Global Land Monsoon Precipitation Changes in CMIP6 Projections

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Abstract Changes in global land monsoon (GLM) precipitation determine the local water resource, affecting two thirds of global population. The future changes in GLM summer precipitation and the sources of projection uncertainty under four scenarios are investigated using the Coupled Model Intercomparison Project Phase 6 (CMIP6) models. The GLM summer precipitation is projected to increase by 1.76 ± 1.57% (2.54 ± 2.22%), 1.33 ± 1.97% (3.52 ± 3.05%), 0.96 ± 2.04% (3.51 ± 4.97%), and 1.71 ± 2.38% (5.75 ± 5.92%) in the near (long) term under Shared Socioeconomic Pathway (SSP) 1–2.6, SSP2–4.5, SSP3–7.0, and SSP5–8.5, respectively. The enhancement is caused by thermodynamic responses due to increased moisture, which is partly offset by dynamic responses due to weakened circulation. The uncertainty in GLM precipitation projection is the largest in SSP5–8.5 long-term projection. The uncertainty of submonsoon precipitation projections is larger than that in GLM precipitation. The uncertainty of monsoon precipitation projection arises from the circulation changes, which can be partly explained by model-dependent response to uniform sea surface temperature warming.

Plain Language Summary The changes of monsoon rainfall under a warmer climate receive much attention. Here we revealed the future changes of summer precipitation over global and submonsoon regions in different periods under four new scenarios designed by the Coupled Model Intercomparison Project Phase 6 (CMIP6). In 2021–2040 (2080–2099), the monsoon summer rainfall will increase by about 1.76 ± 1.57% (2.54 ± 2.22%), 1.33 ± 1.97% (3.52 ± 3.05%), 0.96 ± 2.04% (3.51 ± 4.97%), and 1.71 ± 2.38% (5.75 ± 5.92%) under the low, medium, and two high emission scenarios, respectively. At the end of the 21st century, the monsoon rainfall will increase largest in the highest emission scenario with largest spread. Moreover, the spread over each submonsoon region is much larger than that of global land monsoon. The increase of rainfall is associated with the increase of water vapor but offset by the weakened circulation. The spread of rainfall changes is caused by the spread of circulation projection, which is partly caused by the model-dependent responses of circulation to uniform sea surface temperature warming.

1. Introduction

The global monsoon (GM) consists of regional monsoons, including the Asian-Australian monsoon, the African monsoon, and the American monsoon. Monsoon precipitation has large variabilities and influence the global energy budget and circulation (Wang & Ding, 2008). About two third of global population relies on the water resource from GM summer precipitation (Kitoh et al., 2013; Wang et al., 2012; W. Zhang et al., 2018). Thus, understanding and predicting the changes of GM are critically important.

The GM system is sensitive to global warming, and the projection of GM has received much attention (e.g., Endo et al., 2018; Endo & Kitoh, 2014; Kitoh et al., 2013; Lee & Wang, 2014). Multimodel ensemble (MME) projections suggest that the GM area and summer precipitation would increase in medium and high emission scenarios (Christensen et al., 2013). Regionally, projected changes in the monsoon precipitation exhibit a robust increase in the Northern Hemisphere (NH) but a slight decrease in the Southern Hemisphere (SH; Kitoh et al., 2013), due to the interhemispheric difference in warming rate (Lee & Wang, 2014). Moreover, the projected GM changes exhibit substantial uncertainty. Some recent studies on projected changes for regional precipitation focused on the understanding of uncertainty. The uncertainty of the Asian summer monsoon precipitation changes is associated with the uncertainty of circulation changes (Endo &
Kitoh, 2014), which is caused by the different sea surface temperature (SST) warming pattern (Chen & Zhou, 2015) and the background circulation (Zhou et al., 2017). In the tropics, the uncertainty of regional precipitation over ocean and coastal regions is dominated by the spread of circulation changes associated with the changes of atmospheric radiative cooling (Oueslati et al., 2016) and SST patterns (Ma & Xie, 2013), while the uncertainty over the tropical inland regions is dominated by the difference in the thermodynamic term (TH), which results from the spread in the evaporation changes (Oueslati et al., 2016).

Climate projections are scenario-dependent. The Coupled Model Intercomparison Project Phase 6 (CMIP6) has designed new scenarios called Shared Socioeconomic Pathway (SSP) 1–2.6, SSP2–4.5, SSP3–7.0, and SSP5–8.5 (Eyring et al., 2016; O’Neill et al., 2016). Climate change mitigation and adaptation activities need the projection of GM changes under these new scenarios. More importantly, instead of simply repeating previous analysis by using new scenarios, this study aims to provide projections that cover both the near term, the midterm, and the long term, while previous studies mainly focused on the long-term projection (e.g., Kitoh et al., 2013; Lee & Wang, 2014; Zhang et al., 2019). Climate projections include uncertainties, but sources are unclear. For GM, whether a uniform warming of SST could eliminate the uncertainty of monsoon precipitation or circulation changes need to be investigated. In this study, based on the latest projection in the Scenario Model Intercomparison Projection (ScenarioMIP; O’Neill et al., 2016) of CMIP6 (Eyring et al., 2016), we aim to address the following questions: (1) What are the future changes in global land monsoon (GLM) precipitation under different CMIP6 scenarios in different periods? (2) What are the mechanisms for the changes and what are the sources of uncertainty in GLM precipitation in different projection terms? (3) Whether a uniform warming could reduce or eliminate the uncertainty of GLM precipitation projection?

2. Data and Methods

We use the monthly data from 19 CMIP6 models in historical simulation, and projections under four combined scenarios of the SSPs and the Representative Concentration Pathways (RCPs), viz, SSP1–2.6, SSP2–4.5, SSP3–7.0, and SSP5–8.5 scenarios (Table S1 in the supporting information; Eyring et al., 2016; O’Neill et al., 2016). The first available realization for each model and each scenario is used. Moreover, more than one realization of same model are used to quantify the effect of internal variability (Table S1). The model data are regridded to 2.5° × 2.5° grids before MME by using bilinear interpolation in circulation patterns and first-order conservative interpolation in precipitation, moisture, evaporation, and vertical velocity. The baseline period is 1995–2014 in this study. Three specific periods in future projection are examined and termed as the near term (2021–2040), midterm (2041–2060), and long term (2080–2099), respectively. In addition, to examine the effects of uniform SST warming, we also use output of nine models (Table S2) from the Atmospheric Model Intercomparison Projection (AMIP) and AMIP-p4K experiment for the period of 1995–2014 (Webb et al., 2017). In AMIP, the model was run with prescribe observed SST, while in AMIP-p4K, the model was run with prescribe observed SST, which is subject to a uniform warming of 4 K (Webb et al., 2017; see Table S3 for details).

We focus on the changes in summer precipitation over the GLM area. The GM domain is defined as the area where the precipitation difference between the local summer and winter is larger than 2.0 mmday⁻¹, and local summer precipitation exceeds 55% of the annual total precipitation (Wang et al., 2012). Local summer is defined as May to September for the NH and November to March for the SH. The GLM region is based on the observation. It can be further divided into seven submonsoon regions (Figure 2; Kitoh et al., 2013).

To understand the mechanisms of changes and uncertainty in precipitation under warming, a moisture budget analysis is used in this study (Chou et al., 2009; see Text S1 in the supporting information for details).

To quantify the uncertainty in multimodel projections, the spread from 10th to 90th percentile across models is presented and compared with the results in CMIP5.

3. Results

3.1. Precipitation Changes in the Projection

We first examine the linear trends of GLM summer precipitation for 2015–2099 under different scenarios in Figure 1. The GLM region would experience an overall increasing trend of precipitation in the 21st century
with the strongest magnitude under SSP5–8.5. The projection from CMIP6 includes more gain of precipitation and higher model agreement over the NH monsoon region relative to the SH monsoon region, the most significant increasing trend over the Asian monsoon region, and drying trend over the North American monsoon region. This pattern is comparable to those in A1B scenario (Hsu et al., 2012) from CMIP3 and RCP4.5 (Hsu et al., 2013; Kitoh et al., 2013; Lee & Wang, 2014) and RCP8.5 (Kitoh et al., 2013; Zhang et al., 2019) scenarios from CMIP5.

The projection of GLM precipitation in CMIP6 MME contains large uncertainty (Figure S1 in the supporting information). To quantify the changes and uncertainty in different periods and the regional dependence, the changes over global land and each submonsoon region in nearterm, midterm, and long term projection under the four scenarios are shown in Figure 2. The CMIP6 MME projects a gradually enhancement of GLM precipitation from near term to long term for all scenarios. In the near-term projection, the enhancement of GLM precipitation is 1.76% \((0.19\text{–}3.33\%)\) for the 10th–90th ensemble range, 1.33\% \((-0.64\text{–}3.30\%)\), 0.96\% \((-1.08\text{–}2.99\%)\), and 1.71\% \((-0.67\text{–}4.10\%)\) under SSP1–2.6, SSP2–4.5, SSP3–7.0, and SSP5–8.5, respectively. In comparison, it increases by 2.54\% \((0.32\text{–}4.76\%)\), 3.52\% \((0.47\text{–}6.58\%)\), 3.51\% \((-1.46\text{–}8.49\%)\), and 5.75\% \((-0.17\text{–}11.68\%)\), respectively, for the long-term projection. Both the magnitude of precipitation amount and the projection uncertainty increase with time except for SSP1–2.6. The uncertainty extent \((-11.85\%)\) for the long-term GLM precipitation increase under SSP5–8.5 scenario is the strongest. Moreover, the uncertainty of long-term projection under SSP5–RCP8.5 based on 19 CMIP6 models is larger than that under RCP8.5 based on 29 CMIP5 models \((-10.06\%\); Kitoh et al., 2013; Zhang et al., 2019).

Larger uncertainty in the long-term projection under high scenario is seen over all regional monsoon regions. The North African monsoon region sees the largest \((-31.88\%)\) in the long-term projection under SSP5–8.5 scenario. The precipitation enhances over most submonsoon regions in CMIP6 MME, except for American monsoon region. The increase over Asia monsoon region is robust in the long term, with 6.21\% \((2.38\text{–}10.04\%)\), 8.20\% \((2.78\text{–}13.62\%)\), 10.95\% \((1.24\text{–}20.67\%)\), and 18.21\% \((7.18\text{–}29.23\%)\) over South Asian monsoon region under SSP1–2.6, SSP2–4.5, SSP3–7.0, and SSP5–8.5, respectively, and 8.36\% \((0.41\text{–}16.31\%)\), 9.94\% \((1.46\text{–}18.42\%)\), 9.69\% \((0.54\text{–}18.83\%)\), and 14.03\% \((2.63\text{–}25.42\%)\) over East Asian monsoon region, respectively. Moreover, the changes over land monsoon regions in the NH are larger than that over land monsoon regions in the SH (see Table S4 for quantitative comparison).
3.2. Thermodynamic and Dynamic Contributions to Precipitation Changes and Uncertainty

Given the strongest responses in the long-term projection, we focus on the SSP5–8.5 scenario to reveal the physical processes responsible for projected changes and uncertainty. The moisture budget changes are given in Figure 3. Precipitation increase over GLM region is dominated by the increase of vertical TH (−ző∂pq′/C10/C11), while the effect of vertical dynamic term (−ż∂p′q/C10/C11, DY) and nonlinear term (NL) partly offset the increase in precipitation (Figure 3a). The above changes follow the “wet-get-wetter” scenario (Chou et al., 2009; Held & Soden, 2006). Regionally, the changes over land monsoon regions in the NH are similar to that of GLM and dominated by the increase of water vapor (TH) under global warming (Figure 3b), except for the North American monsoon region where the effects of circulation changes and NL term cause the decline of precipitation (Figure S2). In comparison, the enhancement of precipitation over land monsoon regions in the SH is moderate since the negative contribution from DY and NL is stronger (about double folds) than that in NH (Figure 3c).

As shown in section 3.1, a large spread among the models is seen in the projection of precipitation. To understand the source of uncertainty, we show the relationship between precipitation and the dominated moisture budget terms in each model (Figures 4a–4c). While the vertical TH dominates the MME changes of precipitation, the relationship between vertical TH and precipitation is not significant across the models (Figure 4a). The vertical DY and precipitation are positively significantly correlated in all the projection periods (Figure 4b). The positive correlation coefficient would be slightly reduced but is still statistically significant at the 1% level if changes in water vapor are considered (Figure 4c). Moreover, the circulation...
uncertainty is larger in the midterm and long term than that in the near term. This is consistent with the uncertainty in precipitation. In addition, the connection of circulation uncertainty with precipitation uncertainty is also seen in each submonsoon regions (Figure S3), indicating that the uncertainty of GM precipitation projection is related to the spread in circulation.

Is the uncertainty in precipitation projection and moisture budget terms related to the spread in global mean surface temperature (GMSAT) changes? We find that only a small part of the spread in precipitation changes can be explained by the GMSAT (Figure 4d), especially in the midterm and long-term projections, although the vertical THs in all the three projection periods are well scaled with GMSAT (Figure 4e). We note that the sensitivity of the vertical TH to GMSAT is ~3%/K (Figure 4e), which is smaller than the estimate of 7%/K based on the Clausius-Clapeyron relationship (Held & Soden, 2006), since the percentage change of vertical TH is normalized by the climate mean summer precipitation in our analysis. In addition, over land regions, the projected relative humidity would decrease, which causes the sensitivity of moisture to be lower than 7%/K (Byrne & O’Gorman, 2016). The sensitivity of vertical TH normalized by its climatology ($\frac{\partial q}{\partial p}/\langle C28/C29 \rangle$) is ~5%/K (Figure S4), which is still smaller than the estimate of Clausius-Clapeyron relationship, since the sensitivity of vertical TH is determined by $\omega \frac{\partial q'}{\partial p}$ rather than the pure moisture changes ($q'$). The weak relationship between precipitation and GMSAT is caused by a substantial compensation from the vertical DY, which becomes more negatively correlated with the GMSAT in longer term projection (Figure 4f). A large part of model spread in the vertical DY cannot be explained by the GMSAT changes (Figure 4f), indicating that in the midterm and long-term projections, the spread in global mean warming is not the dominant source of uncertainty in monsoon precipitation. In addition, the uncertainty of NL in the long term is similar to the vertical DY and its magnitude is comparable with the vertical TH and the vertical DY (Figure S5).

There are hints indicating that the uncertainty in regional monsoon circulation projection is partly related to the nonuniform warming of SST (Chen & Zhou, 2016; Park et al., 2015). The uncertainty of regional SST warming pattern, such as the warming gradient over the tropical Indian Ocean and Pacific (Chen & Zhou, 2015; Zhou et al., 2019) and extratropical Atlantic (Dixon et al., 2019; Park et al., 2015), could play some roles in different monsoon circulation changes across models. To examine whether the uncertainty in circulation changes could be eliminated by uniform warming of SST patterns, we calculate the uncertainty of changes in precipitation and moisture budget terms among nine models in AMIP-p4K experiment in which SST is subject to a uniform warming of 4 K (Figure S6, and Tables S2 and S3). A large spread is seen in both precipitation ($-5.41$ to $-7.60$% for the 10th–90th ensemble range) and vertical DY ($-15.47$ to $-8.42$%) changes, indicating that the model-dependent responses to the uniform warming also contribute to the projected uncertainty.

Above results indicate that the spread of CMIP6 models in the midterm and long-term projections is dominated by the uncertainty of circulation. The source of circulation uncertainty can be partly explained by model-dependent response to the uniform SST warming. In comparison to the midterm and long-term projections, moisture change plays a larger role in the precipitation uncertainty in the near-term projection.

Figure 3. The changes of moisture budget terms in the long term under SSP5–8.5 scenario averaged over the (a) global land monsoon domain, (b) Northern Hemisphere (NH) land monsoon, and (c) Southern Hemisphere (SH) land monsoon, relative to the summer mean precipitation in 1995–2014. The bars represent the multimodel ensemble, while the vertical lines indicate the range of 10th to 90th. NL denotes the sum of all nonlinear terms, while Res denotes the residual term. Unit is in percent.
4. Conclusion and Discussion

In this study, we investigated the future changes in GLM summer precipitation and the sources of projection uncertainty under four scenarios using the CMIP6 models. The future GLM precipitation changes and the projection uncertainty in the near-term, midterm, and long-term projections are presented. The relative contributions of the thermodynamic response to moisture availability increase and dynamic response to circulation changes under global warming are identified. The major conclusions are summarized as follows:

1. The summer precipitation over the GLM region will increase significantly under the four CMIP6 scenarios. In the near-term (long-term) projection, GLM summer precipitation will increase by $1.76 \pm 1.57\%$ ($2.54 \pm 2.22\%$), $1.33 \pm 1.97\%$ ($3.52 \pm 3.05\%$), $0.96 \pm 2.04\%$ ($3.51 \pm 4.97\%$), and $1.71 \pm 2.38\%$.

![Figure 4](image-url)
(5.75 ± 5.92%) under SSP1–2.6, SSP2–4.5, SSP3–7.0, and SSP5–8.5, respectively, estimated from the mean model and the range from 10th to 90th. The precipitation changes in near term and midterm are comparable across the four scenarios. The projection uncertainty increases with time except for SSP1–2.6. Regionally, the enhancement of precipitation over the Asian monsoon region is robust, while the American monsoon precipitation will be reduced. The uncertainty in regional monsoon projections is larger than the GLM.

2. The enhancement in precipitation is caused by the thermodynamic responses with increased moisture availability, while partly offset by the dynamic responses to weakened atmospheric circulation. While the projected GLM precipitation changes in MME are dominated by the thermodynamics, the uncertainty is induced by the dynamic changes. The spread of CMIP6 models in the midterm and long-term monsoon precipitation projections is mainly caused by the uncertainty of circulation changes.

3. The uncertainty in the circulation changes is still evident under uniform SST warming. The model-dependent response to the uniform SST warming partly explains the uncertainty in circulation changes.

In addition, while the uncertainties in the midterm and long-term projections are mainly caused by the spread across models, the natural internal variability exerts remarkable influence on the near-term projection (Deser, Knutti, et al., 2012; Deser, Phillips, et al., 2012; Hawkins & Sutton, 2011; Huang et al., 2020; Ting et al., 2009). Based on the analysis of same model projections with more realizations (Figure S7), we also find that in the near-term projection, the spread due to internal variability is comparable to the spread among the 18 CMIP6 models (Figure S7a), indicating the remarkable influence of internal variability on the near-term projection. Further efforts should be devoted to decadal climate prediction, which may improve the near-term projection by using initialized runs (Boer et al., 2016).

The projected increases of GLM precipitation, as well as the mechanisms, in the latest generation of CMIP6 models are qualitatively in agreement with CMIP3 and CMIP5 (Hsu et al., 2012; Kitoh et al., 2013). The regional characteristics of monsoon changes are consistently projected from CMIP3 to CMIP6, including the larger increases in the NH than SH (Kitoh et al., 2013; Lee & Wang, 2014), and the robust intensification over the Asian monsoon region (e.g., Chen & Sun, 2013; Jayasankar et al., 2015; Seo et al., 2013). In addition, the projected increase of GLM precipitation in CMIP6 is stronger (~2%) than that in CMIP3 and CMIP5, partly due to the significant reduction in model bias in CMIP6 models (Xin et al., 2020). Higher resolution helps to improve the simulation of GMs (L. Zhang et al., 2018; Varghese et al., 2020). The increases of monsoon precipitation projected by high-resolution models are stronger (about double folds) than that in low-resolution models (Hsu et al., 2012). High-resolution models can capture the spatial inhomogeneity. For instance, the mean precipitation over west Ghats is projected to decrease by high-resolution models due to the reduction of local moisture transport (Jayasankar et al., 2018; Varghese et al., 2020), which cannot be reproduced by low-resolution models (Kitoh et al., 2013; Lee & Wang, 2014). Future efforts on monsoon projection should be devoted to high-resolution models including convection permitting models (Ban et al., 2015; Haarsma et al., 2016; Li et al., 2018, 2019; Varghese et al., 2020).

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