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Irreversible Response of the Intertropical Convergence Zone (ITCZ) to CO$_2$ Forcing

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With the unprecedented rate of global warming in this century, whether or not human-made climate change is irreversible is the most critical question. Based on idealized CO\(_2\) ramp-up and -down experiments, we show here that the intertropical convergence zone (ITCZ) exhibits irreversible changes. While the ITCZ location does not change much during the CO\(_2\) increasing period, the ITCZ sharply moves south as soon as CO\(_2\) begins to decrease, and its center eventually resides in the Southern Hemisphere. The pattern of the irreversible precipitation changes manifests a permanent extreme El Nino-like pattern, which has distinctive impacts on the global hydrological cycle. It was revealed that the hysteresis behavior of the Atlantic meridional overturning circulation and the delayed energy exchanges between the tropics and extratropics are responsible for the peculiar evolution of the hemispheric temperature contrast, leading to irreversible ITCZ changes.

Earth’s climate has continuously been changing, but the current global warming speed is unprecedented, at least during the last 22,000 years\(^1\). Such unprecedented change has raised a concern that our climate may cross a critical threshold. It has been widely accepted that our Earth climate system has experienced large abrupt and irreversible changes in the past when Earth’s climate system crossed certain thresholds\(^2\)-\(^5\). However, it is unclear whether or not anthropogenic climate changes will be reversible. If they are not reversible, understanding which climate components are irreversible is most critical. Here the reversibility indicates whether Earth’s climate system or an individual climate
component can be returned to its original state within a certain period if the greenhouse gases in the atmosphere are reduced.

So far, climate reversibility and hysteresis have been investigated using climate models with idealized forcing scenarios\textsuperscript{6–15}. It was suggested that the temperature and precipitation responses to the increased greenhouse gases are largely reversible within a century from the global mean perspective\textsuperscript{12,15}. However, several key components in the earth system are expected to exhibit irreversible and hysteresis behaviors, such as the sea-level rise, ocean acidification\textsuperscript{12}, Atlantic meridional overturning circulation (AMOC)\textsuperscript{15}, and the global/regional hydrological cycle\textsuperscript{7}. Particularly, understanding the irreversible and hysteresis behaviors of hydrological cycles is crucial for climate adaptation and mitigation policies.

Tropical rainfall is concentrated in a narrow band known as the intertropical convergence zone (ITCZ), which accounts for 32\% of the global precipitation\textsuperscript{16}. The zonally-elongated intense ITCZ rainfall is maintained by strong low-level convergence, which leads to strong ascending motion, resulting in the meridional overturning Hadley circulation. Thus, slight changes in the ITCZ rainfall can have tremendous impacts on global climate\textsuperscript{17,18}. As it seasonally migrates toward the warmer hemisphere, the ITCZ meridionally migrates when hemispheric asymmetry of the temperature changes by altering the interhemispheric atmospheric heat flux\textsuperscript{19–24}.

Anthropogenic global warming influences the location, width, and intensity of the ITCZ\textsuperscript{25–28}, ultimately leading to regional climate changes. Current climate models simulate the ITCZ narrowing but reduced its strength under greenhouse warming\textsuperscript{25,27}. However, future changes in the ITCZ location are uncertain\textsuperscript{27}, so more attention is
needed. The main overarching questions in this study are as follows. Is the ITCZ change reversible? What determines irreversibility? How does this irreversibility affect global/regional hydrological cycles?

To examine climate reversibility, we conducted an idealized CO₂ ramp-up and -down experiment. In this experiment, the atmospheric CO₂ concentration was gradually increased up to four times the present level and then reduced at the same rate to the present level (see Methods and Fig. 1a). To get robust results, a total of 28 ensemble simulations were conducted with different initial conditions.

**Hysteresis behavior for temperature, precipitation, and ITCZ location**

Figure 1a shows the global mean temperature response to the ramp-up and -down forcing. The temperature increased by ~5K when the CO₂ became four times the present level. The temperature evolution was largely corresponding to the CO₂ changes, suggesting a reversible response, though the peak was delayed for some years \(^7,1^3\). Note that the temperature in 2280 was ~1K higher than in the present state although the CO₂ was returned to its original value. Though the maximum global mean precipitation appeared to be several years more delayed compared with the temperature, the overall evolution followed the temperature evolution well to a large extent, suggesting that the global mean precipitation response is roughly reversible.

However, the regional hydrological cycles show quite different behaviors. Particularly, the ITCZ precipitation and its distribution shows a peculiar evolution in response to the CO₂ ramp-up and -down forcing. To measure the ITCZ latitudinal migration, we adopted an ITCZ centroid index, which is defined as the median of the zonal-
mean precipitation in the tropics
tropic
tropic
tropic

(see Methods). As the CO\textsubscript{2} increased in the ramp-
up period, the ITCZ centroid did not change much. Surprisingly, however, as soon as the
CO\textsubscript{2} began to decrease, the ITCZ centroid sharply moved south, and it continuously
migrated until \sim2230. Thus, the ITCZ centroid was even shifted to the Southern
Hemisphere (SH). After that, the ITCZ slowly moved back north, but it was still located in
the SH even after the CO\textsubscript{2} concentrations returned to the present level. When the model
was integrated 220 years more with the present CO\textsubscript{2} level, the ITCZ centroid moved back
north in the early 100 years but still resided far from the original location (Extended Data
Fig. 1). This result suggests that the ITCZ response to the CO\textsubscript{2} forcing is largely irreversible.

The hysteresis behaviors of the climate system in the present model experiment are
shown in Fig. 1c-e. The global mean temperature shows a nearly linear response to the CO\textsubscript{2}
concentration, indicating a weak hysteresis behavior. The precipitation shows a hysteresis
behavior to some extent\textsuperscript{7,8,13}. However, the ITCZ centroid shows a clearer hysteresis
behavior. The location is mostly southward on the CO\textsubscript{2} ramp-down pathway, and it remains
quite far from the original position by the time CO\textsubscript{2} returns to the initial value.

**Tropical hydrological cycle responses to the ramp-up and -down CO\textsubscript{2} forcing**

To understand the irreversible changes of the ITCZ, Fig. 2a shows changes in the
zonal-mean precipitation over time. To emphasize an asymmetric response to the
symmetric CO\textsubscript{2} pathway, we calculated the difference between the precipitations in each
year and the mean precipitation at the CO\textsubscript{2} peak phase (Year 2135–2145). During the ramp-
up period, the equatorial rainfall considerably increased, but the off-equatorial rainfall
decreased in both hemispheres, suggesting the so-called narrowing ITCZ\textsuperscript{25,27,30} (Extended
Data Fig. 2), which is related to the enhanced equatorial warming\textsuperscript{31,32}. The equatorial rainfall further increased for \(~10\) years after the CO\textsubscript{2} forcing turnabout point, but it gradually decreased until the CO\textsubscript{2} returned to its initial value. The off-equatorial rainfall in the Northern Hemisphere (NH) continuously decreased despite the decrease in the CO\textsubscript{2}, showing an asymmetric behavior. The off-equatorial rainfall in the SH started to increase from the CO\textsubscript{2} peak time, indicating a symmetric behavior to some extent. However, the increasing rate in the ramp-down phase was explosive, so the rainfall became larger than that of any period of the ramp-up phase. The maximum rainfall difference in the SH off-equatorial region (5°S–15°S) appeared in Year 2235, which is five times larger than that of the present climate (Year 2000). The decreasing trend in the NH and increasing trend in the SH indicate a distinctive southward shift of the ITCZ.

Figure 2b shows the difference in the annual mean precipitation between Year 2210 and 2070 when the CO\textsubscript{2} concentrations were identically double the present level. Though the CO\textsubscript{2} radiative forcing is the same, the two periods showed profound differences in the precipitation patterns. First, the precipitation increased in the SH tropics and decreased in the NH tropics, indicating the southward shift of the ITCZ. Such hemispheric contrast is consistently evident over all the Indian, Pacific, and Atlantic basins, suggesting that the southward shift is caused by a global-scale change. Interestingly, in the tropical Pacific region, increased precipitation was also manifested in the equatorial eastern and central Pacific, so the pattern in the tropical Pacific is similar to that during the extreme El Nino (Extended Data Fig. 3). This suggests that the global climate in the ramp-down phase may experience anomalous conditions similar to those of a persistent extreme El Nino period. It was also noted that there is a hemispheric contrast in high latitudes. While the
precipitation increased in the Southern Ocean, a distinctive decrease was evident in the NH subpolar Atlantic Ocean, which can be possibly related to the AMOC change\textsuperscript{33–35}.

The precipitation pattern shown in Fig. 2b is from the single model result and might be model-dependent. To show the robustness of the ITCZ response, we also analyzed six model simulations from the Coupled Model Intercomparison Project Phase 6 (CMIP6) archives\textsuperscript{36} (see Methods). As shown in Fig. 2c and Extended Data Fig. 4, considering the tropical precipitation difference, the most models show essentially the same pattern as the result of the present experiment. As well as the pattern, the temporal evolution was also similar (Extended Data Fig. 5). This suggests that the pattern of the tropical precipitation change is not model-dependent.

The precipitation changes were closely related to the temperature changes. Since the global mean temperature was higher in the ramp-down period, overall warming was evident in the tropics and SH extratropics (Fig. 2d). Particularly, the Southern Ocean and tropical eastern Pacific warming were more distinctive, where the precipitation was largely increased (Fig. 2b). However, it is remarkable that the strongest cooling is in the NH subpolar Atlantic regions despite the higher global mean temperature. This temperature pattern resembles temperature anomalies in the AMOC weakened phase\textsuperscript{34,35}. Since the hemispheric temperature contrast was evident, the ITCZ is expected to move toward the warmer hemisphere\textsuperscript{35,37–39}.

To understand the precipitation changes, the moisture flux was calculated (Fig. 2e and Extended Data Fig. 5). Warming was highest in the Southern Ocean, but in the zonal-mean perspective, there were negligible moisture supplies from the SH extratropics into the SH ITCZ zone, where the precipitation was significantly increased. Instead, the
intensified ITCZ precipitation in the SH was mostly contributed by the cross-equatorial moisture flux, which is associated with the southward shift of the rising branch in the Hadley circulation. Also, a strong moisture convergence is found in the subpolar North Atlantic, where the precipitation was considerably decreased, possibly due to the extremely reduced evaporation.

Irreversible ITCZ responses and global energy exchanges

Though we showed that the southward shift of the ITCZ is maintained by the cross-equatorial moisture flux, this can be interpreted as a result of the coupling between the ITCZ and the overturning Hadley circulation rather than the cause of the southward shift. The difference in the hemispheric temperature distribution (Fig. 2d), can be responsible for the distinct ITCZ responses to the same CO$_2$ forcing. Thus, we introduce an energy flux equator (see Methods), which is defined as the latitude at which the zonal-mean atmospheric meridional energy flux changes the sign$^{37,40}$. Since the energy flux equator mostly corresponds to the rising branch of the Hadley circulation, it is also closely related to the latitudinal location of the ITCZ. Therefore, the ITCZ location was roughly proportional to the sign and strength of the cross-equatorial energy flux$^{37,40}$. For example, the negative (positive) cross-equatorial energy flux indicates the energy flux equator and the located ITCZ in the NH (SH). In the present climate, the atmospheric energy flux at the equator is negative, and the energy flux equator is located at $\sim$2.8°N (Fig. 3a). With the increase in CO$_2$, the cross-equatorial energy flux slowly increased, and the energy flux equator slightly migrated south, in part due to the narrowing ITCZ (Fig. 3a and Extended Data Fig. 2). In Year 2070, the energy flux equator was $\sim$2°N. After the turnabout of the
CO₂ forcing, the cross-equatorial flux began to sharply increase, and its sign was even changed, indicating that the center of the ITCZ moved to the SH. In Year 2210, the flux equator was located at ~1.5°S.

The cross-equatorial energy flux is related to the tropospheric temperature distribution in the tropics. Figure 3b shows a vertically integrated temperature difference in the tropics between the NH and SH (see Methods). Due to the continental distribution and existence of the coldest Antarctic continent, the NH was warmer than the SH, leading to a positive interhemispheric temperature difference in even the tropics. With the increase in CO₂, the temperature difference was expected to increase because continental warming is usually faster than the ocean. Interestingly, however, the temperature difference did not change much during the ramp-up period (Fig. 3b). As soon as the CO₂ decreased, the temperature difference rapidly decreased, indicating that the decrease in the NH temperature is faster than in the SH temperature. Since Year 2230, the temperature difference was flattened.

It is striking that the tropospheric temperature difference evolution was quite similar to that of the ITCZ centroid and maximum zonal-mean precipitation region. This shows that the hemispheric temperature contrast is closely related to the peculiar evolution of the ITCZ, which is clearly far from the CO₂ evolution. These changes in the interhemispheric temperature distribution are largely attributed to the competition between the contributions of the NH continent and SH Oceanic warming (Extended Data Fig. 6). For example, the slower decrease in the SH tropical temperature can result from two factors. First, the SH tropics are covered by more ocean surface, leading to slower cooling. More importantly, the heat exchange between the tropics and extratropics over the SH can
As shown in Fig. 2d, during the ramp-down period, the highest warming was manifested in the Southern Ocean, which plays a role in reducing the poleward heat transfer to the SH extratropics (Fig. 3c), contributing to warming in the SH tropics. This contradicts the increasing poleward heat transport in the NH (Fig. 3c). The Southern Ocean warming is partly due to its large heat storage. Additionally, the AMOC is a key driver for the Southern Ocean warming and NH Atlantic cooling.

Figure 3c shows the AMOC response to the CO$_2$ ramp-up and -down forcing. With the increase in CO$_2$, the overturning circulation was gradually weakened due to the freshening of the Arctic sea-ice decline, the buoyant surface cap, and surface hydrology change. After the CO$_2$ turnabout, the AMOC strength further weakened and reached its minimum value in about Year 2200, namely the AMOC overshooting (Extended Data Fig. 1) due to the salinity build-up in the subtropical Atlantic during the ramp-up phase. Afterward, the AMOC strength started to rapidly recover. As described in the previous studies, the AMOC exhibits a clear hysteresis behavior, and such behavior has critical influences on the ITCZ changes due to the alterations in the hemispheric heat distribution.

In the ramp-up phase, the AMOC weakening induced SH warming and NH cooling, which offset the faster continental warming in the NH, so the hemispheric temperature difference could be flat (Fig. 3b). After the CO$_2$ forcing turnabout, the AMOC was still weakening, and the decrease in CO$_2$ forcing led to the oceanic cooling being slower than the continental cooling, resulting in slower cooling in the SH. By combining these two effects, the hemispheric difference could rapidly decrease (Fig. 3b), leading to the sharp southward shift in the ITCZ. As the AMOC strength began to recover at about Year 2200, it compensated for the slower oceanic cooling, so the hemispheric temperature difference
looks flattened in this period. Therefore, the southward-shifted ITCZ did not come back shortly, implying the irreversible response of the ITCZ. Note that there was a time delay of a couple of decades between the minimum AMOC and tropical temperature difference, which might be interpreted as the time to adjust to the temperature redistribution from the extratropics to the tropics by the energy exchanges. For instance, the energy flux at 30°S was still decreasing until Year 2280, contributing to the slower cooling in the SH tropics and holding the ITCZ in the SH.

In summary, we here suggest that the hysteresis response of the deep ocean circulation and time-delayed responses between the continental and oceanic surface to the CO$_2$ forcing can lead to the peculiar evolution of the hemispheric temperature contrast. The resultant energy exchanges between the two hemispheres and between the tropics and extratropics were found to result in an irreversible change in the ITCZ. Such change might be eventually returned to the original state if the present CO$_2$ forcing is continuously prescribed, but it is not expected to take place within a couple of centuries (Extended Data Fig. 1). Also, in the stabilization period, the precipitation change intensity was weakened, but the spatial pattern was maintained (Extended Data Fig. 7).

Impacts of the irreversible ITCZ responses on the regional hydrological cycles

Though most of the ITCZ precipitation takes place over the ocean, its change has tremendous impacts on the global hydrological cycle by modulating the zonal and meridional overturning circulations$^{17,18,33}$. Figure 4 shows the annual mean land precipitation difference between 2210 and 2070. As the ITCZ moved southward, most of the tropical lands in the NH were drier. Particularly, the arid conditions in the Sahara Desert
and its surrounding areas, Sahel Zone, and the semi-arid conditions around the Mediterranean Sea deteriorated even though the CO$_2$ concentration returned to its original value (Fig. 4b). However, precipitation in the extratropical Northern and Southern Americas increased in the ramp-down phase. It is conceived that these changes are related to the precipitation pattern, which is similar to the permanent extreme El Nino period, leading to heating-induced teleconnections (Extended Data Fig. 3). Particularly, the arid area in the western coastal area of North America greatly became right, implying that this region is one of the most beneficial regions for decarbonization or carbon removal. The Antarctica precipitation largely increased due to the warmer Southern Ocean and the resultant moisture flux (Fig. 2e), which may help in recovering the Antarctic glaciers and thus sea-level changes.

In this study, we conducted idealized climate experiments that provided insights into a hypothetical scenario of carbon dioxide removal, which must be taken into account when assessing the implications of various mitigation options for flooding, water supply, food production, and human health. Also, we here showed that the ITCZ and global hydrological cycle can be changed into a different state or be recovered much later than expected even if we successfully managed to reduce the CO$_2$ concentration. Such irreversible and hysteresis behaviors are incurred because the global hydrological cycle is a combined result of complex climate components that have quite different adjustment timescales in response to anthropogenic climate forcing. While the global mean temperature was widely used for measuring climate risks, our study showed that the global mean temperature alone is a poor metric to measure any changes in our climate system. Additionally, we showed that the evolution of the global hydrological cycle is quite
different from that of the global mean temperature. Finally, our study showed that the CO$_2$

influences, which have already taken place, will persist for a longer time than expected and

that future CO$_2$ emission will bring about further irreversible effects. Thus, a climate

mitigation policy must be taken into account not only for reducing the damages of

immediate climate changes but also to prevent or even reduce the expected irreversible

long-term changes.
METHODS

Dataset used and experimental design

To investigate the irreversible ITCZ responses to CO$_2$ ramp-up and -down forcing, we conducted experimental climate model simulations. The model used in this study is a fully-coupled Community Earth System Model version 1.2.2, which has the same component models and coupling of the CESM1 with the Community Atmosphere Model version 5 (CAM5$^{46,47}$). The atmosphere and land components used a horizontal resolution of $\sim 1^\circ$ with 30 vertical levels. The ocean and sea-ice components used a nominal $1^\circ$ horizontal resolution (meridional resolution is $\sim 1/3^\circ$ near the equator) with 60 vertical levels in the ocean.

We performed two kinds of simulations. One is a present-day run (PD) with a constant CO$_2$ concentration ($1\times$CO$_2$, 367 ppm) of over 900 years, where we extracted initial conditions from the PD run. Also, a CO$_2$ ramp-up and -down experiment was performed. This experiment employed an increasing atmospheric CO$_2$ concentration at a rate of 1\% year$^{-1}$ until CO$_2$ quadrupling ($4\times$CO$_2$, 1478 ppm) and then a decreasing CO$_2$ forcing to the same rate over 140 years until reaching the original value ($1\times$CO$_2$, 367 ppm). Additionally, we integrated a restoring run of 220 years with a constant CO$_2$ concentration ($1\times$CO$_2$, 367 ppm).

Moreover, the irreversible ITCZ responses to the CO$_2$ ramp-up and -down forcing were examined using six models from the CMIP6$^{36}$ (List of the used models: ACCESS-ESM1-5, CanESM5, CESM2, MIROC-ES2L, UKESM1-0-LL, GFDL-ESM4). We used the dataset of the 1pctCO$_2$ scenario from the CMIP6 Diagnostic, Evaluation, and Characterization of Klima (DECK)$^{36}$ and the 1pctCO$_2$-cdr scenario from the Carbon
Dioxide Removal MIP (CDRMIP)\textsuperscript{48}. The experimental setup is quite similar to our simulations except for the initial CO\textsubscript{2} concentration level (pre-industrial level, 284.7 ppm). These data were used after it was re-gridded to a $1^\circ \times 1^\circ$ horizontal resolution.

**Definition of indices**

1. ITCZ centroid\textsuperscript{21,22,29} is defined as the median of the zonal-mean precipitation in the tropics (from 20°S to 20°N), which means the latitude dividing the annual and zonal-mean precipitation equally in half. The precipitation data is interpolated to a 0.1° grid over the tropics to resolve the ITCZ centroid at increments smaller than the original grid spacing.

2. Interhemispheric temperature contrast is defined as the difference between the tropics (0°–30°N and 30°S–0) of the NH and SH annual mean temperature, which is vertically averaged from the surface to 300hPa.

3. AMOC strength is defined as the average of the annual mean Atlantic meridional ocean stream function from 35°N to 45°N at a depth of 1000 m (climatological maximum position in the PD).

**Atmospheric meridional energy flux**

To examine the energy flux equator to approximately follow the ITCZ location, we calculated the atmospheric moist static energy flux using atmospheric energy budgets. As in the previous studies\textsuperscript{37,40,49}, the energy budgets of a whole atmospheric column can be denoted as:

\[
\frac{\partial E_A}{\partial t} = S - L - O - \nabla \cdot \vec{F},
\]  
(1)
where $\frac{\partial E_A}{\partial t}$ is the time tendency of the atmospheric energy storage ($Wm^{-2}$), and $S, L$ denote the net incoming shortwave and longwave radiation values ($Wm^{-2}$) at the top of the atmosphere, respectively. $O$ is the ocean heat uptake ($Wm^{-2}$) (or generally the net surface energy budget), and $\bar{F}$ is the vertically integrated zonal and annual mean of the meridional atmospheric moist static energy flux ($Wm^{-1}$).

The atmospheric energy storage can be written as:

$$E_A = \frac{1}{g} \int_0^{p_s} \left( c_p T + k + L_v q + \Phi_s \right) dp,$$

(2)

where $g$ is the gravitational acceleration ($ms^{-2}$), $c_p$ is the specific heat of the atmosphere at constant pressure ($JK^{-1}kg^{-1}$), $T$ is the temperature ($K$), $k$ is the kinetic energy ($Jkg^{-1}$), which is neglected here due to the relatively small amplitude$^{49}$, $L_v$ is the latent heat of vaporization ($Jkg^{-1}$), $q$ is the specific humidity ($kgkg^{-1}$), $\Phi_s$ is the surface geopotential energy ($m^2s^{-2}$), which is not related with pressure$^{49}$, $p$ is the pressure ($Pa$), and $p_s$ is the surface pressure.

Now, integrating equation (1) with the latitudinal weighting from the South Pole ($\phi = -\frac{\pi}{2}$) to a certain latitude ($\phi$) and all the longitudes in the spherical coordinates results in:

$$F(\phi) = \int_{-\frac{\pi}{2}}^{\phi} 2\pi a^2 \cos \phi \left( S - L - O - \frac{\partial E_A}{\partial t} \right) d\phi,$$

(3)

where the atmospheric meridional energy flux $F$ has a unit $W$, as in Fig. 3a.

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**Author contributions**

J.-H. Oh compiled the data, conducted analyses, prepared the figures, and wrote the manuscript. J.-S. Kug designed the research and wrote majority of the manuscript content. All of the authors discussed the study results and reviewed the manuscript.

**Data availability**

Processed model data will be available on the server, https://www.yonseiircc.com/, and the CMIP6 archives are freely available from https://esgf-node.llnl.gov/projects/cmip6/.

**Code availability**

Processed data, products, and code produced in this study are available from the corresponding author upon reasonable request.

**Correspondence and requests for materials** should be addressed to J.-S. Kug (jskug@postech.ac.kr).
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**Fig. 1 | Evolution and hysteresis of the temperature, precipitation, and ITCZ location.** Time-series of **a**, CO$_2$ concentration (green), the global mean surface air temperature (red), precipitation (blue), and **b**, ITCZ centroid (red). The vertical dotted lines indicate the maximum or minimum Year of each variable, respectively. The solid lines and shadings show the ensemble means and the 99% confidence level in the mean, respectively. **(c to e)** Hysteresis of the global SAT, the precipitation anomalies, and the ITCZ centroid corresponding to the CO$_2$ concentration relative to Year 2000. The thick and light scatters indicate the ensemble means and full ensemble spread, respectively. All the lines and scatters denote an annual mean and are smoothed by the 11-year running mean.
Fig. 2 | Changes in the global SAT and hydrological cycle. a, Evolution of the zonal-mean precipitation anomalies relative to Year 2140. b, Difference in the precipitation between Year 2210 and 2070. c, same as b, but the data from the CMIP6. (d and e) same as b, but for the SAT, the precipitation minus the evaporation (shading) and resultant moisture fluxes (vector). The rightmost shading in panel e indicates the zonal mean of the meridional moisture fluxes. The regions denoted by the cross-shaped dots a, colors (b, d and e), and dots c, indicate where the model consistency is insignificant, significant, and significant, respectively at the 99% confidence level using a bootstrap test. All the calculations were conducted after taking the 11-year running mean.
Fig. 3 | Changes in the atmospheric meridional energy exchanges. **a**, Atmospheric meridional moist static energy flux in the annual mean. **b**, Time-series of the ITCZ centroid (red), the latitude of the maximum precipitation (blue), the temperature contrast (green) between the tropics of NH and SH, **c**, the AMOC strength (blue) and the poleward energy transport at 30°N (red) and 30°S (green). Note that the poleward energy transport at 30°S is the absolute value. The lines, shadings, and time-filter are the same as in Fig. 1b. (see Methods for the calculation details)
Fig. 4 | Changes in the land hydrological cycle. a, Difference in the land precipitation (shading) and 850hPa winds (vector) between Year 2210 and 2070. The precipitation anomalies are percentage anomalies relative to Year 2070. The regions denoted by colors indicate where the responses are significant at the 99% confidence level using a bootstrap test. b, c, d, e, Hysteresis of the area-averaged precipitation anomalies relative to Year 2000 in each region, which shows the significant precipitation changes. Sahara Desert (15°–35°N, 15°W–45°W), North America (30°–50°N, 70°–125°W), South America (10°–55°S, 35°–80°W), Antarctica (60°–90°S, 180°W–180°E). All the calculations were conducted after taking the 11-year running mean.
Evolution and hysteresis of the temperature, precipitation, and ITCZ location. Time-series of a, CO2 concentration (green), the global mean surface air temperature (red), precipitation (blue), and b, ITCZ centroid (red). The vertical dotted lines indicate the maximum or minimum Year of each variable,
respectively. The solid lines and shadings show the ensemble means and the 99% confidence level in the mean, respectively. (c to e) Hysteresis of the global SAT, the precipitation anomalies, and the ITCZ centroid corresponding to the CO2 concentration relative to Year 2000. The thick and light scatters indicate the ensemble means and full ensemble spread, respectively. All the lines and scatters denote an annual mean and are smoothed by the 11-year running mean.

Figure 2

Changes in the global SAT and hydrological cycle. a, Evolution of the zonal-mean precipitation anomalies relative to Year 2140. b, Difference in the precipitation between Year 2210 and 2070. c, same as b, but the data from the CMIP6. (d and e) same as b, but for the SAT, the precipitation minus the evaporation (shading) and resultant moisture fluxes (vector). The rightmost shading in panel e indicates the zonal mean of the meridional moisture fluxes. The regions denoted by the cross-shaped dots a, colors (b, d and e), and dots c, indicate where the model consistency is insignificant, significant, and significant, respectively at the 99% confidence level using a bootstrap test. All the calculations were conducted after taking the 11-year running mean. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square
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Figure 3

Changes in the atmospheric meridional energy exchanges. a, Atmospheric meridional moist static energy flux in the annual mean. b, Time-series of the ITCZ centroid (red), the latitude of the maximum precipitation (blue), the temperature contrast (green) between the tropics of NH and SH, c, the AMOC
strength (blue) and the poleward energy transport at 30°N (red) and 30°S (green). Note that the poleward energy transport at 30°S is the absolute value. The lines, shadings, and time-filter are the same as in Fig. 1b. (see Methods for the calculation details)

Figure 4

Changes in the land hydrological cycle. a, Difference in the land precipitation (shading) and 850hPa winds (vector) between Year 2210 and 2070. The precipitation anomalies are percentage anomalies relative to Year 2070. The regions denoted by colors indicate where the responses are significant at the 99% confidence level using a bootstrap test. b, c, d, e, Hysteresis of the area-averaged precipitation anomalies relative to Year 2000 in each region, which shows the significant precipitation changes. Sahara Desert (15°–35°N, 15°W–45°W), North America (30°–50°N, 70°–125°W), South America (10°–55°S, 35°–80°W), Antarctica (60°–90°S, 180°W–180°E). All the calculations were conducted after taking the 11-year running mean. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

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