not represent the full extent of uncertainty introduced by internal (multidecadal) variability. Also, models generally underestimate observed precipitation changes—a major challenge for quantitative attributions of regional monsoon changes.

CMIP progress and model biases

The CMIP6 models improve over CMIP5 for simulation of present GMP domain and intensity, and reproduce well the annual cycle of the NH monsoon and the leading mode of GM interannual variability and its relationship with ENSO. However, the models have major common biases, including overproducing annual mean SH monsoon precipitation by more than 20%. Simulated SH onset is early by two pentads while withdrawal is late by 4–5 pentads.

Systematic model biases in monsoon climates persist. Regional biases are often related to SST biases. The diurnal cycle is poorly simulated in the tropics due to failures in convective parameterization. Evapotranspiration biases affect boundary layer humidity and height.

The projected twenty-first-century LMR increase is about 50% larger in CMIP6 than in CMIP5 due to models with high (>4.2°C) equilibrium climate sensitivity (ECS), but the range of projected change is *likely* about 50% larger in CMIP6. Meanwhile, monsoon rainfall in CMIP6 has a median sensitivity of 0.8% $°C^{-1}$ in SSP2–4.5, and a median of 1.4% $°C^{-1}$ in SSP5–8.5; the latter is slightly higher than that simulated by CMIP5 models under RCP8.5.

While subtle modeling improvements are 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 a 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. Further, proper simulation of how aerosols modify monsoon rainfall requires improved cloud microphysics schemes.

Future advances

The extent to which recent theoretical advances in tropical dynamics can explain CMIP6 changes in monsoon strength and spatial extent is an open question that should be prioritized; an additional research pathway to more reliable monsoon projections would be to develop emergent constraints applicable to monsoons.

Some features of monsoon meteorology, such as extreme rainfall greater than 1 m day^{-1}, are nearly impossible to simulate in coupled climate models. Convection-permitting regional simulations may more realistically represent responses of short time scale rainfall processes to forcing.

The interplay between anthropogenic forcing and internal modes of variability, such as the interdecadal Pacific oscillation (IPO), Atlantic multidecadal variation (AMV), and SH annular mode, is important in the historical record and near-term future. Improvements in predicting internal modes of variability could reduce uncertainties in near-term climate projections.

METADATA

BAMS: What would you like readers to learn from this article?

Bin Wang (University of Hawai'i at Mānoa): *I want to emphasize the different responses of the monsoon mean precipitation and the extreme precipitation to global warming. Despite the 1.1 degrees of global warming over the past century, the global monsoon precipitation has no significant upward trend. The models-projected near-term changes are largely uncertain due to substantial interdecadal monsoon variability. The long-term change of the mean monsoon precipitation projected by models shows a conspicuous NH-SH asymmetry and an east-west asymmetry in the NH, which contrasts the uniform increases in the specific humidity across monsoon regions. The so-called thermodynamic effect (I would call it the moisture effect) and the "wet-get-wetter" paradigm cannot explain this model projection. The implication here is that the GHG forcing induces horizontally differential heating, and the forcing-induced circulation change must be a dominant factor in driving the regional monsoon mean precipitation change. The top-heavy GHG heating-induced atmospheric stabilization (another thermodynamic effect) offsets the effect of increased moisture, resulting in a moderate response of the precipitation intensity on the global scale.*

Chih-Pei Chang (Naval Postgraduate School and National Taiwan University): *Monsoon rainfall supplies water to more than two-thirds of the world's population, yet its variations are the dominant reason these people suffer from floods and droughts. Climate change will exacerbate its impacts, making monsoon climate change a very important research priority. A lot has been learned, yet progress in modeling has a long way to go. Models underestimate observed precipitation changes. They also have difficulty quantifying the relative contributions of internal variability versus anthropogenic forcing. Improved resolution in the models has led to a larger projected increase in rainfall over land, but the range in this projection has also increased.*

BAMS: How did you become interested in the topic of this article?

C-PC: *My interest grew with the increasing reports of extreme events in different monsoon regions: South Asia, East Asia, Australia, Africa, South America. While there are distinct regional characteristics due to geographic location and influences of terrain and ocean, climate change is the common thread. I also found that study of this topic requires close international cooperation of scientists in observational, theoretical, and complex modeling research, and also with government agencies from the different monsoon regions. I am a believer in globalization, and I think cooperating for the common good can help to promote the well-being of humankind.*

BAMS: What surprises you the most about the work you document in this article?

C-PC: *It was not surprising that, even though the models are far from perfect, they provide signals that point to the increasing trend of extreme weather. Yet it was somewhat frustrating that, with steadily improved model resolution and physics, the progress in differentiating internal variability and anthropogenic forcing is very slow.*

BAMS: What was the biggest challenge you encountered while doing this work?

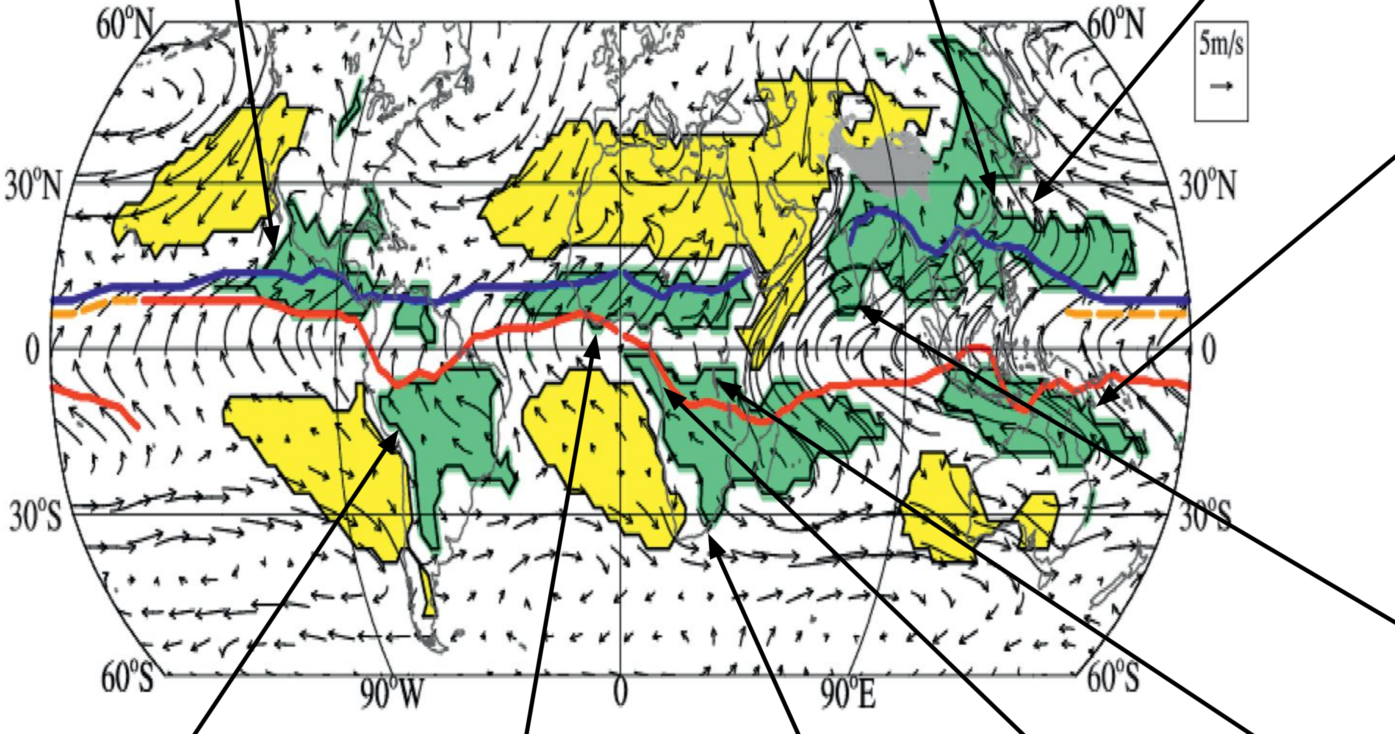
C-PC: *Monsoon regions, spread over all the world's continents except Europe, all have in common heavy rainfall variations that cause flooding and drought, and also all have region-specific characteristics. It was a challenge coordinating the discussion with input from experts studying different monsoon regions and focuses, and in some cases different views and interpretations, to come up with a consensus report of the current state of our monsoon understanding.*

North American monsoon (NAM)

Including Arizona, western Mexico, Central America, and Venezuela. Long-term rainfall trends are negative or null, but vary substantially regionally. For the years 1950–2010, a stronger and shifted monsoonal ridge made transient inverted troughs less frequent in triggering severe weather. Annual maximum daily rainfall has increased 6%–11%° C^{-1}.

East Asian summer monsoon (EASM)

EASM has exhibited considerable multidecadal variability with weakened circulation and a south flood–north drought pattern since the late 1970s—in a phase change of the IPO and aided by GHG-induced warming and increased Asian aerosol emissions. Anthropogenic forcing has contributed to a shift toward heavy precipitation in eastern China and increased July maximum daily precipitation in western Japan. In Seoul, South Korea, annual maximum daily rainfall and the number of extremely wet days are increasing. While extreme rainfall decreased during 1958–2010 in northern China, southern China saw a much larger increase.



South American monsoon (SAM)

In the 1950s to 1990s, a significant positive precipitation trend in the southeast SAM was related to interdecadal variability, ozone depletion, and increasing GHG. The tropical SAM trend is less coherent. Recent decades have seen a longer and drier dry season, especially in southern Amazonia, where vegetation significantly influences moisture transport to the SAM core region. Annual maximum daily rainfall has increased 15%–25% °C^{-1} in the eastern SAM. Over tropical South America, wet and dry extremes display more significant and extensive trends.

West Africa and Sahel

Since the 1950s, NH anthropogenic aerosols may be a significant driver in the Sahel drought. Increasing rainfall since the 1980s has helped regreen the Sahel. Trends in West Africa toward a wetter late season and delayed cessation of rains are qualitatively consistent with the CMIP5 response to GHG.

Southern South Africa

Annual maximum daily rainfall has increased about 10%–14% °C^{-1}.

Congo Basin

Observed precipitation trends are inconclusive, but one study reports earlier onset of spring rains.

The GMP domain (green) is where summer minus winter precipitation exceeds 2 mm day^{-1} and summer precipitation is >55% of the annual total (summer denotes May–September for the NH and November–March for the SH). In dry regions (yellow), local summer precipitation is <1 mm day^{-1}. The arrows show August minus February 925-hPa winds. The ITCZ position is marked for August (blue line) and February (red line). [Adopted from P.-X. Wang et al. (2014).]

Coastal China

Rapid urbanization correlates with increased extreme rainfall (e.g., in the Pearl and Yangtze deltas). In the last 50 years, the decreasing frequency of incoming western North Pacific tropical cyclones (TCs) more than offsets increasing TC rainfall intensity. Even with reduced TC extreme rainfall in southern coastal China, LMR rainfall increased overall.

Australia

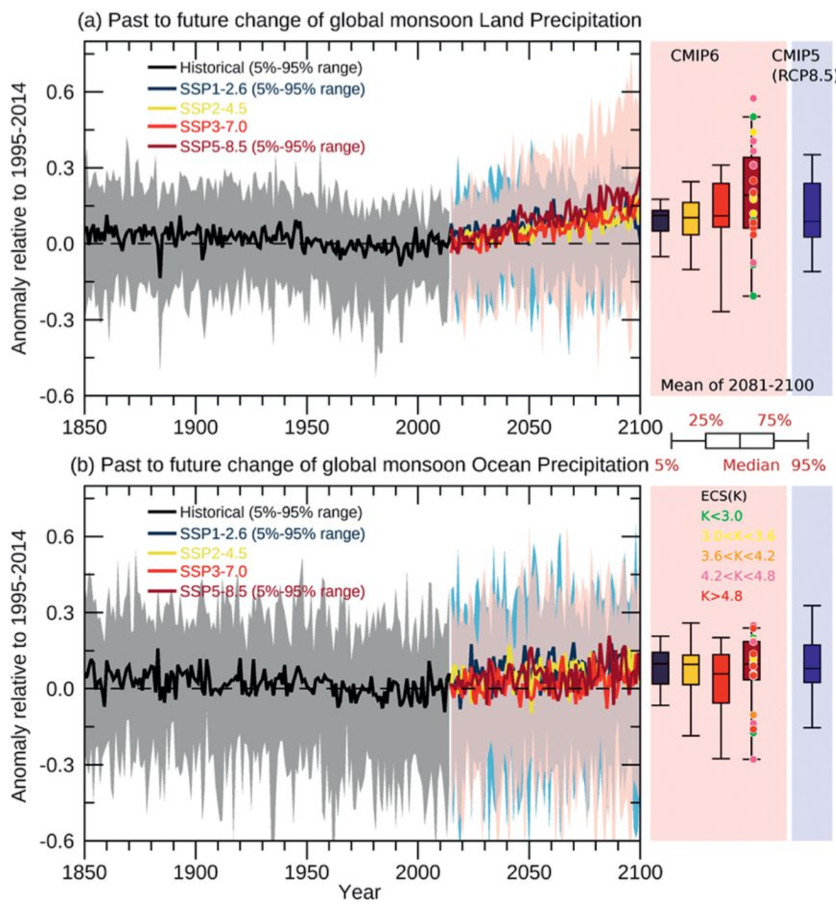
Even with strong decadal variations, Increasing summer LMR since 1970s (especially in the northwest) has been attributed to increasing tropical western Pacific SST and to aerosol and GHG forcing.

South Asian summer monsoon (SASM)

SASM has had circulation decline since the 1950s, weakening local meridional circulation, and notable precipitation decreases (north-central and west coast)—associated with a reduced meridional temperature gradient attributed to anthropogenic aerosols and equatorial Indian Ocean warming (due to increased GHG). The central subcontinent had a significant shift toward briefer, heavier precipitation spells in 1950–2015: annual maximum daily rainfall increased about 8% °C^{-1}.

East Africa

Observed increases in boreal fall short rains are more robust than negative trends in spring long rains. LMR here is sensitive to Indian Ocean SSTs and Pacific variability.



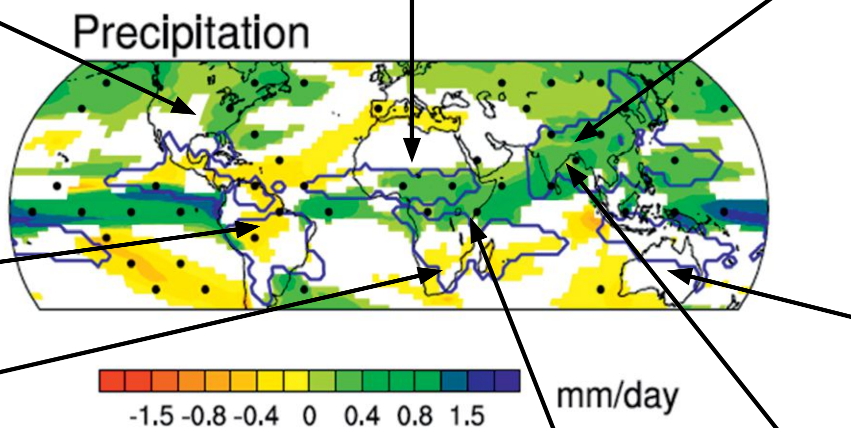
Annual means (mm day^{-1}) relative to 1995–2014 in the historical simulation (1850–2014) and four core SSPs (2015–2100) from 34 CMIP6 models. Pink and blue shading indicate the 5%–95% likely range of precipitation change in the low-emission (SSP1–2.6) and high-emission (SSP5–8.5) scenarios, respectively. Boxplots are 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 ECS of individual models. CMIP6 historical simulations suggest that anthropogenic sulfate and volcanic forcing likely masked the effect of GHG forcing and decreased global (mainly NH) LMR in 1950–1990; however, the recent upward trend may signify the emergence of the GHG signal against the aerosol emissions. Short-period trends may be part of multidecadal variability, primarily driven by the AMV and the interdecadal Pacific oscillation (IPO).

North American monsoon (NAM)

Projections suggest an early-to-late redistribution of NAM precipitation with no overall reduction, and a more substantial reduction for Central American precipitation. However, local biases (e.g., representation of vegetation dynamics, land cover and land use, and soil moisture) and remote biases (SST) may lead to large uncertainties. Confidence in mean precipitation changes is lower than in the projection that precipitation extremes are likely to increase. Factors likely to determine future NAM include expansion and northwestward shift of the NAM ridge, stronger remote stabilizing due to SST warming, and more intense MCS convection. More uncertain is the future of the NAM moisture surges and the track of upper-level inverted troughs.

North African monsoon (NAF) and Sahel

CMIP6 models project (though with a large spread) likely increases in NAF rainfall. Preliminary CMIP6 results (with large uncertainties) show the Sahel becoming wetter, except for the west coast, and the rainy season extending later.



South America

CMIP6 projected (with large spread) precipitation changes that resemble anomalies expected for El Niño: little change of annual mean, drier winter/spring, and increased peak monsoon rainfall—consistent with CMIP5 projections (also low confidence) showing delay and shortening of the monsoon season and prolonged dry spells. A drying climate in eastern Amazonia leads to a real risk of rainforest dieback.

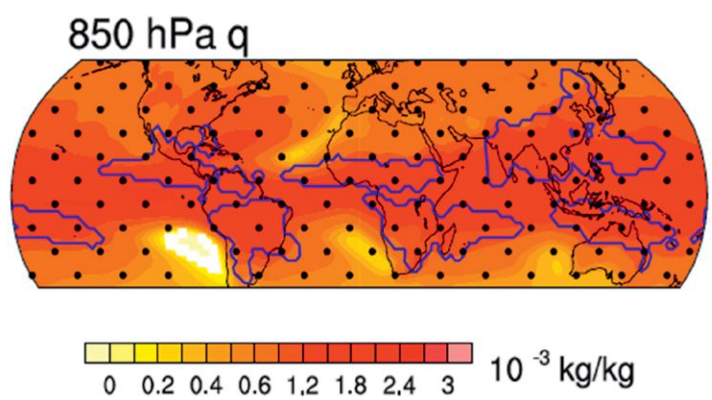
South African monsoon (SAF)

The CMIP6 models under SSP2–4.5 project with low confidence that by the latter twenty-first century rainfall will likely increase in summer but considerably reduce in winter, with no significant change of the annual mean.

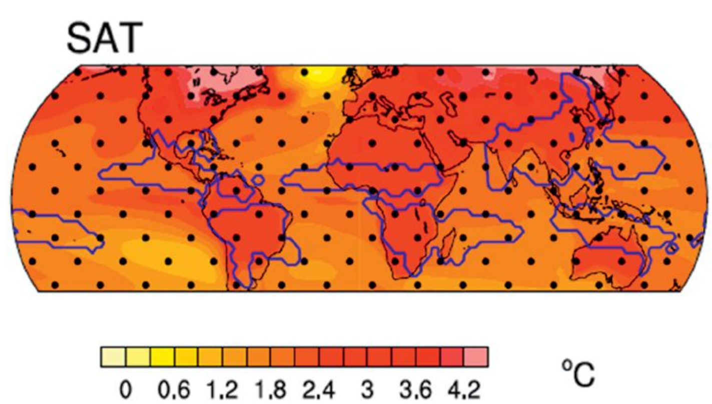
East Africa

Some regional models suggest enhanced short rains and curtailed long rains.

On average, extreme 5-day monsoon rainfall responds approximately linearly to global temperature increase at 5.17% °C^{-1} (4.14%–5.75% °C^{-1}) under RCP8.5 with a high signal-to-noise ratio. Extreme monsoon precipitation in Asia shows the highest sensitivity to warming, while changes in the North American and Australian monsoon regions are moderate with low signal-to-noise ratio.



Unlike mean precipitation changes, heavy and intense rainfall is more tightly controlled by environmental moisture content related to the Clausius–Clapeyron relationship and convective-scale circulation changes. In monsoon regions, increases in specific humidity are spatially uniform.



East Asia

LMR will increase. CMIP6 projections for 2015–2100 indicate western East Asia will confront more rapidly increasing drought severity and risks than eastern East Asia. If a projected northward trend in TCs means more recurvatures, the Korean coast and Japan might get increased extreme rains, and China less. CMIP6 models indicate that, under the SSP2–4.5, EASM precipitation will increase 4.7% $°C^{-1}$. EASM is projected to lengthen by about 5 pentads. CMIP6 models (under SSP2–4.5) project changes of extreme 1-day rainfall of +68% (2065–2100 relative to 1979–2014).

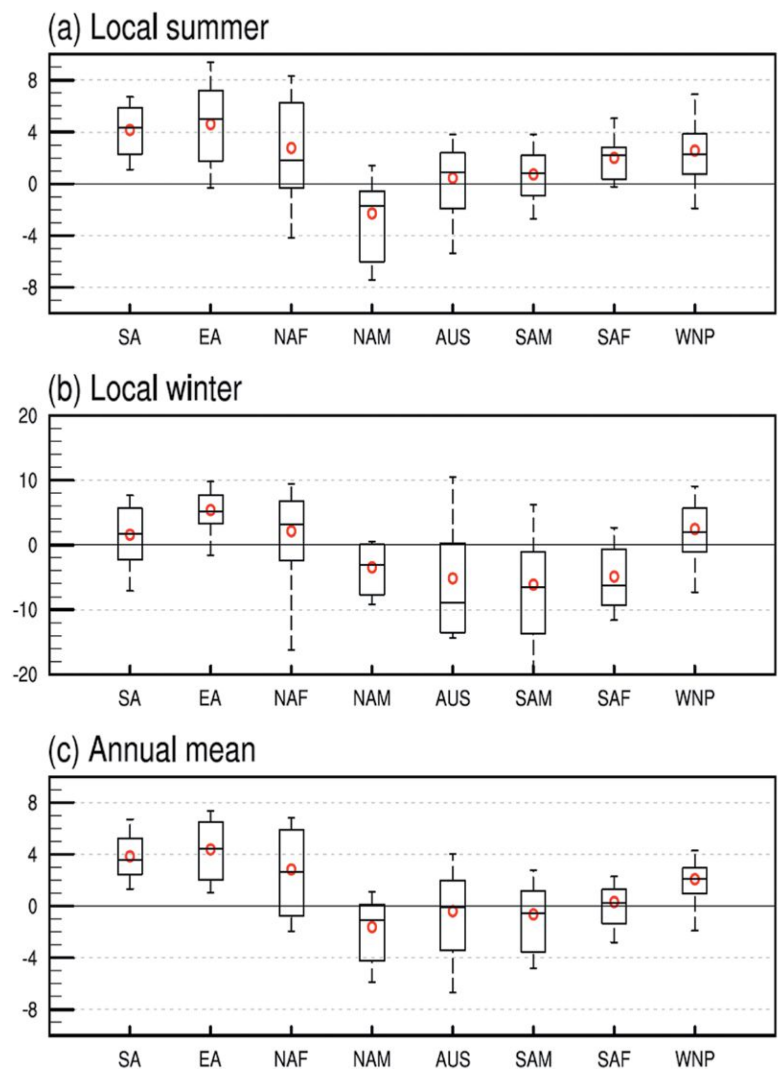
Australia

7 of 10 the CMIP5 models performing best for Australia indicate a 5%–20% increase in monsoon rainfall north of 20°S late in this century, but trends over a much larger region are more uncertain. The Madden–Julian oscillation (MJO) is anticipated to have stronger-amplitude rainfall variability by the end of this century, but the impact on Australian summer monsoon intraseasonal variability is uncertain.

South Asia

LMR will increase. CMIP5 models project more severe floods and droughts. CMIP6 models (under SSP2–4.5) project changes of extreme 1-day rainfall of +58% (2065–2100 relative to 1979–2014).

The future change of GMP pattern and intensity is determined by increased specific humidity and circulation changes forced by the vertically and horizontally inhomogeneous heating induced by GHG forcing. For all three panels here, changes in the annual mean are measured by the SSP2–4.5 projection (2065–2100) relative to the historical simulation (1979–2014) in the 15-model ensemble. Changes in the color-shaded region are statistically significant at 66% confidence level (likely change). In stippled areas, the significance exceeds 95% confidence level (very likely) by Student's *t* test.



Regional LMR sensitivity under the SSP2–4.5—i.e., the percentage change (2065–2100 relative to 1979–2014) per 1°C global warming (% $°C^{-1}$), derived from 24 CMIP6 models. Local summer means JJAS in NH and DJFM for SH, and local winter means the opposite. The box represents the 17th to 83rd percentile range. The line within the box is the median: red circle is the mean. The vertical dashed segments represent the range of non-outliers (5%–95%). 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; for example, variability of monsoon rainfall is projected to increase on daily to decadal time scales over the Asian–Australian monsoon region. Also, the projected mean rainfall changes over SH monsoons have low confidence due to a large model spread.

"NOAA has been flying the VIIRS (Visible Infrared Imaging Radiometer Suite) sensor in the afternoon orbit for a decade now, since the legacy POES (Polar Operational Environmental Satellites) were replaced by JPSS (Joint Polar Satellite System). EUMETSAT will fly a new imager called Metimage on their next-generation MetOp satellites. Building consistent data records from all these sensors will keep us busy for awhile."

—Satya Kalluri, NOAA/NESDIS/STAR

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"This is an international effort of more than two dozen experts and their colleagues and students, organized by the WMO's Working Group on Tropical Meteorology Research. Future collaboration of international experts across observational, theoretical, and modeling studies will continue to be important to advance the understanding of climate change on the global monsoon system and its regional ramifications. Recently, WMO's two major research components, the World Climate Research Programme (WCRP) and World Weather Research Programme (WWRP), jointly established a new international Monsoon Project Office in India. This should be very helpful for future international collaborations."

—Chih-Pei Chang, Naval Postgraduate School and National Taiwan University

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Chih-Pei Chang gives the welcome speech at the Workshop on Monsoon Climate Change and Attribution in 2019.