Contrasting Hysteresis Behaviors of Northern Hemisphere Land Monsoon Precipitation to CO₂ Pathways

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Abstract  Understanding precipitation changes over the Northern Hemisphere land monsoon (NHLM) region, where nearly 60% of the world’s population resides, is fundamental for hydrological projections and adaptations against climate change. There are many studies on the hydrological cycle under various climate change scenarios. However, there is still a lack of research on the hydrological responses to CO₂ removal as a global warming mitigation measure from a global perspective. This study demonstrates the distinguished hysteresis responses of mean NHLM precipitation based on idealized CO₂ ramp-up and ramp-down experiments using the Community Earth System Model|Community Earth System model. The Indian and North African monsoons have time asymmetry in the mean precipitation changes under the CO₂ increase and decrease pathways, while the North American monsoon does not. The zonal contrasting hysteresis is attributed to longitudinally contrasting changes in the intertropical convergence zone position driven by the inter-hemispheric and land–sea thermal contrast. On the contrary, changes in extreme precipitation exhibit little temporal asymmetries over any of the NHLM domains. These results provide new insights into climate hysteresis of the hydrological cycle from regional and global perspectives.

Plain Language Summary  Many studies have shown the effect of increasing CO₂ on hydrological climate. However, insights into the possible hydrological climate responses if CO₂ increases and then restores to the present-day are still unclear and uncertain. To examine hydrological resilience, we show the regional Northern Hemisphere land monsoon precipitation responses to two CO₂ pathways, that is, CO₂ increase and decrease. This study reveals that the Indian and North African monsoons have a strong temporal asymmetry with respect to the mean precipitation changes under both pathways, while the North American monsoon does not. These contrasting zonal behaviors are closely related to changes in the local intertropical convergence zone (ITCZ) over the Asian–African sector driven by interhemispheric temperature difference and land–sea contrast between the Eurasian continent and the Indian Ocean. Meanwhile, the North American monsoon involves relatively symmetric behavior in time by both the local ITCZ over the eastern Pacific and atmospheric circulation over the North Atlantic. We also found that extreme rainfall displays little temporal asymmetries except for the North American monsoon, because of its close association with temperature increase.

1. Introduction

Understanding future monsoon projections is crucial to preventing or mitigating the risk of economic losses from natural disasters, as approximately 60% of the world’s population lives in monsoon countries (Wang et al., 2012). The warmer temperature associated with rising CO₂ levels can increase moisture flux convergence (Held & Soden, 2006) and strengthen global monsoons (Kitoh et al., 2013). A substantial amount of climate research has provided reasonable descriptions of how global and regional monsoon precipitation will change under increasing CO₂ scenarios (Chen et al., 2020; Endo & Kitoh, 2014; Ha, Moon, et al., 2020; Lee & Wang, 2014; Moon & Ha, 2020). Zonal asymmetric monsoon precipitation change has been projected between the western and eastern monsoon regions under a warmer climate, namely precipitation increasing in eastern hemisphere monsoon regions (African and Asian–Australian monsoon regions) and decreasing in western hemisphere monsoon regions (North and South American monsoon region) (Chen et al., 2020; Hsu et al., 2013; Lee et al., 2018; Lee & Wang, 2014;
Wang et al., 2020; Zhou et al., 2008). There is high confidence (Douvile et al., 2021) that Asian monsoon rainfall will significantly increase owing to enhanced land–sea thermal contrast between the Eurasian continent and the ocean (Wang et al., 2020). Moreover, the Intergovernmental Panel on Climate Change (IPCC, 2021) reported that changes in seasonality could result in a delayed wet season, causing a rainfall deficit over the western monsoon regions. He et al. (2020) also mentioned that both direct radiative forcing due to increased CO₂ concentration and El Niño-like sea surface temperature (SST) warming will play key roles in suppressing North American monsoon precipitation in the future. In particular, direct CO₂ radiative forcing could induce an anomalous cyclonic circulation over the Eurasian continent, caused by the enhanced land–sea thermal contrast, and be responsible for reduced rainfall over the western hemisphere monsoon region and enhanced precipitation over the eastern hemisphere. On the whole, atmospheric moistening (thermodynamic effects) generally contributes to enhanced monsoon precipitation under global warming (Christensen et al., 2013; Douville et al., 2021; Hsu et al., 2013; Kitoh et al., 2013; Ma et al., 2018), whereas circulation (dynamic effect) is responsible for asymmetric precipitation changes (Chen et al., 2020; He et al., 2020). Compared with the projected mean precipitation, increases in extreme precipitation are primarily proportional to global temperature warming, which results from thermodynamic contributions (Pfahl et al., 2017).

Future climate projections show more frequent regional hydrological disasters, such as floods and droughts, by inducing a new climate regime (Dai, 2011; Dosio et al., 2018; Guo et al., 2017; Lee et al., 2018). Most monsoon studies on future climate change have focused on precipitation changes when CO₂ emissions increase in the 21st century. However, there has been a recent upsurge of interest in whether or not human-induced climate change can be restored once we cross the climate system threshold. Some studies have focused on understanding climate reversibility and global hydrological sensitivities under changing CO₂ concentrations (Boucher et al., 2012; Yeh et al., 2021). Boucher et al. (2012) explored the reversibility of global mean precipitation. Yeh et al. (2021) found that the contrasting hydrological responses over land and ocean; land precipitation changes under changing CO₂ concentrations were almost time–symmetrical, but ocean precipitation was asymmetric owing to ocean uptake from the atmosphere. From regional perspectives, Wu et al. (2015) found that the South Asian monsoon precipitation increases in response to a CO₂ ramp-up (RUP) and rapidly returns during a CO₂ ramp-down (RDN) period, but that precipitation undershoots are due to rapid cooling of the troposphere over the continent and external factor such as the El Niño state. Song et al. (2022) demonstrated that the East Asian monsoon precipitation asymmetrically responded to CO₂ RUP and RDN forcing; they argued that such temporally asymmetrical response is due to a tropical–subtropical SST response, including an enhanced El Niño-like SST warming and a meridional SST gradient over the western North Pacific. Similarly, Sun et al. (2021) found that responses of monsoon precipitation over East Asia from the Carbon Dioxide Removal Model Intercomparison Project (CDRMIP; Keller et al., 2018) had a strong locality. However, studies on whether and how monsoon precipitation would respond to reduced CO₂ emissions are still needed. In particular, under mitigation and adaptation strategies for climate change from global and regional perspectives, it is necessary to differentiate the regional monsoon responses to changing CO₂ pathways. Furthermore, the possible mechanisms for the changes need to be addressed in more detail.

Local and remote drivers of monsoon need to be considered (An et al., 2015; Ha, Kim, et al., 2020; Wang et al., 2018), such as asymmetric land–sea heating, vertical stability, and meridional shifts of the intertropical convergence zone (ITCZ), and Hadley circulation (Geen et al., 2020; Han et al., 2019; Wang, 2009; Wang et al., 2020; Yancheva et al., 2007). Indeed, the seasonal location of the ITCZ, in-phased with the solar insolation, is connected to seasonal monsoon circulation (Bordoni & Schneider, 2008). Namely, changes in ITCZ shifts are responsible for the enhanced tropical monsoon (Douvile et al., 2021; Gadgil, 2003; Hari et al., 2020; Mechoso et al., 2005). Mamalakis et al. (2021) investigated the future position of the ITCZ as a function of longitude. They reported that the ITCZ shifted to the north over eastern Africa and the Indian Ocean and to the south over the eastern Pacific during the 21st century. These contrasting ITCZ shifts resulted from radiative and dynamic processes due to high SST warming over the Pacific (Schneider et al., 2014).

This study examines whether regional monsoon precipitation is recovered to the previous condition when CO₂ emissions return to their starting level (in this study, the present-day [PD]). Moreover, we also represent the changes in Northern Hemisphere land monsoon (NHLM) precipitation and the relevant local ITCZ under CO₂ pathways. We further show the responses of extreme precipitation to CO₂ RUP and RDN periods and how it is different from the slope of the mean precipitation.
2. Data and Methods

2.1. Community Earth System Model (CESM) Experimental Design

The 1% CO₂ increase and decrease simulations were performed using CESM version 1.2.2 (CESM1.2.2) to check the hysteresis response of NHLM precipitation. The CESM is similar to CDRMIP (Keller et al., 2018) except for the initial CO₂ level. The CDRMIP experiments were designed to understand the hysteresis effect or irreversible change response to CO₂ removal in the Coupled Model Inter-comparison Project Phase 6 (CMIP6). The Atmospheric Model version 5 (CAM5) at a horizontal resolution of 0.93° latitude × 1.25° longitude with 30 vertical levels was used. It was coupled with the Parallel Ocean Program version 2, the Community Land Model version 4, and the Los Alamos Sea Ice Model (CICE4; Hurrell et al., 2013). Moreover, the land carbon cycle was included (Lawrence et al., 2012). The details of the model have been previously described by Conley et al. (2012).

In this study, we performed an ensemble of simulations containing 28 members with different initial atmospheric and oceanic conditions, chosen for different phases of the Pacific Decadal Oscillation (Mantua et al., 1997) and Atlantic Multidecadal Oscillation during the PD period (Trenberth & Shea, 2006). The PD climate was simulated with a fixed CO₂ concentration of 367 ppm for 900 years. The PD experiment used the constant solar levels of greenhouse gases (GHGs), aerosols, and ozone in 2000. For PD simulation, a period of 500 years was used to spin up to a quasi-equilibrium state. It was confirmed that the global mean temperature (GMT) and the global top-of-atmosphere energy balance (figure not shown) adjusted to quasi-equilibrium states. Moreover, the global annual mean surface temperature for the PD simulation was 15.1°C (288.25 K). In the idealized 1% CO₂ experiments, the atmospheric CO₂ concentration increased by 1% per year until it reached 1,468 ppm (quadruple the PD CO₂ concentration) for 140 years (from 2001 to 2140). The CO₂ concentrations were then symmetrically decreased for 140 years (from 2141 to 2280) until the concentrations returned to the PD level (Figure S1a in Supporting Information S1). In addition, a restoration period after the year 2280 was modeled, where the same CO₂ concentration as that in the PD simulation was maintained. Furthermore, the GMT in 2140, when the peak CO₂ concentration occurred, was approximately 5°C higher than in the PD simulation (Figure S1b in Supporting Information S1; An et al., 2021). Note that this study neglects anthropogenic aerosol emissions, which contribute to suppressed monsoon precipitation during the PD period (Hwang et al., 2013; Wang et al., 2016).

2.2. Moisture Budget Equation

To evaluate how dynamic and thermodynamic factors influence changes in monsoon precipitation, we performed the moisture budget analysis using the following equations, where the boreal summer monsoon precipitation is approximately divided into dynamic and thermodynamic components by calculating the moisture content from Equation 1:

$$\delta(P - E) \propto \delta DY + \delta TH$$

(1)

where

$$\delta DY \cong - \langle \nabla \cdot (\delta V q_{\text{ramp-up}}) \rangle$$

(2)

and

$$\delta TH \cong - \langle \nabla \cdot (V_{\text{ramp-up}} \delta q) \rangle$$

(3)

where \(P\) is the precipitation, \(E\) is the evaporation, \(V\) is horizontal wind, and \(q\) is the specific humidity. The \(< >\) notation indicates the mass-weighted vertical integral, ranging from 1,000 to 100 hPa. DY and TH are the dynamic and thermodynamic factors, respectively (Endo & Kitoh, 2014; Hsu et al., 2013; Oh et al., 2018; Seager et al., 2010). The dynamic (thermodynamic) component is influenced by the changes in the horizontal wind (specific humidity) with mean specific humidity (horizontal wind). Quadratic and eddy moisture fluxes (nonlinear processes) were omitted because they are insignificant compared with the dynamic and thermodynamic components (Oh et al., 2018). Evaporation was calculated as the sum of the soil and canopy evaporation, and \(\delta\) indicates \(\langle \cdot \rangle_{\text{RDN}} - \langle \cdot \rangle_{\text{RUP}}\). We designated two periods to check for asymmetry at the same GMT when CO₂ doubles: (a) 31 years (2055–2085) during the RUP, (b) 31 years (2225–2255) during the RDN.
The NHLM domain was defined as regions where the annual range of precipitation exceeded 2 mm day\(^{-1}\), and the summer mean precipitation exceeded 55% of the annual precipitation (Wang et al., 2012; Figure S2 in Supporting Information S1). The annual range represented the difference between summer and winter precipitation, where the Northern Hemisphere summer and winter are May–September (MJJAS) and November–March (NDJFM), respectively. Geographically, the NHLM includes four dominant monsoon regions: East Asia (EA), India (ID), North America (NAM), and North Africa (NAF).

3. Results

3.1. Zonal Contrasts in Monsoon Precipitation Responses to Changing CO\(_2\) Pathways

During the CO\(_2\) RUP period, GMT increases at a rate of 0.04 K per 1% CO\(_2\) change, while it decreases relatively slowly (−0.03 K/1% CO\(_2\) change) during the RDN period. Moreover, the GMT remains higher than the PD climate during the CO\(_2\) restoration period (Figure S1 in Supporting Information S1). This is because the ocean absorbs excess energy during the higher CO\(_2\) concentration periods, and by releasing the stored heat, the Earth maintains a warmer state (Hansen et al., 1985). The global mean precipitation response is well-matched with the GMT change (figure not shown) and also remains higher than the PD climate in the RDN and restoration periods (Chadwick et al., 2013; King et al., 2020; Song et al., 2022). Figure 1 displays the changes in regional monsoon precipitation as a function of the changes in the GMT under CO\(_2\) pathways. We show precipitation increasing in the eastern hemisphere monsoon regions and decreasing in the western hemisphere monsoon region during the RUP period (Wang et al., 2020). Note that steeper EA and ID monsoon precipitation trends compared with those of NAF can be found. Moon and Ha (2020) discovered that precipitation rates over the Asian monsoon increase at a higher value than other monsoon domains in the CMIP6 simulations. Interestingly, the changes in monsoon precipitation driven by increasing and decreasing CO\(_2\) are nearly symmetric over the NAM region but asymmetric over the EA, ID, and NAF regions. The temporal asymmetry in precipitation change over EA with respect to GMT change (Figure 1a) is relatively weak (RUP: 4.5% K\(^{-1}\), RDN −5.6% K\(^{-1}\)) owing to tropical SST responses to changing CO\(_2\) levels. Song et al. (2022) discovered that the enhanced tropical SST condition during the RDN period changed local meridional circulation along 105°E–150°E, resulting in temporally asymmetric monsoon precipitation over EA. The ID monsoon precipitation increases during the RUP period (approximately 4.2% K\(^{-1}\)), whereas it decreases faster (approximately −6.4% K\(^{-1}\)) in the RDN period. In other words, the ID monsoon precipitation rapidly decreases for several decades immediately after the CO\(_2\) peak. Similar behavior is projected for the NAF. While the precipitation over the NAF increases by only 1.9% during the RUP period, it decreases by 3.2% during the RDN period. On the other hand, over the NAM region, the rates of precipitation decreasing and increasing are symmetrical depending on temperature changes, which have similar slopes of −6.5% K\(^{-1}\) (6.9% K\(^{-1}\)) for the RUP (RDN). The common characteristic of overall NHLM domains is that their responses to changing CO\(_2\) concentration more or less recover to PD control values over 100 years during the restoration period. From now on, this study focuses on the changes in the tropical monsoon precipitation and collectively refers to the ID and NAM monsoons as the Asian–African monsoon.

Figure 2 indicates the changes in the summer mean and extreme precipitation over time. The increasing rate of the EA mean precipitation during the RUP period is distinct from its decreasing rate during the RDN period at the same GMT periods. For example, the EA rainfall during the representative RDN period (2225–2255) is 0.18 mm day\(^{-1}\) (greater than the PD simulation), while that during the representative RUP period (2055–2085) is 0.31 mm day\(^{-1}\). The ID monsoon precipitation rapidly decreases once the CO\(_2\) drops and increases to a certain degree during the restoration period. It returns to the same level as in the PD climate. When the two periods of the same GMT are compared, there is a 0.7 mm/day difference in mean precipitation over the ID monsoon domain. The NAF precipitation exhibits similar behavior to the ID monsoon. It increases to 0.24 mm day\(^{-1}\) during 2055–2085, while it decreases to 0.12 mm day\(^{-1}\) during 2225–2255 relative to the PD climate. The NAM rainfall rate decreases during the RUP period, which can be explained by pronounced eastern–western hemispheric monsoon asymmetry under a transient warming climate (the Asian–African monsoon receives greater precipitation, and the NAM receives less precipitation under global warming, according to Lee & Wang, 2014).

In this study, extreme precipitation is defined as the maximum 1 day precipitation (RX1) during the summer, which is used as the intensity-based extreme precipitation index. Extreme precipitation intensity is also expected to increase over monsoon domains in the future (Lee et al., 2018; Li et al., 2019; Zhang et al., 2018). Turner and Slingo (2009) mentioned that extreme precipitation is proportional to atmospheric warming and
the associated increase in specific humidity. Here, the relationships between extreme precipitation and GMT in increasing and decreasing CO2 concentration are shown in Figure S3 of Supporting Information S1, which are overall linear yet different by location. Changes in extreme precipitation (RX1) over the EA during the RUP (41.1 mm day$^{-1}$) and RDN (41.6 mm day$^{-1}$) periods are nearly symmetric ($\pm$6.0% K$^{-1}$), which distinguishes

Figure 1. Changes in global mean surface temperature and regional monsoon precipitation to CO2 pathways. Scatter plots of global mean surface temperature (k) anomalies from the present day simulation and percentile changes in monsoon precipitation (%) during the boreal summer over (a) East Asia (EA), (b) India (ID), (c) North America (NAM), and (d) North Africa (NAF). Red dots indicate the ramp-up (RUP) period (from 2001 to 2140), blue dots show the ramp-down (RDN) period (from 2141 to 2280), and orange dots indicate the restoration period (from 2280 to 2399). The pink (sky blue) dots represent the linear regression for each of the 28 ensemble members during the RUP (RDN). The gray dashed line is the Clausius–Clapeyron (C–C) relation (7% K$^{-1}$).
them from the mean precipitation changes. Different from the mean precipitation over the ID and NAF, the extreme precipitation has relatively symmetric responses to changing CO₂ levels because of its close association with temperature. For the intensity of extreme precipitation during the RDN period (2225–2255), the maximum 1 day precipitation amount is within the range during the RUP period (2055–2085), which is approximately 53.9 mm day⁻¹ for the ID and 26.8 mm day⁻¹ for the NAF. The slopes of the ID and NAF are approximately 10.4% −1 and 8.0% K⁻¹, respectively. The Clausius–Clapeyron (CC) relationship at a rate of ∼6%–7% per 1 K has been used to estimate the effect of global warming on the mean and extreme precipitation (Allen & Ingram, 2002). But, over the tropics, larger increases in precipitation, exceeds the CC relationship, could occur. In other words, while the intensity of the extreme precipitation is almost identical between the RUP and RDN periods, the ID and NAF will experience a drier summer climate during the RDN period than in the RUP period. As for the changing rate of extreme precipitation over the NAM, it slightly increases during the RUP period but exhibits no significant trend. Moreover, the extreme precipitation continues to increase for a while during the RDN (Figure 2c), and is distinct from the mean precipitation. For some reason, changes in North American extreme precipitation do not follow the surface temperature increase. Thus, a further study should be made to answer the question shortly.

3.2. Mechanisms Controlling Zonal Asymmetry of NHLM Precipitation

Two time periods are considered to understand the contrasting changes in the regional monsoon precipitation between the RDN and RUP. That for RUP is from 2055 to 2085 and that for RDN is from 2225 to 2255. The striking features between the two periods are hemispheric thermal asymmetry due to changing CO₂ forcing between the Northern Hemisphere (land) and the Southern Hemisphere (ocean) and a land–sea thermal contrast (King et al., 2020). These are key to contrasting regional monsoon responses to changing CO₂ pathways.

Moisture budget analysis was applied to diagnose the thermodynamic and dynamic effects of the changes in regional monsoon precipitation (Endo & Kitoh, 2014; Hsu et al., 2013; Huang et al., 2019). Precipitation in EA, ID, and NAF significantly decreases during the RDN period compared with the RUP, while NAM precipitation shows the opposite behavior (Figure 3d). Negative dynamic moisture flux convergence, which is combined by moisture advection and convergence, plays an essential role in weakening monsoon precipitation over the ID, NAM, and NAF (Endo & Kitoh, 2014; Seager et al., 2010). When the two periods of the same GMT are compared, the Southern Ocean maintains its warmth owing to its large thermal inertia. This implies less hemispheric thermal
Figure 3.
contrast, together with relatively cooling in the Northern Hemisphere during the RDN period than during the RUP period (Figure 3a). Furthermore, the thermodynamic changes in mean moisture convergence are weaker during the RDN period since the increased water-holding capacity of the atmosphere with temperature over the monsoon domain would be smaller than the RDN period (Figure S4b in Supporting Information S1). Interestingly, the EA and NAM monsoon regions have positive thermodynamic moisture advection (Figure 3d), which contributes to the enhanced monsoon precipitation. The large horizontal moisture gradients from the tropics to the monsoon domain are collocated with the mean winds over the two monsoon domains, leading to monsoon precipitation (Figure S4b in Supporting Information S1). The positive dynamic moisture advection also causes enhanced NAM and ID precipitation by driving water vapor transport (Figures 3d and S4a in Supporting Information S1).

The temporally asymmetric behavior of regional monsoon precipitation between the RDN and RUP originates from changes in the dynamic components (Figure 3d, He et al., 2020; Lee & Wang, 2014). Figure 3a displays differences in surface temperature and pressure between the RDN and RUP periods. It displays El Niño-like SST warming, Southern Hemisphere warming, and Northern Hemisphere cooling. The reduced zonal SST gradient over the tropical Pacific could lead to large-scale weakening and an eastward shift of the Walker circulation (Figure 3b; Tanaka et al., 2004; Vecchi et al., 2006; Vecchi & Soden, 2007). Moreover, anomalous downward motions over the Indian Ocean occur in the RDN period, together with weakened Hadley circulation during the boreal summer (Figures 3b and 3c; Ma & Xie, 2013). The weakened and southward Hadley circulation is related to the southward migration of the ITCZ, which is displaced toward the warmer hemisphere (Broccoli et al., 2006; Byrne et al., 2018; Kang, 2020). Hari et al. (2020) found that the dynamics of the local ITCZ are strongly related to ID monsoon precipitation. When the ITCZ is shifted toward the south, an anomalous low-level northerly flow appears over the northern Indian monsoon domain, resulting in weak dynamic moisture flux convergence.

The zonal mean ITCZ is projected to be shifted south in the RUP period, and it returns to the north in the RDN period. However, the average location of the zonal mean ITCZ is still south owing to the asymmetric climate responses, even though the CO₂ concentration recovers to the PD period (Figure S5a in Supporting Information S1). We obtained the atmospheric energy budget while assuming that the system was in quasi-equilibrium as a combination of net downward shortwave minus outgoing longwave radiation at the top-of-atmosphere, sensible heat flux, latent heat flux through the surface, and net shortwave and longwave radiation through the surface (Mamalakis et al., 2021; Schneider et al., 2014). The interhemispheric energy asymmetry between the RDN and RUP periods supports the southward ITCZ shift (Figure S5b in Supporting Information S1; Broccoli et al., 2006; Kang et al., 2009). The interhemispheric energy imbalance, which is closely linked to changes in surface temperature over various regions such as the North Atlantic Ocean, Northern Hemisphere land, and the Southern Ocean, is responsible for the changes in the zonal mean ITCZ position (Bischoff & Schneider, 2014; Kug et al., 2022).

According to Mamalakis et al. (2021), the contrasting ITCZ responses to CO₂ pathways depend on longitudinal position (Figure 4a). The ITCZ over the Asian–African sector is linked to thermal differences, such as the land–sea contrast and interhemispheric contrast. The Northern Hemisphere land warms faster than the ocean during the RUP period (Figure S6 in Supporting Information S1). Thus, the ITCZ moves to the north during the RUP period, and remains there for a few years. It enhances monsoon precipitation over the ID and NAF regions. When CO₂ forcing decreases, there is a rapid shift in the ITCZ to the south driven by changes in land–sea thermal contrast and hemispheric thermal difference. During the same GMT periods, the land–sea thermal contrast during the RDN (0.6°C) is weaker than that of the RUP (1.2°C). Moreover, the warmer Southern Ocean during the RDN period persists and pulls the ITCZ southward (i.e., weaker hemispheric thermal gradient; Roxy et al., 2015). Thus, weakened local meridional circulation related to the southward ITCZ shift over the eastern hemisphere is apparent (Figure 4b), showing undershoots of precipitation. In contrast, the ITCZ shift over the
Pacific at low latitudes between 10°S and 5°N is determined by SST warming rather than by hemispheric thermal difference (Adam et al., 2016; Mamalakis et al., 2021; Schneider et al., 2014). The ITCZ moves to south (north) as CO2 increases (decreases), and tends to recover rather slowly during the RDN period. This can be explained by the slow response of SST over the Eastern Pacific to decreasing CO2 forcing (Song et al., 2022). Meanwhile, monsoon precipitation over the NAM has been linked to the position of the ITCZ location over the eastern Pacific (Mechoso et al., 2005). However, the question of why the NAM monsoon recovers relatively linearly remains?

During the RND period, the eastern Pacific ITCZ shifts slowly to the north, and a higher surface pressure forms over the North Atlantic; this is related to the weakened Atlantic Meridional Overturning Circulation (AMOC; An et al., 2021), and is a response to decreasing CO2 radiative forcing (Figure 3a). The high pressure driven by the North Atlantic cooling during the RDN period intensifies mean southeasterlies (Figure S4a in Supporting Information S1). This transfers moist air from the Atlantic to the NAM monsoon region, contributing to a recovery of NAM rainfall, together with the enhanced anticyclone over the Eurasian continent. This is consistent with positive dynamic advection (Figure 3d). Thermodynamic advection also plays a critical role in positive monsoon precipitation, and is controlled by changes in atmospheric moisture content over the tropical Atlantic (Figure S4b in Supporting Information S1). This is caused by the asymmetrical hemisphere warming in the Southern

Figure 4. Zonally contrasting shifts of ITCZ and difference in local meridional circulation between ramp-down (RDN) and ramp-up (RUP). (a) Time series of the intertropical convergence zone (ITCZ) positions (°N) during the boreal summer. The ITCZ latitude is defined as the average value of the latitude where area-averaged precipitation (3°S–15°N) is located at each longitude [350°W–110°E] (red) and [180–90°W] (blue) in the boreal summer. Shading corresponds to the standard deviation of each ITCZ latitude. Each horizontal dashed line shows the mean ITCZ position for 399 years over the same longitudinal grid. The gray lines at 2140 and 2280 represent the periods when CO2 forcing peaks and starts stabilizing, respectively. (b) Latitude–pressure cross section of difference in zonal mean meridional stream function (shading, 10^10 kg s^{-1}) between RDN and RUP periods and mean zonal mean meridional stream function during the RUP period (contour) over the Asian–African sector [350°W–110°E]. Negative (positive) values in (b) indicate counterclockwise (clockwise) circulation. The dots represent statistical significance at the 95% confidence level.
Hemisphere relative to the Northern Hemisphere during the RND period. The atmospheric moisture content increases over the tropics and Southern Hemisphere, leading to a positive thermodynamic effect with the mean southeasterly wind over the Atlantic (Figure S4b in Supporting Information S1). These changes offset the slow response of the ITCZ recovery.

In conclusion, the asymmetric behaviors over the ID and NAF monsoon precipitation are characterized by inter-hemispheric and land–sea thermal contrasts and the relevant migration of the ITCZ over the Asian-African sector. In contrast, the relatively symmetric changes in NAM precipitation are closely linked to the slow responses of eastern Pacific SST-related ITCZ and the rapid responses of atmospheric advection driven by the anomalous high-pressure over the North Atlantic. Thus, the thermal responses to changing CO₂ forcing support the distinct behavior of regional monsoon precipitation.

4. Summary and Discussion

This study investigates the zonal contrasting temporal hysteresis responses of mean monsoon precipitation in the Northern Hemisphere to increasing and decreasing CO₂ periods. The increasing CO₂ experiment was designed as idealized 1% CO₂ per year until it reaches its quadrupling peak, followed by the symmetric decrease until the PD climate condition. The mean precipitation over NAM monsoon region shows symmetrical behavior (i.e., no hysteresis), while those over other regions reveal asymmetric behavior. The asymmetric responses are attributed to longitudinally contrasting changes in the ITCZ position caused by the interhemispheric thermal contrast and land–sea thermal contrast. The ITCZ shift in the Asian–African sector is strongly associated with temperature differences such as interhemispheric and land-sea contrasts. Meanwhile, the ITCZ over the eastern Pacific slowly returns to the PD condition during the RDN period, which is more linked to equatorial warming of the eastern Pacific than to interhemispheric thermal contrast. The slow migration of the ITCZ could lead to slow recovery of NAM precipitation. However, the NAM is also related to surface pressure over the North Atlantic. The interplay of the two factors contributes to relatively symmetric changes in mean precipitation over NAM. The enhanced North Atlantic anticyclone during RND period (Figure 3a) is possibly related to ocean surface cooling driven by the weakened AMOC. The hydrologic response over the North Atlantic Ocean to CO₂ forcing leads to a weakened and delayed response of AMOC through the RUP and RND periods, resulting in the strong hysteresis behavior (An et al., 2021). The resultant anticyclone circulation over the North Atlantic presumably has a positive effect on the NAM monsoon precipitation along with the rapid response of the Eurasian continent. Thus, further study of the role of the AMOC in CO₂ forcing on the hydrological cycle is needed.

We also found that the responses of extreme precipitation to CO₂ pathways differ from changes in the mean precipitation (Figure 2). Over the ID and NAF monsoon regions, where hysteresis responses of the mean precipitation occur, the intensity of extreme precipitation is similar during the RDN and RUP periods at the same GMT. The locally increased moisture content corresponds to a warmer climate and leads to extreme precipitation over the regional NHLM regions. This is because extreme precipitation is unlikely to be constrained by the energy budget and occurs a result of moisture availability (Allen & Ingram, 2002). The extreme precipitation trends are related to changes in surface temperature and moisture content (Figure S3 in Supporting Information S1). In other words, the mean precipitation decreases over the ID and NAF during the RDN, while locally enhanced moisture content (moisture flux convergence and surface evaporation) induces strong extreme precipitation over regional NHLM domains. These differences are expected to have substantial implications for policymaking to prevent natural disasters and the consequent economic losses across the NHLM domains. The results of this study improve our understanding of the processes that contribute to hydrological hysteresis responses to CO₂ pathways on a regional and global scale.

Anthropogenic aerosol forcing has played a substantial role in driving the weakening trend of the Asian monsoon (IPCC, 2021). However, this study neglects the impact of aerosol forcing on hydrological climate to emphasize changing CO₂ pathways. Anthropogenic aerosol forcing is known to dominate recent decreases in summer monsoon precipitation, as opposed to the expected intensification due to GHGs. Thus, near-term projections of monsoon precipitation in low emission scenarios might be affected by anthropogenic aerosol forcing, especially for the Indian monsoon and Sahel (Douville et al., 2021). However, to ensure that the results in this study were robust, we focused on periods when CO₂ doubles and anthropogenic aerosol emissions are expected to decrease. Here 1% CO₂ increase/decrease experiments until CO₂ quadrupling (1,478 ppm) have a larger slope than the...
highest emission scenario (SSP5-8.5) in the IPCC Sixth Assessment Report, which is assessed with 2100 CO₂ concentrations of >1,100 ppm. This idealized experiment implies that reducing CO₂ emissions after they have already increased does not result in a return to the previous hydrological climate.

Conflict of Interest
The authors declare no conflicts of interest relevant to this study.

Data Availability Statement
The data are available at https://data.mendeley.com/datasets/3mknx7j5xx/1.

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