Contrasting fast and slow ITCZ migrations linked to the delayed Southern Ocean warming

Wei Liu[1*], Shouwei Li[1], Chao Li[2], Maria Rugenstein[3] and Antony P. Thomas[1]

[1]Department of Earth Sciences and Planetary Sciences, University of California Riverside, Riverside, CA USA.

[2]Max Planck Institute for Meteorology, Hamburg, Germany

[3]Department of Atmospheric Science, Colorado State University, Fort Collins, CO, USA

*Corresponding author. Email: wei.liu@ucr.edu

Migrations of the intertropical convergence zone (ITCZ) have significant impacts on tropical climate and society. Here we examine the ITCZ migration caused by CO_2 increase using climate simulations. During the first one to two decades, we find a northward ITCZ displacement primarily related to an anomalous southward atmospheric cross-equatorial energy transport. Over the next hundreds or thousands of years, the ITCZ moves south. In contrast to early decades, the Southern Ocean has seen significantly delayed surface warming and reduced ocean heat uptake, which increases the inter-hemispheric asymmetry of ocean heat uptake and creates a northward atmospheric cross-equatorial energy transport anomaly to move the ITCZ southward. This southward ITCZ shift, however, is reduced by changes in the net energy input to the atmosphere at the equator by about two-fifths. Our finding highlights the importance of Southern Ocean heat uptake to long-term ITCZ evolution by showing that the (quasi-)equilibrium ITCZ response is opposite to the transient ITCZ response.

The intertropical convergence zone (ITCZ) contributes around one-third of the world's precipitation in the current climate. Because of the ITCZ's sharp meridional profile, even a slight change in its location can cause dramatic changes in rainfall, which has a marked impact on the tropical climate and society. Over long (decadal, centurial, and millennial) timescales, the location of annual mean ITCZ can be strongly modified by a variety of external forcings, such as orbitally driven changes in incoming solar radiation[1,2], ice sheet changes[3,4], anthropogenic aerosols and greenhouse gases[5,6]. Within the Earth's system, radiative feedback[7] and changes in ocean circulations like the Atlantic meridional overturning circulation (AMOC)[8-11] also modulate properties of the ITCZ.

The change in the ITCZ location caused by CO_2, which is the main greenhouse gas produced by human activity and one of the key drivers of past and present climate change, is of particular interest. Previous CO_2 doubling or quadrupling experiments using an atmosphere general circulation model in conjunction with an aquaplanet slab-ocean essentially show a northward ITCZ shift because of radiative feedback from clouds and water vapor[12-14]. However, when the realistic distributions of continents and sea ice are taken into account, models project that the ITCZ could move either northward or southward in response to an increase in CO_2[7]. The large uncertainty of ITCZ location change is mostly related to the uncertainty in the responses of clouds and sea ice. This ITCZ uncertainty persists even after ocean dynamics are included in models, where a dynamic ocean may mediate the extratropical influences on the ITCZ through changes in ocean heat transport[15,16]. For instance, the Coupled Model Intercomparison Project phase 5 (CMIP5) climate models show diverse ITCZ responses to a quadrupling of atmospheric CO_2 concentration[17,18].

Notably, the aforementioned ITCZ location changes in the CMIP5 models are based on a simulation of CO_2 quadrupling primarily over about one and a half centuries. Beyond this time frame, there is a gap in our knowledge of the long-term, toward the millennial evolution of the ITCZ, or in line with climate sensitivity, the equilibrium ITCZ response to CO_2 radiative forcing. This gap will be made even more clear by the fact that it will take thousands of years for the Earth system to return to equilibrium following a CO_2 perturbation[19,20]. On the other hand, elucidating the equilibrium ITCZ response to increasing CO_2 will help us better understand hydrological changes in future centuries[21] and past warm climates such as the warm Miocene and

Pliocene Epochs[22] and Early Eocene[23]. Therefore, bridging the aforementioned gap using climate model simulations serves as the focus of the current study. Following that, we will show distinct transient and (quasi-)equilibrium responses of the ITCZ to rising CO_2 as simulated by a broad range of fully coupled climate models.

A prolonged global ITCZ migration

We begin by examining the changes in the ITCZ location from the perspective of tropical precipitation centroid in the CMIP5 and CMIP6 CO_2 quadrupling experiments, in which the atmospheric CO_2 concertation in the model is abruptly increased from the preindustrial level to four times that level (Method). In comparison to preindustrial times, the multi-model mean exhibits a rapid northward shift of the annual and zonal mean ITCZ over the first one to two decades of CO_2 increases (Fig. 1a), which is consistent with previous results[12-14]. Seen from tropical precipitation centroid (Method), the zonal-mean ITCZ moves northward by 0.18 ± 0.21 degree (multi-model mean $\pm$ one standard derivation among models) during the first 20 years. The displacement of the rain belt to the north is particularly pronounced over the Indian Ocean, with anomalous decreases and increases in the rainfall maximum and to the north, respectively (Fig. 2a). The ITCZ deepens and narrows over the Pacific[24-26], which is likely due to a strengthening of the Hadley circulation manifested as a “deep-tropics squeeze”[27]. This fast precipitation response in the first 20 years reflects some characteristics of a rapid adjustment of the climate system to abrupt CO_2 forcing[28,29] as reported by the Precipitation Driver and Response Model Intercomparison Project (PDRMIP)[29]. For example, precipitation decreases over Central America, the eastern North Pacific, the Caribbean Sea, northern South America, the equatorial South Atlantic and Indian Oceans but increases over the tropical region of Africa and northern Australia. However, our first 20-year precipitation response is based on coupled model simulations, which differs from the PDRMIP fixed sea surface temperature (SST) experiment. As a result, the precipitation response also includes slower SST-mediated changes[29], such as increased precipitation over the equatorial Pacific. After 20 years, the ITCZ starts to move south. By the end of the 150-year CMIP5 and CMIP6 simulations, it is relatively close to its preindustrial location (Fig. 1a). We also observe a high level of model uncertainty in the CO_2-induced change in the ITCZ, which is consistent with previous findings[17,18].

To elucidate the ITCZ evolution over a period longer than one century or two, we investigate CO_2 quadrupling simulations by an eight-model ensemble including seven climate models from the original LongRunMIP[30] with simulation lengths of at least 1000 years and one CMIP6 model with simulation length of 1000 years (referred to as LongRunMIP for the convenience of discussion, Method). The ensemble mean of the LongRunMIP shows a strong northward ITCZ shift during the first few decades (Fig. 1c), particularly over the Indian Ocean (Fig. 2b), which is consistent with previous CMIP5 and CMIP6 model results (Fig. 1a). Tropical precipitation centroid suggests a northward ITCZ migration of 0.16 ± 0.12 degrees (multi-model mean $\pm$ one standard derivation among models) in the first 20 years. After that, the ITCZ shows a trend of southward migration, especially 100 years after the CO_2 increase, at a rate of about 0.02 degrees per century between 100 and 1000 years (Fig. 1c). The southward ITCZ migration is robust over both the Atlantic and Pacific Oceans (Fig. 2c and d).

The physical mechanisms

The atmospheric energy-flux theory[7,31-33], which connects the zonal-mean ITCZ location to atmospheric cross-equatorial energy transport and the net energy input to the atmosphere at the equator (Method), can help understand the non-monotonic zonal-mean ITCZ movement. We apply the atmospheric energy-flux theory to the CO_2 quadrupling experiments, with a particular emphasis on the LongRunMIP and the multi-model mean result. To indicate the location of the zonal-mean ITCZ, we calculate the latitude of the energy flux equator that is determined by atmospheric cross-equatorial energy transport and the net energy input to the atmosphere at the equator (Method). We find that both metrics, the energy flux equator and tropical precipitation centroid, show a generally consistent pattern of ITCZ movement (Fig. 1). For the first two decades, the energy flux equator moves northward by 0.69 degrees (Fig. 1d) primarily related to an anomalous southward atmospheric cross-equatorial energy transport (Fig. 1c) generated by rising CO_2 relative to preindustrial times, given that the contribution of the net energy input change to ITCZ movement (a southward shift by 0.07 degrees) is about one order smaller (Fig. 1d). The anomalous southward energy transport is caused by inter-hemispheric asymmetry of top of atmosphere (TOA) radiation and surface energy (Fig. 3a, Fig. 4a). CO_2 increases bring about dramatic global changes in the TOA radiation feedback (Method) of water vapor, temperature, albedo, and clouds (Extended Data Fig. 1), with these changes offset between hemispheres and individual feedback (Fig. 3b). Water vapor, cloud, and albedo feedback, in particular, contributes the most to the inter-hemispheric asymmetry and results in a slightly less TOA radiation increase in the Southern than Northern Hemisphere (Fig. 3a, Fig. 4a), which is consistent with the results from previous studies[12-14,34]. On the other hand, the rising CO_2 causes ocean heat uptake in global oceans, particularly where the ocean mixed layer is deep (Fig. 5b). The net change in inter-hemispheric surface energy asymmetry indicates that the Southern Ocean absorbs more heat than the northern ones. Note that the CO_2 quadrupling simulations from CMIP5 and CMIP6 produce a consistent result (Figs. 1b and 3, Extended Data Fig. 2) on changes in cross-equatorial energy transport and inter-hemispheric asymmetry of TOA radiation, with the exception that the majority of these models prefer more heat uptake in the northern oceans (Fig. 3a).

After the first two decades, the CO_2-induced southward atmospheric energy transport diminishes and even shifts northward, which is anti-correlated with the southward migration of the ITCZ[35-37](Fig. 1c and d). The energy flux equator and tropical precipitation centroid show significant southward migration trends between years 100 and 1000, of 0.13 degrees per century ($p<0.01$) and 0.02 degrees per century ($p<0.01$), respectively (Method). Herein we depict how atmospheric cross-equatorial energy transport varies in the CO_2 quadrupling experiment during the first two decades and the final 1000 years. In the latter period, we find a northward energy transport anomaly relative to preindustrial times, which is primarily caused by an increased inter-hemispheric asymmetry of surface energy flux. Compared to the first two decades, the subpolar North Atlantic absorbs more heat from the atmosphere while the Arctic and North Pacific take less heat by the end of 1000 years (Fig. 5b, d and f), resulting in a smaller reduction of ocean heat uptake in the northern oceans (Fig. 4). In comparison to the northern oceans, the Southern Ocean absorbs even less heat from the atmosphere (Fig. 5b, d and f), especially between 40°S and 60°S (Fig. 4), which leads to an anomalous inter-hemispheric asymmetry of ocean heat uptake—the atmosphere losing less heat in the Southern than Northern Hemisphere—and thus an anomalous northward atmospheric cross-equatorial energy transport by the end of 1000 years (Fig. 3a). Note that changes in surface turbulent (sensible and latent) heat flux are primarily responsible for changes in ocean heat uptake over the Southern Ocean (Fig. 5f and h, Extended

Data Fig. 3). Compared to the first two decades, despite surface warming enhances over global oceans, the delayed surface warming is especially strong over the Southern Ocean (Fig. 6) due to deep vertical mixing of water[38] and wind-driven upwelling of water from depth[39]. The delayed Southern Ocean warming[20] reduces downward turbulent heat flux at the ocean surface because of a negative turbulent heat flux feedback[37,40], indicating that surface heat flux response acts to dampen SST anomalies.

However, compared to the inter-hemispheric asymmetry of ocean heat uptake, changes in inter-hemispheric asymmetry of TOA radiation have a much smaller effect on the anomalous transport of atmosphere energy (Fig. 3a). This could be due to fact that atmospheric processes modulate the atmospheric energy budget more quickly than ocean processes. Relative to the first two decades, TOA radiation has decreased globally, with the exception of a few areas such as the central and eastern tropical Pacific by the end of 1000 years (Fig. 5a, c and e). The Southern Hemisphere experiences a similar TOA radiation reduction to the Northern Hemisphere (Fig. 4c). In contrast to the Northern Hemisphere, the water vapor and cloud feedback processes result in anomalous positive radiation entering the Southern Hemisphere via the TOA, but their effects are mostly counteracted by the albedo and temperature feedback (Fig. 3b, Extended Data Fig. 1). It is worth noting the hemispheric asymmetries of planetary albedo[34]: further declines in Arctic and Antarctic sea ice by the end of 1000 years cause large increases in TOA radiation in both polar regions via the albedo feedback (Extended Data Fig. 1i). However, both large radiation increases cancel out so that the albedo feedback contributes far less to the inter-hemispheric asymmetry of TOA radiation than other feedback.

In addition, we notice that changes in the net energy input to the atmosphere at the equator have an increasing contribution to ITCZ movements after the first two decades (Fig. 1d). To estimate this contribution, we compare the latitudes of the energy flux equator in two cases, one with the net energy input from the CO_2 quadrupling simulation and the other with the net energy input fixed at its preindustrial level (Method). We find that changes in the net energy input to the atmosphere at the equator can reduce the southward ITCZ shift by 39.5% over years 100-1000.

The (quasi-)equilibrium ITCZ response

We further investigate a subset of LongRunMIP of three models with simulation times of at least 4000 years (referred to as LongRunMIP_sub, Method), which is sufficient for the Earth's climate system to achieve a new (quasi-)equilibrium state following CO_2. perturbation. We find that the global ITCZ for LongRunMIP_sub multi-model mean changes similarly to that of LongRunMIP over the first millennium, followed by a persistent southward shift (Fig. 1e and f). Between years 100 and 4000, the energy flux equator and tropical precipitation centroid exhibit significant southward migration trends of 0.25 degrees per millennium ($p<0.01$) and 0.03 degrees per millennium ($p<0.01$), respectively (Method). Both metrics suggest that the (quasi-)equilibrium ITCZ response by 4000 years appears as a southward shift from preindustrial levels, which differs from the transient ITCZ response during the first few decades (Fig. 1e and f, Fig. 2e).

The southward displacement of the (quasi-)equilibrium ITCZ response can also be explained using atmospheric energy-flux theory. By the end of 4000 years, the quadrupled CO_2 has caused an anomalous northward atmospheric cross-equatorial energy transport, primarily due to the anomalous inter-hemispheric asymmetry of ocean heat uptake (Extended Data Fig. 4). Compared to the first two decades, while TOA radiation generally decreases on a global scale (Extended Data Fig. 5), its inter-hemispheric asymmetry has barely changed because of the cancellation of TOA radiation changes between hemispheres (Extended Data Fig. 4). On the other hand, the Southern Ocean and subpolar North Atlantic experience increased surface warming (Extended Data Fig. 6), which reduces ocean heat uptake in those two regions, primarily owing to the turbulent heat flux feedback (Extended Data Fig. 5). However, because the Southern Ocean is much larger than the subpolar North Atlantic, the Southern Hemisphere experiences a larger reduction in integrated ocean heat uptake than the Northern Hemisphere, which drives atmospheric energy transport northward across the equator and pushes the ITCZ southward. Changes in the net energy change input at the equator also influence ITCZ migrations. They lessen the southward ITCZ displacement by 37.5% over years 100-4000 (Method).

Discussions

We examine the response of the global ITCZ to quadrupled CO_2 using climate simulations. The CO_2 increase results in a northward ITCZ compared to preindustrial times, along with an anomalous southward atmospheric cross-equatorial energy transport during the first one to two decades while atmospheric net energy input at the equator has a minor effect on the ITCZ movement. After two decades, the ITCZ starts to move south. In contrast to the first two decades, the Southern Ocean has experienced significantly delayed surface warming and reduced ocean heat uptake, which enhances the inter-hemispheric asymmetry of ocean heat uptake, produces a northward atmospheric energy transport anomaly, and thus contributes to the southward migration of the ITCZ. However, the change in the net energy input to the atmosphere at the equator reduces this southward ITCZ shift by about two-fifths. We also investigate the (quasi-)equilibrium ITCZ response over 4000 years, which shows a southward shift from preindustrial levels, in contrast to the northward shift of the transient ITCZ response during the first two decades. It merits attention that the time-dependent ITCZ response discussed here is different from that to volcanic eruptions[41] from the perspectives of both forcing scenario and time scale.

Our findings shed light on the role of AMOC change in ITCZ shifts as a result of global warming. Previous freshwater hosing experiments[4] show that an AMOC slowdown caused by ice sheet melt into the North Atlantic can give rise to a southward displacement of the ITCZ owing to abated northward oceanic heat transport across the Atlantic. Our CO_2 forcing scenario, however, differs from this freshwater forcing scenario. The LongRunMIP ensemble mean simulates a CO_2-induced AMOC deceleration in the first century but a subsequent AMOC recovery[20,42] (Extended Data Fig. 7a). This strengthened AMOC over the next 900 years coincides with a southward ITCZ migration, which differs from the results of freshwater hosing experiments. The underlying reason is that, rather than the AMOC, delayed Southern Ocean warming and reduced heat uptake dominate the southward ITCZ shift during this time. An additional analysis reveals that AMOC recovery leads to a trend of ocean heat transport convergence and hence a decline trend of ocean heat uptake[43] in the North Atlantic (Extended Data Fig. 7b). This decline in Atlantic Ocean heat uptake contributes to a decrease in surface energy flux in the Northern Hemisphere within 30^{o}N-65^{o}N (Extend Data Fig. 7b). Nonetheless, the reduced Southern Ocean heat uptake (30^{o}S-65^{o}S) is even faster and stronger than its counterpart (30^{o}N-65^{o}N), and thus essentially controls the change in interhemispheric asymmetry of surface energy flux over years 100-1000 (Extend Data Fig. 7c). Such dominant role of

Southern Ocean heat uptake is robust across models, regardless of AMOC recovery speed uncertainty among models[42]. Our findings underline the significance of the Southern Ocean heat uptake[44] in the long-term ITCZ evolution under climate change.

Our study shows a non-monotonic ITCZ migration under the simple atmospheric CO_2 forcing. The ITCZ migration may become more complex in future scenarios of representative concentration pathways and shared socioeconomic pathways that include other forcings such as anthropogenic aerosols and stratospheric ozone[6], or in scenarios of CO_2 ramp-up and ramp-down[45], or with nonlinearities in ocean warming patterns on century to millennium time scales[46]. For example, the AMOC exhibits a clear hysteresis under CO_2 ramp-up and ramp-down forcings, which contributes to an ITCZ hysteresis[45]. This is because, following the CO_2 forcing turnabout, the AMOC weakens further and reaches its minimum value, causing a Northern Hemisphere cooling and a negative atmospheric net energy input, which promotes the Northern Hemisphere poleward atmospheric energy transport and amplifies the inter-hemispheric energy transport contrast. These changes in the AMOC and ITCZ systems, however, include either their direct responses to the varying CO_2 forcing or the adjustments due to feedback in both systems. The constant CO_2 forcing in our study, on the other hand, excludes the influence of changes in CO_2 forcing and thus allows for a comprehensive analysis of the adjustments within the climate system on different timescales.

Main Reference

1. Joussaume, S. et al. Monsoon changes for 6000 years ago: results of 18 simulations from the Paleoclimate Modeling Intercomparison Project (PMIP). *Geophys. Res. Lett.* **26**, 859-862 (1999).
2. Biasutti, M. et al. Global energetics and local physics as drivers of past, present and future monsoons. *Nat. Geosci.* **11**, 392-400 (2018).
3. Chiang, J.C., Biasutti, M. & Battisti, D.S. Sensitivity of the Atlantic intertropical convergence zone to last glacial maximum boundary conditions. *Paleoceanography* **18**, 1094 (2003).
4. Li, S. & Liu, W. Deciphering the migration of the intertropical convergence zone during the last deglaciation. *Geophys. Res. Lett.* **49**, e2022GL098806 (2022).
5. Hwang, Y.T., Frierson, D.M. & Kang, S.M. Anthropogenic sulfate aerosol and the southward shift of tropical precipitation in the late 20th century. *Geophys. Res. Lett.* **40**, 2845-2850 (2013).
6. Byrne, M.P., Pendergrass, A.G., Rapp, A.D. & Wodzicki, K.R. Response of the intertropical convergence zone to climate change: Location, width, and strength. *Curr. Clim. Change Rep.* **4**, 355-370 (2018).
7. Frierson, D.M. & Hwang, Y.T. Extratropical influence on ITCZ shifts in slab ocean simulations of global warming. *J. Clim.* **25**, 720-733 (2012).
8. Zhang, R. & Delworth, T.L. Simulated tropical response to a substantial weakening of the Atlantic thermohaline circulation. *J. Clim.* **18**, 1853-1860 (2005).
9. Stouffer, R.J. et al. Investigating the causes of the response of the thermohaline circulation to past and future climate changes. *J. Clim.* **19**, 1365-1387 (2006).

10. Liu, W., Xie, S.P., Liu, Z. & Zhu, J. Overlooked possibility of a collapsed Atlantic Meridional Overturning Circulation in warming climate. *Sci. Adv.* **3**, e1601666 (2017).
11. Moreno-Chamarro, E., Marshall, J. & Delworth, T.L. Linking ITCZ migrations to the AMOC and North Atlantic/Pacific SST decadal variability. *J. Clim.* **33**, 893-905 (2019).
12. Merlis, T.M., Zhao, M. & Held, I.M. The sensitivity of hurricane frequency to ITCZ changes and radiatively forced warming in aquaplanet simulations. *Geophys. Res. Lett.* **40**, 4109-4114 (2013).
13. Voigt, A. et al. The tropical rain belts with an annual cycle and a continent model intercomparison project: TRACMIP. *J. Adv. Model. Earth Syst.* **8**, 1868-1891 (2016).
14. Seo, J., Kang, S.M. & Merlis, T.M. A model intercomparison of the tropical precipitation response to a CO_2 doubling in aquaplanet simulations. *Geophys. Res. Lett.* **44**, 993-1000 (2017).
15. Kay, J.E. et al. Global climate impacts of fixing the Southern Ocean shortwave radiation bias in the Community Earth System Model (CESM). *J. Clim.* **29**, 4617-4636 (2016).
16. Hawcroft, M. et al. Southern Ocean albedo, inter-hemispheric energy transports and the double ITCZ: Global impacts of biases in a coupled model. *Clim. Dyn.* **48**, 2279-2295 (2017).
17. Donohoe, A. & Voigt, A. Why future shifts in tropical precipitation will likely be small: the location of the tropical rain belt and the hemispheric contrast of energy input to the atmosphere. Climate Extremes: Patterns and Mechanisms, 115-137 (2017).
18. Atwood, A.R., Donohoe, A., Battisti, D.S., Liu, X. & Pausata, F.S. Robust longitudinally variable responses of the ITCZ to a myriad of climate forcings. *Geophys. Res. Lett.* **47**, e2020GL088833 (2020).

19. Stouffer, R.J. & Manabe, S. Response of a coupled ocean–atmosphere model to increasing atmospheric carbon dioxide: Sensitivity to the rate of increase. *J. Clim.* **12**, 2224-2237 (1999).

20. Li, C., von Storch, J.S. & Marotzke, J. Deep-ocean heat uptake and equilibrium climate response. *Clim. Dyn.* **40**, 1071-1086 (2013).

21. Song, F., Lu, J., Leung, L.R. & Liu, F. Contrasting phase changes of precipitation annual cycle between land and ocean under global warming. *Geophys. Res. Lett.* **47**, e2020GL090327 (2020).

22. Burls, N.J. & Fedorov, A.V. Wetter subtropics in a warmer world: Contrasting past and future hydrological cycles. *Proc. Nat. Acad. Sci.* **114**, 12888-12893 (2017).

23. Cramwinckel, M.J. et al. Global and zonal-mean hydrological response to early Eocene warmth. *Paleoceanogr. Paleoclimatol.* **38**, e2022PA004542 (2023).

24. Wodzicki, K.R. & Rapp, A.D. Long-term characterization of the Pacific ITCZ using TRMM, GPCP, and ERA-Interim. *J. Geophys. Res.: Atmos.* **121**, 3153-3170 (2016).

25. Byrne, M.P. & Schneider, T. Narrowing of the ITCZ in a warming climate: Physical mechanisms. *Geophys. Res. Lett.* **43**, 11350-11357 (2016).

26. Zhou, W., Xie, S.P. & Yang, D. Enhanced equatorial warming causes deep-tropical contraction and subtropical monsoon shift. *Nat. Clim. Change* **9**, 834-839 (2019).

27. Lau, W.K. & Kim, K.M. Robust Hadley circulation changes and increasing global dryness due to CO_2 warming from CMIP5 model projections. *Proc. Nat. Acad. Sci.* **112**, 3630-3635 (2015).

28. Myhre, G., et al. Anthropogenic and natural radiative forcing, in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment

Report of the Intergovernmental Panel on Climate Change, edited by T. F. Stocker et al., pp. 659–740, Cambridge Univ. Press, Cambridge, U. K., and New York (2013).

29. Samset, B. H., et al. Fast and slow precipitation responses to individual climate forcers: A PDRMIP multimodel study. *Geophys. Res. Lett.* **43**, 2782–2791 (2016).

30. Rugenstein, M. et al. LongRunMIP: motivation and design for a large collection of millennial-length AOGCM simulations. *Bull. Am. Meteorol. Soc.* **100**, 2551-2570 (2019).

31. Kang, S.M., Held, I.M., Frierson, D.M. & Zhao, M. The response of the ITCZ to extratropical thermal forcing: Idealized slab-ocean experiments with a GCM. *J. Clim.* **21**, 3521-3532 (2008).

32. Schneider, T., Bischoff, T. & Haug, G.H. Migrations and dynamics of the intertropical convergence zone. *Nature* **513**, 45-53 (2014).

33. Adam, O., Bischoff, T. & Schneider, T. Seasonal and interannual variations of the energy flux equator and ITCZ. Part I: Zonally averaged ITCZ position. *J. Clim.* **29**, 3219-3230 (2016).

34. Rugenstein, M. & Hakuba, M. Connecting hemispheric asymmetries of planetary albedo and surface temperature. *Geophys. Res. Lett.* **50**, e2022GL101802 (2023).

35. Donohoe, A., Marshall, J., Ferreira, D. & Mcgee, D. The relationship between ITCZ location and cross-equatorial atmospheric heat transport: From the seasonal cycle to the Last Glacial Maximum. *J. Clim.* **26**, 3597-3618 (2013).

36. Kang, S.M., Shin, Y. & Xie, S.-P. Extratropical forcing and tropical rainfall distribution: energetics framework and ocean Ekman advection. *npj Clim. Atmos. Sci.* **1**, 20172 (2018).

37. Liu, W. & Fedorov, A.V. Global impacts of Arctic sea ice loss mediated by the Atlantic meridional overturning circulation. *Geophys. Res. Lett.* **46**, 944-952 (2019).

38. Manabe, S., Stouffer, R.J., Spelman, M.J. & Bryan, K. Transient responses of a coupled ocean–atmosphere model to gradual changes of atmospheric CO_2. Part I. Annual mean response. *J. Clim.* **4**, 785-818 (1991).

39. Armour, K.C., Marshall, J., Scott, J.R., Donohoe, A. & Newsom, E.R. Southern Ocean warming delayed by circumpolar upwelling and equatorward transport. *Nat. Geosci.* **9**, 549-554 (2016).

40. Zhang, L. & Cooke, W. Simulated changes of the Southern Ocean air-sea heat flux feedback in a warmer climate. *Clim. Dyn.* **56**, 1-16 (2021).

41. Erez, M. & Adam, O. Energetic constraints on the time-dependent response of the ITCZ to volcanic eruptions. *J Clim.* 34, 9989-10006 (2021).

42. Bonan, D.B., Thompson, A.F., Newsom, E.R., Sun, S. & Rugenstein, M. Transient and equilibrium responses of the Atlantic overturning circulation to warming in coupled climate models: The role of temperature and salinity. *J. Clim.* **35**, 5173-5193 (2022).

43. Liu, W., Fedorov, A.V., Xie, S.-P. & Hu, S. Climate impacts of a weakened Atlantic Meridional Overturning Circulation in a warming climate. *Sci. Adv.* **6**, eaaz4876 (2020).

44. Hwang, Y.T., Xie, S.-P., Deser, C. & Kang, S.M. Connecting tropical climate change with Southern Ocean heat uptake. *Geophys. Res. Lett.* **44**, 9449-9457 (2017).

45. Kug, J.S. et al. Hysteresis of the intertropical convergence zone to CO_2 forcing. *Nat. Clim. Change* **12**, 47-53 (2022).

46. Rugenstein, M.A., Sedláček, J. and Knutti, R. Nonlinearities in patterns of long-term ocean warming. *Geophys. Res. Lett.* **43**, 3380-3388 (2016).

Acknowledgments

This study has been supported by U.S. National Science Foundation (OCE-2123422, AGS-2053121, and AGS-2237743). W.L. is also supported by the UC Regents Faculty Development Award. C.L. was supported by the Clusters of Excellence CLICCS (EXC2037), University of Hamburg, funded by the German Research Foundation (DFG).

Author Contributions Statement

W.L. conceived the study and wrote the original draft of the paper. S.L. and A.T performed the analysis. C.L and M.R provided the data. All authors contributed to interpreting the results and made substantial improvements to the paper.

Competing Interests Statement

The authors declare no competing interests.

Figure legends

Figure 1. CO_2-induced zonal-mean ITCZ changes. (a,c,e) Changes (relative to preindustrial times) in the tropical precipitation centroid ($\Delta\phi_{cent}$, Method, multi-model mean, green; inter-model spread, one standard derivation among models, light green) and atmospheric cross-equatorial energy transport (ΔAET_{EQ}, multi-model mean, purple; inter-model spread, light purple; 1 PW = 10^{15} Watt) in the CO_2 quadrupling simulations by (a) CMIP5/6, (c) LongRunMIP and (e) LongRunMIP_sub models. **(b,d,f)** Same as (a,c,e) but for changes in the energy flux equator ($\Delta\delta$, Method, multi-model mean, blue; inter-model spread, one standard derivation

among models, light blue), $\Delta\delta_p$ (Method, multi-model mean, red; inter-model spread, light red) and $\Delta\delta$ minus $\Delta\delta_p$ (multi-model mean, dark gray; inter-model spread, light gray). A 21-year running mean is applied to all the time series. The first 20-year averages of $\Delta\phi_{cent}$ and $\Delta\delta$, ΔAET_{EQ} and $\Delta\delta_p$, $\Delta\delta$ minus $\Delta\delta$ are plotted at year 10, year 9 and year 8, respectively, for a clear visualization, all of which are in the form of multi-model mean (dot) ± one standard deviation among models (bars).

Figure 2. Maps of CO_2-induced precipitation changes. Precipitation changes (relative to preindustrial times, in units of mm/day) in the CO_2 quadrupling simulations for the multi-model means of (**a**) CMIP5/6 models over years 1-20, and LongRunMIP models over **(b)** years 1-20 and **(c)** years 981-1000, respectively. **(d)** Same as (b) but for LongRunMIP models for the difference between years 981-1000 and years 1-20. **(e)** Same as (b) but for LongRunMIP_sub models for the difference between years 3981-4000 and years 1-20. Stippling refers to the region where at least (a) 33 of 43 CMIP5/6 models, or (b,c,d) 6 of 8 LongRunMIP models, or (e) 2 of 3 LongRunMIP_sub models agree with the sign changes.

Figure 3. CO_2-induced changes in interhemispheric asymmetry of energy flux. (a) Changes (relative to preindustrial times, multi-model mean, dot; inter-model spread, one standard derivation among models, bars) in the atmospheric cross-equatorial energy transport (purple) and interhemispheric asymmetry (SH minus NH, Method) of the net TOA radiation (red), net surface energy flux (blue), surface turbulent heat flux (sensible plus latent, green), and surface radiation energy flux (shortwave plus longwave, orange) in the CO_2 quadrupling simulations by CMIP5/6 models and LongRunMIP models over years 1-20, respectively, and by LongRunMIP models for

the difference between years 981-1000 and years 1-20. **(b)** Same as panel (a) but for contributions to the TOA radiation asymmetry from the cloud (light green), water vapor (light purple), albedo (light red) and temperature (light blue) feedback as well as a residual term (grey). Note that only one LongRunMIP model (ACCESS1-ESM1-5) that has data available for the kernel calculation.

Figure 4. Zonal mean CO_2-induced energy flux changes. Changes (relative to preindustrial times) in the zonal mean (weighted) CO_2-induced energy flux changes (multi-model mean, line; inter-model spread, one standard derivation among models, shading) at the TOA (red) and surface (blue), and their difference (TOA minus surface, blue) in the CO_2 quadrupling simulations by **(a)** CMIP5/6 and **(b)** LongRunMIP over years 1-20. **(c)** Same as (b) but for LongRunMIP models for the difference between years 981-1000 and years 1-20.

Figure 5. Maps of CO_2-induced energy flux changes. (a,b) Maps of changes (relative to preindustrial times, in units of W/m^2) in the net (a) TOA radiation and (b) surface energy flux in the CO_2 quadrupling simulation for the multi-model mean of LongRunMIP models over years 1-20. **(c,d)** Same as (a,b) but for years 981-1000. **(e,f)** The differences between the two periods for the net (e) TOA radiation and (f) surface energy flux (years 981-1000 minus years 1-20). **(g,h)** Same as (e,f) but for surface (shortwave plus longwave) radiation energy flux and surface turbulent (sensible plus latent) heat flux. Stippling refers to the region where at least 33 of 43 CMIP5/6 models, or 6 of 8 LongRunMIP models agree with the sign changes.

Figure 6. Maps of CO_2-induced SST changes. SST changes (relative to preindustrial times, in units of K) in the CO_2 quadrupling simulation for the multi-model mean of LongRunMIP models over **(a)** years 1-20 and **(b)** years 981-1000, respectively. **(c)** Same as (a) but for the difference between years 981-1000 and years 1-20. Stippling refers to the region where at least 6 of 7 LongRunMIP models agree with the sign changes (ECHAM5-MPIOM is not included since SST data are not available for its CO_2 quadrupling simulation).

Methods

Climate models

We use preindustrial and CO_2 quadrupling simulations with 43 CMIP5/6 models (Supplementary Table 1). These models are chosen primarily due to the availability of data for the kernel calculation. The length of the CO_2 quadrupling simulation varies between models but is at least 150 years; we use 150-year simulation outputs for all models. To ensure that each model receives an equal amount of weight in the inter-model analysis, only one ensemble member is chosen from each model.

Furthermore, we use preindustrial and CO_2 quadrupling simulations from an eight-model ensemble (Extended Data Table 1), which includes seven LongRunMIP climate models and one CMIP6 model (ACCESS-ESM1-5) not included in the aforementioned CMIP5/6 models. The length of the CO_2 quadrupling simulation varies between models but is at least 1000 years; we use 1000-year simulation outputs for all models. There is also a LongRunMIP subset of three models (CESM104, GISS-E2-R, and MPI-ESM1-1) with CO_2 quadrupling simulations lasting more than 4000 years (referred to as LongRunMIP_sub, Extended Data Table 1). For these three models, we use 4459-year simulation outputs.

We realize that the double ITCZ bias remains an issue in several generations of climate models [47-51]. This ITCZ bias has been suggested to be linked to Southern Ocean cloud bias[48,50], however, the teleconnection between the Southern Ocean and tropical precipitation biases is muted by adjustments in energy transports in the coupled climate system[15,16]. Furthermore, a direct relationship between the mean-state double ITCZ bias and ITCZ changes is not statistically significant[52].

The atmospheric energy-flux theory

The overturning Hadley circulation transports moist static energy in the direction of its upper branches, that is away from the ITCZ. Since the eddy contribution to the tropical atmospheric energy transport is negligible in comparison to the overturning Hadley circulation contribution, the zonal-mean ITCZ should lie near the "energy flux equator" where the atmospheric meridional energy transport alters sign[7,31-33]. According to the atmospheric energy balance, the energy flux equator (δ) can be expressed as

$$\delta \approx -\frac{1}{a}\frac{AET_{EQ}}{NEI_o} \quad (1)$$

where a denotes the radius of Earth. Eq. (1) states that, to the first order, the energy flux equator is determined by the atmospheric cross-equatorial energy transport (AET_{EQ}) and the net energy input to the atmosphere at the equator (NEI_o). When the temporal change of atmospheric energy storage is neglectable on decadal or longer timescales, AET_{EQ} can be calculated as

$$AET_{EQ} = ATOA_{SH-NH} - ASFC_{SH-NH} \quad (2)$$

where $ATOA_{SH-NH}$ and $ASFC_{SH-NH}$ are the differences of the hemispherical integrations of energy fluxes entering the TOA and the ocean/land surface between the Southern Hemisphere (SH) and Northern Hemisphere (NH), respectively. They are determined as

$$ATOA_{SH-NH} = \frac{1}{2}\left[\int_{-\pi/2}^{0}\int_{0}^{2\pi} F_{TOA}a^2cos(\phi')d\lambda d\phi' - \int_{0}^{\pi/2}\int_{0}^{2\pi} F_{TOA}a^2cos(\phi')d\lambda d\phi'\right] \quad (3)$$

and

$$ASFC_{SH-NH} = \frac{1}{2}\left[\int_{-\pi/2}^{0}\int_{0}^{2\pi} F_{SFC}a^2cos(\phi')d\lambda d\phi' - \int_{0}^{\pi/2}\int_{0}^{2\pi} F_{SFC}a^2cos(\phi')d\lambda d\phi'\right] \quad (4)$$

where ϕ' and λ stand for latitude and longitude. Energy fluxes at the TOA and the ocean/land surface are designated as F_{TOA} and F_{SFC}, respectively. F_{TOA} is composed of TOA shortwave and longwave radiations fluxes, and F_{SFC} is composed of surface shortwave and longwave energy fluxes and sensible and latent heat fluxes. Note that the global mean of surface energy flux is subtracted from the TOA radiation energy flux to ensure that the global integration of vertical energy flux (F_{TOA} minus F_{SFC}) in the atmosphere is zero.

TOA radiative feedback

We employ the CESM-CAM5 radiative kernel[53] to calculate the contributions of climate feedback to TOA radiation changes using monthly mean atmosphere outputs from the CMIP5/6 and LongRunMIP models. To assess the change in TOA radiation relative to preindustrial times, we first compute monthly changes for the targeted variable over the target periods, e.g., years 1-20 for CMIP5/6 and LongRunMIP models and years 981-1000 for the LongRunMIP model, and then multiply this change by the corresponding radiative kernel.

The change in TOA radiation can then be divided into components caused by temperature, water vapor, albedo, cloud feedback, and a residual term. Planck and lapse rate feedback are included in the temperature feedback, and both shortwave and longwave cloud feedback are included in the cloud feedback. Due to data availability for the kernel calculation, the above decomposition of TOA radiation change is only applied to ACCESS-ESM1-5 for the LongRunMIP.

The metrics to estimate the ITCZ location

We adopt two metrics to estimate the location of the zonal-mean ITCZ. The first one is the latitudinal centroid of tropical precipitation:

$$\phi_{cent} = \frac{\int_{\phi_1}^{\phi_2} \phi' cos(\phi') P_r d\phi'}{\int_{\phi_1}^{\phi_2} cos(\phi') P_r d\phi'} \quad (5)$$

where $\phi_1 = 20^o S$ and $\phi_2 = 20^o N$ are the latitudinal integration bounds, and P_r is zonal mean precipitation[32]. The second one is the energy flux equator (δ)[31,32]. We compute the change in each metric with respect to its preindustrial control in the CO_2 quadrupling simulation. For instance, the changes in the energy flux equator and tropical precipitation centroid are represented by $\Delta\phi_{cent}$ and $\Delta\delta$, respectively. We further quantify the contributions of AET_{EQ} and NEI_o changes to ITCZ shifts by defining

$$\delta_p = -\frac{1}{a}\frac{AET_{EQ}}{NEI_{opi}} \quad (6)$$

where the net energy input to the atmosphere at the equator is fixed at its preindustrial level (NEI_{opi}). The difference between $\Delta\delta$ and $\Delta\delta_p$ reverals the effect of changes in the net energy input on ITCZ shifts.

We find a relatively small effect of NEI_o change on δ during the 150-year CMIP5/6 simulations (Fig. 1b), but in longer simulations, the effect of NEI_o change increases. In the LongRunMIP simulations, the trend of δ_p is -0.215 $\pm$ 0.190 degrees per century and the trend of δ is -0.129 $\pm$ 0.112 degrees per century over years 100-1000, respectively. The difference between the two is 0.085 $\pm$ 0.080 degrees per century, meaning that the change of NEI_o can reduce 39.5% of the southward ITCZ shift during this period. In the LongRunMIP_sub simulations, the trend of δ_p is -0.040 $\pm$ 0.002 degrees per century and the trend of δ is -0.025 $\pm$ 0.003 degrees per century over years 100-4000. The difference between the two is 0.015 $\pm$ 0.004 degrees per century, meaning that the change of NEI_o can reduce 37.5% of the southward ITCZ shift during the period.

Statistical significance test

We perform a Student-t test to determine the statistical significance of the linear trend of ITCZ migration. We calculate the p-value to see if the linear trend is significantly different from a zero trend. For the statistical significance of spatial changes in precipitation, energy flux and SST, we use the criteria that changes in the region where at least 33 of 43 CMIP5/6 models, or 6 of 8 or 7 LongRunMIP models, or 2 of 3 LongRunMIP_sub models agree with the sign changes are statistically significant. This statistical significance test of spatial changes, to some extent, is limited by the available models and data.

Data Availability

GPCP v2.3 data are available at https://psl.noaa.gov/data/gridded/data.gpcp.html. CMIP5 model data are available at https://esgf-node.llnl.gov/projects/cmip5/.
CMIP6 model data are available at https://esgf-node.llnl.gov/projects/cmip6/.

LongRunMIP data are available at https://www.longrunmip.org.

Code Availability

The source code of CESM1-CN is available at https://www.cesm.ucar.edu/. Figures are generated via the NCAR Command Language (NCL, Version 6.5.0) [Software]. (2018). Boulder, Colorado: UCAR/NCAR/CISL/TDD (https://doi.org/10.5065/D6WD3XH5).

Methods References

47. Lin, J.L. The double-ITCZ problem in IPCC AR4 coupled GCMs: Ocean-atmosphere feedback analysis. *J. Clim.* **20**, 4497–4525 (2007).
48. Hwang, Y.T. & Frierson, D.M.W. Link between the double-intertropical convergence zone problem and cloud biases over the Southern Ocean. *Proc. Natl. Acad. Sci. U.S.A.* 4935–4940 (2013).
49. Li, G. & Xie, S.-P. Tropical biases in CMIP5 multimodel ensemble: The excessive equatorial pacific cold tongue and double ITCZ problems. *J. Clim.* **27**, 1765–1780 (2014).
50. Adam, O., Schneider, T. & Brient, F. (2018). Regional and seasonal variations of the double-ITCZ bias in CMIP5 models. *Clim. Dyn.* **51**, 101–117 (2018).
51. Tian, B. & Dong, X. The double-ITCZ Bias in CMIP3, CMIP5 and CMIP6 models based on annual mean precipitation. *Geophys. Res. Lett.* **47**, e2020GL087232 (2020).
52. Samanta, D., Karnauskas, K. B. & Goodkin, N. F. Tropical Pacific SST and ITCZ biases in climate models: Double trouble for future rainfall projections?. *Geophys. Res. Lett.* **46**, 2242–2252 (2019).

53. Pendergrass, A.G., Conley, A. & Vitt, F.M. Surface and top-of-atmosphere radiative feedback kernels for CESM-CAM5. *Earth Syst. Sci. Data* **10**, 317-324 (2018).